

Non-ferrous Metal Ores Deposits, Minerals and Plants

(On the example of Former USSR)

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Abstract

For the first time, the comprehensive information about non-ferrous metals: mineral resources, geographical distribution, geology, mining and ore processing plants in the territory of the former USSR are review.

There is an approach to the evaluation of mineral-resources base, forecast of ore concentration and development of technologies. That consists of the combined consideration of the genetic of valuable deposits and the forms of ore bodies – in conjunction with mining, ore treatment technology and complex utilization of raw materials. In examples of complex ores technology of minerals selection is design by superposition of mineral properties and forces in gravitational, magnetic and adsorption-chemical fields. There is a classification of genetic types of non-ferrous ores and use of gravitation, flotation, magnetic separation, leaching and other mineral processing.

This book is intended for geologists, mineralogists, mining engineers, technologists of mineral processing and ore treatment, and businessmen in the field of minerals and CIS investments.

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INTRODUCTION

1. Presentation Structure

The problem of mineral resources has multiple aspects and calls for versatile examination. The production cycle encompasses geology, mining, mineral dressing, metallurgy, ecology, etc. Besides, non-ferrous metal ores are always complex not only in availability of different metals but also in components which can be utilized as building materials, fertilizers, chemical products and so on.

The ores can be classified variously:

- by genetic type - deposit geology,
- from the viewpoint of deposit mining, i.e., by dressing conditions,
- by base metals in the final products, and
- by socio-economic indicators: regional and geographic location, scale,

reserves, valuable component content and so on.

Up-to-date examination of the problem also requires essential extension of the conventional description of mineral reserves in the purely geological & mineralogical and process aspects.

First of all, there is no leaving aside of secondary mineral resources and technogenic raw materials whose value in industrial production grows all the time. There have already appeared non-ferrous metals which output from secondary resources in some countries accounts for 50 per cent and more. The cases in point are first and foremost mercury, tin, lead, tungsten, etc. Besides being a potential resource, technogenic materials solve ecologic problems while having a great economic value. It is natural that conventional technologies of mining, disintegration, dressing and metallurgy are not always applicable to these raw materials. [2].

The very notions of *deposit*, *ore* and *ore preparation*, etc. very although in processing of technogenic raw materials the metal quality is in the final analyses the same as in processing of conventional ores (except aluminum). This is all the more true for raw materials like oceanic concretions, sea and thermal water. New notions, like *non-waste technology*, *complex deposit development*, etc., have emerged. In this connection it is necessary first of all to agree upon definitions of terms and basic notions.

Much attention will be paid in the 1st chapter to the basic notions and definitions established in the mining & metallurgical industry of the former Soviet Union (FSU). The majority of these notions coincides with the generally-accepted ones, but there is some peculiarity owing to the prolonged isolation of the state and of its scientific and professional manpower. Admittedly, a detailed interpretation of terms, classifications and notions, especially in the new and latest trends of development of these industrial sectors, has bound to be useful for the Western reader.

The history of non-ferrous metallurgy in the FSU is also of certain interest. The evolution of modern industrial production can be often traced to the depths of the ages. Today it is of concern as the old fields have not been depleted and can be re-mined on an innovative process basis even at a substantial decrease in ore quality. For example, several Far East gold placers are already being worked for the third time in the 20th century alone.

After the first, (mostly Chinese) free miners and Siberian merchants, *GULAG* operated there in the Stalin's times. In the 80s free miner "artel's" (co-operatives) emerged here again. They use worn-out written-off equipment with primitive dressing plants. In so doing, a fourth revival of these placer mines is possible, despite the fact that, for example, in the Ussuri taiga the openings are healed within three or five years.

We shall present the geological description of the USSR territory in its general outline, bearing in mind geological regions which intersect the borders of the existing CIS states. Geology and mineral resources are discussed in more detail within the framework of the newly-formed republics and regions of Russia.

Furthermore we have found it possible and convenient to unite discussion of certain aspects and characteristics of mineral products with some operations of the process flowsheet. In so doing, the classification of ore complexes is given in combination with geochemistry and paragenesis of minerals. At the same time regional geology affords information on availability of certain deposits. It is natural that the description of deposited orebodies is given together with mining systems.

We are of the opinion that mineralogy combined with genetic ore types and dressing processes is the most important part which dictates the characteristics of the raw material base. Here our developments in the field of classification of ores, fields and other information which were previously published in Russian and verified by time have been made use of. [2,3].

It stands to reason that any classification, including that of fields, ores, processes as well as regional borders, etc., is a matter of convention. We do not lay claim to absolute accuracy and scientific substantiation. We are aware that any self-respecting geologist is certain to give his own scientifically-substantiated classification of fields. The same is true of all other specialists. Our classifications set up a claim principally to convenience of data presentation.

Chapter 1. Fundamental Concepts & Definitions

We think it expedient to discuss notions which sense and meaning are ambiguous in up-to-date conditions. The matter is not only in that science and technology in the USSR have been developing in some isolation but also in that Russian publications reached the English reader in a rather curtailed way. The raw material base of the CIS countries has been formed under somewhat peculiar conditions, and in order to describe the base it is necessary to overcome certain terminological difficulties particularly important to the Western reader.

As has already been indicated, secondary resources, waste and re-mining of fields gain greater and greater importance in industrial production at the end of this century and, especially, at the beginning of the next century. In the FSU the distorted planned economy brought about an enormous reserve of secondary resources owing to a number of reasons: non-complex use of raw materials, lack of investment, neglect of ecology, low quality and short life of equipment and so on. We must introduce a notion of technogenic raw materials, alongside geogenic deposits and ores which are a complex of natural minerals. Besides, this notion becomes more and more actual for the industry of the developed countries.

Along with this we do not consider this book a mere reference guide to present-day businessmen. It is also designed for process specialists, geologists, metallurgical engineers and everyone who is interested in the problems of mineral products and the other raw materials associated with them. We are resolved to maintain the highest scientific level of material presentation in describing of fields, ores and processing technologies.

From our viewpoint, of the greatest interest is an attempt to establish a general classification of ore complexes of geogenic and technogenic nature which combines genesis, technology, ecology and economy. Accordingly, there appears a necessity to link geological, mining, dressing and metallurgical notions from a terminological viewpoint.

1.1. Non-ferrous metals

There exist several classifications of chemical elements which differ in defining the group of metals assigned to the non-ferrous category. In any case manganese and chromium, besides iron, are usually assigned to the ferrous metals group. Sodium and potassium, which are encountered in nature as chloride salts, as well as calcium, strontium and barium tending to nonmetals are

commonly excluded from the consideration. We will adhere to the classifications which take into account the geological & mineralogical and processing properties of metals (Table 1.1).

Table 1.1. Geological & mineralogical and technological classification of non-ferrous metals

	Periodic table group							
Class	I	II	III	IV	V	V	VII	VIII
Heavy	Cu	Zn,Cd		Pb				Ni,Co
Minor		Hg		Sn,Ti,Zr	As,Sb,Bi			
Light	Li	Mg,B e	Al					
Refractory					Nb,Ta,V	Mo,W		
Noble	Ag, Au							Pt,Os,Ir, Ru,Rh,Pd
Rare earth			TR,Sc,Y					
Dispersed	Rb, Cs		Ga,In,Tl	Ge,Hf				
Radioactive		Ra	U,Th,Pu					

The non-ferrous metals industry was among the most high-level sectors of the USSR heavy industry engaged in the mining of ore deposits, including ore mining & concentration and metallurgy with production of non-ferrous metals for further processing. After World War II a sector whose challenge included mining and processing of ores of uranium and other radioactive elements, and later on beryllium and lithium, was separated with a view to creating an atomic bomb.

More than three hundred mines & concentrators, mining & metallurgical complexes and metallurgical works of various capacity have been in operation in the above sectors; each of them employed from several hundreds to tens of thousands of workers and specialists. The gigantic industrial complexes like Norilsk, Ust-Kamenogorsk, Balkhash, Almalyk, Dzhezkazgan, Central Ural and other works were of vital importance.

The main products were concentrates, cast metals & alloys, chemical compounds and non-ferrous metals & alloys products. By-products (sulfuric acid, building materials, some fertilizers and microfertilizers) used to be made from the waste in many cases. The entry raw materials were for the most part comprehensive, and associated components were extracted from ore on numerous occasions. For example, in the lead and zinc sector additional 18 components alongside lead and zinc used to be extracted, with more than 40 saleable product types made on their base. Fifteen components were recovered from copper ore with 40 product types made. About 30 per cent of sulfuric acid in the country were produced in the non-ferrous metals industry.

By the end of the 80s the run-of-mine material amounted to 2.5 bln tonnes, with virtually the same waste tonnage. The basic ore dressing process (about 90 %) was flotation. Metallurgical operations were at a fairly up-to-date level. By contrast, environment control at the plants and works of the sector has led to an ecological catastrophe.

In order to meet the requirements of the national economy and the military industry, the USSR Ministry of Non-Ferrous Metals Industry used to carry out measures on the development of the non-ferrous metals industry and the production build-up.

The Ministry's terms of reference were:

- start-up and commissioning of operations and facilities;
 - renovation and modernization of plants and works;
 - final exploration of deposits, mining operations in open pits and mines,
- among them shaft sinking;
- preparation of standards on estimating explored mineral product reserves, registering state and movement of reserves and depletion of mineral resources in the Earth's interior;
 - comprehensive ore processing with output of non-ferrous, rare and precious metals as well as diamonds;

- general contractor's functions with respect to non-ferrous metals plants under construction abroad with USSR technical assistance.

1.2. Deposits & ores of non-ferrous metals

The virtually unlimited reserves of mineral resources in the territory which occupied one sixth of the Earth's land were the raw materials base of the USSR non-ferrous metals industry. Essentially any genetic deposit type is encountered here. We shall discuss two radically different deposit types: geogenic and technogenic.

A mineral resource deposit on the Earth's surface or in the interior which can be used in industry in quantity, quality, occurrence conditions and processability is called a geogenic deposit. Deposits whose usage is economically feasible at the existing technology and engineering progress level are assigned to the workable category.

Geogenic deposits are composed of one or several orebodies whose generation takes place throughout the whole process of geological evolution and alteration of the Earth's crust in several stages. The concentration of ore-forming minerals of a certain composition under certain geological and physicochemical conditions prevailing at some time period, is an ore-forming stage. The number of these stages usually amounts to four or six, sometimes ten during the orebody generation process.

The ore-forming stage accounts for the whole mineral accumulation period which combines a number of successive phases belonging to one and the same genetic process. The ore deposit is usually composed within one mineral accumulation stage, more seldom two or more. For example, the upper parts of the ore bed may contain the mineral mass of the primary hydrothermal stage and of the stage predetermined by the secondary oxidation of the ore near the Earth's surface. The ore bed may be also formed in several stages of a monotype process common to different geological epochs.

Regional regularities and geological factors of mineral resource deposit formation were the result of endogenic and exogenic processes during the evolution of the Earth's crust.

Substances required for mineral resources to be formed enter from the upper mantle of the crust and from the surface in magmatic melts, liquid and gaseous solutions. Magmatogenic (endogenic) deposits are subdivided into several groups.[4].

Magmatic deposits are formed during impregnation of magmatic melts into the crust and cooling-down of them. The ores of Cr, Fe, Ti, Ni, Cu, Co, the platinum metals group, etc. are associated with the intrusions of the basic composition; the ores of Pd, Ta, Nb, Zr and rare earths (TR) are confined to alkaline massifs of magmatic rocks. The deposits of mica, feldspar, precious stones, Be, Li, Cs, Nb, Ta, partly Sn, U and TR are connected with granite pegmatites by genesis. Carbonatites associated with ultrabasic-alkaline rocks form Fe, Cu, TR, apatite and mica deposits. There are ores of Fe, Cu, Co, Pb, Zn, W, Mo, Sn, Be, U, Au, Bi, rock crystal, graphite and other mineral resources in contact-metasomatic deposits, especially, in scarns. Cu, Ni, Co, Zn, Pb, Bi, Mo, W, Sn, Li, Be, Ta, Nb, As, Sb, Hg, Cd, Ln, S, Se, Au, U, Ra, as well as quartz, barite, fluorite, asbestos, etc. are contained in pneumatolytic and hydrothermal deposits.[5].

Sedimentogene deposits which are formed in exogenic processes are subdivided into sedimentary, placer and weathering. Sedimentary deposits are enenerated on sea, lake, river and marsh bottoms with formation of stratified beds in enclosing sedimentary rocks. Placers containing Au, Pt, diamonds, etc. are accumulated in coastal sediments of seas and oceans as well as in river or lake sediments and on valley slopes. U, Cu, native sulfur ores and sedimentary deposits of Ni, Fe, Mn, bauxite, magnesite, kaoline are connected with the ancient and modern weathering crust of which infiltration deposits are typical. Previously available deposits undergo transformation deep in the interior under the conditions of high pressure and temperature, with the appearance of metamorphogenic beds (for example, the iron ores of the Krivoi Rog basin and the Kursk Magnetic Anomaly, the

gold and uranium ores of South Africa) and marble, andalusite, cyanite, graphite and other deposits newly formed during the rock metamorphism process.[5].

The industrial application field is used to distribute mineral resources into:

- a) fuel and energy resources (oil, natural gas, fossil coal, combustible shale, peat, uranium ore);
 - b) ore resources which are the raw materials base of iron & steel and non-ferrous metals industry (iron and manganese ore, chromite, bauxite, polymetallic ore, copper-nickel, tungsten, molybdenum, tin, precious metals ores, etc.);
 - c) mining & chemical raw materials (phosphorite, apatite, table, potassium and magnesia salts, sulfur and compounds, barite, boron ore, bromium and iodine-containing solutions);
 - d) natural building materials and non-metallic stones (marble, granite, jasper, agate, rock crystal, garnet, corundum, diamond, etc.);
 - e) hydromineral resources (underground sweet and mineralized water).
- The grouping of mineral resources is a matter of convention, since the industrial application fields for one and the same mineral resource may differ, arising depending on technological advance.[4].

We shall give a brief discussion of the regularities of formation and arrangement of mineral resources in time and space.[4-6].

Certain formations of rocks and mineral resources associated with them occurred at successive stages of the Earth's crust evolution. Their repeatability in the crust evolution history brought about repeatability in formation of similar groups of mineral resources from the most ancient to the youngest stages of geological history marked by metallogenic (or mineragenic) epochs.

The successive natural arrangement of formations of rocks and mineral resource complexes associated with them governed their regular distribution in the Earth's crust composition, which implied metallogenic (or mineragenic) provinces. Ore regions subdivided into ore districts stand out within ore provinces. Ore fields or ore plexuses with a totality of deposits united by common genesis and geological structure are isolated in the ore region territory. Ore fields consist of ore deposits enclosing one or several orebodies.

Eight basic ore-forming epochs are distinguished throughout the geological crust evolution history - the Archean, Early Proterozoic, Late Riphean, Caledonian, Hercynian and Alpine.

The metallogenic epochs are the main periods of ore deposit formation which correspond to the major stages of the geological Earth's crust evolution. Eleven stages, establishing the regular sequence of generation of genetic groups of ore deposits, are counted in the history of the geological crust evolution.

The Greenlandic stage (5,000-3,800 mln years ago) coincides with the most ancient moon period of geological history without ore formation symptoms.

The Kola stage (3,800-2,800 mln years ago) coincides with the nuclear period and manifests the start of the formation of the most ancient endogenic ore deposits, usually deeply-metamorphized. These deposits are clearly divided into two groups. One group comprises basaltoid greenstone belts to which the most ancient hydrothermal pyrite and gold-bearing deposits of North Africa and India are assigned. The other group belongs to granitoid nuclei with mica and rare metal metamorphogenic pegmatites known in Siberia, Africa, Australia and Brazil.

The Belomorian stage (2,800-2,300 mln years ago) covers the first half of the protogeosynclinal period and corresponds to the initiation of ancient geosynclines which break up protoplatforms. Protogeosynclinal magmatic deposits of chrome ores and basaltoid titanomagnetites along with metamorphogenic ceramic and rare metal pegmatites of granitoids stand out. Attention is drawn among platform deposits to large dike deposits of chrome ores in Zimbabwe and unique gold-uranium conglomerates of Witwatersrand in South Africa.

The Karelian stage (2,300-1,000 mln years ago) is associated with the flourish and the necrosis of protogeosynclines. The formation of all the world largest basins of iron quartzite fields (Krivoi Rog, Kursk Magnetic Anomaly, the iron ore basin of North American Great Lakes) is assigned to the geosynclinal basaltoid volcanicity of this stage. Mica and mica-rare

metal pegmatites of Belomorye, Siberia and other USSR regions together with gold in metamorphic black slates (the USA, Canada, the USSR) are associated with Karelian granitoids. The largest magmatic deposits of chrome and platinum ores of the Bushveld complex (South Africa), the magmatic sulfide copper-nickel ores of Sudbury (Canada) were formed under the protoplatform conditions of the Karelian period.

The Gothic stage (1,800-1,500 mln years ago) corresponds to the intergeosynclinal period of the geological history which marks a noticeable interruption in the endogenic ore formation.

The Grenville stage (1,500-1,000 mln years ago) is related to the start of a new geosynclinal period with the domination of basaltoid volcanicity from which the pyrite-polymetallic deposits of Sullivan type in Canada originate.

The Baikal stage (1,000-600 mln years ago) shows endogenic deposits of basaltoid and next granitoid series. Magmatic titanomagnetites of Canada, Norway and Ural as well as pyrite deposits of Siberia and North America are associated with basaltoids. Rare metal pegmatites and greisens are the most typical granitoid representatives.

The Caledonian stage (600-400 mln years ago) features predominant basaltoid development, especially that of volcanic fraction with abundant pyrite deposits of Central Siberia, Norway, Switzerland, the Iberian belt of Spain and Portugal, Australia and Burma.

The Hercynian stage (400-250 mln years ago) determines the flourish of geosynclinal magmatism and metallogeny. The magmatic deposits of chrome and titanomagnetite ores (Ural) and pyrite-polymetallic deposits (Ural, Ore Altai, West European countries) are associated with the Hercynian basaltoids. Hercynian orogenic granitoids determine the full range of postmagmatic ore deposits among which unique rare metal pegmatites, albitites, greisens, various scarn and hydrothermal deposits are known. The metallogeny of activated platforms is clearly shown, manifested by belts of alkaline rocks with rare metal mineralization of the Kola Peninsula and Norway, magmatic sulfide copper-nickel deposits in the Siberian platform traps, diamond-bearing kimberlites and rare metal carbonatites of the Siberian and African platforms.

The Cimmerian stage (250-100 mln years ago) is manifested among near-platform suburbs of the Pacific Ocean and the Mediterranean geosynclinal belts by series of granitoids with postmagmatic deposits of non-ferrous and radioactive metal ores.

The Alpine stage (down to 100 mln years ago) features fault tectonics which controls volcanogenic belts with hydrothermal gold and silver ore deposits and porphyric copper formation chains of the Pacific Ocean ore belt as well as carbonatites and diamond-bearing kimberlites of the African, North-American and Siberian platforms.

The Greenlandic and Kola stages correspond to the Archean, from the Belomorian to Greenlandic stages to the Proterozoic, and from the Caledonian to Alpine stages to the Phanerozoic. Each stage ends in granitoid magmatism with formation of granitoid postmagmatic non-ferrous, rare and noble metal ore deposits. For the first time basaltoid mineral deposits appear 3,800 mln years ago and granitoid ones 2,500 mln years ago and are then repeated throughout the all subsequent geological history stages.

Large specific geological structure regions, whose interior contained certain mineral groups and which were named mineral provinces, emerged due to regular formation and arrangement of mineral resources. Province formation depended on type of geosynclines and platforms, their geological age and formation epoch, completeness of geosynclinal and platform geological evolution stage manifestation, occurrence of certain magmatic, metamorphic and sedimentary rock formations within province range, erosion shear depth. Continent territories are zoned into mineral provinces by mapping areas with mature fields of this or that epoch. However, endogenic deposits of succeeding epochs can be imposed on the areal extent of previously formed deposits of several epochs. Therefore mineral provinces of folded regions are defined based on identification of areal extent of the last epoch deposits.

Polycyclic mineral provinces appear within geosynclinal-folded regions owing to imposition of mineral deposits of succeeding epochs on regional areal extent. With due regard to the discussed principles and bearing in mind the mineragenic epochs, the following provinces are

singled out in the Earth's territory: Alpine, Cimmerian, Hercynian, Caledonian, Riphean and Proterozoic-Archean.

Alpine provinces comprise the inner part of the Pacific Ocean ring as well as the vast belt of folded structures which appeared in the place of Tethys and extends from the Alps to the Carpathians, further on through the Caucasus and Tien Shan to the Himalaya and the Pacific Ocean archipelago. While Alpine deposits dominate in these provinces, the latter feature a set of minerals with a maximum number of formation epochs. For example, in the Caucasus Alpine province there are deposits of Archean-Proterozoic, Caledonian, Hercynian, Cimmerian and Alpine epochs. Near-surface, incl. volcanogenic hydrothermal, deposits of non-ferrous metal and gold ores are particularly typical of the province.

Cimmerian provinces are typical of the other part of the Pacific Ocean ring. They show medium-depth hydrothermal deposits of lead, zinc, tin and gold ores. In the USSR territory Transbaikalia, the Maritime Territory (Primorski Krai or Primorye) and the Verkhoyansk Territory are attributed to these provinces.

The Ural-Mongolian belt can be an example of Hercynian provinces. These provinces are especially mature in deposit development, including exogenic and endogenic formations of all geosynclinal development cycle stages, like magmatic deposits of iron, titanium, chrome and platinum ores, and postmagmatic deposits of non-ferrous and noble metal ores.

The Caledonian provinces are limited in extent and in the set of deposits inherent to them. Their example is the Caledonian provinces of Norway and Western Sayan, with typical volcanogenic pyrite deposits of copper and zinc ores.

The Riphean provinces (for example, the southern marginal part of the Siberian platform) contain gold ore deposits.

The Archean-Proterozoic provinces covering formations from the Greenlandic to Grenville stages are included in the composition of ancient platforms which are represented in the USSR territory by the East-European and Siberian platforms famous for metamorphogenic iron ore deposits. Considerable manganese, lead and zinc, gold and uranium ore deposits are available in the ancient Proterozoic provinces of North and South America, Africa, Australia, India and China.

Province types are spotted by dominant rock formations and associated mineral deposits. Provinces of Ural type stand out. They have prevalent formations of basaltoid magma with inherent iron, titanium, vanadium, chrome, platinum and copper ore deposits. They are contrasted with sialic (or Verkhoyansk type) provinces with prevailing formations of granitoid magma and associated tin, tungsten, beryllium, lithium ore deposits. Sometimes the province is called by a combination of typical deposits and geographic location. For example, the tin-bearing province of the Far East and the gold-bearing province of Kolyma stand out.

Non-ferrous heavy metals ore fields are represented by copper, lead, zinc, nickel, antimony ore deposits. Metal reserves in the largest of them amount to tens or hundreds of millions of tonnes with the usual metal content of per cent units in the deposits. A large part of copper ore is available from stratiform cupreous sandstone and shale deposits to which the Dzhezkazgan field in Kazakhstan and the Udokan field in Siberia belong. A large source is also the hydrothermal stockworks of the so-called copper-phosphory ores (Kounradsky in Kazakhstan, Almalyk in Uzbekistan, Kadzharan in Armenia). Copper ores are also mined from volcanogenic pyrite (Ural) and hydrothermal vein (Zangezur in Armenia) deposits. A substantial part of this metal output used to be extracted from the magmatic sulfide copper-nickel fields of Norilsk and Pechenga.

In nature lead and zinc are usually encountered jointly in the composition of polymetallic ore deposits. Stratiform sheet-like deposits in carbonate rocks play a large role among them. The Zhairam and Mirgalimsay deposits in Kazakhstan belong to them. Besides, lead-zinc ores are mined from volcanogenic pyrite deposits (Ore Altai) of hydrothermal metasomatic fields in carbonate rocks both among scarns and without them (Dalnegorsk in the Far East, Gorevsky in the Yenisei Range), hydrothermal vein deposits (Sadon in the Caucasus). The major part of nickel ore is mined from magmatic sulfide copper-nickel deposits and from silicate composition

weathering deposits available in Southern Ural. All antimony ore deposits are attributed to hydrothermal stratified (Kadamzhay in Kyrgyzstan) and vein (Sarylakh in Yakutia, etc.) ones.

The biggest reserves of tin, tungsten, molybdenum, mercury, beryllium, lithium, tantalum and niobium amount to hundreds of thousands of tonnes with metal content in ore of usually not more than 1 per cent. A large proportion of tin ore is mined during working of hydrothermal sulfide-cassiterite and quartz-cassiterite deposits in Kolyma, Primorye, the Amur Territory and Transbaikalia. Tungsten ore is contained in hydrothermal vein and stockwork wolframite deposits (Transbaikalia, Kazakhstan) as well as in scarn deposits (in the Caucasus and Central Asia).

Molybdenum ore is mined in stockwork and vein hydrothermal deposits (Krasnoyarsk Territory, Transbaikalia, Kazakhstan) as well as in scarn deposits among which stratified deposits of mercury ore are of greatest value (in Donbass (Donets basin), Central Asia).

Pegmatite and hydrothermal quartz and fluorite deposits with beryllium, greisen and scarn deposits with helvite and phenacite, volcanogenic deposits of fluorite-bertrandite and gelbertrandite composition are the most essential ones among the various sources of beryllium ore. Lithium is produced from pegmatites and lithium-containing mineral water (lithium ore). Tantalum and niobium ore is mined from magmatic deposits among nepheline syenites, carbonatites, albitites and pegmatites.

The main aluminium ore source is bauxites, whose deposits belong to laterite weathering crusts and marine sediments. Paleozoic bauxite deposits are available in Ural and the East European platform. The Mediterranean and Australian provinces of Mesozoic age bauxites are known. Cenozoic bauxite deposits are available in the tropical belt of Africa, India, Guiana, etc. Non-bauxite aluminium ores include deposits of cyanite, alunite and nepheline-patite res and clays with more sophisticated technology and higher metal production costs involved.

Noble metal ore deposits are represented by gold, platinoid and silver categories. Their reserves commonly amount to tens or hundreds (seldom thousands) of tonnes with the content of, for example, gold which seldom exceeds 10 g/t, i.e., 0.001 %. The most abundant gold-ore deposit type is gold-bearing quartz and other composition hydrothermal veins and stockworks available in the Far East and North-East, Western and Eastern Siberia, Ural, Kazakhstan, Central Asia, Caucasus. Substantial value is attached to mining of old from volcanogenic hydrothermal complex gold-silver ores available in the Pacific Ocean belt in the USSR territory. Previously, placers significantly depleted by now were the main gold source. Platinoids whose composition, besides platinum, includes osmium, iridium, palladium, rhodium and ruthenium are mined mostly during working of Norilsk type complex magmatic sulfide copper-nickel ores containing these metals.

Uranium, thorium and radium ore deposits belong to radioactive ore deposits. In some deposits the uranium ore reserves amount to thousands or tens of thousands of tonnes, seldom more, with a conventional metal content of tenth parts of per cent in ore. The role of sedimentary deposits usually complicated by near-surface infiltration processes is rather large among uranium deposits. Deposits bedded in Paleozoic, especially Mesozoic and Cenozoic rocks are attributed to the above type. Hydrothermal metasomatic and vein uranium ore deposits are various.

Dispersed element ore deposits (actinium, hafnium, allium, germanium, indium, cadmium, protactinium, rhenium, rubidium, selenium, scandium, thallium, tellurium, caesium, etc.) are represented by sedimentogene, magmatogene and metamorphogene series deposits. Dispersed elements are extracted as by-products during processing of other metal ores.

There are no independent deposits of rare-earth elements of the cerium and yttrium groups, ores of these elements are also for the most part extracted as by-products during mining of magmatic, carbonatite, albite, hydrothermal and placer deposits of non-ferrous, rare and radioactive metal ores.[5-8].

1.3. Technogenic deposits

A technogenic deposit is an accumulation of mineral substances on the Earth's surface or in workings which was formed owing to separation of substances from solid massif and storage as waste of mining, dressing, metallurgical and other operations and which is suitable for commercial use in quantity and quality (for extraction of metals and other valuable components, generation of fuel and manufacture of building materials). [4,9].

The deposits include mineral mining dumps, concentrator tailings dumps, ash and slag disposal areas of power-and-heat plants, stored waste of metallurgical and other operations. The so-called industrial waste burial polygons, which serve as dumping grounds for used electric and electronic equipment, automobiles, machinery, devices, and finally municipal waste ("urban res") are classified as technogenic deposits and provide a universal source of many rare and dispersed elements. For example, the main source of germanium is power-and-heat plant ash, of rhenium - roasted molybdenum concentrate dust, of selenium and tellurium - polymetallic ore, of gallium - bauxite and nepheline processing waste. Technogenic deposits become more and more important as a source of many mineral types. In industrialized developing countries up to 80 % on the average of non-metallic building materials are produced from overburden, up to 20 % of copper (more than 30 % in the USA) from oxidized copper ore dumps and concentration tailings by bacterial and acid leaching. The total content of valuable components accumulated over 20-30 years in technogenic deposits is comparable to and sometimes exceed their quantity in annual routine ore output.

Just like conventional deposits, they have a certain valuable component distribution structure, zones of secondary hypergenesis, oxidation, segregation, etc., but unlike natural (geogenic) deposits - a lower valuable component content. Waste is dumped so as to provide more favourable conditions for their downstream recycling (stable slopes, minimum dumping costs, flowline process application). Waste utilization is as a rule economically feasible, since the deposit is on the surface and the material in it is partially disintegrated. However, these deposits must be utilized at the proper time, because in many cases they undergo substantial modifications, losing processability and practical value. For example, deposits containing heavy non-ferrous metal sulfides may be depleted up to total loss of the metals owing to spontaneous bacterial leaching processes. Separate storage is required in some cases for value improvement during dumping, otherwise a technogenic deposit may not form: for example, oxidized ferruginous quartzites, mining and concentration waste in the Kursk Magnetic Anomaly and Krivbas (Krivoi Rog basin), were dumped together with overburden and thus incurred considerable loss as technogenic deposits. Separate dumping entails certain expenses and noticeably increases mining costs in some cases.

1.4. Ways of valuable components extraction

Deposit mining results in output of ore, a natural mineral product containing metals or their compounds in quantity and form suitable for commercial use. Even naturally high-grade ore requires dressing as a rule. Non-ferrous metal ores are polymictic and accompanied by commercially useless minerals. Ores are considered complex if they have associated valuable components (metals, non-metals), whose recovery is economically feasible. Judging from the chemical composition of prevalent minerals, ores are divided in silicate, siliceous, oxide, sulfide, carbonate and mixed. All ores mined from deposits enclosed into native sedimentary, magmatic and metamorphic rocks are called native, while ores produced from river, lake, sea and ocean sands are called placer.

Ore structure is dictated by combination of individual mineral grains in an ore mineral aggregate. Structures are differentiated into equigranular, inequigranular, oolite (with concentrically rounded mineral accumulations), porphyric (with individual coarse mineral grains in an equigranular mass), radiated etc. Ores are divided into those with uniform, nonuniform and extremely nonuniform composition according to the valuable mineral distribution nature.

For ore mining and processing of essential importance are physical properties: hardness, strength, jointing, density, melting point, magnetic and electromagnetic properties, conduction, radioactivity, solubility, sorption, and granulometric composition.

Valuable ore components are the constituent of the mineral resource, whose extraction is technically and economically feasible with the view of commercial application.

Essential and associated (accessory) valuable components are distinguished. Essential valuable components are contained in mineral resources in commercial concentrations, which determine the basic value, application and name of the resource. When two or several essential components are available, the mineral resource is characterized as a complex one (for example, copper-molybdenum or copper-lead-zinc ore). Associated minerals and dispersed elements are mineral constituents, whose extraction is economically feasible only jointly with the essential valuable component. Valuable minerals are incorporated into the mineral resource composition in low concentrations and can be extracted to selective concentrates or accumulated in essential valuable component concentration products. Dispersed elements are contained in the composition of essential or associated valuable components as isomorphic, finely-dispersed or other impurities (usually in low concentrations) and can be extracted only during metallurgical or chemical concentrate separation.

Complete comprehensive recovery and utilization of all valuable components is a condition for efficient use of the earth's interior. The notion of valuable component is not rigid, but varies with industrial requirements, progress in engineering and technology of mining, dressing and processing of mineral products.

The commercial content of an essential component in a mineral resource at which extraction and use are economically feasible is of substantial significance. The commercial content for any mineral product type may vary over a wide range depending on economic-geographic deposit conditions, geological structure, ore composition and properties, mining & processing technology and equipment, geological requirements. Mineral product standards establish limiting values of the commercial content, on whose basis mineral reserves are estimated.

Combined processing [11] of mineral products, which is a production process composed of different dressing and metallurgical techniques and operations, affords the most efficient selection of components. Selection of components by properties (difference in density, magnetic susceptibility, conduction, adsorption, wettability, etc.) is based on creation of a gradient of mineral particle, ion or molecule concentration in a liquid or gas phase as well as at interfaces using different fields of forces and actions: magnetic, electric, gravity, adsorption, etc. Combined processing is carried out by several properties through combination of fields applied in a single apparatus (combined process) or in a line of sequentially arranged apparatus (combined flowsheet).

Combined dressing of mineral products takes place without alteration of the phase and chemical composition of the minerals contained in the ore, i.e., it results from a combination of dressing methods. Combined flowsheets are conventionally composed of primary gravity operation (heavy-media separation, jigging, screw separator dressing, sluicing, etc.) and downstream magnetic separation or flotation. These flowsheets are typical of iron (gravity - magnetic separation), manganese (gravity - flotation) and rare-metal ores (gravity - magnetic or electric separation - flotation). Widely-used combined dressing processes include gravity flotation: concentration table flotation (diamond ore), flotation jigging (rare-metal ore). There are also magnetic field classification (magnetite, titanomagnetite ores), flotation in a magnetic field, run-current field, vibration or ultrasound field.

If it is not possible to produce prime concentrates by dressing methods or their combination, a combination with hydro or pyrometallurgical final concentration is applied. Hydrometallurgical final concentration is carried out by leaching of harmful components from raw concentrates, for example, phosphorus or silica from iron, manganese, tungsten concentrates. Removal of harmful components is also possible in pyrometallurgical processes. For example, concentration of valuable components can be substantially increased through CO_2 combustion during roasting of

carbonaceous ores. Besides, roasting permits alteration in magnetic mineral properties (magnetizing roasting of oxidized iron ores) for downstream magnetic separation. There exist examples of roasting operations applied for alteration of mineral floatability (phosphorites). A specific pyrometallurgical flotation diagram is used in processing copper-nickel ores: they are melted to copper-nickel converter matte which is further ground and separated by flotation into copper and nickel products. Another unique circuit for processing copper-nickel ores is bulk-selective flotation with production of nickel-pyrrhotite concentrates which undergo autoclave-oxidizing leaching with downstream sulfur-sulfide flotation.

Combined flowsheets which apply different methods in a sequential layout afford the most efficient extraction of valuable components from mineral products: combined processes provide the highest concentrate purity.[11].

As the industry transits to refractory ore and coal, non-waste technology, etc., interpenetration and interaction of technological processes, not only in dressing, are in full swing, for example, mechanical activation of ores and minerals, hydrometallurgy in combination with flotation, autogenous grinding with downstream screening, treatment of recirculating water, etc.

Combined processes and circuits are the basis for comprehensive processing of mineral products: disintegration of useful material to final products, into which all valuable components contained in raw materials are extracted and whose processing is technologically and economically feasible.

1.5. Deposit evaluation and mineral resources

Mineral resources are a totality of useful materials in which chemical elements and minerals formed by them are available at much higher concentration compared to their abundance ratio in the Earth's crust, permitting affords their industrial application.[12].

They are nonrenewable natural resources. The part of mineral resources prepared for mining is called a mineral product base, quantitatively evaluated by geological prospecting and exploration. Preparation of mineral resources for mining includes formation of a mineral product base of mining industry by means of geological exploration in order to evaluate commercial reserves of mineral resources at available natural sites and registration of technogenic deposits as mineral sources as well as setting of mining and processing undertakings in these regions.

Prospecting and exploration costs are commonly 1.5-5.0 % of the cost of the metal produced (iron and steel and non-ferrous metals), more seldom 20-30 % (some non-ferrous and rare metals), mining and dressing costs range from 6-10 (for iron or aluminum) to 70-80% (for some non-ferrous and alloying metals) of the total product cost.

Mineral production is in continuous growth, and an especially large scale was reached in the 20th century. The 1901-1980 period accounted for 90-95 % of the total mining output of tin, lead, zinc, silver, mercury and antimony ores, as well as diamonds, 87 % of iron ore, 85% of copper and 70 % of gold ore. At the same time the number of mineral resource types increased drastically, and commercial production of bauxite, titanium, molybdenum, tantalum, niobium and other ores began.

Mining output grew irregularly. The periods from the end of the 19th to the beginning of the 20th centuries and from the middle of the 50s to the middle of the 70s stand out as the time of high rates of output increase in mining of many mineral resource types. For example, in the 1950-1975 period production of niobium concentrates increased more than 20 times, bauxites 11 times, nickel and titanium concentrates 5-5.5 times.

For many types of mineral products output growth was mostly due to working of large and very large deposits. Higher mining rates involve working of deposits with leaner ores and of new

geological-industrial types. For example, at the end of the 19th century the most of the run-of-mine copper ore contained 5-8 % of copper, but this figure fell to 0.7-3 % in 1925 and to 0.4-1.5 % in the late 70s. Active mining of hitherto unworked large copper-porphyry type deposits began in the 50s.

Increased mining output brought about depletion of near-surface fields and larger mining depths which increased from several tens and hundreds of metres to 1,000 m on the average for non-ferrous metal ores (2-3.9 km at particular undertakings). Fields located in remote regions, for example, at Arctic latitudes and on the sea shelf, are being drawn into mining. Increased complexity of the geological conditions, higher power and investment requirements lead to objective increase in the costs of exploration, mining and primary processing of the mineral resources. However, the trend towards higher per-unit cost is largely offset by larger production output and the relative increase in the cost of other goods. Thus, the per-unit costs expressed in terms of prices for other products and services do not exceed those calculated in a similar way for the 1980s when the copper content was 5-8 %. An objective aspect is the increase in environment control costs (8-20 % of all investments in mining in industrialized countries).

Seventy-eighty per cent of the reserves for each mineral resource type in the mineral product balance account for a comparatively small number of large deposits and gigantic fields, while the other part is available in medium and numerous small deposits. Commercial value and reserve amount serve conventionally for distinguishing unique deposits of major importance in the world reserves as a whole, large deposits in large countries rich in mineral resources, medium deposits in medium and small regions of large countries, small and minute deposits in individual districts and undertakings. Table 1.2 presents the reserves of individual types of mineral resources by continent.

Table 1.2. Allocation of main mineral resource* types by continent and country group [12].

Mineral resource	Europe	Asia	Africa	North America	South and Central America	Australia and Oceania	Total	Developing countries	Industrialized countries
Bauxites									
bln t	0.25	1.83	12.35	0.04	3.9	2.42	20.8	18.2	2.6
%	1.2	8.8	59.4	0.2	18.8	11.6	100.0	87.3	12.7
W ore**									
,000 t	159	267	32	367	116	119	1,060	394	666
%	15.0	25.2	3.0	34.6	11.0	11.2	100	37.2	62.8
Co ore***									
mln t	0.05	0.43	1.8	0.26	0.1	0.3	2.94	2.51	0.43
%	1.7	14.6	61.2	8.0	3.4	10.2	100	85.3	14.7
Cu ore									
mln t	8.3	47.6	78.9	122.5	174.3	15.8	447.4	302.8	144.6
%	1.9	10.6	17.6	27.4	39.0	3.5	100	67.7	32.3
Mo ore**									
mln t	-	0.2	-	4.2	2.85	0.15	7.4	3.2	4.2
%	-	2.7	-	56.8	38.4	2.1	100	43.1	56.9
Ni ore***									
mln t	2.1	11.9	5.2	10.1	4.9	16.0	50.2	32.1	18.1
%	4.2	23.8	10.4	20.0	9.8	31.8	100	64.0	36.0
Sn ore***									
mln t	0.2	1.8	0.4	0.1	0.8	0.2	3.5	2.9	0.6
%	5.7	51.5	11.4	2.9	22.8	5.7	100	82.9	17.1
Pb ore***									
mln t	12.9	8.3	11.1	47.0	13.8	23.0	115.6	25.5	90.1
%	11.1	7.2	9.6	40.7	11.5	19.9	100	22.1	77.9
Zn ore**									
mln t	23.3	28.1	24.8	60	21.4	21.0	178.6	56.7	121.9
%	13.0	15.7	13.9	33.7	12.0	11.7	100	31.7	68.3

* Identified and proven reserves as of early 1984 (industrialized and developing countries)

** In terms of oxide

*** In terms of metal

Despite the depletion of individual long-exploited deposits and reduction in explored reserves of mineral resources in some countries, mining levels reached in the early 80s are secure

for the visible future. However, a large part of the identified mineral resources is concentrated in deposits of relatively lean or deep ores and under complex geological conditions.

Commercial development of mineral resources includes their evaluation (geological prospecting and exploration) and working (mining, dressing and processing), whose scope and intensity are dictated by the peculiarities of industrial and socio-economic development, together with position of the mineral product sector in the national economy. Mineral resources are nonrenewable, which dictates judicious utilisation and reduction of losses during mining, processing and handling as well as utilization of the secondary materials and compliance with an ecological and economic approach in exploitation of the mineral resources.

Mineral exploration is carried out with a view to estimating commercial value of mineral deposits given a positive rating in a prospecting and evaluation process. A reserve of replenishing exploration projects are also deposits evaluated in the past, but assigned outside the balance for variance reasons. Their re-evaluation on the basis of new geological-genetic concepts, situation changes, more perfect exploration techniques along with innovative technologies of mineral mining and processing, permits transfer of some of the projects for preliminary exploration without additional field work.

Exploration establishes the geological and industrial deposit parameters required for commercial valuation, planning of a mining enterprise, initiation of the mining and processing of the mineral resources to be extracted. For example, the morphology of mineral bodies is determined in this way, which is of primary importance in selection of a future mining system. The contours of the resource body are established with allowance to the geological boundaries, and average content of essential and associated components, availability of harmful impurities, nature of mineral resource distribution, etc. are set in accordance with the data of deposit testing. The data on valuable component content are the initial basis for substantiation of estimation standards and ultimately for solving the problem of commercial value of the project under exploration. These data are equally useful in determining the processability of the mineral resources. Ore deposits are studied stage-by-stage, with more and more detailed exploration through regular densification of the prospecting hole network pattern, with more and more accurate estimation of the reserves and more and more detailed and complete technical and economic evaluation of deposits under study.

Deposit exploration methods depend on a set of relevant engineering facilities which provide maximally complete information. The key operation in prospecting is drilling: percussion (in placer survey), column (core or coreless) and deep; deep prospect holes, shallow shafts, adits are applied in extra-complex cases (as a rule in exploration of non-ferrous and rare metals ore). The purpose is verification of the prospecting drilling data, clarification of the structure for the most complex deposit areas, technological sampling. Detailed and final exploration is commonly carried out grounded on drilling; deep prospecting and prospecting-operating shafts are also sunk at certain projects. The main types of exploration operations are openings (level, vertical and inclined) and underground (usually short) holes: column and perforator (coreless). In order to obtain maximum information on deposit structure and regularities of useful mineral arrangement at minimum cost, the prospecting holes are distributed so that they cross the whole promising zone (horizon, structure) thickness while the prospecting profiles (prospecting intersection groups) are localized primarily across the zone strike. Prospecting network density depends on the degree of the complexity of the geological deposit structure according to which reserves are estimated. As the preliminary survey moves on to exploration and further on to operation the prospecting network becomes denser. In the case of vein rare-metal ore deposits the prospecting network can be condensed to several tens of metres and even more.

Different geophysical & geochemical methods are applied at all prospecting stages. The main purpose of geophysical works is to find out the deposit structure through clarifying the position and following the ore-controlling and ore-localizing surfaces (for example, contact of limestones lithologically favorable to ore deposition and overlapping screening shales, disjunctive dislocation zones, etc.) as well as through correlation of prospecting intersections. Geochemical

methods are applied for delineation of horizons, zones and blocks (with abnormal distribution of indicator elements) promising in prospecting for buried ore beds.

The choice of engineering facilities for deposit prospecting is dictated by work type: there may be ditchers and shovels for ditch and trench digging, bulldozers for stripping and baring of bedrock, as well as trench exploration of placers, mobile equipment for sinking shafts and mapping-reconnaissance boreholes, descent-ascent mechanisms for sinking deep shafts and holes, drilling machines of different types for prospecting holes, sampling-analyzing devices, computerized geophysical field instrumentation for operational data processing, etc.

Summary horizon-by-horizon plans and sections, which are the basis for estimating mineral reserves, are made up from the primary geological documentation and testing data. The same data are used for composing detailed geological-structural maps, which in turn serve as basis for prognostic maps are constructed. These are the foundation for further projects.

Evaluation of mineral deposits, which is establishment of their commercial value, using combined geological methods (geological evaluation) and economic calculations (economic evaluation) is carried out at all stages of study, prospecting and commercialization, from regional prediction to complete depletion. [10,12].

The early stages of the geological prospecting process (regional study of the territory, geological surveying) include evaluation of potentials for this or that area as a whole (ore province, ore belt, zone, ore region or node, basin, structure, etc.) based on general geological information. Areas (zones, basins, structures) due for more detailed study are identified on geological and specialized (geological-formation, etc.) maps of correspondry scales (1:500,000 - 1:50,000), on the basis of a specific geological concept (geochemical specialization of region and rock complexes, favorable tectonic, magmatic, lithologic-stratigraphic structural and other prerequisites). Probable reserves are also estimated for these areas by analogy with other regions. If there are previously-registered indication of the required mineral type, these reserves can be allocated to more limited areas: zones, structures, etc. Areal extent of prognostic reserves are targets for specialized detailed survey or survey-revision and evaluation works. Probable reserves are usually identified during local predicting (1:50,000 - 1:2,000) preferably on flanks or at deep horizons of the deposits under exploration or operation. They are shown on specially made-up detailed structural-prognostic maps and serve as reserve for expansion of the raw material base of existing undertakings and a foundation for planning more detailed geological prospecting works. Geological evaluation of identified mineral manifestations is based on the results of oriented survey-prospecting works and consists, on the one hand, in determining mineral quality (through testing of outcrops) and possible extension range (by thickness, area and depth) and, on the other hand, in establishing the regional promise for each mineral type (by geological-tectonic location of the project under study, assignation to some genetic and geological-commercial type, geochemical regional specialization, geophysical parameters, etc.). In the case of positive results of geological evaluation a preliminary economic calculation is carried out in order to determine the minimum project scale which would meet industrial requirements under these geographic-economic and geological conditions.

Regional promise is evaluated through division of all identified manifestations of mineral resources into low-promising "roots" of erosion-destroyed mineral beds, independent bodies of varying scale (to be explored if complying with main standard requirement parameters), indicators of larger deep-buried mineral beds (the most promising variant, which affords a very reliable evaluation of the whole structure under study). The optimal ratio of identified ore manifestation groups is usually 20:10:70 for thermal deposits and about 60:30:10 for the very- high-temperature scarn and pegmatite rare-metal deposits. In predicting buried mineral beds, the initial evaluation criteria are the vertical range of expansion of this mineral type, the multiplicity of its localization (for example, the number of lithologically favorable horizons in the geological regional section), availability of certain symptoms of mineral resources in overlapping rock layers (dispersion haloes).

Besides mineral manifestations proper, various geochemical, geophysical and other anomalies as well as promising structures are geologically evaluated. They are assessed initially

by laboratory processing data of the materials obtained (for example, geochemical anomalies are verified through identification of the leading role of supra- or sub-ore indicator elements), with subsequent intersection by single prospecting openings, most often prospecting-structural drillholes. The result is a justified decision on whose basis the recommendation is given whether it is expedient to arrange preliminary prospecting, register the deposit in the reserve - pool or recognise it as unpromising, undeserving of attention and further study. Coincidentally several economic factors: shortage of this mineral product, need for compensation of exhausted reserves in the region of active undertakings, etc. - are taken into account.

The problems of commercial value of the identified deposit, total mineral resource scope and quality (including processability, possible working conditions, etc.) are solved during prospecting. Explored reserves data are used in technical & economic calculations which allow determination of the main indicators of deposit commercialization in several standard versions, taking into account production scope and other parameters - all of which is reflected in a special technical and economic report. Both the geological evaluation of the deposit under study and its region as well as economic assessment are of equal importance at the stage of preliminary prospecting. The former consists in detailed study of mineral localization conditions, impartial estimation of the reliability of the identified reserves and establishment of all potentials for their further expansion; the latter consists in estimation of all cost items (setting-up of mining undertaking, roads, power lines, infrastructure, etc.) which are to be outlaid during commercialization of the project, along with the expected economic efficiency. At the stage of detailed prospecting one main task of the geological evaluation is to determine the degree of reliability of the explored and estimated reserves with a view to exclusion of negative consequences in case of deviation from subsequent mining data.

The morphology of the mineral bodies, their space location, quality and processability, the technical and economic conditions of mining, etc. are finalized. Geological-economic evaluation of deposits under exploration is based on estimation of the identified reserves in turn based on standards. Technical-economic substantiation of estimation standards is based on wholesale prices of the corresponding mineral product type, the shortage level, working conditions, processability and other data.

As the deposit is prepared for commercialization, multi-variant comparative economic evaluation and selection of the most economically profitable project from the explored single-type fields are carried out with a view to determining the profitability level of mining the explored mineral bed, with the time factor included.

Prior to collapse of the USSR geological-prospecting works were carried out by the USSR Ministry of Geology, whose organizations conducted quest and prospecting works in the territory of the country, on the sea shelf (except deep drilling), and on the sea and ocean bottom. They carried out regional geological, geophysical, hydrogeological, engineering-geological and other kinds of terrestrial, aerial geological cosmic surveys for geological structure study, industrial, agricultural and construction needs; they also manufactured various geological prospecting equipment, geophysical devices and rendered technical assistance to foreign countries in geological prospecting works.

Tens of thousands of mineralizations formations of different scope and value were registered in planned geological prospecting operations in the USSR. This information is stored in the archives of regional geological control bodies available almost in every province and republic. In many cases research works were carried out on these mineralizations.

The Committee on Mineral Reserves, operated independently of the above ministry. It was in fact an separate ministry and its head (chairman) held the rank of minister. All more or less interesting formations were approved as mineral reserves after study of dressability, supplementary prospecting, establishment of orebody boundaries. For completely unexplainable reasons, information on non-ferrous metal ore reserves was treated as strictly classified, though the time from reserve approval to metallurgical production amounted as a rule to 20-30 years. Other administrations (the USSR Ministry of Geology, republican ministries of geology and regional geological departments) conducted parallel operations of search and reserve build-up.

Reserves of some mineral resources were accumulated for tens of years ahead, with those on other resources for a few years only. Surveying of technogenic deposits was random in general and their reserves were not evaluated. As a result, information on manifestations is enormous, but disordered.

1.6. Definition of minerals by processing

The processing technology of mineral is based on studying their properties. They are crystalline bodies formed as a result of natural physicochemical (geochemical) processes on the surface or in the interior of the Earth. Unlike synthetic substances, which can be produced under required conditions and at the required component ratio, natural minerals are generated in systems, whose composition depends on the geochemical abundance of particular elements, the geochemical prehistory of their dispersion, concentration and ranges of pressure, temperature, *pH* and *Eh* variation. Despite these constrictions, the diversity of mineral types is vast, because of isomorphism phenomena, crystal lattice defects, ion-exchange processes and effects of tectonism, weathering, metamict transformations, etc. [13,14].

Only a few hundreds out of the large number of minerals available in nature are encountered in exploitable deposits. Of interest in terms of ore dressing technology are minerals containing valuable components and minerals of the enclosing rock. They number about 250 (not counting variants), and we shall confine our discussion to them.[11].

Variants of one and the same mineral may be encountered in different deposits and sometimes within The same deposit, depending on chemical composition, impurities and structural peculiarities. Knowledge of the abundance and paragenetic associations of minerals is of great importance in ore dressing. Ore dressability is to a large extent governed not only by the physical and chemical properties of the mineral, but also as the relative content of components in the ore and the presence of other minerals.

Finally, the characteristics of a formation (particle shape, fracture appearance, availability of groupings and size) often predetermine the choice of extraction method.

Unlike mineralogical manuals, in which descriptions and characteristics are intended mainly for diagnostic purposes, we present only those data which are necessary to a technologist. Mineralogical description of available minerals with associations peculiar to them will help in assessing whether a deposit and mineral associations are typical or unique.

Accordingly, ore and deposit description is based on technological mineralogy concepts.[3,15].

1. In creating ore preparation flowsheets, including homogenization, crushing, screening, presorting, grinding and classification:

- identification of technological ore types for individual dressing and intra-type homogenization, (zoning, space distribution of ore minerals and concentrations of components useful or detrimental to dressing);
- geological-technological mapping of deposits by ore type, establishment of typomorphic peculiarities of minerals and variants, features of mineralogical compositions, determination of mineral paragenesis of different deposit areas with respect to sample dressability;
- assessment of possible ore presorting for component concentration, material composition, dressability, selection of dump products at the primary or intermediate crushing stage with separation of individual minerals or mineral associations by density (heavy media), size (screens), color, luster, luminescence (photometry), natural or induced radioactivity (radiometry), etc.;
- assessment of possible primary dressing or separation of mineral particles by shape, friction factor, grindability, particle size, etc.;
- assessment of mineral hardness, mechanical aggregate strength, grindability,
- assessment of impregnation and interpenetration of minerals, scale of ore gradations for grinding optimization.

2. In designing technological ore dressing circuits:

- study of component composition of ore and valuable minerals, with a view to assessing, possibility of producing selective and bulk concentrates by dressing, determining the complexity nature of a component (in the mineral, in the mineral association, in the dispersed state, etc.);
- study of the component composition of barren rock with a view to assessing the possibility of recycling the dressing waste and creating a non-waste process flowsheet;
- study of minerals enclosed in ore with a view to determining possible methods of their separation by gravity, in electric or magnetic apparatus, by flotation and other methods;
- study of possible modification of a dressability properties by mechanical, thermal, acoustic, chemical, radiative means for better selectivity in component separation;

3. In creating chemical-metallurgical and combined processing flowsheets:

- study of solubility in different solvents with a view to assessing the possibility of hydrometallurgical recovery of components and final concentration;
- study of possible modification of solubility by thermal, bacterial, autoclave, mechanical and other means for improved component recovery and comprehensive ore processing as well as applicability of geotechnological deposit mining.

4. In developing flotation dressing modes:

- investigation of crystallographic-chemical mineral peculiarities, surface properties, conductivity type, nature of sorption-active centers, structure of atom bonds in surface layer with a view to assessing the possibility of applying certain agents for flotation selection of minerals;
- investigation of mineral surface hydration in water suspension, particularly, in the presence of flotation agents are available, with a view to controlled selective flotation;
- investigation of the effect of changes in isomorphic impurity composition and amount, structural defects, conductivity type and other mineral peculiarities which vary within the deposit, on sorption and flotation properties with a view to organization of flotation mode control systems and prediction of dressing parameters.

Mineralurgy [3,10]. We shall designate the theory and technology of mineral selection in industrial processes by the term “mineralurgy”.

Mineralurgy (from *mineral* and Greek *ergon* - work) is a theoretical base for mineral dressing. It includes new direction (ore preparation, selective exposure of minerals controlled modification of natural mineral properties, chemical dressing and recovery of technogenic minerals). Mineralurgy provides effective means for processing lean and refractory ores and for complex utilization of the raw materials, including waste recycling.

Mineralurgy encompasses the whole complex of primary mineral processing operations, including ore preparation, improvement of mineral concentration and selection of minerals by mechanical, physical and physicochemical methods, chemical dressing, dewatering and pelletizing and some other operations required for achievement of the necessary standards of useful component and impurity content, granulometric composition, moisture and other final product quality parameters. Mineral products can undergo chemical-metallurgical processing with output of materials (metals, chemicals) or enter mechanical or other processing operations, when the minerals and rocks have the technical properties which dictate their direct use (for example, piezoquartz, building materials).

Mineralurgical methods will be applied in processing liquid mineral resources (underground water, World Ocean water). Saleable ore was, for a long time, the principal raw material in chemical-metallurgical processing for solid mineral resources rich in valuable components. Prior to the 1st half of the 19th century mineralurgical processes were reduced to mechanical ore processing (crushing, screening, washing, sorting by outward appearance), and products entered the next conversion stage as concentrates. As methods of mechanical grinding in drum mills and gravity dressing along with physical (magnetic, electric separation, radiometric sorting) and physicochemical dressing methods were developed, finely ground mineral concentrates became the final product. Methods of agglomeration (sintering, pelletizing, briquetting) were developed with a view to optimal mineral product size for metallurgical processing.

In the 80s it becomes more and more often advantageous to prepare raw materials as artificial (technogenic) minerals with preset composition and properties. They can be produced from solid minerals separated during dressing by means of recrystallization with introduction (where necessary) of certain additives of other materials (for example, production of metallized and fluxed pellets for the iron & steel industry, fused phosphates for the mining & chemical industry). In chemical dressing of solid minerals and processing of liquid minerals, final products are obtained mostly as chemical concentrates of liquid and solid semiproducts and crude metals.

Processing of lean refractory ores is a multi-aspect problem. Typical traditional dressing circuits became ineffective for deposits of complex genesis. The difficult geological conditions of deep deposit mining, the larger scales of mechanized systems with high excavation capacity result in ore impoverishment by barren rock and make it impossible to maintain the standards for which the dressing circuits are designed. Power costs are dramatically increased, as for producing the same quantity of valuable components from lean ore is correspondently larger quantity of rock must be crushed. Refractory ore is characterized by mineral associations with close properties which are difficult to separate in the absence of the required contrast in differentiating features (gradation of dividing symptoms). In extra-refractory tenacious ores (very fine mineral impregnation, isomorphic impurities), it is impossible to separate individual mineral components into distinct phases during crushing.

The level of mineralurgical processing ("depth"), final product type and structure are dictated, besides quality requirements, by the type of processed raw material type, by the engineering level of applied processes and, in the final analyses, by the economic criterion (minimum total costs over all conversion stages from mining to final processing).

Technological mineralogy, ore preparation theory, the theoretical fundamentals of controlled modification of the natural properties of hardly separable minerals, chemical dressing theory - are included in mineralurgy.

Technological mineralurgy exposes the interrelation of the mineral properties (applied in technology) with compositional and structural peculiarities of the ore and constituent minerals typical of the particular deposit in question. It is the information base in constructing a judicious processing flowsheet for ores of complex composition.

Ore preparation theory makes it possible to set-up a quality control system for conversion of a run-of-mine rock mass into prime ore by means of controlled modification of the strength properties during blasting, imparting the required lumpiness by blasting and mechanical crushing, separation into technological grades, intra-grade homogenization, primary concentration by size (on screens), density (in heavy media), and natural and induced radioactivity (radiometric sorting).

Controlled modification of the natural properties of poorly separable minerals by physicochemical and chemical actions makes it possible to create the property contrast range necessary for improved flotation, magnetic and electric separation efficiency. Application of required action agents is of particular importance for mineral groups typomorphic in surface properties.

The theory of interaction of flotation agents with minerals brought about an extended range of mineral product processing methods.

The theory of chemical dressing opens ways to judicious process flowsheets for tenacious ores, which cannot be dressed by combined circuits with metallurgical refining of the commercial products, direct metallurgical treatment being economically unfeasible. Chemical dressing implies search for low power-intensive techniques of selective exposure of minerals containing valuable components. In this case it becomes possible to concentrate and separate valuable components at ion-molecule level and to perform controlled synthesis of technogenic minerals with required properties. The extended range of pyro-, hydro- and bio-metallurgical processes is resorted to selecting those, which are technologically combined with the dressing operations and economically justified by ore technology of the preparation and downstream processing.

Ore dressing [10,16,17]. Dressability of mineral resources is the most important intermediate link between mining and application.

In Russia mineral concentration improvement processes were initiated in the context of separation of gold from ore. The first concentrating plant for gold recovery was built on the Iset river in 1760. In 1763 M.V. Lomonosov described dressing processes in his book "First Fundamentals of Metallurgy or Ore Mining". His contemporaries I.V. Polzunov and K.D. Frolov constructed several mechanized (water-wheel driven) concentrating plants equipped with ore washing machines.

Depending on mineral composition, valuable mineral content together with impregnation size, mineral dressability is established, and a separation flowsheet consisting of a number of successive processes is chosen. The most general circuit includes mineral "selection", that is, mineral removal from aggregates which is performed by ore crushing and grinding, and mineral separation by dressing processes proper. At first, ore preparation, which incorporates crushing, screening and homogenization is usually carried out. Crushing is performed in several stages, between which the final product can be drawn. Crushed product can be preconcentrated in heavy media or sorted radiometrically for removal of impoverishing rock. Grinding is carried out for ore opening, after which minerals are concentrated by gravity, magnetic separation or flotation. Mills operate in a cycle with classifiers for isolating products of desired size.

Mineral dressing is associated with different methods of separation by physical properties: strength, shape, density, magnetic susceptibility, conduction, wettability, adsorption capacity, surface activity, but without change in aggregation, aggregate-phase state, chemical composition, crystallographic-chemical structure.

When the density of minerals to be separated, differs various methods of gravity dressing are applied, utilizing differences in velocity of particle motion in water or air medium under the effect of gravity or centrifugal forces. These methods include jigging, heavy-media separation, table separation, sluicing. Flotation is based on differences in the physicochemical properties of separated mineral surfaces. When minerals have different magnetic susceptibility, they are separated by magnetic processes. When there are differences in electric properties (conduction, dielectric permeability, frictional charging ability), minerals are separated electrically.

Differences of grain size, shape, brittleness and friction coefficient make it possible to separate them by these symptoms. Gravity, flotation and magnetic methods are the most widely used. When there are contaminating impurities (mainly clay) in the ore, washing is included into the dressing circuit. Mineral selection can be carried out by several properties, using different combinations in a single apparatus (combined process) or in several apparatus arranged straight-away in one line (combined flowsheet). Combined dressing circuits usually incorporate primary gravity processes and downstream magnetic or flotation operations. Such circuits are typical for mixed iron (gravity-magnetic), manganese (gravity-flotation) and rare-metal (gravity-magnetic) ores.

The most widely used combined dressing processes are flotation-gravity: concentration table-flotation (separation of coarse sulfides from cassiterite), flotation jigging (dressing of rare-metal ore). Magneto-hydrodynamic and magneto-hydrostatic separation, classification in a magnetic field, flotation in magnetic field are also well known.

When prime concentrates cannot be produced by dressing methods or their combination, combination with various final concentration techniques are resorted to. Hydrometallurgical final concentration is carried out by leaching of harmful components, for example, phosphorus or silica, from iron, manganese, tungsten concentrates. For example, roasting of carbonatite ore can substantially increase the concentration of useful components through CO₂ removal. Roasting induces changes in the magnetic mineral properties (magnetizing roasting of oxidized iron ore) for downstream magnetic separation. Examples of roasting with a view to changing the flotation ability of minerals (phosphorites) are known. A specific circuit including pyrometallurgy and flotation is used in processing copper-nickel ore, which is melted to copper-nickel converter matte consisting of artificial sulfide minerals with downstream grinding and separation to copper and nickel products by flotation. Another unique circuit for copper-nickel ore processing is bulk-

selective flotation yielding nickel-pyrrhotite concentrates which undergo autoclave-oxidizing leaching with downstream sulfur and sulfide flotation.

Ion flotation, electric flotation, the Mostovich process are attributed to category of combined dressing-hydrometallurgical operations.

Mineral dressing affords a substantial increase in concentration of valuable components. The content of heavy non-ferrous metals (copper, lead, zinc) is 0.3-2 % in the ore, and 20-70 % in concentrate products. Molybdenum concentration rises from 0.1-0.05 % to 47-50 %; tungsten from 0.1-0.2 to 45-65 %; the coal ash level drops from 20-35 to 8-10 %. Separation targets also include removal of harmful mineral impurities (arsenic, sulfur, silicon, etc.). Recovery of valuable components in the concentrate in dressing processes varies from 60 to 95 %.

The key development trends are improvement of individual dressing processes and recourse to combined circuits with a view to maximum improved concentrate quality and recovery of useful components from ore; increase in production rate of particular undertakings through intensified processes and upscaled equipment; higher complexity and recycling of waste (most often for production of building materials); automated production. An important target is minimized environmental pollution.

Since all types of solid mineral resources are subject to dressing, the most essential characteristic is dressability [11,17] of the useful minerals, i.e. technological assessment of the possible recovery rate and concentration of the mineral components depending on mineral composition, texture and structure of the ore. Dressability is an obligatory characteristic of the deposit in evaluation of the reserves, development of the technological flowsheets, engineering of concentrating plant, selection of flotation agents, etc.

Dressability is tested on material obtained from deposit trials. The material composition of samples is studied by mineralogical-petrographic, granulometric, phase and chemical analyses. Based on the findings of fractional analysis, a graphic dressability relationship is plotted in the coordinates of dressing product output component content and recovery. Evaluation of dressability includes study of mineral properties (mechanical, electric, magnetic, semiconductor, adsorption, chemical, etc.) by spectroscopic, nuclear-magnetic and other techniques. The ore preparation schedule is chosen on the basis of the petrographic composition and mechanical properties. It includes crushing, screening, grinding and classification for opening (exposure) of mineral grains at as large as possible particle size. Ore preparation also includes roasting (magnetizing, oxidizing, etc.), and granulation (prior to leaching). Dressing methods and schedules are chosen by comparison of physical and chemical mineral properties with allowance for the separated grain size.

Depending on the distribution of the mineral impregnation size, the dressing schedule is broken down into stages with ore preparation operations interspersed between them. The first stage is aimed at selection of maximum quantity of final exposed useful mineral or barren rock at minimum crushing rate. This stage is predetermined by the content of solid mineralizations or the presence of large amounts of virtually valueable rock. Gravity dressing methods (heavy-media separation, jigging, etc.), dry magnetic separation, bulk flotation are resorted to at the first stage. The second stage is aimed at maximum recovery of all valuable components in rough or bulk concentrates. Here flotation, jigging, table concentration, electric separation, wet magnetic separation are used. The second stage operations for some ores (uranium, gold, copper, etc.) are leaching, cyaniding, sorption, etc. When underground or glomeroblastic leaching is used, ore dressability is evaluated by crushing on occurrence site.

Rough concentrates (bulk or mono) produced by a basic dressing process undergo final concentration or selection. Here either multiply repeated identical operations (for example, recleaning flotation) or chemical-hydrometallurgical operations (colloid-disperse or isomorphic impregnation, etc.) are resorted to. Final concentration terminates with dewatering of the finished products. Metal products (for example, gold, copper) are produced from the concentrates.

The dressability studies are followed by elaboration of a process circuit which includes a combination of diverse dressing and occasionally metallurgical methods and processes, which in turn results in optimal separation of the components by properties (density, magnetic

susceptibility, conduction, adsorption, wettability, solubility, etc.) . In the process, a gradient of mineral particle, ion or molecule concentration is generated in liquid or gas phase, as well as at the interphases boundaries with the aid of force fields and actions (magnetic, electric, gravity, adsorption, etc.). Dressability in a specific separation operation depends on the equipment arranged. Mineral dressability scales are constructed for separation intensity estimation. Dressability tests at different dressing units and plants conclude by sample dressing to a selected schedule with technical-economic assessment. Here parameters like recovery, product quality and output as well as the prime cost of processing to the selected schedule are compared. Dressability criteria: technological, kinetic, thermodynamic, statistical and economic, are established as a function of the totality of the above parameters. These criteria allow evaluation of the dressability at different dressing stages with a view to optimization. Dressability tests are carried out under full-scale, pilot and laboratory conditions, using methods of statistical planning and processing of results according to the corresponding criteria.

In mining of mineral deposits the highest economic efficiency is achieved during comprehensive processing of mineral products, which is ore separation to final products with recovery of all valuable components contained in the initial raw material whose production is technically and economically feasible. This processing is based on the genetic peculiarities of the deposits, which always contain multiple of valuable components, in particular, deposits of non-ferrous metals.

Four levels of comprehensive processing of solid mineral products are distinguished [11,18]:

- separation of a single concentrate containing single or multiple essential valuable components from the initial material by dressing methods (for example, coal from coal fields, a monometallic component from iron and non-ferrous metals ore deposits),
- supplementary separation of individual concentrates which are not basic for this subindustry by dressing methods (for example, molybdenum from copper-molybdenum ore, copper and bismuth from tungsten-molybdenum ore, barite, fluorite, feldspar from non-ferrous metals ores),
- separation of associate elements which do not form independent minerals (rare and dispersed elements) from concentrates by chemical-metallurgical methods or combined processing (for example, selenium and tellurium from sulfides, tellurium and gallium from alumina, germanium from coal, platinoids from copper-nickel ore, part of gold and silver from pyrite concentrates, etc.),
- use of dressing & metallurgical waste for production of building materials and other by-products (for example, road metal, sand and gravel from concentrator tailings, slag wool, phosphate fertilizers from blast furnace slags, sulfuric acid from non-ferrous metal industry gas).

Detailed analysis of the composition of raw materials, dressing products and chemical-metallurgical processing is necessary in comprehensive processing. This analysis is the point of departure for calculation of the valuable component distribution balance on the basis of the processing products, and elaboration of a judicious recovery technology.

The feasibility of separating of relevant components is governing by technical-economic conditions: available production facilities, demand for the product type, in question, transportability, financing of plant and unit construction, prime production cost, etc.

Comprehensive processing is the most crucial concept for all mineral product industrial sectors. In the USSR non-ferrous metals industry it permitted production of by-products, whose total value was about 30 % of the saleable production and recovery of about 70 elements as 700 different product types. Of these about 30 by-product concentrate types out of the above products were produced at dressing plants.

1.7. Mineral losses, waste and secondary resources

When conventional technologies are applied in processing of mineral resources, losses constituting a considerable fraction of the deposit reserves are unavoidable.[2,11].

Mineral losses are part of the balance reserves of solid mineral resources unextracted during deposit mining or wasted during mining and processing. Mining losses are a relative value representing incomplete recovery of the balance reserves during deposit mining. The causes of the losses are various: insufficient and low grade realizing of the geological-prospecting works; resulting in inexact evaluation of the geological characteristics; inconsistency between the designed mining methods and parameters and the deposit working conditions; untimely or incomplete preparation of the resources for mining; irrational selective excavation; inconsistency between the machinery and equipment used for ore extraction and the geological operation conditions; absence of scientifically grounded loss norms or reliable methods of loss registration and control, etc. Losses are classified as mine-wide (pit or placer-wide) and operating. Their amounts are calculated in mass or volume units and as percentages: of the overall mine (pit, placer) balance reserves for the mine-wide category, of depleted balance reserves for the operating losses. For multi-component ores, losses are registered for all valuable components of commercial value. They are evaluated through on-site measurements or under mine on the basis of surveying plans and sections with reliable outlining and testing of deposits or stoping areas. Where is impossible to apply direct methods, indirect ones are used: comparison of the mineral quantities in exhausted balance reserves and the run-of-mine ore.

The valuable component recovery ratio expresses the ratio of the quantity of valuable components extracted from the interior to the quantity of valuable component enclosed into counted balance reserves.

In the mining industry balance reserve losses vary from 2-3 to 40-50 % and even more, depending on working techniques and systems, material value, geological conditions and other deposit exploitation factors. The lowest losses are attributed to open working (3-6 %). In underground mining operating losses account for 12-18 % on the average.

The classification of losses in deposit working which was valid In the USSR (Table 1.3) permitted identification of losses by production stage, working method and system, individual stoping area.

Table 1.3. Classification of mineral losses in ore mining [9,10].

Category	Group	Mineral loss type
I. Mine-wide losses (pit or placer-wide, etc.)		Below mining facilities (near permanent workings along borders of tenement, field, below mine engineering structures). Below units unassociated with mining operations (water reservoirs, natural objects, utility lines, etc.)
II. Operating loss	A. In-massif mineral loss	In unworked pillar part, at development workings (interblock, interlevel, interpanel pillars). In pillars inside stoping area (block, chamber, panel, wall, column, pit field, dredging area). In flat and hanging walls (in soil, roof), along upper and lower borders of orebody, seam, bed lines. In areas of pinching out and on the flanges of bed, seam, orebody. Between stoping layers. In partially exhausted deposit areas. In pillars at geological breaks. In pillars of flooded, fallen-roof gas-permeable areas.
	B. Off-massif broken mineral loss	In development and stoping faces at joint stoping and mixing with embedding rock. Left in gob area: on flat wall (soil), benches; from mixing with caved rock at draw; in filling; on sites of handling, storing and sorting, on transport ways of mining undertaking.

Losses in dressing are a relative value representing incomplete recovery of the valuable component in the final dressing product. Valuable component losses are estimated as the difference $(100-R)\%$, where R is the recovery of the valuable component in the concentrate. The amount unextracted during dressing varies from 5 to 50 %. Losses of associate components because of non-comprehensive processing are the highest and can reach 100 %. Significant losses of non-ferrous, rare and precious metals in ore dressing are due to absence of full-scale processes for extracting valuable components from lean concretions and pulp with undissolved metals.

Technological and mechanical losses are distinguished estimated in process and product balances. Their amounts depend on the composition, structure and properties of the mineral resources and dressing methods (Table 1.4). However, the basis losses are governed by the mineralogical composition and physicochemical properties of the raw materials. In the first place, losses with fine and coarse grades of the dressed ore full under this category. Substantial losses are observed when the ore contains several minerals of the same component. Dressing of such ores are always accompanied by greater losses because different minerals necessitate different extraction methods, or are extractable by the same method, but with different effectiveness. Application of combined circuits is economically justified only if the proposition of the minerals of the component in question is significant.

Table 1.4. Classification of mineral losses in ore dressing [11].

Mineral loss type	Cause of mineral loss	Possible ways of loss reduction
I. Loss depending on quality of entry ore		
1. Loss related to natural material ore composition	Inadequate difference in physico-chemical properties of separated minerals	Improvement of existing and development of new dressing methods
	Thin impregnation of useful mineral particles	Improvement of preparation and dressing
	Poorly separable minerals available in ore	Development of special methods of hardly separable mineral extraction
	Associate minerals and soluble salts reducing dressability of useful component	Ore prewashing, desliming, heavy-media dressing
2. Loss related to deposit working system, mining engineering and method	Ore impoverishment by embedding rock in mining	Decrease of impoverishment in mining or heavy-media predressing
	Penetration of filling materials from gob area into ore (concrete, clay, etc.)	Change in working system, washing or heavy-media predressing
	Ore oxidation during mining	Decrease in time of broken ore residence in stopes, ore-chutes and dumps
II. Technological loss		
1. Loss related to accepted technology	Imperfection of accepted dressing mode or mode inconsistency to individual ore types	Technological studies to be carried out for optimization of ore dressing mode
	Inconsistency of flowsheet to comprehensive processing task	Development of comprehensive processing schedule
	Too high requirements on concentrate quality	Estimate of economically-justified concentrate standard with regard to metallurgical operations
	Circulation and accumulation of middlings impairing dressed ore parameters	Improvement of dressing circuit, individual processing of middlings
	Non-optimal layout of dressing machine line	Optimal designing of dressing cascades, improvement of equipment
	Wateriness of middlings and concentrates	Application of flotation agents, improvement of dewatering process
2. Loss connected with violation of accepted technology	Ore overcrushing	Optimization of crushing in terms of final product quality
	Mechanical loss (overflow, quicksand, washout, dusting)	Accurate registration and reduction of mechanical loss, plant cleanliness
	Unsatisfactory equipment condition	Better condition of repair shops, provision with spare parts and back-up equipment
III. Loss depending on production engineering and control		
1. Loss unconnected with dressing process	Unplanned stoppage because of breaks in supply of ore, water, power, etc.	Elimination of break causes, bin ore stock
	Steep variations of ore composition in component content and ratio	Mined ore homogenization or scheduled ore mining from different deposit areas which permits ore homogenization during mining
	Drying and transportation	Improvement of registration and control of ore, dressing products and transport facilities
2. Dressing loss	Non-optimal mode	Set-up of automatic process monitoring and control depending on entry ore quality

Emergency stoppage	Emergency prevention
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Incomplete recovery of valuable components may be connected with an inadequate level of process and production engineering, composition fluctuations, shortage and low quality of the equipment.

Let it be noted that the notions of valuable component loss in mineral mining (in the interior) and processing (in the waste) differ semantically. Mining loss is waste-free (except the overburden, which contains no valuable components) while processing loss is associated with waste (Fig.1.1).[19].

Cause and place are key factors on classificating mining losses. Clear-cut identification of a loss generation area is impossible in mineral processing operations, in particular, in dressing operations forming a complex system of interrelated and interacting technological processes. For example, ore preparation operations (crushing, grinding, sorting of size) do not lead themselves in principle to evaluation in terms of losses (except of direct mechanical losses like screenings-off, washouts, etc.).

The concentrate of a certain dressing stage, for example, flotation or gravity, which is a middling product, shows losses (through recovery) in partial form, since the whole concentrate or its part enters grinding and other operations as circulating flow, changing in so doing the state of all technological processes.

Only classification of losses and waste by conversion stage is possible when the links of the interconnected flowsheet sections: mining (deposit working) - dressing - metallurgical operations, are examined. Estimation of total losses is an additive function for the subsystems under consideration. However, estimation of losses which reflects the specific peculiarities of each subsystem rules out consideration of this criterion in integral terms.

Accordingly, we proceed to consider the notion of waste as unused residues of raw materials, products or semiproducts which result from production (industrial waste) or consumption (consumption waste) and have no consumer properties in this form.

Mining waste is unutilized mineral mining and processing products separated from the mined rock mass during deposit working, dressing and chemical-metallurgical processing. They are classified by phase composition and production cycle (Table 1.5). The relative waste yield depends on the production cycle, nature of the raw material, the extracted component content in the initial product.

Table 1.5. Types of waste in mining & metallurgical cycle [2].

Phase character- istic of waste	Mining		Dressing		Metallurgy	
	open pit	under-ground	gravity, magnetic, electric	flotation	hydro-metallurgy	pyro-metallurgy
Solid	Overburden	Mine rock	Tailings	Tailings	Precipitates	Slag
Liquid (solutions & suspensions)	-	Mine water	Wash water, slime	Slime, liquid pulp phase	Salt solutions	Cooling water
Gas & dust	Dust	Methane in coal mining, vent air	-	Suction	Vapour	Dust-laden gas

Waste has always accompanied mining and processing operations, but has not been considered a particular problem almost up to the middle of the 20th century. As mineral output grew, waste amount increased, and at a much faster pace than the product yield, since meanwhile the valuable component content in the ore decreased, the coal ash level went up, deposit mining conditions became more and more complex and the amounts of spoil and overburden increased correspondingly. The overall world output of mineral products is estimated approximately at 100

bln tpy and increases 100 per cent each 10-12 years. Not more than 30-40 % of this amount are used (including building materials and combustible minerals).

The mining waste problem is considered in two aspects.

From the ecological viewpoint, the greatest concern is caused by gas waste, for example, sulfur dioxide and other sulfur compounds, carbon and nitrogen oxides which amount to over 1 bln tpy in total. Dust emissions containing metallic compounds exceed by tens of times those of natural sources (volcanoes, forest fires, dust-laden wind, etc.). Consumption and pollution of water by the mining industries is about 10 m³/t of mined product. One tenth of hectare of land area per each one thousand of products on the average is allocated for spoil, and dumps occupy hundreds of millions of hectares of usually unusable, but in some cases quite productive land. The recreation capacity of nature is already unable to cope with the growing amounts of waste quantity which causes irreversible environment pollution.

On the other hand, mining waste has a certain resource potential by generating technogenic deposits. Recovery of gold, uranium, rare metals from old waste has been carried out from early in the 60s. Waste is the source of supplementary production of copper, coal, etc. For example, aluminum, gallium, potash, soda, cement are made from nepheline tailings of apatite flotation. It is predicted that 30-40 % of solid waste will be used as building materials, 20-30 % applied for filling gob mine and pit areas. Bacterial leaching permits additional extraction of heavy non-ferrous metals from dressing tailings. Oxidized ferruginous quartzite accumulated in iron ore deposit dumps and magnetic separation tailings can be reclaimed. Combined dressing circuits for slags, slime, filter cake and other metallurgical waste are under development. Sorption and ion-exchange technologies permit recovery of non-ferrous metals, salts, halogens from drainage, pulp, mine water, etc. In the USSR more than 30 % of the sulfuric acid output were produced from waste gases of the non-ferrous metals industry.

Waste recycling is as a rule connected with the raw materials requirements of allied industries. Technological studies on waste reclamation showed that comprehensive processing of many mineral resources is possible with full or partial transition to production of different product types from waste (Table 1.6).

The economic aspect of the waste problem calls for comparing the economic estimates of the damage from waste discard and the gain from reclamation. Storage of solid waste as potential mineral product source is associated with expenditure on certain protective measures to prevent weathering, oxidation (incl. bacterial), washing-out, as well as occupation of productive land. Plants for mining waste recycling also involve significant investments.

Solution of the waste problem is related to low-waste and non-waste technologies. [2,10].

Under the "Declaration on low-waste and non-waste technologies and waste reclamation" adopted at the All-European conference on co-operation in environment control (Geneva, November, 1979), non-waste technology is defined by the UN Economic Commission for Europe (ECE) as practical application of know how, methods and tools so as to achieve judicious use of natural resources and energy in conjunction with environment control. This definition is too extended and in fact includes all kinds of studies, developments and implementations aimed at judicious use of natural resources, environment control and recreation.[20].

The non-waste technology* notion developed in Russia has gained a more purposive interpretation. Non-waste technology is understood as an individual operation, or a totality of production operations, whose implementation has no negative effect on the environment. A non-waste technological system is a combination of administrative and technical measures, technological processes as well as raw and other material preparation methods providing maximized and comprehensive utilization of raw materials and power and eliminating negative ecological effects or reducing them to an environment-friendly minimum level.

The non-waste technology concept is a matter of convention to some extent. It is envisaged as an ideal production model which cannot be fully implemented in the majority of cases (low-waste technology), but is approached closer and closer in the course of technological progress. The non-waste production concept is criticized as practically and even theoretically unfeasible. Referring to the second law of thermodynamics, it is reasoned that just as energy

cannot be fully converted into work, so raw materials cannot be fully processed into products for manufacture and consumption. This is implausible, since all products should be environment-friendly for maintaining good ecology. It can be exemplified by the non-waste activity of the natural ecological systems.

Complete utilization of solid waste is sometimes called a dump-free technology. A constituent part or a variant of non-waste technology is also a so-called drain-free technology, i.e., one without liquid waste. The main trends in creating a drain-free technology are recourse to waterless technological processes and minimally water-consuming processes, choice of a production complex providing subsequent multiple use of water, maximum development of waste reclamation systems, local treatment of water effluents with recovery of valuable components, improvement of existing and elaboration of new, mostly, agent-free methods of water effluent treatment, substitution of air for water in cooling, removal of process waste, primarily solid-phase or high-concentration, for recycling or backfilling.

The systems listed below can be the subject of investigation in non-waste technology:

- production process or production enterprises;
- grouping of production stages related to one or several subindustries or territorial units;
- territorial-production combinations, including territorial-production complexes;
- the state as a whole;
- groupings of states or border territories of two or several states.

In this context all natural resources of reproducible or irreproducible nature and all negative effects on environment components should be covered.[20].

The idea of creating a non-waste technology emerged in analogy to the interrelationship of natural process, which products of vital activities of one organism are absorbed by other organisms, so that no excess substances accumulate as a result of the circulation. Non-waste technology is the most promising state-of-the-art trend in flowsheet design, including those for mineral processing, thereby solving the problem of more complete comprehensive utilization of mineral reserves and environment protection. Non-waste technology presupposes maximum recovery of all valuable components at minimum output or total absence of solid, liquid or gas waste. Based on inter-industry cooperation it is expected to produce besides the basic component associate iron and non-ferrous metals, building materials, basic chemicals, fertilizers - from run-of-mine ore, and to utilize the spoil for filling gob areas, manufacture of road metal and road paving material, construction of irrigation and hydrotechnical structures, landscape leveling.

The rock mass balance shows that annual accumulation of mining waste is approximately the same as the output of nonmetallic building materials (sand, lime, road metal, etc.). However, in this case full substitution is impossible and economically irrational in terms of transportation conditions, material composition, etc. Only partial substitution is possible, though on a much larger scale than at present (3-4 % in total).[2,19].

It should be noted, however, that if non-waste technology is taken in its wide sense, the scale of waste generation in mineral mining and processing regions makes it possible to pose the question of constructing cheap irrigation systems in the form of hydraulic fill dams, and landscape leveling with subsequent agricultural or power utilization. In this context non-waste technology is aimed at conservation of agricultural land and increased yields through lower environment pollution.

In-principle feasibility of non-waste technology depends on the scale of the system under consideration. For example, it is unlikely that all the input raw materials can be used for making useful products within a single undertaking: plant or concentrator. A large complex producing a wide product range is more suitable for the waste-free idea to be implemented. This idea can largely be put into practice within one region or state.

Low-waste technology tends to complex utilization of mineral resources and environment protection, which implies maximum full extraction of all valuable components from raw materials on the operating site with minimum yield of solid, liquid and gas waste. Unlike non-waste technology, which entails environment-friendly operation with full waste recycling or backfilling, water circulation and dump rehabilitation, it only partially solves the problem of

complex application of raw materials and prevention of irreversible changes in the natural environment. Low-waste technology implies creation and implementation of supplementary product manufacture from waste, development of water circulation systems based on local waste water treatment and elaboration of technologies for industrial waste recycling into secondary material resources.

The need for establishing a low-waste technology appeared in the middle of the 20th century because of the catastrophically growing pollution of the hydrosphere, atmosphere and biosphere by accumulating solid, liquid and gas waste. The scale of pollution in many regions is beyond natural remediation. Low-waste technology makes for a more extensive mineral product base, lower investments and operating costs in manufacture, higher recovery of useful components through complex utilization.

One type of low-waste technology is drain-free industrial use of water, with the larger part of the water in the recycling circuit with low make-up rate. Drain-free systems with full, partial recovery or no recovery of separated components (i.e., with waste storage) are distinguished. Low-waste technologies must be environment-friendly, technically feasible in practice and economically expedient.

In the USSR the first example of a low-waste technology was implemented into practice at the Volhov aluminum plant (1960) which processes nepheline concentrate into alumina, calcined soda, potash and cement with recovery of helium.

Low-waste technology is expected to yield 20-25 % reduction of the rock mass output (mainly due to production of building materials from waste), lower overall prime product cost, and restoration of the environment in mining and processing regions.

As follows from the above discussion, environment protection and ecological problems play a fairly important role in mining and metallurgical industry. These problems will be addressed in detail further on. Here only some ecological notions will be introduced.

Environment pollution is the degree of harmful effect of an industrial project on the natural environment (organic and inorganic) with allowance for social, sanitary and economic factors.

Emission is accidental or deliberate discharge of matter or energy polluting the environment.

Steady-state pollution is regularly repetitive or continuous discharge of matter or energy which polluting the environment.

Normalized emission is the total discharge of pollutants into the environment with allowance for the differences in their degree of harmfulness, determined as ratios of maximum permissible concentrations or on the basis of specialized medical-biological studies.

Ecological-economic damage is actual or potential consequences of resource losses during production or owing to an adverse impact of the undertaking on the natural environment, the agricultural, and water services, forestry or mineral reserves in the interior.

Potential damage is losses due to pollution in the absence of preservation measures and expressed as cost; it can take the form of labor, material, financial resources losses incurred as a result of air & water pollution.

Actual damage is losses expressed as cost and connected with changes in the steady-state equilibrium of the natural environment and social-economic consequences of these changes.

Prevented damage is difference between potential and actual impairment at a certain moment in time in a certain region.

Table 1.6. Possible trends of waste utilization in allied industries

Waste-generating industries	Products from waste for sectors						
	fuel	iron & steel, alloys & compounds	non-ferrous metals, alloys & compounds	fertilizers & basic chemistry products	building materials	materials for nuclear engineering	other fields
Coal industry	Refuse coal, mine methane	Fe from pyrite	Al, Al ₂ O ₃ , Al-Si alloys	Soil liming agents, sulfuric acid from pyrite	Aggloporite, road metal, brick	-	Mine filling, road building
Heat power engineering	Refuse gasification Combustible matter from ash, power-generating plant heat	Fe-Si alloys from alloys	Al-Si alloys from ash, Ge, Ga, Mo	Sulfuric acid from waste gas, micro-fertilizers	Road metal, ash gravel, agglomerite, brick	U, Th	Road building
Iron & steel industry	Furnace heat	Fe from oxidized quartzites	V, Co, Cu, Ni, Ti, Zr, Zn, Mg, Ba, Ta, Nb, etc.	Phosphoric fertilizers	Road metal, slag concrete, cement, refractories, sand, lime	-	Road building, gorge and mine filling, irrigation construction
Non-ferrous metals industry	Autogenous sulfide combustion, metallurgical furnace heat	Fe from pyrite, pyrrhotite, titanomagnetite	Metals from old refuse, slags, tailings dumps, sedimentations, drainage	Sulfuric acid, microfertilizers	Ditto	U, Th, Li, Be	Mine filling
Production of mineral fertilizers (mine chemistry)	-	Magnetite, titanomagnetite, perovskite	Rare earths, Al from nepheline, Ti, Mg	Phosphorus from dressing tailings, soda products from nepheline, fertilizers from dressing waste	-	U, Li from salt water, Th	Ditto
Production of non-metallic building materials	-	Magnetite and Fe in sand cleaning	Ti, rare earths in sand processing	Soil liming agents, soil structure improvement, moisture adsorbent in soil	-	-	Mine and open pit filling, road building, irrigation structures
Nuclear power engineering	Power-plant heat	Fe, Mn	Au, Cu, Zn, Pb	Microfertilizers, phosphoric fertilizers, sulfuric acid	-	Final extraction of U, Th from refuse	Mine filling

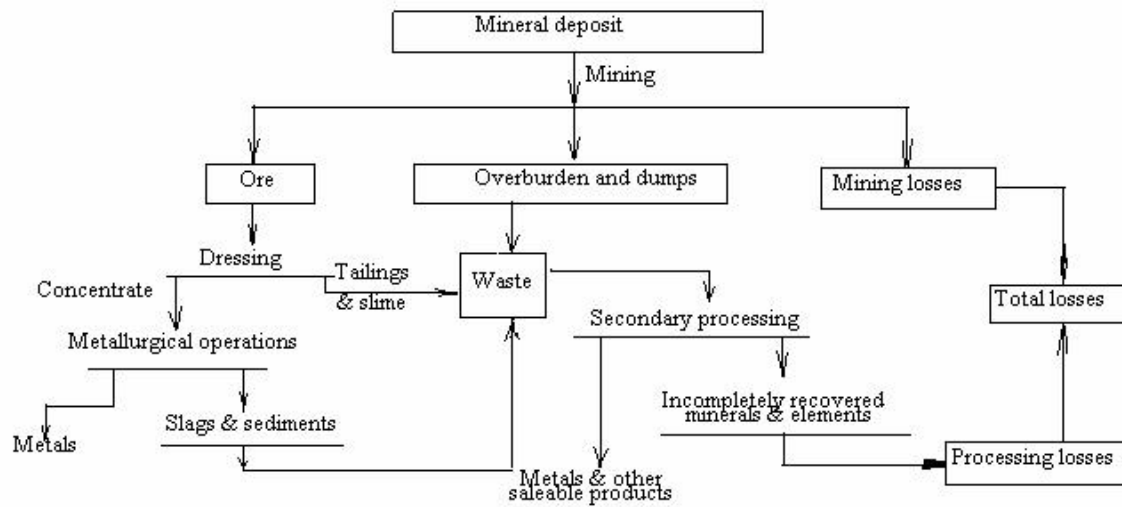


Fig.1.1. Interaction of losses in mineral mining and processing

6. Possible trends of waste utilization in allied

industries

Waste-generating industries	Products from waste for sectors						
	fuel	iron & steel, alloys & compounds	non-ferrous metals, alloys & compounds	fertilizers & basic chemistry products	building materials	materials for nuclear engineering	other fields
Coal industry	Refuse coal, mine methane	Fe from pyrite	Al, Al ₂ O ₃ , Al-Si alloys	Soil liming agents, sulfuric acid from	Aggloporite, road metal,	-	Mine filling, road building

Heat power engineering	Refuse gasification Combustible matter from ash, power-generating plant heat	Fe-Si alloys from alloys	Al-Si alloys from ash, Ge, Ga, Mo	pyrite Sulfuric acid from waste gas, micro-fertilizers	brick Road metal, ash gravel, agglomerite, brick	U, Th	Road building
Iron & steel industry	Furnace heat	Fe from oxidized quartzites	V, Co, Cu, Ni, Ti, Zr, Zn, Mg, Ba, Ta, Nb, etc.	Phosphoric fertilizers	Road metal, slag concrete, cement, refractories, sand, lime Ditto	-	Road building, gorge and mine filling, irrigation construction
Non-ferrous metals industry	Autogenous sulfide combustion, metallurgical furnace heat	Fe from pyrite, pyrrhotite, titanomagnetite	Metals from old refuse, slags, tailings dumps, sedimentations, drainage	Sulfuric acid, microfertilizers		U, Th, Li, Be	Mine filling
Production of mineral fertilizers (mine chemistry)	-	Magnetite, titanomagnetite, perovskite	Rare earths, Al from nepheline, Ti, Mg	Phosphorus from dressing tailings, soda products from nepheline, fertilizers from dressing waste	-	U, Li from salt water, Th	Ditto
Production of non-metallic building materials	-	Magnetite and Fe in sand cleaning	Ti, rare earths in sand processing	Soil liming agents, soil structure improvement, moisture adsorbent in soil	-	-	Mine and open pit filling, road building, irrigation structures
Nuclear power engineering	Power-plant heat	Fe, Mn	Au, Cu, Zn, Pb	Microfertilizers, phosphoric fertilizers, sulfuric acid	-	Final extraction of U, Th from refuse	Mine filling

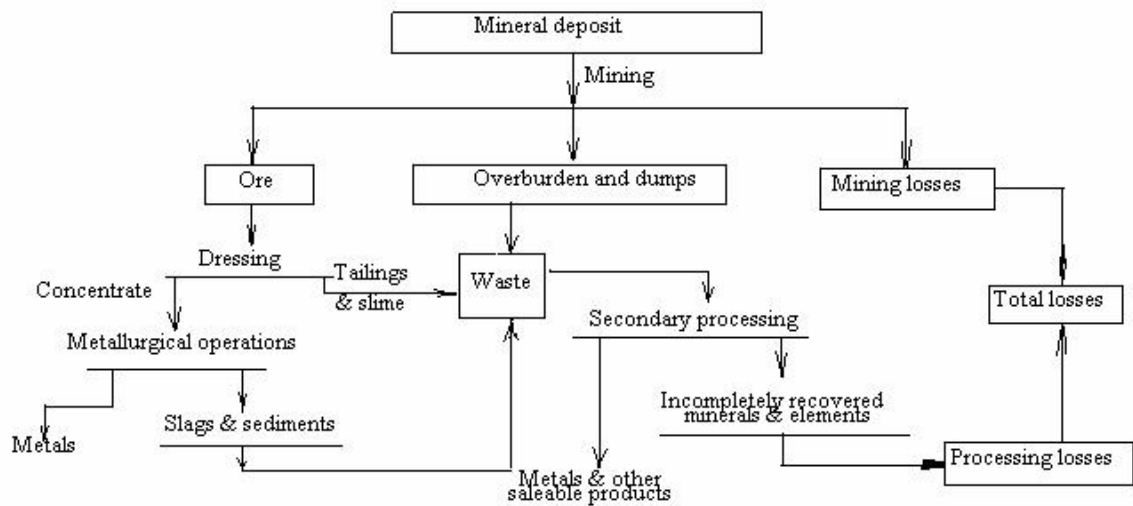


Fig.1.1. Interaction of losses in mineral mining and processing

1. Chapter 2. Geology and Geography of Non-Ferrous Metals Ores Distribution in the Former USSR

Unlike the rest of the book, the information provided in this chapter has an awkward aspect that needs to be explained. The factual data on ore deposits and mining, dressing and metallurgical facilities tend to dynamic change, and - particularly in the territory and period in question - cannot be regarded as constant and reliable.

The initial data were compiled from a variety of sources, published or based on the professional experience of the authors, who had at different times staged at all major dressing plants and metallurgical enterprises of the former USSR.

In our view, the most verified and reliable material is that published in the "Encyclopedia of Mining" [10], in which L. Barsky had participated as a contributor and as redactor of ore-dressing section. In addition, information from [22-46] was processed and corrected on the basis of individual articles and of data from the Non-ferrous Metallurgy Information Institute. A significant amount of data, including the groundwork for the maps indicating deposits and industrial enterprises, was drawn from the composite work [48] carried out by various institutes. The data on Kazakhstan was drawn from [49,50].

Still the reader must be made aware of the need for caution in having recourse to this information. Over the last 7-10 years the mining sector of the former Soviet Union has undergone changes too drastic to be reflected in a book. Besides natural changes associated with depletion, opening of new ones and construction of facilities, a universal upheaval has taken place in the territory in question. Following the social, political and economic transformations, some enterprises have been closed down or converted, while others have flourished; old industrial, technological and economic links have been broken and new ones formed. The basic causes of these transformations are:

- The emergence of new states and new international boundaries, with the corresponding of interests. This has in turn led to breakdown of the technological chain of the mining-processing complex (deposit - mining works - ore dressing - metallurgy - metalworking - consumption). In these circumstances, individual enterprises were forced to close down or curtail their operations, to look for new partners (including foreign ones), etc.

- The disappearance of many former customers, for the originally State ordered production (the military industry complex; the nuclear energy agencies; the central planning Authority with its permanent inconsistencies) - as often as not accompanied by suspension of payments for delivered products and of staff wages.

- Solid changes at the enterprises themselves, following wage delays, privatization, acquisition by former investors, etc.

- The accession of the newly states to the world market, with the attendant effect on the economics of enterprise operation. Working of low-grade ores became unprofitable in absence of planned State orders, and as a result, mining and production of tin, gold, uranium etc. were cut down, while for other metals, now exportable, the prospects have improved.

- Disorganisation through warfare (Caucasus, Tadzhikistan, etc.) national aspirations and claims on Russia (the Ukraine, Kazakhstan, Central Asia), local conflicts (the Far East, the Kuzbass, etc.).

Because of these and other factors, the productivity fluctuations in the mining and associated industries impede reliable forecasting and generalisation. More over, the conversion of these countries from a planned to ordinary market economy aggravates the dynamicism of the changes in terms of structure, scale and establishment.

Still, the information provided in this chapter is unique in its comprehensiveness and scope, and can serve as a sufficiently reliable guideline in predicting the development of the mining and metallurgical industries in the CIS. In any event, the data on the location of non-ferrous metal ore deposits, on the plants operating at these locations, and on existing technological and economic links - are in our opinion of definite interest.

Our apologies to the readers for any errors and inaccuracies due to the factors enumerated above.

2.1. Background

The area occupied by the USSR was 22,403,200 km² (one fourth portion of the country's territory was the European part). The population was 281.7 mln people (as of Jan. 1, 1987). Fifteen union republics composed the USSR: Azerbaijan, Armenia, Byelorussia (new name: Byelarus), Estonia, Georgia, Kazakhstan, Kirghizia (new name: Kyrgyzstan), Latvia, Lithuania, Moldavia (new name: Moldova), the Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan.[10,12,26,27].

The distribution of non-ferrous metal resources in the CIS countries, the production and consumption of minerals in the FSU along with the exports/imports of minerals in the FSU are given in Tables 2.1-2.4.[23,25]. The non-ferrous metals minerals are distributed extremely nonuniformly. The Baltic republics (Estonia, Latvia and Lithuania) as well as Moldavia, Byelorussia and Turkmenistan are virtually deprived of non-ferrous metal deposits.

In the Baltic states mining industries are comparatively small in size or value. There are phosphate deposits at Maardu in Estonia. The former Soviet republics of Estonia, Latvia and Lithuania will go on keeping economic relations with many of the

former USSR republics, involving trade or exchange of mineral and energy resources for the most part.

2.1.1. Basic Features of Geological Structure [4,10,49,54,55,56,61].

The large part of the territory is of platform structure. In the South and East platform areas are framed with cover-folded and roof-block mountain structures which are partially young, Cenozoic, and partially more ancient, from Late Cambrian to Mesozoic, regenerated by the latest movements.

The extreme eastern periphery of the country is the region of the active continental margin of the Pacific Ocean while the northern periphery is the passive margin of the Arctic Ocean.

Ancient platforms have the Early Cambrian base, Archean in the large part. They are the East-European (Russian) and Siberian platforms. The latter is wholly in the USSR territory while the former extends with the bulk of its territory towards the Scandinavian countries, Poland and Rumania. Besides, a small North Barents platform is prominent in the north-east part of the Barents Sea (Franz-Josef Land) while the Hyperborean platform, with the Pre-Cambrian base as well but, maybe, somewhat younger, stands out in the north-east part of the Novosibirsk archipelago and the nearby water area.

The East-European platform occupied almost the whole European part of the USSR, exclusive of Timan and the Pechora lowland, the western Ural slope, the Carpathians and the extreme Moldavian south. The western platform borderline was almost wholly, excluding a small section along the Ciscarpathian foredeep, outside the USSR territory, coinciding with the so-called Baltic-Podolian lineament. The platform is bounded by faults along which adjacent folded systems of different age are thrust over the platform. In some areas in the south-east and south the platform borderline is concealed by the cover of Mesozoic and Cenozoic sediments transient from the ancient

Table 2.1. Distribution of non-ferrous metal resources in the CIS countries (%) [23,25]

State	Cu	Ni	Pb	Zn	Sn	Ti	Sb	Hg	Mo	W	Al	Others
Russia	52.5	92.7	23.9	37.2	84.9	82.0	23.0	50.6	68.3	61.0	52.5	U, Au, As, Ag, Be, Cd, Mg, Co, Pt
Kazakhstan	32.2	5.0	57.6	49.0	4.6	2.0	5.0	-	27.1	30.0	45.5	U, Ag, As, Be, Bi, Cd, Mg, Re, Ag, Au, Ge
Ukraine	-	0.9	0.6	0.7	-	16.0	2.0	4.8	-	-	-	U, Be
Uzbekistan	7.4	-	7.3	6.0	1.4	-	-	6.0	-	4.0	-	U, Au
Georgia	1.8	-	0.4	0.7	-	-	-	-	-	-	-	
Armenia	1.6	-	0.3	0.4	-	-	-	-	1.7	-	-	Au
Azerbaijan	4.5	-	1.6	1.2	-	-	-	-	-	-	2.0	
Kyrgyzstan	-	-	-	-	3.0	-	14.4	38.6	-	3.0	-	U, Au
Tajikistan	-	1.4	8.3	4.8	3.2	-	52.3	-	2.9	2.0	-	Au, U, As, Bi, Cd, Ag

Table 2.2. Mineral production in the former USSR for 1982-1991
(,000 tonnes, unless otherwise specified) [46,51-53]

Mineral (metal)	1982	1986	1990	1991	% of world
Aluminium (primary)	2,400	2,350	2,200	2,300	12.2
Antimony (mine)	6.5	6	5.4	4.8	11.9
Bauxite	6,400	6,275	5,350	4,800	4.3
Bismuth (mine)	0.075	0.084	0.080	NA	2.1
Cadmium (refined)	2.8	2.7	2.4	2.0	9.6
Cobalt (refined)	4.3	4.9	4.9	NA	19.2
Copper (mine)	1,010	1,030	900	840	9.2
Copper (refined)	1,350	1,400	1,260	1,120	10.6
Gold (mine)	0.266	0.273	0.250	0.220	12.3
Lead (mine)	575	520	490	460	13.8
Lead (refined)	800	790	730	670	12.1
Magnesium (refined)	77	86	80	75	21.8
Mercury	1.7	1.5	1.4	1.2	32.9
Molybdenum (mine)	11	11.4	11.5	10.0	8.9
Nickel (mine)	170	185	212	200	23.0
Nickel (smeltery)	190	195	230	210	24.7
Platinum (mine)	0.027	0.023	0.032	NA	25.2
Silver (mine)	1.6	1.6	1.38	1.27	8.9
Titanium (mine)	235	240	230	200	3.6
Tin (mine)	16	16	13	11	6.1
Tin (smeltery)	17	17	13	12	6.2
Tungsten (mine)	9.4	9.0	7.0	NA	16.3
Zinc (mine)	1,020	970	870	800	10.6
Zinc (smeltery)	1,050	1,065	920	800	11.1

Table 2.3. Mineral consumption in the former USSR
(,000 tonnes, unless otherwise specified) [52,53]

Mineral	1982	1986	1990	1991	% of world
Aluminium (primary)	1,880	1,750	1,700	1,100	6.3
Cadmium (refined)	2.3	2.7	2.0	1.8	9.6
Copper (refined)	1,320	1,300	1,000	980	8.2
Lead (refined)	810	760	650	600	11.1
Magnesium	62.0	78.0	77.0	70.0	22.7
Nickel (refined)	138	137	115	85	10.5
Tin (refined)	27.0	31.5	20.0	17.0	7.7
Tungsten (ore)	15.9	15.0	12.0	NA	28.4
Zinc (refined)	1,050	1,010	920	775	11.3

Table 2.4. Mineral exports/imports in the former USSR for 1981-1990,
(,000 tonnes, unless otherwise specified) [23,25,29,43]

Mineral	1982	1986	1990	% of world
<u>Exports</u>				
Aluminium	540	520	650	7.5
Copper (metal)	100	100	200	5.3
Lead (metal)	55.2	50	30.0	2.3
Nickel (unwrought)	47.6	53.4	100	21.9
Nickel (semi)	0.3	0.1	NA	0.17
<u>Imports</u>				
Aluminium (primary)	505.4	600	650	7.1
Bauxite	1	1.5	1	0.011
Copper (ore)	3,459.6	5,000	3,700	10.0
Copper (metal)	48.8	20	10	0.56
Lead (ore)	2.0	0.5	NA	0.01
Lead (metal)	45	40	18	1.6
Nickel (unwrought)	68	45	26	1.8
Tin (ore)	1.7	0.6	-	2.6
Tin (metal)	12	13.8	10	5.5
Tungsten (mine)	6.9	6.0	5.0	28.2

platform to the young one. The platform base is barren in the Baltic and Ukrainian shields, superimposing the zero contour line in the Byelorussian and Voronezh massifs, in the latter one it is stripped by open pits in the region of the Kursk Magnetic Anomaly, being exposed somewhere in the Don River valley. The base is laid bare by numerous drillholes in the rest of the area. Archean formations, among which relics of the most ancient rock with an age of up to 3.9 bln years are encountered, are of prime value in the base structure (the Kola Peninsula, Karelia, the Voronezh massif, the Ukrainian shield). The Early Proterozoic formations with a more limited range compose a protoplatform mantle (Karelia, Pechenga - Imandra - Varzuga in the Kola Peninsula) or protosynclinal folded systems (the Kursk-Krivoi Rog, Odessa-Kanev and Orekhovo-Pavlograd platforms). The sedimentary mantle of the East-European platform composes the Russian platform, including Upper Wendian and Phanerozoic sediments. The mantle base incorporates numerous rift structures made by land and shoaly-marine detrital and partially carbonate sediments, involving basic volcanites here and there.

The shoaly-marine Cambrian-Lower Devonian Russian platform mantle sediments are limited in abundance, located mostly within the Baltic and partially Moscovian synclises. On the contrary, the Middle Devonian - Lower Triassic sediments are the most abundant.

In the Middle Paleozoic a sublatitude uplift streak was formed. It includes the Byelorussian and Voronezh antecises and separates the Baltic and Moscovian synclises from the Pripyat-Dnieper-Donets aulacogen and its eastern continuation, the Donets basin with the heavy coal-bearing Middle Carboniferous rock mass which has turned into the folded Donets Range by the middle of the Early Permian. Mesozoic and Cenozoic sediments are mature mainly in the southern half of the Russian platform, in the Ukrainian and Caspian synclises, on the Black Sea slope of the Ukrainian shield and only partially in the deepest parts of the Baltic and Moscovian synclises. Land and shoaly-marine terrigene sediments of the Upper Triassic and Lower Cretaceous period change to carbonate ones (chalk, marl) of the Upper Cretaceous - Lower Paleogene period and again to terrigene, shoaly-marine and land ones of the Oligocene - Neogene and ultimately to glacial (in the north) and perglacial (in the south) Quaternary ones. The Caspian syncline situated in the south-east angle of the Russian platform shows a unique structure. The central part base sank to the depth of more than 20 km, and the consolidated crust exhibits the suboceanic structure type. In the Devonian and prior to the beginning of the Kungurian age of the Early Permian the Caspian syncline was a deep-sea basin uncompensated by sedimentation. In the Kungurian it became a place of accumulation of heavy salt-bearing

strata which presence is associated with salt tectonics typical of the series in the overlying shoaly-marine, partially land sediments of the Upper Permian, Mesozoic and Cenozoic.

The Timan-Pechora platform adjoins the ancient East-European platform in the North-East. Here the Cambrian base is superimposed with the Riphean folded complex outcropping in Timan, the Kanin Peninsula, the Kildin Island, the Sredny (Middle) and Rybachiy Islands and overlying the mantle of the southern part of the Barentz Sea and the Pechora trough.

The second big ancient platform (Siberian) occupies the area between Yenisei and Lena, Taimyr and the Baikal region. The north-west and northern platform borders are concealed below the margin of the Mesozoic-Cenozoic mantle of the West-Siberian platform, Yenisei-Khatanga depression and the Laptev Sea; the eastern border is along the Cisverkhoyansk depression and to the south along the Sette-Daban Range, the southern border is along the fault limiting the Stanovoye Nagorye (Upland) and farther to the Baikal region. The south-west border extends along Eastern Sayan and the Yenisei Kryazh (Range). The platform base is exposed in the Aldan Shield, Anabar massif, Olenek Uplift and on the south-west platform periphery, in the Sharyzhgalskiy block and the Baikal Region. It is bedded mostly by Archean rocks, the most ancient ones of them are considered to be deeply metamorphized formations: basic and ultrabasic slate, plagiogneiss, charnockite. In the Early Proterozoic the Stanovoy Belt underwent intensive tectonic-thermal regeneration, and the protoplatform land and shoaly-marine sedimentary mantle became to be deposited on the already stabilized Aldan shield. The North Baikal volcano-plutonic belt appeared along the southern platform margin in the end of the Early Proterozoic. The sedimentary mantle on the Siberian platform began to be accumulated in the Late Wendian, and sedimentation and trappean magmatism were concentrated in aulacogenes in the Riphean and early in the Wendian.

In the Riphean and Paleozoic the East-European and Siberian platforms were divided by the wide moving Ural-Okhotsk or Ural-Mongolian geosynclinal belt of meridional strike which turns to the east in the south, gaining latitude strike and separating the Siberian platform from the Chinese-Korean one. The northern belt segment is Ural-Siberian, and the southern one is Central Asian. The latter partially goes out of the USSR territory to China and Mongolia. This belt is considered to be bedded on the Early Pre-Cambrian land crust which is common with the adjacent ancient platform crust but underwent intense destruction during the Riphean, especially in the second half. As a result by the Early Cambrian here appeared extended oceanic crust basins which compose the Paleo-Asian Ocean in which however there were also preserved numerous land crust fragments (microcontinents), Kazakhstan-North Tien Shan, Dzhungar, Tuva-Mongolian and others, more shoaly, particularly, over the ocean periphery.

The second biggest moving belt of the FSU territory is the Mediterranean one which frames the East-European platform in the south and separates it from the African one, and borders directly or almost directly the Ural-Okhotsk belt to the east of the Caspian Sea. The bedding of the Mediterranean geosynclinal belt relates to the Late Riphean, like the Ural-Okhotsk belt, it appeared on the destruction developed and preserved as microcontinents of the Pre-Cambrian land crust.

The eastern marginal land of the USSR also underwent an active development process in the Mesozoic and Cenozoic. The Verkhoyanye-Chukotka folded region which final distortions relate to the Late Jurassic-Early Cretaceous period is situated to the east of the Siberian platform. The large part of this region up to the Chersky Crest in the east was in progress in the Paleozoic and Early Mesozoic period as the passive margin of the Siberian continent. In the Middle-Late Jurassic period the volcanic arch was formed on the edge of the Kolyma-Omolon microcontinent, and the collision with the Verkhoyanye-Kolyma margin of the Siberian continent began. It brought about folded-thrust distortions of the Verkhoyanye-Kolyma system which are rather moderate in the large part of the area but expressed by smooth thrusts along the borderline with the Cisverkhoyanye depression generated already in the end of the Jurassic-Early Cretaceous period, as well as in the collision zone proper.

The Far East geosynclinal region covers Sikhote-Alin, the Seas of Okhotsk and Japan, Sakhalin, Kurylys, Kamchatka, the Koryak Highland, representing one of the segments of the Pacific Ocean geosynclinal belt; the greater part of the region appeared on the oceanic type crust evidenced by various-age ophiolites from Ordovician to Late Cretaceous. However here relatively small detached masses of the Early Pre-Cambrian land crust are also well-known in Kamchatka, in the Taigonos Peninsula, in Sikhote Alin. Supposedly, the large Mediterranean Central massif of the Sea of Okhotsk has equally an ancient base. The folded systems of the region in general extend in line with the contour of the Pacific Ocean trough.

2.1.2. Minerageny [4-6,10,59]

The Archean, Proterozoic, Paleozoic and Mesozoic-Cenozoic mineragenic epochs can be distinguished in the geological history of formation of mineral deposits in the USSR territory.

Magmatic copper-nickel deposits of Monchetundra in the Kola Peninsula, metamorphogenic mica pegmatites of the Liabar massif, Dzhugdzhur, etc., phlogopite deposits of Aldan were formed in the Archean epoch. It is typical of the Proterozoic epoch to develop feldspar, mica and rare metal pegmatites of Siberia, Karelia and Ukraine, ferruginous quartzites of Krivoi Rog, the Kursk Magnetic Anomaly, Kostomuksha, etc., magmatic titanomagnetites of Pudozhgorye and Karelia, iron ore scars of Tayezhny type in Yakutia, pyrites of Karelia, copper-nickel ore of Pechenga, rare-metal albitite, gold-bearing black shale formation, ancient cupreous sandstones of Udokan in Siberia.

The Paleozoic epoch comprising plentiful magmatogenic formations of Baikal, Caledonian and Hercynian cycles of geological development features wide manifestations of magmatic, scarn, albitite, greisen, hydrothermal, stratiform and pyrite deposits of iron, non-ferrous, rare, noble and radioactive metal ores distributed in Ural, Central Asia, Kazakhstan and Siberia. Paleozoic bauxite deposits should be pointed out from the sedimentogene deposits of the epoch.

The Mesozoic-Cenozoic epoch comprising formations of Cimmerian and Alpine cycles is distinguished by abundant development of postmagmatic non-ferrous, rare and noble metals ores deposits shown in Caucasia, Eastern Transbaikalia, Primorye and in the North-East. Titanium deposits should be mentioned among the sedimentogene deposits of the epoch.

In the FSU territory there may be identified the biggest tectonic-mineralogenic subdivisions as follows: East-European platform, Siberian platform, Paleozoic Ural-Mongolian geosynclinal-folded belt, Pacific Ocean geosynclinal-folded belt of the Far East and North-East, Alpine geosynclinal-folded belt.

In the East-European platform there is minerageny of the ancient crystalline base, the Phanerozoic mantle, and the Phanerozoic and tectonic-mineragenic activation zones. Magmatic titanomagnetite deposits are known among green-stone series of the Archean period and Proterozoic gabbro formation rocks. They can be exemplified by the Pudozhgorye deposit on the eastern bank of the Onega lake. Magmatic deposits of copper-nickel ores of the Pechenga-Varzuga spillite-keratophyre and diabase formation of the Kola Peninsula kareliids are typical. Sulfur-pyrite formations are also known within the paleogeosynclinal trough valleys of the regional kareliids. Tin ore in the North Ladoga region scars is confined to the Late Proterozoic granite exocontact. Among the Carboniferous and Jurassic weathering crust products there are laterite, talus lake-moor and alluvial bauxite deposits: Vislov, Severo(North)-Onega, Tikhvin, Timan, etc. Paleozoic, Mesozoic, Paleogene and Neogene titanium mineral placers (the Yarega deposit of the Devonian, the Samotkannoe deposit of the Neogene, etc.) are known in the East-European platform sedimentary rock mantle.

Zones of Phanerozoic tectonic-mineragenic activation of the East-European platform are associated with the formation of apatites in the Khibini, loparite and the Kovdor carbonatite iron ore deposit in the Kola Peninsula as well as hydrothermal deposits of mercury ore of the Nikitovka deposit and lead-zinc ore of the Nagolnyi Kryazh in Donbas.

2.1.3. Non-ferrous Metals Ores [2,10,11,57,58]

Copper-pyrite, copper-porphyry, cupreous sandstones, sulfide copper-nickel and complex polymetallic ores are of the greatest commercial value. There are copper-pyrite ore deposits along the eastern Ural slope (from Ivdel in the north to Mugodzhary in the south) as well as in Northern Caucasia. Copper-porphyry ore deposits include, for example, Kounradsky and Boschekul in Kazakhstan, Kalmakyr (Almalyk) in Uzbekistan, Kadzharan and Agarak in Armenia while cupreous sandstone type deposits include Dzhezkazgan in Kazakhstan and Udokan in the Chita Territory. The former has been mined for about half a century, and the latter located in the Baikal-Amur line route is under preparation for commercialization. Sulfide copper-nickel ores of magmatic deposits of the Norilsk ore region and the Kola Peninsula contain large copper reserves. Complex polymetallic deposits of copper-lead and copper-lead-zinc ores are an essential copper source.

Lead-zinc ores are localized primarily in hydrothermal and sedimentary-exhalation deposits. Hereat the largest deposits are attributed to medium and low-temperature stratiform and pyrite deposits bedded in laminated mass of sedimentary and partially effusive-sedimentary rocks. Deposits of this type have been explored in the Central Kazakhstan ore region, in the Karatau Mountains, in Dzhungar Alatau, in Altai, in Uzbekistan, Buryatia, Transbaikalia, Azerbaijan. High-temperature metasomatic scarn deposits identified in Primorye, Tajikistan and other regions are of important commercial value. The Gorevsky metasomatic deposit in carbonate Pre-Cambrian rocks was explored in the Krasnoyarsk Krai. Medium-temperature vein deposits in eruptive and other rocks are mined in Northern Caucasia and Tajikistan. A majority of lead-zinc ore deposits are of complex composition, containing, along with lead and zinc, copper, silver, often gold, cadmium and rare elements as well as sulfur pyrite, sometimes barite and fluorite. An important zinc source is copper-pyrite ores of Ural and other regions.

The main nickel and cobalt source is magmatic deposits of sulfide nickel ores which are situated in the Norilsk ore region in the north of the Krasnoyarsk Krai and in the Kola Peninsula. An important feature of these ores is their complex multi-component composition: along with nickel and cobalt, the ores are the most important source of copper and other metals. Exogenic silicate nickel-cobalt ore deposits are known in Ural and Western Kazakhstan. Hydrothermal deposits of copper-cobalt, iron-cobalt and cobalt proper ores are identified in some regions (Azerbaijan, Tuva, etc.).

Tungsten and molybdenum ores are centred mostly on scarn contact-metasomatic and hydrothermal vein and stockwork deposits. The Tyrnyauz tungsten-molybdenum ore deposit located in Northern Caucasia is attributed to the first type. Tungsten (scheelite) scarn type deposits are in Uzbekistan and in the Far East. Hydrothermal tungsten deposits of vein and stockwork type are identified in Buryatia and Kazakhstan. Vein and stockwork molybdenum deposits of hydrothermal genesis are explored in Transbaikalia, Western Siberia and Kazakhstan. An important source is Mo-containing copper-porphyry ore deposits of Kazakhstan and Armenia.

Titanium ore deposits are known as sedimentary rutile-ilmenite placers (for example, in Ukraine, in the coastal Baltic Sea sediments, etc.), as metamorphized ilmenite-containing sandstones (the Yarega deposit in Komi) or as magmatic titanomagnetite ores which essential deposits are found in Ural, Western Siberia, the Kola Peninsula.

Paleozoic high-grade bauxite deposits have been explored in Northern Ural (Krasnaya Shapochka, Kaliya, Cheremukhovo, etc.). Here big open pits of the North Ural bauxite-bearing region are in operation. They are the suppliers of raw materials to the Ural aluminium plants. The bauxite deposits explored in Western Kazakhstan are the raw materials base for the Pavlodar Aluminium Plant. As to the European part, the most important bauxite deposits are identified in the Arkhangelsk territory (the North Onega bauxite-bearing region), Komi (the Timan bauxite-bearing province), and in the Kursk Magnetic Anomaly region where bauxites are bedded in the

weathering crust together with iron ore deposits. In Siberia comparatively small bauxite deposits are known in the Salair Kryazh, the Angara River region, Eastern Sayan. Russia was the world first country to put into practice production of alumina, cement and soda products from nepheline ore which deposits are in the Kola Peninsula (apatite-nepheline ore of Khibini), Siberia (Kiya-Shaltyr and other deposits of nepheline syenites), Transcaucasia and Central Asia.

The dominating part of Russian tin ore deposits is of Mesozoic age, connected with the Pacific Ocean ore belt and the Mesozoic activation zone. The most essential deposits represented mainly by cassiterite-sulfide ores have been identified in Yakutia, the Magadan and Chita Territories, the Khabarovsk and Primorski Krai. Tin-ore deposits of Paleozoic age were explored in Kyrgyzstan. Besides original ore deposits, tin-bearing placers are known in Yakutia and the Magadan Territory.

Mercury and antimony ore deposits of hydrothermal genesis have been identified in many regions of the country. The most important explored deposits are situated in Ukraine (Nikitovka mercury), in Kyrgyzstan (Khaidarkan and Chauvay mercury, Kadamdzhay and Terek-Say antimony), in Tajikistan (Dzhizhikrut mercury-antimony) as well as in Yakutia, Chukotka, Kamchatka and Ore Altai.

Placer and original gold deposits are known in the Magadan Territory, Yakutia, Eastern Siberia, Uzbekistan, Kazakhstan, Ural, Armenia. The main *silver* source is silver-containing ores of polymetallic deposits. In the pre-revolutionary Russia *platinum* was mined only from the Ural placers, in the USSR platinum and other metals of this group used to be extracted from magmatic deposits of sulfide copper-nickel ores.

Accumulations of tin, titanium, zirconium, iron, manganese, sometimes gold minerals, mainly as coastal-marine placers, are grouped in near-shore bottom deposits of the Far East seas. Titanium-zirconium placers were identified in the near-shore sediments of the Black and Baltic Seas.

Table 2.5 shows the main deposits, plants and metallurgical works of non-ferrous metals ores, with the general information on essential and secondary metals concentrations along with the basic deposits and their geography. [2,10,47,48,50,58].

Table 2.5. **Mining, dressing plants and works**

<i>Countries, regions</i>	<i>Deposits</i>	<i>Names of works: Mining, pit (P); Dressing plants (D); Metallurgy (M)</i>	<i>Products: Ores (O); Concentrates (C); Metals (M)</i>	<i>Components: base; additional</i>
Russia, Ural	Degtyarskoe	Degtyarsk; P	O	<i>Cu; S</i>
Russia, Ural	Sibay	Bashkirskiy: Sibay; P: mine D: flotation	O C	<i>Cu, zeolite Cu, S</i>
Russia, Ural	Gay: (Borovsk)	Gay: P: mine; quarry D: flotation	O C C C	<i>Cu, Zn Cu, Zn, Au, Ag; Zn, Cu.</i>
Russia, Ural	Uchaly	Uchaly: P: mine; quarry D: flotation	O C C C C	<i>Cu, Zn, S Cu, Zn, Au, Ag; Zn, Cu; S</i>
Russia, Ural	Sibay	Sergeevka P: Sibayskiy, quarry	O	<i>Cu, Zn, S</i>

		P: Bakr-Tau, quarry D: Sibayskaja, flotation	O C C C	<i>Cu,</i> <i>Zn,S,Au;</i> <i>Cu,Zn,Au,</i> <i>Ag</i> <i>Zn, Cu;</i> <i>S</i>
Russia, Ural	-	Sredne-Uralskiy D: flotation M: smelting	C C C M	<i>Cu,Zn,Au,</i> <i>Ag</i> <i>Zn, Cu;</i> <i>S</i> <i>Cu (metal)</i> <i>H₂SO₄</i> <i>P-fertilazer</i>
Russia, Ural	Buribay	Oktjabrskiy P, mine Buribaevskaja D, flotation	O C	<i>Cu, Zn, S</i> <i>C</i>
Russia, Ural	Kirovograd	P: Levichinskiy quarry P: Lomovskiy mine P: Novo-Ezhovskiy mine D: Kirovogradskaja, flotation M: Kirovogradskiy, smelting	O O O C C C M M M	<i>Cu, Zn, S</i> <i>Cu, Zn, S</i> <i>Cu, S</i> <i>Cu,Zn,Au,</i> <i>Ag</i> <i>Zn, Cu;</i> <i>S</i> <i>Cu (metal)</i> <i>Bronze</i> <i>ZnO</i>
Russia, Ural	Turjinskoe, Volkovka	Svjatogor: P: Turjinskiy mine P: Volkovskiy, quarry D: Krasnouralskaja, flotation D: Turjinskaja, flotation M: Krasnouralskiy, smelting	O O C C C C C M M	<i>Cu, Au,</i> <i>Ag,S</i> <i>Cu,Zn,V,,P</i> <i>Cu</i> <i>Zn, Cu</i> <i>Fe-V</i> <i>Cu,</i> <i>Au,Ag,S</i> <i>Cu, Fe</i> <i>Cu (metal)</i> <i>Au, Ag</i> <i>H₂SO₄</i> <i>P-fertilazer</i>
Russia, Ural	Karabash	P: Central mine Secondary recovered <i>Cu</i> M: smelting	O M M	<i>Cu, S</i> <i>Cu (metal)</i> <i>Cu (matte)</i>
Russia, Ural	Medvedevo	D: lotation	C	<i>Cu,Au,Ag,</i> <i>S</i>
Russia, Ural	-	Mednogorsk M: smelting	M	<i>Cu (metal)</i> <i>Au, Ag</i> <i>H₂SO₄</i>
Russia,	-	Kjyshtjym	M	<i>Cu (metal)</i>

Ural		M: elektrolise		Au, Ag
Russia, Ural	-	Urarelektromed M: elektrolise	M	<i>Cu</i> (metal) Au, Ag
Russia, Ural	Shikany	P: mine	O	<i>Cu</i>
Russia, Ural	Larino	Dzhusa	-	-
Russia, North Caucasus	Urup Chudeskoe	P: Urup mine D: Urup , flotation	O C C	<i>Cu,Zn,Au,</i> <i>Ag</i> <i>Cu, Zn, S;</i> <i>Au, Ag, S.</i>
Russia, North Caucasus	Iky-Burul	Kyryl-Dere P D: flotation	O C	<i>Cu</i> <i>Cu</i>
Russia, North Caucasus	Khudes	P D: flotation	O C	<i>Cu, Zn</i> <i>Cu</i>
Russia, East Sibiria	Udokan	-	-	<i>Cu</i>
Russia, Taymyr	Norilsk Talnach	Norilskiy nikel P: Zapoljarniy, mine P: Komsomolskiy, mine P: Majak, mine P: Oktjabrskiy, mine P: Taymyrskiy, mine P: Medvezhiy ruchey, mine P: Talnach, mine D: Norilskaja, flotation D: Talnachskaja, flotation M: Mednaja, smeltind, electrolysis M: Nikelevaja, smeltind, electrolysis, hydrometalurgy M: Nadezhda, hydrometalurgy M: hydrometalurgy	O C- <i>Cu</i> C-Ni C- <i>pyrotine</i> something M C M C C M M	<i>Cu, Ni,</i> <i>Co,</i> <i>Pt, Pd, Os,</i> <i>Ir, Rh, Rt,</i> <i>Au, Ag,</i> <i>Se, Te, S,</i> <i>Fe</i> <i>Cu,Ni,Co,</i> <i>Pt etc.,</i> <i>Ni,Co, Cu,</i> <i>Pt etc.</i> <i>Pt etc.,</i> <i>Cu,Ni,Co</i> <i>Cu; Ni;</i> <i>H₂SO₄;</i> <i>Pt etc.;</i> <i>Ni; Co; Cu</i> <i>Pt etc.;</i> <i>Pt etc.</i> <i>Ni-Co; Cu;</i> <i>Se;Te;</i> <i>Pt, Pd, Os,</i> <i>Ir, Rh, Rt,</i> <i>Au,Ag.</i>
Russia, Kola	Monchegorsk	P D: flotation	O C- <i>Cu</i>	<i>Ni,Co,Cu,</i> <i>S</i> <i>Cu,Ni,Co,</i>

		M: smeltind, electrolysis, hydrometalurgy	<i>C-Ni</i> <i>C- pyrotine</i> M	<i>Pt etc.,</i> <i>Ni,Co, Cu,</i> <i>Pt etc.</i> <i>Pt etc.,</i> <i>Cu,Ni,Co</i> <i>Cu;Ni;Co;</i> <i>Pt;Se;Te;</i> <i>H₂SO₄;</i>
Russia, Kola	Pechenga-group: Zhdanovskoe; Koula; Allarechensk; Nittis; Kumuzhja; Travjanaja	P: Zhdanovskiy, quarry P: Zapadny, quarry P: Seberny, mine P: Vostok, mine P: Kaula-Kotselvaara, mine D: N1, flotation D: N2, flotation M: Ceveronikel	O C M	<i>Cu-Ni-Co</i> <i>Ni-Co;</i> <i>Cu;</i> <i>Cu</i>
Russia, Ural	Rezh group, Lipa	Ufaley: P D: Flotation	O C	<i>Ni-Co</i> <i>Ni-Co</i>
Russia, Ural	Serov; Sinar	Serov: P D: Flotation	O C	<i>Ni-Co</i> <i>Ni-Co</i>
Russia, Tuva	Khovuaksum	Tuva-cobalt: P D: Flotation	O C	<i>Co-Ni, As</i> <i>Co-Ni</i>
Russia,	Pobuzhskoe	Kumary: P	O	<i>Ni-Co</i>
Russia, North Caucasus	Sadon	P: Sadon P: Archon P: Figdon P: Kadat D: Misur, flotation	O C C	<i>Pb-Zn,</i> <i>Au,Ag.</i> <i>Pb, Au,Ag.</i> <i>Zn</i>
Russia, Father East	Nikolaevskoe; Verchnee; Partisanskoe; Lidovskoe; Juzhnoe; Smirnovskoe; Lysogorskoe	Dalpolimetall: P: Nikolaevskiy mine; P: Verchniy, mine; P: Sovetskiy, mine; P: Primorskiy, mine; D: Central, flotation; D: Krasnorechinskaja, gravitation, flotation M: smelting	O O C C C C M M M	<i>Pb, Zn, Bi,</i> <i>Cu,Ag</i> <i>Sn,Pb,Zn;</i> <i>Ag</i> <i>Pb; Zn;</i> <i>Cu</i> <i>Sn;</i> <i>Pb;</i> <i>Zn.</i> <i>Pb</i> <i>Bi</i> <i>Ag (alloy)</i>
Russia, Father East	Vosnesenskoe			<i>Zn, CaF₂</i>
Russia,	Vangash,	Gorevskiy. P: quarry	O	<i>Pb, Zn</i>

East Siberia	Gorevskoe	D: flotation	C	Pb
Russia, East Siberia	Davenda	Preobrazhenskoe. P D: flotation	O C	Pb, Zn Pb; Zn
Russia, East Siberia	Shalkya	Solnechny. P D: flotation	O C	Pb, Zn Pb; Zn
Russia, East Siberia	Savinskoe	P D: flotation	O C	Pb, Zn Pb; Zn
Russia, Father East	Sardana	P D: flotation	O C	Pb, Zn Pb; Zn
Russia, East Siberia	Nerchinsk group: Savinskoe; Vosdvizhen sk; Blagodatsko e; Ekaterino- Blagodatsko e; Kadainskoe; Michailovsk oeN-Akatuy	Nerchinsk-Polimetall P: Klichinskiy, mine; P: Blagodatniy, mine; P: Akatuyskiy, mine; P: Kadayskiy, mine D: Klichinskaja, flotation ; D: Akatuyskiy, flotation; D: Kadayskiy, flotation	O C	Pb, Zn <i>Au, Ag.</i> Pb; <i>Au, Ag.</i> Zn.
Russia, West Siberia	Orlovka	Zheskent. P D: flotation	O C	Pb, Zn, Cu Pb; Zn; Cu
Russia, West Siberia	Salair; Ursk; Agaskur; Kyzyl- Tashtyg	Salair. P D: flotation	O C	Pb, Zn, Cu, <i>Au</i> <i>Ba</i> Pb; Zn; Ba
Russia, North Caucasus	Kakadur- Khanikom	P D: flotation	O C	Pb, Zn Pb; Zn
Russia, Ural	-	Cheljabinskiy Zink- Elektrolit M: smeltind, electrolysis, hydrometalurgy	M: M M	Zn; Cd; In; <i>CuSO₄;</i> <i>ZnSO₄;</i> <i>H₂SO₄</i>
Russia, East Siberia	-	Belovo; Zink M: smeltind, electrolysis, hydrometalurgy	M:	Zn; <i>H₂SO₄</i>
Russia, Father East	Stepnoe	Beresovka: P D: flotation	O C C	Pb, Zn, Au, <i>Ag</i> Pb, Au, Ag Zn
Russia, East Siberia	Bukukum	Solnechnoe: P: quarry D: gravitation	O C	Sn

Russia, Father East	Iultin	P: quarry D: gravitation	O C	<i>Sn, W</i>
Russia, Father East	Ryveem	Pyrkakay: P: quarry D: gravitation	O C	<i>Sn</i>
Russia, Father East	Obryvisty ruchey	Ege-khaya: P: quarry D: gravitation	O C	<i>Sn</i>
Russia, Father East	Krapivna	Festivalniy: P: quarry D: gravitation	O C	<i>Sn</i>
Russia, Father East	Dukat Omsukchan	Industrialniy: P: quarry D: gravitation	O C	<i>Sn</i>
Russia, Father East	Bolshie Kuly	Chingan: P: quarry D: gravitation	O C	<i>Sn</i>
Russia, Father East	Severnoe	Pevek (Valkumey): P: quarry D: gravitation	O C	<i>Sn</i>
Russia, East Siberia	Khapcheran ga	Baley: P: quarry D: gravitation	O C	<i>Sn</i>
Russia, Father East	Ekhabiy East	Solnechniy: P: D: gravity	O C	<i>Sn</i>
Russia, Father East	Astrachano v-ka	Perevalnyi P: D: gravity	O C	<i>Sn</i>
Russia, Father East	Kuiviveem- Gyrgychan	Saralakh: P: D: gravity	O C	<i>Sn</i>
Russia, Father East	D'yakhtar- dakh	Sarylakh: P D: gravity	O C	<i>Au, Sb</i> <i>Au</i>
Russia,				
Russia, West. Siberia	Sora	P D: flotation	O C	<i>Mo</i> <i>Mo</i>
Russia, North Caucasus	Tyrnyauz	P: quarry P: mine D: flotation	O C C C	<i>W, Mo,</i> <i>Cu, Bi</i> <i>W, Mo</i> <i>Mo</i> <i>Cu-Bi</i>
Russia, East Siberia	Shakhtama	P D: flotation	O C	<i>Mo</i> <i>Mo</i>
Russia, East Siberia	Dzhida	Kamensk: P D: gravitation, flotation	O C C	<i>W, Mo,</i> <i>W, Mo</i> <i>Mo</i>
Russia, East Siberia	Aunik	Davenda: P D: flotation	O C	<i>Mo</i> <i>Mo</i>
Russia, East Siberia	Tataurovo	Shumilovo: P: quarry D: gravitation	O C	<i>W</i> <i>W</i>
Russia, West. Siberia	Teya	Kalguty: P D	O C	<i>W, Mo</i> <i>W; Mo</i>
Russia, East Siberia	Terligkhay	P	O	<i>Hg</i>
Russia, Ural	Sherlova gora	Vishnevogorsk: P: mine D: gravitation, flotation	O C C	<i>Sn, Nb, Ta,</i> <i>Sn</i> <i>Nb-Ta</i>

Russia, Kola	Lovozero	P: mine D: gravitation	O C	TR,Nb,Ta, Th TR,Nb,Ta, Th
Russia, East Sibiria	Usugly	Orlovsky: P: mine D: gravitation, flotation	O C	Nb,Ta Nb,Ta
Russia,	Belaja Zima	Stolbovoy: P: mine D: gravitation, flotation	O C	Nb,Ta, P,Th Nb,Ta
Russia, Kola	Apatite	P: quarry D: flotation	O C C	P, Al,Ti,TR P Al(nepheli ne)
Russia, N- W	Tikhvin, Kitely, Pitkyaranta	North Onega: P D: gravitation M: hydrometalurgy; electrolysis	O C M	Bauxite Bauxite Al, Ga,
Russia, Ural	Kurgazak	Bauxite mine	O; C	Al Al
Russia, Ural	Krasnaja Shapochka	Bauxite mine	O C	Al Al
Russia,				
Russia, Ural	Kachkanar	Seregovo : P: mine, quarry D: gravitation, magnetic	O C	Fe, V, Ti Fe- V
Russia, Kola	Kovdor	P: D: gravitation, magnetic, flotation	O C C	Fe, P, Zr Fe Zr
Russia, Ural	Miass	Korkino: P; D: gravitation	C	Au,Ag
Russia, Ural	Solov'eva gora	P; D: gravitation	C	Pt,Au,Ag
Russia, Ural	Sarbay	Kumak: P; D: gravitation	C	Au,Ag
Russia, Kusbass	Berikulsky	P; D: gravitation	C	Au,Ag
Russia, Kusbass	Beresovka	Central: P; D: gravitation	C	Au,Ag
Russia, Kusbass	Nazarovka	Komsomolsk: P; D: gravitation	C	Au,Ag
Russia, Kusbass	Bolshaja Kaura	P; D: gravitation	C	Au,Ag
Russia, East Sibiria	Studenaja	P; D: gravitation	C	Au,Ag
Russia, East Sibiria	Sovetskiy	P; D: gravitation	C	Au,Ag
Russia, East Sibiria	Levaja Zhaima	P; D: gravitation	C	Au,Ag
Russia,	Zun-	P; D: gravitation	C	Au,Ag

East Siberia	Kholbin			
Russia, East Siberia	Isakovo, Chirimba	Olimpiadninskiy P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Oina, Bolshaja Tagna	P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Dzhekinda, Maliy Patom	P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Vacha, Taas- Yuryakh,	P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Marakan, Mochobin	P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Konstanti- novka	P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Darasun, Mukhal	P; D: gravitation	C	<i>Au,Ag</i>
Russia, East Siberia	Baley, Bukachacha	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Deputatskiy , Kular, Zakharenko	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Mayskoe, Pekulneisky , Nagory, Purkakay	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Karamken, Industrealno e-Khataren	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Chenkelen'j a Poljarny	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Malaja Rossomakh a, Nezhdanov o	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Niman	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Okhotsk group, Nadezhda	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Kamchatka group, Aginskoe	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Kluchevsky , Orekitan	P; D: gravitation	C	<i>Au,Ag</i>
Russia,	Ducat	P; D: gravitation	C	<i>Au,Ag</i>

Father East	(Laso)			
Russia, Father East	Odinoky, Adycha	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Lebedinoe	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Berelokh, Natalka	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Ulakhan- Onkuchakh, Kular	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Karalveem	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Vesenny	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Dolgozhdan y, Zolotogorsk	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Valkarem	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Maimakan- Karantsay	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Kharbalakh, Allakh-Yun	P; D: gravitation	C	<i>Au,Ag</i>
Russia, Father East	Kerby, Severnoe Kolendo	P; D: gravitation	C	<i>Au,Ag</i>
Russia, West. Siberia	Sorskoe	Sinyukha.P; D: gravitation	C	<i>Au,Ag</i>
Russia, West. Siberia	Lake Malinovoe	Zolotushino.:P; D: flotation	O C	<i>Pb, Zn Pb; Zn</i>
Russia, West. Siberia	Egor'evsko e; Dodonkovs koe	.P; D: gravity	C	<i>Au,Ag</i>
Russia, East Siberia	Zhireken	Novoshirokinskiy: P; D: flotation	O C	<i>Pb, Zn Pb; Zn</i>
Russia, East Siberia	Barun- Shivey, Bazhenov	P; D: gravity	O C	<i>W W</i>
Russia, East Siberia	Itaka	P; D: flotation	O C	<i>Mo Mo</i>
Russia, East Siberia	Zhuya group: Irokind, Mir, Sputnik	P: quarry D: gravity	C	<i>Au,Ag</i>
Russia, East Siberia	Kunar	P: quarry D: gravity	C	<i>Au,Ag</i>
Russia,	Vangash,			<i>Au,Ag</i>

East Siberia	Sovetsky			
Russia, East Siberia	Boidaibo, khotogo- Murbay			<i>Au,Ag</i>
Russia, East Siberia	Naryn, Malorechen sk			<i>Au,Ag</i>
Russia, East Siberia	Ikibzyakh, Maly Patom			<i>Au,Ag</i>
Russia, Father East	Ayano- Maisky group: Dan, Ket-Kap, Odola, Tomptokan	P; D: gravity		<i>Au,Ag</i>
Russia, Father East	Chardinsky	P; D: gravity		<i>Au,Ag</i>
Russia, Father East	Selemdzha Milkan			<i>Au,Ag</i>
Russia, Father East	Beliberda, Sredniy, Idzhek			<i>Au,Ag</i>
Kazakhstan	Kounrad, Umil, Aksakal Beskempir, Baktag, Ushoky, etc. Kounrad East Sajak	Balkhashmed P: Kounrad, quarry D: flotation M: smeltind, electrolysis, hydrometalurgy P: mine D: flotation M: hydrometalurgy P: quarry D: flotation	O C M M O C M O C	<i>Cu</i> <i>Cu</i> <i>Cu;Se;Te</i> <i>H₂SO₄</i> <i>Au,Ag;Bi</i> <i>Mo,Cu,Re</i> <i>Mo;Mo-</i> <i>Cu Re;Mo</i> <i>Pb,Zn</i> <i>Pb; Zn</i>
Kazakhstan	Zhyrem Stepnyak	P: D: flotation	O C	<i>Pb, Ba</i> <i>Pb; Ba</i>
Kazakhstan N-E	Akbakay, Kosmurun, Akbastau, Muzek, Priorskoe	Akbakay, P: D: flotation	O C	<i>Pb,Zn,Au,</i> <i>Cu</i> <i>Pb; Au-</i> <i>Cu; Zn</i>
Kazakhstan	Kutessay	P: D: flotation	O C	<i>Pb, Zn, TR</i> <i>Pb; Zn;</i>

				TR
Kazakhstan N-E	Karagaily	P: D: flotation	O C	Pb, Zn, Ba Pb; Zn; Ba
Kazakhstan	Kairakty	P: D: flotation	O C	Pb, Zn, Ba Pb; Zn; Ba
Kazakhstan	Achisay Karaoba	P: D: flotation	O C	Pb, Zn, Ba Pb; Zn; Ba
Kazakhstan N-E	Belousovka Alaigir	P: D: flotation	O C	Pb, Zn, Pb; Zn;
Kazakhstan	Akchatau	P: Akzhal P: Akchatau P: Zhambul D: Akchatau, flotation	O O O C	Pb, Zn, Au Au, Mo Be, Pb, Zn, Be; Pb- Au; Zn; Mo
Kazakhstan	Zhezken, Orlovsky	Zhezken: P: Orlovsky, mine D: Zhezken, flotation	O C	Cu, Zn, Pb Cu; Zn
Kazakhstan N-E	Ridder- Sokolnoe, Chekmar, Shubino, Tishinskoe, Dolinnoe	Leninogorsk: P: D: flotation D- technogen, gravity M: smelting, hydrometallurgy	O C C M	Pb, Zn, Cu, Au Pb; Zn; Cu-Au Pb Pb
Kazakhstan N-E	Ubileynoe, Snegirichinsk, Anisimov Kluch, Irtysk, Belousovka	Irtysk: P: mine D: flotation M: smelting, hydrometallurgy	O C M	Pb, Zn, Cu, Au Pb; Zn; Cu-Au Cu; Au
Kazakhstan N-E	Irtysk	Irtysk: P: mine D: flotation M: smelting, hydrometallurgy	O C M	Ti Ti Ti; Mg
Kazakhstan	Obuchovo			Ti-Zr
Kazakhstan	Karagaily	Aktash: P: quarry	O	Sn
Kazakhstan	Bestyube	Karaoba: P: quarry	O	Sn, W, Mo, Bi
Kazakhstan	Karaoba, Stepnoe	Aktas, P	O	Hg
Kazakhstan	Semizbugy	Belogor'e		Nb, Ta
Kazakhstan	Novo- Archipovo			Be, Li
Kazakhstan	Kundybay			TR, Y
Kazakhstan	Bolshoe Yarovoe lake	Pavlodar: P: quarry M: hydrometallurgy	O M	Al₂O₃ Al₂O₃

	East-Agat			
Kazakhstan	Vasilkovka, Lisakovsk	Krasny Oktyabr, P	O	Al_2O_3
Kazakhstan	Zaozer'e	Taunor: P: quarry D:	O C	Al_2O_3
Kazakhstan	Kachar	Ayat: P: quarry D:	O C	Al_2O_3
Kazakhstan	Turgay Krasny May	P: quarry D	O C	Al_2O_3
Kazakhstan	Uvanas; North Karamurun, Kanzhugan, Munkuduk	P: Underground leaching M: hydrometallurgy	Solution C	U U
Kazakhstan	Grachevskoe	Volodarskoe: P		U
Kazakhstan	Taskora	P: quarry D: gravity	O; C	Au
Kazakhstan	Suzdalskoe			Au
Kazakhstan	Yubileiny, Vodi; Kusmurun	P: quarry D: gravity	O; C	Au
Kazakhstan	Bakurchik, Boshevik, Vasilievskoe, Kyzilovskaya Akzhal-Bokonskaya , Mukurskaya , Zhanan-Chinrauskaya	P: quarry D: gravity	O; C	$Au; Sb$
Kazakhstan	Vasilkovsky , Madeniet	P: quarry D: gravity	O; C	$Au; As$
Kazakhstan	Bestyube, Zhalauly	P: quarry D: gravity	O; C	Au
Kazakhstan	Akbeit, Karabaur	P: quarry D: gravity	O; C	Au
Kazakhstan	Sarymbet, Aksu, Quarzive Hill	P: quarry D: gravity	O; C	Au
Kazakhstan South	Altyun-Almaz Akbakay, Tort-Kuduk,	P: quarry D: gravity	O; C	Au, Ag

	Alpyuz, Zhalair- Naimanskay a			
Kazakhstan	Zholombet, Kosacha	P: quarry D: gravity	O; C	<i>Au, Ag</i>
Kazakhstan	Smirnov, Stepnyak	P: quarry D: gravity	O; C	<i>Au</i>
Kazakhstan	Altyn Arka, North Kostube Chang, Gerek			<i>Au</i>
Kazakhstan	Kedey			<i>Au</i>
Kazakhstan	Andas- Altyn, Mijaly, Mukurt			<i>Au</i>
Kazakhstan	Aktastju, Akzhal, Gornyak			<i>Au</i>
Kazakhstan	Misek			<i>Au</i>
Uzbekistan	Almalyk Mirgalimsa y Altyn- Topkan	Almalyk: P: Kalmakyr, quarry P: Sary-Cheku, quarry P: Altyn-Topkan, quarry D: Almalyk, flotation D: flotation M: smelting, hydrometallurgy	O O O C C M	<i>Cu, Mo, Au Cu, Mo, Au Pb, Zn, Au Cu, Mo, Au Pb; Zn Cu, Au</i>
Uzbekistan	Ingichki, Sulyukta	P: D: flotation	O C	<i>W, Mo W; Mo</i>
Uzbekistan	Yakhton, Beurdeshik			<i>W</i>
Uzbekistan	Muruntau, Zaravshan Balasau- skandyk	Navoi: P: D: M: hydrometallurgy	O C M	<i>U, Au U; Au Au: U</i>
Uzbekistan	Mardzhanb u-lak, Kirpichla	P:	O	<i>Au</i>
Uzbekistan	Airakty, Chadak	P: D:	O C	<i>Au</i>
Uzbekistan	Angren			<i>Coal; Ge</i>
Kyrgyzstan	Khaidarkan, Mardzhan-	P: D:	O C	<i>Hg Hg</i>

	bulak	M:	M	Hg
Kyrgyzstan	Chanvay	P:	O	Hg
Kyrgyzstan	Tereksay	P D	O C	Sb, Au Sb; Au
Kyrgyzstan	Boguty	Makmal: P; D	O; C	Au
Kyrgyzstan	Tujuksu	P; D	O; C	TR
Tajikistan	Anzob, Dzhizhikrut	P: D:	O C	Sb Sb
Tajikistan		Regar: P: D: M: hydrometallurgy	O C M	Al₂O₃ Al₂O₃ Al₂O₃; Al
Tajikistan	Dzhilau, Taror	P; D	O; C	W; Au
Tajikistan	Yakhsu			Au
Georgia	Madneuli	P: quarry D: flotation	O C C	Cu, Au, Ba Cu-Au; BaSO₄
Georgia	Kvaisy Kuschevskaya	P: D: flotation	O C	Pb, Zn Pb; Zn
Azerbaijan	Paragachay	P; D: flotation	O C	Cu, Mo Cu; Mo
Azerbaijan	Zaglik	Kirovobad	M	Al
Armenia	Zangezur	Kadzharan P: quarry D: flotation	O C	Cu, Mo, Re Cu; Mo-Re
Armenia	Kafan	Kafan: P: mine D: flotation	O C	Cu Cu
Armenia	Agarak	P; D	O; C	Cu; Mo
Armenia	Shamlug	P; D	O; C	Cu
Armenia	Zod	Ararat P: Zod, quarry Ararat: D; M: flotation; hydrometallurgy	O C; M	Au, As, Cu, Sb Au
Ukraine	Pobuzhskoe, Kumaru	P: D; M: flotation; hydrometallurgy	O C M	Ni, Co Ni-Co Ni; Co
Ukraine	Grushevoe	P:	O	Ni, Co
Ukraine	Slava	Vyshkovo: P D: flotation	O C	Hg Hg
Ukraine	Nikitovka	P; D	O; C	Hg
Ukraine	Samotkan	Volnogorsk: P: quarry D: gravity	O C	Ti, Zr Ti; Zr

2.2. Regional Geology and Deposits of Russia

2.2.1. General Background [2,10,11,12,23,25,61]

The Russian Federation was by far the largest out of the fifteen former Soviet republics. It occupied three quarters of the total territory of the FSU. It also had the most essential mining industry which accounted for a significant share in the total mineral production. The Russian Federation is situated in the eastern part of Europe together with the northern part of Asia. The area occupied is 17.08 mln km². The population numbers 145 mln people (as of January 1, 1987).

Russia possesses a great deal of reserves of any type. It accounts for up to 10 per cent of mercury and titanium ore output in the FSU. In 1993 Russian gold reserves were estimated at 333.5 t, up from 290 t early in 1992.

The enormous Russian land area can be divided into several mineral-rich regions, notably, the Far East, Siberia, Ural and the Kola Peninsula. Ural, one of the country's oldest mining regions, developed the copper industry early in the 18th century. As of today ten important copper-zinc mines and four smelters are situated in Ural as zinc-producing facilities. Ural is composed of a number of key industrial clusters or complexes focused on big mining cities, production facilities and electric power sources. They include the Serov (steel, aluminium, coal), Nizhny Tagil (steel, copper), Sverdlovsk (copper, aluminium, gold, asbestos), Chelyabinsk (steel, copper, nickel, tantalum, columbium), Magnitogorsk (steel, copper-zinc), Orsk (nickel-cobalt, steel, copper, asbestos) complexes and Western Ural (salt, potash).

Eastern Siberia is famous for a variety of small non-ferrous metal ore deposits. The Siberian non-ferrous metal industry is of greater significance to the Russian economy since non-ferrous metal mines are throughout the eastern areas of the north from Norilsk to the Far East mines of Chukotka and Magadan. The crucial source of Russian nickel is the great Norilsk nickel complex in the Arctic zone of Eastern Siberia. Owing to the Norilsk production operations, the USSR has become the world biggest nickel producer by 1990, ahead of Canada. Nevertheless, the facilities (110,000 tpy of refined nickel and 110,000 tpy of nickel matte) of the smelters and the refinery near Norilsk are not utilized to the full capacity. In addition, Norilsk produces platinum, copper and cobalt.

The Russian Federation accounted for a major share of gold, diamond, platinum and base metals output. Russia has the longest history as a gold producer out of the CIS primary mineral producers. Although sometimes surpassed by the USA, Canada and Australia in the last century, Russia (and consequently the USSR) has been second only to South Africa in gold output for the last 150 years.

Table 2.6 outlines the distribution of mineral resources in the Russian Federation by region. As to value, the largest resource potential belongs to the Far East economic region although the area occupied has been slightly explored as yet. Only 1.6 per cent of the reserves in the Far East have been identified whereas 97 per cent were counted based on geological evidence. Western and Eastern Siberia containing more than a half of the explored Russian reserves are also comparatively wealthy in mineral resources. The North and Ural regions are well endowed with minerals and moderately explored. In the North region more than one third of the reserves has been explored which accounts for 18.5 per cent of the total explored reserves in Russia. The Central, North-West and Volga-Vyatka regions possess the fewest portion of the total Russian resources.

Russian mineral resources include the value of explored and blocked-out, prospected and extrapolated reserves (Soviet categories A, B and C₁, respectively), inferred reserves (category C₂), and probable reserves (P₁, P₂, P₃). Russian resources in minerals and energy account for nearly 90 per cent of the total value of these products in the former USSR.

Table 2.6. Distribution of Russian mineral resources by economic region [23,28]

Economic region	Value share of Russian resources / Value share of region resources ^a		
	Total reserves	Explored reserves ^b	Probable resources ^c
Far East	34.4/100	5.2/1.6	40.4/97.4
Western Siberia	26.2/100	45.9/18.3	23.5/74.4
Eastern Siberia	26.1/100	12.3/4.9	28.5/90.7
North	5.4/100	18.5/35.9	3.0/56.4
Ural	3.1/100	8.7/28.9	0.9/24.8
Black Earth Centre	2.3/100	3.1/14.2	2.0/71.6
Volga	1.4/100	2.9/21.9	1.1/66.1
Northern Caucasia	0.8/100	2.4/30.6	0.5/44.4
Centre	0.1/100	0.4/32.4	-/33.4
North-West	0.1/100	0.4/39.0	0.1/31.0
Volga-Vyatka	0.1/100	0.2/28.6	-/23.6
Russian Federation	100/100	100/10.4	100/82.9
Non-ferrous metals	6.8	3.8	3.0

^a Percentage of resources in individual economic region which is limited to explored reserves and probable resources. Figures indicate the level and extent of exploration in each region.

^b Explored or proven reserves encompass categories A, B and C of the USSR mineral resource classification. Explored resources consist of the most highly proven part of mineral base which has been investigated thoroughly, explored in detail and definitely delineated (category A), prospected reserves consisting of deposits which characteristics have not been evaluated so thoroughly but only preliminarily surveyed (category B), and resources which have not been well-defined or delineated (category C) which include extrapolated or indicated reserves composed of deposits of complex geological structure or inadequately prospected in new areas (C₁) along with promising reserves identified outside the explored parts (C₂).

^c Probable or undiscovered resources of basins, areas and fields are estimated by analogy with similar explored resources elsewhere. They are subdivided into three categories: probable resources of explored deposits or those under exploration (P₁), probable resources of undiscovered deposits presumed to exist on the basis of evidence from geological surveys, prospecting, and geophysical and geochemical tests (P₂), and probable resources of potentially promising areas where new deposits may be discovered (P₃).

2.2.2. Non-ferrous Metals Ore Deposits [1,10,11,22,27,61,62]

The main *copper ore* reserves are concentrated in sulfide copper-nickel, copper-pyrite deposits and in cupreous sandstone deposits. Large sulfide copper-nickel ore deposits connected with the Lower Mesozoic traps are situated in the Norilsk ore region (Norilsk-1, Talnakh, Oktyabrsky, etc.). The deposits of these ores are known in the Kola Peninsula where they are associated with Pre-Cambrian intrusives (Zhdanov, Kaula, Allarechensk, Nittis-Kumuzhya-Travyany, etc.). Copper-pyrite ore deposits are the most abundant in Ural, they were identified along the eastern slope from Arctic Ural in the north to Mugodzhary in the south (Krasnouralsk, Kirovograd, Karabash deposit groups, Degtyarsk, Uchala, Sibay, Named after XIX Parts'ezd (Party Congress), Gay, Vesenny, Aralcha, Named after 50th October Anniversary, etc.). The copper-pyrite mineralization in these deposits is confined to Paleozoic heavily-metamorphized volcanogenic strata, concentrated mainly in basalt-liparite formation rocks and presented by solid massive and impregnated ores. The copper content in the ores is from per cent portions to

20 per cent. Pyrite deposits of Northern Caucasias are bedded in Middle Paleozoic sedimentary-volcanogenic formations (Urup, Khudes, etc.). Sedimentary deposits of cupreous sandstone type are laid in the strata of metamorphized terrigenous sediments of the Lower Proterozoic (the Udokan deposit in the Chita Territory). The copper content in the ore is 0.2-4.0 %. Substantial copper reserves are concentrated in complex polymetallic deposits.

The main source of nickel and cobalt ores is magmatic deposits located in the Norilsk ore region (Norilsk-1, Talnakh, Oktyabsky, etc.) and in the Kola Peninsula (Zhdanov, Kaula, Allarechensk, Nittis-Kumuzhya-Travyany, etc.). The sulfide ores of these deposits are complex: they contain copper, nickel, platinum. Exogenic deposits of silicate nickel-cobalt ores are known in Ural (Serov, Cheremshany, Sinar, Lipovtsy, Buruktal, etc.). The complex Khovu-Aksy deposit of arsenic-nickel-cobalt ores has been explored in the Tuva republic.

The largest reserves of lead-zinc ores are contained in deposits of pyrite and stratiform types with much smaller reserves accumulated in metasomatic, scarn and vein deposits. Paleozoic pyrite deposits include numerous polymetallic deposits of Ore Altai, among them those located in the Altai Krai territory (Korbalikha, Stepny, Sredny, Zolotushino and other deposits). The lead-zinc-copper mineralization of these deposits is mainly confined to Middle Devonian metamorphic deposits of volcanogenic-sedimentary rocks. The ores usually contain more zinc than lead and more lead than copper. Northern Transbaikalia where the Ozero and Kholodny deposits are identified is the region of the Paleozoic pyrite polymetallic mineralization. Small pyrite deposits are located in the Altai-Sayan folded region (the Salair and Ural deposit groups, the Kyzyl-Tashtyg deposit). The majority of explorers attribute the Gorevsky metasomatic deposit located in the Yenisei Kryazh to stratiform deposits. Lead is the dominating element in the deposit ores (the average Pb to Zn ratio is 1:0.2). The Sardana deposit on the Aldan River relates to the same deposit type (the Pb to Zn ratio is 1:4). Deposits bedded in the Lower Cambrian carbonate rocks of Eastern Transbaikalia (Blagodatnoe, etc.) are attributed to metasomatic ones. Lead-zinc deposits of scarn type are known in the Sikhote Alin folded region (the Far East group deposits) and in Southern Primorye (the Voznesenskoe zinc-fluorite deposit). Vein polymetallic deposits in Northern Caucasias (Sadon, Zgidy, Arkhon, Elbrus, etc.) and in Eastern Transbaikalia (the Nerchinsk group deposits) are Mesozoic. Vein deposits and mineralizations of Post-Mesozoic age were identified in Southern and Western Verkhoyanye, in the Yana-Chukotka region and in the Kamchatka Peninsula. The major part of the lead-zinc deposits shows complex ore composition: along with lead and zinc, they contain copper, tin, noble metals, rare metals and elements as well as sulfur pyrite, sometimes barite and fluorite.

The predominant part of Russian tin ore deposits of Mesozoic age is connected with the Pacific Ocean ore belt and Mesozoic activation zones in Eastern Transbaikalia. The deposits are represented mainly by cassiterite-sulfide and cassiterite-quartz ores. Tin ore deposits are in Yakutia (Deputatskoe, Ege-Khaya, Alys-Khaya, Ilin-Tas, Burgochan, Kuster), in Chukotka (Iultin, Valkumey, Pyrkakay tin-ore node), in the Khabarovsk Krai (Solnechnoe, Festivalny, Perevalny and other deposits of the Komsomolsk ore region), in the Primorski Krai (Khrustalnoe, Verkhnee, Arsenievo, Levitsy, Dubrovka), in Transbaikalia (Khapcheranga, Sherlovaya Gora, Etyka, etc.). Tin ore deposits were also identified in Karelia (Kitley located near the Pitkyaranta deposit). Tin-bearing placers are in Yakutia and the Magadan Territory.

Tungsten and molybdenum ores are available mainly in scarn, hydrothermal vein and stockwork deposits. The first type includes the Tyrnyauz deposit of complex tungsten-molybdenum ores in Northern Caucasias. It is confined to the heavy zone of scarn and scarnized marble zones. Tungsten deposits of scarn-greisen-sulfide type are known in the Far East (Vostok-2, Lermontov). Greisen deposits include the Orekitkan stockwork molybdenum and Spokoininsky tungsten (Transbaikalia) deposits. Hydrothermal deposits of molybdenum and tungsten are in Transbaikalia (molybdenum: Shakhtama, Bugdain, Zhiren; tungsten: Kholtoson, Inkur), in the Kuznetsk Alatau (Sorskoe molybdenum), in Chukotka (Iultin tin-tungsten).

The major source of titanium ores is ancient (buried) coastal-marine and alluvial-deluvial placers of ilmenite and other titanium-bearing minerals of Neogene, Paleogene, Mesozoic and

Paleozoic age. They are widespread in the East-European platform, in Ural, in Eastern and Western Siberia, in Transbaikalia. Metamorphogenic placers of the Bashkir anticlinorium which are rich in ilmenite and zircon are of considerable interest. In the Komi republic there is the Yarega deposit in oil-bearing sandstones of the Middle Devonian which is a buried ancient placer in which leucoxene is the principal ore mineral. Magmatic deposits include the Kusima group of ilmenite-magnetite and ilmenite-titanomagnetite ore deposits in Southern Ural (Kopan, Medvedevo, Matkal, etc.) which are confined to gabbro massifs. The Pudozhgorye (Karelia), Elet-Ozero (the Kola Peninsula), Kruchina (Transbaikalia), Lysan and Malotugal (Eastern Sayan) deposits are also attributed to this type. Metamorphic deposits are known in ancient crystalline shales in Central (Kuznechikha) and Southern (Shuba) Ural.

In Ural gabbro-pyroxenite-dunite formation rocks are widely developed. Vanadium-containing titanomagnetite deposits (Kachkanar, etc.) are connected with them. There are also small vanadium deposits in polymetallic ore oxidation zones. Coastal-marine placers of vanadium-containing titanomagnetite sands are found on the shore of the Caspian Sea and on the Kuril Islands. Higher vanadium content is established in coal and iron ore deposits as well as in the high-sulfur oil of the Volga-Ural province.

Reserves of aluminium ore: bauxite, nepheline and other types of aluminium raw materials. Geosynclinal type high-quality bauxite deposits are explored in Northern Ural. Bauxite deposits formed under geosynclinal or subgeosynclinal conditions were also identified in Southern Ural. Platform type bauxite deposits are located in the European part of Russia, they are redeposited bauxites of the Tikhvin (35-49 % Al_2O_3) and North Onega (49-53 %) bauxite-bearing regions, together with deposits connected with weathering crust fracture in the Siberian platform (the Chadobets, Angara and Tatarsk deposit groups). Laterite (residual) bauxite deposits in the Lower Paleozoic weathering crusts were identified in the Belgorod district of the Kursk Magnetic Anomaly (the Vislov deposit: 49-51 %) and in Middle Timan (Vezhayu-Vorykva, etc.: 36-55 %). Alumina and aluminium production from nepheline concentrates of apatite-nepheline ores of Khibini deposits (the Kola Peninsula) and from nepheline syenites (urtite) of Kiya-Shaltyr deposit (Kuznetsk Alatau) has been put into practice. The so-called synnyrite (potassium-alumosilicate rocks of the Synnyr massif), cyanite shales of the Keiva plateau in the Kola Peninsula, sillimanite shales of Buryatia (the Kyakhta deposit), alunite of the Far East (the Askum deposit), etc. are considered promising aluminium-containing raw materials.

The most valuable deposits of antimony ores in the Russian territory are hydrothermal deposits of vein type in the Yenisei Kryazh (Razdolnoe and Uderey), in Yakutia (Sarylakh, Sentachan).

Hydrothermal deposits of mercury ores are of much greater abundance. Among them there are Perevalny, Sakharinsky, Belokamenny, etc. in Northern Caucasia, Beloosipovsky in Kuznetsk Alatau, Chagan-Uzun, Aktash in Ore Altai, Chazadyr, Terlig-Khaya in the Tuva republic, West Palyana and Plamennoe in Chukotka, Tamvatney, Olyutor, Lyapganay, etc.), Chempura, etc. in Kamchatka, Svetlovsky in Sakhalin.

Rare metal ores. In the Kola Peninsula, the Caucasus piedmont, Ural, Siberia and the Far East there are ore deposits, manifestations and mineralization zones of different types which contain higher concentrations of rare and dispersed elements. Tantalum-niobium ores in alkaline rocks are arranged within the Baltic shield. They are attributed to multi-phase intrusives of central type. Loparite is the principal ore mineral. Various niobium-containing carbonatites connected with in-depth faults in ancient niobium shields and platforms are another genetic type of rare metal deposits. High tantalum content is registered in tantalum-bearing pegmatites of Eastern Siberia. Rare-metal pegmatites and feldspar metasomatites, scarns and other mineral formations are carriers of beryllium mineralization.

There are gold ore deposits of different genetic types. Scarn deposits are in Siberia (Olkhovskoe). Ore bodies are represented by lenses and veins complicated with tongues. Hydrothermal deposits among which different gold-quartz formations stand out are the most abundant. The Berezovka deposit in Ural, the Darasun deposit in Transbaikalia are attributed to

the gold-quartz-sulfide formation. Volcanogenic hydrothermal deposits in Archean ophiolite rocks in platforms and young late-geosynclinal andesite-liparite complexes (the Pacific Ocean ore belt region) are of practical interest. Complex ore composition and nonuniform bonanza gold concentration, often jointly with silver, are typical of these deposits. Gold-quartz-chalcedony-sulfide formation deposits (Baley, Taseyevsky in Transbaikalia) are represented by stockworks, linear vein zones and individual veins accompanied by impregnated mineralization aureoles. Workable gold ores form ore shoots in their limits. The Karamken deposit (the Okhotsk-Chukotka belt) in the North-East of Russia which is represented by veins and their bundles is attributed to the gold-silver-quartz-adular formation. In Siberia metamorphic black carbonaceous shales of Pre-Cambrian age are widely abundant. Their dispersed primary gold content was regrouped under the effect of metamorphized agents and gold ore deposits were generated. Placer deposits among which alluvial placers are of greater importance have been identified and explored in the Magadan Territory, Yakutia, Eastern Siberia, Transbaikalia.

All workable *silver ore* deposits are postmagmatic. The greater part belongs to volcanogenic-hydrothermal formations. The Khakandzha deposit in the Okhotsk-Chukotka volcanic belt is attributed to the silver-gold formation while the Mangazeya group of silver-polymetallic deposits in Yakutia belongs to the silver-lead formation.

Platinum group metal deposits are represented by late-magmatic original and placer types. The late-magmatic Nizhny Tagil deposit is included into the so-called Ural platinum belt. In Russia there are eluvial, deluvial and alluvial platinoid placers. The Late Quaternary Ural alluvial placers extended over river valleys for several kilometres and substantially depleted are of greater commercial value among them. Platinum and platinum group metals are extracted as by-products also out of sulfide copper-nickel ores of magmatic deposits.

2.2.3. Non-ferrous Metal Resource Mining History [10,63]

Copper production operations appeared in the second half of the fourth millennium and in the third millennium B.C. in the Ural region, Ural, the Minusinsk basin, etc. In the end of the third millennium and especially from the middle of the second millennium B.C. copper, lead and tin deposits were mined in Altai, Siberia and, in particular, in Central and Southern Ural where about 150 ancient openings of outcropping copper ores were found. The workings of the Karagailinskoe deposits of cupreous sandstones relate to the same period. In the second and first millennium B.C. large-scale operations were carried out in the Gumeshevo malachite pit where the working depth reached tens of metres. In the second half of the second millennium and at the beginning of the first millennium B.C. tin ore was mined in the Kalba pits (the Chud, Kryk-Churuk, Urunkhay and other deposits). Copper, tin, gold ores were mined from pits of the Bronze Age (in Ural, Altai, in the Minusinsk basin). Operations were carried out in pits, ditches, trenches (i.e., by an open technique) and dig holes or primitive shafts. In the first millennium B.C. and first centuries A.D. the working projects were gold, lead, silver, copper ore deposits which became famous in the 18th century: Zmeinaya Gora, Salair, Zolotushino, Berezovka, Ridder, Bukhtama, Zyryanovo, Saigach, etc.).

In the first millennium B.C. the Ugro-Finnish tribes, which were later named “chud’”, lived in the Ural region, the North Dvina and Pechora basins. Bronze and copper instruments, metallic dishware together with traces of primitive mining of copper ore were discovered in their tombs.

In the 6th-9th centuries Slavonic tribes with first industrial centres were settled throughout the East-European territory. It brought about a dramatic increase in output of iron and copper ore, stone materials (mainly, limestone), clay, mineral paints, salt, precious stones (gems). “Pit” hearths in which iron was made in the 9th century were found in the land of the Vyatic tribes. Approximately at the same time iron ore was mined in the Ustyug-Zheleznopolye region, on the Mologa river.

When the Moscow state was established and the Tartar-Mongolian yoke was overthrown (1480), the feudal-class monarchy was formed, industry and trade were progressing, and intensive settlement of Ural and later on Siberia began. Mines set up by the merchants and craftsmen, who got the tsar deeds for search and working of mineral resources (except gold and silver ore), evolved.

In 1491 the first Russian special expedition went to the Pechora River for search of silver ore. The expedition discovered silver and copper ore deposits on the Tsylma River where a copper mine was built. This afforded minting of small change coins from domestic metal.

In the 17th century small industrial enterprises of manufacturing type, among them mines, emerged. Owing to growth of industrial production active works on search of iron, silver, copper ore, mica, gems started. They were conducted by search teams who served the tsar or big merchants or by local inhabitants throughout the vast territory, including Ural and Siberia, where mining development was accompanied by construction of new towns: Tyumen (1586), Tobolsk (1587), Mangazeya (1601), Yeniseiski Ostrog (1619), Krasnoyarski Ostrog (1628), Bratski Ostrog (1631), Yakutski Ostrog (1632).

In 1617-1618 the Kuzhgor and Grigorov deposits of cupreous sandstones were discovered on the Yaiva River (the Kama tributary) and on the right Kama bank. Their mining led to the set-up of the Pyskorsky copper smeltery in 1635. In the 2nd half of the 17th century copper ore occupied the first position in terms of significance among mineral resources.

Mining and metallurgical operations have been arranged in the Olonets Krai since the 1660s: in 1666 copper ore deposits were discovered, and their mining started. In 1670 at the inflow of the Spirovy Ruchey (stream) to the Put Ozero a copper smeltery was built. The entry ore was likely to be mined in the Kovzhezersky and Uspenskoe open pits and in Mednoyan (in 1679 the Spirovsky plant was set up at this site). Coastal people have been mining silver since 1669. It was used mostly in making of church utensils.

Siberian ore mining was promoted by the establishment of the Siberian “prikaz” (department) which arranged search teams with involvement of skilled ore miners and surveyors, mainly in pursuit of reports of local inhabitants. In particular, such search crews surveyed outcrops of silver ore on the left Yenisei bank.

In 1678 silver ore deposits were discovered in the Nerchinsk Krai, the Nerchinski Ostrog was founded, and the Bolshoy (Big) and Maly (Small) Kulruk mines went into operation. In 1700 the Nerchinsk Silver Smeltery was set up. In 1666 in Ural near the Verkhoturksky Road (the Murzinka settlement) Dmitry Tumashov, ore miner, discovered copper ore deposits and precious stones, among them two emeralds (first Ural emeralds). In 1668 Zh.Oglobinskikh, ore miner, discovered “crystal stones” and “light blue and red” stones in Kolyma.

In the last quarter of the 17th century the state borders were extended to the East and North-East up to Amur, Anadyr and Dezhnev Cape. By this virtue search operations were especially active in Siberia, in particular, in Transbaikalia.

In 1698 Moscow masters pursued a test smelting of silver ore found in Southern Transbaikalia, on the Argun River, near the settlement of Nerchinski Zavod. In 1704 on the Altacha River a silver smeltery was set up near the ancient mines on the Kultuchnaya Mountain.

In the 17th century capital was accumulated in the hands of small commodity producers, production operations became specialized, big deposits began to be mined which resulted in set-up of manufacturings, including mine undertakings.

Peter the Great arranged the first Russian mining administration named Ore Mining Department (Prikaz rudokopnykh del). Money reward was established for ore discovery with punishment for concealment. The decree of Peter the Great on freedom of mining, i.e., separation of the right for bowels of the Earth from the right for surface (cancelled by Catherine the Second), became a great motivation of mining development in Russia. Training of mine surveyors began at mining schools set up in Nevyansk (1709), at Olonets mine undertakings (1715), Kungur and Uktus mines (1721), at the mine school in Ekaterinburg (1724).

It afforded qualified geological search, ore testing and mining process improvement. Due to these measures the mining industry was progressing at a rapid pace.

In the 1730s the Voitsky ore mine was built near the Vyg River source. Manufacture of mining equipment started up at the Olonets enterprises.

In 1725 the Polevsky Copper Smeltery (based on the Gumeshevo deposit) was set up, with the Troitsky (Talitsky) Copper Smeltery in 1731.

A real event turned out to be the discovery of the Berezovo deposit by E. Markov, peasant, in 1745; in 1757 a mine and a plant were set up. They proved to become a cradle of the Ural gold industry. In 1760 the first Russian dressing plant for gold recovery was built on the Iset River.

In 1725 A. N. Demidov set up the Altai first Loktevsky (Kolyvano-Voskresensky) Copper Smeltery. The essential silver content in the ore allowed Demidov to arrange secret melting of this metal at the plant along with coinage as well as to establish several plants nearby which were totally named Kolyvano-Voskresensky. In 1746 these plants were handed over to the tzar family. In 1749 silver ore on the Tyra and Kandoy Rivers were surveyed and a mine was set up. In the 1730s copper ore mining was progressing along with the construction of plants in the Kazan province and the Kungur district.

In 1733 F. Pryadunov and E. Sobinsky, Arkhangelsk merchants, reported to the empress that 36 pounds of pure silver were mined on the Medvezhiy Island in the White Sea, later on mines (Orel, Nadezhda, Strelna, Boyare) were built there (1735-1741). At that time coastal people discovered copper ore and gold nuggets which were later on mined in the Laplan mines (closed in 1745).

Since the middle of the 18th century the mining operations were transformed into a big industrial sector in Russia: in 1750 seventy-two iron ore mining undertakings and twenty-nine copper smelteries were in operation. They made 3,000 tpy of pig iron (the first world position) and 900 tpy of copper. Ural occupied the leading place. In 1754 the Miass deposit of copper ore was discovered (in 1776 the Miass Copper Smeltery was built). I. A. Mosolov, mining businessman, discovered new deposits of copper ore in the Bashkirian land late in the 1760s - early in the 1770s. In 1770 F. Salatanov, employee of the Dobryanka Copper Smeltery (nowadays the Dobryanka settlement) of the Stroganovs found copper ore on the Systukhanskaya River; in 1782 N. Permyakov and K. Tretyakov, ore miners sent by the plant, discovered copper ore in seven areas on the Chusovaya, Komarikha and Kamenka Rivers.

In 1788 copper mines in the Aginsky steppe and in the Onon and Borzya River heads were put into operation. About 500 deposits on the whole out of which 120 ones were mined were discovered in the Nerchinsk Krai in the 18th century and at the beginning of the 19th century.

In the 2nd half of the 18th century the metallurgical industry of silver smelting was established in Altai, Yakutia and Transbaikalia owing to high-silver polymetallic ore deposits put into operation. For example, in Altai large deposits were mined. They were Zmeinaya Gora (1744), Berezovo (1756), Semenov (1763), Cherepanovo, Ridder (1786), Petrovka (1787). The same base is used in the development of a silver making centre: Barnaul (1739-1893), Pavlovka (1764-1893), Suzun (1764-1880), Loktevo (1783-1893) silver smelting plants. By virtue of silver ore mining expansion, lead smelting grew drastically (more than one third of world output). In the south of Transbaikalia silver smelteries (Duchar, 1760; Kutomar, 1763; Shilka, 1769; Vozdvizhenskoe, 1776; Ekaterininskoe, 1777; Gazimur, 1778; Sibiryakovo, 1776) were built. The silver ore deposit which was mined in 1774-1781 was discovered on the Yundybal River in Yakutia in 1765. In this period silver ore was also mined in the Echigal and Myukesey mines on the Lena river. All this allowed Russia to be promoted to one of the world leading positions in silver production.

After low-melting rich copper ore deposits were exhausted, the Central Ural copper plants began to be closed. In the south of Ural similar plants still went on with operation on deliveries of the Karagaily copper deposit ore (5 % Cu), and in the north of Ural the plants

operated on Turya mine ore (15 % Cu). Early in the 19th century Ural, like before, retained the monopolic position in copper mining and making in Russia (more than 30 deposits were in operation). Tin ore was mined in two regions: the Pitkyaranta deposit in Karelia (discovered in 1814, mining in 1842-1904) and the Aginskoe deposit in the middle current of the Onon River (mined in 1811-1859).

Development of placer gold and silver deposits which became Russian mining leaders for a long period has gained the highest value since the beginning of the 19th century. A great event was the development of an effective full-scale gold placer washing technique by L.I. Bresnitsyn, miner, in 1814 in the Berezovka and Pyshma River valleys where he set the Melkovo, Danilovo and Stanovoy mines. This manifested start-up and rapid development of Ural gold placers, establishment of Russian gold industry. Inflow of labour into this industry took place. Progress in gold mining was promoted by permit of private work. The first plant to be engaged in the development of gold-bearing placers in 1819 was the Neivinsk plant which belonged to the Yakovlevs, and in 1869 the plant's mines produced 270 kg of gold. As compared to mining operations, gold-bearing placer working featured low investments, short production cycle, high final product price and steady demand for gold. In the 20s and early in the 30s the annual gold mining reached 640 kg, and up to 1,000 people worked in the mines. The first Siberian gold placers found in the Mariyinsky taiga (the Tcherikyul, Makarak and Kundat Rivers) by merchant A. Popov's search teams in the 1820s led to the set-up of big mines there. This discovery brought about extensive survey works in Siberia. In 1830 Mordvinov found gold on the Fomikha River (the Egorievsk gold mine), and later on gold placers along the Suenya, Berezovka, Troitskaya, Chesnokovka, Nikolayevka, Poperechnaya, Belaya, Osipovaya and other Rivers were found. In 1836 gold placers of the Khorma River were discovered. In 1832 in Transbaikalia the richest gold placers were found on the Kara River (the left inflow of the Shilka River) which laid the foundation of gold industry in this region. In the 1840s big mines which work at many tens of placer gold fields in Transbaikalia were set up (Innokenievsky, 1844; Eleninsky on the Vitim River, 1845).

In 1840 merchant T. Zotov's crews discovered gold over the Oktolina River, the Vangash inflow, along with placers over the Sevaglikon and Kalami Rivers. The discovery of gold in Eastern Siberia involved big gold mining undertakings built there. The Russian government required more and more gold which forced gold fund replenishment sources to be searched. Therefore in the 2nd half of the 19th century the Russian government sent geological crews for search of new gold-bearing areas.

In the 50s on incorporation of the Amur region into the Russian territory gold search started in the Far East. In 1840 there were discovered the Bodaibo gold-bearing area placers which mining began, and at the same time the Olekma placers were found (in full-scale operation since 1852). The Lena gold mining companionship (Lenzoloto) was founded in 1891 in order to mine these fields. In 1845 gold was searched in Kuznetsk Alatau mountains from the Tom River heads to the Verkhnyaya Ters River, early in the 2nd half of the 19th century the Altai plant management transferred gold search works to the Biya, Lebed, Peschanaya and Anui Rivers as well as to the eastern slopes of the Kalba Khrebet. The Ural and East-Siberian mines produced (pure gold metal, t): 1820 - 0.32, 1830 - 6.27, 1850 - 7.5, 1860 - 24.42, i.e., in the middle of the 19th century Russia accounted for 40 % of world gold output (the 1st world position).

After the first platinum placer was found on the Uralikha River (1819), the Tsarevo-Aleksandrovsk platinum mine was built there in 1824. Later on mine officer Gallyakhovsky discovered the platinum placers: Pokrovka on the Izvestnaya River, Tsarevo-Elisavetinsk on the Melnichnaya River, etc. Soon on the Nizhny Tagil River there were found the richest Sukhoy Visim fields of placer platinum (big nuggets were encountered), the Isovscoe gold-platinum field (in 1829). The more detailed Ural interior examination allowed the first Russian graphite deposit to be discovered in 1826, with the first diamond field (in the Koiva River basin) found in 1829.

By the beginning of the 19th century Altai has gained the leading position in the mining of polymetallic deposits. In the 19th century rich deposits of polymetallic ores (Zyryanovo, 1791, working since 1798; Zavodinskoe, 1820; etc.) were identified, and the operation of tin ore deposits began (the Onon, Kulunda, Zavitino tin mines).

Ore prospecting was arranged in the Kuznetsk Krai, here the Gurievsky silver making plant was built in 1816.

In 1847 a copper deposit was found on the Maloye Pechische River (Sayan), and the construction of the Spassky Copper Smelter began. In 1850-1872 about 50 t of lazurite and 10 t of nephrite were mined in the Malaya Bystraya River valley. In the 1870s the Solnechnoe, Purinsky, Novotroitsky and other fluorite deposits were explored, their ore went to silver smelting operations.

In the 2nd half of the 19th century iron, copper and silver ore mining curtailment was intensified in Ural and Siberia. Ural copper mines became closed (the Karagaily and Turya deposits were mined longer than all other deposits). Only several tens out of eight hundred of the explored Altai deposits were in operation. Silver ore mining was terminated, and Transbaikalian silver smelteries were shutdown: Ducharsky (1949), Ekaterininsky (1852), Vozdvizhensky (1852), Nerchinsky (1953) and other plants. Late in the 19th century big Altai mine enterprises were shutdown: in 1893 - Barnaul, Pavlovka, Loktevo, Zmeyerovsky Silver Smelteries, in 1897 - Suza copper smelter, etc. Depression of mining & metallurgical industry of Ural, Altai, Transbaikalia and some other regions in the 2nd half of the 19th century is attributed to obsolete technology designed for high cheap labour intensity. However Ural remained the main Russian iron ore base which provided about 75 per cent of the total output (Central Russia accounted for 20-25 per cent). In Ural the first Russian deposit of nickel ore (Petrovka) was mined (since 1855) which permitted nickel industry foundation to be laid (in the 1870s).

In the 70s prof. A. A. Inostrantsev found the lead mineralization on the seashore of the Kola Peninsula, and in 1875 a lead-zinc mine was set up on the Medvezhiy Island. In the 1880s silver ore deposits were discovered in the areas of the Pechenga and Bazarnaya Rivers.

Gold prospecting and mining gained momentum in the 1860s - 1880s. Full-scale gold mining began in Khakassia (the Prorok-Iliya and Veseloe mines on the Bolshoy Kyzas River, 1868). The mines on the Lena River and its inflows (Vitim and Olekma) were the biggest.

Transbaikalia which accounted for about 40 per cent of gold output in Russia remained the most important gold mining region in the 80s. In that period the simplest dredge design is applied for placer working and gold was extracted at gold washeries.

Prior to that Ural had no competitors in copper ore mining. The depletion of upper zones of easy-melting ore with 5-15 % metal content required use of cupreous pyrites (2.5-3.5 % Cu). The method of copper smelting from pyrite was developed at the Karabash copper plant (Central Ural) early in the 20th century. In 1988 the Degtyarsk copper ore deposit which working began in 1914 was discovered. In 1910 polymetallic ore mining started in Primorye (the Tetyukha Joint-Stock Company) on the basis of the Dalnegorsky group of lead, zinc and tin deposits.

In 1910 about 1,100 small gold mines were in operation (approximately 60 per cent of gold were mined by prospectors). The mechanization rate was low: 54 dredges and 75 small hydraulic units were available. The foreign capital share in Russian gold mining accounted for about 50 per cent (1913). The Russian gold mining industry held the 2nd position among mining industries in operating personnel number (84,000 people, 1913).

In Aldan gold was found in 1910-1911. Rich placers were discovered on the Timpton River where the Lebedinsky mine was set and also on the Sutam River. In Aldan gold search was resumed on the Tommot River, and in 1916-1917 gold was found on the Tyrkanda River. In Khakassia gold mining was growing: in the Dumny undertaking (the Abakan River basin, 1898), the big Bogomdarovannoe open pit (the Bely Iyus River basin, 1899) was put into operation. By the beginning of the 20th century the greatest gold share was mined in Eastern Siberia.

Virtually the total platinum output was produced in Ural. Silver ore was mined mainly in Altai, Ural and Transbaikalia. In 1897 in the Primorski Krai the Dalnegorsk polymetallic deposit

(worked since 1932) was discovered. The mineral product base of lead and zinc industry was composed of the deposits of Northern Caucasia (Zgid, Sadon, Elbrus), Western Siberia (Zmeinaya Gora, Zolotushino, Lazurnoe, Salair), Transbaikalia (Blagodatskoe, Kadain, Mikhailovskoe, Savinskoe), the Far East (Tetyukha).

In the 19th century the discovery and mining of mineral deposits in Russia were the basis of industrial operations arranged in this country and motivated the development of Ural, Transbaikalia and other regions of Siberia and the Far East. But the mining of the deposits discovered was affected by imperfect mining equipment, only high metal content deposits, as a rule, of low depth were involved in mining. Owing to this, many deposits were not involved into the mining operations, a great quantity of deposits were exhausted only partially, i.e., a rich easily-accessible ore part was extracted after which mines were shutdown. Imperfect prospecting methods and equipment failed to identify mineral deposits at relatively large depths and in difficult (among them, northern) regions.

In the history of development of mineral resources of Northern and Eastern Siberia it is necessary to point out the role of GULAG which succeeded in continuation of the Russian tradition of mineral mining using prisons and exiles and actively functioned in these regions from the beginning of the 30s. For example, the Norilsk Copper-Nickel Complex was built by prisoners on the site of the deposit discovered in 1919-1922 by the N.N.Urvantsev's expedition. Not only mining but also geological prospecting were conducted by prisoners and exiled geologists who discovered deposits of gold, tin, tungsten and other mineral resources.

2.2.4. Mineral Resources and Mining Industry of Russian Economic Regions

Eleven economic regions are distinguished in the Russian territory with regard to natural and economic peculiarities. However not all the regions are connected with the non-ferrous metals industry. We have taken six regions:

- North-West, including the Kola Peninsula,
- Northern Caucasia,
- Ural,
- Western Siberia, including Altai,
- Eastern Siberia (the Baikal area, Transbaikalia, the Krasnoyarsk Krai, Tuva),
- the Far East (Primorye, Sakhalin, the Amur Territory, the Khabarovsk Krai, Kolyma, Kamchatka, Yakutia).

2.2.4.1. North-West of Russia

This economic region covers the Leningrad, Novgorod, Pskov, Vologda, Arkhangelsk (including the Nenets Autonomic District), Murmansk and Kaliningrad Territories, Karelia and Komi. The area is about 1.6 mln km². The population is 15.1 mln people (as of January 1, 1987).

Geological structure and mineral resources

The Late Archean (Kola) geological evolution stage was characterized by generation of Kola-Belomorian metasedimentary-volcanogenic complex, intensive manifestation of magmatism, metamorphism and folding. The iron ore deposits (jaspilite) are connected with basalt-decite-rhyolite formations while the copper-nickel (Lovno) and titanomagnetite (Kolvitsy) mineralization is connected with gabbro-norite-lherzolite and websterite-gabbro-norites. The sulfide copper-nickel mineralization is connected with gabbro-norite-peridotite (Monchetundra) and gabbro-verlite (Pechenga) complexes while mica and amazonite pegmatites and rare metals are connected with granitoids.

In the Late Proterozoic period the Kola ore region underwent marine erosion. The Caledonian-Hercynian period was manifested by tectonic-magmatic activity, deep fault formation, introduction of alkaline gabbroids, alkaline-ultrabasic rocks, nepheline syenites with

which deposits of complex apatite-magnetite (Kovdor), apatite-nepheline (Khibini and Lovozero tundra) ores are connected.

Mining & metallurgical industry

The industrial production structure consists of fuel, mining & chemical, iron & steel and non-ferrous metals industry as well as building materials industry. Deposits of apatite-nepheline, iron, copper-nickel and rare earth ores, coal, natural gas and oil, bauxites and mica, noble metal ores, turf, combustible shales and others are being worked. The biggest Apatite and Nickel Production Associations, Pechenganickel Mining & Metallurgical complex, Olenegorsk Complex, Kovdor Mine & Concentrator, Lovozero Mine & Concentrator, Kovdorslyuda Complex are operating on the deposit basis. These enterprises supply raw materials for production of mineral fertilizers, iron & steel, non-ferrous and rare metals, mica, feldspar, valuable grades of building stone.

The copper-nickel ore deposits are being worked in the Kola Peninsula (deposits of Monchetundra and the Pechenga area). In 1935-1938 the Nickel Concentrating Complex (production association at present) was built based on the Nittis-Kumuzhya deposit. After World War II the Kaula, Kammikivi, Kotselvaara deposits were discovered, and the Zhdanov deposit of impregnated ore was explored. They are the base of the Pechenganickel and Severonickel Mining & Metallurgical Complexes.

The Kitely tin deposit was explored in Karelia.

Bauxite mining was initiated based on the Tikhvin deposits found in 1916. The Volkhov Aluminium Plant was put on stream in 1932. The North Onega bauxite area located in the south-east slope of the Baltic shield was discovered in the Arkhangelsk Territory in 1949. The North Onega bauxite mine was put into operation on the basis of the Iksa deposit in 1936. The entry raw materials for aluminium smelting are the Tikhvin and North Onega deposit bauxites and the Kola Peninsula nephelines. Further product output build-up may be due to better utilization of nephelines and mining of the Middle Timan bauxites.

Apatite, nepheline, iron, rare metal, baddeleite, vermiculite concentrates along with nickel, copper, cobalt are produced based on apatite and Kovdor iron-mica deposits. Unique technologies of production and processing of sphene, aegirine and titanomagnetite concentrates have been elaborated, and production of fused magnesium phosphates is being put into operation.

Mineral products feature multicomponent compositions. The major part of ores contains a wide range of valuable components which can be extracted to saleable products at a modern state of technology and equipment.

Reserves of rare and dispersed elements in complex ores are of great value. In addition to rare metals produced as concentrates: baddeleite (Zr) - the Kovdor Mine & Concentrator; loparite (Ta, Nb, TR, Th) - the Lovozero Mine & Concentrator, an essential number of dispersed elements is present in the concentrates of other mines & concentrators. Copper-nickel ore contains Pt and platinoids, Au, Ag, Se, Te, etc. Apatite concentrate includes rare earths (TR), Th, and Ti can be also extracted (perovskite). Aluminium ore (bauxite and nepheline) contains Ga (Fig.2.1 & 2.2).

The extraction of these elements has not been put into practice to an adequate extent though the technologies are developed and in the town of Apatity there is a special institute of chemistry and technology of rare elements. For instance, apatite concentrates were exported (more than 30 % of output), and extraction of associate components was set up in Germany.

2.2.4.2. Northern Caucasus

The North Caucasus economic region incorporates the Krasnodar and Stavropol Krai, the Rostov Territory, Dagestan, Kabardino-Balkaria, Chechnya and Ingushetia. The area is 335,000 km². The population is 16.5 mln people (as of January 1, 1987).

The most important industrial sectors are oil, gas, coal, iron & steel, non-ferrous metals industries along with machinebuilding and building materials industries.

Mineral resources

The region has at its disposal a large combination of mineral resources: oil, natural gas, coal, zinc, copper, molybdenum, tungsten, mercury ores, salt, gypsum, building materials, mineral water, etc.

Copper ore is mined by an open pit method in the Stavropol Krai based on the explored Urup deposit. Here the Urup Mine & Concentrator which products are copper and sulfur pyrite is in operation.

It is promising to develop the copper pyrite deposits of Kizil-Dere in Dagestan. Underground lead-zinc ore mining is carried out at the Sadon Lead & Zinc complex which work on the Sadon and Fiagdon ore region deposits in Northern Ossetia. In the pre-war time the region supplied about 37 per cent of zinc and 7 per cent of lead produced in the country.

Tungsten-molybdenum ore is mined by the Tyrnyauz tungsten-molybdenum complex which works the like deposit in Kabardino-Balkaria.

Mercury ore is extracted by an underground method in the Sakharinsky deposit in the Krasnodar open pit (Fig.2.3 & 2.4).

2.2.4.3. Ural [64-66]

The Ural economic region includes the Kurgan, Orenburg, Perm, Sverdlovsk, Chelyabinsk Territories, Bashkiria, Komi and Udmurtia. The area is more than 0.8 mln km². The population is 20.1 mln people (as of January, 1987).

Ural is the country's oldest mining region of iron & steel and non-ferrous metals industries, woodworking industry, building materials industry, oil and gas production and refining.

Mineral resources

Ural is rich in various mineral product resources.

Copper-pyrite deposits are confined to volcanites (Gay, Sibay, Degtyarsk, the Kirovograd group, etc.). Copper-porphyry deposits are abundant in Central and Southern Ural. Placers and native gold (the Berezhovo and Kochkar deposits) and platinum deposits (Isovo) are available. Polymetallic ore deposits (Saur, Kuzha, etc.) were found in carbonate blocks. The largest bauxite deposits (the Northern Ural bauxite region and other regions) are connected with Middle Devonian carbonate sediments. Different rare metal deposits, molybdenum, tungsten and other ore manifestations were encountered in granitoid complexes and carbonatites of different age, in particular, the Late Paleozoic. A mineralization of radioactive nature and of younger (Triassic-Jurassic) age was registered with regard to tectonic-magmatic activation processes on the eastern slope of Ural and in Transbaikalia.

Mining & metallurgical industry

Ural occupies a particular place in various mineral resources. The mineral resources of fuel, ore chemical raw materials and non-metallic useful materials feature high quality, complexity and favourable geological conditions. Ural is a leader in the CIS non-ferrous metals industry. Aluminium and copper industries are the most developed branches (Fig.2.5 & 2.6).

Fifty-two copper deposits are available in the territory of the Ural economic region (in Bashkiria, the Sverdlovsk, Chelyabinsk and Orenburg Territories). Big aluminium plants operating on their base have become prosperous. The intensive working caused the deposit depletion and lower copper ore output. Meanwhile the total registered reserves remain essential for the region due to reserved and new deposits. The main raw materials base of the Ural copper industry is copper-zinc pyrite deposits. These ore reserves are mostly in Southern Ural while the copper smelteries are in Central Ural. Complex copper-pyrite deposits are available in the Sverdlovsk Territory (Degtyarsk, Named after 3rd International, Krasnogvardeisk, Tarnier, Valentor, Shemur, Chusovoe), Bashkiria (Sibay, Uchala, Oktyabrsky, Yubileiny, Podolsk,

Uzelga, Molodezhny, etc.), in the Chelyabinsk Territory (Chebachye, Aleksandrovka, Talgan, Named after XIX Parts'ezd), in the Orenburg Territory (Blyava, Gay, Dzhusa, Vesenny, Letny, Osenny, Komsomolsk).

The Krasnouralsk Copper Smeltery carries out working of the Volkovo and Vadimo-Aleksandrovsky deposits. The smeltery's concentrator is provided with local raw materials for 91.2 per cent, and the rest part is delivered from Southern Ural. The raw materials base structure may be much improved due to involvement of explored deposits of Northern Ural (in the Ivdel District): Valentor, Shemur, Novo-Shemur. Ore has been supplied from the Safyanovo deposit (the Sverdlovsk Territory) since 1995.

The Kirovograd Copper Smeltery works by an underground method the Levikha and Lomov deposit groups (the Lomov open pit was closed in 1993). A project for mining of the extra Novo-Shaitan deposit has been made up. The concentrator is provided with the local ore for 82.4 per cent, and the rest part of ore is delivered from Southern Ural. The copper smeltery is focused on melting of secondary materials, and copper smelting from local ore accounts for only 6 per cent of the smeltery's capacity.

The Central Ural Copper Smeltery processes 600,000 tpy of ore from the Degtyarsk deposit and 400,000 tpy of ore delivered from Southern Ural. The ore has been supplied from the Safyanovo deposit since 1995. The concentrate recovery rate by plant is: Turya - 93.55 %, Krasnouralsk - 74.86 %, Kirovograd - 86.36 %, Sredneuralsk - 76.3 %. The rate of recovery to blister copper in reverberatory furnaces is 94.8 %, sulfur recovery is 54 %, the copper recovery rate at the Pyshma Copper Electrolysis Plant is 99.3 %.

An effect of concentrator tailings on the environment is unfavourable. At four concentrators 90 mln t of tailings with 0.09-0.35 % Cu, 0.24-0.61 % Zn, 0.2-1.3 g/t Au, 2.6-15.8 % Ag, 7-27 % S were accumulated in slime settlers. More than 52 t of slags with 0.4-0.48 % Cu, 2.46-4.53 % Zn were collected in slag dumps of three copper smelteries.

A new group of copper pyrite deposits (Tarnier, Shemur, Novo-Shemur, Safyanovo) was identified in Northern Ural. They feature higher content of essential and associated components (zinc, noble metals, cadmium, indium, cobalt, etc.).

Several copper pyrite deposits part of which is being already mined have been found in Southern Ural. The copper ore reserves of these deposits with a set of associate valuable components (zinc, sulfur, gold, silver, lead, cadmium, indium, selenium, tellurium, barium) provide the Uchala Mine & Concentrator for several decades. Besides, in Ural there is the whole number of small deposits which mining is not expected in the near future owing to different reasons though it can be profitable judging from geological and economic calculations. It must be also noted that considerable reserves of copper as an associate component are in iron ore deposits however copper extracted from this ore during processing has been almost completely lost so far.

Copper is extracted from the copper-iron-vanadium ore of the Volkov deposit and copper-scarc ore of the Turya deposit.

The Mednogorsk Copper Sulfur Works mines the Blyava deposit reserves left using an underground leaching method. Ore is concentrated by bulk-selective (the Gay and Uchala Mines & Concentrators) and direct selective (the Bashkirian Copper Works) methods. Ten copper and copper sulfur plants and works in total are in operation in Ural. Besides copper, they produce sulfuric acid, blue vitriol, rare and noble metals. Zinc concentrates are also produced from copper pyrite ore of the Gay, Uchala and Sibay deposits. Their further processing is carried out at the Chelyabinsk Zinc Plant.

Ore processed at present is rich and refractory. The total recovery rate is only 80 %, with 67 % of zinc, 30-45 % of gold and silver, 54 % of sulfur, from units to first tens of per cent for selenium, tellurium, cadmium, indium, bismuth, zinc and some other components. One can substantially increase product output, profit and improve environment situation in copper smeltery areas due to introduction of new technologies of ore processing, application of overburden for building purpose, recycling of concentrator tailings, exhaust gas and

metallurgical slags of copper smelteries, i.e., by means of more complete utilization of primary raw materials.

Considerable high-quality copper and copper-zinc ore reserves available in Ural (copper content in Ural ore is approximately 1.4 time above the average in the Russian copper industry) predetermine the necessity of further progress of the Ural copper ore base. Replenishment of the depleted capacity involves working of the Southern Ural and Bashkirian deposits where large registered copper reserves are available. Here of primary importance is the mining of the Gay, Uchala, Uzelga mining areas which have a mature infrastructure and big labour resources. In Central Ural it is intended to put into operation the 2nd stage of the Volkov mine and the new Safyanovo deposit.

Prospecting and preparation of copper porphyry deposits discovered in different Ural areas lately are in sight. There is an outlook for identifying commercial copper-molybdenum-porphyry deposits and cupreous sandstones in Ordovician sediments of Arctic Ural.

Complex rare metal ores containing niobium, selenium, tantalum, etc. are being worked at the Vishnevogorsk mine. The ores are concentrated by direct selective flotation and gravitational flotation.

In Ural noble metals are mined from placers (from Krasnouralsk to Orsk) and native deposits. The Beresovo deposit is mined by an underground method, mainly, through a system of sublayer drifts, more seldom by horizontal layers with filling and ore stoping. Ore is flotation dressed.

Gold, silver and platinum deposits are available or newly discovered for the last decades virtually in all large geological structures, from the Arctic Circle to Mugodzhary. Twelve gold-bearing and about two hundred placer deposits are state registered in the Chelyabinsk, Sverdlovsk and Perm Territories alone. Gold-quartz veins and placers have been the main workable types of gold deposits so far. New gold-bearing deposits of veinlet-impregnated type were identified. These deposits are located in the periphery of granitoid blocks in the zones of Late Paleozoic tectonic-magmatic activation. There are data on higher gold content of the West Ural zone - Central Ural Upland structure. However there are no gold ore projects essential in scale on the western slope of the Urals as yet, and gold mining operations are grouped mainly on the eastern slope, the eugeosynclinal region.

Mining of medium and even small-scale gold-bearing deposits located near the existing mine undertakings is profitable in Ural with its highly-developed industry. Now three gold ore deposits, 84 gold-bearing and 12 platinum placers are being worked in the Sverdlovsk Territory, with four gold ore deposits and 26 gold-bearing placers in the Chelyabinsk Territory and two gold-bearing placers in the Perm Territory.

The Berezovo and Kochkar deposits are the gold ore base, with the mining of the new Svetpa and Vorontsovo deposits in future, while the raw materials base of gold placers is replenished with 14 new placers.

At present gold mines are provided with reserves in the following way: underground mines for 24-30 years, placer deposits for 15-20 years at dredge working and 15-20 years at hydraulic working.

Platinum is mined from placers along the Is river.

The Ural diamond-bearing region is located in the Perm and Sverdlovsk Territories as well as in Bashkiria. The first Ural diamonds were found in the Koiva River basin, in the Krestovozdvizhenskoe placer area in 1829. Planned search and prospecting started up in 1938. Placers have been worked in the Chusovaya River basin since 1941 and later on in the Vishera River basin. Placers are focused mostly on the western slope of the Urals in the zone of meridional strike of more than 1100 km in length where western and eastern bands are separated. Placers, mainly of Quaternary age, are in the western band (the Kolva, Krasnovishera, Kusya-Aleksandrovna and other groups). The eastern band (the Verkhnyaya Vishera, Verkhnyaya Kosva, Verkhnyaya Koiva and other groups) is confined to intermountain depressions elongated over the Main Ural Range, and traced in the south along the eastern margin of the Bashkirian

Upland. Placers are for the most part of Paleogene-Neogene age. Ancient placers are commonly presented by solid sandstones and conglomerates, modern ones are composed of loose rocks (gravel, sand and clay). Diamonds are of various shape but rhombododecahedrons and octahedrons dominate. Crystals are frequently damaged and presented by aggregates from several individuals. Jewelry stones are encountered in a considerable amount. Diamond placer formation is associated with fracture of ancient (supposedly of Medium Proterozoic - Lower Paleozoic age) of undiscovered kimberlites. A close spatial connection of a majority of enriched placer areas with outcrops of sandstone sediments of Takatin suite of the Middle Devonian which play an obvious role of intermediate diamond collectors is noted.

Placers are mined by an open pit method using shovels and dredges. Diamond-bearing sands (loose or cemented sand-clay pebble-boulder material) are separated. Screened and deslimed material is separately concentrated by jigging. Concentrate (heavy fraction) and tailings (light fraction) are produced. Tailings are delivered to dumping, with concentrate to processing by roentgene-luminiscent separation.

Bauxite ore beds of Devonian age are found on the eastern slope of Arctic Ural. The genetic and formation similarity of bauxites of the eastern Arctic Ural slope with North Ural ores gives grounds to expect that the North Ural bauxite belt extends farther to the north, within the eastern slope of Arctic Ural.

The South Ural bauxite mines located on the western slope of Southern Ural, and the workable reserves in the Chelyabinsk Territory are at an extremely low level. At present the only raw materials base of the mines is the Uluir-1 section with about 2 mln t of reserves.

The comprehensive processing rate for the Ural bauxites is low. Virtually alumina alone is extracted (overall recovery: 80 per cent). During alumina production an essential part of components transits to red slime and is accumulated in recycling solutions in industrial concentrations. The concentration in slimes is adequate for economic production of iron, titanium, zirconium, vanadium, gallium, germanium, scandium, niobium compounds, besides additional aluminium amount (10 per cent).

2.2.4.4. Western Siberia

The Altai Krai, the Kemerovo, Novosibirsk, Omsk, Tomsk and Tyumen Territories are incorporated into the West-Siberian economic region. The area is 2.4 mln km². The population is 14.4 mln people (as of January 1, 1987).

Mineral resources

A wide area is occupied by the West-Siberian platform associated mostly with oil and gas fields. The ore part of the region is Altai, a link of the Ural-Mongolian geosynclinal belt.

In Altai there are several ore belts (from east to west): mercury (the Katun anticlinorium), molybdenum-tungsten and iron-ore (the Kholzun-Chuy anticlinorium), polymetallic (Ore Altai), tungsten-tin-copper (the Kolba zone). The polymetallic deposits of Ore Altai are localized in the Devonian volcanic block extent area, are closely connected with them, and form a family of lead-zinc-copper-barite pyrite deposits of volcanogenic origin. The main deposits of copper-lead-zinc ores are as follows: Korbalkha, Stepny, Talovsky, Nikolaevka, Belousovo, Berezhovo, etc.; of lead-zinc ores: Ridder-Sokolnoe (Leninogorsk), Zyryanovo, etc. Altai is long famous for rich marble beds and valuable industrial stones (jasper, porphyry, etc). Four groups of thermal water discharges: Abakan, Arzhan, Belokurikha (to the south of the town of Biysk), Rakhmanovo and Dzhumala springs, are confined to Cenozoic faults.

Mining & metallurgical industry

The region is rich in oil and gas, hard coal, turf, iron and non-ferrous metals ore, mining & chemical raw materials, building materials.

The non-ferrous metals deposits are the base of the Leninogorsk Polymetallic, Irtysh Polymetallic, Belogorsk Mining & Concentrating, Zyryanovo Lead Complexes. The key ore

mining areas are Southern Ural (copper, gold, mercury, lead, zinc), Ore Altai (lead, zinc, copper, barite), Mine Altai (mercury, tungsten, gold) (Fig.2.7 & 2.8).

2.2.4.5. Eastern Siberia

The East-Siberian economic region includes Buryatia, Tuva, Krasnoyarsk Krai, Irkutsk and Chita Territories. The area is 4.1 mln km². The population is about 9 mln people (as of January 1, 1987).

Transbaikalia and the Baikal area are the mining regions of Southern Siberia which covers Buryatia, the Chita and partially Irkutsk Territories.

A considerable part of Eastern Siberia is situated in the so-called zone of Arctic North. It is limited by the Polar Circle in the south (66° 33' of north latitude). It features a wide abundance of morains and permafrost zone which is up to 400 m in thickness and a seasonal defrosting layer of less than 70 cm which means specific conditions for construction and mining operations.

The region is rich in oil and gas, coal, turf, iron ore, non-ferrous and noble metals, different non-metallic valuable materials.

Mineral resources

The Siberian platform takes up a large part of the territory. Copper-nickel sulfide deposits are associated with traps in the Norilsk ore area, and cupreous sandstones are mature in the Udokan series in the Aldan shield.

Deposits of pyrite-polymetallic ore in Proterozoic green-stone blocks (Kholodny), gold (placers and small ore deposits) are of primary importance in the Baikal mine country. There are fluorite-polymetallic deposits in carbonate blocks (Barva, Tabor, etc.), manifestations of nickel, molybdenum, tungsten, rare elements. Gold, hard coal, copper and iron are the most important for the Aldan shield. Besides gold ore deposits (the Aldan area) there are numerous placers. Cupreous sandstone beds are in the west of the Aldan shield (the Udokan deposit). The deposits of copper-cobalt ore with platinoids (Chiya), rare elements were found. Gold mining is of commercial value; formations of molybdenum, cupreous sandstones, polymetallic ores, mercury, rare elements were identified. The Mongolian-Okhotsk system and the Bureya massif show numerous placers and small gold ore deposits, tin-polymetallic ore and molybdenum manifestations.

In the south the Siberian platform is framed by the Altai-Sayan folded region.

Deposits of copper, molybdenum, tungsten and other ores are associated with the West Sayan Paleozoic structures; of copper ore, gold and other materials with Wend-Cambrian structures.

Deposits of titanium, aluminium, lead-zinc ore, gold, rare and rare-earth metals are known in Eastern Sayan. Large titanomagnetite deposits (Lysan, Kedran) are associated with Upper Proterozoic basic rocks. Aluminium ores are represented by bauxites of geosynclinal type (Bokson deposit), urtites connected with alkaline intrusives of Paleozoic activation of Pre-Cambrian structures (the Bogotol deposit), and by sillimanite-containing Proterozoic shales (the Bazybay and Kitoy deposits).

An abundance of cupreous sandstone deposits and hydrothermal gold, copper, manifestation of tin and tungsten ore deposits are associated with Baikal folding.

Transbaikalia and the Baikal region are rich in various mineral resources: cupreous sandstones (the Udokan deposit), lead-zinc ore, nickel (the Chay deposit), aluminium raw materials (the Mukhal deposit) and mercury ore (the Kiya deposit); deposits of tungsten-molybdenum and lead-zinc ore, potassium-alumina raw materials (the Synnyr deposit) are connected with Paleozoic and Mesozoic magmatic rocks.

In the east of the Verkhne-Chukotka folded region granite magmatism is connected with the stage of marginal volcanic belt formation. Tin, gold, mercury, polymetallic ore deposits are associated with it.

Mining & metallurgical industry

Copper ore mining in the South Siberian regions is traced from ancient times (the Khakassian deposits). The largest Udokan deposit of cupreous sandstones was explored and is being developed for mining in the Chita territory.

The raw materials base of the nickel industry is copper-nickel deposits of the Norilsk district (the Krasnoyarsk Krai) where the Norilsk Mining & Metallurgical Complex, a powerful centre of non-ferrous metals industry, is in operation.

The Khovu-Aksy deposit of cobalt ore is being mined by the Tuvacobalt Complex.

Lead-zinc ore is mined in Transbaikalia. The Nerchinsk Polymetallic Complex mines the Vozdvizhenskoe, Pokrovka, Savinskoe, Novochirokinsky and other deposits.

In the Krasnoyarsk Krai the Gorevsky Mine & Concentrator exploits a cognominal lead-zinc deposit.

In Buryatia the Kholodny deposit has been prepared for operation.

Tin ore is mined from the Sherlovaya Gora and Khapcheranga deposits in the Chita Territory. The mining of the Shakhtama, Davenda and other deposits of tungsten-molybdenum ore in Transbaikalia was of a large value to military industry during World War II. In Eastern Siberia the Dzhida Tungsten-Molybdenum Complex is in operation in Transbaikalia (the Kholtoson and Inkur deposits), and the Sorskoe Molybdenum Complex works based on molybdenum deposits in Khakassia. The steeply-dipping vein ore bodies of the Kholtoson deposit are worked by a cognominal underground mine.

The molybdenum deposits in the Chita Territory are being prepared for mining (the Zhireken Complex). Rare metal ore is mined in Transbaikalia (the Orlovka Mine & Concentrator) and in the Irkutsk Territory, the Terligkhay mercury deposit is mined in the Tuva republic. Native and placer deposits of gold are in operation in the Chita (Baley, Darasun) and Irkutsk (the Bodaibo District) Territories, in the Yenisei taiga, Khakassia and Tuva (Fig.2.9 & 2.10).

2.2.4.6. The Far East [10,23,25]

The Far East economic region includes the Primorski and Khabarovsk Krai, the Amur, Magadan and Sakhalin Territories, Yakutia. The area is about 63 mln km². The population is 7.8 mln people (as of January 1, 1987).

The Far East region is of particular importance to the Russian mining future as this area was the USSR leading producer of gold and diamonds as well as tin, antimony, and other minerals. The Far East region which is considered by many to be a new field for investment is richly endowed with natural resources and advantageously positioned from the geographic viewpoint over the north-west Pacific Ocean belt. It borders China, Korea and Japan (already its biggest partner), and is also quite accessible to the North American market (Fig.3.1). It is a vast area covering about 37 per cent of the Russian territory.

However only 5.4 per cent of population live here. This results in poor development of the territory, shortage of labour for industrial advance.

Minerals and mining

From the geological viewpoint the region encloses over 70 mineral types, including gold, diamonds, tin, zinc. The Far East though vast in territory and scarcely populated is fairly well mapped geographically, with 1:50,000-scale or better maps available for a lot of mineral-producing districts. In the last three five-year plan periods, the geological survey operations more than doubled in this region. The high quality maps commonly comprise prospecting and mineral evaluation data.

The Far East, with major reserves of non-ferrous, rare and noble metals, mercury and other minerals, has long been a key provider of mineral resources for the former USSR. Non-ferrous and precious metals are found in metallogenic zones along the Pacific Ocean coastline. Only a limited number of deposits have been sufficiently identified, evaluated and mined though some notable exceptions include large deposits of tin, antimony, tungsten (24 % of reserves and

37 % of output), lead (8 % of reserves, 49 % of output), zinc (4 % of reserves, 14 % of output). The Far East gold and precious stones are mined in abundance in the Kolyma, Indigirka and Upper Amur River basins. Over 90 per cent of Russian diamonds are extracted in the Far East or Yakutia (Fig.2.11 & 2.12).

In the Sikhote Alin system the leading role belongs to tin mining (the Komsomolsk, Badzhal and other districts), there are also gold and tungsten ore deposits.

In the Magadan Territory tin has been mined since 1937. Native and placer deposits are being mined. There are in operation the Pevek Mine & Concentrator, the Omsukchan and Iultin Mines & Concentrators in Chukotka, the Khrustalnoe Mine & Concentrator in Primorye, the Deputatskoe Mine & Concentrator in Yakutia, the Khingalovo Complex and the Solnechny Mine & Concentrator in the Amur region. The Pevek Mine & Concentrator mine the vein ore bodies of the Valkumey deposit by an underground method.

Tungsten ore is mined as associate material from the Iultin Mine & Concentrator deposits. The Primorski Mine & Concentrator develops the Vostok-2 tungsten deposit.

Lead-zinc ores have been mined in Primorye since late in the 19th century. The Dalpolymetal PO (Production Association) undertakings produce zinc metal, zinc concentrate and several associate metals. The association incorporates four underground mines which work on nine deposits.

After new deposits (the Sadovoe, Nikolskoe and other deposits) were found in the 30s-60s, the raw materials base of the Far East Mine & Concentrator was essentially expanded. The complex comprises an open pit, a concentrating plant, and a zinc smelter. The Sarylakh antimony ore deposit is being mined by an underground method in the north of Yakutia. Mercury ore deposits (West Palyana, Tramvatney) have been prepared for working.

Gold ore and placers are mined in Yakutia. In the Amur region (the oldest gold-bearing region) gold is mined by dredges and partially by hydromonitors of the Amurzoloto Production Association. In the Magadan Territory mining operations are performed by Severovostokzoloto Production Association. Gold was first found there in 1928, and in 1931 five fields were already in operation. In 1958 the first gold-mining undertaking was put on stream in Chukotka. Shovels, dozers, dredges and other equipment are applied in the fields while electric bulldozers are used in underground mines. The location of gold-mining undertakings is of seat nature (mainly by field groups) and depends on aerial extent of deposits under working as well as on united services, power stations, building and other facilities established for this or that group of fields. Gold is mostly mined by an underground method.

The richest zinc deposits were discovered, in particular, in the Sikhote Alin Mountains of Primorye, southern districts of the Khabarovsk Territory, Yakutia and Chukotka. Tin ore (cassiterite) found is of special interest, as is copper ore at Udokan of Southern Yakutia and bauxite deposits of the Khabarovsk Territory. Tin discovered here indicates that the region will be a suitable target for commercial tin mining. Dozens of tin deposits have been in successful operation in the area.

The region also plays a vital role in tungsten production. On an equivalent basis, the Far East mineral industry is more developed than this sector in the USA Alaska. The Far East can be easily divided into four mining areas:

- the southern zone which incorporates parts of the Khabarovsk Territory and the Amur region (tin, gold and coal);
- the Pacific Ocean zone which includes Primorye and Sakhalin with Kamchatka (polymetallic ores and tungsten);
- the northern central zone which covers Yakutia, the Magadan territory and part of the Khabarovsk Territory (precious and non-ferrous metals, diamonds, coal, iron ore);
- the Far North zone which embodies the Chukchi National District (non-ferrous metals, gold).

Coal and diamonds are mostly mined in the Kolyma and Indigirka River basins and Yakutia as well as in the Upper Amur river basin. As an example of the gold mining scope in the

Far East, approximately 13 dredges and up to 200 open-pit placer mines are operating at Susuman of the Kolyma mining district, about 150 km to the north of the town of Magadan. Vein mining also takes place based mostly on stockworks in diorite and sheeted shear zones, and the mineralization is similar to that in the Juneau gold belt and the Valdez Creek mining district of Alaska. The total output in the Susuman area is about 350,000 tr.oz/y or approximately 35 per cent of the total annual output of the whole Kolyma region. Less than 10 per cent of gold resources of the Magadan region are reported to be currently worked.

The mining potential for numerous mineral deposit types found in the Far East is shown in Table 2.7. Below are enlisted several very promising deposits: Udokan - stratiform copper-sandstone body, Bugdain - tungsten-molybdenum stockwork, Agylkin - copper tungsten scarn, Katugin - tantalum-niobium body, Bolshoy Seyim - titanium body.

Table 2.7. Subjective evaluation of Far East deposit mining potential by mineral deposit type [22]

Mineral type	Development potential					
	Present			Future		
	High	Medium	Low	High	Medium	Low
Norilsk Cu-Fe-PGE	X			X		
Alaskan PGE	X			X		
Placer PGE-Au	X			X		
Diamond pipes	X			X		
Low-sulfide Au-quartz veins	X			X		
Porphyry Cu	X			X		
Scarn Cu deposits			X		X	
Porphyry Cu-Mo	X			X		
Sediment-hosted Cu	X			X		
Volcanic-hosted Cu-As-Sb			X			X
Algoma Fe			X		X	
Superior Fe			X			X
Scarn Fe deposits			X		X	
Sn veins	X				X	
Scarn Sn deposits	X					X
Scarn W deposits	X					X
Polymetallic veins			X		X	
Sedimentary exhalative Zn-Pb	X			X		
South-East Missouri Pb-Zn			X	X		
Sandstone-hosted Pb-Zn			X			X
Polymetallic replacement deposits			X		X	
Scarn Zn-Pb deposits	X					X
Simple Sb deposits			X			X
Serpentine-hosted asbestos			X			X
Volcanogenic Mn			X		X	
Sedimentary Mn			X		X	

Upwelling -type phosphate deposits	X					X
Laterite-type bauxite deposits	X				X	
Laterite Ni			X			X
Carbonatite deposits			X		X	
Shoreline placer Ti	X			X		

2.3. Mineral Resources of Ukraine

Ukraine is situated in the South-West of the FSU. The area is 603.700 sq km. The population is 51.7 mln people (1989).

2.3.1. Geological Structure and Mineral Resources

The Ukrainian shield located in the Central part of the country is bedded by very dislocated Archean and Lower Proterozoic metamorphic, intrusive and metasomatic formations. Iron, titanium, nickel ore, graphite and other deposits are associated with them.

Mercury deposits are connected with the Donets folded region. The Black Sea depression contains *bauxite, polymetallic and manganese* deposits.

The Transcarpathian internal deflection with volcanogenic-sedimentary formations contains mine *salt, zeolite, barite, alunite, mercury* deposits (Bolshoy Shayan, Borkut), as well as vein *gold-polymetallic and barite* (Begansky) deposits. Stratiform *pyrite-polymetallic, copper pyrite, barite and iron-manganese ores* are manifested in the metamorphic complex.

Small deposits of *silicate nickel ores* (Kapitanovka, Derenyukha, Ternovsky) are identified in the Bug region (Pobuzhye). They are associated with serpentinite weathering crust. The ore deposits are bedded by nontronites, limonites and ochre with 1 % Ni and 0.1 % Co in average.

Lead-zinc ore manifestations are available in the Transcarpathian region (Beregovoe, Begansky), in Donbas (Nagolnyy Kryazh) and the Ciscarpathian region. Transcarpathian volcanogenic hydrothermal deposits are of commercial value. Here the mineralization is closely connected with Miocene-Pannonian volcanic zones and massifs, characterized by knot distribution and confined to the internal volcanic arc. The deposits are bedded by various volcanites (andesites and their pyroclasts) together with their subvolcanic derivatives. The orebody distribution depends on fracture structures, explosive breccia development sections, intensive permeability and porosity zones. The vein ore bodies are up to 5 m thick, and contain up to 2 % Pb, 3-4 % Zn, as well as silver. There are tin and copper ore manifestations.

Mercury ores are presented by hydrothermal volcanogenic deposits in the Donets ore province (the Nikitovka ore field deposits). In the Transcarpathian region the mercury mineralization is associated mostly with hypabissal intrusives (diorite-porphyrites and granodiorite-porphyrites). The ore bodies are columns elongated on dip, flattened lenses and nests. The mineralization is for the most part complex mercury-polymetallic, more seldom mercury and mercury-antimony with arsenic. The Donbas deposits are confined to roof parts of anticlines. The subconcordant beds in sandstone layers and the nests match the intersecting bodies in the anticline fold nuclei. The ores are virtually monomineral (cinnabar) with slight antimonite content.

Titanium ore deposits are presented by native, residual and placer types. The native ores are connected with olivine gabbroid intrusives. Small dykes or stocks are confined to abyssal fracture zones. Ilmenite and apatite in them amount to 25 and 12 %, respectively. The residual deposits are spatially and genetically connected with essential rock weathering crusts. The ore layer is up to 25-30 m thick, with an ilmenite content of 150-200 kg/m³. Besides ilmenite,

alluvial (the Irsha and other deposits) and coastal-marine (the Malyzhevo deposit) beds are available. The alluvial placers are up to several kilometres long. The productive layer (up to 10 m in thickness) contains up to 300 kg/m³. The coastal-marine placers feature layer or lens-shaped ore deposits which thickness is up to several tens of metres with length of several tens of kilometres. The productive layer is bedded by quartzite sands. There are rutile and zircon, besides leucoxenized ilmenite.

2.3.2. History of Non-ferrous Metal Deposit Mining

First copper tools appear at the end of the 5th and in the beginning of the 4th millennium B.C. when the Tripolian archeological culture of the Copper Age was developed on the right bank of the Dnieper River and Western Ukraine. The mineral products for their manufacture were delivered from the mining & metallurgical centres of the Balkan-Carpathians. In the Copper Age (the middle of the 4th and the beginning of the 2nd millennium B.C.) copper and antimony bronze entered Ukraine mainly from the Caucasus and partially from the Balkan-Carpathians. In the middle of the 2nd and the beginning of the 1st millennium B.C. surface outcrops of copper-bearing deposits were widely mined in the Donbas territory. Numerous pits and shallow mines were initiated for extraction of malachite with downstream pyrometallurgical processing (the area of Kartalysh, Pilipchatino, Klinovy Khutor, etc.).

Full-scale mining trials of iron ore deposits are attributed to the middle of the 19th century when gold which reserves were exhausted after a short time period was produced. Lead-zinc ore deposits near the Truskavets town have been known since 1836. In the Ciscarpathian region potash salt has been mined since the 19th century. The Borislavsky oil field considered one of the Europe's largest fields has been known from the 2nd half of the 18th century. In 1879 the commercial mercury mineralization was discovered in Donbas.

2.3.3. Mining & Metallurgical Industry

Ilmenite and zircon-rutile-ilmenite deposits are open pit mined by the Irsha Mine & Concentrator and the Upper-Dnieper Mining & Metallurgical Complex using bucket-wheel and chain excavating machines and draglines. Sands are gravity separated at concentrators with a mineral recovery rate of 80-90 %.

Nickel ores are open-pit extracted by the Pobuzhskoe Nickel Plant. The oxidized ore of the Pobuzhskoe deposit group is mined and downstream processed by electric melting.

Ukraine accounted for a considerable part of the all-union *mercury* production. Mercury ore output was focused on Donbas at the Nikitovka Mercury Works which mined the like-named deposit by a combined method. The mercury ore was processed in fluidized-bed furnaces, with mercury recovery of about 85 %. Nowadays the deposit has already been depleted for the most part and is reminded only owing to large mercury pollution of the environment (Fig.2.13 & 2.14).

2.4. Mineral Resources of Georgia

Georgia is situated in the central and western part of Transcaucasia. The area is 69,700 sq km. The population amounts to 5.17 mln people (as of January 1, 1984).

2.4.1. Geological Structure and Mineral Resources

The Late Alpine tectonic-magmatic activation process of the Big Caucasus completed foldness regions is of great importance to metallogeny of Georgia. Formation of barite and barite-polymetallic mineralization widely abundant in the Gagra-Dzhava and Okrib-Sachkher zones must be considered the beginning of the above activation process. The Kvaisy near-

fracture lead-zinc zone, rare metal-arsenic belt of Racha and Svanetia and echelon-like alternating mercury belts of Abkhazia, Svanetia, Racha and Southern Ossetia are confined to next activation stages.

Manganese, copper, arsenic, lead and zinc ores, some rare and noble metal ores are the most important mineral resources of Georgia.

Copper ores are focused for the most part in the Bolnisi ore region where complex copper-barite-polymetallic deposits (Madneul, Tsitelisopelsky, Kvemo-Bolnisi, Tamarisi and others) are located. They are confined to the Upper Cretaceous volcanogenic-sedimentary strata; the orebodies are shaped as metasomatic beds of solid and vein-impregnated ores, more seldom stocks and columns. Vertical zonality is typical, the lower deposit horizons have mature sulfur and copper-pyrite ores overlapped by copper-zinc, polymetallic and barite ores. The key minerals are pyrite, barite, chalcopyrite, sphalerite, galenite. The average copper content is 1-1.5 % with up to 2-4 % in separate areas. The Magneul deposit is being mined. Vein copper-polymetallic deposits connected with Pre-Upper Eocene intrusives of syenite-siorites are abundant in the Adzharia-Trialeti zone. The explored Merisi ore knot contains up to 50 steeply-dipping quartz-sulfide veins. Several vein fields are identified in the area of about 180 sq km. The copper content in veins is 1.5-2 % in average. Copper-pyrrhotite and pyrite-polymetallic mineralization is widely abundant in the Jurassic black shale strata in the southern slope of the Big Caucasus. Ore fields (Adangey, Artan, Akhalsopelsky, etc.) with very uneven, sometimes high, copper concentrations are being explored.

Lead-zinc ores are available in the above types of pyrite and vein copper-polymetallic ores and are also independent in lead-zinc and polymetallic formation deposits. The Kvaisy deposit is confined to the Late Alpine fracture zone traced up to 8 km along the strike and more than 1 km down the dip. Columnar bodies of lead-zinc ores are bedded in Bajocian porphyrite suite rocks and Upper Jurassic limestones. The zinc and lead content in the ores is 5.7-7.8 and 1.9-2.6 %, respectively, in the Upper Kvaisy and Nadarbazi areas. The Valkhokh and Varakhkom ore-bearing structures have been explored, the Pb to Zn ratio is 0.4.

In the Bolnisi region barite mineralization is an associate to *copper-lead-zinc* mineralization; barite is extracted as associate at the Magneul deposit.

The ore reserves amount to about 1 mln t, the barite content is 32-53 per cent.

Mercury ore deposits and numerous cinnabar mineralization manifestations are located over the southern slope of Big Caucasus. The Akhey and Avadkhar deposits in Abkhazia are the most essential ones. They are represented by a hydrothermally changed zone confined to sandstones and clay shales. The metal content is 0.4-9.1 and 0.27-0.41 % in the first and second deposits, respectively. The Ertsoy deposit has been discovered in Southern Ossetia.

Antimony ore deposits are located over the southern slope of the Main Range of Big Caucasus. The Zopkhito deposit in Upper Racha is of commercial value. It is represented by numerous quartz-antimonite veins confined to Lias clay shales and Paleozoic granitoids. The metal content is 7-17 %.

Arsenopyrite and realgar-orpigment veined deposits of hydrothermal type are widely abundant in the southern slope zone of Big Caucasus. The Lukhum deposit in Upper Racha and the Tsan deposit in Lower Svanetia are of commercial value. The former is presented by rich realgar-orpigment ore and relatively poor ore as individual nests, interlayers and impregnations in lateral rocks (shales and limestone of the Upper Jurassic and Lower Cretaceous periods). Five ore bodies have been identified, with metal content from 3.6-13.3 %. The Tsan deposit ores are arsenopyrite-containing quartz in metamorphized clay shales, with an arsenic content from 3.32 to 29 %.

Non-ferrous metals ores are under full-scale mining at the Magneul *copper-barite-polymetallic* and Kvaisy *lead-zinc* deposits. The Magneul deposit has been mined since 1974 by an open-pit method. The ore is processed by flotation at the Magneul Mine & Concentrator.

The Kvaisy deposit has been mined by an underground method since 1949. The heavy bulge (up to 8-10 m) of a steeply-dipping (82-85 m) ore body of the Nadarbazi area is being worked.

Steel is made at the Rustavi Steel Works. There is also a chemical complex producing arsenic and other preparations (Fig.2.15 & 2.16).

2.5. Mineral Resources of Armenia

Armenia is situated in the south of Transcaucasia. It borders Georgia on north, Azerbaijan on east, Iran on south and Turkey on west. The area is 29,800 sq km. The population is 3,222,000 people (1983).

Despite small land area the country is rich in various mineral resources which permitted set-up of projects to mine *copper*, *copper-molybdenum* and *gold*-bearing ores.

There are ore mining undertakings in Armenia. They are Arm Gold (which operates the Zodsky underground mine and open pit), and Arm Non-ferrous Metals (copper and molybdenum stockworks and veins).

The *copper* ores of the hydrothermal genesis of the Kafan deposit are represented by the vein and veinlet-impregnated mineralization in the Middle Jurassic volcanogenic rocks. In the north of Armenia there are the Shamlug and Alaverdy vein-type copper ore deposits bedded in the Middle Jurassic volcanogenic rocks.

Armenia is one of the CIS leaders in *molybdenum* ore reserves. In the Kafan region there is the Kadzharan deposit presented by a stockwork with veinlet-molybdenum ores containing *rhenium*, *selenium*, *tellurium*, *bismuth*, etc. as associates. The hydrothermal deposit is confined to the monzonite intrusion of the northern part of the Megrin pluton. The Agara hydrothermal *copper-molybdenum* deposit confined to the same pluton is situated in the south-eastern part of Armenia (Fig.2.15).

History of mineral resource mining

The mining operations in this region are attributed to the most ancient ones in the history of the mankind.

In Armenia there was one of the largest copper ore mining and copper smelting centres in the Bronze epoch (the middle of the 4th and the beginning of the 1st millennium B.C.). The Middle Ages and current openings destroyed the majority of the earliest shallow funnel-shaped pits and holes. However there are still certain evidences that the most ancient workings were focused on the regions of Northern Armenia: the Alaverdy-Kirovokan deposit group (Alaverdy, Shamlug, Akhtala, etc.), probably, Antonovka as well, and on the regions of Southern Armenia: the Zangezur deposit group (Kafan, Kadzharan, etc.). Arsenic ores (the Metsdzor, Solvartin, Daridag deposits) which were used as master alloys in bronze production have been mined since the middle of the 4th millennium B.C. For the same purpose antimony ores (maybe, Angekhtun, Manaskert) have been mined since the middle of the 3rd millennium. A relatively large number of tin articles from the Lchashen grave on the Sevan Lake shore of the middle of the 2nd millennium B.C. brings about a supposition on probability of local tin ore sources. From that time on tin bronze has become the dominating alloy type. At least from the beginning of the 1st millennium B.C. iron ore deposits (probably, Agartsin, Varazhnunik, etc.) have been used on a large scale. Alongside this, the operation of the above copper ore deposits have not been terminated up to the Middle Ages and new times. In the Middle Ages the Akhtala silver-lead deposit, the Zangezur polymetallic deposits and the Alaverdy group copper deposits were mined. The regular development of the Akhtala, Alaverdy and Shamlug deposits are attributed to the middle of the 18th century. In 1760-1770 the Akhtala and Shamlug Copper Smelteries were set up. During the invasions of Omar-Khan Lezginsky in 1785 and Aga-Mahomet-Khan Persian in 1795 the Akhtala, Alaverdy and Shamlug open pits were destroyed. After the Caucasian territory

was included into the Russian state (early in the 19th century) specialized expeditions were sent there in order to explore mineral resources. From 1886 on the French company of Akhtala open pits resumed the working of the Alaverdy and Shamlug copper deposits. In 1900 this company transferred their rights to the Caucasus industrial & metallurgical society which leased the Privolnoe polymetallic deposit as well from 1912 and owned the Dragil-Zami and Gyumush-Magara polymetallic open pits in Zangezur from 1915. The ore entered the Manes Plant at Alaverdy. Besides, in the 19th century polymetallic deposits in Southern Armenia (Agarak, Kafan, Pirdoudan (Kadzharan) and others) were also intensively mined. The Agarak, Pirdoudan, Kafan and Galidzor Copper Smelteries were built. In 1847-1867 eleven new copper smelteries (among them, 7 in Zangezur) were set up in Armenia. In the 1860s Armenia occupied the leading position in Transcaucasia as copper producer (up to 99 %).

Mining & metallurgical industry

The raw materials base for *copper and molybdenum* concentrate production is the copper-molybdenum ores of the Kadzharan and Agarak deposits as well as the copper ores of the Kafan and Shamlug deposits. The Zangezur Copper-Molybdenum Works has been in operation since 1952 based on the former. The Agarak deposit has been in operation since 1963. Owing to a small overburden rock mass the Kadzharan and Agarak deposits are mined by an open-pit method, the Kafan deposit both by open-pit and underground methods. Copper-lead-zinc ores are mined by an underground method at the Akhtala open pit of the Alaverdy Mining & Metallurgical Complex and dressed at the concentrating plant. More than 90 per cent of non-ferrous metal ores are mined by an open-pit method. The ore is concentrated by flotation.

The Kadzharan deposit is one of the world's largest copper-molybdenum deposits which profitable reserves explored can be mined for more than one hundred years at the current output level while the indicated reserves will afford mining for more than two hundred years. Another similar project is the Agarak Copper Mine & Concentrator which reserves are limited to approximately 15 years. Only high grade ores of the Kadzharan deposit are mined presently while the lower quality ores are dumped and lost despite their being economically acceptable. Ironically the recovery value of these "poor" ores is above the average recovery value of the Agarak deposit which is located 30 km from the Kadzharan field.

The Kadzharan and Agarak Concentrators produce copper concentrate, besides molybdenum concentrate. Copper concentrate is also made at the Kafan Concentrator where the copper ores of the Kafan deposit are processed.

In the last decades Armenia has emerged as one of the world's noteworthy *gold-bearing* provinces. About ten gold ore and gold complex fields have been discovered. Extractable reserves of six gold fields have already been proved, two of them are now under extensive evaluation. The large Zodsky deposit in Eastern Armenia is worked by combined open-pit and underground methods. Underground mining is carried out by a cut-and-fill stoping method. Zodsky is a medium-sized mine which annual output is 80,000-95,000 troy ounces.

The gold ores of the Zodsky deposit are processed at the Ararat Plant. The process flowsheet includes gravity and flotation dressing and hydrometallurgical processing with cyanide solution and downstream sorption gold extraction (Fig.2.16).

2.6. Mineral Resources of Azerbaijan [10,23]

Azerbaijan is situated in the eastern part of Transcaucasia. It is washed by the Caspian Sea in the east, borders Dagestan on north, Georgia on north-west, Armenia on west, Iran and partially Turkey on south. The area is 86,600 sq km. The population is 6,303,000 people (1982).

Azerbaijan is an industrialized-agricultural republic and the main oil-producing district of Transcaucasia. The key sectors of the heavy industry are machinebuilding (manufacture of oil-field equipment, electronic, electrical and instrument making branches) and metal working, fuel, chemical and oil chemical industries, power generation, iron & steel and non-ferrous metals industry, etc. Mining industry is presented by oil and gas production, iron ore, alunite and lead-zinc ore mining. Oil and gas sector occupies the leading place in the nation's industrial structure.

Copper ores are presented by copper-pyrite and copper-porphyry beds. Copper-pyrite ore bodies are available in the Kedabek region where they are placed as stockwork-shaped bodies in upper horizons of Bajocian quartz plagioporphry thickness. The upper stockwork horizons are bedded by copper and copper-zinc ores, the lower ones by sulfur-pyrite ores. The essential minerals are chalcopryite, pyrite, sphalerite, galenite, arsenopyrite, etc. Copper-porphyry ores are focused in the Ordubad ore district and are spatially connected with apical and peripheral parts of Paleogene-Miocene Megri-Ordubad granitoid batholith. The essential minerals are chalcopryite, molybdenite and pyrite. The ores oxidized on the surface contain 0.2-1 % Cu, with 0.3-0.6 % in average in deed horizons. Several manifestations of virgin copper which form a band extended for about 60 km are located in the Araks zone over the line of the Nakhichevan fracture, the area of Oligocene-Lower Miocene volcanite development; separate copper-bearing layers are 0.5-9 m in thickness.

Lead-zinc ores are connected with pyrite-polymetallic deposits of Belokan-Scheka metallogenic zone of the southern slope of Big Caucasus (Filizchay, Katsdag, Katekh, Dzhihikh, Cheer, Katsmala, etc.). The Mekhmana lead-zinc deposit in the Middle Jurassic volcanogenic thickness is available in the Somkhit-Agdam zone of Small Caucasus. There are two small deposits of lead-zinc ores in the Nakhichevan Territory: Gyumushlug confined to Middle-Upper Devonian limestones and Agdara confined to Eocene volcanites.

The most important manifestations of cobalt mineralization are available in the Dashkesan and Ordubad ore regions. The former being superimposed on scarn-magnetite ores is genetically connected with the Dashkesan granitoid intrusive, the latter is in the scarn zone of the Megri-Ordubad pluton. The key minerals are cobaltite, allosclerite, glaucodot, safflorite, cubanite, cobalt-pyrite.

Aluminium ores are presented by beds of alunites and bauxites. Alunite deposits are available in the Dashkesan, Shamkhor and Ordubad regions. The most famous deposit is Zaglik confined to Middle and Upper Jurassic volcanic-sedimentary strata broken by the Dashkesan intrusive. Alunite is associated with kaolinite, quartz, hematite, limonite, chalcedony, opal, etc. The bort alunite content is 25 per cent. The stratiform beds are 20-m thick, the ore mass (alunite and quartz) accounts for 95 per cent, clay minerals amount to 5 per cent. The Zaglik deposit (on stream since 1960) is the raw materials base of the Kirovabad Aluminium Plant. Bauxite manifestations are discovered in the Nakhichevan Territory in Devonian-Permian terrigene-carbonate sediments as stratiform and lens-shaped bodies of 2-13 m in thickness and 1.5-2 km in length. The silicon modulus is of 2:1 type (allites and siallites).

Molybdenum ores are associated with copper and lead in the Temiruchandag-Bagysarkhsky deposit (the Kelbadzhar region). The Paragachai molybdenum deposit is being mined. It contains 0.2-1.1 % Mo, 0.002-2.1 % Cu, 0.04 % Re in molybdenite, 0.006 % Se, 0.02 % Fe.

Tungsten ore manifestations are available in the Nakhichevan Territory and in the Kelbadzharsky District; scheelite is noted in quartz veins. Tungsten-bearing ore bodies are confined to Upper Eocene hornfels in the contact zones of the Megri-Ordubad and Dalidag plutons.

Arsenic ores are presented by the Bittibulag deposits (enargite) in the Kedabek District and the Darrydag (orpiment-realgar) deposit in the Dzhulfa District (in operation prior to 1941).

Mercury ore deposits were identified in the central part of the Sevan-Karabakh zone (Levchay, Shorbulag, Agyatag, Agkay, and Narzanlik).

Antimony is observed in the Lev and Kesandag (the Nakhichevan Territory) mercury deposits.

As to non-fuel minerals, Azerbaijan produces aluminium, copper-molybdenum, iron ore, lead and zinc. Cobalt associated with magnetite deposits has been also mined since the 19th century. Azerbaijan is one of the four former USSR republics which export aluminium.

Non-ferrous metals ores are mined at the Zaglik (alunites), Paragchay (molybdenum and copper), Gyumushlug and Agdara (lead, zinc) deposits. Aluminium plants operate based on the Zaglik alunite deposit. Besides alumina, sulphuric acid and calcium sulfate are produced from aluminite. The deposit is mined by an open-cut method.

Minor mining operations are carried out in Nakhichevan, an autonomous republic separated from the rest of Azerbaijan by Armenian territory. In the last decades silver, lead and zinc, molybdenum, gold and mercury were extracted from various deposits throughout the republic. The Paragchay molybdenum mine located in the south-east and mined since World War II is related to the more significant deposits located across the Armenian border.

Copper-molybdenum ores have been mined since 1952 by an underground method in the Paragchay deposit. The dressing operation is flotation.

Lead-zinc ores have been mined since 1954 by an underground method in the Gyumushlug and Agdara deposits (Fig.2.15 & 2.16).

2.7. Mineral Resources of Kazakhstan [10, 38, 48, 50]

2.7.1. Regional Geology and Deposits of Kazakhstan

Kazakhstan is situated in the south-west of the Asian part of the former USSR. The area is 217,000 sq km, the population amounts to 15,250,000 people (1984).

Kazakhstan, like the Russian Federation, Ukraine and Tajikistan, is richly endowed with mineral and energy resources. Mining has historically been considered critical to the nation's economy. The non-ferrous metals industry comprises the primary metallurgical sector, involving production of copper, lead, zinc, titanium, aluminium, tungsten, gold, silver, tantalum, uranium, plus minor metals which include antimony, rhenium, tellurium, scandium and many others. The Ust-Kamenogorsk and Leninogorsk Lead & Zinc plants, the Irtysh Chemical & Metallurgical Plant and the Ust-Kamenogorsk Titanium & Magnesium Plant are all located in the Altai region; lead and zinc are also produced at the Chimkent plant, and copper is made at Dzhezkazgan and Balkhash plants. Pavlodar is a centre of alumina production, and all of these facilities for the most part use local raw materials as their base. The current estimates of the country's mineral production output and capacity are shown in Tables 2.8 & 2.9.

Sulfuric acid production is centred at the non-ferrous metals smelteries in Balkhash, Chimkent, Ust-Kamenogorsk and Leninogorsk. Kazakhstan is a significant producer of iron & steel, non-ferrous and precious metals, including aluminium, chrome, copper, gold, iron ore, lead-zinc, molybdenum, silver, steel, titanium and tungsten. Thirty-six ore mines, besides seven major metallurgical plants, operate in the country. The republic which accounted for about 6 % of the USSR gold output is the third largest gold producer among the CIS countries.

Kazakhstan is a leader in the former USSR in key economic minerals both in terms of explored reserves and scope of extraction and processing. Namely, the republic accounts for great shares of the FSU strategic mineral mining and processing as follows: chromites, 97 %; bismuth, 95 %; tungsten, 52 %; lead, 47 %; zinc, 40 %; copper, 36 %; bauxites, 25 %. Kazakhstan's mineral deposits are unique in amount and quality, and can support high-capacity industrial facilities.

Table 2.8. Kazakhstan's mineral resources and production output as a percentage of the CIS total

Mineral product	Reserves		Production output	
	%	Position held in FSU	%	Position held in FSU
Copper	28	2	30	2
Lead	38	1	64	1
Zinc	35	2	56	1
Bauxite	22	2	36	2
Tungsten	54	1	4	3
Tin	2	3	2	2
Molybdenum	29	2	5	4

Table 2.9. Estimated output of Kazakhstan's mineral products (metals)

Metal (tonnes)	1992	1993	Estimated capacity (as of 1/01/94)
Alumina	1,100,000	1,000,000	1,200,000
Bauxite	500,000	500,000	600,000
Beryllium (metal)	NA	NA	NA
Bismuth	55	50	70
Cadmium	1,000	1,000	1,200
Copper (metal content)			
mines	250,000	250,000	250,000
smelteries	225,000	225,000	440,000
refined metal	225,000	225,000	440,000
Gold	24	20	30
Lead (metal content)			
mines	170,000	160,000	250,000
primary smelteries	160,000	150,000	250,000
Magnesium	20,000	20,000	45,000
Marketable	35,000	50,000	200,000
manganese ore			
Molybdenum (metal)	3,000	3,000	6,000
Silver	900	900	1,200
Tin metal (mines)	500	500	700
Titanium (metal)	25,000	25,000	35,000
Tungsten metal (W content)	500	500	800
Zinc			
mines (metal content)	250,000	240,000	450,000
metal	240,000	230,000	315,000

Source: *Mining Annual Review 1994* (Kazakhstan. By R.M.Levine, US Bureau of Mines)
Geological outline.

The great part of the Kazakhstan's territory is situated within the Ural-Mongolian folded belt comprising Paleozoic formations found in the southern part of Ural (Mugodzhary), the Melkosopochnik area and in Tien Shan, Dzungar, Chingiz-Tarbagatai and Altai in the south of the country. The Ciscaspian basin (the south-eastern part of the East European platform) is located in the north-western part of Kazakhstan.

Large areas in the west and north of Kazakhstan are overlaid by Hercynian platform cover deposits (the Turan and West Siberian plates). The platform cover of three plates was formed during the Triassic-Neogene. It is 2-4 km thick (locally 6-8 km). The Archean and Lower Proterozoic crystalline basement of the Caspian basin is overlaid by a thick (up to 20 km) succession of Riphean-modern sedimentary deposits.

The eroded surface of the folded and heavily metamorphized crystalline basement was covered in the Late Proterozoic with the deposition of both sedimentary and volcanic formations which represented the protoplatform cover. This cover was studied in the outcrops of a few small massifs of Pre-Cambrian age. The break-up of the protoplatform began in the Middle Riphean but did not take place simultaneously over the whole territory of what is now Kazakhstan. Separation zones with new areas of ocean-type crust and associated island-arc zones, were formed along the faults.

The Ural-Mongolian folded belt was generated as a stable continental block between the Vendian and the Permian. The study of the belt evolution has not been completed as yet from the viewpoint of up-to-date tectonic concepts as many important structures are buried beneath the platform cover or overlapped by thrusts. Repeated stages of tectonic movement occurred during Caledonian and Hercynian orogenies and were related to the displacements of the nearby East European, Siberian and Tarim platforms which resulted in intensive folding, volcanism and intrusive magmatism. Three geosynclinal folded systems can be identified by nature and evolution of tectonic structure: the Ural-Tien Shan system in the west and south-west, the Kazakhstan system in the centre and south-east, and the Irtysh-Altai system in the north-east of the country.

Relatively small massifs of Pre-Cambrian rocks (measured by a few tens or hundreds of kilometres) were found within the Paleozoic structure in many regions. They are exemplified by the East Ural, Kokchetav, North Tien Shan and Atasu-Dzungar massifs among others. The Pre-Cambrian assemblage consists of porphyries and various heavily-metamorphized greenschist rocks, calc-alkali island-arc volcanic rocks, reef carbonates, diabase and siliceous-carbonaceous shales. Granitoid magmatism is widely abundant.

An ocean crust area was developed in what is now North-East Kazakhstan from the Late Vendian to the Cambrian, with cherts, jasper, carbonates and diabase-splite rocks deposited. Elsewhere from this basin rift-type complexes were formed which contain basalts, carbonaceous-siliceous and carbonate rocks, and often carry metalliferous deposits. These areas include the Kokchetav massif, the Karatau and Dzungar Ranges, and other places. Island-arc volcanism (from basalt to rhyolite) and intrusive magmatism (gabbro, granite, and syenite) originated from the Middle Cambrian.

The Ural-South Tien Shan and Zhungar-Balkhash basins with gabbro hyperbasite basement as found in the Kempisari massif in Ural and the Kenterlau block in the north of the Balkhash region, originated from the Ordovician. Formation of thick flyschoid successions and andesite-basalt volcanic rocks is typical of that time. The Dzungar-Balkhash basin was formed by volcanic arcs from the east and north-east (the Chingiz Range) and from the west (the Stepnyak-Betpak Dala area) with andesite-basalt volcanism. The Ural basin was also formed from the east by a zone of island-arc volcanism.

The formation of basalts, carbonaceous-siliceous slates and jaspers occurred in the Altai basin in the Ordovician, and thick turbidites were deposited in the more easterly areas of Altai, as in the Cambrian.

Active tectonic movements during the Silurian resulted in the creation of the orogenic folded massif between the Ural-South Tien Shan and Dzungar-Balkhash ocean basins. Heavy deposits of siliciclastic (terrigenous) sediments were deposited in the central part of the Dzungar-Balkhash basin while flysch, basalt and andesite were formed around the basin margins where overthrust sheets also appeared. The volcanism level in the Ural region decreased during the Silurian as a result of tectogenesis.

Orogenic movements during the Late Silurian were responsible for wide distribution of terrestrial sedimentation and volcanism in the Devonian. The greater part of the massif which divided the Ural and Dzungar-Balkhash paleobasins dried up, and a wide belt typified by active andesite-basalt volcanism and thick red molasse was formed around the massif. Meanwhile in the basins a sedimentation pattern similar to that of the Silurian was kept. In the Middle Devonian intensive thrusting transformed the western part of the Dzungar-Balkhash basin into an orogenic area with widespread basalt-rhyolite volcanism and granite intrusions. Red molasse was also widely distributed, and marine metal-bearing clay-carbonate and black shale sediments were deposited locally. Devonian volcanic and sedimentary formations (some salt-bearing) were widely distributed from the residual basin, and nowadays they have been found in the locations like the Karatau Range and Shu-Ili Mountains, and the Teniz, Shu-Sarysay and Turgay depressions.

In the Ural region active tectonic movements commenced in the Middle Devonian which resulted in folding and closure of some basins while marine sedimentation and underwater volcanism went on in the others. To the east the Valeryanovsky zone exhibited island-arc volcanism while a deep water trough in the Altai region between the Chara ophiolite belt and the Irtysh folded zone featured jasper and basalt depositions. Basalt and chert accumulation also occurred in the area to the west of the island-arc environment while the eastern active margin of the Altai basin, the Ore Altai island-arc system, was overthrust in the central part to the south-west along the Irtysh folded zone. Kazakhstan's tin, tungsten, molybdenum, gold, copper, tantalum and other mineral deposits are related to Devonian-aged volcanic rocks and granites, and sulfide deposits containing copper, lead, zinc and gold are associated with andesites and basalts.

The Hercynian tectonic period began in the Late Devonian (Famennian). Basal volcanism was reactivated in the Dzungar-Balkhash basin, and a new volcanic arc appeared some 100-150 km to the south of the Devonian arc. This system was incorporated with rifting, including the Uspensky and Spassky rifts. Deep-water sediments were formed in these rift structures with basalt-trachite-rhyolite and ultrabasite deposits and with polymetallic and iron-manganese mineralization while the Caledonides of the western part of Central Kazakhstan were almost universally covered by shallow-water seas.

The ocean evolution phase in the Ural and Altai regions continued virtually uninterrupted for the Famennian and Early Carboniferous although terrestrial sedimentation areas gradually increased. Shallow-water carbonate and alternating siliciclastic or carbonate sediments were deposited in the Early Carboniferous outside the ocean basins in the western and southern country's areas. Coal-bearing sediments (the Karaganda and Ekibastuz coalfields) and multicoloured copper-bearing sediments (Dzhezkazgan) were deposited in continental environments. Tectonic movement intensity increased highly in the Middle to Late Carboniferous and resulted in Paleozoic folding and closure.

The main tectogenesis phase occurred late in the Late Carboniferous which resulted in active folding and orogenesis, and granite intrusion to which many of metalliferous deposits of Central and Eastern Kazakhstan are related.

Continental volcanism was very active in the Permian and Triassic during which time both the western Beltau-Kuraminsky and south-eastern Balkhash-Ili (or Cisbalkhash-Ili) belts were formed. Multicoloured molasse was formed in the western Shu-Sarysay depression during the Permian, and coal-bearing formations were deposited in some grabens in Eastern and North-East Kazakhstan; examples are the Kenderlyk and Pavlodar coalfields.

The intrusion of alaskite or alkaline granite is recorded in some places in the Early Triassic, and trap effusions of basalt took place in the Turgay depression and in the Irtysh area (Irtyshye). The active tectonic-magmatic evolution of the Ural-Mongolian belt was completed, and it was transformed into a stable continental block, the young platform. The paleoids of the Ural-Mongolian belt form a distinct arc, with folded zones of various geological ages which stretch for many hundreds of kilometres and curve from the north to the south and south-east.

North and north-west directions predominate in the north end of the arc while it changes to sub-latitudinal (Mongolian) in its south end.

During the Mesozoic and Cenozoic the western and northern parts of the belt were covered by 2-5 km of platform sediments of marine and terrestrial origin to which deposits of oil, phosphorite, coal, iron, strontium, uranium, bauxite and other mineral resources are related.

Altogether, more than 3,000 occurrences of various economic minerals have been explored in Kazakhstan, with about 815 of them under mining.

2.7.2. Non-Ferrous Metals Ores

Ores out of which sixty chemical elements are extracted are mined out of the Kazakhstan's interior. Complex ore composition and high quality are the valuable features (Fig.2.17).

Copper ores.

Five deposit types are known to exist: copper porphyries, cupriferous sandstones, massive sulfides, scarns and vein-type deposits.

Cupriferous sandstones.

Deposits of this type include Dzhezkazgan, Zhaman-Aibal and the deposits of the Zhelandy group, all of which are located in the Shu-Sarysay basin in Central Kazakhstan. The deposits here are hosted in grey sandstones and conglomerates within Upper Palaeozoic red formations, the stratiform mineralization occurring as lenses and bedded deposits.

The ores are complex, containing an average of 1.24 % Cu with associated lead, zinc, silver and rhenium. Ore minerals include bornite, chalcocite, chalcopyrite, galenite, sphalerite, native silver and lead-rhenium sulfide (dzhezkazganite). Copper, copper-zinc, copper-lead, zinc, lead-zinc and lead ores are all recognised, the copper ore being the most important. The alteration around the ore zones is represented by discolouration of the epigenetic grey colour of the host rocks through the loss of iron, along with the presence of silica, albite, chlorite and sericite.

Potential for new discoveries of cupriferous sandstones remains greatest in Shu-Sarysay.

Five workable fields (Central Dzhezkazgan, Itauz, Kipchakpay, Saryoba, Akchi-Spassky) have been identified and explored in the Dzhezkazgan deposit group. They are bedded in the variegated Dzhezkazgan suite of Middle-Upper Carbonaceous age (700 m in thickness). The mineralization is confined to grey-coloured sandstones, its section is multi-level. The orebodies are laminated, veneer-shaped, banded concordant to enclosing rocks. The ores are complex. The essential minerals are chalcocite, bornite, chalcopyrite, galenite, sphalerite.

The mineralization of the Zhelandy group is monometal (1.0 % Cu). The Tachor, Zhaman-Aibat deposits and several big manifestations are associated with this formation in the Chu-Sarysay depression. Several hundreds of small-scale manifestations along with the Kenek deposit are known in the Tangos depression in the Devonian-Permian red-coloured sediments.

Several hundreds of small manifestations associated with the Paleozoic and Permian-Triassic red-coloured complex are known in the Turgay deflection, Karatau, Ulatau, Sarysay-Tengiz, Aktyubinsk Ural region, Mine Mangyshlak and Caspian depression.

Massive sulfides.

Massive copper-bearing sulfide deposits are grouped on three districts: the Kazakhstan-Irtysh region, the Chingiz Range and the Mugodzhary Mountains. They are found in paleo-volcanic structures represented by lavas and tuff formations, and occur as lenticular and tabular orebodies of massive or disseminated sulfides. Orebody dimensions amount to hundreds of metres in length and tens of metres in thickness.

The Sredneorsky, Domarovsky and Verkhneorsky ore regions are singled out. Copper-pyrite, copper-zinc and zinc-pyrite ores are identified. Some manifestations are also available in the Sakmar and Irgiz zones of Mugodzhary. In the Chingiz-Tarbagay folded system pyrite deposits are distributed in Cambrian, Ordovician and Devonian volcanic rock masses. The

essential minerals are pyrite, chalcopyrite, sphalerite. Single manifestations of pyrite type are known in the North Balkhash region, the Agadyr and Ulutau districts.

The Orlovka and Nikolaevka deposits in the Irtysh district are related to Devonian terrestrial volcanic rocks while the Akbastau, Kosmurun and Mizek deposits in the Chingiz Range are associated with Ordovician volcanic arcs. The Priorsky and other deposits in the Mugodzhary Mountains are located in Lower Paleozoic greenstones. In each case, the ore is similar, being composed of three main types: massive pyrite, disseminated pyrite and vein gold-barite-polymetallic.

The copper content is 1-2%, zinc up to 5-7%, lead 0.5-1%, and gold 1-2 g/t, locally rising by an order of magnitude. The predominant minerals are pyrite, chalcopyrite and sphalerite, and ore structures include massive, breccia-banded, banded and colloform.

Copper porphyries.

Copper porphyries are distributed throughout Kazakhstan, and are usually associated with upper Paleozoic volcanic-plutonic belts or with Early Paleozoic rift zones. The copper porphyries of Central, North-West and Eastern Kazakhstan fall into the former category, while those found in the north of the country and in the Spas district are located in paleorifts.

In both cases, copper mineralization is found in large magmatic structures in which volcanic deposits have been intruded by moderately acid granitoids. Small porphyry intrusions or breccia pipes are surrounded by wide hydrothermal alteration zones, the stockworks being pipe, cup or cylinder-shaped.

The mineralization typically consists of pyrite, chalcopyrite, molybdenite and magnetite, either disseminated or in veinlet systems. The copper content varies from 0.2 to 0.7%, with associated molybdenum, gold, silver, selenium, tellurium, rhenium and, in some cases, platinum.

In some cases a cementation zone has been developed which caused two or three-fold ore enrichment (Kounradsky, Benkalinka, Sokyr). The Mo content is 0.1-0.005 %.

The size of the deposits varies from those like Aktosay, Aidarly, Kounradsky, Boschekul, Koksay, Samarsky, Kaskyrmys and Kokraszhal which have large resources to those like Borly, Kenkuduk and Kaskyrkazgan. Only the Kounradsky deposit out of them is currently in operation. Outlook for discovery of further copper resources of this type is good.

The Chingiz Range and the Mugodzhary Mountains are considered to offer the best promise of new massive sulfide discoveries.

In Northern Kazakhstan some deposits are bedded in Lower Paleozoic rock masses cut by big fractures and younger granitoids (Bozshakol, Odak, Satpak). The orebody shape is solid or hollow cylinder, overturned cone or separate fragments of these configurations.

Scarn deposits.

Of commercial value are vein copper deposits of the Kendyktas Mountains.

Scarn copper deposits are typified by the Sayak group in the Northern Balkhash region which, together with the Kounradsky porphyry copper deposit, provide the feed for the Balkhash Copper Refinery. Other scarn-type deposits include Irisu in the Talas-Alatau Range in Southern Kazakhstan and Karatas in the North-West Balkhash region.

The features of this type of deposit are relatively high copper content (1-3 %) and associated mineralization - 0.01 % Mo, cobalt, 0.5-1.0 g/t of gold, silver, bismuth, selenium, tellurium and iron ore. In some places, molybdenum ore with 0.1-0.2 % Mo, gold-cobalt ore with 5-10 g/t of gold and 0.1-0.2% Co, and borates (10-12 % of boric anhydride) are of independent commercial value.

The Sayak deposit is typical of scarn copper, and is the most important economically. It is located at the boundary between Middle Carboniferous limestones, interbedded with tuffaceous mudstone and sandstone, and Late Carboniferous granitoids. Faults that run through the zone are often filled with diorite and porphyritic dykes, scarns and metasomatic mineralization, partly or completely replacing the limestone near-fault zones and igneous contacts.

The ore occurs as lenticular and tabular bodies between the scarn zones, the intrusives and the unaltered limestones. Individual orebodies can be 1,000-1,500 m long, 600-700 m wide and normally 10-15 m thick, sometimes as much as 30-50 m. The predominant minerals in the original ore are magnetite, chalcopyrite, bornite and molybdenite, with occasional pyrite, pyrrhotite, cobaltite and boron minerals. The ores can be massive, in stacked veins or disseminated.

Outlook for further discoveries of scarn copper deposits is good, promising results having been achieved from drilling at a depth of 600-1,500 m in the Sayak area and at the Irisu copper-magnetite deposits in the Talas-Alatau Range.

Of commercial value are vein copper deposits of the Kendyktas Mountains. They are represented by echelon-like steeply-dipping zones composed of quartz-calcite aggregates.

Vein copper deposits.

The Chatyrkul and Zhaisan deposits in the Kendyktas Mountains in Southern Kazakhstan are representative of this type of mineralization, being located in the central part of the Chatyrkul Caledonian granite massif. The Chatyrkul deposit consists of three large vein systems hosted in extensively hydrothermally altered syenodiorites and granites. The veins dip at 45-80°, and converge in the southern part of the intrusives.

Ores consist of quartz-sulfide-magnetite, quartz-calcite-sulfide and disseminated-vein assemblages, occurring in lenticular bodies of up to 1,000 m long, 300-700 m wide and 6-38 m thick. The predominant minerals are magnetite, chalcopyrite, molybdenite and uranite. The average Co content is 3.6-4.5 %, but can locally reach 20 %, with 0.02 % Mo, 52 % Fe, 1 g/t Au, and 20 g/t Ag. Rhenium, bismuth, selenium and tellurium are often associated.

The deposit has been explored only to a limited extent, and the potential exists to increase both the reserves and the copper content substantially. About 30 per cent of the currently identified and developed ore reserves are available for open-pit mining.

Lead and zinc.

Kazakhstan has large lead and zinc resources with the main deposit types as follows: stratiform (in carbonate and terrigene-carbonate rocks), pyrite and scarn (in Devonian and Wendian-Piphean stratigraphic levels). The Karatau group of stratiform deposits are localized in the terrigene-limestone-dolomite formation of the Famennian stage (the Mirgalimsay, Achisay, Baizhansay, Shalkiya deposits). Cadmium, barite, along with lead and zinc (4.5 % in total), are of commercial value in the deposit ores. The Atasuy group of stratiform deposits is localized in silicon-carbonate-terrigenic formation of the Famennian stage. The orebodies are laminated beds in conjunction with intersecting veins and zones. The ores are complex, lead-zinc-barite, the total lead-zinc sum is 4.8 %, 30-50 % of barite. The impurity elements are Cd, Bi, Se, Te, In. The deposits of Southern and Central Kazakhstan are related to the Famennian-Tournaisian stage. The ore beds are shaped as heavy lenses, interrupted interformational bodies, intersecting zones. Pyrite-polymetallic deposits are grouped on the oldest Kazakhstan's ore region of Ore Altai.

Altai-type deposits are found in Eastern Kazakhstan, forming the Leninogorsk, Zyryanovo and Irtysh ore fields which have laid the basis for major mining operations. The deposits in operation include Orlovka, Nikolaevka, Kamyshin, Novo-Berezovo, Irtysh, Belousovka, Ridder-Sokolnoe, Tishin, Zyryanovo and Grekhovo. The deposits which have been evaluated but not brought into operation include Maleevka, Novo-Leninogorsk, Chekmar, Artemievka, Yubileino-Snegirikhinsk and Strezhansky. Table 2.10 lists typical grades for these deposits.

The ore is hosted in Devonian volcanic formations, occurring mainly in downwarps in basaltic and rhyolitic lavas, and in limestones and sandstones. Orebodies occur in various shapes, reaching up to 3,000 m long by 100 m thick. Reserves in individual orebodies can be as much as 4.5 mln t. The mineralization includes galenite, sphalerite, pyrite and chalcopyrite, the average content being 0.7-7.4 % Pb, 1.5-11.9 % Zn and 0.1-2.0 % Cu. Gold, silver, cadmium, barite, selenium, mercury, antimony, bismuth, gallium, indium and germanium are often present.

Atasuy-type base metal deposits are found mainly in Central Kazakhstan in the Atasui, Agadyr and Karkaraly ore fields. Deposits in production include Zhairam, Ushkatun, Akzhal and Karagaily while those evaluated but still unworked include Uzynzhal, Besrubinsky and Alashpav.

Deposits of this type are typified by grouping of minerals on clay-siliceous carbonaceous rocks, with a tight spatial association between lead, zinc, barite, iron and manganese ores. The predominant mineral varies at different deposits; hence in the Karazhal deposit iron and manganese are more important, while at the Besrubinsky deposit barite-lead-zinc ores predominate. The lead-zinc ores underlie the iron-manganese ores stratigraphically, the mineralization occurring in lenticular deposits of sedimentary and hydrothermal-sedimentary origin. Metasomatic lead-zinc, barite-lead-zinc and barite ores also occur.

The ores contain barite, galenite, sphalerite and pyrite, the lead:zinc:copper ratio being 1:2:0.1. Individual orebodies measure 700-1,600 m along strike and 200-600 m wide. Their thickness varies from 2 to 100 m and the reserve in individual orebodies can be as high as 5.0 mln t. The lead content varies from 1.5 to 15 %, with that of zinc from 1.0 to 10 %. The other metals normally present are silver, cadmium, barite, copper, mercury, indium, germanium, selenium, and tellurium.

Table 2.10. Metal content and reserves of selected lead-zinc deposits

Deposit	Reserves (Pb)	Reserves (Zn)	Grade, % (Pb)	Grade, % (Zn)
Kamyshin	1,300	6,300	0.40	0.50
Novo-Berezovo	1,900	51,100	0.18	4.89
Irtys	104,900	684,300	0.85	5.53
Berezovo	36,000	123,300	3.64	7.27
Ridder-Sokolnoe	182,900	403,900	0.45	1.16
Tishin	405,800	2,348,500	1.11	6.20
Zyryanovo	541,100	928,300	0.78	1.40
Grekhovo	140,300	424,500	0.51	1.75
Maleevka	413,500	2,748,300	1.19	7.84
Novo-Leninogorsk	446,400	1,174,800	1.44	4.05
Chekmar	711,000	1,941,800	0.80	2.17
Anemievka	—	—	2.77	8.05
Yubileino-Snegirikhinsk	33,900	219,500	0.89	5.87
Orlovka	399,900	1,279,500	1.00	3.42
Nikolaevka	182,000	142,300	0.50	3.77

Deposits in the Karatau district in Southern Kazakhstan are of Mirgalimsay type which is stratiform lead-zinc occurrences hosted in dolomite limestones. Jointing often exercises structural control on ore zones, and deposits frequently exhibit multiple alternation of ore-bearing horizons. Orebodies measure up to 2,000 m along strike and 1,000 m in width, up to 100 m in thickness. Individual orebodies can contain up to 5 mln t. In some places, galenite is the basic mineral where the lead to zinc ratio is 3-4:1 while elsewhere sphalerite predominates. The lead and zinc content is 0.6-4 and 0.9-7 %, respectively. The Dzungar-Alatau district in Southern Kazakhstan is the only location where Tekeli-Kholodny-type lead-zinc deposits have been found. Hosted in dolomite limestones, the orebodies are banded and brecciated, having undergone hydrothermal and contact metamorphism. Lead, zinc, copper, silver, cadmium and

antimony are contained in the ores which have 0.5-2.5 % Pb and 2.5-5.5 % Zn. The individual orebodies contain up to 0.5 mln t.

There is a potential for polymetallic deposits being hosted in Pre-Cambrian metamorphic rocks, although there has been little exploration for them as yet. The Kokchetav district is known to have stratiform copper-lead-zinc mineralization. Other exploration targets include areas where Mesozoic-Cenozoic weathering has produced secondary enrichment above primary ores, and outlook for this type of deposit exists on both edges of the Turgay basin and in the Karatau foothills.

Nickel and cobalt.

Kazakhstan's nickel deposits of nickel-silicate type are predominantly associated with the weathering of ultrabasic rocks. Nickel sulfide deposits have never been discovered in Kazakhstan. About 40 nickel-silicate deposits have been investigated, and nickel is produced from the Kempirsay massif in Southern Ural.

Typically, the nickel-bearing zones form an eluvial blanket over primary rocks and comprise nontronitic (iron-rich clay) and leached serpentine zones. Highest nickel concentrations are associated with nontronite, average values being 1.0-1.2 % Ni and 0.02-0.06 % Co.

A cobalt-nickel silicate deposit has recently been identified at Shevchenkovsky, in the western part of the Turgay basin. The orebodies vary from 1 to 100 m in thickness, containing up to 0.95 % Ni and 0.06 % Co. Other areas of similar nickel-cobalt mineralization are found in the Ekibastuz-Barnaul region, and in the Char and Gomosray ultramafic belts in Eastern Kazakhstan.

Tin, tungsten and molybdenum

Although there is the evidence of historical tin production in several areas of the country, the current output is limited to the byproducts of tungsten and tantalum mining at five locations: Karaoba (tungsten) and Belogorsk, Bakerny, Yubileiny and Akhmetkino (tantalum). Four types of tin occurrence have been identified in Kazakhstan: pegmatites, scarns, greisen quartz stockworks and placers.

Tin ores are identified in the Kalba-Naryn, Kokchetav, Shu-Ili, Sarysay-Tengiz, Ba-Yankol and other regions. There are distinguished cassiterite-silicate, cassiterite-sulfide and scarn-greisen tin-ore formations. Morphologically they are veins, mineralized zones, stockworks. The associate components are tungsten, bismuth, etc. The majority of manifestations are Caledonian, partially Hercynian. Tin placers (alluvial, deluvial) are known in Southern Altai, Northern Kazakhstan, Ulutau. Some of them were mined previously.

Examples of stockwork-type occurrences are the Syrymbet and Donets deposits. Syrymbet, 100 km to the west of Kokchetav in Northern Kazakhstan, is hosted in Middle Devonian granites which have intruded Upper Proterozoic rocks. The unique deposit consists of stockworks of quartz-cassiterite veins with associated tourmaline, topaz, fluorite and sulfides. The average tin content is 0.1-0.5 %. The ore also contains tungsten, copper, bismuth and molybdenum. The primary stockwork is overlain by the weathered crust in which the tin grade is enhanced to 0.23 %. The Donets deposit exhibits a similar structure, and has 0.22% Sn.

Tin-bearing pegmatites are found in the Altai district in the east of the country, tin being produced as a by-product from tantalum and niobium mining at the Bakerny and Yubileiny deposits. The tin content of the pegmatites varies from 0.01 to 2-3 %. Scarn tin deposits have been located in the Shu-Ili district, but have not proved to be commercial. Promising areas for further discoveries of tin mineralization are centred in the Kokchetav and Altai districts. The Ongevsko-Bakerny area of the Central Kalba district also has a potential for tin.

Kazakhstan has the world's largest reserves of tungsten and substantial molybdenum resources. The first discoveries were made in 1936, and until recently all commercial deposits have been comprised of either stockworks or greisen quartz veins. Recent exploration has revealed tungsten-bearing scarns and deposits hosted in weathering crusts.

Above 300 deposits of tungsten ores (hydrothermal quartz-greisen stockwork and scarn-greisen deposits associated with Hercynian postorogenic granites) are known. The ores of the first two types are complex molybdenum-tungsten with associate bismuth, more seldom tin.

Molybdenum, copper, bismuth, besides tungsten, are contained in the scarn-greisen deposits. The 1st and 3rd type deposits have a relatively high WO_3 content (0.25-0.65 %), while the stockwork deposits have a relatively low value (0.1-0.2 %). The morphology of the orebodies is as follows: veins, lenses, stockworks, mineralized zones. There were identified promising stratified metamorphogenic deposits (new for Kazakhstan) of scarnoids with scheelite among the Proterozoic rocks (tactite type) and tungsten-bearing weathering crusts developed in hypogenic ores. Bismuth, copper, zinc, together with tungsten, are contained in the crusts.

Molybdenum ores are concentrated in quartz-greisen and stockwork deposits. It implies that a part of molybdenum reserves is also in copper-porphyry, copper-scarn ores as well as in vanadium-bearing shales (Talas Alatau, Karatau). The molybdenum deposit ores also contain tungsten and bismuth. The morphology of the ore bodies is as follows: stockwork zones, veins, lenses. The average Mo content (%) is 0.15-0.50 in quartz-greissens, 0.05-0.12 in stockworks, 0.005-0.05 in molybdenum-containing copper, 0.02 in vanadium-bearing shales. The major Mo reserves are in the stockwork and copper-porphyry deposits.

The predominant tungsten deposits are stockworks which hold over 90% of the country's tungsten and molybdenum reserves. Tungsten-bearing deposits include Karaoba, Akmaya and Bainazar while those in which scheelite is the main mineral include Bogut (Figure 5.7), Verkhnee (Upper) Katrakty, Batystau and Cherdoyak. Molybdenum-bearing stockwork deposits include Koktenkol and Shalgiya while Boschekul, Kounradsky, Aktogay, Aidarly, Koksay and Borly are copper-molybdenum deposits.

Some of these orebodies (for example, Verkhnee Kairakty, Bogut and Koktenkol) are substantial, typified by containing complex, low-grade mineralization. Bismuth, copper, rhenium, selenium and tellurium are also present. Principal features of this type of deposit are the absence of clear-cut boundaries, the depth of mineralization (up to and in excess of 1,000 m) and the development of low-temperature metasomatism in the surrounding rocks.

Typical of this type of deposit is Verkhnee Kairakty, which is predominantly a tungsten deposit with subordinate molybdenum. The stockwork lies above a leucogranitic intrusion and consists of an elliptical, sheet-like body. The mineralization is contained in exocontact zones, the tungsten content being dependent on veining density. The minerals present include sericite, quartz, feldspar, pyrite, scheelite, tungstenite, bismuth minerals, molybdenite and chalcopyrite. The average content is 0.13% WO_3 , and 0.005% Mo.

Typical of scarn-type tungsten and molybdenum deposits are Bayan in the Kokchetav district, and Severny (Northern) Katpar and the Promezhutochny (Intermediate) Koktenkol Uchastok (Section) in the Dzhezkazgan district. Scheelite and molybdenite are associated with bismuth and copper minerals, with silver, rhenium, tellurium, indium and germanium also present. The composition has 0.2-0.35 % WO_3 and 0.04-0.07 % Mo in average. The Karatas-I deposit in the north-west of the Balkhash district is a molybdenum-rich scarn with the ore containing 0.05-0.7 % Mo and 0.6-0.7 % Cu, which is found in lenses and veins associated with quartz diorites and granodiorites.

Greisen vein tungsten and molybdenum deposits contain a small proportion of the country's total reserve. The deposits are typically small but have higher metal content than elsewhere (0.3-0.8 % WO_3 and 0.14-0.42 % Mo). The veins are usually found above granite domes or within granites proper. In addition to tungsten and molybdenum, tin, bismuth, tantalum, niobium, scandium, silver, selenium and tellurium also occur in this type of deposit.

Tungsten-bearing weathering crusts sometimes overlie scarns and greisen veins, and exhibit enhanced tungsten, bismuth and copper content. Tungsten-bearing placers are also found, but they generally contain only small resources.

Koktenkol is primarily a molybdenum deposit containing 46 per cent of the country's reserves. The stockwork lies within volcanogenic sediments above the Permian granite intrusion. The essential ore minerals are molybdenite, tungstenite, scheelite and bismuth and copper minerals, average metal content being 0.071 % Mo and 0.057 % WO_3 . The molybdenum content of copper-molybdenum porphyry deposits varies from 0.005 to 0.01%.

Titanium

While a number of titanium deposit types are known, only placers and eluvial deposits are potentially viable. Economically expedient deposits occur in the Irtysh, Kokchetav, and Turgay districts, and in the North Aral and Caspian regions.

The magmatic type is a dominating one (ilmenite-titanomagnetite deposits: Velikhovo, Karaoba; titanomagnetite: Masal, Irisuy; schorlomite-ilmenite-titanomagnetite: Krasnomaiskoe). Of narrower distribution are titanium-bearing pegmatites and greisens in granitoids and rutile mineralization in secondary quartzites. Their orebodies are presented as isometric and lens-shaped schlieren and beds of hundreds and thousands of metres in length. The exogenic titanium manifestations are localized near projections of Caledonides and Hercynides. Clay titanium-bearing weathering crusts are developed in gneissic amphibolites, gabbro and granitoids (the Kundybay, Karaotkel and other deposits). The ilmenite content is from tens of kilograms per tonne and more. The orebody form is laminated, the contacts are gradual. In the north and north-west of Central Kazakhstan there are identified and explored complex ilmenite-zircon, zircon-rutile-ilmenite placer deposits where they are associated with buried coastal sands of Mesozoic-Cenozoic mantle (Tobol, Obukhovo, Kumkol, Alasor, Zayachiy, etc.). The ore sands are up to 25 m thick, the shape is laminated, lenticular or banded. Titanium placers are also known in the North Aral region, the Pavlodar Irtysh region and in the Zaisan depression.

In Northern Kazakhstan, Eocene placers extend along the edge of the Kazakh shield from the Ishim River to the Irtysh River. Small and medium-sized deposits of ilmenite-leucoxene-zircon are found, usually close to the surface and 1 to 8 m in thickness. The content is 20-50 kg/m³ of ilmenite and somewhat less for zircon.

Small ilmenite deposits of Oligocene age are found in the Turgay district, with grades of up to 40 kg/m³, and averaging 1-2 m in thickness. Much larger are the Oligocene placers in the Aral region, where the content is up to 50 kg/m³ of ilmenite and 10 kg/m³ of rutile in 5-15 m thick horizons.

Placers in the East Caspian basin are connected with Eocene sands, and are found in synclines and troughs associated with salt dome structures. The deposits are compact and have high ilmenite content with lesser rutile, leucoxene and zircon.

The Shokhash deposit in the Martuk district is the most promising titanium-rich placer in the country. Measuring 4,500 m by 700 m, it is located in a syncline associated with the Shaida salt massif, and represents a near-shore marine placer deposit. There are two ore horizons, of which the upper, 1.0-7.5 m thick, contains 90% of the resources. Average content is 122.5 kg/m³ of ilmenite, 7.9 kg/m³ of rutile, 5.1 kg/m³ of leucoxene and 14.7 kg/m³ of zircon. The content in the lower horizon, 2-8 m thick, is about one-tenth of these.

Kundybay, in the Zhetygara district, is an example of an eluvial deposit, formed through the weathering of primary mineralized rock. The deposit measures 20 by 2 km, with ore horizons of up to 5 m in thickness. The ilmenite content is from 40 to 120 kg/m³ with 2-10 kg/m³ of rutile and 5-10 kg/m³ of monazite. The deposit also contains kaoline and churchite.

Promising areas for placers exist in the Or-Temir-Emba River system, and in the Irtysh River district while the potential for Kundybay-type eluvials exists in the South Mugodzhary, Ulutau and Kokchetav districts.

Vanadium ores are represented by complex titanomagnetite, placer (ilmenite-rutile and magnetite-zircon-ilmenite), infiltration, copper-lead-zinc deposits. They also form independent deposits in black shale rock masses. The V₂O₅ content is 0.1-0.6 % titanomagnetites (Mugodzhary, Transural), and lower in brown iron ores (Ayat, Lisakovsk and other deposits). Vanadium-black shale (coaly-siliceous clay) rock masses are known in North-East Karatau, Talas Alatau, Ulutau, Dombalytau in the west of the Balkhash region. In Talas Alatau the vanadium-bearing bench belongs to the Cambrian coaly-siliceous-shale formation. The V₂O₅ content is up to 3.64-3.93 %. In the Balasaushandyk ore field (North-West Karatau) the V₂O₅ content is up to 1.22 % in individual interlayers of coaly-siliceous-clay shales of vanadium-

bearing bench. The vanadium reserves in the Cambrian shales of Kazakhstan are very significant but they are not involved into mining operations.

Tantalum, niobium, rare earths, strontium

Tantalum and niobium resources occur in both pegmatites and greisen quartz veins, the former being the more important. Economic pegmatite-hosted resources are concentrated in Altai, in the Kalba district of Eastern Kazakhstan where five such deposits have been evaluated.

Tantalum deposits, rare-metal granite pegmatites and rare-metal granites with complex mineralization (tin, niobium, caesium, feldspar, mica, quartz, etc.), are associated with acidic magmatism of Devonian-Carboniferous and Permian ages of orogenic and postorogenic zones. Niobium manifestations are represented by columbite-zircon late magmatic, rare metal-granite (gagarinite-pyrochlore-zircon type), rare-metal pegmatite (pyrochlore-monazite-zircon, monazite-orthite-fergusonite types) and alkaline-feldspar metasomatic (columbite-fergusonite-bastnasite-xenotime-zircon type) formations. Zirconium, rare-metal elements, etc. associate with niobium and sometimes form independent manifestations (scarn, albitite, carbonatite, rare-metal, apatite-greisen, hydrothermal, volcanogenic formations) which are connected with Caledonian and Hercynian magmatic formations. Weathering crusts and deluvial-alluvial placers containing niobium and tantalum are known in Northern and Eastern Kazakhstan.

Typical of the above is the Bakenny deposit which is situated in a vein structure in the central part of the pegmatite belt. The orebody is located at the edge of the Permian granitic batholith, the mineralization distributed irregularly throughout the deposit. Some 70 minerals occur in the pegmatite veins, the main ones being albitite, microcline, quartz, muscovite, columbite-tantalite, spodumene and cassiterite. The average content is 0.0082 % Ta_2O_5 and 0.23 % Nb_2O_5 . In addition to tantalum and niobium, the other minerals produced are beryllium, feldspar, muscovite and quartz.

Outlook for further pegmatite discoveries is high, as even in the Altai district much exploration remains to be undertaken. Other possibilities include albitite-garnet formations in the Kokchetav, Altai, Zharmasaur and Tien Shan districts which, although low-grade, also contain zirconium and rare earths.

Kazakhstan has an excellent potential for the development of rare earths production, with five genetic deposit types identified in the country. Primary rare earth production has yet to commence, output in the past having been obtained from uranium ore processing.

The Verkhnee Espe deposit in the Semipalatinsk district is genetically connected with an alkaline granite mass, and contains niobium, zircon, yttrium, rare earths and beryllium. The deposit although incompletely evaluated, is considered to have the greatest potential. The orebodies are contained in alkaline pegmatites and in fenites, the average content being 0.4% of rare earths, 0.2 % of yttrium and 0.1% of cerium. The main minerals present are zirconium, pyrochlore thorite, gadinolite, monazite and xenotime. Similar deposits are known at Chingiz-Tarbagatay in the Kokchetav district, and in other places.

The other potential rare earth sources of significance include uranium-bearing deposits in the Ciscaspian basin of Western Kazakhstan which also contain yttrium and cerium-group rare earth elements; carbonatite occurrences which contain complex zircon, tantalum, niobium and rare earth mineralization (an example is the Krasnomaiskoe deposit in the Kokchetav district); weathering crusts which contain rare earths absorbed by clays.

Strontium ores are concentrated in sedimentation-diagenetic and epigenetic deposits. Of commercial value are epigenetic deposits (Mangyshlak). The ores are mostly celestite which implies a barite impurity; they are bedded among Miocene clay-carbonate sediments as layers and lenses of 0.5-8.0 m in thickness and up to 10 and more km in length.

Kazakhstan possesses considerable strontium resources, although there are no mining operations at the moment. Six deposits have been delineated in the Mangyshlak Peninsula in the west of the republic. One, the Auyrtas deposit, has been evaluated.

Here celestite is contained in lenticular and interbedded deposits within Upper Miocene coquinas, marls, clays and sands. The ore horizon lies on the base of shelly limestone, and

consists of a sheet-like deposit of some 10 km in length and an average thickness of 4 m. In addition to large celestite reserves, the deposit also contains significant barite resources. Lying within 25 m from the surface, and virtually horizontal, it has a good potential for supporting open-pit mining operations.

Aluminium ores

Bauxite deposits are related to a single platform type and are connected with Mesozoic-Cenozoic continental sediments of the Epi-Hercynian platform of Central Kazakhstan. In Kazakhstan bauxite accumulation took place from the Upper Triassic to the Paleogene inclusive.

Economically important bauxite deposits are found around the edges of and in the uplift zones of the Turgay basin. The Arkalykskol, Krasnooktyabrsk, Ayat and other deposits are the main raw materials base of the Pavlodar Aluminium Plant.

Most of them are platform-type deposits resulting from Cretaceous-Paleogene lateritic weathering and formation of continental sediments. Viable deposits are eluvial-sedimentary and fall into two categories: karst which comprise 95% of Kazakhstan's reserves, and slope-morphological.

Bauxite production is centred on the east and west edges of the Turgay basin. In the West Turgay area 12 karst deposits have been delineated, with six in the eastern Turgay area. One viable karst deposit is known in the central Turgay basin, and further two in the Mugodzhary district, but these have yet to be developed.

Kazakhstan's karst bauxite deposits are usually compact, up to 50-60 m thick, and suitable to open-pit mining. The deposits are located along the boundaries of limestones and alumino-silicate rocks, and are represented by iron-kaoline-gibbsite formations.

A typical example of the karst deposits is the Krasnooktyabrsk property in the western Turgay bauxite zone. Bauxite is found at the boundary between carbonates and volcanic rocks in which a thick weathering profile has been developed. The karst holes in the limestones were filled with clays and bauxite.

The orebodies are linear, up to 1,000 m long and 100-200 m wide. The bauxite thickness is 50-60 m. The essential aluminium mineral is gibbsite, with associated kaoline, iron oxide, titanium dioxide and siderite. The average content is as follows: 40-44 % Al_2O_3 , 11.0-14.0 % SiO_2 , the modulus is 3.6-4.1.

Slope-type bauxite deposits, which are widespread in the Central Turgay area and in the Mugodzhary district, are typically thin and of lower grade than the karst deposits, with higher silica content. They are generally unfeasible from a commercial viewpoint. Bauxite deposits are also identified in the Tselinograd, Chimkent and Pavlodar Territories. Bauxites of geosynclinal type are also available.

In Kazakhstan there is a significant outlook for mining deposits of non-bauxite aluminium raw materials (alunites, low-feriferous kaolines, nepheline syenites, etc.).

Two main areas of kaoline occurrences have been evaluated, in the Kokchetav and Mugodzhary districts, where commercial eluvial deposits have been formed through weathering of acid and intermediate intrusive rocks. Evaluation has been carried out on the Alekseevka and Eltay deposits in the Kokchetav region, and on the Soyuzny, Yaroslavsk and Koshensay deposits in the Aktyubinsk region. The proven reserves of primary kaoline total 940 mln t, with the Kokchetav and Aktyubinsk districts holding 400 and 540 mln t, respectively.

Alekseevka contains high-grade kaoline in 18 beds which vary in areal extent from 20,000 to 2,500,000 m^3 . The average thickness of the kaoline layer is over 21.9 m, with less than 5 m of overburden. Kaoline is derived from the weathering of plagiogranites and diorites. In terms of iron and titanium oxides content, the quality of kaoline is comparable to that developed in West European countries, and while finely dispersed mica in the final concentrate restricts the use of this type of kaoline in ceramics, it makes it eminently suitable for paper coating.

Soyuzny was formed through the weathering of granodiorites, resulting in a kaoline deposit which measures 4,300 m long, from 250 to 1,700 m wide and 13-14.5 m thick beneath 5

m of overburden. Kaoline from both Soyuzny and Yaroslavsky is suitable for ceramics production.

Kazakhstan has a good potential for further discoveries of high-quality kaoline in both the Kokchetav and Mugodzhary districts. The former already has a kaoline industry aimed at producing paper coating and filler-grade material, while the latter has the potential for producing high-quality kaoline needed for ceramics production, for domestic use and for export.

Gold

Gold deposits occur throughout Kazakhstan, particularly in the eastern and northern regions. Geologically, the republic possesses nearly all types of the precious metal resources, except gold-bearing conglomerates. The various types of gold resources are grouped on regions, including gold-rich sulfides, scarn deposits and epithermal gold in the east, gold-bearing quartz in both the north and south, and pyritic gold in Central Kazakhstan. There are estimated 15-20 large or world class gold deposits in Kazakhstan, in addition to hundreds of small and medium-sized occurrences.

Endogenic gold-bearing deposits are distributed in Paleozoic rock masses. Exogenic deposits (for the most part, alluvial Quaternary placers) are arranged in foothill valleys, more seldom in plain river valleys. Placer manifestations of Cretaceous-Paleogene age are known. Endogenic deposits are presented by gold-quartz, gold-sulfide, gold-scarn, gold-metasomatic (bersite, listvenite), gold-quartz-adular, gold-sulfide-quartz, gold-sulfide-carbonaceous formations. The gold probe is from 450 to 900, and higher in oxidized ores. The orebodies are veins, lenses, lenses of complex configuration, linear zones, stockworks, etc.

The basic gold-ore mineralization took place in the orogenic and postorogenic stages of the regional development. As to formation time, gold was settled in the Pre-Cambrian period (Ulutau) but the main part of the deposits was generated in the Caledonian and Hercynian metallogenic epochs.

In gold-containing complex deposits gold is encountered primarily as fine-dispersed inclusions in sulfide minerals and is extracted as by-product.

There have been gold mining operations in Kazakhstan since the Stone Age, the earliest open pit workings having been dated to 4,000 B.C. Following a long gap, in 1725 the production was resumed from copper-gold ores in the Altai district, and the discovery of alluvial gold in the Aganakty River valley in Eastern Kazakhstan in 1778 prompted production from placers in the Altai rivers. By the start of the 20th century, gold output was around 2,500 kg per year.

Since the 30s, there has been systematic prospecting for gold deposits throughout the republic, and the Kazzoloto and Altaizoloto enterprises were established to produce gold in the north and east of the country, respectively. In the early 90s they were combined to form the Kazalmazzoloto organisation which in 1993 was reorganized into Altynalmaz, the national gold company. Altynalmaz is focused on gold production from primary deposits, by-product gold from polymetallic mines being the responsibility of other organisations.

The main types of primary gold deposit found in Kazakhstan are quartz veins, stockworks, and mineralizations associated with black shales, which hold about 65 per cent in total of the republic's gold resources. Gold deposits associated with surface weathering and recently identified are believed to hold a great potential. Alluvial gold deposits are of limited significance.

Vein quartz deposits

Typical of these occurrences are the Akbakay, Beskempir, Akbeit, Aksu and Stepnyak deposits which are associated with small diorite or granitodiorite intrusives. The mineralization is restricted to the metamorphized contact zone between the intrusives and the country rocks and to the altered rocks nearby.

The orebodies consist of quartz veins and vein zones with low sulfide content. The gold content varies from a few to hundreds of grammes per tonne: the gold distribution within the veins is heterogeneous, and the gold to silver ratio varies from 1:2 to 1:50.

A typical example of this deposit type is Akbakay, in the Shu-Ili gold belt of Southern Kazakhstan. The mineralization is hosted in Upper Ordovician sediments intruded by granodiorite massif. Lamporphyre and porphyry dykes play an important role in the ore control and distribution.

Two series of fault-controlled quartz veins occur, dipping at 70-80° and 25-40°. Gold occurs native and in association with sulfides, the content ranging from 7.8 to 17.6 g/t.

Other potential areas for discoveries of this deposit type include areas around Akbakay in the Zhalaier-Naiman and Sarytum districts of Southern Kazakhstan, and in the Aksu-Bailustay district of Central Kazakhstan. Near-surface gold-silver mineralization potential exists in the south, as well as in the North Dzungar and North Balkhash districts.

Black shale associations.

Gold mineralization occurs in association with black shales in Lower and Middle Carboniferous sediments intruded by small diorite and porphyry bodies. Discrete orebodies with high carbon content are found in folded and metamorphized rocks, the mineralization being associated with pyrite and arsenopyrite. Delineation of the orebody limits is possible using assay data.

Gold is finely disseminated within sulfides, with the content ranging from 4.6 to 9.6 g/t. Antimonite is sometimes present, and the ores can be difficult to process because of arsenic presence.

Deposits of this type include the Bakyrchik, Bolshevik and Vasilievka properties. The Bakyrchik deposit, located in the Kyzyl folded district of the West Kalba gold belt in Eastern Kazakhstan, occurs in Lower and Middle Carboniferous sediments intruded by porphyry dykes. The host rocks have been extensively altered to schist, with some silicification and sericitization. The orebodies occur as bands and lenses, with an average content of 8.4 g/t; assaying is required to determine orebody limits.

Other areas with this deposit type potential include the Kyzyl, Akzhal-Bokon, Murur and Zhanan-Chinrau districts of Eastern Kazakhstan, black schists of the Kokchetav massif, and carbonaceous formations of the Shu-Ili gold belt in the south of the country.

Stockworks

Gold-bearing stockworks are generally contained within diorite or granodiorite intrusive bodies, with gold occurring native in quartz veins or in association with sulfides. Arsenopyrite, pyrite and chalcopyrite are commonly present, with galenite, antimonite, grey copper ores and bismuth also found. The gold content varies from 3.6 to 7.0 g/t, and the ores are often difficult to be processed because of arsenic presence. The Vasilkovo deposit, on the northern margin of the Kokchetav massif in the North Kazakhstan gold district, is typical of this type of occurrence. Contained in Ordovician gabbro-diorites, the deposit occurs at the intersection of two major faults. The arsenic content varies from 1.28 to 8.5 %, and two distinct types of gold mineralization are found.

Uranium

Kazakhstan is one of the principal areas of uranium resources in Asia, the country holding an estimated 65 % of the total resources of the former USSR. The current production is about 40 % of the CIS total. Two types of uranium deposits have been located: hydrothermal veins and sedimentary hosted. Hydrothermal vein deposits have been discovered in the Kokchetav massif in Northern Kazakhstan, and are associated with linear zones of alkaline and acid metasomatism in Devonian volcanogenic-sedimentary complexes.

The principal source of uranium is from sheet-infiltration deposits contained in Mesozoic and Cenozoic platform sediments in Southern Kazakhstan. Two large uranium-bearing provinces have been discovered in which the ore occurs in sheet-like form in aleuinite sandstones. The deposits were formed at the coincidence of acidic and alkaline geochemical barrier zones in the path of underground water migration.

In the Shu-Sarysay district, almost all of the deposits are confined to Paleogene and Upper Cretaceous sediments, forming up to six ore horizons separated by clay strata. In the Syr-Darya district, deposits occur in Lower Cretaceous, Upper Cretaceous and Paleogene sediments, of which the Upper Cretaceous ones are the most productive. The uranium content is about 0.1% throughout, and the minor constituents include rhenium, scandium, yttrium, selenium and rare-earth elements.

The favourable geological conditions in both districts mean that uranium can be produced by in-situ leaching with minimal environmental impact.

2.7.3. History of Non-ferrous Metals Ore Mining

The history of mining and metals production in Kazakhstan dates back to the period prior to the 2nd millennium B.C., by which time the area was already one of the key centres for Cu-Sn bronze output in Eurasia based on numerous local copper deposits (Dzhezkazgan, Kenkazgan, Altyn-Tyube, etc.) The mining scale in Dzhezkazgan and Kenkazgan reached approximately 1 mln t and 800,000 t, respectively. Oxidized copper ores were mostly mined. Workings are represented by openings of up to several hundreds meters long, small mines, adits and trenches. Ancient mining operations of tin ores (cassiterite) are known first of all at deposits of the Kalba and Naryn Ranges in Ore Altai. They are also dated by the second half of the 2nd and the beginning of the 1st millennium B.C. Copper and tin mines were operated by the population of the Andron cultural-historical entity. Markings of developed metallurgical operations are often encountered in the territory of their settlement (Atasu, etc.). At the same time a significant gold output took place. Cutdown in copper ore mining was stated at the beginning of the 1st millennium B.C. owing to commissioning of numerous iron ore mines.

Archeological digging led to the discovery of Dzhezkazgan, an ancient copper mine of the Late Bronze epoch, in the north of the Betpak Dala desert. The copper ores in the oxide enrichment zone were mined in which malachite and partially azurite dominated. They were extracted by openings of up to 500 m long, 140 m wide and 17.5 m deep. Thirty-fifty thousand tonnes of copper were melted. The most active mining operations were carried out in the second half of the 2nd millennium and at the beginning of the 1st millennium B.C.

The relics of ancient mining provided a guide to later exploration, and by the 19th century a number of large-scale deposits of various metals have been discovered. The 18th and 19th centuries marked the start of industrial mining of Kazakhstan's minerals, based on deposits of copper, lead, gold and silver which were found both by commercial circles and local people.

In connection with joining of Kazakhstan to Russia and working of non-ferrous metal ores and gold deposits in Eastern and Central Kazakhstan which began under the decree of Peter the Great, mining of ore deposits in the north-west of Altai started up in the 1st half of the 18th century.

In the 2nd half of the 19th century the interior of Central Kazakhstan was mined by S.Popov. an industrialist who arranged several mines (at the Berkara, Kushoka, Kzyl-Espe, Besshoka deposits, Maikyuben coal mine, etc.) and a smeltery in the Kuu tract. From the middle of the 19th century the mining of Karaganda's hard coal began, with that of oil in Embelate in the century. In the end of the 19th century and at the beginning of the 20th century small and medium-size mines, gold pits and hard coal fields were in operation throughout the Kazakhstan's territory, with their significant part being in the hands of foreign concessionaires in 1905-1920.

In the 1920s, responsibility for both exploration and mining passed under state control, with high priority afforded to mining of mineral deposits. Local geological organisations were

set up with the responsibility for geological and geophysical surveying, prospecting and exploration.

Deposits in Altai, Dzhezkazgan, Karatau, an open pit at the Kounradsky deposit, a copper smeltery at Balkhash operated in the pre-war 30s.

The first copper porphyry bed discovered in the Soviet Union was located at Kounradsky. In 1928 the Balkhash Mining & Processing Plant, which was constructed on the basis of this deposit, produced its first ore. The Dzhezkazgan Mining & Metallurgical Plant was built after World War II and is now the largest CIS copper producer.

During World War II manganese ores of the Dzhezkazgan-Ulatau region, chromites of the Kempirsay deposits, tin-tungsten ores in Kalba and Central Kazakhstan, a number of lead-zinc deposits in Southern and Central Kazakhstan were actively mined.

At present Kazakhstan is one of the most developed regions in the field of mineral products for non-ferrous metals industry.

The level of geological, geophysical and geochemical knowledge of Kazakhstan is satisfactory. Annotated geological and geophysical maps are available for the whole country at scales of 1:200,000, 1:500,000 and 1:1,500,000, and small-scale tectonic, metallogenic, paleogeographical and other maps have been published. Over 40 per cent of the country's territory are covered by surveys at 1:500,000, these being primarily the areas of metalliferous potential in Central, Southern, Eastern and Western Kazakhstan. Today Kazakhstan produces about 4.4 % of the total world copper, and 29 % of the CIS copper output.

2.7.4. Mining & Metallurgical Industry

Kazakhstan's mining and metallurgical complexes occupy a key position in the country's industrial sector due to their economic significance. There is also an extensive oil and gas industry. The ratio of the Kazakhstan's mining industry is about 15 per cent of industrial output. Surface workings were found near extensive copper, gold or polymetallic deposits delineated by drilling in modern times. Exploration geologists still use the occurrence of ancient workings as a guide to the possibility of orebodies being found at depth nearby. Copper, copper-lead and lead deposits such as those at Dzhezkazgan, Kurgasyn, Berkara, Uspensky, Aleksandrovka, Chatyrkul, Maikain, Tekely, etc. were discovered by following the evidence of such prehistoric workings.

Twenty per cent of ore are mined by an open-pit method and 80 per cent by an underground one.

The Kazakhstan's reserves of specific minerals are frequently close to the top of the world "league", in terms of actual output Kazakhstan falls into the range of 10-20 in the table, indicating the excellent potential for expansion of the mining industry. The majority of reserves is contained either within existing operations or in deposits ready for exploitation. Table 2.11 shows the status of Kazakhstan's mineral reserves on a product-by-product basis.

The Kazakhstan's non-ferrous metals sector is one of the largest industrial contributors to the country's economy. It is divided into seven subsectors which comprise 28 large production organisations. Kazakhstan's non-ferrous metal products are of world standard, and the republic currently exports them to over 30 countries.

The *copper* subsector is centred on two production complexes, Dzhezkazgantsvetmet NPO (Scientific & Production Association) which comprises open pit and underground mines, concentrators and a smeltery, and Balkhashmed PO (Production Association), with similar facilities. Finished products of these operations include refined *copper*, *sulfuric acid*, *lead*, *bismuth*, *gold and silver*, *molybdenum* concentrate and calcium molybdate.

Table 2.11. Status of commercial mineral deposits in Kazakhstan

Mineral	Total	Number of	Deposits	Deposits	Other
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	number of commercial deposits	deposits mined	ready to be mined	with proven reserves	commercial deposits
Titanium	5	-	-	5	-
Lead/zinc	58	29	4	15	10
Copper	74	25	9	27	13
Aluminium	22	7	1	2	12
Nickel	31	13	11	2	5
Tungsten	12	2	-	4	4
Molybdenum	26	7	3	12	4
Tin	6	2	1	3	-
Tantalum	12	4	-	8	-
Gold	190	65	8	55	62

The *lead-zinc* subsector encompasses ten integrated mining and processing complexes, the biggest amongst them are the Leninogorsk and Irtysh Polymetallic Works, the Syryanovo Lead Plant, the East Kazakhstan Lead & Chemical Plant and the Zhezkent Mine & Concentrator (Mining & Dressing Plant). In Central Kazakhstan, the production operations are centred on the Zhairem, Karagaily and Akchatau Mines & Concentrators, and in the south at the Tekely Lead-Zinc Plant and the Achisay Polymetallic Works. There are also three non-ferrous smelteries, in Leninogorsk and Ust-Kamenogorsk, where they are constituents of lead-zinc complexes, and at the Chimkent Lead Plant. These plants can process hundreds of thousands of tonnes of lead and zinc concentrates annually, obtaining raw materials produced from lead, lead-zinc and copper-zinc ores, both local and imported, and from secondary resources.

Bauxite is produced by the Krasnooktyabrsk and Turgay Mining Works and is processed at Pavlodar. Gold production is the responsibility of the Altaizoloto, Kazzoloto, Bakyrchik, Akbakay and Vasilievka Mines & Concentrators, and of the Maikainzoloto Integrated Complex. Tungsten and molybdenum are produced at the Akchatau Mine & Concentrator. Rare metals and uranium are produced by the Belogorsk Mine & Concentrator and by the Ciscaspian and Tselinny Mining & Chemical Complexes with rare metals being smelted at Irtysh. The Ust-Kamenogorsk Titanium-Magnesium Plant is amongst the world's largest.

Most of the country's coal production comes from two large associations, Karagandaugol and Ekibastuzgol. Oil and gas production is the responsibility of six companies, which are located in Aktau, Atyrau, Kulsary, Aktyubinsk and Kzyl Orda.

Copper

Kazakhstan ranks seventh amongst world copper producers, with 17 deposits in active operation, three being copper mines and the remainder being copper polymetallic operations. In 1992 domestic consumption amounted to just 8% of output, with 22% exported to the other CIS countries and 70 % to other countries.

The copper industry is presented by the Dzhezkazgan and Balkhash Mining & Metallurgical Complexes, Zherikent Mine & Concentrator, Eastern Kazakhstan Copper & Chemical Complex, Bozshakol Mine & Concentrator, Irtysh Smeltery, etc. Copper ore is mined both by underground (50 %) and open-pit methods.

There are two main areas of copper production, Northern Balkhash and Betpak Dala. Two large copper mining and smelting complexes have been established in the centre of the country, while there is also a group of smaller polymetallic mines and a smeltery in the Ore Altai district. Huge copper deposits, including those at Dzhezkazgan and Kounradsky, have been mined for years.

The Dzhezkazgan Mining Complex is the country's largest copper producer, working cupriferous sandstone deposits. It comprises three underground mines, two open pits, three

concentrators and a smeltery. In 1992 the complex produced 200,000 t of refined copper and increased copper exports from 35,000 to 115,000 tpy in 1987-1992. The ore has up to 1.0% Cu, the deposits are suitable to large-scale mining and the recovery plant yields high-grade concentrates. A new underground mine, Annensky, was to begin production in 1994. The Severny (Northern) mine consists of two open pits which exploit the Zlatoust-Belovsky and Akchiy-Spassky deposits. The total output of the mines is 4.7 mln tpy from shovel-and-truck operations. The underground mining capacity is 28.5 mln tpy from the Vostochny (Eastern), Yuzhny (Southern) and Zapadny (Western) deposits. The Complex will mine the Annensky deposit and the underground sections of the Akchiy-Spassky deposit. The trackless mining methods applied include room-and-pillar and panel pillar sloping, the equipment used includes foreign-made drills and load-haul-dump machines.

The first concentrator processes copper, complex and lead sulfide ores, and has a design capacity of 8.1 mln tpy. The second plant processes copper sulfide and oxide ores, and has a capacity of 14.2 mln tpy while the third one processes copper-lead ores and has the potential to treat copper-lead-zinc and lead-zinc ores if necessary. Its design capacity is 4.1 mln tpy.

The smeltery has a design output of 265,000 tpy of refined copper, with a purity of 99.99 %. The complex produces blister, cathode and refined copper, with byproducts including sulfuric acid, lead, gold, silver, rhenium, nickel and cadmium in dusts, cakes and slimes.

The operating company, Dzhezkazgantsvetmet, is now evaluating the possibility of recovering underground pillars using open pits, as the ore tied up in gob areas accounts for about 20 % of the total Dzhezkazgan reserve.

With the operations to the north of the Balkhash Lake, the country's other copper producer, Balkhashmed, mines the Kounradsky, Sayak I & II and Tastau deposits at a complex consisting of three mines, copper and molybdenum concentrators and a copper smeltery. Facing the exhaustion of its own reserves, the company now receives copper concentrates from Ore Altai, Central Kazakhstan and other sources.

Though further reserves have been delineated in the Boschekul, Koksay, Aktogay, Aidarly, Chatyrkul, Karatas and Borly deposits, their mining will require huge capital investment. A mine is planned to come into operation at Boschekul in 1996, with Aktogay and Aidarly following by 2000, thus maintaining the full utilization of the Balkhash Metallurgical Plant's capacity.

The Kounradsky open pit has a design capacity of 10 mln tpy which was achieved in the past. More recently the output has declined to between 7.3 and 8.1 mln tpy. Ore and waste are handled by a mixed dump truck and rail haulage method using 40-t and 75-t trucks and 105-t rail wagons.

Output from the Sayak deposits is 3.2 mln tpy from shovel-and-truck operations. Because of orebody morphology, recovery from the scarn deposits is only 56 %. The Sayak and Kounradsky ore is processed at the Balkhash Concentrator, with downstream smelting and refining within the complex. Oxygen-free copper products of the concentrator are of the quality suitable for trading at the London Metal Exchange. In addition, Balkhashmed produces lead, zinc and bismuth from smeltery dusts, gold, silver, selenium and tellurium from refinery slimes, sulfuric acid, magnetite and molybdenum concentrates, and rhenium.

Copper is also produced by the East Kazakhstan Copper Chemical & Metallurgical Complex based on the Ore Altai polymetallic orebodies. They have adequate reserves to sustain production for many years to come. Output from Kazakhstan's copper industry consists mainly of blister copper, with two major companies also producing anode and refined metal. About 10% of the refined copper output is processed to bronze, brass and copper-nickel rolled products.

Nickel and cobalt.

Four mines are currently working nickel silicate ore deposits in Western Kazakhstan; all are associated with the Uralnickel Complex located just across the border in the Russian town of Orsk. The Rozhdestvenskoe, Scherbakovsk, Molodezhny and Kzylkay deposits are all worked by open pits. Additional reserves have been located at the Shevchenkovsky deposit which

contains both nickel and cobalt. The deposit is located 50 km to the south-west of the Zhetugara Mountains on the western edge of the Turgay basin.

Lead and zinc

There are numerous lead-zinc polymetallic mines in Eastern and Southern Kazakhstan which are supported by a lead smelter and two zinc smelteries. Kazakhstan's importance as a base metals source is highlighted by its having accounted for 56% of the CIS zinc ore output in 1991, and 64% of its lead, and it ranks amongst the top five world miners in run-of-mine lead and zinc ore.

Kazakhstan exports 56,000 tpy of lead and 73,000 tpy of zinc outside the CIS. The future of the industry is, however, obscure as few of the mines have above 5 per cent of combined lead and zinc, and unless there are associated precious metals, not all of these mines will be viable in market economy conditions. Production of lead and zinc is the responsibility of 12 mining and processing complexes.

Ust-Kamenogorsk Lead & Zinc Works	(UKLZW)
Leninogorsk Polymetallic Processing Works	(LPMW)
Irtysk Polymetallic Processing Works	(IPMPW)
Zyryanovo Lead Metallurgical Works	(ZLMW)
East Kazakhstan Copper Chemical & Metallurgical Complex	(EKCCC)
Zhezkent Mine & Concentrator	(ZhMC)
Chimkent Lead Metallurgical Works	(CLMW)
Achisay Polymetallic Processing Works	(APMPW)
Tekely Lead & Zinc Metallurgical Works	(TLZMW)
Zhairem Mining & Concentrating Works	(ZhMCW)
Karagaily Mine & Concentrator	(KMC)
Akchatau Mine & Concentrator	(AMC)

LPMW is located in the town of Leninogorsk in Eastern Kazakhstan and obtains raw materials from three ore zones. The Ridder-Sokolnoe zone is worked by three underground mines while the Tishin and Shubin zones each have one underground mine. Development of the Novo-Leninogorsk open pit in the Chekmar district has been delayed because of lack of finance, and production start-up is now expected by 2000.

Chekmar located 45 km from Leninogorsk consists of three deposits, Guslyakovo, Yugo-Vostochny (South-East) and Chekmar. Access is via a dry weather road, and the narrow-gauge Leninogorsk-Sinyushonok railway is 15 km from the site. Overburden stripping and construction of surface facilities is currently under way, with the ore produced being treated at Leninogorsk Concentrators Nos. 1&2. An underground mine is also planned, with a total capacity of 2 mln tpy of ore.

Concentrators Nos. 1&2 produce lead, zinc and copper concentrates. Selenium, tellurium, thallium and mercury are associated with zinc concentrate while cadmium, indium, germanium and gallium are recovered with lead one. Gold and silver mainly adhere to the copper concentrate, and the pyrite concentrates are also known for their high content of precious metals. The concentrates are treated at the Leninogorsk and Ust-Kamenogorsk plants while the gold-bearing concentrates are delivered to the Dzhezkazgan Copper Smelter for treatment.

IPMPW operates three underground mines, Irtysk, Belousovo and Novo-Berezovo, of which the two latter are approaching the end of their reserves. The company is setting up joint ventures to develop the Yubileyno-Snegirikhinsky and Anisimov Klyuch deposits. The facilities include two concentrators with a combined throughput of 400,000 tpy of gold-bearing polymetallic ore.

ZLMW operates the Zyryanovo and Grekhovo mines and is proceeding with the development of an underground mine at the Maleevka deposit. Its plant produces copper, lead and zinc concentrates. Selenium and tellurium are recovered with copper, cadmium and indium

adhere to the zinc concentrate, and bismuth is recovered from the copper and lead concentrates. The operations currently run at 30-40 % capacity only.

In Eastern Kazakhstan EKCCC mines polymetallic ores containing lead, zinc, copper, precious metals and a range of minor metals from three deposits, Nikolaevka, Shemonaikha and Kamyshin, and develops the Artemovka deposit for production. ZhMC operates a similar deposit at Orlovka and is currently in the process of constructing its own concentrator.

The Nikolaevka open pit commissioned in 1968 has a design capacity of 1.5 mln tpy of ore. Actual production was 1.3 mln tpy in 1991 and 1.1 mln tpy in 1992, the shortfall being largely a result of the limited demand for the types of concentrate produced. The pit, conventional shovel and truck operations, has reached a depth of 180-200 m, with a final design depth of 420 m. The ore is processed at the Nikolaevka concentrator to produce copper-zinc and copper concentrates delivered to the Irtysh and Balkhash smelters for downstream treatment.

In 1992, the output at the nearby Shemonaikha open pit reached 312,000 t of ore, somewhat higher than the design capacity. The mine was put into operation in 1986, and has a design depth of 270 m. The ore is transported to the Nikolaevka concentrator.

In Southern Kazakhstan APMW works the Mirgalimsay, Shalkia, Turlan (Achilay) and Baidzhansay deposits near the town of Kentau. The ores are processed in two concentrators at Kentau and Mirgalimsay where lead, zinc and barite concentrates are produced. Silver is recovered in the lead concentrate. The Achisay underground mine works lead carbonate deposits which ores are used to produce Waelz oxides; the capacity of the plant now significantly exceeds the mine output.

TLZMW produces polymetallic ore from the Tekely, West Tekely, Koksus and Central Suuktyube deposits. The former two have separate underground operations, and the company has its own concentrator for ore processing. The Koksus underground mine is now completing the extraction of the other two deposits.

ZhMCP is located in Central Kazakhstan and operates open pit at the Zhairem and Ushkatyn deposits. The ores are shipped to the Kentau and Tekely concentrators for processing, to produce lead, zinc and barite concentrates.

KMC produces lead and barite from the Karagaily deposit. In addition, the ore contains zinc, copper, silver and cadmium; the operations have their own concentrator.

AMCC operates open pits at the Akzhal lead-zinc deposits, with the output of both lead and zinc concentrates. Precious metals in the ore adhere to the lead concentrate, and cadmium is recovered with the zinc concentrate.

Tungsten, molybdenum, tantalum

Tungsten output is relatively low in comparison to the country's resources of the metal. It is produced by two associations, Kazvolfram and Balkhashmed. Kazvolfram has two mines in the Akchatau district, the Yugo-Vostochny (South-East) one which has been operating since 1941 at the Akchatau deposit, and Zhambyl which has been using the Karaoba deposit since 1951. Both deposits are veined and greisen-type quartz deposits. Kazvolfram produces tungsten, tin molybdenum and bismuth concentrates which also contain the other metals like tantalum, niobium, scandium and tellurium.

Mining projects include opening of mines at the unique Verkhnee (Upper) Kairakty and Koktenkol deposits, and the construction of a pilot plant at the Verkhnee Kairakty stockwork deposit. The ores are complex and, in addition to tungsten, contain recoverable amounts of molybdenum and bismuth as well as a range of minor metals.

The Belogorsk mining complex produces tantalum from three deposits: Belogorsk, Ognevka and Yubileiny. The ore is processed to produce crude tantalite-cassiterite concentrate which is then treated to yield separate tantalum and cassiterite products. The tantalum is recovered at the Ulba Metallurgical Works which also produces niobium from beryl ores found in pegmatite deposits, as pure metal and niobium compounds.

The Belorogsk Complex was the leader in tantalum production in the former USSR. It accounted for about 40 per cent of the total output. The current production is lower owing to demand fall.

Bauxite and alumina

Kazakhstan has two associations responsible for bauxite production, at Arkalyk in the Turgay Territory and near Oktyabrsk in the Kustanai Territory. Bauxite is transformed to alumina at the Pavlodar Alumina Plant, its products being exported to Russia for smelting. The Turgay operations, in the Amangeldy District, covers four deposits: Arkalyk, Verkhne-Ashut, Nizhne-Ashut and Severny (Northern). Currently the Ushtoba deposit containing both bauxite and fireclay, and another, Aktas, deposit are being evaluated. The deposits have limited reserves to afford an increase in bauxite output, but have a sufficient resource of high-alumina fireclay to support the development of the refractory industry. This will assist in supplies of raw materials and finished products to domestic and export markets while there is also an opportunity for their use in ceramics production and as fillers in rubber and plastic making.

The Krasnooktyabrsk operations produce bauxite from the Belinsk and Krasnooktyabrsk deposits in the west of the Kustanai Territory. Open pit mining is applied, the bauxite being mostly of caking quality. The association produces about two-thirds of the raw materials for the Pavlodar Plant.

Gold

Kazakhstan was the former USSR third gold producer after the Russian Federation and Uzbekistan. In 1991 Kazakhstan produced approximately 5.3 % of the total CIS output, and 50 % of silver. Commercial gold mining is carried out in Central and Eastern Kazakhstan. In addition to underground mines, some part of output is provided by diggers' teams and dredge operations.

Gold deposits are found throughout the country, particularly, in the east, south and north. The major gold-mining centres include Akbakay, Aksu, Zholymbet, Bestobe, Maikain, and Bakyrchik. The river beds and terraces of the Dzungar and Altai Mountains have also been shown to contain alluvial gold, and gold is recovered as a by-product of polymetallic ore processing in Eastern Kazakhstan.

In mid-1991 the government established a state diamond and gold fund, and in 1993 a consortium (Altynalmaz), with the purpose of increasing gold production, was set up. A new gold processing plant has been commissioned at the Ust-Kamenogorsk Lead & Zinc Complex. Together with the National State Bank of Kazakhstan, Altynalmaz has drawn up a programme aimed at quadrupling gold production by 1997. This would enable Kazakhstan to have a stable gold reserve for support of the national currency, the tenge, as well as a possibility of encouraging industrial use of gold and of establishing an export-oriented jewellery industry.

Most of the current country's gold output comes from the areas of Northern, Eastern and Southern Kazakhstan, and the Maikain-Boschekul region. The principal producer is the Kazzoloto company which, in 1992, alone produced nearly half of the country's gold. Other companies include Altaizoloto (16% of 1992 total output), Maikainzoloto (15 %), Akbakaisk (12 %), Bakyrchiksk (4 %) and Vasilkovsk (3 %). About 55 % of Kazakhstan's gold are derived from primary deposits, with the remainder coming from the processing of polymetallic ores from the Ore Altai deposits. Smelting of gold concentrates is undertaken at the Balkhash, Chimkent and Ust-Kamenogorsk metallurgical plants.

Kazzoloto operates four mines, Bestobe, Zholymbet, Aksu and Akbeit each of which has its own concentrator. Other deposits mined by this company include Kvartzitovy Gorki, Bailusty, Tokhtarov, Severny (Northern), Karasu, Ushshoki, Dolinny and Pustynny of which the latter three support open pits while the remainder are underground operations. Virtually all the gold is recovered by gravity concentration and flotation.

Altaizoloto produces gold from the Vasilievka, Zherek, Taskora, Bolshevik, Suzdalskoe, Akzhal and Mizek deposits, and from a number of gold placers. Suzdalskoe, Zherek, Akzhal and Bolshevik are open pits, the remainder being underground mines. While easily separable quartz

vein ores are mined in most of the deposits, the Bolshevik and Vasilievka deposits contain gold-bearing sulfides which are further processed at the Akzhal concentrator.

The Suzdalskoe open pit mine is located 70 km from Semipalatinsk and has an output of 100,000-120,000 tpy of direct shipping ores. The mine uses conventional shovels and 40-t haulers to work a steeply-dipping oxidized orebody which varies in thickness from 1 to 20 m. Output is shipped to non-ferrous metals smelteries in Kazakhstan, Uzbekistan and Russia for the recovery of gold and silver. Future plans include the construction of a concentrator on site.

Production from the Maikainzoloto Mining Board's operations comes mainly from open pit mining of the Alpis, Abiz, Souvenir and Mizek deposits. The Maikain operations are underground. In addition to gold, there are recovered silver, copper, zinc, cadmium and other minor metals, together with barite.

Located 320 km from Semipalatinsk, the Mizek deposit contains gold-barite and gold-quartz mineralization. The orebodies consist of a series of steeply-dipping lenses which vary in thickness from 10 to 17 m. An oxidized zone extends to a depth of 40 m. Open pit mining is used, with production in recent years averaging about 110,000 tpy; the planned capacity is 200,000 tpy. Gravity and flotation processes are used to recover gold at the Maikainzoloto's Tortkun Concentrator.

During 1994 at Bakyrchik a company was formed by the Australian firm, Minproc Resources, and Chilewich International Corporation of the USA to work in partnership with Altynalmaz. Located in Eastern Kazakhstan, the Bakyrchik mine was commissioned in 1965 on the basis of a major gold resource. In recent years, it has been producing about 80,000 tpy of gold ore from underground and open-pit operations. At the first stage of the planned expansion, it is intended to increase underground mining to 150,000 tpy, to build a small-scale demonstration plant to treat sulfide ore using the Redox (nitric acid oxidation) process to produce approximately 27,000 oz/y and to develop 200,000 tpy heap leaching or other oxide operations to produce further 11,000 oz/y. A gold refinery capable of producing London good-delivery bars is also planned.

At the second stage of the expansion programme, to be funded in late 1994, the goal is to invest about \$100 million in order to raise sulfide ore output to approximately 1.0 mln tpy and gold output from these ores to 221,000 oz annually. Incorporation of the oxide operation would result in a combined annual output of 230,000 oz of gold.

Production from the Akbakay company is centred on the Akbakay and Arkharly mines, both of which are underground operations. Gravity and flotation are used to produce concentrate from the finer ore sizes, while the remainder is shipped as self-fluxing ore to the Balkhash and Irtysh Metallurgical Plants.

The Vasilkovsky mine is located 17 km to the north-west of Kokchetav and has been under development since 1979. The pilot operations were carried out in 1980-1987, with some 1.5 mln t of ore and 1.2 mln t of low-grade material being mined from an open pit. About 30,000 t of material was stockpiled for potential heap leaching. The project was shutdown between 1988 and 1993 due to financial constraints, work being resumed on the construction of a concentrator in 1993. The mine is a conventional shovel and truck operations, using 75-t haulers. The design capacity is 2.2 mln tpy to be processed by gravity concentration and cyanidation. Full-capacity production is scheduled for 2000 (Fig.2.18).

2.8. Mineral Resources of Uzbekistan [10,23,34,37]

Uzbekistan is situated in the northern and central part of Central Asia. It borders Kazakhstan on north-east, Turkmenistan on south-west, Kyrgyztan and Tajikistan on north-east and south-east, and Afghanistan on south. The area is 477,400 sq km. The population is 19.9 mln people (as of January 1, 1989).

A variety of metals and minerals is produced in Uzbekistan. They include copper, molybdenum, tungsten, uranium, in addition to gold, lead and zinc. The Almalyk Integrated

Copper Complex based on a big open pit is one of the CIS largest. The huge Kalmakyr open-pit reserves amount to 1 bln tonnes of low-grade ore having 0.4 % Cu, plus some molybdenum. In 1990 Uzbekistan accounted for 8 per cent, or 81,220 t of the USSR copper output.

Uzbekistan produces a reported quarter of the former USSR total annual gold output, with about 80 per cent coming from the mines in the Navoi desert in the north-western part of the country. Uzbek officials are actively seeking foreign assistance in order to expand and modernize ten primary gold mining undertakings as the country loses at least 10 per cent of annual gold production owing to waste from the application of outdated and inefficient extraction technology. Leaching process will be used to treat the estimated 165 mln short tons of stockpiled materials at the Muruntau gold mine which gold content is 0.034 ounces per ton.

Mining operations are scheduled to start in the near future at three silver deposits in the Kyzyl Kum area which will mark the first example of silver production in the country. Open-pit mining will be applied with an output of silver, in addition to gold, nickel, platinum and cobalt ore.

More than 850 deposits of 1,600 ore manifestations have been found in the Uzbekistan's interior.

There are essential reserves of natural gas, gold, copper, lead, zinc and tungsten ores, salts, aluminium raw materials, non-metallic building materials.

2.8.1. Deposits of Non-ferrous Metals Ores

There are about 900 deposits and manifestations of *copper ores* of different genetic types. Copper-porphyry deposits in the Almalyk district of the Tashkent Territory are of commercial value. The copper content is as follows: 0.3-1.0 % in the commercial ore, 0.32-3.0 % in the oxidized ore, 0.3-4.0 % in the secondary sulfide enrichment zone, the Mo content is up to 0.01 %. Moreover, the ores contain higher concentrations of gold, silver, rare metals, etc. Manifestations of cupreiferous sandstones of Neogene and Cretaceous age are abundant in the Fergana and Surkhandarya Territories. Copper-pyrite type ore manifestations are available in the south-west spurs of the Gissar Range and Kyzyl Kum.

Lead-zinc ores are presented by plutogenic scarn-hydrothermal polymetallic, volcanogenic stratiform deposits. The scarn-hydrothermal deposits are confined to contacts of carbonate rocks with intrusions of syenite-diorite compositions. The veinlet-impregnated, sometimes massive sulfide ores are composed of galenite, sphalerite, pyrite, chalcopyrite, grey ores, hematite, magnetite. Rare metals, besides Pb and Zn, are available. Commercial volcanogenic stratiform deposits are identified in rhythmically-alternating Devonian volcanogenic-sedimentary rocks. Laminated and lens-shaped orebodies are bedded by galenite, sphalerite, pyrite, more seldom by chalcopyrite, marcasite, covellite, bornite; barite, calcite and dolomite out of non-metallic minerals. Besides Pb and Zn, Ba, S and rare metals are available in commercial concentrations. The Pb to Zn ratio is 1:1.5. The large pyrite-polymetallic deposits in the Lower Carboniferous volcanogenic-sedimentary rocks (the Gissar Range) contain Pb, Zn, Cu, Ag, Bi and rare metals in commercial quantities. The Pb to Zn ratio is 1:2.2. Vein deposits are available in the Kuramin Range.

A problem of the Angren coalfield *kaolines* to be applied for aluminium production was regularly posed.

Primary kaolines bedded in the coalfield soil and secondary kaolines bedded in overburden are used as raw materials for production of cement and ceramic ware, they are also considered to be alumina raw materials in future.

Germanium, which extraction out of flue gas and dust emissions of a power station in operation in Angren is put into practice, is contained in some coal seams.

Above 40 manifestations and deposits of *strontium* ores of sedimentary origin are known. The only commercial deposit has been identified in the Paleocene sulfate-carbonate sediments (the Bukhara Territory).

In Uzbekistan the *gold and silver* ore reserves are available in gold-ore proper and complex deposits where fine Au and Ag inclusions are impregnated into sulfide, more seldom vein minerals and are extracted as associates. Endogenic gold-ore proper and gold-silver deposits are represented by postmagmatic formations of volcanic and plutogenic types. The volcanogenic type of hydrothermal deposits is associated with volcanic and subvolcanic rocks of andesite, trachyandesite and dacite-andesite composition of the Middle Carboniferous-Early Permian age (the Kuramin zone), the plutogenic type in terrigenous rocks is connected with stocks and dykes of diorite-granodiorite formation of the Late Carboniferous-Early Permian age which break the metamorphic coaly shales of the Ordovician and Silurian (the Southern Bukantau, Turkestan-Alai and Zarafshan-Turkestan zones). Free gold accounts for about 70 per cent, the rest is associated with sulfide minerals. The average gold probe is 890-910. The exogenic deposits are alluvial and proluvial, more seldom eluvial Quaternary placers (Fig.2.19).

2.8.2. History of Mineral Resources Mining

Mining of ores out of which arsenic, antimony and other copper-based alloys were produced started in the Bronze Age. Mining of noble metal ores and turquoise has been known since the 1st millennium B.C. Saki tribes used turquoise-encrusted gold and bronze-made arms. Working of tin and magnetite-hematite ores along with tin smelting and ironmaking was attributed to the same time. Specialized smelting centres appeared in the 3rd-7th centuries. In Uzbekistan mining operations feature primitive labour implements, and low-productivity domestic undertakings prevail. For the most part small-scale ores with rich metal content were worked, with mining operations carried out in zones of fragmentation, fractures, thin lenses.

The mining operations peak fell on the 10th-11th centuries. More than 10,000 mines were in operation in the Chatkal and Nuratin Mountains, in Karamazar, the Fergana and Sultanzidag suburbs. They included silver mines: Lashkerek, Kandzhol, Taboshar, Kansai, Kanimansur, Aktepa, Rizak; gold mines: Kyzylalma, Chadak; polymetallic mines: Dugan, Kenkol; iron ore mines: Akhangaraut, etc.; copper mines: Aktau, Sheikhdzheli; lead mines: Uchkulach, Ilanchi; turquoise pits: Ungurlikan, etc. Besides, there were produced copper vitriol, mercury, tin, antimony, resin, asphalt, oil, coal, ammonium chloride, sulfur, mineral paints, potters' clay, alum, serpentine, buhrstone, soapstone, amethyst, various building materials. Open-pit mining was combined with underground working. Mines which depth was over 300 m were equipped with ventilation chambers and sophisticated roofing systems, up to a full set. The mining technology incorporated flame or wedge-hammer breaking, roofing by pillars, timber props, frames, dragnet delivery to hoisting shafts, timber or metallic capstan winding.

Beginning from the end of the 11th century owing to state decentralization mineral mining output fell, and in the 13th-18th centuries mining operations were in depression because of the Tartar-Mongolian invasion. Gold, polymetallic and iron ores together with turquoise, building stone, sand and clay were fragmentarily mined. Only late in the 18th century mining of copper ores, mineral paints, coal, oil and some other minerals was resumed in small proportion. The mining operations were concentrated mostly in the Fergana valley.

2.8.3. Mining & Metallurgical Industry

The proportion of mining industry in the total industrial output of Uzbekistan was 9.9 %. Oil production and non-ferrous metals ores mining were sectors of all-union value in the FSU.

Tungsten (Chargandon, Oigaing, Lyanga, Karatyube) and *tin* (Karnab, Lapas) ore deposits have been mined since the 40s, and by now the greater part of them have been already exhausted. Beginning from the 70s *bismuth* ore is mined at the Ustasay deposit, tungsten ore is mined at the Ingichka and Koitash deposits from the 40s. The mining operations are by an underground method with horizon stripping by adits and shafts. A gob road battery breast-and-

pillar system is applied, mined-out space is supported by pillars. The ore is delivered to local concentrators by dump trucks.

Copper and molybdenum ores are mined at the Kalmakyr and Sarychek deposits while lead and zinc ores are produced at the Uchkulach deposits. The Almalyk Mining & Metallurgical Works carries out open-pit mining operations. The lead-zinc ores are delivered to the Almalyk Concentrator by railway in order to produce metal concentrate. The plant also processes dumps of off-balance ores of the depleted Kurgashinkan lead-and zinc deposit.

Gold ore is full-scale mined in Western and Eastern Uzbekistan by the Uzbekzoloto Complex. The mining operations are open-pit, using shovels and draglines without transportation, flotation dressing is applied. The largest deposit under mining is Muruntau where uranium and tungsten concentrates are produced as by-products. Moreover, gold is extracted out of copper-molybdenum ore (Fig.2.20).

2.9. Mineral Resources of Kyrgyzstan [10, 23, 34]

Kyrgyzstan is situated in the north-east of Central Asia. Its borderline is with Kazakhstan in the north, with Uzbekistan in the west, with China in the south-west and east. The area is 198,500 sq km. The population numbers 3,886,500 people (as of 1/01/84). Bishkek is the capital.

Kyrgyzstan was the USSR principal producer of *antimony and mercury* metal, one of the primary sources of uranium ore and concentrates, and a major supplier of coal for Central Asia. Kyrgyzstan accounted for 55 per cent of the USSR production of mercury which sometimes occurs in conjunction with fluorite. The main deposits are located along the northern foothills of the Alay Mountain Range which extends along the southern regions of the Fergana valley. Kyrgyzstan has sizable reserves of antimony and mercury, in addition to smaller reserves of tin and tungsten.

Other Kyrgyzstan minerals include *gold, lead, salt and arsenic*. Kyrgyzstan recently announced that Canadian Cameco Corp., a big low-cost integrated uranium producer, may soon participate in the mining of the significant Kumtur gold deposit located approximately 50 km from the Chinese border. Kumtur Co., a Cameco's wholly-owned subsidiary, is carrying out a C\$10 mln feasibility study at the deposit and has reportedly confirmed the earlier-made Soviet estimates of a 500-tonne gold reserve. On completion of the evaluation in November 1993, Cameco was to decide whether or not to proceed with raising over C\$300 mln required to mine the deposit. Most of the investments will be needed for construction of a gold mine which could take three to four years to complete.

2.9.1. Geology of Deposits

Tin, mercury, antimony, polymetallic and rare-metal deposits are of commercial value; deposits of pyrite and sedimentary iron ore are available; molybdenum-vanadium mineralization was identified; there are oil, gas and coal fields.

Copper ore is presented by different commercial-genetic types: copper-porphyry (the Taldy-Bulak, Andash, Karakol deposits) and scarn (the Kuru-Tegerek deposit); ore manifestations of cupreiferous sandstones, hydrothermal vein bodies, and as ore zones are usually of small size. The copper-porphyry deposits are associated with intrusions of Paleozoic diorite porphyrites and granodiorites. The Cu content varies from 0.2 to 0.6 %. The associate components are molybdenum and noble metals. Scarn deposits are represented by complex ores with 0.6-1.0 % Cu.

Lead-zinc deposits of stratiform type are abundant in the Hercynian structures of Middle Tien Shan (the Chatkal Range, the Gava-Sumsar region, the Moldo-Too Range). The average Pb content is 2-3 %. Crevice-metasomatic bodies in magmatic sedimentary formations (Boorda, Ak-Tyuz, Granitogorsky, Ak-Kul, Kurgan, Shanyk, Shyrgyi, Arsa, etc.) are widely distributed in some Caledonian structures of Northern Tien Shan which were activized in the Hercynian time.

Antimony ore is abundant in the Chatkal-Kuramin and Fergana-Kakshaal structure-facies zones of Southern Tien Shan. In the former antimony deposits are confined to the Terek-Kassan ore region (the Terek-Say and Kassan deposits), in the latter to the South Fergana mercury-antimony belt (the Kadamdzhay, Northern Ak-Tash and Abshir deposits). The antimony mineralization is controlled by deeply-bedded fractures. The deposits are represented by jasperoid-antimonite ore formation. The essential metallic mineral is antimonite. The Kadamdzhay, Terek-Say and other deposits compose the raw materials base of the Kadamdzhay Antimony Complex. In the eastern district of the Alay Range there is the Irkesh-Savoyarda ore region where antimony-polymetallic mineralization represented mainly by quartz-carbonate-jamesonite ores is mature in steeply-dipping fracture zones among the Silurian-Devonian shales.

Mercury ores mature in the Kyrgyzstan territory occupy the central part of the Central Asian mercury province. The mercury mineralization is located in two mercury belts: Southern Fergana and Zarafshan-Gissar. The South Fergana mercury-antimony belt features the following major mercury deposit types: jasperoid (Khaidarkan, Chauvay), listvenite and carbonate (Aldyr-Koo, Kursala, Birksu, Symap). The mercury mineralization is often associated with the antimony one. The essential ore minerals are cinnabar, sometimes metacinnabarite, livingstonite. Mercury and complex (mercury-antimony-fluorite) ores are distinguished in mining. Kyrgyzstan occupied the leading position in the USSR in explored mercury reserves. The raw materials base of the Khaidarkan Mercury Complex are the explored Khaidarkan, Chauvay and other deposits.

Mono and polymetallic *arsenic ore* deposits and mineralizations are known in Kyrgyzstan; arsenic is available in considerable quantity as impurity in ores of polymetallic and other deposits where it can be extracted as associate to essential components.

Tin ores are available in all the folded regions of Kyrgyzstan. The ores represent virtually any known formation types of tin deposits. The Turkestan Range manifestations, where many hundreds of pegmatite veins containing tin and mica are known, are attributed to the tin-bearing pegmatite formation. The typical representatives of the greisen formation are the Chon-Kyzylsuy deposit in the Terskey-Ala Too Range and the Uzun-Bulak deposit in the Chatkal Range. The greisen body shape is zones, lenses, nests of different size. Wolframite, scheelite and other minerals occur alongside cassiterite. Numerous tin ore manifestations of scarn formation are mature in the western end region of the Kyrgyz range (Beregovoe, Chirkanak and others). Several tens of orebodies are identified in metasomatites by higher cassiterite concentration. Chalcopyrite and magnetite are mature alongside cassiterite. The Chat-Karagay deposits in the Talas Range and the Sary-Bulak deposit in the Kakashaal Too Range are attributed to the cassiterite-sulfide formation. At the Chat-Karagay deposit tin is identified in conjunction with lead and zinc in vein bodies. The Saru-Bulak deposit is of tubular shape (up to 500 m in depth) of fully-oxidized complex (tin, copper, zinc, lead) jacobsonite ores in the Devonian limestones in contact with the like granitoid intrusion. Numerous quartz-tourmaline veins with cassiterite, wolframite, scheelite and fluorite which are developed among granitoids and terrigene formations in the east (in the Sary-Dzhaz tungsten-tin ore region) are attributed to the cassiterite-quartz-silicate formation.

Tungsten ores are mainly represented by two types: contact-metasomatic (scarn) and hydrothermal. The scarn orebodies with scheelite are the most mature in Middle Tien Shan (the Kumbel, Kashka-Suy, Turegelda, Ken-Suy deposits) where they are developed in exo-contact parts of granitoid massifs as lens-shaped metasomatic beds with impregnated mineralization. The hydrothermal tungsten ores (wolframite and scheelite) are associated with tin in the quartz-tourmaline and quartz veins of the south-eastern part of Southern Tien Shan, in the Sary-Dzhaz tungsten-tin ore region.

Aluminium ores are represented by ore manifestations of bauxites, deposits of nepheline syenites, andalusite-sillimanite shales, alunites and kaolines. Middle Carboniferous and Late Triassic-Early Jurassic bauxites are known in the mountain frame of the Fergana valley, in the Turkestan and Alay Ranges.

The ore quality is satisfactory, the silicon modulus is 1.0-12.0. The average percentage in the bauxites is as follows: about 40 % Al_2O_3 , 30 % SiO_2 , 12 % FeO , 2 % Fe_2O_3 . Nepheline syenites are known in all the folded Kyrgyzstan's regions. Nepheline-containing rock massifs have been explored at the Sandyk and Zardalek deposits. The areas of higher alumina concentration (19.2 and 22.6 % at the Sandyk and Zardalek deposits, respectively) are identified; the silicon and alkaline moduli are 2.8 and 0.91, respectively. Andalusite-sillimanite shales are developed among the Proterozoic Talas rock masses but have not been studied as alumina raw materials. Alunites and kaolines are available in many Kyrgyzstan's regions but have not been regularly studied on alumina content (Fig.2.21).

2.9.2. History of Ore Deposits Development

Archeological finds from the ancient mines of Northern Kyrgyzstan testify that mineral deposits were mined in its territory in the ancient epoch and Early Middle Ages (the 3rd-5th centuries). According to written sources, in the mountains, in the suburbs of the Sheldzhi town, situated in the eastern part of the Talas valley, there were silver mines. More than one hundred of Middle-Age mines were identified in this region in the mountains of the Talas Alatau and in the southern slopes of the Kyrgyz Range; there were at least six open pits with large-scale mining (for that time). Openings were filled with account of ore body bedding conditions. The ore extracted was crushed and dressed. Silver was extracted by cupellation. In the Sheldzhi district, besides silver-lead ore, which mining was essential, deposits of native and placer gold were worked (the largest open pit was in the Chonur River head). The Sheldzhi open pits were most actively mined in the 9th-11th centuries. The ore mining went on in the 12th-14th centuries, judging from archeological sources. In the 10th-12th centuries open pits in the mountains of Southern Kyrgyzstan, in the Fergana region, were in active operation. Written sources reported the mining of mercury as well as lead, oil, etc. in this area. Ancient mine openings, slag accumulations and big ore-melting centres were found throughout the whole Turkestan and Alay Ranges. A sophisticated process with sublimation and condensation of mercury metal from ore in ceramic vessels was applied for mercury metal to be produced. Like in the rest regions of Central Asia, the boom in the mining sector in the Kyrgyzstan's territory falls on the 9th-12th centuries. Beginning from the 13th century, a noticeable depression occurred in the mining operations. For the period from the 9th century and up to the 19th century, with some interruptions, the most various metallic and non-metallic deposits have been mined. Copper mining was focused on the deposits of the Chu River basin (for example, no less than 20 tilted pit-like openings of up to 35 m in length were identified at the Bala-Tegerek deposit). The Ak-Tash and Kara-Kyshtan (the Kyrgyz Range) copper deposits, at which ancient mines of 20-60 m in depth were reported, operated. In the Middle Ages lead-silver ore mining increased (the Talas region deposits, the Ken-Shanyk deposits, the Dzhangiz-Archa open pit). Slags were also detected in the Ken-Shanyk region. Mercury, antimony and sometimes arsenic were mined at several deposits of Southern Kyrgyzstan (the Chauvay deposit where ancient adit-like openings were deepened up to 120 m in the mountain slopes, the Galbit-Kamar deposit on the Shakhimardan River, in the Altynbishik Range where ancient openings were noted at an elevation of up to 6 km, in the Adygen Too Mountains near the Birk-Suu River, the Khaidarkan deposit). Gold was mined over the Chatkal River slopes, near Santalash.

2.9.3. Mining & Metallurgical Industry

The proportion of the mining industry in the total industrial output of the republic is 4.8 %. Rare-metal oxides, antimony and its compounds are exported to over 50 countries.

Non-ferrous metal ores have been mined since 1941. From 1942 on the Kadamdzhay *antimony* and Khaidarkan mercury deposits have been in operation. In the 50s the explored

Chauvay mercury, Terek-Say antimony, Ak-Tyuz, Ak-Kul, Boorda, Sumsar and Kiya polymetallic deposits were included into the mining operations.

New *mercury* (Symap, etc.) and *rare metal-polymetallic* (Ak-Tyuz) deposits started up operation in the 60s. The Kadamdzhay Antimony, Khaidarkan Mercury and Kyrgyz Mining & Metallurgical Complexes operate on their base. The Kyrgyzstan's ore deposits were initially mined by an underground method owing to their mining and geological condition features (small scale, rangy relief, dispersion of ore deposits), and by an open-pit method from the beginning of the 50s. Underground stripping is by adits (the Terek-Say open pit), by vertical shafts (the Khaidarkan Complex mines), combined by adits and vertical shafts (the Kadamdzhay mine). The mining systems are shrinkage breast-and-pillar, sublevel undercutting, sublevel caving. The ore is delivered to concentrators and metallurgical plants by dump trucks, exclusive of the Kadamdzhay mine (locomotive haulage).

The Ak-Tyuz and partially Khaidarkan deposits (complex *mercury-antimony-fluorite* ores) are mined by an underground method. The working system is transport, mining equipment is shovels and dump trucks. Methods of joint blasting of embedded rocks and ores, controlled caving as well are applied. The ore is delivered to the concentrator by dump trucks through blending storage yards. The ore is crushed by jaw and cone crushers, ground by ball mills, and dressed by flotation. The monometallic mercury ores are processed by roasting in rotary kilns, with the mercury concentrates processed by electric vacuum roasting and in fluidized bed (Fig.2.22).

2.10. Mineral Resources of Tajikistan

Tajikistan is situated in the south-east of Central Asia. It borders Uzbekistan and Kyrgyzstan on west and north, China on east, Afghanistan on south. The area is 143,100 sq km. The population is 5,112,000 people (as of January 1, 1989).

Mining operations in Tajikistan are active, including a wide range of energy and mineral resources. Tajikistan has a variety of non-fuel minerals, among them, *silver* at the Bolshoy (Big) Kanimansur deposit, *mercury, molybdenum and precious metals* in the North Karamazar Mountains. *Lead, zinc, silver, bismuth and copper* concentrates are processed at the Adrasaman Complex while there exists placer *gold* in the Darvaza district at Yakh-Su and vein gold deposits at Taror in the West Zarafshan Mountains. Antimony output has been particularly high in recent years, ranking second among the fifteen ex-Soviet republics. *Tungsten* has been mined since the middle 40s in Tajikistan where the major ores are scheelite (calcium tungstate) and *copper, with molybdenum and columbium* as by-products.

Tajikistan is one of a few CIS states which export *aluminium*, approximately 150,000 t in 1992. This country accounts for about 15 per cent of the CIS aluminium output and exports amount to more than 60 per cent the country's foreign trade revenues. Aluminium production at the Tajikistan huge Tursunzade smeltery reached an estimated 360,000 t in 1992, slightly below 370,000 t produced in 1991. The Tursunzade plant near the Uzbekistan border has an annual output of 517,000 t, and is now dependent on Russian alumina as Azerbaijan cut down supplies after several payment disputes.

In Tajikistan *gold* (or "tilo" in Tajik) has been mined for centuries though no data on output was ever released by the USSR government. Tajik officials hoped to increase gold output to 1.5 t in 1993 and 4 t in 1994. The 1993 estimate falls short of an official target of 1.8 t of gold.

The primary gold concentrate production centre is the city of Kansay just 40 km to the north of Khojend. The Kansay plant was commissioned in the 1920s for processing of polymetallic ores. In the 80s the plant was retrofitted; the plant now processes only gold ores from placer and vein deposits in the Kara Kum area. The plant has 40 concentrating tables, each with a 3.2 cu m/hour capacity. It is the second largest concentrator in Tajikistan, with the largest near Pendzhikent at Taror in the south-west.

2.10.1. Geology of Deposits

The territory is at the junction of the Ural-Mongolian geosynclinal belt and the Mediterranean Sea geosynclinal belt.

Northern Tajikistan (Karamazar) includes the southern slopes of the Kuramin Range and the Mogolau Mountain. There are polymetallic, gold, silver, bismuth, tungsten, molybdenum ore deposits identified in the region.

North-East Tajikistan occupies the western part of the Fergana intermontane depression. Oil and coal fields are associated with the latter. Central Tajikistan is attributed to Hercynides of the South Tien Shan folded system. Deposits of antimony, mercury, tungsten, tin, gold ores, fluorite and coal were identified in the region.

Deposits of oil, combustible gas, rock salt, celestite, placer gold have been found in South-West Tajikistan. South-East Tajikistan incorporates Pamir where deposits of tin ore, borosilicate, rare metals, magnesia raw materials and gem-stones were discovered.

The main reserves of *copper* ores are connected with polymetallic (Altyn-Topkan, Taror, etc.), tungsten, gold-bearing and copper-bismuth deposits of Karamazar (Kaptarkhon) which contain 0.3-1.0 % Cu. Moreover, in the Darvaza area two stratiform manifestations of cupreiferous sandstones and conglomerates of the Upper Permian age which contain 1-2 % Cu have been identified (Ravnous, Daraitang).

Three manifestations of *nickel* ores are identified in Pamir. The mineralization is confined to hyperbasites. The ores are impregnated massive and brecciated pyrrhotite-violarite composition complex copper-nickel. Besides Ni, Cu and Co are contained.

Lead-zinc ore reserves are associated with complex polymetallic deposits widely distributed throughout the Tajikistan's territory. The major part of the explored reserves is grouped on the Karamazar ore province. The ore fields of Western Karamazar (Aptyn-Topkan, Kurusay, Kansay, etc.) contain mainly scarn-type deposits. The orebodies of lens and column-shaped form with high Pb, Zn and low Cu, Ag content occur in the contact of weakly-acidic granitoids and Devonian carbonates. The essential metallic minerals are galenite, sphalerite and pyrrhotite; minor ones are chalcopyrite, galenobismuthite, etc. Crevice-vein hydrothermal deposit type (Kanimansur, Zambarak, Chukurdzhilga, etc.) with veinlet-impregnated nest and aggregative ores is typical of the ore fields of Eastern Karamanazar. Telethermal deposits (Iokundzh) are typical of Darvaza.

Tajikistan occupied one of the USSR leading positions in *antimony* ore reserves. The deposits and manifestations are confined to the Zarafshan-Gissar mercury-antimony belt. The greater part of them, stratiform beds of laminated lens-shaped form, is connected with brecciated jasperoids and related to the quartz-fluorite-antimonite formation. The ores are antimony and mercury-antimony (the Dzhizhikrut deposit, the Shing-Magiansky deposit group). Of smaller abundance are hydrothermal veined and stockwork deposits (the Konchoch ore field) where Au, more seldom fluorite are available as associate components. Antimony as associate component in complex polymetallic ore is of no commercial value.

Celestite (Sr) deposits were identified in the south-west of the republic.

Tin ores of different genetic types are known in Pamir (Trezubets-Zarechny) and in Central Tajikistan (Maikhura, Tagobikul). Of greatest interest are quartz-cassiterite-sulfide and scarn ore types. Stannite ores (the Kaznok-Mushiston ore field) are typical. Moreover, cassiterite is an associate mineral in some tungsten ore deposits.

Molybdenum ores are available in scarn deposits of the Mogoltau Mountains, in Central Tajikistan and Pamir. Of commercial value are the Yuzhno-Yangikan molybdenum (proper) deposit which column-shaped ore bodies are bedded by molybdenite, pyrite and scheelite as well as the Chorukh-Dairon tungsten deposit where molybdenum-tungsten ores are replaced with copper-molybdenum ores in scheelite scarns from a depth of 100-150 m.

Commercial deposits of *tungsten* ores are concentrated in Karamazar (Chorukh-Dairon, Shaptala) and Central Tajikistan; promising deposits are in Pamir (Ikar). The ores contain 0.25-1 % W and Sn, Cu, Mo, Zn, etc. as by-products.

Deposits of *bismuth* ores are distributed in Karamazar, Central Tajikistan and Pamir. The deposits are represented by two types: scarn (iron-bismuth) and hydrothermal (copper-bismuth with associate Ag and Au). Orebodies as veins, lenses and columns are developed in exocontact parts of granitoid massifs and volcanogenic complexes of dacite-liparite composition. Bismuth as associate component is present in tungsten, gold and polymetallic ore deposits. *Mercury* ore deposits and manifestations are confined to the Zarafshan-Gissar mercury-antimony belt. Mercury mineralization of hydrothermal genesis is localized in contacts of carbonate and terrigenous rocks, in breccia and jointy sections of homogeneous rocks. The ores are mostly mercury-antimony. Morphology and size of orebodies, their quantity within the deposit vary widely. The largest deposit is Kavnok.

Complex deposits of *rare metal* ores are concentrated on Central and South-East Tajikistan. The rare-metal mineralization is associated with pegmatites and zones of albitization and greisenizing in granites. Small ore bodies of various morphology do not form commercial beds.

Aluminium ores are represented by deposits and manifestations of bauxites, alunites and nepheline syenites. Bauxites of Middle Carboniferous and Late Triassic-Early Jurassic age are known in Central Tajikistan and Pamir. Orebodies as nest lenses and seams contain up to 30 % Al_2O_3 in average. Alunite deposits in Karamazar are connected with hydrothermal processing of andesite-dacites and contain up to 26 % Al_2O_3 . The most significant deposits of nepheline syenites are in Central Tajikistan (Gurpa, Tutek). The alumina content in big syenite stocks is 22 %.

Gold ores are concentrated in gold-ore proper and complex deposits. Four gold-ore belts and eighteen promising areas are identified in the Tajikistan's territory. The greater part of the deposits was formed in the Hercynian metallogenic epoch. Exogenic gold-ore deposits proper are associated with alluvial Quaternary placers in mountain valleys and plain river terraces (the Darvaza, Pamir, Zarafshan districts). Endogenic native deposits are presented by six types. The greater part of the reserves is connected with gold-quartz (Karamazar), gold-scarn (Central Tajikistan) and gold-quartz-sulfide (everywhere, except intermontane depressions with gold placers) deposits. Some deposit ores are complex, containing high Ag, Cu and Bi concentrations.

Silver ore deposits are known in Karamazar, Central Tajikistan and Pamir. Orebodies of column or lens shape and vein form contain silver as independent minerals (argentite, pyrargyrite, proustite, virgin silver) and as isomorphic impurity in galenite and bismuth minerals. The deposits are of hydrothermal and scarn origin. All silver deposits proper were mined in ancient times, the silver content in ancient pillars is above 1,000 g/t. Silver as by-product has a commercial value in polymetallic, copper-bismuth, tungsten and gold ores of Eastern Karamazar. Veinlet-impregnated, more seldom nest and aggregative ores form orebodies of crevice-vein type. Silver deposits proper are available in Karamazar, Pamir (Tokuzbulak), etc. (Fig.2.23).

2.10.2. History of Non-ferrous Metal Ore Resources Mining

Neolite marked the beginning of mining metallic ores, and first melting shops appeared in that period. Later on metallurgical operations were proliferated throughout the territory, mainly oxidized ores of copper, tin, antimony and other metals were used for smelting. Mining of gold ore and lazurite in Darvaza and Badakhshan has been known from the 3rd millennium B.C. In the Tajikistan's territory mining industry reached its fullest flower in the 9th-11th centuries which is testified by the markings of ancient mining openings and metallurgical operations in the Karamazar Mountains (Kanimansur - the Mansura mine), in the north-east of Central Tajikistan (the Kondara Ore Gorge, the Koninukra Silver Mine), Pamir, Darvaza ("the Ruby Mountain": Kukhilal, the Lyadzhvardara Lazurite Gorge), etc. Ore mining and metal-

producing operations incorporated excavation of pits; sinking of adits, slopes, shafts; flame and wedge-hammer breaking; roof support by pillars, timber props and frames; ore delivery by leather bags, dragnets, separation grading by crushing and grinding; natural ventilation, lighting with slivers, water reflux, smelting in open-type furnaces. Gold-bearing sand was mined by animal skin washing over the valleys of the Zarafshan, Sauksay, Pyandzh Rivers and in the Darvaza Mountains. About 1,500 open pits and mines with up to 300 sq m chamber area, shafts of up to 200 m in depth were arranged at the Kandzhol silver deposit in Karamazar. The total volume of removed rocks amounted to 3.5 mln cu m. The same scale mining operations were carried out in the area of the Darvaza gold-bearing placers, in the Akdzhilga ore field of Pamir at an elevation mark of 4,000-5,000 m and in other districts. Alongside metallic minerals, different building rocks, mineral paints, glass raw materials, etc. were actively produced which is testified by architectural monuments in Pendzhikent, Gissar, Kurgan-Tyube and other places. In 13th-19th centuries mining arrived to a depression. Scarce local industries: mining of rock salt, iron ore, placer gold in Darvaza, went on functioning. Commercial mining of placer gold was resumed late in the 19th - early in the 20th centuries in a small scale.

2.10.3. Mining & Metallurgical Industry

The proportion of mining industry in the total industrial output of the country is 6.4 per cent (1988).

Tajikistan occupied a significant position as producer of some non-ferrous metals in the CIS and world.

Non-ferrous metal ore mining operations have been on stream since the 1930s, with grouping on the northern and central districts. Beginning from the 40s, the Chalata, Sardob and Altyn-Topkan Polymetallic Mines are in operation in Karamazar which raw materials base is used for the Adrasman Mine & Concentrator, the Almalyk Mining & Metallurgical Complex (in Uzbekistan). The Anzob Mine & Concentrator carry out mining of the Dzhizhikrut antimony ore deposit in Central Tajikistan. The Leninabad Rare Metals Works which made use of the Chorukh-Dairon tungsten ore deposit from the 30s has been operating on the base of the Yuzhno(South)-Yangikan copper-molybdenum deposit since the 60s. The deposits are mined by an underground method.

Separation is performed by flotation in pneumatic and mechanical cells, etc. *Copper, lead, zinc, mercury, antimony* concentrates together with *molybdenum* middlings were delivered to Kazakhstan and other places. *Bismuth* concentrate was processed by the Isfar Hydrometallurgical Plant.

In Tajikistan commercial ore mining has been on since the 50s by diggers' artels (teams) in the Darvaza and Rankul mines. From 1968 on *gold*-bearing deposits have been explored and mined by the Tajikzoloto Mine & Concentrator. The native deposits of Northern and Central Tajikistan are mined by underground and open-pit methods, respectively. In Southern Tajikistan placer gold is mined by an open-pit method, with dredges applied in 1972-1980 which were later on replaced by hydromonitors. Small-scale placers are mined by the Pamir diggers' artel. Battery, level caving, and pillar-and-chamber systems are applied in underground mining of gold-bearing quartz ore. The ore is broken in shallow blastholes, delivered by cars to the surface with downstream gravitational and flotation separation and cyaniding (Fig.2.24).

2.11. Mineral Resources of Turkmenistan

Turkmenistan is situated in the south-west of Central Asia. The country borders Kazakhstan on north, Uzbekistan on north-east, Afghanistan on south-east, Iran on south and is washed by the Caspian Sea in the west. The area is 488,000 sq km. The population is 3,534,000 people (as of January 1, 1989).

The most important mineral resource are oil and combustible gas, mining & chemical and other industrial raw materials, as well as nonmetallic building materials. The mineral product base of the non-ferrous metals industry is not developed, and, consequently, the industry is small-scale.

Copper ore manifestations are represented by sedimentary and hydrothermal genetic types. The former is distributed in the Gaurdak-Kugitang district and is confined to Upper Jurassic and Lower Cretaceous red colours. The mineralization forms lenses of 0.1-0.15 m in thickness, more seldom up to 1.5-5 m. Horizons are traced throughout the district territory. The essential rock-forming minerals are malachite and azurite. The Cu content is 0.15-0.58 %. The numerous hydrothermal manifestations in Western Kopetdag are represented by small veins with small Cu concentration and are associated with barite-witherite and lead-zinc manifestations.

Small-scale *lead-zinc* ore deposits and numerous ore manifestations are known in different republic districts. The Kugitang and Bazartyube deposits are bedded in Upper Jurassic limestones. Beds of 160-1,200 m in length have the form of slightly-tilted ore shoots, more seldom lens-shaped or crevice-vein. The ores are almost fully oxidized. The essential metallic minerals are smithsonite, cerussite, etc. The average Pb and Zn content is 2.77-6.21 and 1.7-4.08 %, respectively. The ores also contain Ag.

The sand massifs of Meshed and Geirdzhany, the Tedzhen and Mergab River deltas, the Kushka and Kashana interfluvium and the Kushka down-stream are famous for *titanium-zircon* placers with commercial concentrations of ilmenite, zircon, leucosene.

Molybdenum ores of hydrothermal genesis are known in the zone of tectonic dislocation in the Upper Jurassic limestones of Bolshoy Balkhan. The Mo content is more than 1 %. Commercial Mo concentrations have been identified in the Triassic sandstones of the Tuarkyr district. Abnormal metal concentrations are connected with Paleogene clays and combustible shales.

Numerous *mercury* ore manifestations are controlled by zones of dislocations with breaks in continuity in terrigenous-carbonate sediments of the Lower Cretaceous period; the ore bodies are 0.2-2.5 m thick, the mercury content is 0.13-0.58 %.

Hydrothermal manifestations of *tellurium* ores are known within the Cheleken brachy-anticline. *Celestite* (Sr) mineralization is widely distributed in sedimentary deposits from the Jurassic to Neogene age. The commercial celestite concentration is associated with Paleocene sulfate-carbonate deposits. The major reserves are concentrated in sedimentary-epigenetic deposits where laminated and lens-shaped beds run to 15-25 m in depth. The ores are continuous and veinlet-impregnated. Sedimentary-epigenetic manifestations of laminated celestite are observed in Lower Cretaceous lagoon-continental deposits of South Karabogaz region. Celestite, jointly with barite, is found in a significant concentration in Neogene and Quaternary placers and modern Cheleken hydrothermal fields.

Chapter 4. Mineralurgy. Ore Dressing

4.1. Technological Systematization of Minerals

4.1.1. Technological Definition of Mineral

Unluckily we cannot make use of numerous definitions of a mineral from reference and text books on mineralurgy which are oriented to diagnostics or genesis of minerals.[13,14,56,59,61]. Our concern is the notion of a mineral as an industrial raw material selected from ore using technological processes.

Numerous native mineral types and variants are associated with variability of chemical composition at one and the same crystalline structure. Rich natural diversity of such variations (up to continuous transitions from one chemical formula to another with different extremes) predetermined that mineralogists failed to come to a unique definition of mineral type.

From the viewpoint of mineralurgy the definition of mineral type must meet the following conditions:

1. Distinctions in chemical composition of mineral type should not lead to different technical assessment of selected minerals. From this standpoint potassium and sodium feldspars are related to different mineral types. Scheelite (CaWO_4) and povellite (CaMoO_4) which form a continuous isomorphous series are also assigned to different mineral types, with mineral assigned to the type which dictates the industrial value of the ore in molybdenum or tungsten, depending on the Mo to W ratio in the Ca [W, Mo] O_4 series in the deposit. On the contrary, hubnerite (MnWO_4) and ferberite (FeWO_4) related to the wolframite group ($[\text{Fe}, \text{Mn}] \text{WO}_4$) are among the same mineral type from the viewpoint of mineralurgy.

2. Minerals of one type must have similar processing properties and be concentrated in the same products in technological processes:

- a) in gravitational, magnetic and electrical fields;
- b) have close mechanical properties: hardness, fragility, elasticity;
- c) have close adsorption properties with respect to solute chemical reagents;
- d) feature similar solubility in process solutions.

From this standpoint, sphalerite ($\alpha\text{-ZnS}$), wurtzite ($\beta\text{-ZnS}$) and marnolite ($[\text{Zn}, \text{Fe}]\text{S}$) are assigned to different mineral types. Pyrite and marcasite (FeS_2), chalcopyrite and cubanite (CuFeS_2) differing in floatability are differentiated.

In so doing, one mineral type incorporates minerals of monotype structure which composition is in conformity with individualized chemical compounds (among them, extremes and means of continuous solid solutions and may vary within the limits determined by:

1) impossibility of equilibrium existence of two or several phases in the temperature and pressure ranges of natural physicochemical process,

2) continuity of change in useful component value within the limits of technical value of this or that mineral,

3) invariability of processing properties: physical, mechanical, chemical and adsorption, involving concentrating of all variants of this process type in the same processing products.

From the viewpoint of this definition, optical properties, colour (?) of minerals, for instance, are of no great value in the process, and they are essential only as a reflection of quantity and composition of isomorphous impurities. Just like in mineralogy, minerals of one composition but different structure, polymorphous modifications, are assigned to different mineral types.

For example, graphite - diamond, calcite - aragonite, etc. Here the physicochemical field of stability, within which it is impossible for one modification to exist at genesis of mineral type, corresponds with the physicochemical field of technological process.

Less dramatic, gradual structural changes, polytype modifications, which show identical parameters of elementary cell in two directions and a variable one in the third direction, may cause changes in mineral type or not. Most often polytypes of layer minerals do not change processing properties of mineral type since crystalline lattice elements are shifted relative to each other between layers while the structure inside the elements separated during ore crushing is preserved. Polytypes of different degree of order of ion arrangement in the lattice, for example, feldspar - orthoclase, are assigned to different mineral types.

Morphology of minerals which is governed by their internal structure, genesis and conditions of crystal growth leads to formation of different forms and aggregates differing in processing properties. Morphological variants are characterized by crystal habit, monocrystalline formation size, and, at last, mutual orientation of minerals in mineral aggregates, and consequently in growths.

Dislocations on margins of monocrystal concretions in blocks of one mineral or mineral aggregate substantially affect ore preparation and dressing processes. Breaks of ideal periodicity of monocrystals, scarps, pinching out of atomic plane, distortion of mutual parallelism of atomic planes are dictated by growth conditions. Intrusion of foreign particles, isomorphous substitution

of ions, complexes and impregnations of other minerals are also possible. Dislocation of crystals is characterized not only by type but also by density.

Mineral non-uniformity is most greatly influenced by different type impurities governing composition and, to some extent, properties of mineral variants. Nonuniform mineral composition may be connected with different types of deviations from idealized chemical formula.

Microinclusions of solid heterogenic mineral phases are trapped from the environment during crystallization due to co-precipitation, disintegration of solid solutions, crystallization of colloids during desorption. The microinclusions involve individual microparagenesis for each mineral which does not necessarily coincide with macroparagenesis. In particular, some minerals of dispersed elements (indium, rhenium, platinoids, etc.) may be encountered only as microinclusions. It is these heterogenic microinclusions that are responsible for value of nickel and platinum-bearing pyrrhotites. Flotation properties of minerals may be substantially dependent on these microinclusions. Here the classic example is sphalerite containing chalcopyrite inclusions. Floatability of this sphalerite is similar to that of chalcopyrite which controls problems of selective flotation of copper-zinc ore and low parameters of separation.[14,56,58].

Microinclusions of liquid, gas-liquid, gas salt solutions and melts being residues of crystallization medium also have an effect on flotation and, if in substantial quantities, on leaching as well.

Nonstructural ion and molecule microimpurities located in crystalline lattice defects, in dislocation areas and on the borderlines of lattice blocks can be leached without distortion of crystalline lattice of minerals. Grinding and conditioning of sludge before flotation always brings about a large quantity of the so-called "inevitable" ions appeared in the liquid phase which have a substantial effect on the process. In some cases it is required to resort to special jigging by water, alkalis or acids for removal of "inevitable ions", as, for instance, in flotation separation of beryllium ore, final dressing of scheelite concentrates, flotation of quartz, etc.

Finely dispersed and colloid-dispersed minerals and minerals with mature surface (coal, zeolites, clays) can sorb impurity elements, especially, with large ion radii. For example, sorption processes are responsible for great losses of platinoids with iron hydroxides during processing of nickel-bearing pyrrhotites. In flotation natural sorbents are sometimes specially introduced into sludge for trapping of gold, solute copper, etc.

Impurity elements in radioactive ores may be of radiogenic origin, with concentration as a function of mineral age. Thus, radiogenic lead is always present in uranium ores, calcium in potassium ores, strontium in rubidium ores, and osmium in rhenium ores. Radiogenic impurities also influence floatability and solubility of minerals.

Many minerals forming isomorphous series behave in dressing processes depending on substitution degree. Thus, for instance, molybdo-scheelites are floated the worse the larger is the degree of substitution of isomorphous molybdenum for tungsten, here povellite is floated much worse than scheelite. The similar is the difference in floatability of tantalite and columbite, potassium and sodium feldspars, etc. The like discrepancies are also observed in electrical separation processes. The rate of iron recovery in the hematite - magnetite series has a substantial influence on magnetic properties of iron-containing minerals.

The cation - anion ratio is responsible for the type of conductivity (ionic or hole) for semiconductor minerals, for example, sulfides, sulfo salts, etc. Control of conductivity type using electrical sludge processing permits substantial improvement of selectivity of flotation separation minerals and higher recovery to concentrate.

The enlisted forms of mineral composition variants along with polytype modifications, morphological varieties, nature and density of crystals lead to large number of variants of one and the same mineral type. From the viewpoint of mineralurgy, variants of one and the same mineral at similar behaviour, i.e., with concentrating in one product during mineral processing, may differ in recovery rate to this product, i.e., in intensity of concentrating process.

4.1.2. Isomorphism and Mineral Variants

The notion of isomorphism, i.e., ability of substances similar in chemical composition to be jointly crystallized in identical forms, is the most essential to parametric description of mineral composition with respect to processing properties.[13,14,42,58].

According to ideas of crystal chemistry, isomorphism is the ability of chemical elements atoms and ions to substitute one for another provided the dimensions of atoms, ions and their groups composing crystalline lattice are close, charge signs are identical, and polarization values are relatively close. Isomorphism of native compounds is responsible for affinity of chemical formula, closeness of geometric type of lattice structure and chemical bond type.

The concept of isomorphous elements or components forming isomorphous mixtures or solid solutions are widely used in mineralogy at present. The extremes of isomorphous mixtures are called isomorphous minerals and form isomorphous series. In accordance with degree of miscibility in isomorphous series the following isomorphism types are distinguished: unlimited (perfect) and limited (imperfect). Examples of the former are the isomorphous series of wolframite (hubnerite MnWO_4 - ferberite FeWO_4) and the series of olivine (forsterite $\text{Mg}_2[\text{SiO}_4]$ - fayalite $\text{Fe}_2[\text{SiO}_4]$). Imperfect isomorphism between Zn and Fe in sphalerite has been established.

Considerable flexibility of chemical mineral composition causes a regular change of structural and processing parameters, density, hardness, refractive indices. Effect of smaller isomorphous impurities on physical properties is insignificant but sometimes a sharp change in electrical properties, emergence of colour and luminescence are connected with such impurities. Their effect on surface properties of minerals is also significant.

Heterovalent isomorphism with retention of general number of atoms can be manifested in various ways: (1) conjugate replacement of pairs: for example, in fluorite there is a replacement of Ca^{2+} ions by TR^{3+} ions and of F^- ions by O^{2-} ions according to the pattern: $\text{Ca}_{1-n}(\text{TR}^{3+}_{\text{Ca}^{2+}})_n \text{F}_{2-n}(\text{O}^{2-}_{\text{F}^-})_n$, (2) replacement of two similar atoms by two atoms of different elements of different valency with retention of summary charge of the type $2\text{R}^{4+} \rightarrow \text{R}^{2+} + \text{R}^{4+}$, for example, in cassiterite, according to the pattern: $\text{Sn}^{4+}_{1-2n}(\text{F}^{4+}_{\text{Sn}^{4+}})_{11n}(\text{W}^{6+}_{\text{Sn}^{4+}})_{2n}\text{O}^{2-}_2$, (3) replacement of two pairs of atoms of different elements with retention of summary charge of the type $\text{R}^{2+} + \text{R}^{3+} \rightarrow \text{R}^{2+} + \text{R}^{3+}$, for example, in plagioclases according to the pattern: $\text{Na}^{+}_{1-n}(\text{Ca}^{2+}_{\text{Na}^{+}})_n[\text{Si}^{4+}_{3-n}\text{Al}^{3+}(\text{Al}^{3+}_{\text{Si}^{4+}})_n\text{O}^{2-}_8]$.

Under heterovalent isomorphous replacements accompanied by changes in atom number in mineral structure, compensation redundant charges occurred in some cases is marked off by formation of atom vacancies of the type $\text{R}^{2+}_3 \rightarrow \text{R}^{3+}_2(\text{V}_\text{R})_1$, as is the case with ferberite: $\text{Fe}^{2+}_{1-3n}(\text{Sc}^{3+}_{\text{Fe}^{2+}})_{2n}(\text{V}_{\text{Fe}^{2+}})_{11n}\text{W}^{6+}\text{O}^{2-}_4$.

In other cases isomorphous replacements take place with filling of interstitial positions, for example, in fluorite by replacing Ca^{2+} ions by TR^{3+} ions by synchronous entering of F_i^- ion into interstitial position according to the pattern: $\text{Ca}^{2+}_{1-n}(\text{TR}^{3+}_{\text{Ca}^{2+}})_n \text{F}_2(\text{F}_i^-)_n$.

The isomorphism conditions, proximity of dimensional parameters of isomorphous components or volume of an elementary cell of isomorphous mineral and atomic radii of isomorphous elements and ions, difference of ionic radii of isomorphous ions to radius of smaller ions ($\Delta r/r$) should not exceed 15 % with <40 % for more complex compositions. Similarity of electronic structure of isomorphous elements, proximity of chemical properties and consequently character of chemical bond in isomorphous minerals. The rule of polarity, according to which the entering of the ion of smaller radius or greater charge is more preferable than that of the ion of larger radius or smaller charge. The examples of polar isomorphism are the heterovalent series of Li^+ (0.069) - Mg^{2+} (0.075) - Sc^{3+} (0.081) - Zr^{4+} (0.082) in magnesium micas and Na^+ (0.098) - Ca^{2+} (0.105) - Y^{3+} (0.106) in pyrochlore and other rare-earth minerals where the value of ionic radii in nanometres is given in brackets. We come across unilateral isomorphism for the pair of elements with one and the same radius, for example, Zn^{2+} and Fe^{2+} . In ZnS (sphalerite) zinc

permits entering of up to 20 % Fe, but there is absolutely no Zn in FeS. The reason for this is that Fe can have both a quaternary and hexad coordination while Zn always has a quaternary coordination in sulfides.

At high temperature the limits of isomorphous miscibility for many minerals of variable composition are higher, often up to formation of perfect solid solutions with unlimited miscibility (feldspars). The extremes of isomorphous mixtures are called isomorphous minerals, they form isomorphous series. Unlimited (perfect) and limited (imperfect) isomorphism are distinguished depending on degree of miscibility in isomorphous series.

... Limitation of isomorphous miscibility is in many cases connected with concentration of impurities. For example, commonly low content of Cd in sphalerite, Ni in olivine, Cr in beryllium is first of all predetermined by low content of these impurities in the mineral-forming medium. In some cases isomorphous miscibility depends on the ratio of concentration of ions of one and the same element of different valence which is connected with redox conditions of mineral formation. In so doing, the Mo content in molybdenoscheelite ($\text{Ca}(\text{W}, \text{Mo})\text{O}_4$) in many cases is a function of not only temperature but also in what form, oxidized or reduced, it is present in mineral-forming solutions.[42]. ...

Though an effect of small isomorphous impurities on physical properties is slight, sometimes a sharp change in electrical properties along with colouring and luminescence are associated with impurities. ... In so doing, for instance, parameters of hexagonal elementary cell of apatite permit an evaluation of the content of, on one part, ions of F^- , Cl^- , $(\text{OH})^-$, O^{2-} and attribution of apatite to fluorapatite, chlorapatite, hydroxylapatite, oxyapatite, and, on the other part, an evaluation of the content of ions substituting for Ca^{2+} , Ba^{2+} and Sr^{2+} . [56].

Isomorphism is a more general notion than ionic exchange running in channel and layer compounds, for instance, between particles in zeolite channels or in interlayer cavities of silicates and aluminosilicates. Substitutions prohibited from the viewpoint of thermodynamics of macroisomorphism may take place in ionic exchange. In so doing, cations differing in dimensions and properties, for example, Ca^{2+} and Cs^+ in zeolites, may substitute for one another.

In general there are gradual transitions between isomorphism, microisomorphism, formation of interstitial solid solutions and ionic exchange.[14].

In so doing, during parametric description of mineral varieties the following is identified: (1) nature of substitution, i.e., naming of substituted and substituting elements, (2) character of substitution, type of isomorphism or analogues and mechanism of substitution, (3) quantitative assessment of substitution of each type.

4.1.3. Crystalline Structure of Minerals

Minerals are defined as crystalline matters, and atoms of chemical elements entering into compositions are found to be in regular distribution in lattice points and maintained in the state of equilibrium by forces of mutual attraction and repulsion. Nature and value of the forces are dictated by properties of interacting atoms of chemical elements. The properties unique for different chemical elements are conditioned by nucleus charge, electronic structure of atoms according to the periodic system.

Formation of minerals may be taken to be a convergence of free atoms until a certain distance between them is reached at which point forces of attraction and repulsion are brought into the state of equilibrium. The latter corresponds to the minimum of energy since in chemical compound the potential energy of atoms is smaller than that of free, disconnected atoms. The difference between the value of energy of free atoms and the minimum potential energy of atoms in a bound state is determined as the energy-producing measure of chemical bond. In crystals it is called the energy of crystalline lattice.[14].

Energy zones in crystalline bodies may be completely or partially filled with valent electrons or have no them at all. The energy zone completely filled with valent electrons is called a valent zone. The free zone located energetically above the valent zone or the zone

incompletely filled with valent electrons is called a zone of conductivity. Depending on solid body structure and building of atoms comprising the body, there may be an energy break between the valent zone and the zone of conductivity (Fig.4.1a) or the zones may overlap each other (Fig.4.1b).

The energy break between the valent zone and the zone of conductivity is called an exclusion zone, and the ΔE (usually in eV) a width of the exclusion zone.

Depending on zonal structure, crystalline bodies may possess properties of metals, i.e., may be good conductors of electric current, of dielectrics, i.e., do not virtually conduct electric current, or semiconductors in which conductivity emerges at some temperature and increases with temperature rise. Emergence of electric current in crystal which necessitates movement of electrons inside the crystal is explained by transition of electrons from one energy level to another within the zone of conductivity.[13,15].

Positive holes appear in the valent zone on the place of electrons emitted, and conductivity in the zone takes place through movement of electrons into holes, i.e., it is accompanied by the seemingly transfer of holes to the side opposite to the movement of electrons (Fig.4.2), hole conductivity appears. This pattern explains larger conductivity with temperature rise as it is accompanied by higher concentration of carriers (electrons in conductivity zone and holes in valent zone). On the contrary, lower temperature keeping electrons in valent zone leads to disappearance of covalence electrons, and transformation of a semiconductor into a dielectric.

Besides intrinsic conductivity, semiconductors possess impurity conductivity emerging in semiconductor compounds with these or those impurities at temperature lower than that of intrinsic conductivity.

Electron-conductive semiconductors are called n-type semiconductors, in this case impurity atoms play the role of donors. A hole-conductive semiconductor is a p-type semiconductor in which impurity atoms play the role of electron acceptors.[13].

Extrinsic conductivity emerges in semiconductors also under the effect of crystalline lattice defects of different type, among them, dislocations.

Depending on zonal structure and chemical bond type which are closely interconnected, crystalline bodies are subdivided into four types: (1) covalent, (2) ionic, (3) metallic, and (4) molecular crystals.

Covalent bond similar to covalent bond in individual molecules in intrinsic nature is typical of crystalline bodies of the first and last types.

Covalent bond shows strict directionality. The coordination number of anions is defined by the correspondence between the number of external electron pairs and the number of acceptor orbitals of cations taking these pairs.

The crystalline structure of covalent crystals results from the donor-acceptor correspondence of the number of vacant orbitals of cation and electron pairs of anion which is reflected in the formation of certain electron ensembles.

The energy characteristics of the covalent bond are governed by atomic properties, in particular, the energy of bond break is directly proportional (within each period) to the orbital radii of atomic shells completely deprived of valent electrons.

Ionic crystals characterized by zonal structure of dielectrics. The bond between individual particles in them is subject to fundamentals of electrostatic interaction, and is considered to be a bond between opposite-charged ions formed owing to loss of valent electrons by one atoms which became cations and acquisition of them by other atoms which became anions.

The most significant feature of ionic bond is absence of certain directionality, delocalization.

Effective ionic radii of anions much exceed orbital atomic radii, and effective ionic radii of cations are smaller than the latter but larger than the corresponding orbital ionic radii.

Structures of ionic crystals are designed under the principle of the densest packing of large anions; cations are arranged in tetrahedron and octahedron cavities or, if larger, move them apart.

Coordination numbers (CN) of cations depend on the ratio of their radii and radii of anions. The structural details are governed by the ratio of the number of cations and anions in the formula which is subject to the rule of electric neutrality, the CN of cations (gradation of inhabited cavities), pattern of cation distribution in cavities. [13,42].

Metallic crystals differ in that individual energy zones overlap in them. The chemical bond called metallic one in this case is executed between atomic shells characterized by covalence (overlapping in energy) external orbitals and covalence electrons of “electron gas” into which atomic shells are immersed.

Number and type of shared electrons, type of orbital sharing depend on valence of atomic shells which in turn is established by the value of insuperable energy barriers of ionization.

In each particular case the covalent bond is characterized by certain ionicity, covalence and metallicity. The bond mechanism and nature may be complicated by appearance of metallic or covalent bond component at crystals with ionic and covalent or metallic bond, respectively. Alongside homodesmotic crystals with covalent, ionic or metallic bond, there are a great number of heterodesmotic crystals with covalent bond between particles (for instance, within complex anionic radicals) and ionic bond between these radicals and cations (salts of oxygen acids, etc.) as well as molecular crystals with covalent bond in molecules and residual bond between molecules.

Greater metallicity of covalent bond decreases width of exclusion zone. Transition from covalent matters to ionic or metals with overlapping valent and conductivity zones and shared electrons takes place spasmodically (polymorphic and morphotropic transitions), it may be gradual in series of solid solutions.[13].

Different types of imperfection of crystalline lattice are typical of real minerals while total electrostatic balance is kept in it.

Elementary imperfections of mineral structure are point defects, vacancies and interstitial atoms. Concentration of these defects is connected mainly with temperature conditions of formation, in this connection they are called thermal or equilibrium.

Vacancies are free, unoccupied positions of ideal crystalline structure atoms, for instance, vacancies of copper atoms, V_{Cu} , in crystals of copper nugget. There may be cation, V_c , and anion, V_a , vacancies in ionic crystals. Interstitial atoms, M_i , may be imagined as shifted from their positions to neighbouring interstices. The coordination number of interstitial atom may differ from CN in its usual position. For example, Interstitial Na atoms in halite, NaCl, occupy free tetrahedron cavities with CN = 4. Point defects of minerals (except nuggets) feature redundant or, to be more exact, effective charges. For instance, anionic vacancy with positive charge is V_a^+ , cationic one with negative charge is V_c^- . Interstitial ions have redundant charge and sign corresponding with valence. For example, in fluorite, CaF_2 , the interstitial ion of fluorine has a redundant negative charge: F_i^- [42].

As a rule *point defects* of different types simultaneously present in minerals. They have redundant charges differing in value and sign at common electrostatic neutrality. If intrinsic point defects are locally compensated, pair and more complex associate defects are generated. The interstitial atom - atomic vacancy pair $[M_i V_m]$ is called Frenkel defect. Twinned anionic and cationic vacancies $[V_c^- V_c^+]^x$ are Schottky defect with neutral charge. Non-equilibrium point defects are radiation ones which emerge as a result of atom shift along the high-energy particle path. If the rate of radiation defects is high, crystal structure of minerals may fracture, transforming into a metamict state close to amorphous one (pyrochlore, zircon, samarskite, etc.)

Regular deflections from ideal arrangement of atoms along some directions (lines) in crystal structure of minerals are called dislocations and may be presented by two types, edge and screw. Stressed states of compression or extension of structure are created along the dislocation lines, here atoms are in unusual coordinates with nonsaturated bonds due to which

dislocations acquire redundant charges. Edge dislocations are most often formed as a result of mechanical deformations, shifts of crystal structure of minerals which are accompanied by changes in crystal grain shape while screw dislocations are formed during crystal growth. Impurities are as a common confined to dislocation lines in minerals. Variability of mechanical properties and morphology of minerals is associated with dislocations.[42].

Grain surface and margins are two-dimensional defects characterized by irregular arrangement of atoms and redundant surface energy. They feature high chemical and surface activity, composition and coordination of atoms. Surface is of growth or deformation nature.

Each defect is a local violation of electric neutrality. In so doing, at anionic vacancy a defect acquires positive charge, becoming a trap for electrons. When an electron is trapped by an anionic vacancy, a F-centre is formed. At cationic vacancy in the local point the vacant position becomes negatively charged and is compensated at the expense of redistribution of electrons in the electronic shells of the anions enclosing the vacancy in which a shortage of electrons ("hole") appears. In so doing, numerous electron-hole centres connected with local defective areas emerge in lattices of real minerals. This explains many mineral properties: electrostatic, luminiscent and thermoluminiscent, colour change, etc.

Several centre types are distinguished by *electronic structure and chemical bond type* [13,42]:

(1) cationic, in which electronic transitions take place between different cation levels (Fe^{2+} , Fe^{3+} , Cr^{3+} , Mn^{2+} , Pb^{2+} , TR^{3+} , etc.);

(2) molecular, in which electronic transitions run between level of a molecule retaining its peculiarities in the crystal lattice (S_2 , O_2 , UO_2^{2+} , etc.);

(3) connected with oxygen complexes, in which electronic transitions take place between molecular orbitals of the complex (i.e., electronic transition from cation to oxygen or from oxygen to cation);

(4) radiation, associated with an effect of ionizing radiation on the mineral;

(5) donor-acceptor pair, appeared in minerals with covalent bond due to formation of a dipole from cationic and anionic vacancy.

Crystal structure is characterized by:

- minimum element of repeatability, symmetry and dimension of elementary cell,
- coordinates of atoms (ions) in this cell,
- interatomic distances and angular parameters of interatomic vectors,
- atom coordination, coordination number, coordination polyhedron type and symmetry,
- degree and character (type) of ordering in ion dispersal by positions, especially, isomorphous substitutions are developed or interstitials are formed,
- degree and character (type) of ordering of different elements of crystal structure (chains of Polyhedrons, layers, etc.),
- imperfection of structure (presence of vacancies and holes).

Polymorphic modifications of one composition but different symmetry of elementary cell may be formed. They can be exemplified by crystallization of TiO_2 in the form of rutile, anatase or brookite; of FeS_2 in the form of pyrite or marcasite; $(\text{Fe}, \text{Mn})(\text{Ta}, \text{Nb})_2\text{O}_6$ in the form of tantalite or tapiolite.[56].

The position of atoms and ions in the elementary cell may be changed due to their nearing together under the conditions of higher pressure. In so doing, the modification of the structural variant of scheelite - powellite, with the coordination numbers of cations of 4 and 8 into wolframite with the coordination numbers of 6 and 6, is typical of the $\text{Ca}(\text{W}, \text{Mo})\text{O}_4$. The mutual transition of the types is reversible and manifested in a change in symmetry of the elementary cell, coordinates of atoms in it, their coordination, interatomic distance values. This transformation involves a change in the monoclinic angle typical of wolframite-fergusonite groups, and a change in the coordination number, i.e., oxygen cation enclosure defined by physicochemical conditions and composition. The crystal structure of casiterite shows a modification of the coordination oxygen octahedron around the Sn^{4+} ion; the octahedron may be

regular, flattened or elongated, depending on temperature and pH of the crystallization medium of genetically-different cassiterites.

In the columbite-tantalite group a change in the character of arrangement of cations in the octahedron coordination leads to lowering of crystal lattice symmetry from rhombic to monoclinic which alters interatomic distances and dimensions of elementary cell of minerals and their processing properties as well. In so doing, in the ordered crystal structure there is an alteration of (Ta, Nb)-octahedron layers and (Fe, Mn)-octahedron layers. In disordered columbite-tantalites with ixiolite structure there is an equiprobable dispersal of any layer in any layer (Ta, Nb, Fe, and Mn). During acidic leaching Mn and Fe easily transit to solution in ordered variants, and with a great difficulty, only at full fracture of the mineral, in disordered variants. The ordered chalcopyrite is CuFeS_2 of tetragonal systems, the disordered one is cubic. The latter feature higher temperature in formation conditions and is worse in floatability.[56].

Below are enlisted five types of crystal mineral structures which differ in atomic arrangement character [42]:

(1) *Coordination type*. It shows equal distances between atoms. The densest packing of metals (nugget gold), anions (for instance, oxygen in hematite) or cations (calcium in fluorite) is typical of minerals with metallic and ionic chemical bond.

(2) *Island type*. Complex anion radicals or closed molecules are as if separate islands, clusters within which interatomic distances are smaller and chemical bond strength is much higher than in the rest part of the structure. For example, realgar $[\text{As}_4\text{S}_4]$, nugget sulfur S_8 , silicates with isolated tetrahedron anion radical $[\text{SiO}_4]^{4-}$, olivine $(\text{Mg, Fe})_2 [\text{SiO}_4]$. Sometimes there are formed twin radicals $[\text{Si}_2\text{O}_7]^{6-}$ (for example, calamine $\text{Zn}_4[\text{Si}_2\text{O}_7](\text{OH})_2 \cdot \text{H}_2\text{O}$), and more complex rings (for example, $[\text{Si}_6\text{O}_{18}]^{12-}$ in beryllium).

(3) *Chain type*. Structures are formed by endless one-dimensional radicals which consist of linear-linked coordination polyhedrons. The distance between atoms within the chain is shorter and the strength of the chemical bond is higher than those parameters between chains (?). Single or twinned chains are possible (for example, in sillimanite $\text{Al}[\text{SiAlO}_5]$ or twinned (anthophyllite $\text{Mg}_7 [\text{Si}_4\text{O}_{11}]_2 (\text{OH})_2$).

(4) *Layer (plate) type*. Interplane distances within the plate (layer) are shorter than between layers, and consequently atoms are stronger bonded with neighbouring atoms of the layer than with atoms of another layer (graphite, talc $\text{Mg}_3[\text{Si}_4\text{O}_{10}](\text{OH})_2$, brucite $\text{Mg}(\text{OH})_2$).

(5) *Shell type*. It shows a large volumetric compound of coordination polyhedrons by common peaks or edges: quartz SiO_2 , and feldspars, for example, albite $\text{Na}[\text{Si}_3\text{AlO}_8]$. Atoms large in dimensions may be arranged in shell voids.

Minerals are not ideal but real systems of interacting atoms characterized by breakdowns in periodicity of crystal structure.

4.1.4. Morphology of minerals

Internal structure of minerals and formation conditions are responsible for morphology. Minerals are virtually always present in the form of monomineral or polymineral intergrowths or aggregates. Mineral individuals entering into composition of aggregates are distinguished by outer appearance, i.e., size and morphology.

Dimensions of mineral individuals may be fairly different, from the finest particles distinguished only at microscopic magnifications of tens and even hundreds of thousands of times to gigantic crystals with a volume of several cubic metres. Depending on dimensions, there are distinguished finely dispersed (10^{-6} m and less), cryptocrystalline (10^{-6} - 10^{-5} m) individuals non-visible without a microscope, very fine (10^{-5} - 10^{-4} m), fine (10^{-4} - 10^{-3} m), medium (10^{-3} - 10^{-2}), coarse-grained (10^{-2} - 10^{-1} m) and gigantic (10^{-1} m) individuals. Some minerals form no large crystals, for instance, particles of clay minerals are always smaller than hundredth and even thousandth millimetre parts. Most often minerals are represented by fine crystal grains of no

more than several millimetres in size. Many of them, in particular, quartz, feldspar, mica, etc., can be encountered as very fine grains and very large crystals.[42].

Idiomorphism degree and habit are a function of crystal structure and growth conditions. Crystals of various habit: normal (for example, halite, galenite, sphalerite, olivine, etc.), lamellar and flaky (for example, molybdenite, mica, talc), blade (barite), columnar and needle-like (rutile, actinolite, tourmaline). Typical striation, growth and solution forms as well are visible on some crystals.

Feceted mineral individuals of regular shape are called idiomorphous, for instance, crystals of diamond and quartz in effusive rocks, magnetite in metamorphic rocks, zircon in alkaline pegmatites, very fine particles of kaolinite clay. Unlimited or partially limited mineral individuals have an irregular shape or repeat contour of other individuals which they are in integrpwth and are called xenomorphic.

Morphology of mineral individuals (Fig.4.3) which is characterized by isometry degree is expressed in different ratio of individua; length, width and thickness. Depending on this, morphological types, subtypes and variants of minerals are identified. Noral crystals or grains have similar dimentions in all three dorections, for instance, crystals of diamond, magnetite, garnet, sphalerite and pyrite. As a common unlimited normal grains of minerals, like quartz, feldspars, olivine, calcite compose different rocks.[42].

Columnar, neddle-like, fibrous or filamentous variants are encountered among minerals of oblong type. Oblong minerals may be exemplified by tourmaline, beryl, natrolite, scapolite, jamesonite, chrysolite-asbestos, etc. Complanate minerals are represented by tabular, thin-tabular, laminated and thin-flaky variants. Ilmenite, hematite, biotite, chlorite, torbernite, etc. are commonly of complanate habit, while wollastonite, spumene, cyanite, antomonite. etc. are of complanate-oblong habit, with columbite, gypsum, barite of oblong-complanate habit.

Crystal structure type is mainly responsible for morphology of minerals. For example, minerals with chain and banded structure versions are most often encountered as oblong and those with layer versions as complamate individuals. Minerals with the closest cubic paking of atoms are ususally normal, with hexagonal complanate or oblong.

Parameters of elementary cell are also responsible for habit of minerals of medium and lowest symmetry categories. If the parameter ratio c_0/a_0 is nearing a unit, the minerals encountered are more often in the form of normal crystals. In opposition to this situation minerals of oblong morphological type show lower value of this ratio while for the minerals of complanate type this value is more than a unit.

The habit of minerals related to one and the same sytem is governed by their attribution to this or that symmetry class and the rate of facet maturation of corresponding simple forms. For example, pyrite crystals are often encounterd as cubes, pentagondodecahedrons, octahedrons or their combinations but never covered tetrahedron or rhombododecahedron facets.[42,77].

Minerals are seldom encountered as regular crystals. Most often they are represented by distorted forms with unequal facet dimensions, are of stepped structure or curved, are often covered with striation and different growth or solution patterns. Distortions are involved by unequal facet maturation. Complanate forms of pyrite, scheelite or other minerals confined to thin veinlets are predetermined by gwth under restricted conditions. Quartz crystal asymmetry expressed by nonuniform maturation of rhombohedron facets is explained by their unequal orientation with respect to mineral-forming solution flow direction.

The facet relief of many minerals is peculiar in distortion which often connected with mechanical deformations and dislocation shifts found, for instance, for antimonite, galenite, molybdenite. Sliding striation is often visible on the facet surface of these minerals. Convex facets of combination type are inherent in spheroidal habit minerals, for example, diamond, named octahedroids and dodecahedroids. Facets of split crystals forming saddle-like, fan-like or twisted habitus forms (dolomite, pyrite, quartz, desmine, etc.) are also of distorted or stepped-mosaic structure. Angular disorientation of subindividuals in split minerals are related to trapping of impurities and formation of edge dislocations during growth.

Alongside usual volumetric-convex faceted individuals, many minerals are encountered as ‘skeleton’ crystals of different habit which are described as one-dimensional (linear), two-dimensional (flat) and three-dimensional (volumetric) edge, apical and many-facet prisms (faceted bundles). Filamented crystals (whiskers) are attributed to one-dimensional, for example, jamesonite as thin fibres, helicoids (twisted, along elongation or similarly to spring) or even closed as rings, hair-like small crystals of rutile or actinolite.

Mineral aggregates. In nature, alongside individual crystals, aggregates are also formed. They are both regularly oriented with respect to one another (twins, parallel and epitaxial aggregates) and with no mutual orientation. As to morphology, there are druses (dendrites, granular, dense and earthy masses, salts (?), spherulite, secretions, concretions, various sinter aggregates typical of minerals of exogenic origin.

Minerals are commonly in nonregular aggregates which may be bedded by one or several minerals. Mineral aggregates differ in size, shape and nature of spatial arrangement of mineral individuals constituting the aggregates. There are coarse, medium and fine-grained, crystalline-grained and cryptocrystalline, uniformly and nonuniformly grained aggregates with regular or irregular orientation of mineral grains. Mineral grains can be dense or massive, porous, earthy, viscous, loose or bulk. The majority of erupted, metamorphic, sedimentary rocks and different ores as well are bedded by crystalline-granular aggregates of minerals. Porous and loose aggregates are typical of products of volcanic eruptions, many sedimentary rocks, soils, etc.

Parallel aggregates of two and more individuals with identical crystallographic orientation are as a rule monomineral. Some of them are syngenetic aggregates, for example, of fluorite or quartz crystals, others, epigenetic are formed when the later generation of minerals is built up over the preceding one. As are usually represented by independent variants differing in morphology, impurity composition and concentration, structural peculiarities or physical properties. Twin intergrowth planes are commonly parallel to faces or directions with the largest reticular density. The twin axis may be a normal to these faces and directions and coincide with the direction of edges at the intersecting point of the densest atomic nets or be perpendicular to these edges if the axis is in the twin plane.

Incrustate aggregates, druses, crustalline, sinter and spherulite crusts, compose voids different in dimensions and shape (secretions). Large secretions (from several centimetres to several metres in size) are called geodes, bags, pogrebs, ventholes while small ones (less than one centimetre) are named misroles and amygdules. Secretions may be made fully or partially of crystals or spherulites of one or several mineral types. Mineral individuals composing incrustate aggregates in secretions may have a random or, more seldom, regular, usually parallel, orientation. Disorderly oriented individuals are formed out of a variety of small crystalline nucleations with random fixation on rough void walls. Oriented aggregates also emerge through crystallization on the porous wall, with formation of parallel-fibrous aggregates of filamented crystals, for example, gypsum, chalcantite, etc. Besides, an orienting effect on the individuals may be produced by the base on which crystallization takes place. It may be a regularly oriented net, joints, a bedding of enclosing rocks or a coarse crystal which is substrate in epitaxial growth.

Globular-shape, nodular, oval, reniform and other rounded mineral aggregates are called concretions, setarian nodules, and oolites. Opposite to secretions, concretions are formed during crystallization from centre to periphery and have concentric shelly or zonal structure. Formation of concretions is associated with collective crystallization in porous, usually sedimentary rocks owing to dispersed material.

We shall consider the classification of mineral segregations by size and the significance of morphological types of structures and textures in dressing of ores. The characteristics of mineral segregations are the background of elaboration of process flowsheets and prediction of dressing parameters.[11,77].

Idiomorphism is a group notion which covers various crystalline forms of different system minerals. Mineral segregations with incompletely mature crystalline faces are named hypidiomorphic. The outline of allotriomorphic or xenomorphic segregations depend on the

shape of the space which they fill. If mineral segregations are formed during crystallization of solutions, they are called crystalline grains. Mineral segregations formed during metasomatism are named metagrain. Different shapes of colloid formations result from coagulation of colloid solutions. Blastograins are formed during recrystallization and crystallization of colloids. Crystalline structure is the peculiarity of these mineral segregations. The metagrain shape depends mostly on crystallization growth rate. In this case only grains of minerals which crystallization growth rate is the highest will have idiomorphic outlines.

Fragments of brittle minerals crushed and crumpled under the effect of idiomorphism angular outlines (pyrite, arsenopyrite, quartz, etc.). Fragments of soft and ductile minerals are flattened of smoothed contour (gold, silver, copper, platinum, etc.). Fragments of minerals with distinct cleavage in one direction have an appearance of flakes, and plates (molybdenite, graphite, sericite, etc.). The shape of fragments formed during weathering also depends on physical and chemical properties of minerals. The oxidation degree has a great effect on the fragment shape. Fragments of easily oxidized minerals feature an irregular shape and meandering outlines (sphalerite, pyrrhotite, etc.). Minerals stable to solution and oxidation show a stable shape of grains and fragments (granite, quartz, cassiterite, etc.). Fragments rolled and rounded by water flow during carryover are called fractions. [42].

Mineral aggregates are bedded by metallic and nonmetallic minerals of hypogenic or hypergenic origin. Polymineral aggregates bedded by several minerals are widespread, monomineral aggregated bedded by one mineral are more seldom encountered.

The above data show that structure and morphology of mineral formations have been so far described qualitatively for the most part. The main parameters are as follows [11,77].:

- (1) distribution of mineral segregation dimensions,
- (2) type and parameters of crystalline structure,
- (3) list and density and crystalline structure defects,
- (4) Preferential and morphological type, mineral habit and shape distortion,
- (5) type of intergrowth,
- (6) type of mineral aggregates.

4.2. Mineralogy of Non-ferrous Metals

Only several hundreds out of a great number of minerals available in nature (about 5000) are encountered in full-scale deposits. Minerals containing valuable components and minerals of enclosing rocks are of interest to processing of ores. Such minerals number about 260 (not counting variants). [11].

Variability in content of impurities in minerals is very great even for one and the same type. Form of their inclusion in minerals is different. A part of them is connected with mechanical inclusions of minerals of another composition. Chemical impurities mainly occupy positions of type-forming elements, functioning as quasi-substitutes, or are located in crystalline structure interstices. Besides, chemical impurities often correspond to dislocations or are concentrated on the boundaries of individuals in crystallogained mineral aggregates, and are also absorbed in dispersed minerals. Certain deviations from the ideal composition of minerals may be connected with unstoichiometry. Minerals of the latter type are as a rule distinguished by high concentration of anion or cation vacancies and unusual charges of ions. Non-stoichiometry of minerals is often predetermined by inclusion of interstitial ions which redundant charges are offset by higher ion charges of the counterpart.

4.2.1. Classification of Minerals of Non-ferrous Metals

In accordance with mineral classification non-ferrous metals may be represented by the following classes [42,58,61]:

- (1) native elements,

- (2) sulfides and their analogues, e.g., arsenides, antimonides, bismuthides, tellurides, selenides,
- (3) oxides and hydroxides,
- (3) salt-forming minerals,
- (4) silicates, aluminosilicates and analogues represented by titanosilicates, zirconium silicates, and beryllium silicates. This class is important as enclosing rocks and nonmetallic components.

Rock-forming minerals belong to classes of silicates, carbonates, oxides, chlorides, and sulfates. As to percentage in rock, there are distinguished essential (above 10 %), auxiliary (1-10 %), accessory (below 1 %) minerals. The most widespread rock-forming minerals are quartz, feldspars, micas, amphiboles, pyroxenes, olivine, clay minerals, etc.

Rock-forming minerals are light (salic, leucocratic): quartz, feldspars, feldspathoids, etc.), and dark (mafic, melane): biotite, amphiboles, pyroxenes, olivine, etc. Silicate, carbonate and halogenic rock-forming minerals are distinguished by composition of essential mineral, with different essential rock types distinguished by paragenesis. Rock-forming minerals which dictate rock name are called cardinal (e.g., quartz, microcline, oligoclase in granites).

Primary (syngenetic to formation of the entire rock) and secondary (emerging in any rock transformations) are distinguished. Chemical elements composing the essential rock-forming mineral are called petrogenic (*Si, Al, K, Na, Ca, Mg, Fe, C, Cl, F, S, O, H*).

Native elements are composed of atoms of *Cu, Ag, Au, Pt, Os, Ir* and others. The industrial meaning have only minerals of precious metals.

Natural sulfides are the class of minerals representing sulfur (sulfides proper) and selenium compounds (selenides) connected interconnected by isomorphic relations. About one hundred of mineral types attributed to natural sulfides are known in nature, and only some twenty of them are encountered in large quantities. Natural sulfides of alkaline and alkali earth elements exhibit an ionic bond with S (or Se), are easily hydrolyzed, and only oldhamite (CaS) out of them is known in nature. The latter is encountered very seldom (for example, in some meteorites). The most widespread natural sulfides are chalcophile elements, and iron and molybdenum family elements; V, Cr, W, Pt, Ga, In, Te, Cd sulfides are known. A covalent bond is typical of them, sometimes with a metallic component (pyrrhotite, pentlandite, etc.), low water solubility, stability to hydrolysis. The chemical composition of natural sulfides is usually complicated by numerous isomorphic impurities, mainly in the cationic part. Variable valence element sulfides, first of all, Fe and Cu, often form families of minerals close to or deviated from the composition stoichiometry (families of pyrrhotite, chalcocite, etc.). Only a few of natural sulfurs, being relatively pure, turn out to be colourless, transparent, adamantine-lustrous (cleiophane) while the overwhelming majority have polymetallic or metallic lustre. The common colour is from iron grey (galenite, antimonite, bismuthine) to black (martite, acanthite, chalcocite, covellite), some of them have a unique copper-yellow (chalcopyrite), cocoa brown (pyrrhotite, pentlandite) hue. A few of natural sulfurs are brightly coloured which is their typical diagnostic symptom (vivid red realgar, yellow orpiment, hayunite, dark red cinnabar). Tarnish involved by tin film of secondary oxidation products on the surface of some natural sulfurs (bornite, covellite, chalcopyrite, sometimes antimonite, etc.) is their diagnostic symptom.

A lot of natural sulfides feature cleavage in several directions (galenite, sphalerite, etc.), with cleavage along one plane is typical of lamellar structure sulfides (molybdenite, orpiment). Hardness of natural sulfides varies from one for molybdenite to 6-6.5 for marcasite and pyrite. Density varies from medium (Pb, Hg sulfides) to high (Pt sulfides).

The majority of sulfides are semiconductors or those possessing metallic conductivity (sulfides with metal-metal clusters in the structure). Some natural sulfurs feature magnetization (clinopyrrhotite), ductility (chalcocite, acanthite). The main bulk of natural sulfurs are hydrothermal generated, sulfides of magmatic and metamorphic genesis are also known, some of them result from exogenic processes. Natural sulfurs often form large clusters (pyrite and polymetallic deposits), and they are also typical of scarns where they are as a rule products of

later hydrothermal stages. Pyrite, sphalerite, galenite, chalcopyrite and some other natural sulfurs are typical of hydrothermal sediments (the Cheleken Peninsula), active volcanism regions (Kamchatka, etc.), they may emerge on the Earth's surface as well under reducing conditions (for instance, in H_2S -contaminated basins, sedimentary rocks - coals, phosphorite concretions, etc.), in cementation (secondary sulfide enrichment) zone of ore deposits. Minute teardrop sulfide phenocrysts in lavas of several volcanoes of the Klyuchevka group, Kunashir and Paramushir Islands, as well as differentiated teardrop chalcopyrite-pyrrhotite-pentlandite formations in basic rocks (for instance, at the Norilsk copper-nickel deposits).

Sulfide semiconductors (except cinnabar) are easily oxidized under surface conditions with transition to sulfates (often easy-soluble), and are replaced by oxides, carbonates, sometimes elementary substances (nugget copper, silver and other metals), silicates (hemimorphite by virtue of sphalerite), halogenides (halogenides of silver, lead, mercury and other metals).

Sulfide ores include compounds of heavy metals with sulfur (sulfides). Selenious, tellurios, arsenous and antimonious compounds of metals as well as pyrite deposit ores are also attributed to them. Sulfide ores are the basic source of nickel, copper, zinc, lead, molybdenum, bismuth, antimony and mercury. Depending on the ratio of sulfides and other minerals, there are identified massive ores, with the domination of sulfides, and veinlet or impregnated, with the domination of nonsulfide minerals. Sulfide ores can be simple or monometallic, and complex or polymetallic. Polymetallic sulfide ores which comprise sulfides of copper, zinc and lead, as well as complex ores of nickel and cobalt, antimony and mercury are particularly abundant. Platinum, gold, silver, cadmium, indium, selenium and tellurium as impurities are available in many sulfide ores. The overwhelming majority of sulfide ore deposits is attributed to endogenic deposits, with the domination of hydrothermal ones. Most often they form veins; besides, seams, lenses, stocks and pipe-like beds are available among them. Such sulfide ore bodies extend in length and depth by hundreds of metres and even kilometres; their ore reserves amount to hundreds of millions and even billions of tonnes, with metal reserves of up to tens or hundreds of thousands and even several millions of tonnes (with the metal content in the ore from tenth parts till several tens of per cent).

Natural oxides are chemical compounds of different elements with oxygen. Oxides of Si, Fe, Mn, Al and Cu and U to a lesser extent are the most abundant. The majority of them are ionic bond compounds but minerals of silica feature a covalent bond, just like those of As, Se, Te and chalcophile elements (Cu, Pb, Zn, Sn, Hg, Cd, In, Bi, Sb). The oxide class includes hydroxides and oxyhydrates containing O^{2-} and OH^- .

Simple natural oxides comprise minerals containing only one crystallochemical type of cations, i.e., compounds of RO , R_2O_3 , RO_2 type, among them isomorphic mixtures with the typical formulae as follows, for example, with isovalent isomorphism: Mg^{2+} , Fe^{2+} , Mn^{2+} , Fe^{2+} , Al^{3+} , Fe^{3+} , etc.).

The most widespread minerals are quartz, corundum, hematite, rutile, cassiterite, pyrolusite, uraninite, baddeleyite.

The most complex are minerals with two or more crystallochemical types of cations, the typical formulae are ABO_3 , AB_2O_4 , AB_2O_6 , $AB_1B_2O_6$, etc., for instance, spinel, chrysoberyl, titanotantaloniobates, wolframite, etc. The most widespread are magnetite, chrome-spinellids, spinel, ilmenite, wolframite, columbite-tantalite, pyrochlore-microlite, perovskite, loparite. Iso and heterovalent isomorphism is often manifested in oxides. isomorphic series are known among titanotantaloniobates.

The complex oxide series is characterized by substantial deviations of composition from stoichiometry which are connected with phenomena of ionic exchange and isomorphic introduction of high-charge ions (for example, U^{4+} , Th^{4+} , TR^{3+} instead of Ca^{2+} , and so on), adsorption of impurities and transition to metamict state.

Crystalline structures of the majority of natural oxides are constructed based on the concept of filling of voids in the densest packing of O^{2-} anions by cations. Here the densest

packing in simple natural oxides of high-charge cations (Ti^{4+} , Zr^{4+}) is very distorted. Even greater distortions are observed in complex natural oxides, for instance, titanates and titanotantaloniobates, which show a large variety of structural variants: chain, sublamellar and other, up to the loosest ones, shell variants (perovskite, pyrochlore). In general the density of natural oxides is lower than that of sulfides while the hardness is higher.

Titanotantaloniobates are distributed in pegmatites, carbonatites, rare-metal granites. Natural oxides are usually stable to oxidation processes and often accumulated in placers (magnetite, ilmenite, rutile, cassiterite, columbite, loparite, etc.) or weathering crusts (pyrochlore, columbite). On the contrary, individual natural oxides are formed in a narrow range of conditions, and therefore they are typomorphic of certain geological environments (for example, baddeleyite of carbonatites, chrysoberyl of scarn-greisen deposits).

The large practical value of natural oxides is predetermined by the fact that the most important ore minerals, like cassiterite, ilmenite, rutile, loparite, pyrochlore, microcline, tantalite, columbite, wolframite, baddeleyite, etc. are attributed to them.

The most abundant of salt-forming minerals are *carbonates*, salts of carbonic acid (H_2CO_3). More than 120 carbonates are known in nature. The following salts are distinguished: bicarbonates - acidic salts, hydrocarbonates - basic salts, water-free and water normal carbonates, complex carbonates (?) containing additional anions of F^- , Cl^- , $[\text{SO}_4]^{2-}$ or $[\text{PO}_4]^{3-}$. Uranile-carbonates occupy a particular position among carbonates. The leading cations in carbonates are Ca^{2+} , Mg^{2+} , Na^+ , Fe^{2+} , carbonates of Ba, Sr, Mn, Pb, Zn, Cu are more seldom encountered. Cations of Na^+ , K^+ , and $(\text{NH}_4)^+$ more often form bicarbonates or bi-salts (?). A series of carbonates and fluorocarbonates with (UO_2) , Ce^{3+} , La^{3+} .

Continuous isomorphism is manifested by Fe^{2+} - Mn^{2+} and Mg^{2+} - Fe^{2+} . The carbonate structure is mainly island with flat isolated triangular radicals.

Carbonates are typical vein minerals of medium and low-temperature hydrothermal deposits (lead-zinc, grey ore, arsenide, etc.). Vein bodies with rare-earth fluorocarbonates (bastnesite, cynchisite) in association with barite, fluorite, hematite of hydrothermal origin.

Carbonates of Pb, Zn, Cu, (UO_2) , more seldom Co, Ni are typical minerals of oxidation zones of ore deposits.

Wolframates, salts of tungsten acid (H_2WO_4), are of large value. A complex tetrahedron radical, $[\text{WO}_4]^{2-}$, stable in compounds with large cations, scheelite (CaWO_4) and stolzite (PbWO_4), is typical of them. Wolframates are crystallized in tetragonal syngony, island structures, isometric or tabular crystals.

The representatives of monocline wolframates are wolframite, $(\text{Fe}, \text{Mn})\text{WO}_4$, and samarskite, $(\text{Zn}, \text{Fe})\text{WO}_4$. Isomorphic replacements of WO_4^{2-} with MoO_4^{2-} (up to 20 % MoO_3 may be in scheelite) which lead to lower density of Mo-containing phases, as well as isomorphic Fe^{2+} - Mn^{2+} - Zn^{2+} replacements inherent of wolframite and samarskite which affect density are typical. Wolframite are formed during hydrothermal and scarn processes. Scheelite and wolframite are essential minerals of tungsten ores.

Molybdates are salts of molybdenum acid, RMO_4 , where R is mostly Ca, Fe, Cu, Pb, Bi, $\text{U}^{4+}(\text{UO}_2)^{2+}$. Impurities of W, As, Sb, P, etc. are sometimes available.

An isomorphic replacement of molybdenum with tungsten is typical. It means that a part of molybdates is crystallized in tetragonal (powellite, CaMoO_4 , and wulfenite, PbMoO_4), rhombic [ferrimolybdate, $\text{Fe}_2(\text{MoO}_4)_3 \cdot 7\text{H}_2\text{O}$, koechlinite, $\text{Bi}_2(\text{MoO}_4)_2\text{O}_2$, sedovite, $\text{U}^{4+}(\text{MoO}_4)_2$, etc.] and monoclinic syngony [lindgrenite, $\text{Cu}_3(\text{MoO}_4)_2(\text{OH})_2$, etc.]. Many uranyl molybdates are crystallized in rhombic and monoclinic syngony: umohite, $(\text{UO}_2)[\text{MoO}_4] \cdot 2-4\text{H}_2\text{O}$, iriginite, $(\text{UO}_2)[\text{HMoO}_4] \cdot 3\text{H}_2\text{O}$, calcumolite, $\text{Ca}(\text{UO}_2)_3[\text{MoO}_4]_3(\text{OH})_2 \cdot 7\text{H}_2\text{O}$, natrumolite $\text{Na}_2(\text{UO}_2)_5 \cdot [\text{MoO}_4]_5(\text{OH})_2 \cdot 8\text{H}_2\text{O}$, etc. Besides molybdates proper, a number of minerals which are arsenic-molybdenum and phosphorus-molybdenum compounds is attributed to molybdates. Molybdates are typical minerals of oxidation zones of polymetallic molybdenum and uranium deposits. Powellite is the most widespread secondary mineral of molybdenite deposits. Ferrimolybdate is typical of these deposits only with higher content of rhyolite or pyrrhotite in ore. They both have

no independent value though, if their accumulations are substantial, they can be used jointly with molybdenite as ore to produce molybdenum. Wulfenite is formed in oxidation zone of lead deposits which ores contain impregnation of molybdenite (polymetallic deposits of Central Kazakhstan), in some cases it is of industrial value (for example, for example, the Mammoth-Mine deposit, Arizona, USA).

Silicates are salts of silicic, iso and heteropolysilicic acids. Silicates account for for up to 75 per cent of the Earth's crust and about 25 percent of mineral types. More than seven hundreds of silicates, including rock-forming minerals (feldspars, pyroxenes, amphiboles, micas, are known in nature, etc.).

The crystalline structure of silicates is based on tetrahedron radicals, $[\text{SiO}_4]^{4-}$ or polymetric radicals, in which bridging O atoms bond two Si atoms of adjacent SiO_2 -tetrahedrons (in isopolysilicic radicals) or T atoma (T: Si, Al, B, Be, Fe^{3+} , etc.) in TO_4 - terrahedrons (in heteropolysilicic tadicals). Depending on T atom, the latter acquired the name pf alumo, boro, beryllo, ferri and other silicates.

The role of cations is played by Na, Mg, Al, Fe, K, Ca, Mn. The are the most abundant elements in the crust, containing up to 99 per cent of the crust's volume tpgtther with O and Si. Ti, Zn, TR are also usual elements. Slicates of V, Ni, Nb, Th, U, Sr, Cs, Ba. A particular position is occupied chalcophile elements: Cu, Zn, Sn, Pb, As, Sb, and Bi.

4.2.2. Properties of Minerals

Table 4.1 shows compositions, genesis, paragenesis of main minerals of non-ferrous ores as well as the CIS deposits in which these minerals play a substantial role. Some large world deposits associated with these minerals are also indicated for orientation.

Table 4.1. The main industrial minerals of non-ferrous metals [11, 16, 58, 78]

<i>Metal, mineralogy class, name, chemical formula</i>	<i>Composition, %</i>	<i>Generation, genesis</i>	<i>Paragenesis, associations of minerals</i>	<i>Examples of regions and deposits</i>
<i>Cu, sulfide Chalcopyrite CuFeS_2</i>	<i>Cu 31.5-34.4; Fe 30.6-32.4; S 35.0-36.5; Mn<3.0; As<1.5; Sb<1.0; Bi; Zn; In; Tl; Ag; Au; Pb; Sn; Se; Te; Co; Ni; Cd; Ge; Ga.</i>	<i>Exogenic; magmatic; scarn; hydrothermal</i>	<i>Pyrite; pyrrhotite; sulfides of Pb, Zn, Cu; magnetite; scheelite; andradite; etc.</i>	<i>Ural: Degtyarsk, Gay, Turya, Kalatinsk, Komsomolsk; Siberia: Norilsk, Talnakh, Udokan; Kazakhstan: Dzhezkazgan, Kounradsky; Uzbekistan: Almalyk; Armenia: Alaverdy; Canada: Sudbury; USA: Bingham; Zaire; Chile:</i>

<i>Cu</i> , sulfide Bornite <i>Cu₅FeS₄</i>	<i>Cu</i> 63.0-63.9; <i>Fe</i> 11.2-10.8; <i>S</i> 26.3-25.2; <i>Ge</i> ; <i>Re</i> ; <i>Se</i> ; <i>Te</i>	Hydrothermal, <i>Cu</i> -porphyric, <i>Cu</i> - sandstones; secondary enrichment zone	Chalcopyrite; pyrite; galenite; molybdenite; <i>Ag</i> ; <i>Cu</i> -sulfides; titanomagnetite; etc.	Chuquicamata; <u>Zambia</u> <u>Ural</u> : Volkovo, Levikha; <u>Caucasia</u> : Urup; <u>Armenia</u> : Alaverdy, Kafan; <u>Azerbaijan</u> : Kedabek <u>Kazakhstan</u> : Uzpenskoe, Dzhezkazgan; <u>Chile</u> ; <u>Mexico</u> : <u>USA</u> : Pioneer; <u>Yugoslavia</u> : Bor; <u>Namibia</u> : Tsumeb; etc.
<i>Cu</i> , sulfide Chalcocite <i>Cu₂S</i>	<i>Cu</i> 79.8; <i>S</i> 20.2; <i>Ag</i> < 0.2	Secondary enrichment zone	Bornite, covellite, chalcopyrite, pyrite, galenite, sphalerite, etc.	<u>Ural</u> : Turya, Talnakh; <u>Uzbekistan</u> : Almalyk; <u>Kazakhstan</u> : Kounradsky, Dzhezkazgan; <u>Namibia</u> : Tsumeb; <u>USA</u> : Butte, Bingham, Bisbee; <u>Yugoslavia</u> : Bor
<i>Cu-As</i> , sulfide Enargite <i>Cu₃AsS₄</i>	<i>Cu</i> 45.7-49.0; <i>As</i> 14.0-15.9 <i>S</i> 32.7-33.2; <i>Fe</i> < 2.5; <i>Sb</i> < 6.0; <i>Zn</i> ; <i>Se</i> < 1.0	Hydrothermal (medium and low- temperature)	Bornite, covellite chalcopyrite, chalcocite, pyrite, galenite, sphalerite, etc.	<u>Kazakhstan</u> : Kounradsky, Dzhezkazgan; <u>Armenia</u> : Kadzharan; Menz-Dzor; <u>Azerbaijan</u> : Bitty-Bulakh; <u>Uzbekistan</u> : Almalyk; <u>Yugoslavia</u> : Bor; <u>USA</u> : Butte; <u>Namibia</u> : Tsumeb; <u>Chile</u> : Chuquicamata; <u>Peru</u> ; <u>Japan</u>
<i>Cu</i> , oxide	<i>Cu</i> 88,8;	Exogenic;	Bornite, covellite	<u>Ural</u> :

Cuprite Cu_2O	$PbO < 0.9$; Fe_2O_3 , ZnO , Se , Ge , In .	weathering; oxidation zone of sulfide deposits	chalcopyrite, chalcocite, pyrite, malachite, gold, molybdenite, enargite, etc.	Mednorudyan- skoe; Turya, Gumeshevo; <u>Kazakhstan</u> ; Dzhezkazgan <u>France</u> : Shessy; <u>Namibia</u> ; Onganja; Otavi <u>Ural</u> ;
Cu , carbonate Malachite $Cu_2CO_3(OH)$	Cu 57.4; CaO , Fe_2O_3 , SiO_2	Exogenous: weathering; oxidation zone of sulfide deposits	Asurite, cuprite, chrysocolla; oxides & hydroxides of Cu , Fe , Pb , Zn , Mn	Mednorudyan- skoe; Turya, Gumeshevo; <u>Kazakhstan</u> ; Dzhezkazgan; <u>Zaire</u> ; <u>Namibia</u> ; <u>Israel</u> : Holan; <u>Germany</u> : Mansfeld <u>Norilsk</u> , Talnakh
Cu , sulfide Cubanite $CuFe_2S_3$	Cu 23.4; Fe 41.1; S 35.4 Ni , Au , Ag	Hydrothermal (high- temperature)	Chalcopyrite; pyrite; pyrrhotite, pentlandite, gold, galenite, magnetite	<u>Norilsk</u> , Talnakh; <u>Kola</u> ; Monchetundra; <u>Primorye</u> : Verkhnee; <u>Ural</u> ; <u>Yugoslavia</u> : Trepcha; etc.
Ni , Co , Pt ; Rh ; Ir ; Pd ; Ru ; Os , sulfide Pyrrhotite $Fe_{1-x}S$	$0 < x < 0.1$ $Ni < 8.8$; $Co < 0.4$; $Cu < 5.8$; Pb ; Mo ; As ; Se ; Sn ; Ag ; Pt ; Rh ; Ir ; Pd ; Ru ; Os .	Magmatic; scarn (contact- metasomatic); hydrothermal; metamorphic and oxidation zone	Pentlandite, pyrite, chalcopyrite; sulfide of Cu , Pb , Zn , Ni , Co , As ; magnetite	<u>Norilsk</u> , Talnakh; <u>Kola</u> ; Monchetundra; <u>Primorye</u> : Verkhnee; <u>Ural</u> ; <u>Yugoslavia</u> : Trepcha; etc.
Ni , Co , sulfide Pentlandite $Fe_4Ni_4(Fe, Ni,$ $Co)_{<1}S_8$	Fe 32.5; Ni 34.2; S 33.2; $Co < 1.3$; $Cu < 6.5$	Magmatic	Pyrrhotite; pyrite, chalcopyrite; sulfide of Cu , Fe , Pb , Zn , Ni , Co , As ; magnetite	<u>Norilsk</u> , Talnakh; <u>Kola</u> ; Monchetundra, Pechenga; <u>Canada</u> : Sudbury; Langis; <u>RSA</u> : Bushveld; <u>Finland</u> : Varislachty <u>Norilsk</u> , Talnakh; <u>Kola</u> ; Monchetundra; <u>Tuva</u> ; <u>Azerbaijan</u> : Dashkesan; <u>Canada</u> : Cobalt; <u>Mexico</u> : Sonora; <u>Zaire</u> ; <u>Norway</u> ;
Co , Ni , As , arsenide Cobaltite- gersdorffite $(Co, Ni)[AsS]$, smaltite $(Co, Ni)_4[As_4]_3$	$Co < 35.4$, Ni ; As 45.3; Fe ; $Rh < 5.8$; $Ir < 3.3$; $Ru < 3.3$; $Os < 3.2$; $Pt < 0.9$; $Te < 2.9$; $Se < 0.4$.	Hydrothermal	Arsenopyrite; sulfide of Cu , Pb , Zn , Ni , Co , As ;	<u>Norilsk</u> , Talnakh; <u>Kola</u> ; Monchetundra; <u>Tuva</u> ; <u>Azerbaijan</u> : Dashkesan; <u>Canada</u> : Cobalt; <u>Mexico</u> : Sonora; <u>Zaire</u> ; <u>Norway</u> ;

<i>As</i> , arsenide Arsenopyrite <i>FeAsS</i>	<i>As</i> 43.0-46.9; <i>Fe</i> 27.3-35.6; <i>S</i> 17.1-21.3; <i>Co</i> < 12.0; <i>Sb</i> ; <i>Bi</i> < 4.1; <i>Cu</i> ; <i>Pb</i> ; <i>Au</i> ; <i>Ag</i>	Hydrothermal (high and medium temperature), pegmatite, scarn	sulfide of <i>Cu</i> , <i>Pb</i> , <i>Zn</i> , <i>Ni</i> , <i>Co</i> , <i>Mo</i> ; gold; silver; cassiterite; scheelite; wolframite, etc.	<u>Czechia</u> ; <u>Morocco</u> . <u>Ural</u> : Kochkar, Dzhetygara; <u>Siberia</u> : Darasun, Zapokrovsk; <u>Norilsk</u> , Talnakh; <u>Kola</u> : Monchetundra, Pechenga; <u>Tuva</u> ; <u>Uzbekistan</u> : Uch-Imchak; <u>Azerbaijan</u> : Dashkesan; <u>Primorye</u> : Dalnegorsk; <u>Canada</u> : Cobalt; <u>Sweden</u> <u>Georgia</u> : Lukhumi; <u>Kyrgyzstan</u> : Khaidarkan; <u>Ore Altai</u> : Kamyshino, Novo- Solotushino; <u>Kamchatka</u> ; <u>Turkey</u> ; <u>Chile</u> ; <u>USA</u> ; <u>Greece</u> ; <u>Italy</u> ; <u>Czechia</u> ; <u>Japan</u> ; <u>Rumania</u> <u>Ore Altai</u> : Ridder, Zyryanovo; <u>Ural</u> : Berezovo; <u>Uzbekistan</u> : Altyn-Topkan; Kansay; Kurgashinkan; <u>Primorye</u> : Verkhnee; <u>N.Caucasia</u> : Sadon; <u>Transbaikalia</u> : Nerchinsk; <u>Yenisei</u> : Gorevsky; <u>Kazakhstan</u> : Mirgalimsay, Zhairam,
<i>As</i> , arsenide Realgar , <i>As₄S₄</i> ; Auripigment , <i>As₂S₃</i>	<i>As</i> 60.9-70.0; <i>S</i> 30.0-39.0; <i>Sb</i> < 3.0; <i>Cu</i> ; <i>Ag</i> ; <i>Hg</i> ; <i>Zn</i> ; <i>Pb</i> ; <i>Ge</i> ; <i>Se</i> .	Hydrothermal (low- temperature)	Sulfide of <i>Cu</i> , <i>Pb</i> , <i>Zn</i> , <i>Ni</i> , <i>Co</i> , <i>Mo</i> ; gold; silver; antimonite; marcasite	<u>Georgia</u> : Lukhumi; <u>Kyrgyzstan</u> : Khaidarkan; <u>Ore Altai</u> : Kamyshino, Novo- Solotushino; <u>Kamchatka</u> ; <u>Turkey</u> ; <u>Chile</u> ; <u>USA</u> ; <u>Greece</u> ; <u>Italy</u> ; <u>Czechia</u> ; <u>Japan</u> ; <u>Rumania</u> <u>Ore Altai</u> : Ridder, Zyryanovo; <u>Ural</u> : Berezovo; <u>Uzbekistan</u> : Altyn-Topkan; Kansay; Kurgashinkan; <u>Primorye</u> : Verkhnee; <u>N.Caucasia</u> : Sadon; <u>Transbaikalia</u> : Nerchinsk; <u>Yenisei</u> : Gorevsky; <u>Kazakhstan</u> : Mirgalimsay, Zhairam,
<i>Pb</i> , sulfide Galenite <i>PbS</i>	<i>Pb</i> 86.6; <i>S</i> 13.4; <i>Ag</i> ; <i>Sb</i> ; <i>Bi</i> ; <i>Se</i> ; <i>Te</i> ; <i>Tl</i> ; <i>Cd</i> ; <i>Mn</i>	Hydrothermal (medium and low- temperature); scarn, veins; metasomatic bodies	Sphalerite; pyrite; pyrrhotite; sulfides of <i>Cu</i> , <i>Ag</i> , <i>Fe</i> , <i>Zn</i> ; barite; quartz; calcite	<u>Czechia</u> ; <u>Morocco</u> . <u>Ural</u> : Kochkar, Dzhetygara; <u>Siberia</u> : Darasun, Zapokrovsk; <u>Norilsk</u> , Talnakh; <u>Kola</u> : Monchetundra, Pechenga; <u>Tuva</u> ; <u>Uzbekistan</u> : Uch-Imchak; <u>Azerbaijan</u> : Dashkesan; <u>Primorye</u> : Dalnegorsk; <u>Canada</u> : Cobalt; <u>Sweden</u> <u>Georgia</u> : Lukhumi; <u>Kyrgyzstan</u> : Khaidarkan; <u>Ore Altai</u> : Kamyshino, Novo- Solotushino; <u>Kamchatka</u> ; <u>Turkey</u> ; <u>Chile</u> ; <u>USA</u> ; <u>Greece</u> ; <u>Italy</u> ; <u>Czechia</u> ; <u>Japan</u> ; <u>Rumania</u> <u>Ore Altai</u> : Ridder, Zyryanovo; <u>Ural</u> : Berezovo; <u>Uzbekistan</u> : Altyn-Topkan; Kansay; Kurgashinkan; <u>Primorye</u> : Verkhnee; <u>N.Caucasia</u> : Sadon; <u>Transbaikalia</u> : Nerchinsk; <u>Yenisei</u> : Gorevsky; <u>Kazakhstan</u> : Mirgalimsay, Zhairam,

<i>Zn, Cd</i> , sulfide Sphalerite , (Wurtzite, Marcasite, Claiofane, Bruncite) <i>ZnS</i> Grinokite <i>CdS</i>	<i>Zn</i> > 67.1; <i>Fe</i> < 3 0; <i>Mn</i> < 5; <i>In</i> < 0.1; <i>Cd</i> 0.5-1; <i>Ge</i> < 0.3; <i>Ga</i> < 0.1 <i>Cd</i> 77.8	Hydrothermal (medium and low- temperature); scarn, veins; metasomatic bodies. Exogenic: sedimentary rocks; coal deposits	Galenite, pyrite, pyrrhotite; sulfides of <i>Cu</i> , <i>Ag</i> , <i>Fe</i> , <i>Zn</i> ; barite; quartz; calcite; coal	Achisay; <u>Canada</u> ; Sullivan; <u>USA</u> ; <u>Mexico</u> ; <u>Chile</u> ; <u>Australia</u> ; Broken Hill, McArthur. See galenite
<i>Pb, Sb</i> , sulfide Boulangerite <i>Pb₅Sb₄S₁₁</i> Jamesonite <i>Pb₄FeSb₆S₁₄</i>	<i>Pb</i> 40-58; <i>Sb</i> 23-32; <i>Cu</i> < 3.5; <i>Zn</i> < 6; <i>As</i> ; <i>Ag</i> ; <i>Bi</i> ; <i>Fe</i> ; <i>Mn</i> ; <i>S</i> 19- 22.	Hydrothermal (medium and low- temperature); veins	Galenite, sphalerite; pyrite, pyrrhotite; grey ores; arsenopyrite; carbonates	<u>Transbaikalia</u> : Algacha, Klichka, Zerentuy; Pochechuy; Spasskoe; <u>Uzbekistan</u> : Terek-Say, Gurdara; <u>Armenia</u> : Azatek; <u>Rumania</u> : Baja Sprie; <u>Yugoslavia</u> : Trepcha, Bor <u>Kazakhstan</u> : Achisay, Zmeinogorsk; Turlandsk; <u>Transbaikalia</u> : Kadainskoe; Nerchinsk; <u>USA</u> : <u>Aidaho</u> . <u>Kazakhstan</u> : Achisay; <u>Transbaikalia</u> : Kadainskoe; Nerchinsk; <u>Primorye</u> : Dalnegorsk; <u>USA</u> : <u>Ledwill</u> ; etc.
<i>Pb</i> , carbonate Cerussite <i>PbCO₃</i>	<i>Pb</i> 77.5; <i>SrO</i> < 3.2; <i>CaO</i> ; <i>ZnO</i> < 4.5; <i>Fe</i>	Exogenic: zone of oxidation	Galenite, anglesite, malachite, asurite , smitsonite, wulfenite, pyromorphite, etc.	<u>Transbaikalia</u> : Kadainskoe; Nerchinsk; <u>USA</u> : <u>Aidaho</u> . <u>Kazakhstan</u> : Achisay; <u>Transbaikalia</u> : Kadainskoe; Nerchinsk; <u>Primorye</u> : Dalnegorsk; <u>USA</u> : <u>Ledwill</u> ; etc.
<i>Zn</i> , carbonate Smitsonite <i>ZnCO₃</i>	<i>Zn</i> 52; <i>CuO</i> < 3.5; <i>Fe</i> ; <i>Mn</i> ; <i>MgO</i> < 7.6; <i>CoO</i> < 10; <i>CdO</i> < 2.7; <i>In</i>	Exogenic: zone of oxidation	Cerussite, malachite, asurite , limonite, opal, calcite	<u>Transbaikalia</u> : Kadainskoe; Nerchinsk; <u>Primorye</u> : Dalnegorsk; <u>USA</u> : <u>Ledwill</u> ; etc.
<i>Sb</i> , sulfide Antimonite	<i>Sb</i> 71.4-71.8; <i>As</i> ; <i>Pb</i> ; <i>Ag</i> ; <i>Au</i> ;	Hydrothermal (low-	Cinnabar, pyrite; fluorite, calcite;	<u>Kyrgyzstan</u> : Kadamdzhay;

(stibnite) <i>Sb₂S₃</i>	<i>Hg; Cu; Fe.</i>	temperature)	barite, quartz, chalcedony	<u>Krasnoyarsk region:</u> Razdolnoe; <u>Yakutia:</u> Sarylakh; <u>China:</u> Chsi Kuang-Shan; <u>Japan:</u> Ishinokawa
<i>Bi</i> , sulfide Bismuthinite <i>Bi₂S₃</i> Bismuth native <i>Bi</i>	<i>Bi 76.5-80.0; Se<5.0; Cu; Pb;</i> <i>Bi <100.</i>	Hydrothermal (high-temperature); veins, greisen, scarn	Bismuth native, pyrite, wolframite, chalcopryrite, cassiterite, quartz, topaz	<u>Transbaikalia:</u> Belukha, Bukukan; <u>Kazakhstan:</u> <u>Karaoba,</u> Akchatau; <u>Tajikistan:</u> Ustarasay, Adrasman; <u>Bolivia:</u> Tacna; <u>China:</u> Ta-U; Thsjan-Si, etc.
<i>Au, Ag, Cu, Ni, Co, As, Hg, Se, Tl</i> , sulfide Pyrite Marcasite <i>FeS₂</i>	<i>Fe 46,5; S 53.4; Cu, Au, Ag, Co, As, Hg 0.n-0.0n; Se, Tl 0.0n-0.00n;</i>	Magmatic; hydrothermal; sedimentary; metamorphic	Sulfides of <i>Cu, Ni, Pb, Zn, As, Sb, Fe, Zn;</i>	<u>Ural:</u> Kalatinsk, Uchala, etc. <u>Spain:</u> Rio-Tinto; <u>Norway:</u> Sulitjelma; See: deposits of <i>Cu, Ni-Co; Pb-Zn; As, Sb, Bi, Hg; Au-Ag</i>
<i>Hg</i> , sulfide Cinnabar <i>HgS</i>	<i>Hg 86.2; Se<1; Sb, As, Te, Cu, Zn, Cd</i>	hydrothermal (low-temperature);	Antimonite, pyrite, realgar, fluorite, barite, chalcedony, carbonates	<u>Kyrgyzstan:</u> Khaidarkan, Chauvay; <u>Donbas:</u> Nikitovka; <u>Kazakhstan:</u> Aktash, Chagan-Uzun; <u>Chukotka:</u> Plammenoe; <u>Spain:</u> Almaden; <u>Italy:</u> Monte Amiata; <u>USA:</u> <u>China:</u> <u>Yugoslavia</u> <u>Transbaikalia:</u> Davenda, Dzhida; Shakhtama; <u>Krasnoyarsk</u> <u>Krai:</u> Sorskoe;
<i>Mo, Re</i> , sulfide Molybdenite <i>MoS₂</i>	<i>Mo 60.0; Ti<2; Re 0.n-1.8; Nb, V, Se, As, Zn <0.0n</i>	Hydrothermal (high, medium temperature); pegmatitic veins, scarn	Pyrite, chalcopryrite; sulfide of <i>Cu, Fe, Bi, As;</i> quartz, cassiterite,	

			scheelite, wolframite, etc.	<u>N.Caucasia:</u> Tyrnyauz; <u>Armenia:</u> Kadzharan; <u>Kazakhstan:</u> Eastern Kounradsky, Karaoba; <u>Uzbekistan:</u> Almalyk; <u>Mongolia:</u> Erdrnet; <u>USA:</u> Climax; <u>China:</u> <u>Morocco:</u> <u>Burma</u> <u>Transbaikalia:</u> Davenda, Dzhida; <u>Krasnoyarsk</u> <u>Krai:</u> Sorskoe; <u>N.Caucasia:</u> Tyrnyauz, Lermontov; <u>Primorye:</u> Vostok -2; <u>Armenia:</u> Kadzharan; <u>Kazakhstan:</u> Eastern Kounradsky, Verkhnee Kairakty; Bogut; Akchatau; <u>Tajikistan:</u> Charukh- Dairon, Manchar; <u>Mongolia:</u> Erdrnet; <u>USA; Korea:</u> <u>Australia:</u> <u>Austria:</u> <u>Bolivia; etc.</u> <u>Transbaikalia:</u> Dzhida, Bukukan, Sherlovaya Gora; <u>Kolyma:</u> <u>Uzbekistan:</u> Kalmakyr;
<i>W, Mo,</i> tungstate, molybdate Scheelite <i>CaWO₄</i> Powellite <i>CaMoO₄</i>	<i>WO₃ 80.6;</i> <i>Mo 8-12;</i> <i>Mn<0.8;</i> <i>TR<0.5; Cr,</i> <i>Cu;</i> <i>MoO₃ 72.0;</i> <i>W<7; TR</i>	Hydrothermal (high and medium temperature); pegmatic veins, scarn; Exogenic: zone of oxidation	Pyrite, chalcopyrite; sulfide of <i>Cu,</i> <i>Fe, Bi,As;</i> quartz, cassiterite, wolframite	
<i>W, Sc, Nb, Ta,</i> tungstate Wolframite <i>(Fe,Mn)WO₄ ;</i> Ferberite <i>FeWO₄ ;</i> Hubnerite	<i>WO₃ 76.5</i> <i>Mn 17.6-23.4;</i> <i>Mg<0.5; Sn;</i> <i>Nb; Ta; Sc; Ti;</i> <i>TR;</i>	hydrothermal (high, low- temperature); pegmatitic veins, scarn; sedimentary rock	molybdenite, cassiterite, beryl; columbite, scheelite, gematite, quartz, fluorite	

$MnWO_4$				<u>Kazakhstan:</u> Akchatau, Karaoba; <u>Georgia:</u> Zopkhito, Racha; <u>China:</u> <u>Burma;</u> <u>Bolivia;</u> <u>Japan;</u> <u>Mongolia</u> <u>Portugal</u>
<i>Mo, Pb,</i> molybdate Wulfenite <i>PbMoO₄</i>	<i>PbO 60.7;</i> <i>MoO₃ 39.3;</i> <i>W, Cr, V, Ca,</i> <i>Cu, Mg</i>	Exogenic: zone of oxidation	Hydroxides of <i>Fe, Cu, Pb, Zn;</i> calcite; etc.	<u>Kazakhstan:</u> Sulemansay <u>Tajikistan:</u> Charukh- Dairon; <u>Yugoslavia:</u> Trepcha; <u>Kolyma:</u> <u>Chukotka;</u> <u>Yakutia;</u> <u>Primorye:</u> Khrustalnoe, Dalnee; <u>Khabarovsk:</u> Solnechnoe, Perevalny; <u>Transbaikalia:</u> Ononsk; Khapcharanga, Etyka; <u>Tajikistan:</u> Maikhura; <u>Bolivia;</u> <u>Thailand;</u> <u>Burma;</u> <u>Indonesia;</u> etc.
<i>Sn, oxide</i> Cassiterite <i>SnO₂</i>	<i>Sn 78.8;</i> <i>Nb, Ta, W, Fe,</i> <i>Zn, Mn</i>	hydrothermal (low temperature); pegmatitic veins, scarn; sedimentary rock	Wolframite, lepidolite; vismutin; columbite, scheelite; molybdenite, chalkopyrite etc.	<u>Transbaikalia:</u> Etyka, Belukha, Bukukan; <u>Primorye:</u> Sinyukha <u>Bolivia:</u> Sjero- Riko, Ljaljgua <u>Ural:</u> Sysert; Kutim, <u>Kazakhstan:</u> Semiz-Bugu; <u>Norway;</u> <u>Madagascar;</u> <u>Alps.</u> <u>USA:</u> Nelson,
<i>Sn, sulfide</i> Stannite <i>Cu₂FeSnS₄</i>	<i>Sn 27.6; Cu</i> 29.6; <i>Zn; Ag</i>	Hydrothermal (low- temperature)	Cassiterite, sphalerite, chalopyrite, pyrrhotite, etc.	<u>Eastern</u> <u>Transbaikalia:</u> Etyka, Belukha, Bukukan; <u>Primorye:</u> Sinyukha <u>Bolivia:</u> Sjero- Riko, Ljaljgua <u>Ural:</u> Sysert; Kutim, <u>Kazakhstan:</u> Semiz-Bugu; <u>Norway;</u> <u>Madagascar;</u> <u>Alps.</u> <u>USA:</u> Nelson,
<i>Ti, Nb, Ta,</i> oxide Rutile, Anatase, Brookite <i>TiO₂</i>	<i>Ti 60.0; Fe<11;</i> <i>Nb; Ta; Sn; V;</i> <i>Cr</i>	Magmatic; metamorphic; hydrothermal;	Cyanite, quartz, pyrophyllite, albite, sphene, apatite, fluorite	<u>Kazakhstan:</u> Semiz-Bugu; <u>Norway;</u> <u>Madagascar;</u> <u>Alps.</u> <u>USA:</u> Nelson,

<i>Ti</i> , oxide Ilmenite $FeTiO_3$	<i>Ti</i> 31.6; <i>Fe</i> .8; <i>Mn</i> ; <i>Nb</i> ; <i>Cr</i> 36; <i>Mg</i> ; <i>V</i>	Magmatic (pegmatite)	Feldspar, nepheline; sphene, biotite, kimberlites; carbonatites	Colorado; <u>Australia</u> <u>Ural</u> : Ilmen Mountains; Vishnevaya Gora; <u>Kola</u> : <u>Khibini</u> ; <u>Ukraine</u> : Samotkannoe; <u>Canada</u> : <u>Australia</u> ; <u>India</u> : <u>Sierra Leone</u>
<i>Ti</i> , <i>Nb</i> , <i>Ta</i> , <i>TR</i> , oxide Perovskite $CaTiO_3$ Loparite (<i>Ca</i> , <i>Na</i> , <i>Ce</i>). (<i>Ti</i> , <i>Nb</i>) $_2O_6$	TiO_2 58.9; Nb_2O_5 <26; TR_2O_3 <8; <i>Ta</i> ; <i>Th</i> ; <i>Fe</i> ; <i>Mg</i> ; <i>Sr</i> ; <i>Zr</i> ; <i>V</i>	Magmatic (pegmatite); contact- metasomatic, scarn	albite, sphene, apatite, fluorite, garnet, pyroxene, vesuvianite, chlorite	<u>Ural</u> : Shishim, Nazyam; <u>Kola</u> : Lovosero, Vuoriyarvi; <u>Transbaikalia</u> : Tazeran; Burpaly; <u>Sikhote Alin</u> : <u>Tuva</u> : Kogeredaba, Dugdu;
<i>Ti</i> , <i>Nb</i> , <i>Ta</i> , <i>TR</i> , oxide Sphene (titanite) $Ca(TiO)[SiO_4]$	TiO_2 40,8; TR_2O_3 <12; Nb_2O_3 <7; SnO_2 <10; Fe_2O_3 <8; Al_2O_3 <6; MnO <4; ZrO_2 ; <i>F</i> ; <i>Cl</i> ; <i>Sr</i> ; <i>Mg</i>	Magmatic (pegmatite); contact- metasomatic, scarn	Nepheline, garnet, apatite, fluorite, ilmenite, aegirine, zircon, magnetite pyrochlore, biotite, diopside, andesite	<u>Kola</u> : Khibini, Lovosero; <u>Baikal</u> : Slyudyanka; <u>Ural</u> : Ilmen, Vishnevaya Gora; <u>France</u> : Bressan; <u>Austria</u> : Alps; <u>Brazil</u> : <u>Kola</u> : Kovdor
<i>Zr</i> , oxide Baddeleyite ZrO_2	ZrO_2 96.5-98.9; HfO_2 <3.0; Fe_2O_3 <1	Magmatic (carbonatite)	Zircon, magnetite, nepheline, garnet, apatite, fluorite, ilmenite, aegirine, turmaline, corundum, perovskite, pyrochlore	
<i>Zr</i> , oxide Zircon $ZrSiO_4$	ZrO_2 67.0; <i>Hf</i> ; <i>A</i> ; <i>To</i> ; <i>A</i> ; <i>OR</i> ; <i>A</i> ; <i>Be</i> ; <i>A</i> ; <i>Or</i> ; <i>A</i> ; <i>No</i> ; <i>A</i> ; <i>A</i> .	Magmatic (pegmatite); hydrothermal	Ilmenite, rutile, pyrochlore, aegirine, albite, biotite, sphene, apatite, fluorite, ortite, thorite	<u>Ukraine</u> : Samotkannoe; <u>Ural</u> : Ilmen, Vishnevaya Gora; <u>Kola</u> : Khibini, Lovosero; <u>Kazakhstan</u> :

<i>Be</i> , silicate	<i>Be</i> 5-12;	Pegmatite	Feldspar; quartz;	<u>Altai; Tuva,</u>
Beryl	<i>SiO₂</i> 55-70; <i>Ca</i> ,	veins;	muscovite,	<u>Yakutia,</u>
<i>Be₃Al₂(Si₆O₁₈)</i>	<i>Al, Fe, Mn, Na,</i>	High-	tourmaline,	<u>Nothorn</u>
Phenacite	<i>Ce, Y, Li, Rb,</i>	temperature	albite, topaz,	<u>Kyrgyzstan:</u>
<i>Be₂(SiO₄)</i>	<i>Sc</i>	hydrothermal	wolframite,	<u>Norway:</u>
Bertrandite			cassiterite,	<u>Australia; Sri-</u>
<i>Be₄(Si₂O₇)</i>			molybdenite	<u>Lanka; Chile;</u>
<i>(OH)₂</i>				<u>Namibia;</u>
Helvite				Karibaba;
<i>Mn₄(BeSiO₄)₃S</i>				<u>Kampuchea;</u>
				<u>Mogouka;</u>
				<u>Ural;</u>
				<u>Transbaikalia;</u>
				<u>Kazakhstan;</u>
				Akchatau;
				Kentau;
				<u>Ukraine;</u>
				<u>USA:</u> Nevada,
				S.Dakota;
				Colorado; <u>RSA;</u>
				<u>Madagascar;</u>
				<u>Afghanistan;</u>
				<u>Columbia;</u>
				<u>Brazil:</u> Minas-
				Gerais; <u>France:</u>
				Frimont;
				<u>China</u>
<i>TR, Y, Th,</i>	<i>TR₂O₃ <21;</i>	Magmatic,	Monazite,	<u>Ural:</u> Ilmen
silicate	<i>ThO₂ <2.8;</i>	pegmatite	zircon,	Montains;
Orthite	<i>U₃O₈ <0.01;</i>		magnetite,	Vishnevaya
<i>Ce₂Fe₂AlO</i>	<i>Y₂O₃ < 12;</i>		apatite, ilmenite,	Gora; <u>Baikal;</u>
<i>(OH)[SiO₂]</i>			rutile,	Slyudyanka;
<i>[Si₂O₇]</i>			pyrochlore,	<u>Kola:</u> Lovosero;
			aegirine, albite,	<u>Ukraine:</u>
			biotite, sphene,	Saltychya
			fluorite, thorite	Mogila; <u>Tuva:</u>
				Ersin;
				<u>Primorye:</u> Maly
				Khingan;
				<u>Uzbekistan:</u>
				Kara-Tyube;
				<u>Kyrgyzstan:</u>
				Basy-Gya;
				<u>Armenia:</u>
				Kadzharan;
				<u>Brazil:</u> Pokos-
				do-Saldos;
				<u>USA;</u> Germany;
				<u>India</u>
<i>TR, Th,</i>	<i>TR</i> 50-68;	Pegmatite,	Orthite, zircon,	<u>Kola; Ural;</u>
phosphate	<i>Th</i> 4-9;	pneumatholite	magnetite,	<u>Kyrgyzstan:</u>
Monazite	<i>U</i> 0.25-19.6;	-	apatite, ilmenite,	<u>India:</u>

(Ce, La...)[PO ₄] Xenotime Y[PO ₄]	P ₂ O ₅ 22-31.5; Ca, Fe, Pb, Al	hydrothermal; metamorphic- weathering	rutile, pyrochlore, biotite, fluorite, thorite, uraninite	Travancore; <u>Sri Lanka</u> , <u>Madagascar</u> ; <u>Brazil</u> ; <u>USA</u> ; <u>RSA</u> ;
TR, P, phosphate Apatite Ca ₅ [PO ₄] ₃ (F, Cl, OH, O)	P ₂ O ₅ 41-42.3; TR < 9; Th < 4; Sr < 19; U, Mn, Fe, Mg, Al, F, Cl	Magmatic, pegmatite vein, carbonatite	Nepheline, calcite, magnetite, perovskite, diopside, muscovite, phlogopite	<u>Kola</u> ; <u>Khibini</u> , <u>Kovdor</u> ; <u>Baikal</u> ; <u>Oshurkovo</u> , <u>Slyudyanka</u> ; <u>Moscow basin</u> ; <u>Egorievsk</u> ; <u>Yakutia</u> ; <u>Seligdar</u> ; <u>Kasakhstan</u> ; <u>Karatau</u> ; <u>Morocco</u> ; <u>Algeria</u> ; <u>Tunisia</u> ; <u>Norway</u> ; <u>India</u>
F, halide Fluorite CaF ₂	F 48.8; Sr, TR, Mn, Mg, Y, Be	Low- temperature hydrothermal, scarn	Barite, calcite, sulfides, topaz, muscovite, quartz, tourmaline, wolframite, cassiterite, garnet	<u>Primorye</u> ; <u>Transbaikalia</u> ; <u>Kalanguy</u> ; <u>Arkhangelsk</u> ; <u>Amderma</u> ; <u>Tajikistan</u> ; <u>Aurachmat</u> , <u>Takob</u> ; <u>Kasakhstan</u> ; <u>Badam</u> ; <u>Uzbekistan</u> ; <u>Khaidarkan</u> <u>USA</u> ; <u>Mongolia</u> ; <u>Italy</u> ;
Li, silicate Spodumene LiAl[Si ₂ O ₆]	Li ₂ O < 8.1; Al, Na, Cs, K, Fe, Mn	Pegmatite	Quartz, feldspar , tourmaline, beryl, lepidolite, cassiterite, tantalite, muscovite	<u>East.Siberia</u> ; <u>Pervomaiskoe</u> ; <u>Kasakhstan</u> ; <u>USA</u> : <u>S.Dakota</u> ; <u>Canada</u> , <u>Madagascar</u> ; <u>Brazil</u> <u>Afghanistan</u> ;
Li, alumosilicate Lepidolite KLiAl [Si ₃ AlO ₁₀] (OH, F) ₂ ; Zinnvaldite KLiFeAl [Si ₃ AlO ₁₀]	Li ₂ O 1.23-5.9; Rb < 4; Cs < 1.8; Na < 1; K 4-12; Fe, Mg, F	Pegmatite, greisen	Quartz, feldspar , tourmaline, beryl, spodumene, cassiterite, muscovite	<u>Ural</u> , <u>East.Siberia</u> ; <u>Pervomaiskoe</u> ; <u>Kasakhstan</u> ; <u>Ukraine</u> ; <u>Czechia</u> ; <u>Rosena</u> ; <u>Zinnvald</u> ; <u>USA</u> : <u>Men</u> ; <u>Sweden</u> ; <u>Utah</u>

<p><i>Nb, Ta, TR, U</i>, tantaloniobate Columbite $(Fe,Mn)Nb_2O_6$ Tantalite $(Fe,Mn)Ta_2O_6$ Samarskite $Y(Fe,U)$ $(Ta,Nb)_2O_8$</p>	<p>$Nb+Ta < 80$; $TR < 2$; $Ti < 2$; $W < 0.5$; $Zr < 0.7$; $U < 1$; Mn, Fe, Sn</p>	<p>Pegmatite, albitized granites</p>	<p>Albite, quartz, microcline, lepidolite, zircon; tourmaline, beryl, spodumene, cassiterite, muscovite, apatite, biotite, phosphates of <i>Mn, Fe</i> Microcline, zircon, ilmenite, aegirine, titanite, magnetite, albite, spodumene, lepidolite</p>	<p><u>East.Siberia:</u> Belaja Zima; <u>Transbaikalia:</u> <u>Kazakhstan:</u> <u>Brazil:</u> Nazareno; <u>ARE:</u> Abu Dobabb; <u>Nigeria</u> <u>USA:</u> Black Hills; <u>Norway:</u> <u>Madagascar</u> <u>Ural:</u> Ilmen, Vishnevaya Gora; <u>Yakutia:</u> <u>Kazakhstan:</u> <u>Tanzania</u></p>
<p><i>Nb, Ta, TR, U</i>, tantaloniobate Pyrochlore $NaCa[Nb_2O_6$ $(OH,F)]$ Microlite $NaCa[Ta_2O_6$ $(OH,F)]$ <i>TR</i>, carbonate Parisite $Ce_2Ca[CO_3]_3$ F_2 Bastnesite $Ce[CO_3]_3F$</p>	<p>$Nb+Ta < 80$; $TiO_3 < 13$; $U < 20$; $TR < 13$;</p>	<p>Pegmatite, carbonatite</p>	<p>Orthite, calcite, albite, aegirine, titanite, zircon, pyrochlore, barite, fluorite</p>	<p><u>East.Sayan:</u> <u>Kola:</u> <u>East.Yakutia:</u> <u>Ural:</u> <u>Yenisei</u> <u>Krai</u> <u>USA:</u> Mountain Pass; Snowberd; <u>Sweden:</u> Bastnes; <u>Columbia:</u> Muso <u>Vietnam</u> <u>Povolzhye:</u> <u>Arkhangelsk</u> <u>Uzbekistan:</u> Lyakkan; <u>Kazakhstan:</u> Mangyshlak <u>Italy:</u> Secily; <u>Germany, UK,</u> <u>USA</u> <u>Ural:</u> Kachkanar (<i>V</i>), Kusin, Nizhny Tagil, Pervouralsk (<i>Ti</i>); Magnitogorsk, Sokolovsk, Sarbay; <u>Kursk:</u> <u>Mountain</u></p>
<p><i>Sr</i>, sulphate Celestite $SrSO_4$</p>	<p>SrO 56.4; Ba, Ca</p>	<p>Volcanic, sedimentary low- temperature hydrothermal</p>	<p>Gypsum, calcite, barite, native copper</p>	<p><u>USA:</u> Mountain Pass; Snowberd; <u>Sweden:</u> Bastnes; <u>Columbia:</u> Muso <u>Vietnam</u> <u>Povolzhye:</u> <u>Arkhangelsk</u> <u>Uzbekistan:</u> Lyakkan; <u>Kazakhstan:</u> Mangyshlak <u>Italy:</u> Secily; <u>Germany, UK,</u> <u>USA</u> <u>Ural:</u> Kachkanar (<i>V</i>), Kusin, Nizhny Tagil, Pervouralsk (<i>Ti</i>); Magnitogorsk, Sokolovsk, Sarbay; <u>Kursk:</u> <u>Mountain</u></p>
<p><i>Fe, V, Ti</i>, oxide, Magnetite $FeO.Fe_2O_3$ Titano- magnetite $TiO_2.FeO$ Fe_2O_3</p>	<p>Fe 72.4; $TiO_2 < 7.5$; $V < 4.8$; $Al < 15$; Ni, Mn, Ga, Be</p>	<p>Magmatic; scarn; hydrothermal; metamorphic</p>	<p>Apatite, hematite, perovskite, ilmenite, pyroxene, sulfides, carbonates, etc.</p>	<p><u>USA:</u> Mountain Pass; Snowberd; <u>Sweden:</u> Bastnes; <u>Columbia:</u> Muso <u>Vietnam</u> <u>Povolzhye:</u> <u>Arkhangelsk</u> <u>Uzbekistan:</u> Lyakkan; <u>Kazakhstan:</u> Mangyshlak <u>Italy:</u> Secily; <u>Germany, UK,</u> <u>USA</u> <u>Ural:</u> Kachkanar (<i>V</i>), Kusin, Nizhny Tagil, Pervouralsk (<i>Ti</i>); Magnitogorsk, Sokolovsk, Sarbay; <u>Kursk:</u> <u>Mountain</u></p>

<i>Al, Ga</i> , oxides and hydroxides Bauxite: Gibbsite $Al(OH)_3$; Diaspore $AlOOH$; Boehmite $AlO(OH)$	Al_2O_3 65-98; <i>Fe, Cr, Ti, Mg, Ga</i>	Exogenic, weathering	Oxides and hydroxides of <i>Fe</i> , corundum, alunite, kaolineite, calcite, pyrolusite	<u>Shoria; Baikal</u> , <u>Ukraine: Krivoi Rog</u> , <u>Azerbaijan</u> <u>Dashkesan</u> ; <u>Kazakhstan</u> <u>Kochkar</u> , <u>Kurzhunkul</u> ; etc. <u>N. and S.Ural:</u> <u>Krasnaya Shapochka</u> , <u>Kosoy Brod</u> , etc. <u>St.-</u> <u>Petersburg:</u> <u>Tikhvin</u> ; <u>Siberia:</u> <u>Jamaica</u> , <u>Guiana, Guinea</u> , <u>Australia, USA</u> , <u>Surinam, India</u> , <u>Cuba</u>
<i>Al, Ga</i> aluminosilicate Nepheline $KNa_3[SiAlO_4]_4$	$Al_2O_3 < 34.6$; $Na_2O < 17$; $K_2O < 11$; <i>Fe, Ca, Mg, Ti, Ga, Li, Rb, Cs</i>	Magmatic: syenite, pegmatite	Apatite, aegirine, feldspar, biotite, ilmenite, sphene, zircon, albite, quartz, zeolite	<u>Kola: Khibini</u> ; <u>Lovosero</u> ; <u>Ural: Ilmen</u> , <u>Vishnevaya Gora</u> ; <u>Kusnetsk</u> <u>Alatau:</u> <u>Belogorsk</u> ; <u>Canada:</u> <u>Kamchatka:</u> <u>Ural:</u> <u>Azerbaijan:</u> <u>Zaglik</u> ; <u>Ukraine:</u> <u>Uzbekistan:</u> <u>China: Taichow</u> ; <u>Italy: USA:</u> <u>Ural: St.-</u> <u>Petersburg:</u> <u>Troitsko-Bainovsk</u> ; <u>East.Siberia:</u> <u>Caucasia:</u> <u>Ukraine:</u> <u>Chasov Yar</u> ; <u>Glukhovo</u> ; <u>Uzbekistan:</u> <u>Angren</u>
<i>Al, Ga</i> , Sulphate, Alunite $KAl_3[SO_4]_2(OH)_6$	Al_2O_3 37; K_2O 11.4; $Sr < 5.9$; $TR_2O_3 < 1.7$; <i>P, Ga</i> ,	Hydrothermal -volcanic	Oxides and hydroxides of <i>Fe</i> , corundum, alunite, kaolineite, calcite, pyrolusite Feldspars, quartz, muscovite, corundum, coal.	
<i>Al, ceramics</i> , aluminosilicate Kaolineite $Al_4[Si_4O_{10}](OH)_8$	Al_2O_3 39.5; <i>Fe, Mg, Ca, Ba, Na, K</i>	Exogenic, weathering		
<i>Al</i> , abrasive, precious	Al_2O_3 96-98.6; <i>Fe, Ti, Cr</i>	Magmatic: pegmatite;	Bauxite, feldspar,	<u>Ural: Berezovo</u> , <u>Ilmen, Kosoy</u>

stones, oxide Corundum Al_2O_3		contact- metamorphic	nepheline, shpine l carbonates, garnet, hematite,	Brod; Raiz <u>Kazakhstan</u> ; Semizbugy; <u>Yakutia</u> ; <u>Burma</u> , <u>Sri</u> <u>Lanka</u> ; <u>India</u> ; <u>Thailand</u> ; <u>Greece</u> <u>Ural</u> ;
<i>Mg, refractory material, oxides and hydroxides</i> Brucite $Mg(OH)_2$ Periclase MgO	<i>MgO 69-80; MnO < 18; Fe, Zn, Ca, Al</i>	Contact- metasomatic	Dolomite, magnesite, asbestos, chromite, talc, chloritoid, calcite	Bazhenov; Baikal; <u>Yakutia</u> ; <u>Kazakhstan</u> ; Almaz- Zhemchuzhina; <u>Canada</u> ; <u>Italy</u> ; <u>Korea</u> ; <u>USA</u> <u>Ural</u> : Satka,
<i>Mg, refractory material, carbonate,</i> Magnesite $Mg[CO_3]$	<i>MgO 47.6; Fe, Mn, Ca, Si, Co, Ni</i>	Metasomatic, hydrothermal, weathering	Carbonates, talc, chloritoid, barite, serpentine	<u>Khalilovo</u> ; <u>Baikal</u> ; Savinskoe; <u>China</u> , <u>Austria</u> ; <u>Canada</u> ; <u>Spain</u> ; <u>USA</u> <u>Ural</u> ;
<i>Mg, K, Br, halide</i> Carnallite $KMgCl_3 \cdot 6H_2O$	<i>Mg, K, Na , Fe, Br, Rb, Cs, Tl, Ni, Cu</i>	Chemical sediment	Gypsum, anhydrite, halite, sylvite, bishofite	<u>Byelarus</u> ; Starobinsk; <u>Transcarpath-</u> <u>ians</u> : <u>Kalush</u> ; <u>Israel</u> : <u>Dead</u> <u>Sea</u> ; <u>Germany</u> ; Strassfurt
<i>Mg, halide,</i> Bishofite $MgCl_2 \cdot 6H_2O$				

4.3. Mechanical Properties of Minerals. Ore Preparation

Mechanical properties of minerals are variable not only within different specimens of one and the same mineral but also within each specimen. This is connected with anisotropy of crystals which properties are varying along different crystallographic directions. Here not only deformation, hardness, ductility values differ but, for instance, crystal may behave as ductile along one direction and fragile along the other direction. Mechanical properties of minerals become manifested when mechanical actions are applied to them by external forces during compression, stretching or impact. This involves changes in mineral form and continuity. Deformations distinguished are as follows: elastic, embrittlement and plastic.

4.3.1. Deformation of Crystals

Tensile and compression crystal deformation behaviour is illustrated in Fig.4.4. Stress σ characterizes value of internal forces P per unit of area S of the specimen under tension: $\sigma = P/S$, kg/cm². Relation elongation (or compression): $\delta (\epsilon) = (\Delta l)/l$.

At initial tension stages crystal stresses grow approximately in proportion to deformation, therefore the curve in the O-A section is shown as a straight length. Deformation within this section is reversible, being completely removed at disloading, that is why it is named elastic. Maximum stress up to which value crystal retains elastic properties is named elastic limit, σ_s . Loads above the elastic limit cause residual crystal strains, here the crystal is rapidly stretched, decreasing the σ - δ curve tilt with respect to the axis δ (the AB section). Some crystals in this curve length show a horizontal plateau (Fig.4.4a) named “yield plateau”. It exhibits a moment when the crystal elongation grows without load increase, i.e., crystal begins “to flow”. Stress corresponding to it is named “yield strength, σ_T ”. Transition to yield plateau sometimes starts from a sharp peak or “yield drop” (Fig.4.4b). In this case upper (σ_{T1}) and lower (σ_{T2}) yield limits. Residual deformation, σ_{res} , retained on removal of external load is called plastic (the BC length). Further load increase and stress growth lead to rupture and crystal fracture. The largest stress which was induced in crystal during the test time and led to specimen rupture shows tensile strength, σ_B . Under these circumstances it also corresponds to maximum external load. The area formed by the tension curve and the axis δ accounts for the energy consumed in crystal rupture.

If a crystal diagram shows plastic deformation region, the crystal is called plastic. If a crystal reaches the fracture point without any large pre-elongation and the tensile strain-stress diagram is broken off just after the elastic limit, the crystal is called brittle. Brittleness is the ability of minerals to crumble as a result of instantaneous application of external forces, be broken without noticeable plastic deformations (no more than 5 per cent of fracture deformation value). The majority of rocks are predisposed to such fracture and is therefore attributed to fragile materials.[79,80].

Brittleness is governed by mineral composition, structure-texture characteristics and external fracture conditions: temperature, rate of force application, load type (tensile, compression, shift).

Powder which is easily blown off remains on the scratch edges for a brittle mineral, for example, grey ore. An even-edged bright groove is left on the surface of chalcocite, nugget metals which change the shape and are flattened on impact, i.e., they feature ductility.

Elasticity is inherent of minerals which initial dimensions and shapes are restored after external loads are removed. For instance, micas show high elasticity. Elasticity is connected with strength and type of interatomic bonds. As temperature increases elasticity falls. If elastic limit is exceeded, brittle or plastic deformations emerge.

Deformation rate produces a substantial effect on deformation behaviour. Higher deformation rate promotes brittle fracture.

A scale factor is of great importance: very fine crystals feature much higher strength as compared with coarse crystals of the same mineral.[11,79,80]

The phenomenological theory of elasticity studies crystal to be an anisotropic homogenous body which elastic properties do not depend on a position of the point under examination inside the body and depend on the totality of constants which are functions of thermodynamic parameters. A change in the state of the crystal under elastic stress are dictated by deformation tensor components in the vicinity of a randomly-selected crystal point. It depends on forces affecting the body element and constitutional features of the crystal. A parametric description of elasticity and stressed state of crystals owing to anisotropy and unstability of characteristics is fairly sophisticated. The classic Voigt's theory connecting components of stress and deformation tensors in the form of the Hooke's law ($\sigma = c\epsilon$) for anisotropic crystals required a recording of the fourth order tensor which is defined by the matrix of coefficients with a dimension of 9×9 . Bearing in mind that each mineral must be additionally

characterized by statistical distribution of these parameters with adequate sampling, it is unlikely to suppose practical application of mathematical models of deformation theories.

Besides elastic reversible alterations subject to the Hooke's law, reversible deformations of different nature are not seldom observed in real crystals. They are subordinate to the Hooke's law. These reversible alterations are sometimes called incomplete elasticity which features backward slip during stress changing or, conversely, forward slip. According to Claisen-Neklyudova, it is presumed that incomplete elasticity is caused by motion of atoms (ions) in crystal which is predetermined by combination of various elementary diffusion processes during smoothing of temperature fluctuations, microscopic and macroscopic atom diffusion brought about by nonuniform distribution of foreign atoms, diffusion resulted from stress-induced anisotropic distribution of atoms, diffusion associated with ordering of crystal structure, magnetic diffusion, etc.

Plastic deformation leads to substantial changes in properties of crystalline materials, however at the heaviest strain crystalline state and crystalline structure type are preserved, plastically-deformed crystal is in the state of metastable equilibrium. In crystals slip planes are crystallographically molded-in and deformation nature depends much not on the direction of the force applied but on the position of slip planes and slip direction.

Slip planes are usually planes with the largest number of atoms and greatest interplane distance, they are commonly crystal planes with high symmetry degree. Slip takes place along the direction with the least interatomic distance since in this case the distortion in the atomic arrangement is minimum. Displacement of crystalline layers may take place both in this direction and in the opposite one (corresponding to tension or compression of crystals). Macroscopically, plastic deformation of slip goes on by means of displacement of thin crystalline layers along the slip elements (Fig.4.5). Value of displacement in translation slip may be different depending on deformation degree but obligatorily n -fold of the lattice parameter. Therefore in ideal translation slip the displaced crystalline layers do not leave the position of full mutual correspondence, and the crystalline lattice is not distorted. Protrusions as steps (slip striation) appear on the surface of the deformed specimen.[79,80].

I.V.Obreimov and A.V.Shubnikov showed the formation of incomplete (blind shears in crystals) and based on these experimental data I.V.Obreimov put forward a hypothesis of dislocations emerged in deformed crystals.

The edge dislocation corresponds to that atom arrangement in the crystal volume when one atomic plane is torn off or an extra atomic OM plane called an extraplane is introduced (Fig.4.6). Therefore row 1 above the shear plane has one atom more than the underlying row 2. The heaviest distortions are concentrated in the direct vicinity of dislocation centre 0. Distortions become the lower the greater is the distance from the centre, and at a distance of several atomic diameters they are so small that crystals have an almost complete structure. The region of maximum distortions near the dislocation centre is called the dislocation nucleus, and the region far off the nucleus centre where deformations are so small that the theory of elasticity may be applied to then is called the elastic region. If a supplementary plane is introduced into the upper part of the lattice, as in Fig.4.6, the dislocation is considered to be positive, if it is introduced into the lower part, it is considered negative. Unit dislocation is understood to be dislocation which parameter b is equal to the lattice constant, when this dislocation passes the crystal section its parts are displaced at the value b .

Screw dislocations are formed by the border between the displaced and non-displaced plane parts in case if this border is parallel to shear vector. In the region of this border atoms of the upper plane are displaced with respect to atoms of the lower plane the more the far they are from the border which is the dislocation axis. The travel from one atom to the other within the screw dislocation region takes place in a screw line (Fig.4.7), the right and left screw dislocation are distinguished respective to the screw direction. The screw pitch may be from one to several interatomic per one turn.

Dislocations are not stable structural defects, they can travel, migrate within the crystal volume. Multiplication of dislocations is possible when stresses exceed the yield point of the material though dislocation may move at lower stresses. In so doing, yield point corresponds to that stress at which the potential barrier of plastic deformation is overcome.

Anchored dislocation emerge when crystal stresses are distributed nonuniformly during deformation. This is promoted by defects on the crystal surface (scratches, cracks, notches), crystal mosaic development, nonuniform distribution of impurities in the crystal or nonuniformity of external stress field.

Plastic deformation of crystals owing to mechanical twinning goes on in the same way if the development of translation slip is hindered by the unfavourable orientation of slip planes with respect to the force applied or if structural peculiarities of the crystal and deforming conditions favour twinning. During twinning individual crystal areas are re-oriented as a result of displacement of particles so that crystal lattice inside twin becomes a mirror reflection of the lattice of the crystal part non-deformed.

At certain peculiarities of stresses stair twin interlayers may appear not only in one plane but also in several systems of intersecting planes. A rhomboid channel (Rise channel) which can penetrate the whole crystal is formed in the point where twin interlayers are met, for example, in calcite. A dense grid of such very thin channels may lead to greater crystal volume.[79,80].

4.3.2. Destruction of Crystals

If stresses in a solid body reach (in value) tensile strength, brittle fracture takes place. Direction of breaking load applied and peculiarities of crystal structure are responsible for brittle fracture of crystals, so that crystal fracture goes on in fixed crystallographic directions. Fracture surface shape is also dependent on position of crystallographic planes. Brittle fracture of crystals according to the system of smooth fixed crystallographic planes which orientation is dictated by directions of weakened force of bond between elementary particles of crystalline structure is called cleavage.[79,80].

Cleavage is manifested as crystal ability to be split along certain crystallographic planes with formation of bright surfaces. Cleavage may be exhibited in one, two, three, four and six crystallographic directions. Mica crystals can be split by cleavage to very thin leaves: cleavage in one direction to pinacoid (001). The rhombohedron calcite crystal is easily split in three direction (to rhombohedron) while cleavage planes are not formed in other directions.

Anisotropy is connected with cleavage planes which are parallel to directions of grids of spatial structure of crystal lattice with the largest interplane distances. The cleavage scale is of qualitative nature:

- 1) very perfect cleavage: crystal is split to very thin plates with mirror surface (mica),
- 2) perfect cleavage: crystal is split in certain directions in any place, forming smooth, sometimes stepped surfaces (calcite, galenite),
- 3) medium cleavage: during splitting both even cleaved and uneven surfaces (feldspars, hornblende),
- 4) imperfect cleavage: even cleaved surfaces are scarce, incorrect cleavage surface is formed during splitting (beryl, apatite),
- 5) very imperfect cleavage: crystals have uneven surfaces in splitting (quartz, cassiterite).

Crystal cleavage may be identical or equal in perfection degree in different directions. Minerals without cleavage or with imperfect cleavage are split by uneven fracture surfaces. In character of these surfaces fracture in minerals can be uneven (nugget sulfur, apatite, cassiterite), stepped (feldspars), splintery (actinolite, tremolite), shell-like (quartz, chalcedony, opal), hackly (nugget elements: gold, copper, platinum) and of other types.

Parting is the ability of minerals to be split with even surfaces formed on cleavages in directions coinciding with twinning planes, with epitaxial concretions, with oriented inclusions of solid solution disintegration products, with non-uniformities and inclusions in growth zones,

etc. For example, parting in pinacoid (001) which is connected with very thin inclusions of muscovit is typical of corundum.[42,61].

4.3.3. Hardness of Minerals

Hardness of minerals is taken to be resistance to mechanical fracture under the effect of a stronger body. There are several techniques of hardness measurement. The Mohs' scale is acknowledged in mineralogical practice.

Table 4.2. gives the scale of mineral hardness and fragility. The scale, besides evaluation of crushing and grinding processes, permits an analysis of possible selective crushing, grinding or attrition. Downstream sorting in size affords concentrate to be produced.[11].

Hardness accounts for firmness of chemical bonds among atoms and depends on chemical bond type. Low or moderate hardness (halite) is inherent of minerals with an ionic type of chemical bond while minerals with a purely chemical bond are very hard (diamond). Minerals with a mixed type of chemical bond usually have lower hardness and those with hydrogen and Van der Waals bonds have low hardness. According to this many lamellar, water and molecular crystals feature low hardness. Moderately high hardness is inherent of minerals with densest packing or shell structure. Comparison of minerals similar in structural aspect and analogous in chemical aspect shows that hardness grows as cation or anion charge increases.

Hardness of minerals varies together with composition in isomorphic series; it is especially significant if here ionicity - covalence of chemical bonds, valence of ions, their dimensions and, consequently, packing density and coordination are changed.

Study of mechanical parameter - composition relationships make it possible not only to apply mechanical tests for approximate evaluation of content of these or those elements in mineral but also to judge of tightness of interionic bonds and type of introduction of isomorphic impurity into crystal lattice points. An effect of isomorphic impurities on hardness of minerals is exemplified in Fig.4.9.[79].

A noticeable effect on microhardness of crystals is produced by spot defects: vacancies, interstitial atoms and microimpurities, dislocations and perfection rate (blocking) of crystal individuals. It is well-known that theoretical strength of crystals is much higher than real one. Only dislocation-free whisker crystals have strength commensurate with calculated one. Anisotropy of hardness is inherent of minerals, especially in heterodesmic minerals of chain or lamellar structure (Table 4.2).

Table 2. Classification of minerals by hardness and fragility [11].

Hardness (Mohc)	Minerals		
	Brittle	Non-brittle	Ductile and elastic
10-9	Diamond	Corundum	
8.0	Topaz	Spinel, almandine, pyrope	
7.5	Beryl, phenacite, tourmaline		
7	Quartz, sillimanite, andradite, spodumene	Spessartine, andalusite, staurolite, zircon, zuniyte	
6.5	Bertrandite, diaspore, uraninite, hematite (specular), distene, iridosmine, sysertskite,	Grossular, zoisite, baddeleyite, uranophane, vesuvianite,	

	pyrite, columbite, tantalite, cassiterite, olivine, braunite, humite	epidote, piedmontite, rutile	
6	Gudmundite, prehnite, chromites, markasite, magnetite, orthite	Leucoxene, feldspars, polycrase, euxenite	
5.5	Actinolite, anatase, clinohumite, diopside, anthophyllite, bravoite, breithauptite, willemite, wolframite, hausmanite, gersdorffite, cobaltite, coffinite, monasite, nepheline, pyrolusite, microlite, monticellite, sphene, samarskite, datolite, melilite, goethite, niccolite	Glaucophane, ilmenite, loparite, brookite, helvite, augite, aegirine, rhodonite, bustamite, hornblende, perovskite	Arsenopyrite, aeschnite
5	Apatite, glaucodot, limonite		
4.5	Hemimorphite (calamine), wollastonite, hematite (red iron ore, kasolite, scheelite, xenotime, margarite, parisite	Brannerite, thorite	Platinum
4	Pyrrhotite, manganite, rhodochrosite, tennantite, tetrahedrite, fluorite	Algodonite, stannite	Iron
3.5	Azurite, alabandite, alunite, allemontite, dlomite, cuprite, malachite, pentlandite, siderite, nugget arsenic, pyromorphite, spalerite, chalcopryrite, cerussite, domeykite, millerite, mimetesite, barite, bismuthite, witherite, adamite, andorite, greenockite	Boltwoodite, dyscrasite, powellite	
3	Nuggent antimony, metacynnabarite, aktaite, anhydrite, bornite, vanadinite, wulfenite, calcite, serpentine, chrysocolla, celestite, enargite, thenardite, jarosite	Cubanite	Chalcocite

2.5	Aguilarite, anglesite, boulangerite, bournonite, calaverite, crocoite, valentinite, clausenthalite, xanthoconite, berthierite, beta-uranophane, ulexite, boronatrocalcite, bismuthite, galnate, jamesonite, carnallite, cryolite, cinnabar, coloradoite, phlogopite, antimonite, carnotite, aikinite, pyrrargyrite	Brucite, polybasite, polyhalite, zinnwaldite, hydrargyllite, autunite, chlorites	Copper, gold, biotite, muscovite, lepidolite, silver, nugget bismuth, argentite
2	Borax, proustite, stephanite, torbernite, epsomite, halite, hydroboracite, (?), nugget sulfur, sylvite, nitre	Orpiment, graphite, realgar, vermiculite, molybdenite, pyrophyllite	
1	Kaolinite		

4.3.4.Ore preparation

The objective of this stage is preparation of raw materials for downstream dressing (maximum opening of valuable minerals with regard to possible application of these or those dressing methods). Along with this, ore preparation is aimed at selection of maximum amount of overburden at minimum rate of grinding by any simple and cheap method. [3,16,83]. This stage is necessitated by that a substantial proportion of rock does not contain valuable minerals during mining of deposits, particularly, by high-capacity techniques (open-pit working, bulk caving system, placer mining). It is understood that dump tailings of the first dressing stage must contain no more valuable component than plant tailings without such preliminary dressing. However more high-grade tailings of the first stage may be economically justified since high concentration rate at this stage not only makes overall processing much less expensive but also affords higher recovery at downstream stages.

At this stage mostly spectroscopic and gravitational dressing processes are applied. They are heavy-media separation, jigging, sluice separation, sometimes magnetic separation, collective flotation of sulfides, and lately bacterial leaching.

Downstream grinding is a preparatory operation closely connected with concentration technology.

On the one hand, possible losses of valuable components with slime in re-grinding, and, on the other hand, dimensions of impregnated valuable minerals must be taken into account. In addition to grinding, the preparatory stage may include magnetizing, sulfatizing or other roasting and conditioning of sludge prior to flotation (aeration, reagent treatment).

Size of particles attributed to slime depends on dressing technique and mineral type: 3-1 mm in heavy-media separation, 0.5-0.1 mm in jigging, 0.1-0.05 mm table concentration, 0.1-0.05 mm in magnetic separation, 0.02 mm in flotation.[11].

This stage affords maximum dressability of raw materials (Fig.4.1)..

Production mineral particles implies selection of straight differences to individual fractions of preset size range. For this the following operations are applied:

- *disintegration (crushing and grinding)*. Methods of improving disintegration are aimed at splitting of ore lumps preferentially along intercrystalline faces. This is achieved using ball-free milling: pebble and autogenous, jet milling; Snider process, electrohydraulic effect, high-frequency current, heating, roasting and decrepitation;

- *size classification*. Hydraulic cyclons are of the greatest value out of numerous classifying machines. Process improvement implies more correct selection of fractions and higher production rate due to imposition of different frequency vibrations up to ultrasonic and application of dispersers (liquid glasses);

- *selective aggregating* of fine particles by techniques of flocculation with chemical agnets, magnetic or electric flocculation (on air bubbles).

Preparatory operations are for the most part responsible for process parameters in dressing, to be more exact, opening of minerals and size of particles produced as a result of grinding. Re-grinding, higher yield of fine fractions, hampers many dressing operations, can be reduced using a lot grinding machines in which fragmentation of particles takes place preferred by borders between mineral grains (intergranularly). Ball mills of routine application meet these requirements to the least extent, and, besides, have low power efficiency. It is more promising to use autogenous mills, blast fragmentizing, vibromilling, grinding with counterflow jet material motion and with pressure drop, HF and ultrasonic grinding, etc. The above is grounded, in particular, on that in some cases ore and ore-pebble crushing permits, besides savings on consumption of grinding bodies, better process parameters of dressing due to more selective grinding, and in other cases it affords adequate opening of ore grains with coarser grinding than in ball mills. Autogenous and ore-pebble grinding are applied at tin, copper, zinc-lead, gold extracting and other plants. Full autogenous grinding of 300-500 mm ore essentially reduces prime cost of ore processing owing to elimination of grinding operations.

Autogenous milling is the process of reducing size of materials in milling machines without special machines (balls, bars, etc.). There are several types of autogenous grinding. Primary ore milling is grinding in ball mills with longer material motion path due to high-lifter lining with 250-350 mm entry size, sometimes 500-600 mm without crushing. Semi-autogenous grinding is primary autogenous grinding with loading of 3-12 per cent of the mill drum capacity by large steel balls for offset of shortage of large ore lumps in entry material and for prevention of critical size fractions to be formed in the mill, i.e., too coarse to be fragmentized by large or lumps and too small for being grinding bodies. Primary autogenous grinding (ore and semi-autogeneous) combines operations of medium fine grinding and milling, providing simpler ore preparation flowsheets, lower investments, high labour productivity, reduced consumption of grinding bodies, better selectivity of opening and, in most cases, higher recovery of valuable components. The disadvantage of primary autogenous grinding is 1.2-1.3 time higher, as compared to conventional ore preparation, specific power consumption. Primary autogenous grinding is performed in closed and open circuits with downstream ball or ore-pebble milling, sometimes at one stage to final fraction.

Ore-pebble grinding is grinding in traditional drum mills where ore pebbles (lumps of certain size are grinding bodies. Ore-pebble autogenous grinding provides reduced specific consumption of balls and power, better dressing parameters but causes lower production rate of mills and supplementary operations for selection and metering of ore pebble. It is more efficient to apply ore-pebble autogenous grinding at fine milling because in this case the difference in production rate between ball and ore-pebble grinding becomes minimum. Ore pebble grinding is used at the second and third stages and at re-grinding of concentrates. Dry autogenous grinding in drum mills found no wide application in mining industry because of the necessity to dry wet ores and is applied extremely seldom at grinding of building materials.

Full ore autogenous grinding (grinding without grinding steel bodies along the whole ore preparation flowsheet) in some cases allows specific energy consumption reduced to the level of conventional ore preparation (crushing and ball grinding) in processing of viscous clay ores.

In the CIS autogenous grinding is widely applied in processing of diamond and gold-containing, iron, tungsten-molybdenum, rate-metal, polymetallic ores, chemical raw and other materials.

It is necessary to indicate the development of radically innovative disintegration techniques which provide intergranular splitting of mineral aggregates, large uniformity of granulometric composition of ground products, greater efficiency and productivity of machines. [83].

Alongside cascade mills, Aerofall and other autogenous mills are more and more widely-used. Jet grinding is effective when fine milling is required. Here, besides air, water steam, CO₂, etc. can be applied as a working medium. A jet grinding variant is the Snider process based on rapid rarefaction of steam or compressed working liquid under pressure together with material to be ground. In opposition to widely-used grinding processes when disintegration results from compression, impact or attrition, rarefaction leads to particle breaking, preferred intergranular. Works goes on in electrohydraulic, electrothermal and vibrating grinding. [11].

Sometimes ore preparation includes *techniques of preliminary separation* of maximum quantity of waste rock at minimum rate of grinding by any simple and cheap technique. This stage is necessitated because a large amount of rock does not contain valuable components in mining of deposits by especially high-productive techniques (open-pit operations, bulk caving system, placer mining). It is understood that waste tailings of the first dressing stage must contain more valuable component than plant tailings without such preliminary dressing. However more high-grade tailings of the first stage can be economically justified since high concentration rate at this stage not only substantially reduces processing as a whole but also affords higher recovery at downstream stages...

Heavy-media dressing is widely-used in processing of coal, phosphorites and iron ore, and in dressing of lean materials (ores of non-ferrous, rare and noble metals, diamonds, etc.).

At present annually heavy-media separation is used in processing of more than 1 billion tonnes of run-of-mine minerals. Operation of existing plants shows that main advantages of this technique are the efficient processing of initial materials from 2-5 to 360 mm in size with high production rate (up to 600-1000 tph) with dump products containing a slight amount of components as well as possible separation of raw materials to products at slight difference in density. Besides, this dressing technique shows low investments and operating costs predetermined by low consumption of power, water, thickener and small operating personnel; the operation can be easily automated.

Granulated ferrosilicon, magnetite or its mixture with ferrosilicon, more seldom barite, pyrite, sand, etc., are applied as weighing compounds. High sensitivity to separation density make it possible to reduce substantially losses of valuable components with dump tailings as compared to jigging.

One state-of-the-art trend in mining industry is a flowline cycle applied in open-pit mining of deposits in combination with ore preparation and preliminary dressing. In this case coarse crushing is performed directly in open pits while radiometric sorting is used on conveyers delivering ore from the open pit to the plant.

4.4. Physical Properties of Minerals. Primary Concentration

Not only individual physical properties of minerals but also their combination as well as size of particles are essential in processing of mineral products. Certain physical properties can be made use of in dressing of mineral mixture only in a limited range of fraction size. It must be taken into account that many physical properties of minerals can be changed by chemical methods, for example, roasting. Physical properties of minerals can be identified and measured only as a result of applying external forces (?).

4.4.1. Mechanical properties

Hardness and fragility of minerals, besides processes of crushing and grinding, allows analysis of selective crushing, grinding or attrition. Downstream classification is a dressing operation.

Selection in friction and shape is based on using differences in speeds of motion of particles under separation along the tilted plane. At a preset angle of tilt it is a function of particle surface state, shape, moisture, density, fraction size, properties of the surface along which particles move and nature of motion (rolling or slip). Mineral particle shape is mainly responsible for friction factor value.[16,80].

Particles can move under the effect of gravity (when moving along tilted planes), a centrifugal force, (when moving along the horizontal plane of a rotating disc), and as a result of a combined action of gravity, centrifugal force and friction force (screw separators).

Friction factor grows with particle size diminishes. Therefore narrow classification in size is required for efficient separation. Commonly attrition dressing is applied on materials of -100 - +10 (12) mm in size. For example, mica lumps of platelike form move along the tilted plane more slowly than the rock lumps and, penetrating the slot, fall onto the next plane where they are re-cleaned.

In complex plane system separation of waste rock is assisted by a difference in elastic ratios since difference in paths of movement of waste rock lumps, mica aggregates and lumps increases as a result of impacts onto the baffle surface.

A screw separator is a double tilted surface twirled around the fixed axis by a helical line in form of a double-threaded screw. Particles of different friction factor move at various distances with respect to rotation axis. Particles of great friction factor have small radius of trough movement path, while those of lower friction factor have large radius according to which their separation takes place.

The slip friction factors of heavy minerals (wolframite, cassiterite, magnetite) are higher than the friction factors of quartz, according to which separation of particles on a dry screw separator must take place also by density.[16].

In practice these methods have already lost their value as ores with large nuggets of non-ferrous metal minerals are exhausted. They can be used at placer deposits as preliminary concentrating operations in dressing of ores containing wolframite, cassiterite, garnets, zircon, magnetite, gold, pyrite, arsenopyrite, mica, fine abrasive powders and asbestos.

Dressing in elasticity is grounded on the difference in paths along which mineral particles of different elasticity are thrown off at collision with the surface. This process is applied in dressing of building materials (road metal and gravel for manufacture of high-grade concrete), asbestos. It is carried out in special drum separators and in inclined steel plate separators.

4.4.2. Spectroscopic and Radiospectroscopic Properties of Minerals

Up to lately the diagnostic symptoms of minerals have been colour, lustre, absorption, reflection and radiation in ultraviolet and infrared adjoining visible spectral regions. In dressing of minerals resources hand sorting was first applied which later on with exhaustion of deposits containing coarse crystals lost its value. However in last years when sorting machines appeared these properties again attracted attention of dressing engineers.

These methods are of little application in dressing of non-ferrous metal ores because of fine impregnation of extracted minerals. Sorting is effective at lump size from several centimetres. Therefore preliminary ore concentrating by spectroscopic techniques is applied only at the stage of ore preparation.[81,82].

This is necessitated if ore of "all or nothing" deposits is processed. For example, metal-containing ore veins are mined together with embedding rocks and bedded minerals (for instance, quartz with gold) is impoverished by surrounding rock. Separation of sulfides from silicate minerals which usually intergrow together can be performed in a similar way.

First sorting machines were based on account of natural radioactivity of minerals and were applied for dressing of uranium ores. Later on sorting plants using induced radioactivity appear. Not only γ and β but also neutron rays were employed, for example, for beryllium ores. Nowadays it is possible in principle to sort for ray radiation or absorption in any spectrum part. However expediency of a particular technique depends on radiation source chosen, possibility of automatic recording of radiation and resolution.

Radiation-material interaction is characterized by the atomic or nuclear section δ defined as probability of interaction of radiation quanta with the number N of irradiated centres. Physical processes characterized by fairly high section of interaction with chemical elements can be applied for radiometric dressing. No gamma-quanta of high energy (above 20-30 MeV), multicharge particles and ions, fast neutrons (above 10-15 MeV in energy).

Methods of radiometric dressing of nonradiative mineral resources were classified by V.A. Mokrousov and V.A. Lilev (Table 4.3). [81].

Table 4.3. Classification of methods of radiometric dressing of mineral resources

Physical process of interaction with material	Separation symptom used for dressing	Method	Application field, examples of mineral dressing
Group 1. γ -radiation. wavelength: no less than 10^{-2} mm			
Photonuclear (γ, n)-reaction (nuclear photoeffect)	Density of neutron radiation flux	(a) Photoneutron	At $E_\gamma > 1.67$ MeV: beryllium ores. At $E_\gamma > 10-20$ MeV: manganese, iron, tin, copper, molybdenum, tantalum, bismuth, etc. ores.
Excitation of intrinsic X-ray fluorescent radiation	Intensity of X-ray fluorescence	(b) γ -fluorescent	Minerals resources with elements of atomic number $Z > 19$: manganese, copper-ickel, niobium, tin, caesium, barium, tantalum, tungsten, lead-zinc, etc. ores
Scattering on electron atomic shells	Intensity of back scattered γ -radiation	(c) γ -reflective	Mineral resources with heavy elements; lead, mercury, iron, chrome ores
Photoelectric absorption and Compton scattering on electron atomic shells	Intensity of γ -radiation passed through lumps	(d) γ -absorption	Ores with elements of atomic number > 25 : iron, chrome, lead-zinc, tin, caesium, barium ores, coal, combustible shales, etc.

Group 2. β -radiation. Wavelength: 10^{-3} - 10^{-2} mm			
Excitation of intrinsic X-ray fluorescent radiation	Intensity of Y-ray fluorescence	(a) β -fluorescent	Mineral resources with elements of atomic number >35 : molybdenum, tin, tungsten and other ores.
Scattering on electron atomic shells	Density of back-scattered β -radiation	(b) β -reflective	Mineral resources with heavy elements: lead-zinc, antimony-mercury and other ores.
Group 3. Neutron radiation. Wavelength: 10^{-2} - 10^{-1} mm			
Radiation trapping of thermal and slow neutrons by nuclei with induced radioactivity formed	Density of induced radiation flux	(a) Neutron-activation	Mineral resources with activation section (σ_a) no less than 1 barn: ores containing indium, iridium, vanadium, silver, gold, copper, etc.
Radiation trapping with emission of of intrinsic γ -ray spectrum	Intensity of intrinsic γ -radiation	(b) Neutron-radiation	Mineral resources with elements of radiation trapping section $\sigma > 1$ barn
Trapping and scattering of thermal and slow neutrons on chemical element nuclei	Density of neutron radiation flux after passage through lumps	(c) Neutron-absorption	Mineral resources with elements of large section of trapping thermal neutrons, e.g., boron, lithium, cadmium, rare-earths; boron, boron-tin, lithium ores, etc.
Group 4. X-ray radiation. Wavelength: $5 \cdot 10^{-2}$ - 10 mm			
Excitation of intrinsic X-ray fluorescent radiation	Intensity of X-ray fluorescence	(c) X-ray-fluorescent	Application field: similar to group 1(b)
Excitation of luminescence in visible spectrum part, ultraviolet or infrared	Optical flux of X-ray luminescence	(b) X-ray-luminiscent	Mineral resources containing minerals glowing in X-rays, diamond-bearing, fluorite, zircon, celestite, spodumene, scheelite and other ores.
Scattering on	Intensity of back-	(c) X-ray-reflective	Application field:

electron shells	scattered X-ray radiation		similar to group 1(c)
Photoelectric absorption and Compton scattering	Intensity of X-ray radiation after passage through lumps	(d) X-ray-absorption	Application field: similar to group 1(d)
Group 5. Ultraviolet radiation. Wavelength: $(10-3.8) \cdot 10^2$ mm			
Excitation of luminiscence in visible spectrum part, ultraviolet or infrared	Optical flux of photoluminiscence	(a) Photoluminiscent	Mineral resources containing minerals glowing under action of ultraviolet radiation: flurote, cscheelite, barite ores, dolomite, gypsum, calcite, diamonds
Group 6. Visible light. Wavelength: $3.8 \cdot 10^2$			
Diffusive reflection	Optical flux of diffusively-reflected light	(a) Photometric	Mineral resources which separable components differ in diffusive reflection coefficient (colour): talc, gypsum, rock salt, dolomite, limestone, gold-bearing, abarite, caesium, tin, manganese, ilmenite and other ores
Mirror reflection	Optical flux of mirror-reflected light	(b) Mirror photometric	Mineral resources with one component having high mirror reflection corfficient. e.g., quartz, halite, micas, etc.
Polarization of reflected light	Optical flux of polarizationally-reflected light	(c) Polarization photometric	Ditto
Optical absorption and scattering	Oprical flux after passage through dressed particles	(d) Photoabsorption	Mineral resources which separable component has high transparence, e.g., optical quartz, diamonds, halite
Group 7. Infrared radiation. Wavelength: $7.6 \cdot 10^2 - 10^4$ mm			
Thermal absorption and further	Intensity of emitted inrdared radiation	(a) Inframetric	Mineral resources which separable

emission of infrared radiation			components differ in specific heat capacity, e.g., asbestos ores
Group 8. Different-wave radiation. Wavelength: 10^5 - 10^{14} mm			
Absorption and redistribution of radio-frequency filed	Alteration of electromagnetic field energy	(a) Induction radioresonance	Mineral resources which separable components differ in electric conductivity, ρ) (sulfide ores of non-ferrous and rare metals): copper-pyrite, molybdenum-copper, copper-nickel, lead-zinc, tin, tungsten, gold-arsenic ore, etc., coal, shales, graphite
Polarization of dielectrics and generation of displacement current	Alteration of electromagnetic field energy	(b) Capacitance radioresonance	Mineral resources which separable components differ in capacitivity (μ): magnesite, bauxite, sulfur, muscovite and biotite-containing, tin, tungsten and other ores
Absorption and reflection of radiowaves	Intensity of radiation after passage through dressed lumps	(c) Radioabsorptive	Mineral resources which separable components differ in specific conductivity, ρ : sulfide ores of non-ferrous and rare metals, coal and shales
Magnetizing by external magnetic field, absorption of magnetic field energy	Alteration of intensity and energy of magnetic field	(d) Magnetometric	Mineral resources which separable components differ in magnetic permeability: iron and non-ferrous metals ores

Differences in mineral properties during irradiation or weakening of radiations are applied in radiometric mineral dressing. Depending on this, the following radiometric methods are

distinguished: (1) emission, based on determination of intensity of mineral irradiation, and (2) absorption, based on determination of rate of weakening of penetrating radiation of minerals.

Natural radioactivity.

Radioactivity is transformation of instable chemical element isotopes into isopoes of other elements with irradiation of elementary particles. Natural radioactivity is attributed to minerals which composition contains radiation-instable isotopes of uranium, radium, radon, potassium, strontium, etc.

Moderate and low radioactivity is caused by small admixture of U, Th isotopes as well as other radioactive isotopes contained, for example, I pyrochlore, samarskite, aeschynite, monazite. Low radioactivity of sylvyte, microcline, muscovite and other potassium minerals is predetermined by constant admixture of radioactive potassium isotope (^{40}K).

Natural or induced radioactivity grounded on different capacity of minerals to absorb or reflect radioactive γ , β or neutron radiation is applied in ore dressing by radiation techniques.

The correspondence between valuable component contained in ore and radiation intensity may be violated when another, in addition to the main one, natural radioactive chemical element (uranium together with a considerable portion of thorium) is available in ore, or if there is radioactive equilibrium between the main radioactive element and products of its decay.

Radiometric separation is the main technique of uranium ore dressing due to high selectivity.

Interaction with X-ray and γ –radiation.

X-ray and gamma-radiation are electromagnetic waves interacting with electrons and atomic nuclei of material. the interaction may result in photonuclear reaction, photoeffect, Compton effect, electron-positron pairs. These processes are probable depending on radiation energy.

Photonuclear reaction of (γ, n) , (γ, p) , (γ, d) types, i.e., reactions when neutrons, protons or alpha-particles are formed (nuclear photoeffect), run under the effect of high energy irradiation. Protons and alpha-particles have large mass and charge, low penetrating capacity and virtually do not penetrate the bulk of the material irradiated. Therefore only a neutron-emitting reaction is of interest to radiometric dressing.

The prerequisite for photonuclear reaction is that the gamma-quantum energy E_γ is more than the neutron parting energy E_n , i.e., $E_\gamma > E_n$. The full number of neutrons formed depends on the source activity I , photonuclear reaction section $\delta_{n,r}$, the distance r from the source, the full coefficient μ of gamma-radiation weakening, and the chemical element content C entering the reaction.

Each chemical element shows a certain threshold of (γ, n) -reaction and effective section, $\delta_{p,r}$. The minimum threshold of photoneutron reactions is inherent of beryllium (1.67 MeV) and deuterium (2.23 MeV), and the maximum threshold is typical of carbon (18.7 MeV) and gallium (20.6 MeV). Threshold energy is within the range of 6-16 MeV is for the most part of the other chemical elements.

Photoneutron method of dressing is grounded on differences in intensity of neutron radiation emitted in irradiation on ore with gamma-rays. This process is applied for dressing of beryllium ores because beryllium nuclei can emit neutrons in radiation by gamma-rays of relatively low energy.

The photoneutron method can be also applied for manganese, copper-zinc, copper-nickel, iron, molybdenum, tin, tungsten and other ores.

The dominating type of interaction in the field of low gamma-quantum energy (approximately 0.01-0.5 MeV) is photoeffect, Thompson scattering is also observed. Compton scattering is predominant in the region of intermediate energy (0.3-3 MeV), while the effect of forming pairs dominates, beginning from 1.022 MeV level corresponding to the threshold of forming electron-positron pairs.

Photoeffect is the process of interaction of gamma-quantum with fixed electron at which the total gamma-quantum energy transmits to the electron. Here the electron is ejected outside the atom with the energy $E_e = E_\gamma - I_i$, where I_i is the potential of atom shell ionization.

The space on the electron shell which becomes empty as a result of photoeffect is filled with electrons from other atomic levels which is accompanied by emitting typical roentgen radiation of fluorescence. The photoeffect section δ_p is a function of atomic number of the material and gamma-radiation energy E_γ .

The Compton scattering section δ_γ of gamma-quantums on electrons is a function of energy of only gamma-quantums proper. A linear coefficient of gamma-radiation weakening depends on the density ρ , the atomic number Z , the atomic mass A and gamma-quantum energy E_γ .

Ores and rocks may noticeably differ in value of gamma-radiation weakening which is used for radiometric dressing.

A gamma-absorption method dressing is grounded on differences in mineral capacity to absorb X-ray or γ -radiation penetrating them. The relative value of gamma-radiation absorption is subject to the exponential law: $I/I_0 = e^{-\mu}$, where I and I_0 is the intensity of gamma-radiation before and after passage through the material, μ is the linear coefficient of absorption.

The μ value is a function of energy of primary gamma-radiation quanta as well as atomic number and atomic weight of material under radiation. It is equal to the sum of linear coefficients of absorption intrinsic to each of three types of interaction of gamma-quantums with the material.

Sources of gamma-radiation with energy within the range from 0.020-0.03 to 0.15-0.20 MeV should be applied for gamma-absorption separation of minerals of different types.

The mass absorption coefficients μ_p are much higher for chemical elements with large atomic number ($Z > 25$) which creates prerequisites for gamma-absorption technique to be applied for dressing of iron, chrome, tin, barium, antimony, caesium, lead-zinc and other ores. In some cases a gamma-absorption technique can be applied if components to be separated, slightly differing in atomic number, are substantially different in density. This can be exemplified by separation of coal and shales, selection of diamonds out of embedding rocks.

Photoeffect leads to ionization atom, removal of electrons located on certain energy levels (K, L, M, N, etc.) in a normal state. Here atom turns out to be in an energized state and goes to another level with lower energy. Redundant energy is carried away by photons; secondary radiation formed in this way is called typical roentgen radiation of fluorescence.

A radiometric dressing method based on differences in intensity of typical secondary fluorescent radiation is named gamma-fluorescent. When the gamma-fluorescent dressing is implemented, of the main value are energies of K-edges of absorption and energy of main lines of roentgen fluorescent spectrum. Since the photon energy of typical radiation of K-series is 7-8 times higher than that of photons of L-series, this radiation is expedient to be applied as separation symptom. The gamma-fluorescent process can be applied for elements with $Z > 20-25$ in dressing of manganese, copper-nickel, niobium, molybdenum, tin, lead-zinc, caesium, tungsten and other ores.

If energy is low (up to 0.1 MeV) scattering (or reflection) of gamma-radiation can be applied for radiometric dressing. The property of elements to disperse incipient gamma-radiation is quantitatively manifested by mass coefficients of coherent and incoherent scattering. The gamma-reflecting process may be applied in dressing of ores containing heavy elements, for example, iron, lead-zinc, chrome, mercury. The phenomena of weakening primary roentgen flux, secondary roentgen radiation of fluorescence, scattering may be used in the corresponding way.[81].

Interaction with β and neutron radiation.

Beta-radiation is flux of electrons. When it passes the material, ionization deceleration and scattering are observed. During ionization deceleration the electron energy is spent on energizing and ionization of atoms of the medium which the electron passes. This process is accompanied by intrinsic roentgen radiation of fluorescence. The fluorescent radiation spectrum is dictated only by atomic properties of the medium under radiation, just like in case of exciting gamma-rays.

The radiometric dressing method is grounded on differences of ore and rocks in intensity of secondary intrinsic fluorescent radiation excited by beta-rays. Beta-fluorescent dressing features less dependence on variations of mineral material composition than in case of gamma-rays. Beta-fluorescent dressing can be applied for ores containing heavy elements with the atomic number $Z > 35$, for instance, molybdenum, tin, tungsten, lead, etc.

Radiometric dressing method based on differences and intensity of back-reflected beta-rays can be used for dressing of ores containing heavy elements.

Neutrons are subdivided in several groups in energy: thermal (up to 0.025 eV), slow ($0.1 - 10^3$ eV), intermediate ($10^3 - 10^5$ eV), and fast (above $5 \cdot 10^5$ eV). Wave properties being of vital importance at low energy are responsible for interaction of neutrons with nuclei.

On collision of a neutron with a nucleus the former is trapped or scattered. If it is trapped, a composite nucleus is formed which turns out to be in an excited state owing to the neutron bond energy released during the trapping. Transition of nuclei from excited to lower energy state may take place by means of decay with emission of any particles or gamma-quantums, or both. One variant of decay of the excited composite nucleus implies emission of alpha-particles, i.e., (n, α) -reaction. This reaction is observed on a small number of light nuclei in case of slow neutrons while it is of little probability in case of fast neutrons because of competition of other processes. In case of slow and thermal neutrons (n, α) -reaction runs on nuclei of ^{10}B and ^6Li . The (n, α) -reaction section is 754 and 70.4 barns for the natural mixture of boron and lithium, respectively. The section of this reaction is three-six orders lower for other chemical elements. During the decay of the excited nucleus (n, ρ) -reaction occurs, but it exhibits a low section comparable to the section of (n, α) -reaction on a majority of elements, besides boron and lithium.

During neutron trapping of the widest proliferation is (n, γ) -reaction, with emission of gamma-rays, called radiarion trapping. In case of neutrons with an energy from 0.1 to 10 eV the radiation trapping section is the largest for slow and especially thermal neutrons. There is also an increase in the section of (n, γ) -reaction during transition from light to heavy elements. Intensity and energy of gamma-rays of (n, γ) -reaction are properties individual for each element which can be used for radiometric trapping. As to the majority of nuclei, radiation trapping leads to instable (radioactive) isotopes formed. These isotopes eject gamma-quantums, electrons or positrons. Intensity of induced radioactivity depends on section of activation and content of chemical element in the mineral mass under irradiation.

Another process of interaction with nuclei, elastic scattering occurring on nuclei of any element, is of noticeable importance for thermal and slow neutrons. Here a neutron is deviated from the primary directions, and a part of its kinetic energy is transferred to the nucleus. Elastic scattering is the most probable process in interaction of slow neutrons with light nuclei and medium-mass nuclei. Scattering section is small on heavy nuclei as compared to neutron trapping section.

A radiometric dressing method based on differences in weakening of neutron flux by separated mineral components is called neutron-absorption. A symptom of separation in neutron-absorption dressing is the flux density of neutrons which passed through the dressed mineral matter. The neutron-absorption method can be applied to ores containing chemical elements with large section of neutron trapping, for example, to boron, lithium ores as well as to ores containing cadmium and rare-earth elements. The neutron-activation method is expedient to be applied, most probably, when the neutron-valuable component interaction section is no less than barns which is necessary for reliable recording of secondary radiation. This requirement is met by ores containing chrome, iron, nickel, copper, silver, gold, rare-earth elements. This is also fair for the conditions of applying the neutron-radiation method.

Photometric properties.

Owing to action of electromagnetic field of light wave on electrons their oscillations are excited in the direction coinciding with the direction oscillation of electric vector of incipient light wave. Dipole electric moments regularly alter during forced oscillations of charged

particles in molecules. Here secondary electromagnetic waves which length is equal to the incipient light wavelength are radiated. Primary and secondary waves are mutually coherent and can interfere. When the electromagnetic light wave falls on the interface of two different media a reflected wave propagating in the same medium as the primary wave and the refracted wave propagating in the second medium are formed as a result of the interference of the primary and secondary waves. The ratio of the light fluxes of the reflected and incipient waves (the coefficient) is an optical parameter of the material. The reflection of natural light is accompanied by partial light polarization which results in the fact that some part of the reflected light gains certain orientation of electric and magnetic intensity vector.[81].

The photometric method of dressing is grounded on the difference in coefficients of reflection of dissipated light of minerals and rocks. Lumps or particles of ore to be processed are illuminated in the photometric chamber on the background specially-selected in colour, and the reflected light is collected by a sensor. The spectral composition of the incipient light has no substantial effect on the separation process. A certain spectrum range in which the greatest difference in the reflected light is selected from the reflected beam using optical filters. Photometric sorting is not virtually applied in dressing of non-ferrous metal ores. It is of interest for extraction of large diamonds. It is known that photometry is applied in automatic control of flotation process where it is used to identify the foam layer loading in flotation cells and foam product quality.

Luminiscent separation

This is the mineral selection process based on illumination capacity of minerals under the effect of ultraviolet and roentgen rays. It is made use of in dressing of minerals luminiscent in roentgen (diamond-containing, scheelite, fluorite, zircon, apatite, spodumene and other ores) or in ultraviolet rays (fluorite, scheelite and other ores).[15,16,42].

Luminiscent glow is characterized by excitability, colour, intensity and duration. Luminiscence appears only in case of absorbing energy required for electron transitions from the main state levels to the excited levels and further transition. Optimal value of exciting energy is responsible for excitability of luminiscence. It amounts to several eV, relevant excitation bands in luminiscence spectra are usually located in ultraviolet, more seldom in short-wave parts of the visible region. Luminiscent glow of one minerals is excited only the short-wave part of ultraviolet light which is typical of, for example, scheelite ($\text{Ca}[\text{WO}_4]$). Other minerals, for instance, ruby ($\text{Al, Cr}_2\text{O}_3$), glow during irradiation with long-wave ultraviolet light. Many minerals are excited in a wide range of wavelengths, for example, manganese-containing calcite. The number of roentgen and cathode-luminiscent minerals is much greater than those excited in ultraviolet light. Some non-glowing minerals become glowing after special treatment (Table 4.4).

The nature of luminiscent centres which are impurity or structural spot defects is responsible for electron transition and luminiscent mineral properties associated with Absorption and radiation of exciting energy occur within the centres or with the transfer of energy among centres.

Ions of transition metals, like Mn^{2+} , Cr^{3+} , and rare earths TR^{2+} and TR^{3+} . Luminiscence in these centres is connected with electron transitions between d or f-levels split by the crystalline field. A wide band of orange or red luminiscence with a maximum of about 60 nm is connected with Mn^{2+} -centres in calcite as well as in wollastonite, anhydrite, apatite, spodumene, etc.

The Cr^{3+} ion replacing aluminium is responsible for the red glow of ruby and spinel, emerald, alexandrite, cyanite, etc. In fluorite the band of violet luminiscence with a maximum of 425 nm is associated with the Eu^{2+} impurity while the yellow-green band excited only at low temperature is connected with the Yb^{2+} impurity ($\lambda_{\text{rad}} = 540 \text{ nm}$). The narrow luminiscent lines in fluorite, apatite, monazite, zircon, scheelite and other minerals are involved by transitions on TR^{3+} ions.

Luminiscence stemming from electron transitions in tetrahedron anionic oxygen complexes of transition elements is most of all intrinsic of calcium molybdates and

wolframates. The wide bands of blue luminiscence of scheelite ($\text{Ca}[\text{WO}_4]$) and yellow one of powellite ($\text{Ca}[\text{MoO}_4]$) and molybdoscheelite $\text{Ca}[(\text{W}, \text{Mo})\text{O}_4]$, are excited only in the distant ultraviolet region.

Recombination luminiscence occurs at recombination of excited donor-acceptor pairs in some sulfides (sphalerite, cinnabar, realgar) and diamond. Blue sphalerite luminiscence is connected with transitions in the associated centre: cationic vacancy ($\text{V}_{\text{Zn}^{2+}}$) and impurity (Ga^{3+}); yellow - in the centre: ion (Cu^+_{Zn}) and anionic vacancy ($\text{V}_{\text{S}^{2-}}$); red - in the centre: ($\text{Cu}_{\text{Sn}^{2+}}$) and ($\text{Ga}^{3+}_{\text{Zn}^{2+}}$) or ($\text{In}^{3+}_{\text{Zn}^{2+}}$). Recombination luminiscence of cinnabar and realgar is also connected with donor-acceptor pairs of (V_A) - (V_K) type. Luminiscence of diamond is explained by recombination transitions in the associative centres of ($\text{N}^{5+}_{\text{C}^{4+}}$) - $\text{Al}^{3+}_{\text{C}^{4+}}$ - blue glow lines, ($\text{N}^{5+}_{\text{C}^{4+}}$) - ($\text{V}_{\text{C}^{4+}}$) - yellow glow lines, etc.[42].

Table 4.4. Luminiscence of minerals [17]

Minerals	Colour in ultraviolet rays	Colour in cathodic rays
Native element		
Diamond	Blue, violet, green-yellow	Blue, blue-violet
Sulfides		
Sphalerite	Yellow	Yellow
Oxides		
Quartz	-	Soft bluish-white, for milky variants
Corundum	Bluish, red, violet, yellow-brown	Bluish, red, violet, yellow
Microlite	Sometimes soft brown	
Spinel	Orange-red or ruby-red for soft-coloured variants	
Carbonates		
Witherite	Pink, yellow-orange, white	White
Dolomite	Soft white, bluish, yellow, reddish, pink	Orange and reddish-orange
Calcite	Orange, red, yellow, bluish-white	Orange, paprika red
Magnesite	Blue, white, reddish	Blue, red
Smitsonite	Blue, white, red-pink, yellow	Red, orange
Cerussite	Yellow, white	Blue
Sulfates		
Anglesite	Yellow, red, more seldom pink and white	Blue
Celestite	White, yellowish, pink	-
Phosphates, arsenates		
Apatite	Yellow, violet, blue, pink	Yellow, violet, blue
Mimetesite	Yellow, orange-yellow	-
(?)	Bright green-yellow	Bright green-yellow
Molybdates and wolframates		
Molybdenite	-	Green
Powellite	Yellow, green-yellow, soft blue	Yellow, green-yellow
Scheelite	Orange, yellow, blue	Blue
Silicates		
Beta-uranophane	Soft green, sometimes	-

Thorite	bright green	
Phenakite	Light green	-
Zircon	-	Soft light blue
	From light till bright-yellow, orange, yellow	Yellow, blue
	cocoa brown, white	
Beryl	Seldom bluish-violet	Blue

Luminescence separation is distinguished by exciting method and separation mode. As to exciting method, there are roentgene-luminiscent and photoluminiscent separations, as to separation mode, there are lumpy luminescence method for low-contrast ores and flow luminescence method for high-contrast ores at low content of the mineral to be separated.

Absorption or interference optical filters are used for improvement of selectivity and sensitivity of mineral separation. Such optical filters provide maximum irradiation in a narrow spectrum range which coincides with the luminescence band of the mineral to be selected.

Luminescent separation is performed in roentgene-luminiscent and photoluminiscent separators. The most widely-used are roentgene-luminiscent separators for dressing of diamond-containing ores.

Luminescent separators consist of a feeder, an inclined trough, a detector (composed of a roentgene tube, photoelectric multiplier, and radiometer) and a shutoff (as a solenoid-driven rotating vane). They are equipped with an automatic control device. The material entering the separator is fed with the help of the drum feeder onto the inclined trough. The monolayer moving with acceleration along the trough crosses the band of collimated roentgene radiation. The luminescent flux is received by the multiplier which transforms it into electric current. The current amperage is proportional to the luminescent flux, and if some threshold is exceeded the radiometer switches the solenoid of the shutoff selecting the luminescent mineral. Glowing minerals and adjacent rock lumps enter the concentrate trough, and the waste rock containing no glowing minerals is delivered to the tailings trough.

...

4.4.3. Density of Minerals. Gravity Concentration

? ? ? ? 3 pp.

[16,84]

Rounded	0.8-0.9
Angular	0.7-0.9
Tabular	0.6-0.7

Water, air, heavy liquids, suspensions, electrolyte melt placed into crossed electric and magnetic fields are applied as gravitational separation media. They are characterized by flow parameters (density, viscosity, shear resistance limit, stability, etc.).

The enlisted medium properties made use of in dressing machines affect the speed of motion of particles to be separated and separation efficiency. Grains are segregated for one distributing symptom by means of hydro and aerodynamic actions on the mineral mixture. The distributing symptoms may be: (1) flow parameters of the separation medium, (2) flow parameters of the medium subject to electric and magnetic field actions, (3) grain motion speed

in the pulsating fluid flow, (4) grain motion velocity in the fluid stream flowing along the inclined plane, (5) grain motion velocity in the vertical fluid flow.

The *classification of gravity separation methods* is given below

- (1) Segregation in media: hydraulic, pneumatic, heavy, liquid, suspension, headralic & pneumatic, electrolytic (MHD separation)
- (2) Grain segregation in the pulsating flow of the separating medium: hydraulic and pneumatic jigging, vibrating trough separation, pneumatic separation, pulsator separation
- (3) Grain segregation in the liquid jet flowing along the inclined plane on troughs, in sluices, in jet concentrators, on concentration tables, in screw separators
- (4) Grain segregation in curvilinear separating medium flow in hydrocyclones and centrifuges
- (5) Grain segregation in vertically ascending flows of separating media: hydraulic and pneumatic sorting
- (6) Grain precipitation in separating media: thickening
- (7) Washing

4.4.4. Mineral Magnetism and Magnetic Separation

Magnetic properties of minerals emerge and are manifested in a magnetic field. Only a few minerals show magnetization adequate for attracting magnetic powders or iron filings while the major part of minerals manifest magnetic properties only in a heavy magnetic field of high intensity.

Magnetic induction generated by the magnetic field varies if a mineral is present. Its variation is measured by magnetic permeability (μ_m) and magnetic susceptibility ($\chi = \mu_m^{-1}$) which dictates the relations of magnetization (M) and magnetic field intensity (H): $M = \chi H$ or $\chi = M/H$.

Susceptibility and magnetization depend on the number of unpaired electrons, with each characterized by certain magnetic moment (spin), or Bohr magneton: $\mu_B = eh/4\pi m$, where e is the charge, m is the electron mass, h is the Planck constant. Several types of minerals which correspond to different magnetism kinds are distinguished during heating or cooling as a function of magnetic susceptibility and magnetization of minerals and nature of variability of these parameters in the magnetic field of different intensity. [77].

Minerals are divided into dia, para, and ferromagnetic by magnetic susceptibility and character of dependence of magnetic properties on intensity of external magnetic field. Besides, there are nonmagnetic, light and heavy magnetic minerals which specific magnetic susceptibility is less than 10^{-5} , $10^{-5} - 6 \cdot 10^{-4}$ and more than $6 \cdot 10^{-4} \text{ cm}^3/\text{g}$. The classification is arbitrary and depends on the magnetic separation equipment level.

Diamagnetic minerals have a negative susceptibility, and magnetization, $J = \chi H$ is directed opposite to external field. A lot of salts, oxides, sulfides and other minerals without paramagnetic ions are diamagnetic. The specific susceptibility of diamagnetic minerals is $10^{-7} - 10^{-6} \text{ cm}^3/\text{g}$. Diamagnetism is the common property of all bodies but in many cases it is overlapped by para or ferromagnetism. As χ is small, diamagnetic minerals fall into nonmagnetic category during magnetic separation. [81].

Diamagnetic minerals are ejected out of the magnetic field. The highest diamagnetic properties are manifested by native bismuth, graphite while native silver and gold, fluorite, calcite, quartz, etc. show these properties to a lesser extent.

Paramagnetic minerals feature ions with unpaired electrons (mainly, elements with unfilled d and f-levels) in composition and chaotic spin orientation. Therefore when there is no magnetic field magnetic moments are aligned, and minerals show no magnetization. Minerals are positively magnetized in the magnetic field owing to spin orientation and attracted in the magnetic field direction. During heating of paramagnetic minerals magnetization and susceptibility decrease because of spin disordering. Magnetization increases when magnetic field

intensity goes up. Moderately magnetic minerals (ilmenite, hematite, chromite, wolframite, siderite, pyrolusite and iron-containing silicates) belong to paramagnetics. Paramagnetic minerals are weak magnetic, the specific susceptibility is no more than $10^{-4} \text{ cm}^3/\text{g}$. The main contribution to paramagnetic magnetization is made by electron paramagnetism of ions with unfilled internal shell which the paramagnetics are composed of (transition and rare-earth elements) as well as atoms, ions and free radicals with an odd number of electrons. Paramagnetism of conductivity electrons is essential for metals. In some cases, if there are no paramagnetic ions, weak temperature-independent paramagnetism caused by polarization of electron shells is exposed (for instance, rutile).[77].

Paramagnetic crystals show anisotropy of magnetic properties which is predetermined by crystal structure and state of electron shells of magnetophore ions.

Ferromagnetic minerals contain transition element ions with unpaired spins which magnetic moments are oriented by the crystalline field within magnetic domains, they may be imagined micromagnets from one micrometer to one millimeter in size. magnetic domain miments with no magnetic field have different orientation, and therefore magnetization of, for instance, our native iron is not manifested. In the magnetic field domains, like spins in paramagnetics, are oriented which causes domain disorientation in some minerals immediately, after some time in other minerals and with remanence preserved in third minerals. This is connected with different mobility of magnetic domains in different minerals which depends on availability of dislocations, inclusions of other minerals, for example, products of decomposition of solid solutions, zonality or mosaic structure of crystals and other heterogeneities. Stability of remanence is expressed through energy necessary to be spent on demagnetization which is called "a coercive force". Ferromagnetic minerals feature high positive value of magnetic susceptibility greatly dependent on magnetic field intensity and temperature. Just like in paramagnetics there is spin disordering during heating, magnetic domains are disoriented in ferromagnetics, and at certain temperature (the Curie point) magnetic moments are completely offset and magnetization disappears (as ferromagnetic is turned into a paramagnetic).

Native iron, ferroplatinum, iron-containing gold belong to very high magnetized ferromagnetics.

Unique ferromagnetic properties are connected with the so called exchange interaction between electrons which results in mutual orientation of elementary magnetic moments.

Antiferromagnetic minerals distinguished by that spins of neighbouring ferromagnetic ions have an antiparallel orientation under the effect of crystal field. Partial disordering occurs above a certain temperature level (the Neel point). It is accompanied by an insignificant rise in magnetic susceptibility. Antiferromagnetics comprise certain sulfides, pyrite (FeS_2), chalcopyrite (CuFeS_2), troilite (FeS), oxide ilmenite (FeTiO_3), as well as other minerals containing ions of iron, manganese and a number of rare-earth elements: tourmaline, monazite, orthite, sphene, pyrochlore, and others.

Ferromagnetic minerals, just like antiferromagnetic ones, show an opposite orientation of spins but feature an incomplete compensation of magnetic moments. Ferrimagnetic magnetization is proportional to the number of redundant ions of transition elements with unpaired spins. For instance, in magnetite ($\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$) 8 Fe^{2+} 3 α^6 ions (CN=6), 8 Fe^{3+} 3 α^5 ions (CN=6) and 8 Fe^{3+} 3 α^5 ions (CN=4) fall on an elementary cell. Iron ion spins in octahedron and tetrahedron coordinations have an opposite orientation but are completely compensated only with Fe^{3+} ions (antiferromagnetism). The Fe^{2+} ions in the octahedron coordination have four electrons on three lower α -levels. Two of these three electrons are antiparallel while on the upper levels there are two unpaired electrons which is in line with a high-spin configuration.

In so doing, the magnetic moment of each of the 8 Fe^{2+} ions is equal to the product of the unpaired spins by the Bohr magneton. The magnetite magnetization M referred to the elementary cell volume V and equal to the product of the N number of Fe^{2+} ions by the magnetic moment of each ion ($n\mu_B$)_n can be calculated by the formula

$$Nn\mu_B$$

$$M = \frac{\text{-----}}{V}$$

Ferrimagnetic and ferromagnetic minerals belong to high-magnetic minerals but are distinguished by magnetization value which is mainly connected with presence of nonmagnetic cations and anions. Maximum magnetization is shown by magnetite easily attracting a magnetic needle.

Titanomagnetite, pyrrhotite, jacobsonite, maghemite, cubanite and other rare minerals are less magnetic. Magnetic structure of domain is typical of them all but domain mobility is extremely low. Hence ferrimagnetic minerals feature a high degree of *residual magnetization* and expose magnetization without the magnetic field present. The orientation of magnetic moments in these minerals coincides with the magnetic field direction at the time of formation.

The magnetic memory of minerals re-establishes directions of the paleomagnetic Earth's field and is widely applied for reconstructing the positions of the magnetic poles in various geological epochs as well as the classification of sedimentary and igneous rocks by age. The diagnostic significance of magnetic properties is restricted to the identification of only some high-magnetic minerals, like ferro and ferrimagnetic substance which residual magnetization is high.[42].

Impurities and inclusions make a considerable contribution to magnetic properties of low-magnetic properties. Transition metal or rare earth impurity ions introduced into the lattice bring about paramagnetism inherent of this mineral type. Inclusions of other minerals also lead to magnetic susceptibility. Magnetizing power under the effect of magnetic field is dictated mostly by the content of ferromagnetic mineral inclusions (mainly minerals of titanomagnetite group). Magnetic susceptibility value is also influenced by shape and size of ferromagnetic mineral grains and grain arrangement with respect to one another. When magnetic susceptibility is measured it may vary in the same rock depending on magnetic field value and magnetic history of rock. Original magnetic susceptibility (in a weak magnetic field) is the most essential for rocks. As in ferromagnetic minerals susceptibility has a substantial relationship with the magnetizing field, differential magnetic susceptibility is introduced which shows the dependence of magnetization on field intensity in each point of the magnetizing curve. During magnetizing and demagnetizing of ferromagnetics reversible and irreversible phenomena in magnetization may take place under the effect of magnetic field owing to which reversible or irreversible susceptibility is distinguished. In practice susceptibility calculated per unit of volume (volumetric magnetic susceptibility) or mass (specific magnetic susceptibility) of rocks is applied in magnetic separation.

The highest values (up to 0.2) of magnetic susceptibility are shown by ferruginous quartzites. In intrusive rocks where iron oxide content grows as basicity increases magnetic susceptibility goes up from acidic differences towards basic ones (no more than 10^{-5} in granites for the most part, and up to 10^{-2} in gabbro). Ultrabasic rocks show the widest range of susceptibility variation: from low or very high-magnetic ones, with serpentinization leading to a sharp increase in susceptibility (up to 10^{-2}). Magnetic susceptibility is as a rule not high in metamorphic rocks (no more than $5 \cdot 10^{-6}$). The lowest susceptibility values are inherent of chemogenic sedimentary rocks (down to $3 \cdot 10^{-7}$).

Of interest to industrial practice is the opportunity of considerable change in magnetic susceptibility of some low-magnetic minerals by means of thermal treatment, for instance, increase in magnetic susceptibility of sphene, rutile and leucoxene owing to short reducing roasting. [16].

The magnetic dressability scale is plotted in Fig.4.12 where the logarithm of specific magnetic susceptibility is laid off as ordinate and high, medium, low and non-magnetic minerals are marked. Selection of minerals in separators takes place mostly according to these groups in existing methods of magnetic separation. Sometimes low-magnetic minerals can be separated when the difference in magnetic susceptibility is essential.

Mostly magnetite and titanomagnetite ores as well as rare-metal ores are dressed by dry magnetic separation. Wet magnetic separation is applied for dressing of high and low-magnetic ores.

Polygradient separators based on sludge filtration through the magnetic ball layer afford a substantial increase in magnetic field intensity and gradient, surface area on which separation occurs, fall of relative velocity of particle motion and, consequently, size of dressed material.

Magnetic separation

The process is grounded on differences in magnetic properties (magnetic susceptibility, remanence, coercive force, etc.) of separable components in heterogeneous permanent or variable magnetic fields. [85].

The selection mechanism implies that mineral grains of higher magnetic susceptibility are attracted to poles of magnetic system of separators and, using transport devices, are transferred to receiving devices for magnetic products while low or non-magnetic grains are taken off by the flow to receiving devices for non-magnetic products.

Magnetic separation performed mostly in heterogeneous permanent magnetic fields is the main technique of dressing iron (about 70 % in the world and 90 % in the CIS) and manganese (over 90 % in the CIS) ores and as final operations after gravity dressing for non-ferrous and rare metals ores.

Depending on magnetic susceptibility of material, magnetic separation is subdivided into low and high-magnetic, and into wet and dry magnetic separation, depending on the medium in which separation is performed. Thermal treatment (magnetizing roasting) in oxidizing (siderite, carbonate and other ores) or reducing (oxide ores) atmosphere.

Magnetic separators of different types (drum, roll, belt, disc, rotary, etc.) are applied, depending on physicochemical properties and size of separable material. [85].

4.4.5. Electric Properties of Minerals and Electrostatic Separation

Electric properties of minerals are made use of in electrostatic separation and flotation processes or influence the process running. Electric conductivity, dielectric permeability, triboelectrification are the most essential properties for electrostatic separation. Properties depending on electrochemical potential, forbidden zone width, impurity concentration and type. This is manifested, particularly, in the effect of charge carrier concentration and sign (observed in some cases) on adsorption of collectors and natural hydrophobicity of semiconductor minerals to which a great number of sulfides, oxides, etc. are attributed.

Electric conductivity is measured by electrical resistivity (ρ) or conductivity ($\chi = 1/\rho$). Depending on conduction and electron structure type, all minerals are subdivided into semiconductors with $\rho = 10^{-6} - 10^2 \text{ Ohm}\cdot\text{m}$, semiconductors with $\rho = 10^3 - 10^{10} \text{ Ohm}\cdot\text{m}$, dielectrics with $\rho = 10^{10} - 10^{14} \text{ Ohm}\cdot\text{m}$. Conductor minerals mostly include native metals with metallic type of chemical bond. The valent zone of conductors is occupied by electrons for a half and partially overlapped by the zone of conductivity. The valent zone of dielectrics is fully occupied by electrons. This zone is separated from the zone of conductivity by a wide zone of forbidden states with energy of several eV. Semiconductors feature a relatively narrow zone of forbidden states (usually less than 3 eV) and partial filling of the zone below the conductivity one by electrons. If in the partially filled zone the number of electrons is not large, they belong to the n-type with electron conduction, if electrons predominate in the zone, they are of the p-type with hole conduction.

In semiconductors conduction especially depends on content of impurities and structural defects and drastically increases with temperature rise. Intrinsic conduction of semiconductors is connected with the transfer of a part of electrons from the valent zone to the conductivity zone during heating with formation of an equal number of free electrons and holes. The impurity conduction is predetermined by ionization of isomorphous impurities with redundant charges. Redundant charges also appear in nonstoichiometric minerals. Ionic conduction running

according to vacancy mechanism is also possible in semiconductors and dielectrics at high temperature.

Polarization and dielectric permeability of minerals are connected with displacement of positive and negative charges to opposite sides under the effect of electrical field. Polarization emerge in dielectric minerals and is not accompanied by electron conduction. There are electron (asymmetric displacement of electrons with respect to nuclei), ionic (displacement of ions of different sign), orientation (orientation of dipoles) polarizations. Dielectric permeability gives a measure of polarization. Impurities and defects have virtually no effect on dielectric properties. Electrification of minerals, i.e., emergence of electrostatic charges of this or that sign on the mineral surface, is connected with polarization. Attraction of mineral particles takes place in case of contact with the mineral surface of opposite charge. In the contrary, on contact, for instance, with the grounded surface conducting minerals give off the negative charge and gain the positive one which results in repulsion. These differences between dielectric and conductive minerals are used in dressing by electrostatic separation. [42,86].

Electrostatic charges appear on the dielectric mineral surface as a result of thermal and mechanical actions.

Conductivity of minerals is the basis of the scale of electrical dressing techniques (Fig.4.13). In individual types of one and the same mineral this value varies within a much larger extent than density and magnetic susceptibility. Literary sources also give different values of conductivity, and the discrepancies are substantial. Therefore during dressability studies it is recommended to measure conductivity of ore minerals and introduce appropriate corrections to the scale.

The mineral properties which define electric charge, and, consequently, separation as well cover conduction, dielectric permeability, triboelectrification (triboadhesion effect), contact potential and pyroelectric effect. Besides, there are piezoelectric effect and unipolar (detector) conductance of crystals which are not used in dressing processes as yet.

In summary tables minerals show a wide range of conduction and dielectric permeability. [86]. For example, according to the published data the resistivity $\rho = 10^{-1} - 10^{-6}$ Ohm·m for some galenite specimens. In natural galenite specimens both electron and hole conductance is observed, the concentration of charge carriers varies in a large range, coefficients of thermoelectromotive force as well as temperature-dependent resistance are different. Resistivity varied from $10^{-2} - 10^2$ Ohm·m, and variations of other electrophysical characteristics were simultaneously recorded for relatively pure crystals of cassiterite. When the relative dielectric permeability (ϵ) changed the scatter was also large though less than for conductance.

Dielectric permeability significantly depends on alternating current frequency for some minerals. For instance, for dolomite specimens $\epsilon = 6.7-7.2$ and 11.2 at 50 and 100 Hz measurements.

Temperature and moisture have a large effect on the results of electric measurements. Account of moisture is especially important for hygroscopic and porous specimens since $\epsilon \sim 80$ (?) of water are supplemented in measurement of dielectric permeability. A water film on the surface can change the result by several orders in measurement of dielectric resistance.

Electrostatic separators are applied for separating the mixture of dry minerals to constituent components as well as for separation by size (electrostatic sorting).

Techniques of electric separation are as follows: electrostatic (electrostatic field: particles are charged by contact or inductive method), corona (corona charge field: particles are charged through ionization), dielectric (electrostatic field: uncharged particles are separated under the effect of ponderomotive forces), combined techniques: corona-electric (corona charge and electrostatic fields, particles are charged through ionization and by other methods), corona-magnetic (corona charge and magnetic fields, particles are charged through ionization), triboadhesive (particles are charged due to a triboelectric effect, adhesion, etc.).

Drying, dedusting, size sorting, treatment with surface-active agents, and other operations can be applied for preparation of materials and electric separation (depending on characteristics

of entry material and conditions of processing). Drying eliminates the effect of atmospheric air humidity, make behaviour of separable particles more stable and affords their free motion in a separator under the action of mechanical and electric forces).

Separation efficiency is more controlled by the properties of minerals (substances) and less by the state of material surface.

The natural state of the surface may be changed, for instance, by cleaning, removal of some constituents and formation of surface films using agents of selective action on different substances. Sludge agitation is required for cleaning if during the cleaning process the constituents to be removed from the particle surface cannot volatilize, disperse or be abraded.

The surface either in dry (gaseous) or wet (solute) state can be treated by surface-active and film-forming agents. In this case downstream drying of treated material is needed.

The surface of basic pegmatites is treated by hydrofluoric acid or salt (from 100 g/t and more). Minerals contaminated with iron compounds may be etched by sulfuric acid or zinc hydrosulfite. Benzoic acid may be applied for selective formation of films on basic (ullexite, zoisite, etc.) and chemically less active or neutral minerals (cyanite, sillimanite, zircon).

When the mixture of quartz and feldspar is treated with sulfuric acid vapour, the conductive film of fluoric potassium and fluoric aluminium is formed on the feldspar while the quartz undergoes almost no change (the surface is "engraved", and fluoric silicon vapour volatilizes). When the mixture of quartz and fluorite is treated in the same way, the conductive film of fluorides is formed on the latter. After spodumene (lithium) ore is treated likewise spodumene becomes more conductive than associated minerals: albite, microcline, and quartz. Besides, separation of zoisite from plagioclase is improved. During final processing of diamond-containing concentrates the entry material is pretreated by water solution of sodium chloride.[86].

Electric separation

The process of selection of dry mineral particles in electric field by value or sign of the charge formed on particles depends on electric properties, chemical composition, dimensions, etc. It is used for final processing of rough concentrate of diamond and rare-metal ores: tantalum-zirconium, tantalum-niobium, tin-tungsten, rare-earth (monazite-xenotime). Electrostatic, corona, dielectric and triboadhesive separations are distinguished by method of forming charge on particles and charge transfer during electric separation.[86].

In electrostatic separation selection is performed in electrostatic field, particles are charged by contact or inductive methods. Corona separation is carried out in corona charge field, particles are charged by means of ionization.

Triboadhesive separation is grounded on the difference in adhesion of triboelectrified particles. Friction can appear during transportation of particles along a special substrate, in fluidized bed on contact of particles with one another.

A relatively narrow application field of electric separation is due to high energy consumption, sophisticated high-voltage equipment to be applied, requirements to careful predrying of material which is difficult to be provided for at concentrators where mostly wet processes are used.

Dielectric separation is performed owing to ponderomotive forces in electrostatic field, here particles of different dielectric permeability move over different paths.

Dielectric constant is defined by the ratio of electric field intensity in minerals and rocks to the field intensity in vacuum. The dielectric constant varies from 3 to 10, seldom to 25 for the majority of rock-forming minerals (among them any silicate), with 40 for wet rocks.

Dielectric separation process is grounded on the difference in dielectric constants of minerals and applied for mineralogical study or for selection of mineralogical fractions. The dielectric separation process can be applied in full-scale practice in separation of finely ground valuable minerals (slime) and in final processing operations.[68].

Minerals of different dielectric constant are placed into a non-conductive fluid which dielectric constant is intermediate in value between dielectric constants of separable minerals and

generate an electric field with radially spreading lines. Mineral particles are polarized, forming a dipole one end of which is directed towards a strong field and the other end towards a weak one. As a result of this particles which dielectric constant is higher than that of the fluid will move towards the more intensive field and particles with lower constant towards the weak field. This motion of polarized particles towards the highest intensity side may be called dielectrophoresis.

4.5. Physicochemical Properties and Floatability of Minerals. Flotation

4.5.1. Crystallochemical Characteristic of Surface

Mineral particle surface formed by virtue of ore preparation operations (crushing, grinding, washing) have a number of important properties on which flotation, flocculation, electric separation processes are based. Of the greatest significance to flotation are wettability and adsorptive ability of mineral surface which are dictated first of all crystallochemical properties and then by morphological peculiarities: microheterogeneity, crystal lattice defects, conductance type.

Energy of crystals, like other phases, is put together from internal and external surface energies. As the phase surface features disruption or loosening of ties between phase components, it makes a positive input into the total phase energy. The surface energy of the phases is connected with the free surface energy which is governed by the surface tension σ (erg/cm² or dyne/cm), energy consumed in forming one square centimetre of surface area.

When minerals interact with various chemical agents in liquid, gaseous and even solid states, there is a change or disintegration (decomposition) of minerals, uneven as far as character and degree are concerned.

Changes and destruction of minerals which result from various external forces usually begins with the surface of mineral grains. The impact of these forces on minerals is dictated by micromorphological and crystallochemical features of the surface and depends to a large extent on macro and microheterogeneity as well as defect rate.

Surface energy of crystals is numerically equal to half of energy of disrupted chemical bonds and a function of interatomic distances and charge of structural units. In general case the surface energy of crystals is lower on the planes of fracture with maximum interatomic distance, i.e., on planes of cleavage with low crystallographic indices, and especially cleavage faces of different orientation show higher energy. In anisotropic crystals faces with different indices (hkl) and cleavage faces of any possible direction for this crystal will also have different surface energy.

Surface energy is closely connected with free surface energy for which surface tension is responsible. In minerals of monotype in chemical aspect surface energy decreases as the cleavage perfection degree increases. Similar is the relationship between surface energy and hardness predetermined by chemical bond strength: the higher the hardness, the larger the surface energy. However estimation of chemical bond strength in different directions is very approximate. Bond strength may be conceptually examined based on thermodynamic data directly connected with crystallochemical peculiarities of minerals.[13,14].

Strength of chemical bonds may be compared only among the minerals of one structural type, for example, calcite, dolomite, phoschrosite, magnetite, siderite, while aragonite already falls out of the examination because different atom packing methods are implemented in different modifications and structural types.

At low surface energy on cleavage plane (very perfect) minerals have natural hydrophoby: graphite, molybdenite, talc, pyrophyllite, etc. Very perfect cleavage in the above minerals is attributed to heterodesmic nature of interatomic bonds. Rigid covalent bonds predominate within individual layers and lamellar packs while very loose residual Van der Waals bonds prevail between them. In this case the peculiarity of cleavage face is that charges are almost ideally compensated within layers or packs.

When crystal grains of minerals with mostly ionic or ionic-covalent bond types, in particular, haloids and oxygen salts, as well as silicates, are split, most often cation-anion bonds are broken, and cleavage face gains a redundant (uncompensated) positive or negative charge. The charge value and the quantitative cation-anion ratio on the “open” surface in the long run dictate value and sign of electrostatic potential of cleavage face.

The crystallochemical estimation of flotation activity of minerals with predominantly ionic bonds in crystal structure is connected with atomic structure of cleavage face. Here mainly steric factors are taken into account, and distribution of charges is associated with electrostatic interaction. The opportunity of estimation of type and strength of chemical bond (with regard to heterodesmic nature) in crystal structures affords an application of crystallochemical analysis when explaining flotation process not only for crystals with ionic structure but also for more complicated objects, like silicates.

Surface energy is not only higher on random cleavage faces than on cleavage planes but have a wider range of values owing to diversity of grades and greater shatter of interatomic distances.[15].

Sign and value of *electrostatic component* of surface potential may be estimated in accordance with crystallochemical data. Projection series parallel to cleavage or fracture face surfaces and perpendicular to them are plotted along the coordinates of atoms in corresponding crystal structure of minerals. The former give the picture of distribution and value of redundant charges of different sign, the latter present the position of atoms with respect to fracture face. The largest redundant charge, even at the same quantitative ratio of plus and minus is introduced by the ions protruding above the other ones and fairly distant from the opposite sign ions. They are also the most probable centres of absorbing flotation agents.[15].

Different variants of distribution of charges are implemented at splitting of mineral grains. Completely compensated electrostatic oxygen ions are exposed in lamellar structures, like talc, on the surface of perfect cleavage. More loose cation-complex anion bonds in main structures (sulfates, carbonates, phosphates, wolframates) are commonly broken owing to strong covalent bonds inside $[\text{SO}_4]^{2-}$, $[\text{CO}_3]^{2-}$, $[\text{WO}_4]^{2-}$, $[\text{PO}_4]^{3-}$ complexes. Therefore oxygen ions of complex anionic radical (A) and cation (C) turn out to be on fracture faces. In this case redundant negative charge with a maximum of up to $-1/2$ emerges on oxygen ions provided all cation-radical (?) oxygen bonds are broken. Value of redundant positive charge on cations in the mixed C-A grid depends on the coordination of this cation and the number of broken bonds with anions. A very substantial input to surface charge is created in structures with supplementary O^{2-} , OH^- , Cl^- , F^- and other anions exposed on the fracture face.

Complete cleavage in chain and band structures usually passes along endless silicon-oxygen radicals ($[\text{Si}_2\text{O}_6]^{4-}$ and $[\text{Si}_4\text{O}_{11}]^{7-}$). When bonds are broken along cleavage, for instance, in pyroxenes, two types of oxygen atoms: bridge ones divided by two silicon atoms of pyroxene chain ($[\text{Si}_2\text{O}_6]^{4-}$) and lateral ones introduced into coordination of alkaline earth cations (Ca, Fe, Mg). The former feature a completely compensated charge. When the $\text{Si}\dots\text{O}\dots\text{C}$ bond is broken, lateral atoms of oxygen in chain radicals are short of negative charge, and accordingly silicon atoms gain a redundant positive charge. Moreover, fracture also exposes coarse two-valent cations which make their input into distribution and sign of a redundant surface charge.

Any fracture in shell-like structures of quartz or aluminosilicate type because of broken $\text{Si}\dots\text{O}\dots(\text{Si}, \text{Al})$ bonds will show either an excess of negative charge in case of surface exposure of oxygen ions or predominance of positive charge owing to exposure of silicon or aluminium atoms. Highly-coordinated coarse K^+ and K^{2+} cations exposed on the fracture face also have a minor redundant charge. Positive charges emerged in shell-like structures are easily compensated due to joining of hydroxyl group and leaching of large ions exposed on the fracture face.

Possible self-compensation of redundant surface charges also owing to redistribution (transfer) of charges between cations should be taken into account during crystallographic estimation of surface charges.

Self-compensation takes place, for instance, in pyroxenes where Ca^{2+} , Mg^{2+} , Fe^{2+} and Mn^{2+} polyhedrons form double zigzag-shaped columns with common edges, similar variants are present in the granite structure where columns consist of Al^{3+} , Fe^{3+} , Mn^{3+} octahedrons and Ca^{2+} , Fe^{2+} , Mn^{2+} octoapical figures (?). The redundant positive charge emerged in this case can be compensated by means of trapping an electron of the neighbouring two-valent ion, i.e., in fact, oxidation. Even greater significance is acquired by self-compensation in minerals with semiconductor and metallic properties, i.e., in the majority of sulfides, some oxides and native metals. In consequence of this the negative charge of the surface increases. [13,14].

4.5.2. Hydration of Mineral Surface

Wettability of minerals completely depends on crystallochemical characteristics and type of uncompensated chemical bond inherent of fracture face. Hydrophilic minerals are easily wetted in water as compared to hydrophobic ones which are not wetted and are ejected to the borderline separating fluid from air. This property is made use of in flotation enrichment of ores. Mineral particles with natural floatability, hydrophobic ore minerals, become adhesive to air bubbles, go onto the surface and are grouped in the foam which, together with ore minerals, is mechanically parted from hydrophilic minerals. Hydrophobic minerals include minerals with completely compensated charges (gold, copper), platinum, etc.), layer minerals with noticeably perfect cleavage and molecular crystals with weak hydrogen bonds or Van der Waals bonds (graphite, talc, molybdenite, sulfur, realgar, etc.). Weak (?) hydrophobic minerals include semiconductor minerals with completely or partially compensated covalent or covalent metallic bonds (sulfides: galenite, pyrite, chalcopyrite, etc., as well as diamonds). Natural floatability is not inherent of hydrophilic dielectric minerals with strong uncompensated ionic or ionic-covalent bonds (barite, calcite, quartz, scheelite, feldspar, spodumene, etc.). [42].

During grinding crystals of natural minerals contact the liquid phase of flotation sludge which is a water solution of different ions and molecules. A hydrate layer is formed on the surface if the mineral has fairly hydrophilic surface.

Water is one of the strongest polar solvents (dielectric permeability: 80). Coulomb interaction of cations and anions of crystal lattice decreases by a factor of 80 which explains a strong dissolving ability of water with respect to ionic crystal lattices. The ion tearing off from the crystal surface because of thermal fluctuations or any other interaction falls into the water phase where its electrostatic field weakens.

Cationic and anionic points present on the mineral surface are usually hydrated by water molecules of liquid phase. In first approximation crystal lattice energy is equal to sum of hydration energies of both lattice ions. Aquacomplexes neutralize electrostatic fields of liquid phase ions approximately in the same degree in what one ion neutralizes each other in crystal lattice.

The formation of hydrated surface is connected with surface energy which governs interaction of water molecules with mineral particles. From a macroscopic viewpoint changes in hydrophilic and hydrophobic surface properties is controlled by the ratio of the adhesion energy A_{adh} and the cohesion energy A_c on the interface. $A_a > A_c = 2\sigma_{\text{l.g.}}$ for hydrated surface, and $A_a < A_c = 2\sigma_{\text{l.g.}}$ is fair for hydrophobic surface.

Cohesion energy spent on overcoming intermolecular forces during formation of a new liquid-gas interface which is numerically equal to energy of breaking the bond between water molecules per unit of the newly-formed interface. [76].

Equilibrium among phases in three-phase contact is controlled by the equation of final edge angle of wetting:

$$\cos\theta = (\sigma_{\text{s.g.}} + \sigma_{\text{l.g.}})/\sigma_{\text{s.l.}}$$

where θ is the edge angle of wetting, $\sigma_{\text{s.g.}}$, $\sigma_{\text{l.g.}}$, $\sigma_{\text{s.l.}}$ are the surface tension between contact phases, respectively. The $\sigma_{\text{s.l.}}$ and $\sigma_{\text{s.g.}}$ values for a macroscopically heterogeneous particle are not permanent but vary on different surface sections. The edge angle of wetting will be

approximately estimated by a sum characteristic of interphase tension over the three-phase perimeter, and the Dupreau equation will take the form

$$\cos\theta \sim \frac{\sum_1^n \sigma_{s,g} S_{s,g} + \sigma_{l,g}}{\sum_1^n \sigma_{s,g} S_{s,g}}$$

The compensated system tends to construct the surface with minimum energy consumption. the liquid will send to the surface mostly those ions and molecules which provide for free energy minimum of the interface.

The difference in concentration of the surface and in the volume of the liquid phase is controlled by the Gibbs adsorption equation

$$G = - \frac{C}{RT} \frac{d\sigma}{dC}$$

where C is the concentration of water-dissolved ions and molecules, σ is the surface tension, R is the universal gas constant, T is the absolute temperature.

Ions of large size and small specific charge have a loosening effect on the quasicrystalline water structure and make the bond of water molecules with one another weaker. The energy field of the surface affects oscillatory and translational motions of water molecules. A particle flux directed to decrease in free interface energy emerges in the boundary layer of the liquid. Ions of negative hydration violate the short-range tetrahedron order of water molecules, with this violation not seldom propagating to second and even more long-range coordination spheres of quasicrystalline water lattice (up to 30-50 Å). Further violation of short-range order of water molecules which surround the negatively-hydrated ion causes an energy field generated by gradual change of order in liquid structure under the action of the ion. [76].

If water contacts the surface of the mineral treated with a hydrophobized agent, the near-surface layer structure is also disordered because of nonwettability of apolar parts of diphile (?) molecules of a collector agent. Surface energy of apolar parts of the collector agent molecules is commensurately lower than this parameter for water.

A compensating energy field which vector is a function of sign of difference in free energies of phases in contact is formed as a result of the difference in free energies of surfaces of solid body and water in contact with solid body.

An energy field present near the hydrophilic surface is the main reason for the layer of counter-ions which compensate a difference in free energy of solid body and water phase surfaces.[76].

4.5.3. Adsorption Ability of Minerals

The adsorption ability of minerals which is various in nature is manifested in that minerals adsorb molecules and ions on the surface. The adsorption ability is particularly high in dispersed minerals owing to a high-density surface measured in the units of area by the units of mass (cm²/g). Adsorption is said to be chemical if strong chemical bonds are formed between the adsorbent and the adsorbate. Physical adsorption is the other adsorption type characterized by the fact that the adsorbent molecules can be easily escaped (?). In the first case adsorption can be likened to the formation of chemical compositions containing combined atoms which belong to the adsorbent and the adsorbate at the same time. In the second case these compositions are not formed. Hygroscopicity, i.e., adsorption of moisture by insoluble minerals can be referred to as an example of physical adsorption of water.

It is required for formation of a strong adsorption bond that the anionic agent electron would transit to the crystal lattice of the mineral. In case of cationic agent the electron forming of

the bond transits onto the cation of the flotation agent. The transition of agent anion electron is the most probable in the region of the cation point of the crystal lattice surface owing to the highest concentration of the electron orbits on this lattice area. This ability affords a selection of electron transition zone which is limited on the one side by the mineral crystal surface, and on the side by the layer of oriented ions and molecules of the liquid phase of the flotation sludge.

The number of agent anions able to be fixed on cation points of mineral crystal lattice is a function of liquid phase component composition, concentration and chemical nature near the mineral particle surface. In the liquid phase of the sludge there are anions able to compete with agent anions in the formation of an adsorption bond. The fixing of the agent anion depends on the time of residence in the electron transition zone and in an adsorbed state or the strength of the bond of the anion with the cation point of the crystal lattice. The agent anion being in an adsorbed state is predetermined by the mobile nature of solid-liquid interface equilibrium.[76].

Application of various *flotation agents* affords alteration in natural floatability which assists in enriching the mineral. Application of apolar agents (organic oils, kerosene, etc.) improves floatability of hydrophobic minerals adhesive to drops of these substances.

Chemical adsorption of polar anion and cation agents is made use of in flotation of weak hydrophobic and hydrophilic minerals. The anions (?) are attached to the surface of minerals with redundant negative charges, with the cations to the surface of those with the positive charges. As a result each grain is surrounded by molecules which free ends are not wetted by water and consequently the hydrophobic nature and floatability of the mineral increase. Various surface defects affect (?) adsorption of mineral floatability because of locally uncompensated charges connected with them. Since mineral fracture takes place for the most part along the more defective directions of crystal grains, concentration of defects on the surface of fractured mineral particles can be very substantial.[76].

At present flotation is the most widespread method of dressing mineral products: 90 per cent of all non-ferrous and rare metal ores are dressed by flotation techniques which affords processing of extremely lean, finely impregnated ores of complex composition with copper, lead, zinc, molybdenum, tungsten, tin, and other metals.

In general case both electrons and positively or negatively charged ions can pass the interface on contact of the semiconductor and the solution. Greater work function of the electron exiting the crystal always promotes lower positive or larger negative potential of the surface mineral layer, and the opposite pattern is observed when the work function of the electron exiting the solution goes up.

When *semiconductor minerals* are floated, the the process of attracting the ionogenic collector agent to the mineral surface can be controlled by means of changing the work function of the electron exiting the solution. This situation can be traced if oxidizing or reducing agents are added to the water phase of the sludge.

Oxygen being the main electron acceptor causes displacement of chemical electron potential value and brings about higher concentration of free electron vacancies. The opposite pattern is noticed when the reductant is put in the process: oxygen concentration becomes lower, work function of electron exiting water falls, contact potential value is shifted to the negative side, electron concentration in the surface mineral layer goes up which causes lower sorption of anionic agent. This concept is the background of electric processing of flotation sludge and agent solution.

There are chemical adsorption when strong chemical adsorbent-adsorbate bonds are formed and physical adsorption when adsorbed molecules can be easily removed. In the first case Adsorption may be likened to the formation of a chemical compound containing common ions belonging to the adsorbent and the adsorbate.[87].

4.5.4. Floatability of Minerals

Mineral wettability fully depends on crystallochemical peculiarities and types of uncompensated chemical bond which characterize the fracture face. Hydrophilic minerals ...

When the dressability of ores by flotation is studied, the most difficult aspect is to select modes and agents. In many cases flotation recovery of minerals depends not only on floatability of this or that mineral but also on composition of associate components as well as on genesis, impregnation, availability of isomorphous impurities in the mineral and other factors.

Floatability of minerals of different classes is presented in the classification of M.A.Eigeles. More detailed formulations of agents elaborated by S.I.Mitrofanov [87] and G.S.Berger are generalized in [3,76].

Table 4.5. Classification of minerals by flotation properties (after M.A.Eigeles)

Group	Minerals	Flotation properties	Typical collector agents
Apolar nonmetallic minerals	Graphite, native sulfur, talc, bituminous coal	High natural hydrophobicity. Partially floated in presence of one foamer agent. Flotation of largest (several centimetres) particles is possible due to low density and high strength of bubble attraction	Apolar agents (oils). Foamers also often fulfil functions of collectors
Sulfides of heavy metals and native metals	Chalcopyrite, galenite, sphalerite, stibnite, molybdenite, etc. Gold, silver, platinum	Relatively hydrophobic. Very sensitive to oxidation. Actively and selectively interact with xanthates	Xanthates
Oxidized minerals of heavy metals	Carbonates and sulfates of copper, lead, zinc, and salts of these metals and other oxygen-containing acids (azurite, malachite, cerussite, anglesite, smithsonite, wulfenite, etc.)	No natural hydrophobicity. Coated by sulfide film under action of sulfuric sodium and other sulfidizers. After sulfiding floated by xanthates, without sulfiding by fatty acids and their soaps	Xanthates after sulfiding of minerals with sulfuric sodium. Sometimes fatty acids and their soaps
Polar salt-like with alkaline earth metals (calcium, magnesium, barium, strontium)	Schelite, apatite, powellite, calcite, barite, fluorite, phosphite, magnesite, etc.	Virtually no flotation by xanthates. Actively floated by fatty acids and cation agents. Very sensitive to ionic sludge composition	Fatty acids and their soaps

Oxides, silicates and aluminosilicates	Quartz, corundum, diaspore, rutile, hematite, cassiterite, cyanite, andalusite, pyrolusite, beryl, feldspars, micas, kaolinite, etc.	Actively floated by cation type collectors and fatty acids. Sometimes activation by sludge cations is required. Flotation properties are greatly dependent on mineral formation conditions	Fatty acids and their soaps (sometimes after activation by heavy metal salts). cation collectors
Considerably water soluble salts of alkaline-earth metals	Gypsum, hydroboracite, inyoite, etc.	Water-soluble in flotation but not to the degree of saturation. High salt concentration in solution requires particular agents to be applied (with polar sulfogroup, etc.), cation agents and flotation controllers	Collectors of cation and anion types with particular polar groups
Highly water soluble salts of alkaline and alkaline-earth metals	Halite, sylvite, kainite, langbeinite, etc.	Floated in saturated (mother) solutions. Flotation much depends on medium composition. Possible partial transformation of some minerals into other ones during flotation	Ditto

Accurate classification of minerals by floatability is very difficult. The universal flotation method, and the diversity of agents and flotation conditions prevent a formal scale of flotation dressing to be developed. Nevertheless in order to compose auxiliary flotation scales it is possible to apply an acknowledged sequence of floatability of minerals in case certain collectors are used (?) as well as natural floatability of minerals. Flotation agents do not as a rule violate but intensify the difference in natural floatability of minerals. In so doing, naturally hydrophobic minerals can be arranged in the following sequence of decreasing floatability due to apolar agents: hard coal, native sulfur, graphite, molybdenite, realgar, bismuth, talc, diamond. The other industrial minerals are extracted in the presence of heteropolar collectors. Minerals may be arranged in the following sequence according to decreasing floatability due to xanthates: enargite, chalcocite, covellite, argentite, chalcopyrite, sphalerite (copper-activated), marcasite, pyrite, arsenopyrite, proustite, stephanite, pyrrhotite, sphalerite (unactivated). This sequence known from Taggart's papers can be changed by selection of special collector and activator agents. However during primary dressability studies, and in some case when process flowsheets are developed, the sequence indicated should be taken into account as the most probable one for selective flotation of minerals.

Lately a trend to drastic reduction of collector consumption in selective flotation appeared, and in some cases to agent-free flotation applied (only with foamer), which affords a primary rich product to be made in the initial operations. This product consists of easily-flatable minerals. This trend not only meets the requirements of the downstream final processing but also is of great economic and ecological value.

When examining the Taggart's sequence, one can notice that the most naturally-hydrophobic sulfide minerals (molybdenite and galenite) can be collector-free floated without surface oxidation or with reduction of oxidized forms by sulfiders.

The group of copper minerals, of the next rank in natural floatability, is floated only in the presence of heteropolar collectors. As a matter of fact, it is possible to improve dressing efficiency by means of agent-free flotation with a foamer alone.

It is difficult as yet to make up similar sequences of minerals floated by other agents owing to absence of systemized data. However the possibility of similar dependences can be used in practical studies. It is a common knowledge that minerals of industrial deposits may differ much in natural floatability from pure variants. Therefore when the floatability of minerals by these or those agents is assessed the sequences made up are recommended to be corrected by the experimental findings.[11].

4.5.5. Flotation Agents [11, 87,88].

Flotation agents are chemical substances added to the sludge during flotation for control of interaction of particles with gas bubbles, chemical reactions and physicochemical processes in liquid phase, on interfaces and in a foamy layer with the view of creating conditions of selective separation of minerals. In accordance with functional purpose collectors, foamers and controllers (modifiers) are distinguished. Collectors are designed for hydrophobization of mineral particles and divided into apolar and polar substances. Apolar hydrocarbon liquids are mostly of oil origin (kerosene, fuel oils, etc.) and intensify natural hydrophobicity of apolar minerals, like native sulfur, talc, molybdenite, graphite, diamond. The asymmetric structure of a molecule consisting of two parts: apolar and functionally polar, is typical of polar collectors. A functional polar or hydrophilic group is affine to chemical dissociation or chemical interaction. Polar collectors are subdivided into anionic and cationic compounds in accordance with the polar part charge (many of them are also active in a molecular form), they are applied in flotation of non-ferrous metals ores, etc. (Table 4.6).

Table 4.6. Polar collectors and application fields

Agent name	Application fields (in flotation)
<i>Anionic collectors</i>	
<i>Xanthates</i>	
Ethylxanthate	Sulfide ores: Cu-Zn, Cu-Pb-Zn
Isopropylxanthate	Sulfide ores: Cu, Pb, Zn, Au, Ag, Co, Ni, FeS ₂
Pentylxanthate	Oxidized sulfide ores, Co-Ni sulfide ores
<i>Dithiophosphates</i>	
Diethyldithiophosphates	Cu-Zn sulfide ores (except Pb)
Dicresyldithiophosphates (15% P ₂ S ₅)	Sulfide ores: Al-Cu-Pb
Ditto (25% P ₂ S ₅)	PbS and Ag ₂ S
Ditto (31% P ₂ S ₅)	PbS and Ag ₂ S
<i>Thionocarbamates</i>	Cu sulfides or activated Cu
	ZnS in presence of FeS ₂
	FeS ₂ in acidic medium (pH: 4-5)
<i>Fatty acids</i>	
Tallow oil (contains mostly oleic acid)	CaF ₂ , Fe chromite, apatite, ilmenite, CaCO ₃ , MgCO ₃ ores
Refined oleic acid	
Na soaps of fatty acids	
<i>Alkylsulfates</i>	Fe, garnet, chromite, barite, carbonates, Cu,

Alkylsulfonates (with radicals from C ₁₂ to C ₁₆)	CaCO ₃ CaF ₂ , CaNO ₄
Primary amines	Cationic collectors
Secondary amines (in kerosene)	Separation of sylvite, KCl, and halite, NaCl, at selective flotation of sylvite in saturated salt solution, selective flotation of rare-metal ores,
Quaternary ammonium salts of fatty series	separation of feldspar from quartz in presence of hydrofluoric acid, flotation of oxidized zinc minerals after sulfiding

The adhesive character of attaching *apolar collectors* owing to Van der Waals forces is intensified during dispersing drops of collector emulsion (e.g., by ultrasound). A majority of apolar collectors contains polar substances, therefore their interaction with mineral particles and air bubbles is of more complicated behaviour since chemical interaction, along with adhesive one, takes place.

Controllers are applied for improved selectivity of attaching collectors on the surface of certain minerals, stronger attachment, reduced collector consumption and alteration of foaming character. When the controller affects the mineral surface directly, promoting better attachment of the collector and activating flotation, it is called an activizer. For instance, addition of sodium sulfide sulfides the surface of oxide minerals of non-ferrous metals and affords xanthate molecules to be attached to it. The controller making the interaction of the mineral with the collector more difficult is called depressant (suppressor). For instance, liquid glass prevents attachment of soaps to silicate minerals, suppressing their flotation, lime and cyanides depress pyrite flotation. Besides activators and depressants, there are controlling agents which give the medium certain alkalinity and acidity (medium controllers). Controllers which drive apart (peptize) particles of micron dimensions (fine sludge), e.g., sodium silicate, by reducing their negative action on flotation are called peptizer agents and are most often nonorganic compounds; organic controllers are used more seldom.

Certain range of agents and order of feed which constitute the background of flotation mode are used in flotation. A controller is usually added to the sludge, then a collector and later on a foamer. An optimal time of sludge contact with each agent is observed. In many cases the agent action is complex, and the classification indicated is conventional.

The adsorption ability of the surface is always specific with respect to certain types of agents soluble or emulsified in water base. Collector agents (Fig.4.14) and flocculants (Fig.4.15) interact with the mineral surface directly or with the help of controller agents (Fig.4.16). In some flotation cases it is enough for foamer agent to be present (Fig.4.17).

4.5.6. Flotation Processes [76,87,89,91,92,]

Flotation is the main method of dressing non-ferrous metals ores. Flotation is also used for water treatment from organic substances (petroleum, oils), bacteria, finely dispersed salt precipitates, etc. Besides processing branches of mining industry, flotation is applied in food, chemical and other sectors for treatment of industrial effluents, speeding-up of settling, precipitation of solid suspensions and emulsifiers, etc. Wide application of flotation involved a great number of process modifications in different symptoms (Fig.4.18).

The first offer was *oil flotation* (W.Hynes, UK, 1860). Here ground ore is mixed with oil and water, sulfide minerals are preferentially wetted with oil, float with it attached and are taken off the water surface while rock (quartz, feldspars) are drowned in water. In Russia oil flotation was applied for fressing of graphite ore (the town of Mariupol, 1904). Later on this process was improved: oil was dispersed to an emulsion state which permitted extraction of fine slimes, e.g., of manganese ores.

The ability of hydrophobic particles to be retained on the water surface while hydrophilic ones are drowned in water was made use of for development of film flotation (A. Nibelius, USA, 1892; A. McKuisten, UK, 1904). *Film flotation* was not widely applied but turned out to be a prototype of foam flotation, both from the viewpoint of using the water-air interface and from the viewpoint of using flotation agents because it was noticed that film flotation runs much more effectively in the presence of small oil quantities.

During *foam flotation* particles treated by agents are driven out onto the water surface by air bubbles, forming a foam layer whose stability is controlled by adding foams. Different methods were proposed in order for air bubbling. They are formation of carbon dioxide owing to chemical reaction (S. Potter, USA, 1902), emission of gas from solution with pressure drop (F. Elmore, UK, 1906): vacuum flotation, active agitation of sludge (mechanical flotation), passage of air through small holes (pneumatic flotation). Finely dispersed flotation bubbles are also produced from solutions at electrolytic decomposition of water with oxygen and hydrogen gas formed (*electric flotation*).

Diversified techniques of forming air bubbles and combination of these techniques correspond to different types of flotation machines. Arrangement of flotation cells in a certain sequence with delivery of foam and cell product flows to final grinding, recleaner or final flotation composes a flotation circuit which affords a production of concentrate of required quality at preset recovery of the valuable component.

In foam flotation ore is ground to 0.5-1 mm size in case of naturally hydrophobic nonmetallic minerals with low density (sulfur, coal, talc) and to 0.05-0.2 mm size for non-ferrous metals ores. Flotation agents are added to the sludge in order to create and intensify a difference in hydration of separable minerals and to impart adequate stability to foam. Then the sludge enters flotation machines. Flotation aggregates (particles and air bubbles) are formed when minerals collide with air bubbles.

Flotation is influenced by ionic composition of liquid phase of sludge, gases (especially oxygen) dissolved in sludge, sludge temperature and density. Flotation circuit, agent mode and grinding rate which provide for fairly complete separation of minerals are chosen based on the study of mineralogical-petrographic composition of mineral resource to be dressed. Most of all grains of 0.1-0.04 mm in size are separated by flotation. Finer particles are worse separated, and particles of below 5 μ in size deteriorate flotation of coarser particles. A negative action of below 5 μ particles is reduced by special agents. During flotation coarse (1-3 mm) particles tear off from bubbles and are not floated. Therefore foam separation methods at which sludge is fed onto the foam layer which keeps only hydrophobized particles have been developed in Russia. The same objective was in mind when flotation machines of fluidized bed with ascending flows of aerated fluid were developed.

An accessory process often occurs in *flotation machines*. This is precipitation of hydrophobic particles on walls and especially on timber parts, so-called solid wall flotation. This effect was laid in the foundation of floating fine slimes (-10 μ) with the help of carrier mineral, hydrophobic particles of flotation size which selectively interact with extractable slimes; aggregated formed underwent conventional foam flotation.

The hydrophobization effect is also applied in dressing on *sticky surfaces* at adhesion separation (diamonds, clays, soluble salts).

An ionic flotation method was developed for water cleaning and recovery of components from diluted solutions in the 50s.

Late in the 60s - early in the 70s an innovative and promising trend appeared in dressing mineral resources. It was column flotation based on counterflow movement of sludge and air bubbles. High efficiency of column flotation permits shorter process front, reduced number of recleaner operations and lower circulating load in the flowsheet with better stability and reliability of the flowsheet performance. Column cells have two fundamental differences from other machines: counterflow movement of sludge and air bubbles, and the cell height exceeding the diameter several times. Intensive propagation of column flotation cells is involved by high

performance, possible dressing of fine particles (coarse-grained material), easy process control, low energy consumption, effective flotation of dense sludge and, consequently, lower machine volume and agent consumption, no moving parts, small installation site, simple design.

Gravity flotation is a combined process uniting flotation and gravitation. Gravity flotation is performed on concentration tables, in screw separators, belt sluices, concentrators and jigging machines in which aeroflocs of certain minerals with lower density than particles non-interacting with air bubbles are formed due to treatment by flotation agents and injection of air bubbles into slurry. Here the difference in density promotes more effective separation of mineral particles of lower size than in gravitational dressing.

In industry gravity flotation is used for selection of sulfide minerals from gravitational tungsten and tin concentrates as well as for separation of apatite and phosphorite from quartz, zircon from pirochlore, scheelite from cassiterite, and for selection of other minerals. Gravity flotation circuits include operations of dewatering with desliming, agitation of dense slurry with agents, and gravity flotation proper.

Foam separation is the process of separating mineral particles for wettability during passage downwards through the moving foam layer formed on the surface of the aerated fluid. Hydrophobic particles are concentrated in the upper foam layer while hydrophilic ones are washed out of the foam by fluid flow entering the foam together with the slurry from the top. Conditions of counterflow movement of particles and air bubbles which intensify separation process are created in the foam.

In foam separation the different velocity of particles passing the foam, depending on particle surface properties (natural or agent-induced floatability) is responsible for selection. The size of extracted material is, e.g., for phosphotite from 0.2 to 1.2 mm, manganese minerals from 0.2 to 2.5 mm, sylvite from 1 to 5 mm, heavy metal sulfides from 0.3 to 2.5 mm, native sulfur and coal from 0.5 to 5 mm. High separation velocity is dictated by short time and distance of counter movement of free particles towards air bubbles, shorter path of mineralized bubbles till their exit to the concentrating trough.

Duration of mineral selection in foam layer depends on rate of removal of hydrophilic particles from the foam, here coarse particles precipitate 4-5 times more rapidly than fine ones. Foam separation kinetic characteristics are firstly governed by the foam carrying capacity, i.e., the force with which hydrophobic particles placed onto or into the foam are driven out upwards. It depends on several factors among which the main ones are surface properties of particles. The physicochemical fundamentals of foam separation are common to those of flotation but differ in hydrodynamic mode in the zone of forming the mineral-bubble complex. When the slurry passes through the foam, the favourable conditions are created for contact and attachment of particles on air bubbles due to larger probability of their collision and mineralization, absence of centrifugal and inertia forces of tearing the particle off the bubble in the foam. The size of extractable particles is 5-10 times higher than in flotation.

4.6. Chemical and Thermal Properties of Minerals. Hydrometallurgy.

4.6.1. Solubility in Inorganic Solvents

Chemical stability of minerals depends on constituent peculiarities and chemical environment parameters of selective action: concentration, acidity or alkalinity, redox potential, temperature and pressure. Under the effect of chemical environment minerals are partly or completely dissolved, hydrated, oxidized or reduced, evaporated and enter chemical reaction with new matter forms created.

Solubility of minerals is usually established with respect to water and water solutions of acids (sulfuric, nitric, hydrochloric, hydrofluoric, acetic), alkali (KOH, NaOH) and various salts (mainly Na_2CO_3). Minerals hard to be dissolved in aqueous solutions are first melted with

sodium carbonate, phosphate, borax, or sodium fluoride so as to produce alloys soluble in water solutions of acids or alkalis.[11,93,94].

Grain size is responsible for the rate at which minerals are dissolved. Therefore minerals are first crushed and ground. Mineral solubility increases during heating.

Chemical properties of minerals govern possibility of hydrometallurgical processes applied. Lately besides conventional leaching more and more widely used become methods of preliminary preparation which alter solubility of minerals together with bacterial and thermal treatment.

Chemical changes of mineral structure or surface assist in affecting magnetic and flotation properties of minerals. Of particular concern are electrochemical techniques. Here not only surface chemical reactions but also finer mechanism of compensation or creation of crystal lattice defects are possible.

Only cheap solvents can be applied in full-scale ore leaching. More expensive solvents (organic extractants) are used for final processing of concentrates or cleaning of solutions.

Table 4.7 shows solubility of minerals in different solvents. Minerals are divided into two groups by solubility: readily and slightly soluble. Solubility of minerals inside the group is not one and the same. This is connected with a diversity of factors which are responsible for the rate of dissolving naturally occurring minerals, namely: oxidation degree, availability of isomorphous inclusions and impurities, size of particles.

Minerals are less soluble in water. Those readily dissolved in water include chlorides, fluorides, borates, sulfates, and carbonates of alkalis and some other metals.

Table 4.7. Solubility of minerals in inorganic solvents

NaOH	NaOH	NH ₄ OH, NH ₄ Cl	Na ₂ CO ₃	H ₂ O
<i>Readily soluble</i>				
Azurite	Orpiment	Azurite	Orpiment	Borax
Argentite	Vanadinite	Anglesite	Wulfenite	Halite
Bornite	Wolframite	Brucite	Calcite	Kainite
Gold	Hemimorphite	Gypsum	Magnesite	Carnallite
Cuprite	Hydrargillite	Calcite	Malachite	Mirabilite
Malachite	Diaspore	Cuprite	Realgar	Sylvite
Tetrahedrite	Crocoite	Malachite	Rhodochrosite	Thenargite
Chalcocite	Mimetesite	Chalcocite		Epsomite
Chrysocolla	Pyrite	Chrysocolla		
Enargite	Powellite	Scheelite		
	Realgar			
<i>Slightly soluble</i>				
Covellite	Anatase	Anhydrite	Crocoite	Alunite
Electrum	Anglesite	Copper	Marcasite	Boronatrocalcite
	Antimonite	Smitsonite	Powellite	Hydroboracite
	Boehmite		Siderite	Gypsum
	Bismuth		Smitsonite	Inyoite
	Marcasite		Scheelite	Calcite
	Pyrargyrite			Malachite
	Pyromorphite			Nephelite
	Tetrahedrite			Powellite
	Cerussite			Polyhalite
	Scheelite			Rhodochrosite
				Celestite

HCl		H ₂ SO ₄		HNO ₃		
Readily soluble						
Azurite	Magnetite	Azurite	Malachite	Azurite	Cobaltite	Siderite
Apatite	Magnetite	Alunite	Native	Anhydrite	Cuprite	Smitsonite
Bornite	Malachite	Anglesite	copper	Antimonite	Limonite	Stephanite
Boronatro- calcite	Manganite Mimetesite	Apatite Barite	Mimetesite Nepheline	Apatite Argentite	Magnesite Marcasite	Aphalenite Tetrahedrite
Braunite	Autunite	Biotite	Autunite	Orpiment	Malachite	Torbernite
Brucite	Parisite	Boronatro- calcite	Parisite	Bornite	Copper	Uraninite
Boulangerite	Pentlandite		Pyrolusite	Boronatro- calcite	Mimetesite	Fluorite
Vanadinite	Pyrolusite	Braunite Brucite	Pyrrhotite Psilomelane	Brucite	Nepheline Autunite	Chalcocite Chalcopyrite
Bismuth	Pyromorphite	Vermiculite	Rhodochrosite	Boulangerite	Parisite	
Witherite		Witherite			Pentlandite	Celestite
Garnierite	Pyrrhotite	Hausmannite	Siderite	Vanadinite	Pyrargyrite	Cerussite
Hausmannite	Powellite		Smitsonite	Bismuth	Pyrite	Enargite
	Polyhalite	Goethite	Sphalerite	Witherite	Pyromorphite	Jarosite
Goethite	Psilomelane	Hydroboracite	Sphene	Galenite		
Hydroboracite	Rhodochrosite	Gypsum	Uranite	Hausmannite	Powellite	
Gypsum		Dolomite	Fluorite	Goethite	Polybasite	
Dolomite	Siderite	Inyoite	Chlorites	Hydroboracite	Proustite	
Inyoite	Smitsonite	Calcite	Celestite		Realgar	
Calcite			Scheelite	boracite	Phosphochrosite	
	Sphalerite	Cuprite	Aeschnynite	Dolomite		
Carnotite	Enargite	Limonite	Jarosite	Inyoite	Sulfur	
Crocoite	Jarosite	Magnesite		Calcite	Silver	
Cuprite						
Limonite						
Slightly soluble						
Augite	Olivine	Anhydrite	Molybdenite	Alunite		
Alunite	Realgar	Argentite	Monacite	Anglesite		
Anhydrite	Serpentine	Orpiment	Pentlandite	Arsenopyrite		
Anglesite	Chalcocite	Bismuth	Perovskite			

Anti-	Chlorites	Bismuthin	Pyrochlore	Wolframit
monite	Chryso-	e Wolframit	Rutile	e Wulfenite
Argentit	colla	e Wulfenite	Samarskit	Garnierite
e Biotite	Chrysotil	Hemi-	Silver	Hemi-
	e-			
Vermi-	asbestos	morphite	Serpentine	morphite
culite	Chromat	Hydro-	Topaz	Garnets
	es			
Wollasto	Celestite	argillite	Phlogopite	Cassiterite
n-				
ite	Zeolites	Garnet	Chrysotile	Covellite
			-	
Wolfram	Cerussite	Diaspore	asbestos	Crocoite
-				
ite	Zinnwal	Kaolinite	Chromites	Magnetite
	d-			
Wulfenit	ite	Cassiterite	Zinnwaldit	Molybden
e			e	ite
Hemi-	Scheelite	Covellite	Zircon	Monacite
morphite	Egirine	Columbite	Egirine	Niccolite
		-		
Hydrargi	Electrum	tantalite	Enargite	Zinnwaldi
l-				te
lite		Cryolite		Scheelite
Garnets		Magnetite		Electrum
Ilmenite		Manganite		
Cassiteri		Margarite		
te				
Covellite		Marcasite		
Margarit				
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Nephelin				
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4.6.2. Redox Properties

Redox reactions between minerals and different agents are possible if the mineral composition includes element atoms which can change the charge. Changes in solubility of sulfide minerals is connected with oxidation reactions which can occur spontaneously as a result of oxidizing roasting and with the help of bacteria.

The papers of I.N.Plaksin and his colleagues showed that the oxidizability of the mineral surface much affects flotation properties.

The rate of chemical and bacterial oxidation of sulfides is a function of crystal lattice energy and electron potential.[75].

Sulfides of lower crystal lattice energy are much easier oxidized. The lower is the crystal lattice energy the higher is the sulfide solubility (Table 4.8).

Table 4.8. Solubility of sulfides and sulfates

Sulfide	Solubility at 18°C, mol/l	Sulfate	Solubility at 20°C, mol/l
ZnS	$70.6 \cdot 10^{-6}$	ZnSO ₄	3.37
MnS	$71.6 \cdot 10^{-6}$	MnSO ₄	5.32
FeS	$70.1 \cdot 10^{-6}$	FeSO ₄	1.74
CuS	$3.51 \cdot 10^{-6}$	CuSO ₄	1.30
PbS	$3.6 \cdot 10^{-6}$	PbSO ₄	$1.3 \cdot 10^{-4}$
Ag ₂ S	$0.522 \cdot 10^{-5}$	Ag ₂ SO ₄	$2.5 \cdot 10^{-2}$

According to the value of electrode potential minerals are arranged into a series which corresponds to their oxidizability (Table 4.9).

Table 4.9. Electrode potentials in distilled water with respect to copper electrode

Mineral	Potential	Mineral	Potential
Marcasite	+0.37	Galenite	+0.15
Argentite	+0.23	Chalcocite	+0.14
Chalcopyrite	From +0.18 to +0.3	Niccolite	+0.02
Enargite	From +0.18 to +0.23	Domeykite	+0.01
Molybdenite	+0.2	Copper	+0
Covellite	+0.2	Antimonite	From -0.17 to -0.6
Pyrite	+0.18	Sphalerite	From -0.2 to -0.4
Bornite	+0.17		

The following series of deterioration of mineral oxidation rate are identified:

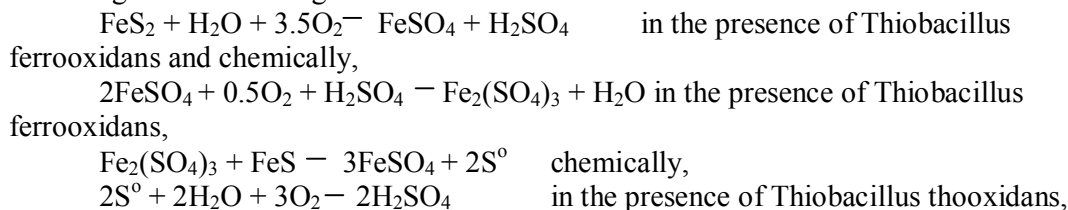
- (a) by value of electron potential without buffer redox systems for acidic and alkaline media: marcasite, pyrite, covellite, chalcopyrite, arsenopyrite, bornite, chalcocite, pyrrhotite, galenite, pentlandite, smaltite, molybdenite, sphalerite;
- (b) in water-air medium: galenite, pyrite, chalcopyrite, pyrrhotite, chalcocite, sphalerite;
- (c) in 0.125 H₂SO₄ solution: pyrrhotite, tetrahedrite, galenite, sphalerite, chalcopyrite, arsenopyrite, marcasite, pyrite;
- (d) by oxidizability in 0.05 H₂SO₄ solution: pyrrhotite, sphalerite, galenite, chalcopyrite, pyrite;
- (e) in 0.1 solution of iron sulfate: pyrrhotite, tetrahedrite, galenite, arsenopyrite, sphalerite, pyrite, enargite, marcasite, chalcopyrite.

Based on findings of calculation isobar-isometric potential of sulfide sulfatation in the range 100-200°C, minerals are arranged in the order below: pyrrhotite, galenite, sphalerite, chalcopyrite, pyrite, covellite, chalcocite.

4.6.3. Bacterial Methods of Solubility Alteration [75]

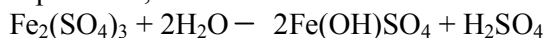
Methods of bacterial leaching of ores are grounded on oxidation of sulfide minerals with the help of bacteria to a soluble state. In order to apply bacterial leaching, besides conventional geologic-mineralogical characteristic it is required to know distribution or possible dispersal of corresponding groups of microorganisms in the deposit. Properties and applicability of

microorganisms in ore processing are given in [26]. However the oxidation mechanism is dependent not only on bacteria properties but also on some other factors. The oxidation process runs according to the following reactions:

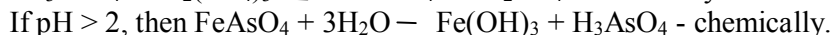
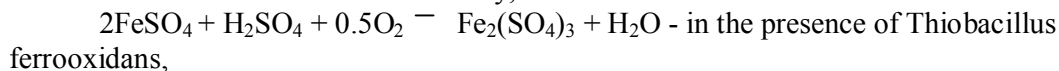
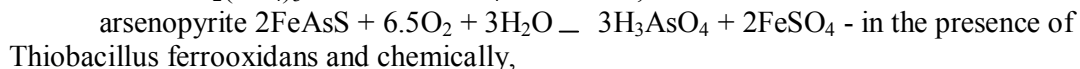
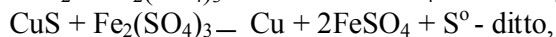
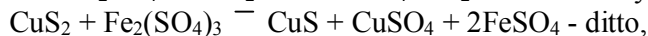
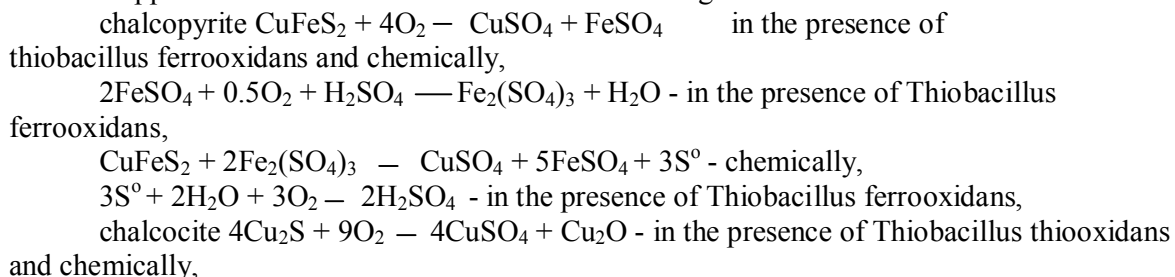


Thiobacillus ferrooxidans.

If $\text{pH} > 3.5$, then



Copper and arsenic sulfides are oxidated according to the reactions:



Surfactants and some mineral salts also accelerate the oxidation process. Thiobacillus ferrooxidans needs mineral salts, in particular, phosphates and ammonium salts. Sulfur treated with phospholipid-phosphatidylinositol is oxidated more rapidly than untreated one. Twin-20 (polyoxyethylene derivative of ester, sorbitol and 0.003-0.004 lauric acid) and X-100 triton are effective for sulfides of copper, zinc and nickel.

4.6.4. Thermochemical Properties

When minerals are heated, atoms which they are composed of are displaced with respect to equilibrium position and oscillate with a certain frequency. Forces of repulsion and attraction between oscillating atoms also vary, and accordingly kinetic energy are transformed into potential one and vice versa. [16,42]

Heat capacity of minerals is responsible for energy to be consumed in heating one mole by 1 degree.

Thermal expansion is defined by growth of amplitude of atom oscillations during mineral heating. Accordingly, distance between atoms increases and chemical bond strength decreases. Linear expansion coefficient is an anisotropic value, dependent on crystal structure of minerals. Thermal expansion is also connected with displacement of atoms from equilibrium position and transfer to interstitial positions, i.e., with thermal defects formed, anionic vacancies and interstitial atoms. Concentration of thermal defects is exponentially temperature-dependent.

Therefore greater thermal expansion corresponds to larger concentration of vacancies in mineral structure.

Minerals are melted with atomic distance and specific volume becoming larger. The exclusions are ice and bismuth of denser structure in fluid state. The melting heat is the energy required for decomposition of crystal structure with formation of melt at a certain melting temperature inherent of each mineral. Melting temperature falls if the concentration of point defects and isomorphous impurities.

Heating on minerals is as a rule accompanied by diffusive atom movements. Here phenomena of disordering take place in some of them while homogenization of phases (aggregations of solid solution disintegration products) occur in other minerals and phase transformations (polymorphous transitions) often accompanied by volume increase, for example, during polymorphous aragonite-calcite transformation, run in third minerals.

Thermal decomposition of minerals takes place below melting point and is manifested by thermal dissociation, for instance, of calcite ($\text{Ca}[\text{CO}_3] \rightarrow \text{CaO} + \text{CO}$) or hematite ($\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}^{2+} \text{Fe}^{3+} \text{O}_4 + \text{O}_2$) and thermal dehydration of minerals containing water, for instance, gypsum ($\text{Ca}[\text{SO}_4] \cdot 2\text{H}_2\text{O} \rightarrow \text{Ca}[\text{SO}_4] + 2\text{H}_2\text{O}$). Some minerals are oxidized or burned in open air, i.e., in oxidized environment. In some cases metal (shots) is smelted during heating of certain sulfides, oxides or salts together with their dissociation or oxidation. Sublimation or evaporation of minerals during heating is observed for native mercury, cinnabar, realgar, orpiment, graphite, bismuth, gold and other metals, especially, in reducing conditions and under vacuum. Table 4.10 shows thermal methods of changing mineral properties.

Table 4.10. Thermal methods of changing mineral properties[16]

Roasting	Purpose	Roasting conditions	Application in practice
Oxidizing $\text{MeS} + 1.5\text{O}_2 = \text{MeO} + \text{SO}_2$	Complete or partial removal of sulfur and transformation of sulfides into the form of oxides later on transiting to solution	Zinc concentrates at 900-950°C. Enrichment of air blast with oxygen (up to 30 %) intensifies oxidation of sulfides. Oxidation of simple sulfides is accompanied by heat release.	In metallurgy of copper, nickel, cobalt, zinc, tin, mercury, antimony, selenium, tellurium, molybdenum and noble metals with formation of mercury, selenium and tellurium as sublimates.
Sulfating $\text{MeS} + 1.5\text{O}_2 = \text{MeO} + \text{SO}_2$ $2\text{SO}_2 + \text{O}_2 \rightarrow 2\text{SO}_3$ $\text{MeO} + \text{SO}_3 \rightarrow \text{MeSO}_4$	Transformation of sulfur and extracted metals into the form of water-soluble sulfuric compounds and iron into the form of insoluble oxide of iron or magnetite	Low-temperature at 500-600°C, high-temperature at above 600°C	In metallurgy of copper, zinc and, in some cases, cadmium, selenium, tellurium and noble metals (results of oxidizing and sulfating roasting are estimated by degree of desulfurizing or sulfation of components)
Reducing	Reduction of	At 500-900°C,	In hydrometallurgy of

$\text{MeO} + \text{C}$ $\text{Me} + \text{CO}$ $\text{MeO} + \text{CO}$ $\text{Me} + \text{CO}_2$ or $3\text{Me}_2\text{O}_3 + \text{CO}$ $2\text{Me}_3\text{O}_4 + \text{CO}_2$	free and fixed metallic oxides of ore or concentrate to metal or its lower oxides	sometimes at 1200- 1300°C with fine coal, coke or reducing gas (CO , H_2 , hydrocarbons). There are techniques using elementary sulfur and metal scrap. Process usually feature heat adsorption.	copper in processing of rebellious oxidized ores containing chrysocolla and diopside. In metallurgy of zinc, antimony and cadmium roasting is accompanied by transition of metal melt to gaseous state; in metallurgy of germanium, molybdenum, tungsten and titanium for production of pure metal from oxides. In processing of aluminates for removal of sulfur and production of raw materials for alumina In metallurgy of nickel during processing of limonite nickel ores prior to ammoniacal leaching In processing of low- ferruginous nickel ores Mainly in flowsheets of dressing oxidized iron ores; in non-ferrous metals industry for separation of iron oxides from extracted metal
Magnetizing	Transformation of nonmagnetic and low-magnetic oxides of iron into magnetic: artificial magnetite, ferromagnetic oxide (magnetite)	750-780°C 1300°C	
Reducing $3\text{Fe}_2\text{O}_3 + \text{CO}$ = $+ 2\text{Fe}_3\text{O}_4 +$ $\text{CO} +$ $+ 8870 \text{ cal}$ $3\text{Fe}_2\text{O}_3 + \text{H}_2\text{O}$ $- 1000 \text{ cal}$ $3\text{Fe}_2\text{O}_3 + \text{CO}$ = $= 2\text{Fe}_3\text{O}_4 +$ $\text{CO}_2 + 8870$ cal $\text{CO}_2 + \text{C} =$ 2CO $- 37,710 \text{ cal}$ $3\text{Fe}_2\text{O}_3 + \text{C} =$ $= 2\text{Fe}_3\text{O}_4 +$ CO		From 550-600 to 900-1200°C for 0.5-1 h in fluidized bed furnaces, 1-3 h in rotary and shaft kilns. Solid reductant (coke fine, hard and brown coal) at above 900°C, BF, CO and natural gas	For porous ores (brown ironstones) of 50 mm in size in rotary kilns. For dense ores, crystalline, of 25 mm in size; extra dense, 5(3) mm in rotary kilns; 50+10 mm in shaft kilns

<p>- 28,840 cal</p> <p>Reducing to metallic iron</p> $3\text{Fe}_2\text{O}_3 + \text{CO} = 2\text{Fe}_3\text{O}_4 + \text{CO}_2 + 8870 \text{ cal}$ $\text{Fe}_3\text{O}_4 + 2\text{CO}_2 = 6\text{FeO} + 2\text{CO}_2 + 9980 \text{ cal}$ $6\text{FeO} + 6\text{CO} = 6\text{Fe} + 6\text{CO}_2 + 19,500 \text{ cal}$ $3\text{Fe}_2\text{O}_3 + 3\text{CO} = 2\text{Fe} + 3\text{CO}_2 + 18,390 \text{ cal}$	<p>In case of low-effective reduction to oxides; at moderate temperatures due to fine impregnation and intimate intergrowth of minerals or considerable iron silicate amount available</p>	<p>950-1050°C</p>	<p>Processing of lean oxidized iron ores without melting of barren rock; with production of burned product (metallized concentrate) after magnetic separation;</p>
<p>Oxidizing</p> $3\text{FeCO}_3 = 3\text{FeO} + 3\text{CO}_2$ $3\text{FeO} + \text{CO}_2 = \text{Fe}_3\text{O}_4 + \text{CO}$ $\text{FeCO}_3 = \text{Fe}_3\text{O}_4 + \text{CO} + \text{CO}_2 - 36,700 \text{ cal}$ <p>Reducing-oxidizing</p> $2\text{Fe}_3\text{O}_4 + 0.5\text{O}_2 = 3\text{Fe}_2\text{O}_3 + 50,000 \text{ cal}$	<p>Transformation of iron oxides from ore to magnetite</p> <p>Transformation of magnetic iron oxide into ferromagnetic</p>	<p>1300-1350°C</p> <p>When solid reductant is applied heat release takes place during process</p> <p>Neutral and oxidizing environment at 500-700°C in shaft rotary kilns and sinter machines</p> <p>Ferromagnetic iron oxide (magnetite) is formed at oxidation of iron oxide produced after reduction of hematite at 300-450°C, at above 450°C oxidation takes place before paramagnetic modification of iron oxide</p> <p>Burden size: 0.088 mm</p>	<p>with partial melting of barren rock and formation of metallic shots (bar) separated by magnetic separation of burned product</p> <p>Roasting of siderite ores</p> <p>In processing of complex iron-manganese ores (Germany)</p> <p>In metallurgy of aluminium in production of alumina</p>

$\begin{aligned} &\text{Na}_2\text{CO}_3 = \\ &2\text{NaAlO}_2 + \\ &\text{CO}_2 + \text{H}_2\text{O} \\ &\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O} + \\ &\text{Na}_2\text{CO}_3 = \\ &2\text{NaFeO}_2 + \\ &\text{CO}_2 \\ &+ \text{H}_2\text{O} \\ &\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot \\ &2\text{SiO}_2 + \\ &4\text{CaCO}_3 = \\ &2\text{NaAlO}_2 + \\ &2(2\text{CaO} \cdot \\ &\text{SiO}_2) + \\ &4\text{CO}_2 \end{aligned}$	metals into forms of water-soluble compounds		from bauxite, nepheline and other alumina-containing raw materials
Partial dissociation of CaCO_3 , then $(\text{Na}, \text{K})_2\text{O} \cdot$ $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ $+ 4\text{CaO} =$ $2(\text{Na}, \text{K})\text{AlO}_2$ $+$ $2(\text{CaO} \cdot \text{SiO}_2)$		1150-1250°C 1250-1300°C Alkali or limestone are added for binding	Bauxite-soda-lime burden Nepheline-limestone burden
		With soda or alkali at 500-600°C With soda at 900- 950°C	Transformation of selenium, tellurium, tantalum, niobium, zirconium into solution as water-soluble sodium salts. Sintering of tungsten concentrates for transformation of slightly soluble naturally occurring wolframites of calcium, iron and manganese into readily water-soluble sodium wolframate
Chlorinating (1) $4\text{MeS}_2 +$ $11\text{O}_2 =$ $2\text{Me}_2\text{O}_3 +$ 8SO_2 $2\text{MeS} + 3\text{O}_2 =$ $2\text{MeO} +$ 2SO_2 $\text{MeS} + 2\text{O}_2 =$ MeSO_4 (2) $2\text{NaCl} +$ $\text{SO}_3 + 0.5\text{O}_2 =$	Transformation of insoluble sulfides, oxides and silicates of metals into soluble chlorides	Addition of naturally occurring chloric compounds: NaCl , sylvinites, carnallite, chlorine gas	In hydrometallurgy for preprocessing of roasted residues of pyrite ores and concentrates containing up to 90-99 % of copper, iron, cobalt and lead, rare and noble metals, for extraction of metal residues; chloride sublimation with fractional condensation of low-boiling metal chlorides in metallurgy of titanium,

$\begin{aligned} &\text{Na}_2\text{SO}_4 + \text{Cl}_2 \\ &2\text{NaCl} + \text{SO}_2 \\ &+ \text{O}_2 = \text{Na}_2\text{SO}_4 \\ &+ \text{Cl}_2 \end{aligned}$		niobium, tantalum, germanium and silicon	
(3) Chlorination of metal compounds with chlorine gas and dissociation of chlorides by oxygen			
$\begin{aligned} &2\text{NaCl} + \text{SiO}_2 \\ &+ \text{H}_2\text{O} = \\ &\text{Na}_2\text{SiO}_3 + \\ &2\text{HCl} \\ &2\text{CuO} + 4\text{HCl} = \\ &\text{Cu}_2\text{Cl}_2 + \\ &2\text{H}_2\text{O} + \\ &\text{Cl}_2 \\ &2\text{Cu}_2\text{Cl}_2 + \text{C} + \\ &2\text{H}_2\text{O} = 4\text{Cu} + \\ &4\text{HCl} + \text{CO}_2 \end{aligned}$		Reducing atmosphere, 760- 780°C, small amount of NaCl and coal	Segregation of of copper from oxidized ores
Decrepitation	Fracture of readily cracking minerals	At 950-1200°C in rotary kilns for 1-2 h	Dressing of spodumene ores, in dressing of mica, barite, fluorite and brucite

Heating may be also applied in sorting for infrared radiation (inforametric (?) separation). The technique is based on that minerals and rocks have different heat capacity and adsorb different amount of heat energy. Intensity of infrared irradiation emanated is also different.

4.6.5. Leaching and Hydrometallurgy [10,75, 93-96]

Leaching is performed with a view to selective transformation of metals into dissolved state for their downstream recovery or removal of deleterious impurities. Ores and products of ore dressing (concentrates, middlings, tailings), pyrometallurgical products (residue, matte, anodic slime, etc.) as well as waste formed in treatment of metals and alloys) are involved into leaching. Leaching is widely applied in production of uranium, copper, gold, zinc, molybdenum, tungsten, aluminium and other metals. If necessary, prior to leaching the material is crushed and ground, or “opened” during chemical treatment for transformation of the component to be extracted from a slightly soluble compound into a readily soluble one. With this view in mind different kinds of roasting (oxidizing, reducing, chlorinating, sulfatating), sintering, oxidation or reduction by agitation are employed. Opening is exemplified by oxidizing roasting of sulfide concentrates during which the metal transits to the form of oxides readily dissolving in water solutions of alkalies (leaching of molybdenum) or acids (leaching of zinc). Commonly leaching is performed using water solutions of inorganic acids (sulfuric, hydrochloric, nitric), alkalies (sodium hydrate, ammonia) and salts (sodium or ammonium carbonate, cyanides, etc.). A solvent is selected judging from properties and composition of the material with account of selectivity,

toxicity, stability of composition, corrosive action, possible regeneration and other properties as well as cost and shortage. Sometimes leaching is just simple dissolving (for instance, water leaching of heavy metal compounds after sulfating or chlorinating roasting). In most cases dissolution in leaching is accompanied by the following processes: complexing (for example, in gold cyaniding, sulfide or nickel treatment with ammonia solutions); exchange reaction (in leaching of metal oxides or carbonates with acidic solutions); redox reaction (in leaching of electrically negative metals with acids, leaching of sulfides with acidic solutions).

The leaching process consists of three stages: supply of reacting substances to solid surface, chemical reaction, and delivery of soluble reaction products to solution. Most often leaching runs in the diffusive region, i.e., the 1st and 3rd stages are responsible for the process rate. However the kinetic conditions are also possible. Here the slowest stage is the chemical reaction of slurry (and, consequently, regularities of chemical kinetics as well as the mixed diffusive-kinetic condition are responsible for the process rate).

Higher leaching efficiency is possible due to mechanical-chemical, ultrasound, thermal effects, in combination of leaching with ionic exchange (what is called sorptive leaching), at elevated (up to 300°C) temperature and higher (up to 0.5 MPa) pressure achieved in autoclaves, and owing to different bacteria. For leaching the ore is conventionally ground to 0.074-0.2 mm (except underground and heap leaching). Leaching rate can be increased by means of intensive agitation, heating, leaching in mills and autoclaves, etc.

Leaching of non-ferrous metals from ores incorporates oxidation of sulfide minerals with downstream dissolving of metal salts formed. Metals contained in ore as oxides are most easily leached. Mainly sulfuric acid salts are applied as solvents. Rare elements isomorphously replacing Cu, Pb, Zn, etc. in crystal lattice pass into solution during leaching.

Heap leaching is the method of chemical or bacterial leaching treatment of byproduct off-balance or lean balance lumpy ores stored in dumps extraction of useful component from which by conventional dressing or hydrometallurgical techniques is unprofitable. [74].

This technique is applied in recovery of copper, gold and uranium. Experimental works are under way on application of heap leaching in recovery of other metals.

Water solutions of mineral (sulfuric, hydrochloric, nitric) and organic (e.g., acetic) acids, soda, ammonium salts, etc. are used as agents in heap leaching.

Sites for strong heaps and ore dumps are prepared by providing relevant slopes to the side of solution collectors, covered by hydroinsulative materials (clay, asphalt, cement, hardener solutions of synthetic resins, etc.), drainage systems in the form of perforated tubes made from materials inert to action of leaching agents are constructed. Heap and dump height and ore filling technique (by dozers, trucks, shovels, etc.) are chosen depending on physicochemical properties and compactibility.

Two modes of heap leaching (infiltration and filtration), depending on physicomachanical properties of ore, are possible. The infiltration mode is applied in heap leaching of strong ores unsuceptible to compaction. If saturation of these ores by irrigation with leaching agent is low, the agent fails to fill all the voids (like in the filtration mode) and only wets the surface of ore lumps by a thin film, occupies capillars and gradually flows down to the bottom of the site. In the filtration mode agents are supplied in a cyclic way by alternating irrigation and settling cycles, using special irrigating devices (perforation hoses, jets, sprayers, etc.). Cycle duration can be different (depending on mineral and material composition of ores). In heap leaching lump size has no substantial value for ores with mineralization localized by jointing because lumpiness of the broken rock mass corresponds to natural lumpiness of the massif. In infiltration heap leaching the dominating factors for impregnated mineralization are rate and depth of penetration of agent solution into ore lump.

In some cases pre-screening of ore with selection of coarse material with low metal content to dumps affords lower processing costs and higher production rate of the heap leaching plant. In other cases screening, sorting and final grinding of ore bring about an essential increase in metal recovery (sometimes 1.5-1.7 time). The filtration mode is applied in heap leaching of

san-clay ores subject to comaction. Here the agent is supplied along holes drilled from the surface of the heap or dump.

For more intensive heap leaching, depending on particular conditions, heaps and dumps are aerated using perforated tubes built-up during ore filling, shock clasts, higher temperature and solution pressure together with surfactants, etc. are employed.

When a heap leaching mode is developed, the factors enlisted below must be taken into account.

Ore composition. If there are minerals reacting with H_2SO_4 pH grows rapidly. This results in conditions unfavourable to bacteria (impregnated, sulfide-leaned ores, and ore containing silicates, aluminosilicates, carbonatic and secondary sulfides, Cu-CuS and Cu_2S). Copper is not leached from carbonatic ores with sulfuric acid and bacterial techniques.

Sulfide particle size. Oxidation rate goes up when grinding size is lower. If the operation is not underground, grinding to 0.07-0.04 mm is recommended.

Temperature. If temperature goes up, bacterial oxidizing processes are decelerated and chemical ones are accelerated. The optimal oxidizing temperature is 35°C for iron, $20-35^\circ\text{C}$ for chalcopyrite, synthetic sulfides of copper 30°C , chalcocite 25°C , arsenopyrite 30°C , sulfide minerals of nickel and zinc 35°C . Oxidation of copper pyrite ores is intensified by heating of ore by virtue of exothermal oxidizing reactions.

In particular, oxidation of FeO is accelerated by aeration and agitation. Aeration is performed by air blowing. It is better to use rotating rockers and magnetic mixers for agitation.

Cyanation is the method of leaching gold and silver from relatively lean, fine-impregnated ores, tailings and other dressing products. It is grounded on selective dissolving of metals in weak solutions of cyanides (NaCN , $\text{Ca}(\text{CN})_2$, KCN) and downstream metal precipitation from solutions on zinc dust, ionites, activated coal.

Selectivity of dissolving is achieved by low concentration of solution (0.03-0.3 % of cyanide) due to which it slightly interacts with other ore components. Dissolution of gold and silver in cyanic solution takes place in the presence of water-dissolved oxygen, higher oxygen concentration intensifies the process. Cyanation is performed in alkaline environment because hydrolysis of cyanide ($\text{CN}^- + \text{H}_2\text{O} = \text{HCN} + \text{OH}^-$) brings about the formation of highly-volatile hydrocyanic acid and insoluble AuCN . Gold dissolution rate goes up with higher concentration of CN^- and oxygen ions, at their ratio nearing 6. The oxygen solubility of about 8 ml corresponds to the KCN concentration nearing 0.01 %. The leaching process theory is based on regularities of kinetics of dissolution on heterogeneous surface (at cathodic depolarization with oxygen) and diffusive dissolution of metals (at simultaneous diffusion of cyanide and oxygen).

Cyanation advantages are selectivity with respect to gold, silver, and other noble metals, relatively low consumption of cyanides (0.2-0.5 kg/t of ore), presence of gold and silver as anionic complexes easily separable from cationic impurities on ionic-exchange sorbents. There is no expensive acid-proof equipment, and process temperature is conventional.

Roasting is applied most often prior to cyanation for removal of volatile impurities (sulfur, antimony, arsenic, bismuth, mercury, etc.), and organic substances as well. Sometimes sulfides are removed by preliminary alkaline treatment or oxidation of sulfides to sulfates with potassium permanganate. Depending on metal impregnation, cyanation at fine grinding is carried out in machines with air agitation (...), at coarse milling in mechanical reactors. Finely-ground ore (6-12 mm) of adequate porosity is cyanated in percolators. Lumpy ore is leached in heaps and dumps (especially typical of the USA). Gold-uranium ores are cyanated in combination with sulfuric acid leaching of uranium (RSA).

High-grade gold is easy to be leached, while cupreous gold and gold tellurides are the most difficult to be leached. Salts of Pb, Bi, Hg, Te accelerate cyanation, and sulfides as well as ions of copper, zinc and iron make the process more difficult. Sulfides form rhodanides inert with respect to gold, copper and zinc form soluble cyanides and films of insoluble compounds on gold. Similar insoluble films are formed $\text{Pb}(\text{CN})_2$, xanthates of gold, peroxides of calcium.

Coarse gold is poorly cyanated, gravity methods (jigging, centrifugal machines) with downstream amalgamation or cyanation of gravity concentrates are employed for gold extraction in grinding cycle. Precipitation (cementation) by zinc dust and activated coal is applied for gold recovery from solutions, besides sorption on anionites. Platinum metals are separated from gold during electrolysis (platinum and palladium are concentrated in electrolyte, with rhodium, iridium and ruthenium in anodic slimes).

In ore preparation autogenous grinding and combination of grinding with cyanation and cyanation with sorption are employed. Lately this process gained a large value in connection with technology of extracting gold and silver from electronic scrap solderings. Chemical dissolution of salts (sometimes underground) along with removal of deleterious impurities, for example, iron oxides in dressing of phosphates, quartz sands, potassium fertilizers are connected with leaching processes. Leaching is the first stage of hydrometallurgy which results in production of metals by separation from solutions with methods of extraction, precipitation, electrolysis, sorption, etc.

Copper from Rio-Tinto deposits (Spain) in the 16th century was first extracted by hydrometallurgical processes. Later on hydrometallurgical processes of production of many other metals were developed: platinum (1827), nickel (1875), aluminium from bauxites (Russia, 1892), gold (New Zealand, 1889), zinc (Canada and USA, 1914) etc.

In the CIS *hydrometallurgical methods* are applied in production of Al, Zn, Cu, Ni, Co, Cd, U, rare and precious metals. More than 20 % of Cu, 50-70 % of Zn and Ni, 100 % of Al oxides and Cd, Co and other metals are produced by hydrometallurgy. As compared with pyrometallurgical processes, hydrometallurgy has rather a smaller effect on atmosphere.

Variation in leaching conditions affords different degrees of metal oxidation by action on rate and limits of solubility of metal compounds. For example, salts of Fe^{3+} , Cr^{3+} , Al^{3+} form slightly soluble compounds (hydrolytical cleaning), and Fe^{2+} , Ni^{2+} , Co^{2+} , Zn^{2+} , Cd^{2+} are left in solution, U(IV) and Mo(IV) oxides, opposite to U(VI) and Mo(VI) oxides, are slightly soluble. By controlling conditions of leaching sulfide sulfur it is possible to produce sulfur in elementary form or as sulfuric acid and its salts.

In electrolytic separation of Cu, Ni, Pb, etc. on cathode, electrically positive impurities are left in slime of electrode baths: Au, Ag, Pt, Bi, Se, Te, As, etc. On separation of metal-containing solution and washing of tailings on filters or in thickeners, components hindering downstream operations or contaminating the product are precipitated (for example, redundancy of iron in copper electrolyte results in higher power consumption though cathodic copper composition does not deteriorate; presence of Cu, Ge, Co in zinc electrolyte prevents precipitation of zinc on cathode). Cleaning of solutions from certain impurities permits concentration of impurities in sediments and further extraction in saleable form (Co in production of nickel, Cd in production of zinc). Dilute solutions unsuitable to direct production of saleable metals owing to technical or economic reasons are made in leaching of lean raw materials. In these cases different techniques of concentrating and preliminary separation of metals from solutions are applied (for instance, cementation of copper by iron metal with downstream flotation: Mostovich method; nickel and cobalt are precipitated by hydrocarbon by agitation in autoclaves from untreated solutions separated from tailings of oxidized nickel ore leaching). Concentrating by sorption on ionic exchange resins is employed in production of uranium, copper, gold, etc.; sorbed metal-containing ions are desorbed (eluted) by small amount of eluent with concentrated solutions produced. Sorption may be combined with leaching.

High-purity metals are produced by liquid extraction which is recovery of metals from aqueous solutions by water-insoluble organic substances (extractants): tributyl phosphate, amines, carboxylic and phosphororganic acids, oxides, etc. commonly applied as kerosene solutions. Extraction and downstream re-extraction are carried out in agitator-settler machines, column, centrifugal and other machines. The extraction rate is much higher than the rate of ionic exchange on solid sorbents. Pure metals are extracted from solutions by electrolytic or chemical reduction; depending on electrolysis conditions metals are produced in a compact or powder

form; chemical reduction by hydrogen and other gases is performed in autoclaves with metal powders produced. The hydrometallurgical flowsheet ends with crystallization or precipitation of a pure chemical metal compound (for instance, in aluminium or uranium production, etc.).

Amalgamation is a process of selective extraction of metals (mainly, noble ones) from ores which is based on the ability of metals to form mercury alloys when they are wetted with mercury. Amalgamation has been well-known for more than 2 thousand years. G.Agricola described the process in the 16th century. Up to the 20s of this century amalgamation had been the leader in extraction of noble metals. Beginning from the 50s it became applied mostly in processing gravity concentrates (flotation and cyanation are more effective in ore processing).[10,16].

Internal amalgamation is performed together with ore grinding, external amalgamation is carried out on sluices: during slurry movement metals are trapped by mercury plated on copper (sometime silver-plated) sheets. Gold-silver ore is amalgamated in an alkali medium, while platinum ore is amalgamated in an acidic medium in the presence of zinc amalgam. A modification is electric amalgamation at which wettability is improved by means of direct current action: mercury gains a negative charge with a positive one acquired by slurry on sluice. Depending on the mercury to metal ratio, at an ambient temperature amalgam can be liquid, semi-liquid or solid. Extra mercury is removed from liquid and semi-liquid amalgams by filtration through suede under pressure. Amalgamation is most widely applied in gold extraction. Solid amalgam containing 40-60 % of gold is decomposed by heating up to 750-800°C, mercury is distilled and recycled. the gold recovery to amalgam (Depending on the rate of metal surface exposure) sometimes achieves 99 %, 0.1-1 % of mercury is left in the gold sponge produced. Mercury loss is 6-7 g/t of concentrate. Gold sponge is remelted. A reduced scope of amalgamation application is caused by low rate of extracting some gold forms in the presence of sulfides, especially, pyrrhotite. Amalgamation disadvantages are that it is difficult to secure safety measures in mercury operations, and the environment contamination is possible while the advantage is that direct and rapid recovery of gold in one operation is implemented.

4.7. Concentrating and Selection of Minerals

Mining and use of mineral resources is grounded on concentration of minerals and chemical elements with further selection of them to individual products. Original concentration of elements takes place in natural conditions owing to geochemical and geological processes by which mineral deposits are generated. Run-of-mine ore is artificially concentrated by dressing methods.[3]. Concentrates produced undergo chemico-metallurgical concentrating processes with metals selected.

4.7.1. Dressability of Minerals

In processing of mineral products not only particular properties of minerals but also their combinations and particle size are of value. Certain physical properties can be made use of in dressing of mineral mixture only in a limited range of size. It must be borne in mind that many physical properties may be altered by chemical methods, for example, roasting.

Tables 4.11 & 4.12 show the estimation of possible losses in dressing as a function of structure-texture characteristics of ores. [77].

Table 4.11. Significance of morphological structure types in ore dressing [77].

Mineral grain shape	Ore structure groups as a function of valuable component loss in dressing		
	No losses	Small losses	Large losses
Idiomorphic	Idiomorphic-	Idiomorphic-	

Allotriomorphic	granular	metagranular	
	Idiomorphic-blastic		
	Allotriomorphic-granular	Hypidiomorphic-metagranular	
	Hypidiomorphic-granular	Poikilitoblastic	
	Porphyroid-granular		
	Sideronitic		
	Allotriomorphic-blastic		
	Hypidiomorphic-blastic		
	Porphyroblastic		
	Orientation-granular recrystallized		
Colloid	Orientation-granular pressure		
		Convergence zonal recrystallized	Aphanic-granular
			Aphanic-metagranular
			Gel
			Colloform
			Colloform-metacolloid
			Solid-solution decomposition emulsion
			Laminated, grating, reticulate, zonal solid-solution decomposition
Emulsion			
Laminated	Cataclastic crumpled		
Relict		Skeleton, relict and eroded corrosive	
Fragments	Crushed		
Debris	Granoblastic		
	Porphyroclastic		
	Orientation clastic		

Table 4.12. Significance of morphological texture types in ore dressing. [77].

Mineral aggregate shape	Ore texture groups as a function of valuable component loss in dressing		
	No losses	Small losses	Large losses
Streaks, interlayers and other mineralizations	Banded and pseudo-layer liquation and crystallization Banded, layer and lens-shaped sedimentary and	Banded, diffusive-banded metasomatic-ally-replaced	

	diagenetic		
		Banded, incrustate void-filled Shaly, plicated, greissous crushed and crumpled Shaly, plicated, lens-shaped and greissous flowed and recrystallized	
Veinlets and dendrites	Veinlet liquated and crystallized Veinlet and piercing sedimentary and diagenetic Veinlet void-filled Veinlet weathering void-filled	Veinlet, filiform, reticulate, grating, subgraphically- replaced Sudgraphic and graphic flowed and recrystallized	
Cement		Filiform, netted, reticulate, grating, subgraphic and graphic weathering Cement sedimentary and diagenetic Cement metasomatic-ally- replaced Cement weathering	
Balls, oolites, pseudo-oolites, nodules and other mineralizations	Nodular liquated and crystallized Oolite, pseudo- oolite sedimented and diagenetic	Impregnated and spotty liquated and crystall-ized Cocarde, spotty meta- somatic-ally- replaced	Emulsion-like metasomaticall- replaced
	Ocellar metamorphized Secreation, concretion cocarde and geode weathering	Impregnated and spotty metasomatically- replaced	
Organogenic		Organogenic sedimented and diagenetic	
Sinter			Colloform- metacolloid, convergence zonal, swedimented and diagenetic Colloform- metacolloid,

			bread-crust, stalactite and stalagmite weathering
Limbate	Cocarde void-filled	Reaction-limbate metasorphism Limbate, bread- crust metasomatically- replaced Limbate and bread- crust weathering	
Debris	Conglomerate sedimented and diagenetic Detrital weathering		
Fragments	Breccia liquated and crystallized	Brecciform liquation and crystallization	
	Breccia void-filled Breccia crushed and crumpled Breccia weathering	Brecciform metasomatic- replacement Brecciform weathering	
Relict		Skeleton, crumbled-relict metasomatic- replacement Relict-crumbled weathering	
Framework			Porous vesicular, spongy, cellular, box and cavernous weathering
Indefinable	Massive for any genetic group Earthy, powdery weathering Earthy and powdery metamorphic Earthy, powdery sedimentation and diagenetic		

All separating processes are based on differences in physical and chemical properties of particles to be separated, in ability to form these or those compounds. Separating process efficiency depends on many parameters: degree of difference of factors taken as defining for the method, sequence of application and combination of methods, choice of separating machinery, conditions of process running.

Existing classifications of separating processes for the most part are grounded on one symptom. For instance, gravitational separation methods are based on density of minerals.

Differences in hardness and fragility are used in sorting and opening of grains at the stage of preparation for dressing, while differences in reflectivity and absorptivity of minerals are made use of in dressing for colour, lustre and transparency. Luminescence intrinsic and induced radioactivity is in the basis of photo and radiometric dressing methods. Magnetic and electromagnetic separation is grounded on differences in magnetic susceptibility of mineral particles, with dielectric separation on differences in dielectric permeability. Discrepancies in properties, like shape, triboelectrization and cracking during heating and cooling are used. Chemical properties of minerals are responsible for possible application of hydrometallurgical processes. For example, different solubility of minerals in inorganic solvents are made use of in leaching.

Selective wettability of mineral surface is one defining characteristic of floatability of mineral particles. Wettability is varied by selection of corresponding agents. Use of magnetic, electrochemical, vibrating, high-frequency, radiation and other actions affords alteration in surface properties of minerals, properties and composition of liquid slurry phase, physical properties of solid material, etc., which is applied for improving separation processes provided action conditions are correspondingly chosen.[3,11].

Choice of separating process is closely connected with particle size, besides physical and physicochemical properties of minerals. This parameter is the basic limiter of applicability of any method (Tables 4.13 & 4.14).[11].

Table 4.13. Classification of mineral segregations by size and methods of their recovery from ores

Mineral segregations	Dominating size, mm	Technological processes applied in recovery of mineral segregations
Large	20-2	Jigging, heavy-media separation, magnetic separation
Fine	2-0.2	Table concentration, magnetic separation, heavy-media separation, electric separation, foam separation
Thin	0.2-0.02	Flotation, special table concentration, hydrometallurgy
Very thin (emulsion)	0.02-0.002	Flotation, hydrometallurgy
Submicroscopic	0.002-0.0002	Hydrometallurgy
Colloid-disperse	>0.0002	Ditto

Table 4.14. Processes of mineral separation at different size of mineral particles

Size of particles, mm	The basic properties for mineral selection				
	Density	Magnetisation	Electrical conductivity	Wettability and adsorption ability	Solubility
> 10	Heavy suspension; jigging	Dry magnetic separation	Separation of metallic nuggets	---	Under-ground leaching
10-1	Heavy medium; jigging; table;	Wet magnetic separation	Electrostatic separation;	Foam-	Heap-leaching

	spiral;			separation	
1-0.02	High frequency jigging; slime-table; stream-separator	Wet magnetic; magnetic-hydro-static separation	Electrostatic coronal separation	Flotation	Tank-, bacteria-leaching
< 0.02	---	Poligradient magnetic, wet-stream magnetic separation	Electro-filtration	Ultra-flotation, electro-flotation, ion-flotation	Tank-, bacteria-leaching

A certain rate of ore gringing with relevant size of product particles is chosen depending on impregnation size of minerals to be extracted. Here distribution in impregnation is responsible for possible application of some methods of preliminary dressing withn selection of barren rock part or collective concentrates, for instance, heavy concentrates in processing of placers.

4.7.2. Separating Processes

Processes of separating components, mineral complexes, solutions and other mixtures occupy a significant place in the up-to-date technology of mineral products, water treatment, oil refining, processing of agricultural products, etc. Here experience gained in each branch is of great interest for developing innovative processes and machines in mineralurgy. [3,97].

There is a number of consecutive steps in separating minerals (Table 4.15).

Table 4.15. Mineral separation steps

Step	Stage	Process
I. Ore preparation	1. Crushing	(a) Crushing (b) screening
	2. Preliminary concentrating	(a) Heavy-media separation (b) Radiometric separation (c) Spectrophotometric separation (d) Screw separation (e) Washing
	3. Blending	Blending
	4. Grinding	(a) Grinding (b) Classification
II. Dressing	1. Gravitation	(a) Jigging (b) Table, etc. concentration (c) Hydrocycloning
	2. Magnetic separation	(a) Wet magnetic separation (b) Dry magnetic sepsration
	3. Electric separation	(a) Electrostatic separation

	4. Flotation and flocculation	(b) Triboadhesive separation (a) Collective flotation
III. Final operation	1. Flotation 2. Magnetic separation 3. Chemical dressing	(b) Selective flotation (c) Foam separation (d) Selective flocculation Final flotation Polygradient separation (a) Leaching (b) Sorption (c) Extraction (d) Ionic exchange (e) Ionic flotation, electric flotation
	4. Dewatering	(a) Thickening (b) Filtration (c) Drying
IV. Recycling	1. Water circulation	(a) Thickening (b) Flocculation (c) Ionic flocculation, electric flotation (d) Water preparation and water conditioning
	2. Recycling and storage of tailings	(a) In-wash of dams and storage of tailings (b) Production of fill (c) Production of cement, lime, bricks and other building materials (d) Leaching of dumps

A totality of crushing, screening, preconcentrating, grinding and sorting is defined as ore preparation process.

Preparation of particles for separating may include the operations indicated below.

1. Treatment by chemical agents which is applied mainly in flotation and in electrostatic separation and filter separation as well. Selectivity of agent adsorption can be raised by electrochemical, thermal (steaming), radiation, ultrasound and magnetic methods of processing minerals, slurry and agent solutions.

2. Washing applied for removal of slime coats from particles prior to photometric or luminiscent sorting, sometimes before flotation. Washing can be intensified by vibration, ultrasound, addition of partitioning agents (liquid glass, etc.), abrasive substances (quartz sand) and solid sorbents (activated coal, zeolites, etc.).

3. Electrostatic surface charging prior to electric separation by electrostatic, triboadhesive and thermoelectronic methods.

4. Radioactivation of particles, mainly in radiometric sorting. It may be also of use in electrostatic separation and flotation. The radiation types are X, γ , β -rays (electrons), neutron radiation, ultraviolet light.

5. Thermal treatment, prior to any dressing process, by oxidizing, sulfatation, reduction, magnetizing, sintering, chlorinating roasting or crepitation, steaming, electrolysis, HF current, infrared irradiation.

6. Chemical decomposition or transition to soluble form before leaching, treatment with acids (H_2SO_4), HCl, HF), alkalies (NaOH, Na_2CO_3) and complexing agents (NaCN, etc.), bacterial methods (Fig.4.17).

Material ground approximately to 200-100 m and below is basically dressed. This step is split to three stages: preapration of particles for separation (Fig.4.19), creation of concentraion gradient with different properties (Fig.4.20), and selection of dressing products (Fig.4.21).

Rough concentrates (collective or mono) produced as a result of the basic derssing process are finally processed or selected. Here either repeated operations (for example, recleaner flotations) or chemical-hydrometallurgical processes are used, if production of prime material required removal of components at the very fine level of inclusion (colloid-disperse, isomorphous, etc.). Final processing ends with operations of dewatering finished products.

At last, state-of-the-art production calls for examination of the step of storage or recycling of waste. This step is split to two stages: (1) use of liquid phase for water circulation and extraction of soluble components, and (2) utilization of solid phase, storage into tailings dumps, filling of mined-out mine areas, production of building materials and other by-products.

Creation of particle concentration gradient is transfer of partciles with certain properties to one place and particles with other properties to another place. Here the operaions depicted below should be noted.

1. *Arrangement of phases and interphase boundaries.* The space of a sepraor may be single-phase, dual-phase or multi-phase. In the last two cases of dominating value in the separating process are phase boundaries: solid - water - organic liquid - gas (most often air).

Types of interphase boundaries and forces acting on the boundaries are given in Table 4.16. [11].

Table 4.16. Forces acting on phase boundaries

Phase	Phase			
	Solid	Water	Organic liquid	Gas
Solid	Adhesion	Hydration	Surface tension	Adsorption
Water		No boundary	Interphase tension	Surface tension
Organic liquid			Intephase tension, if there is no mutual soluton	Ditto
Gas				No boundary

Consequeive action of different forces may occur in multi-phase systems. Introduction of a third phase creates an effect of carrier. Separation using carriers (liquid, solid or gaseous) are widely applied. For instance, during flotation of fine slime with a carrier first selective attachment of slome on the surface of a hydrophobic carrier takes place, then carrier particles are attached to air bubbles which can be considered as a carrier in a gravitational field in an aqueous medium.

Magnetic carriers may be applied, for example, in flotation of low-magnetic manganese slime. Mechanism of interaction of extractable components with carrier may be various: adsorption (including, with preliminary carrier treatment with agents), magnetis or electric interaction as well as soluting extractable substances in liquid carrier.

Design arrangement of process of separating with a carrier is different: from carrier dispersing in the separating medium to slurry penetration of the carrier layer, for example, extraction of microscopic hydrophobic particles by means of slurry passage through screens or the hydrophobic-surface layer. It should be noted that a carrier effect emerges as a result of interaction of extractable particles. For instance, in flotation flocculation of hydrophobized

particles affords an extraction of fine slime to foam product. The carrier effect can be intensified by higher concentration of hydrophobic particles through introducing of earlier floated concentrate into the slurry as in jet flotation, in flowsheets with tuel and circulation of middlings.

Such process can be imagined with five-six carriers: flotation of fine slime with an adhesive disposal of foam and an agent-hydrophobized carrier applied. Here an adhesive drum may be taken as a carrier permitting a more selective removal of foam product and a production of higher-grade concentrate.

Greater process efficiency is possible if the phase boundary surface is increased owing to dispersing of phases through intensive agitation, imposition of vibrations up to ultrasound ones, aeration, introduction of surfactants, stabilizers (emulsions, micelle) or peptizers, when phase boundary forces go up, temperature is changed, and magnetic and electric fields are applied.

2. Superimposition of force field. [97].

Mineral complexes must be selected in the gravitational, magnetic, electric, adsorption-chemical fields and their interactions. Their combination, and superposition of vibration fields of different frequency, as well as introduction of air-bubbles and fluid or solid carriers, provide conditions for intensification of the selection process. Flocculation, coagulation, adherence, sorption of chemical reagents permit accelerated mineral concentration. Each field determines limits for its use in ore treatment in connection with the distributed probability of a particle property. For example, electrochemical treatment of each mineral particle by itself affects flotation, but cannot be used in flotation plants because of the variance of particle characteristics. This permits diagnosis of the possibility of recovery of valuable components from ore, ways of complex use of raw material, and a prospective technology for a scheme of ore treatment. In approaching this problem we accumulated the information in accordance with this classification, indicating the ways for diagnosis of mineral complexes. The correspondence between ores is examined in the technological sense.

Establishment of selective process.

Unlike chemical ions and molecules, as well as macro-aggregates, mineral selection processes have the following distinctive features:

- there is a spectrum of particles with intermediate properties (for example, concretions); the probability of whose extraction in concentrates or tailings depends on process condition;
- the efficiency of the selection process depends on the distribution of particle sizes; each ore-dressing apparatus has its own optimum of particle sizes;
- the processes are subject to the laws of statistics and probability theory; it is impossible to achieve 100% extraction or concentrate quality.

The natural properties of mineral particles may be modified for optimal selectivity in different ways:

- Treatment by chemical reagents used for flotation and electrostatic separation; the selectivity of reagent adsorption can be improved through electrochemical treatment of the reagents solutions; steaming, ultrasonic, radiation, magnetic treatment of pulps.

- Washing and desliming prior to photometric or luminescent sorting, sometimes flotation. These processes can be intensified by vibration, addition of peptizing-agent, abrasives (sand), solid sorbents (coal, zeolites), etc.

- Thermal treatment: roasting, reduction, oxidizing, sulfating, sintering etc. for leaching and magnetic separation; high-frequency current; decrepitation.

- Surface charging by radiation, electrostatic, frictional adhesion for electroseparation.

Preparation of the ores includes grinding to -100 or -200 microns, choice of the process is dictated by the size spectrum (*Table 4.14*).

The general process of mineral beneficiation is based on creation of a concentration gradient in the force fields. Separation takes place either inside the phase (water, organic liquid, air) or at the phases interfaces (water-air, water-solid, solid-gas, water-organic liquid). The forces inside the phases are: gravity, magnetic, electric. The forces at the interfaces are: adhesion, adsorption, hydration, surface tension. Mineral processing uses all these forces (*Table 4.17*) and their combinations (*Table 4.18*).

Use of force fields and effects

Ore-dressing processes	Force fields and effects				
	ultrasound, high-frequency vibration	vibration	electric	magnetic	chemical
Gravity concentration	High-frequency jigging	Tables; heavy suspension; lock; jaggging	Magnetic-hydro-static	Gravity-magnetic separation	Heavy suspension with surface-active reagent
Magnetic separation	+	+	Magnetic-hydro-dynamic	Super-magnetic separation	Treatment by magnetic liquids
Electric separation	+	Vibro-electric separation	Tribo-adhesion separation	Electro-magnetic separation	Treatment by reagent prior to electric separation
Flotation	Dispersion	Flotation in	Electro -	Floto-	All kinds of

	or desorption of reagents	jigging; vibro- flotation; table- flotation	treatment of water, pulp, reagent solutions. Treatment by high- frequency current	magnetic separation. Magnetic treatment of water, pulp, reagent solutions.	flotation
Leaching	+	+	Electro- chemical leaching	Magnetic treatment of solution	Chemical, thermo- chemical treatment
Dewatering	Ultrasound coagulation	Vibro-hydro- cyclone	Electro- coagulation	Magnetic treatment of pulp	Flocculation

Note: +- possible process.

In a multiphase system forces may act in tandem. A third phase often serves as carrier (for example, the air bubbles in flotation), which can also act in tandem. For fine slime flotation bigger particles can be used, which adsorb the slime, and the resulting aggregates are floated by air bubbles in the gravity field.

Carrier have diverse uses. For example, for flotation of manganese oxide slimes, which are weakly-magnetic, magnetite particles can be used as magnetic carrier; and the aggregates can be floated after reagent treatment. This product is ready for the ferro-manganese industry. The variants of carrier use are emulsion flotation, flocculation flotation, liquid extraction with flotation of extractant, etc. These processes use the carrier as dispersed particles.

Another variant of carrier is a layer of adsorbed or adhered bed consisting of a multiphase substance. For example, the foam-separation process uses a foam-bed as carrier. If a pulp containing fine gold particles flows through a wood-sawdust bed, the gold-particles adhere to the wood. Dispersed sawdust in pulp works as well. This method is used for extraction of fine gold lost in drag tailings. The wood-sawdust is mixed with drag tailings in the river, then they rise to the surface and are collected. After burning the gold is recovered in the ash.

The stream-flotation process, with part of the froth-concentrate introduced in the feet of the flotation machine, is known. That concentrate is a carrier of flotation minerals. The stream-process improves recovery and the quality of the concentrate.

The interface activity can be improved by increase of the surface - dispersion of the carriers. The methods of dispersion are agitation, vibration, ultrasound, addition of surface-active substances, peptizing agents, elevated temperatures. Many chemical reagents can be used in all processes, not only in flotation. Considerable importance attaches to surfaceactive agents, flocculants, coagulants, etc.

A radical alternative is imposition of another field.

The gravity field is always present, but its forces can be enhanced by imposition of a centrifugal force in a rectilinear or spiral flow in an apparatus (for example, concentration in a hydrocyclone). Magnetic or electric forces can be superposed on the gravity field. This idea was realized in magnetic-hydro-static and magnetic-hydro-dynamic apparatus.

If separation takes place under superposed fields, we have to deal with a combined process; if it takes place in tandem fields, we have a combined technology. A combined process yields cleaner concentrates, but a combined technology yields fuller extraction of the mineral.

Tables 4.14-18 indicate a new possibility in mineral processing synthesis, as well as of new apparatus in the existing fields. These processes utilize the phase state of the minerals. To put it differently, the minerals are not smelted, or sublimated, or dissolved, etc. We use organic liquids, solid-liquid suspension, combinations of fields, as well as three-phase interfaces.

There may be different variants of mineral treatment apparatus in the same phase or phases interface. For example, for the solid-water interface with adsorbtive-chemical forces there are amalgamation, ion exchange, flotation by solid wall, concentration of diamonds on an adhesive surface, extraction of gold fines by activated coal, etc. The gravitation processes also have many different variants.

Removal of products (concentrates and tailings) outside the separation apparatus is of great importance. This process can be realized under static or dynamic regimes. As a rule, under a static regime a calm zone inside the appratus can be initiated, where separation of particles take place (for example, the heavy medium separator). A dynamic regime operates via the differential velocities of the particles or streams. The efficiency of separation can be enhanced by imposition of fields, for example, vibration, etc.

. Separation cascades

The rate of separation governs, on the one hand, the capacity apparatus, and on the other, the separation selectivity.[5]. Both purposes are achieved on a cascade, from which the optimum materials can be drawn in each apparatus.[6].

Optimization of separation cascades and apparatuses is based on the rule of minimum desconcentration of mixing flow products. When two flows with different concentrations (contents) of the extraction components are mixed, there is loss of separation work and

deterioration of the separation process. Thus, pure and reach materials (in terms of the content of extraction components) should be treated in the different apparatuses. By the same a reasoning, an apparatus with ideal displacement (interrupted action) is more efficient as separator, then one with ideal mixing (uninterrupted action), but has less capacity. This conclusion can be interpreted by the sequence of probabilities of particle and carrier interaction; these probabilities are in direct proportion to concentration of extraction particles. Their content in the separation zone decreases as the concentrate and pure product are mixed in the bulk of the separator.

In uninterrupted processes arrival of new raw material, drawing of concentrate and tailing take place in time. The optimum rate of drawing and capacity depend on the structure of the cascade of operations. It is possible to calculate the relations between primary, recovery and re-cleaning cycles. In some cases a secondary concentration of the rich product may be effective.

Separating processes are improved by different irradiation, various force fields and frequency actions applied. Table 4.17 shows the examples of existing or possible combinations of force fields many of which were implemented in dressing practice. Chemical agents are applied virtually in any basic dressing processes, from gravity separation till product dewatering.

Tables 4.18 and 4.18a present the classification of separating processes unassociated with changes in the aggregate state of separable substances available in the original heterogeneous mixture. These processes, mostly of dressing and hydrometallurgical character, do not involve melting, evaporation, crystallization, sublimation and condensation of separable substances. Processes running in a single phase are the simplest ones. There may be a combination of two force fields, for instance, in magnetohydrodynamic separation.

It is evident from the table that there is a stock of processes not applied as yet. The majority of them is connected with organic liquids too expensive so far (even if regenerated) for dressing of a larger part of mineral products. Another potential of innovative separating processes is a combination of magnetic field with adsorptive-chemical or gravity action.

Table 4.18. Classification of separating processes

Phase	Field						
	gravitational	magnetic-electric	adsorptive-chemical	gravitational-magnetic-electric	gravitational-adsorptive-chemical	magnetic-electric-adsorptive-chemical	gravitational-magnetic-electric-adsorptive-chemical
Air	Air separation	Electrostatic separation	Not applied	Dry magnetic separation	Not applied (rectification)	Electrostatic separation with agents	Not applied
Water	Gravitation	Wet magnetic separation	Leaching, segregation of surfactants	MHD separation	Not applied (carrier gravitation)	Electrolysis	Separation of noble metal slime after electrolysis
Organic liquid	Heavy-media separation	Dielectric separation	Not applied	Not applied	Not applied	Not applied	Not applied
Air-water	Flotation of naturally occurring hydrophobic minerals	Not applied (carrier bubble flotation)	Ionic flotation	Not applied (magnetic field flotation)	Foam flotation using agents, film flotation	Not applied (ionic flotation in magnetic field)	Not applied (foam flotation in magnetic field)
Air-organic fluid	Not applied	Not applied	Not applied	Not applied	Not applied	Not applied	Not applied
Air-solid	Dressing by friction, elasticity or shape	(flotation processes in organic liquid which are similar to processes in water medium)			Not applied	Triboadhesive separation	Ditto
		Magnetic separation with magnet sunk in material	Gas chromatography (radiometric sorting)	(inclined-plane dressing in magnetic field)	Not applied		

Water-organic liquid	Separation of water and oil	Not applied	Not applied	Not applied	Liquid extraction, oil flotation	Not applied	Not applied (liquid extraction in magnetic field)
Water-solid	Heavy-media separation	Polygradient separation	Amalgamation, solid-wall flotation Sticky surface floatation	Ditto	Heavy-media separation using surfactants	Ditto	Not applied
Organic liquid-solid	Not applied	Not applied	Not applied	Ditto	Not applied	Ditto	Ditto
Air-water-organic liquid	(processes in organic liquid which are similar to processes of flotation in water medium) Flotation of liquid organic inclusions (oil, etc.)	Not applied	Extractive flotation	Not applied	Emulsion floatation	Ditto	Ditto
Air-water-solid	Gravity flotation	Ditto	Mostovich process	Ditto	Carrier flotation	Ditto	Ditto

. *Movement of separable particles* with different velocity which dictates the production rate of the machine in many cases. Higher velocity can be sometimes achieved through intensive agitation of the medium, creation of settling zones in the machine, imposition of vibrations for berakinf suspension struction, electrophoresis forces. Diversified design engineering of processes which belong to one and the same class, according to the classification shown in Table 4.18, and different substances forming solid and liquid phases should be noted. For instance, below are enumerated separating processes performed on the solid-water interface by virtue of adsorptive-chemical action of extractable particles on the interface boundary (amalgamation, sticky surface dressing, ion exchange, solid wall flotation, extraction of hydrophobic particles of noble metals by ligneous filings, activated coal, etc.). Different process mechanization is also possible, equipment modifications of gravitational processes are especially numerous.

Separating can be carried out in different phases and on the phase boundary not only by one property (difference in density, magnetic susceptibility, conductivity, etc.) bu also by combination of these properties, either in one machine (a combined process) or in a straight-through layout (a combined flowsheet).

Table 4.18. Classification of separating processes and possible combinations by class

By phase	By force field	By method of attachment on a carrier	By type of physicochemical reaction	By frequency actions
Solid - 1	Gravitational - A	No carrier - I	No reaction - a	No frequency - a
Air - 2	Adsorptive-chemical - B	Chemical - II	Radioisotope - b	Mechanical - b
Water - 3	Magnetic - C	Adsorptive - III	Ion exchange - c	Acoustic - g
Organic liquid - 4	Electric - D	Magnetic - IV	Oxidation- reduction - d	Ultrasound - d
		Radiation - V		
		<i>Possible combinations</i>		
2 - 4	A - B	II - III	b - c	
2 - 3	A - C	II - V	b - d	
2 - 1	A - D	III - V	c - d	
3 - 4	B - C			
3 - 1	B - D			
4 - 1	C - D			
2 - 3 - 4	A - C - D			
2 - 3 - 1	B - C - D			
3 - 4 - 1	A - B - C - D			
2 - 3 - 4 - 1				

We shall examine the *efficiency of combined flowsheets* and combined processes performed by means of combination of effects in a single machine from the viewpoint of probable losses (underrecovery) of valuable components and probable contamination of the concentrate with foreign particles.

If the entry product is sequentially delivered to two processes, probable losses are added together. For example, in the first process the recovery e_1 is 0.9, and in the second process e_2 is 0.8, the total recovery according to the combined flowsheet $e = e_1 \cdot e_2 = 0.9 \cdot 0.8 = 0.72$. In the process the losses $1 - e = 0.1$, in the second process the losses are applied only to the material which emerged from the first process: $e_1(1 - e_2) = 0.9 \cdot (1 - 0.8) = 0.18$. The total losses $0.1 + 0.18 = 1 - 0.72 = 0.28$.

In the combined process the entire material is simultaneously subject to both actions. Therefore the losses are estimated as the product of probabilities: $(1 - e_1)(1 - e_2) = 0.1 \cdot 0.2 = 0.02$. In the first and second process the respective recovery $e_1 = 0.9$ and $e_2 = 0.8$, a part of losses connected with the first interaction, i.e., $0.1 \cdot 0.8 = 0.08$. The total recovery $e = 0.9 + 0.08 = 1 - 0.02 = 0.98$.

The combined process is more economical than the corresponding combined flowsheet from the viewpoint of recovery.

As far as the concentrate quality is concerned, contamination of concentrate with foreign particles will be higher in a combined process than with a combined flowsheet.

Recovery and quality of concentrate is as a rule better in cases when content of extractable component is higher. Therefore when two flows with a different content of extractable component are mixed, a part of separation work is as if lost, i.e., impoverishment of entry stock causes lower efficiency of the separating process in which the impoverished mixture was processed in comparison with the total efficiency of particular processes in which lean and high-grade materials were individually treated. This can be also explained from statistical viewpoint, bearing in mind that probability of separating any particle depends on the probability of its collision with a carrier or the probability of penetrating a certain zone of the separating machine; these probabilities are proportional to the concentration of an extractable substance in the mixture. Based on the same statistical approach, in case of a continuous process the recovery in machines with perfect agitation should be estimated to be at a lower level than in machines with perfect frothing or in a batch process which is connected with impoverishment of more high-grade feedstock with low-grade chamber product in a continuous process during agitation. This circumstance is necessary to be taken into account in the layout of combined flowsheets and in the comparison with combined processes. On the other hand, there must be borne in mind a positive effect of material blending from the viewpoint of possible choice of a steady-state optimal mode of separating with on-line process control.

A part of the phase is taken off during separating in air phase. Dressing products are selected fairly simply and definitely in air, electrostatic and dry magnetic separation machines. In mechanical sorting sampling frequency depends on clear identification of ore lumps. In solid-phase separation there are applied scraping-off (amalgamation, solid-wall flotation, adhesive flotation, magnetic separation) and washing-out (sluices, concentration tables). In liquid-phase separation a part of the phase (layer) is taken off or the film is removed from the surface. In multi-phase separation one of the phases is selected. In particular, air phase can be presented with a foam layer.

The continuity of the process involves steady feed of make-up material and product selection. Better separation can be achieved by evaluation of optimal selection velocity and machine production rate in entry material, secondary concentration in the selection zone, for instance, in the foam flotation layer, and engineering techniques preventing agitation during selection.

Cascade process layout envisages interrelation of basic, control and recleaner operations. Process improvement may result from optimal circulation of recycled middlings, counterflows and jet flowsheets arranged.

4.8. Prediction of Ore Dressability

4.8.1. Dressability of Genetic Complexes

Up to recently geological and technological studies of ore complexes have been as a rule carried out individually, both in time and methodically. Moreover, geological data used by dressing engineers have been restricted to the analysis of material composition of ores.

Available classifications of ores by dressability which are based on technological symptoms do not as a rule take into account genetic classification of geologists. Accordingly, geologists indicating only content of valuable components and minerals do not examine technological properties of the ore. We have undertaken an attempt to make up an interconnected genetic-technological classification of ores.

The genesis of deposits and paragenesis of minerals determine the treatment technology of ores. An optimum correspondence exists between the mineralogy of an ore and technological circuit.[11,97]. It is necessary for the mining industry and for estimation of mineral resources to obtain information on mineralogical and beneficiation data in each concrete case. Experience in ore beneficiation makes it possible to diagnose the technology of ore dressing on the basis of superposition of mineral properties, their mutual intergrowth, dissemination and distribution of the contents in the ore. An apriori diagnosis ensures for the investigator an optimum way for the technology project and the raw material used.

The information system for this aim is based: 1) On the prognoses of behavior of minerals (for fixed size and mineralogical complex); 2) On the experience in dressing ores of this type (geological genesis).

System of ore diagnosis

Diagnosis of ore treatment technology must be correlated with the contents of minerals, their sizes and genesis of deposit.[3,11]. First, we created scales of minerals concentration on the basis of their physical and chemical properties. The scales include the ranges of density, magnetic susceptibility, solubility, etc. The table of minerals flotability include reagent regimes. These scales and tables facilitate choice of the sequence of separation processes.

The following table contains and patented methods for dressing of ores of different genesis types. It is based on experience in ore dressing plants and investigations of ore beneficiation. The ore and plant analogues are particularly useful.

Obviously, the diagnosis system must be combined with experimental research of ores and technology.[17]. The tables, scales, modeling, simulation, calculation and design of technology are very useful in creation of mineral separation processes.

Table 4.19 gives the classification of genetic types of non-ferrous metals ore formations together with the dressing methods.

Table 4.19. Genetic types of ore formations, mineral complexes and dressability

S.No.	Formation, mineral complexes	Processing methods	
		applied	promising
ENDOGENIC			
Magmatic			
Crystallization			
(a) Early crystallization			
1	Chromite ores Chromite, olivine, Cr	Washing, manual sorting Heavy-media separation Magnetic separation Jigging; table, sluice and screw separator dressing Flotation of chromite, olivine, serpentine (fatty acids in neutral medium) with downstream separation Flotation of chromite (oxidized kerosene, amines, oil sulfonate, oleic acid, mixture of alkylaryl sulfonates and ammonium soaps, ..., tallow oil, Pinotan, Maraspers, ..., liquid glass, Aeropromotor 825, diesel oil, H ₂ SO ₄ , NaOH)	Production of chromite concentrates by magnetic separation in strong magnetic field table dressing with downstream electric separation
2	Platinum and platinum group metals: Pt, Os, Ir, Pd, Rh, Ru Native platinum, chromite, olivin (titanomagnetite, diallage)	Washing Trapping of platinum and gold on longitudinal and lateral sluices Table and screw separator dressing Flotation	Electric flotation
3	Diamond Diamond, pyrope, chrome-diopside, ilmenite, magnochromite	Washing Manual sorting heavy-media separation (medium passes magnetis field for flocculation of FeSi fine) Jigging, screw and pan separation	Foam flotation of diamonds of below 1 mm size (Aerofloat 25, cresyl acid or Dupon B-25 foamer)

		Fatty surface dressing (fat coating: refined petrolatum, fish oil, pine oil, yeloow and red petrolatum)	Flotation of diamonds of 0.6 mm in size
		Electrostatic separation with antecedent treatmeny of material with NaCl solution	Flotation of diamond grit MHS separation (H=18,000 Oe, working liquid: water solution of ManCl of 1.48 g/cm ² density)
		Gravity flotation	
		Flotation (amines, aerofloat)	
		Luminiscent sorting	
	(b) <u>Latr crystallization</u>		
4	Titanomagnetite ores: Fe(Ti,V), Cu, Pt (seldom) Titanomagnetite, magnetite, ilmenite	Table concentration Magnetic separation (H=1500 Oe) Electric separation (E=50 kV)	Heavy-media separation Magnetic sepsration in superstrong fields Flotation with magnetic carrier MHD separation
		Oxidizing roasting with downstream leaching, cementation and flotation of copper Flotation of sulfides (xanthate, pine oil) Flotation of ilmenite (tallow oil, oelic acid, diesel oil, kerosene, flotation oil, oxidized recycle, emulsion of tallow oil and etaxol (?), H ₂ SO ₄ , Na ₂ SiF ₆ , HF, Starch: NaF) Ilmenite and apatite are floated if apatite is present, ilmenite from collective cioncentrate is produced by magnetic separation, apatite by flotation Flotation of ilmenite with counterflow of foam products (tallow oil, Kerosene), flotation of ilmenite from slime fractions	
5	Apatite-magnetite ores, Fe(P) Magnetite, apatite	Magnetic separation (H≤ 1500 Oe) Flotation of apatite (see No.6)	Flotation in magnetic field

		Back flotation with magnetic concentrate produced in chamber product	
6	Apatite ores, P Apatite, nepheline	<p>Flotation of apatite (mixture of sulfate soap and soapmaking waste, mixture of soaped crude talloe oil, distilled petrolatum, fatty acids, liquid glass)</p> <p>Flotation of nepheline from tailings containing titanomagnetite, aegirine, sphene, nepheline (mixture of sulfate soap and soapmaking waste, sulfuric iron, NaOH)</p> <p>Flotation of dark-coloured iron-containing minerals: magnetite, ilmenite, etc. (fatty acids and salts, Na₂SiF₆) with nepheline produced in chamber matter</p> <p>Magnetic separation of iron-containing minerals</p>	<p>Foam flotation of washery waste (tallow oil, fuel oil, solar oil, soda, liquid glass)</p> <p>Foam separation of apatite (sulfate soap, tallow oil)</p>
7	Loparite ores: Nb (Ti, Zr) Apatite (lomonosovite, mourmanite, eudialyte)	<p>Jigging, table, screw separation, jet concentrator dressing</p> <p>Magnetic separation</p> <p>Electrostatic separation (conductor: loparite)</p> <p>Flotation of apatite (sodium oleate, loquid glass; crude or distilled tallow oil, soda; distilled or oxidized petrolatum)</p> <p>Flotation of loparite (fatty acids) and salts, sodium sulfide, Fe³⁺ salts, NaOH)</p> <p>Gravity flotation</p>	<p>Heavy-media separation</p> <p>Flotation jigging</p> <p>Magnetic separation in superstrong fields</p>
		<i>Liquation</i>	
8	Copper-nickel ores: Ni, Cu, Pt, Pd, (Co, Se, Te, Ag, Au)	<p>Antecedent heavy-media separation</p> <p>Flotation of bulk Cu-</p>	<p>Flotation jigging</p> <p>Magnetic separation in superstrong fields</p>

with H_2S , removal of magnesium by ion exchange, additional recovery of nickel by dilute sulfuric acid

Pegmatite

9	Rare-metal pegmatites Li, Ta, Nb, Zr, Sn, Ti, Mo Quartz, feldspars, micas, zircon, tantalocolumbite, cassiterite (ilmenite, molybdenite)	Jigging, table, sluice, screw separator dressing with selection of columbite, cassiterite, tantalocolumbite, ilmenite Magnetic separation with coarse garnet produced Electric separation Heavy-media separation Flotation of tantalocolumbite (sodium oleate, amines, alkylsulfates) Flotation of columbite (fatty acids, Na_2SiF_6) Flotation of rutile (oxidized recycle and kerosene, H_2SO_4 , Na_2SiF_6) Flotation of garnet (distilled tallow oil soap, soda, liquid glass, sulfite-cellulose lye) Flotation of glaucophane (distilled tallow oil soap, ANP-14) Flotation of spodumene (NaF , aerodepressant 610, aeropromoter 765, sodium oleate, fatty acids and soaps, naphthene acids, pine oil, liquid glass, $NaOH$, quebracho, milk acid) Roasting of spodumene concentrate with downstream flotation; back flotation (lime, dextrin, cation collector)	Flotation jigging (crude tallow oil soap, H_2SO_4) Foam separation of associate apatite (... , liquid glass, still residue) Magnetic separation in superstrong fields Electric flotation Hydrometallurgy Air separation
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Flotation of pyrochlore
(HF, Aeromin 3037,
sodium alkylsulfate,
sodium
isoalkylphosphate)
Decrepitation (thermal
dressing) with
downstream screening
or air separation)
Chemical processing
of lithium ores by
sulfate, limy or sulfuric
methods with
downstream leaching
of lithium salts,
precipitation and
selection

Postmagmatic

Scarn

10	Quartz cassiterite Sn (W, sometimes Ta, Nb, Bi)	Jigging, table, sluice, screw separator dressing Magnetic separation	Flotation of low-grade tin concentrate (10-12 %) with final operation by shaft smelting or sublimation as tin sulfide; iron oxides are removed by leaching with HCl or chlorination and sublimation of FeCl ₃ , chlorine is regenerated by combustion of FeCl ₂ with oxygen or dry air with transition of Fe to oxide Flotation in magnetic field Electric flotation of slime Flotation of cassiterite (<i>p</i> -polylarnone acid)
	Ore-bearing scarns Fe (Co), Cu, W-Mo, W-Sn, Pb-Zn, As-Au, Nb, Mn Garnets, pyroxenes, epidote, magnetite, scheelite, molybdenite, chalcopryrite, galenite, arsenopyrite (koppite, native Au, cassiterite)	Fe Washing Magnetic separation Oxidation roasting with downstream leaching, precipitation and flotation of copper Flotation of copper and apatite from leaching tailings Cu Magnetic separation Flotation (xanthate,	Heavy-media separation Bacterial and chemical leaching Electric flotation Magnetic separation in superstrong fields Flotation in magnetic field

flotation oil, pine oil,
lime)

W-Mo

Table separation

Flotation of
molybdenite

Flotation of sulfides
(kerosene, terpene oil,
alcohol foamer,
tanning extract,
sodium, liquid glass)

Flotation of scheelite

(oleic acid or
substitutors, kerosene,
soda, quebracho,
wetting agent D-40),
steaming (liquid glass)

Flotation of scheelite
from barite
(alkylsulfates in acidic
medium)

Leaching of apatite and
calcite (industrial
HCl), neutralization
(lime); lime precipitate
is processed by soda
agitation method

Pb-Zn

Flotation of bulk
copper-lead-zinc
concentrate with
downstream selection

Direct selective
flotation

Selective-bulk flotation
(soda, cyanide, zinc
vitiol, xanthate,
sodium sulfide, foamer
D-3)

As-Au

Jigging, table, sluice
screw separation

Flotation of gold and
sulfides, cyanation of
sulfide concentrate

Direct cyanation

Deep hydrothermal

(a) High-temperature (300-500°C)

- | | | |
|----|---|---|
| 12 | Rare-metal
carbonatites
Nb, P (Zr, Ta)
Phlogopite, carbonates, | Table and screw
separation
Magnetic separation
Electric separation |
|----|---|---|

Flotation of ultrafine
scheelite flocs
(flocculation, agitation
with $6 \cdot 10^{-4}$ M of
sodium oleate and 10^{-4}
of sodium silicate at
pH 10 for 60 minutes;
flotation: density 0.2-1
& sol., supply of
foamer and air)

Jet flotation of
scheelite

	pyrochlore, apatite, (baddeleyite, zircon, perovskite)	<p>Flotation of titanium-containing minerals (fatty acids with calcium alkylsulfate, naphthene soap, oxidized petrolatum. alkylsulfate, soda, liquid glass, starch, H_2SO_4)</p> <p>Flotation of perovskite and ilmenite (soap in acidic medium, oleic acid, tallow oil, H_2SO_4, NaF, H_2SiF_6)</p> <p>Flotation of perovskite (sodium oleate, sodium bichromate, soda, H_2SO_4)</p> <p>Flotation of pyrochlore (cation collector, liquid glass, oxyquinoline, fatty acid collectors and salts, acid)</p> <p>back flotation with pyrochlore produced in chamber matter (fatty acids, liquid glass, soda)</p> <p>Gravity flotation</p> <p>Roasting of ore, water quenching with downstream gravity dressing, magnetic separation, flotation and acid treatment</p>	
13	Quartz wolframite W, Mo (Sn, Bi) Quartz, wolframite, molybdenite (scheelite, cassiterite), bismuthite, arsenopyrite, topaz, fluorite)	<p>Jigging, table dressing</p> <p>Flotation of fluorite and scheelite</p> <p>Flotation of fluorite (oleic acid, alkylsulfates, α-nitro-β-naphthol)</p> <p>Flotation of wolframite (cation collectors, H_2SO_4, $KMnO_4$)</p> <p>Flotation of sulfides (kerosene, soda, liquid glass, terpene oil)</p> <p>Flotation of scheelite (oleic acid, kerosene, soda, transformer oil, liquid glass, Na_2SiF_6)</p>	<p>Heavy-media dressing</p> <p>Production of WO_3 off-grade tungsten concentrates from gravity slime for processing by acid-ammonia or soda-agitation method</p> <p>Foam separation of fluorite ores of below 2 mm in size</p> <p>Electric flotation</p>
14	Quartz-gold-	Jigging, table, sluice,	Bacterial leaching

	<p>arsenopyrite Au, As (Bi, Co, Sn, W, Fe) Quartz, arsemopyrite, native gold (pyrrhotite, ..., bismutite, glaucodote, scheelite, tourmaline, tellurides)</p>	<p>screw separation Flotation of sulfides and gold (xanthate, aerogloat, lime, soda, copper vitriol, creosote, dauffros 250) (?) with cyanation of roasted bulk concentrate Flotation of gold-bearing pyrite (xanthate, soda, sodium sulfide) Direct cyanation of ore with downstream flotation of pyrite (xanthate, oine oil, copper vitriol, sulfurous gas), roasting of pyrite concentrate and cyanation of residue Cyanation of gold from gravity and flotaion dressing tailings</p>	<p>Electric flotation Electrochemical treatment of solutions and slurries</p>
15	<p>(b) Medium-temperature (200-300°C) Copper-molybdenite Cu, Mn (Se, Te, Re, Bi, Au, Ag) Chalcopyrite, molybdenite. quartz, quartz (bornite, enargite, grey ores, sphalerite, carbonates)</p>	<p>Flotation of bulk copper-molybdenum concentrate (mixture of kerosene and oil SU (?), xanthate, oxidized turpentine, mixture of dauffros (?) and pine oil, mixture of butyl xanthate with aerofloat, with apolar oil, allyl ethers of xanthic acids, mixture of thiophosphates or thioarsenides, terpene oil, aerofloat 238, (?), z-200 agent, soda, lime, liquid glass, sodium sulfide) Flotation of copper (xanthate, pine oil, mixture of cyanide, zinc vitriol and hydrpgen pyroxide, ferrocyanide, apolar oil, sodium hypochloride abd potassium ferricyanide,</p>	<p>Ion exchange method using strongly basic anionites for searation of rhenium and molybdenum Seperation of bulk copper-molybdenum concentrtaes with autoclave steaming of slurry under pressure at 150-350°C Flotation by ethyl vinyl butyl ether (MIG-4E), dibutyl acetal of thetrotol aldehyde (MIG-4A) Recovery of molybdenite from copper sulfide concentrates by back flotation (gitation with lime up to pH 11.5, treatment with lignin sulfonate for depression of molybdenite, addition of surfactants, foam</p>

		dicresyldithiophosphate) Flotation of molybdenum (kerosene, sodium thioarsenate, synthex L, pine oil, phosphates, sodium sulfide, apolar oils, cyanide, ferrocyanide) Leaching, precipitation and flotation for extraction of oxidized copper Flotation of molybdenite from ores and concentrates containing hydrophobic talc (treatment with solution and metaic salt of weak base and strong acid or water-soluble salt of weak acid . from 1 to 60 min, foam flotation) Stage flotation Steaming and roasting of bulk concentrate with downstream leaching Jigging	flotation of copper minerals) Antecedent electric treatment of ore slurry for selective depression of minerals by selecting electrode material (excluding toxic depressors of copper minerals)
16	Gold-sulfide Au, Pb, Zn, Cu, (As, Bi)	Bulk flotation of sulfides and gold (xanthate, lime, oil), tank aeration (pyrolusite, activated coal); flotation of sulfides, except arsenopyrite (xanthate, flotation oil, KMnO_4 , lime) bulk copper-lead flotation (xanthate, lime, H_2S) Flotation of arsenopyrite (xanthate, daufros A-25, cyanide, $\text{Pb}(\text{NO}_3)_2$, zinc dust); cyanation, precipitation, fire refining	Heavy-media separation Processing of lean sulfide ores by oil agglomeration (conditioning agent: vacuumated still residues, tributyl phosphate, dimethyl sulfoxide, secondary butyl xanthate) with downstream calcination and cyanation Replacement of cyanide by solutions of malononitrile, bromomalononitrile, cyanoform Foam separation of gold-bearing ores (mixture of xanthate,

		<p>Dorfmann rocess for coaly ores: treatment of ore with kerosene or fuel oil and cyanation)</p> <p>Processing of ore by oxidizers (KMnO_4, sodium bichromate, calcium hypochlorite)</p> <p>Flotation of coal; sulfide flotation (xanthate, methylisobutylcarbinol, aerofloat, quebracho, coal depressant: agent 1 SM, mixture of dextrin, guar, lignin)</p> <p>Direct cyanation with tailings delivered to flotation (kerosene, lime, aerofloat, pine oil, copper vitriol, zinc dust); roasting of flotation concentrate, cyanation of residue</p> <p>Amalgamation</p> <p>Flotation of sulfide and oxidized minerals from alamgamation tailings (xanthate, pine oil, lime, sodium sulfide)</p> <p>Heap and percolation leaching</p>	<p>fuel oil and solar oil, T-66, mixture of heteropolar and polar collectors)</p> <p>Bacterial leachinh</p>
17	<p>Polymetallic Pb, Zn, Ag (Cu, Cd, Ga, Se, Te, Au)</p> <p>Galenite, sphalerite, grey ores, pyrite, chalcopryrite, quartz, carbonates, barite, serocite</p>	<p>Jigging; heavy-media separation</p> <p>Bulk copper-lead-zinc flotation (xanthate, aerofloat, pine oil, sodium sulfide, fatty acids with short hydrocarbon chains, mixture of xanthates) with downstream selection of bulk concentrate (xanthate, soda, lime, pine oil, copper and zinc vitriol, cyanide, Sikewest 3223: acryl polymer)</p> <p>Solution of CuCl_2, CuCO_3 or both salts may be supplied as activator instead of cpper vitriol during</p>	<p>Electric flotation</p> <p>MHD separation</p>

		flotation of sphalerite Cationic flotation (IM-11, ANP) Flotation of gold selenides and tellurides from copper electrolysis slime (sulfuric acid), collector); flotation of nickel (oleic acid, tallow oil)	
18	Sulfide-cassiterite Sn (Pb, Zn, Ag, As) Cassiterite, tourmaline, chlorite, pyrrhotite, arsenopyrite (pyrite, sphalerite, galenite, chalcopyrite, stannite)	Heavy-media separation Table separation and sluicing; jigging Flotation of cassiterite Flotation of stannite from stannite-pyrite concentrate (lime, cyanide, copper vitriol, collector) If there are many sulfides in ore, antecedent bulk or selective flotation, then table separation and sluicing are applied	MHS separation for deslimed ores of -6 mm in size and low-grade tin concentrate (H=18,100-18,200 Oe, working medium: MnCl solution) Foam separation of sulfides from gravity tin-sulfide concentrates (H ₂ SO ₄ , butyl xanthate, diesel oil, Flotation in magnetic field
	(c) Low-temperature (50-200°C)		
19	Stibnite-cinnabar-fluorite Sb, Hg (CaF ₂ , sometimes As) Stibnite, cinnabar, fluorite, quartz (pyrite, grey ores, realgar, orpiment)	Jigging, table separation Flotation of antimony (xanthates, pyridine, kerosene, cresyl acid, liquid glass, mixture of fuel oil and shaly resin, oleic acid, lead nitrate, OP-10, OP-7, OPSB, IM-68, DS, soda, camphorated oil) Flotation of oxidized antimony ore with preheating (xanthate, sulfurous gas) Combined gravity-flotation-cyanide method (fuel oil, flotation oil, shaly resin, xanthate, polyacrylamide, lead nitrate) Trapping of mercury	Heavy-media separation Flotation recovery of antimony from mortar (butyl xantahte, spindle oil), re-pulping (sodium sulfide) Repulping residue (Cinnabar-carbonaceous concentrate) to roasting Deslomed flotation tailings are delivered to tanks with mercury traps Selective flocculation (extraction of fine fluorite ores)

20	Cuprous sandstones Cu (Pb, Zn, Re) Chalcopyrite, bornite, chalcocite, sphalerite, galenite, pyrite, grey ores, carbonates, quartz, barite (arsenopyrite, marcasite, dzhezkazganite)	Flotation of bulk copper-lead-zinc concentrate with downstream selection Flotation of copper (xanthates, aerofloat, cyanide, lime, triethoxibutane, thiocarbanilide, hexametaphosphate, flotation oil, heavy pyridine, OPSB, cresol, xyleneol, diesel oil, terpene oil, lubrication oil, z-200; mixture of xanthate, aerofloat and z-200 or xanthate and apolar oil; chlorides of hydrocarbon oils, methylisocarinol, aerofros 65) Individual flotation of sands and slimes	Foam separation Electric flotation for additional recovery of heavy metal ions Selective flocculation for complex copper ores: flocculants - 2.1, PAMG 6 and 7 agents being copolymers of glyoxal-bis polyacrylamide (2- hydroxylanil, Calgon (sodium hexameta phosphate) and Displex 40 (low-molecular acrylate of copolymer type with high hydroxyl content) should be supplied for reduced effect of slime
21	Lead-zinc (in carbonate rocks) Pb, Zn (Cd) Galenite, sphalerite, pyrite, carbonates, quartz, barite (grey ores, greenockite)	Heavy-media separation, jigging Flotation of bulk lead- zinc concentrate with downstream selection (xanthate, pine oil, soda, cyanide, sodium sulfide, copper vitriol, lime, liquid glass) See No.11 as well	Foam separation of oxidized zinc ores with calcium and magnesium carbonates produced in foam matter (...), oleic acid, tallow oil and fatty acid fraction, Na ₂ S, IM-68), zinc- ferruginous product in tailings
<i>Low-deep (less than 1 km) hydrothermal</i>			
(a) High-temperature (300-500°C)			
22	Copper-tourmaline Cu (As, Sn, Mo) Quartz, tourmaline, pyrite, enargite, tennantite (cassiterite, sphalerite)	Flotation of copper- molybdenum concentrate (minerec, kerosene, aerofloat 243, Powell agent, cyanide, sulfuric acid, lime, Noxe agents (see No.15) Flotation of copper (xanthate, solar or transformer oil, xyleneol, terpene oil) (see No.15) Flotation of molybdenum minerals (see No.15)	See No.15

		Extraction of cassiterite from flotation dressing tailings by gravity methods	
23	Magnetite-ferrite Fe Magnomagnetite, carbonates (hematite, quartz, apatite)	Washing Magnetic separation Reduction or redox roasting with downstream magnetic separation Heavy-media separation Jigging, table separation	Foam separation of oxidized ferruginous quartzites (NaOH, slop, mixture of solar and crude tallow oil) Flotation in magnetic field
24	Tin (rhyolite) Sn Cassiterite, quartz, sericite, seldom hematite, fluorite, sulfides	Heavy-media separation Jigging, table separation, sluicing Flotation of tin from gravity separation slimes (sodium oleate, wood oil) Flotation of sulfides from gravity dressing tailings Flotation of fluorite from tin concentrate (see No.18)	MHD separation Foan separation
	(b) Medium-temperature (300-200°C)		
25	Pyrite Cu, Zn, Pb, BaSO ₄ (Au, Ag, Se, Te, Cd, Ga, As, Bi, Co) Pyrite, pyrrhotite, chalcopyrite, sphalerite, galenite, barite (bornite, grey ores, bismuthine, enargite)	Washing Bulk flotation of sulfides (xanthate, soda, aerofloat, pine oil, copper vitriol, zinc vitriol, cyanide, lime, z-200, daufros 250, quebracho, liquid glass, calcium silicate, sulfuric acid) Flotation of copper (mixture of xanthates and aerofloat, lime, cyanide, soda, heavy piridine, quebracho, pine oil, OPSB, dixanthate, zinc vitriol, sulfur, mixture of sodium sulfite and iron vitriol, H ₂ SO ₄ , minerecs, mercaptobenzothiazol, secondary butyl	Pyro and hydrometallurgical processing of bulk sulfide flotation tailings: chlorinating roasting, sulfating roasting Electric flotation

		xanthate) Zinc flotation (xanthate, pine oil, copper vitriol) Flotation of barite from lead--zinc flotation tailings (oleic acid, liquid glass, soda, aeropromoter 825) Leaching, precipitation and flotation of oxidized ores (aerofloat, ..., xanthate, dithiophosphate) Heavy-media separation of coarse- impregnated ores, magnetic separation, table separation Individual dressing of sands and slimes	
26	Siderite Fe Siderite (barite, pyrite, hematite, galenite, chalcopryrite, arsenopyrite, chlorite, sericite)	Washing Heavy-media dressing Jigging, table separation Reducing roasting at 550-600°C or redox roasting with downstream magnetic separation Oxidizing roasting with downstream leaching of copper Flotation (tallow oil, ..., liquid glass, ammonia alum)	Magnetic separation in superstrong fields Flotation in magnetic field
	(c) Low-temperature (50-200°C)		
27	Gold-silver Au, Ag (Te) Electrum, pyrargillite, stibnite, gold and silver tellurides (cynabar), chalcedony, carbonates	Flotation of gold selenides and tellurides from copper electrolysis slimes (collector, foamer, sulfuric acid); flotation of nickel (oleic acid, tallow oil)	Magnetic separation (H=10,000-12,000 Oe) MHS separation (H=20,000 Oe, working medium: MnCl of 1.4 g/cm ³ density)
28	Stibnite-cynabar- ferberite (scheelite) Hg, Sb, W (Au, Ag, Te, As) Cynabar, stibnite, ferberite, scheelite, chalcedony (gold and silver tellurides,	Jigging; table, sluice and screw separation Flotation of mercury (amyl xanthate, derivatives of tannin, alcohol foamer, mixture of aerofloat and pine oil, pine oil,	See Nos.13, 14 and 19

	realgar, orpiment)	soda, copper vitriol, see Nos.13, 14, 18 as well)	
29	Realgar-orpiment As (Sb, Hg) Realgar, orpiment, carbonates, chalcedony (stibnite, cinnabar)	Heavy-media separation table separation Magnetic separation Flotation of arsenic- containing minerals (xanthate, pine oil, copper vitriol, liquid glass, lead acetate, flotanol, cyanide, H ₂ SO ₄ , dithiophosphate, wood-tar oil, xanthate mixture) Trapping of mercury, see No.19 as well	Foam separation of arsenic-containing ore, see No.19 as well
		<i>Exhalation</i>	
30	Siliceous-iron ore Fe Hematite, magnetite	Washing Roasting - magnetic separation Flotation Back flotation, see Nos,4 and 26 as well	See Nos.4 and 26
31	Siliceous-manganese ore Mn Pyrolusite, psilomelane, braunite, rhodonite, rodochrosite, chalcedony, carbonates (hematite, barite, agate, sulfides)	Washing Jigging Magnetic separation Heavy-media separation Electrostatic separation Flotation of manganese minerals (solar oil, tallow oil, oronite-S, sulfurous gas, soap, fuel oil, quebracho, lime)	Flotation in magnetic field with carrier Emulsive flotation Leaching Flotomagnetic separation in counterflow pneumatic machine of column type Processing of off-grade manganese concentrates by autoclave-soda method See No.25
32	Pyrite (exhalative- sedimentary) Cu (Zn, Fe) Pyrite, chalcopyrite, sphalerite, etc.	Flotation of copper minerals (xanthates, pine oil, potassium bichromate, zinc vitriol, liquid glass) Flotation of copper- lead concentrate (xanthates, sulfurous gas, sodium bisulfite, zinc vitriol, Tragol 4, Cyanide) with downstream selection Flotation of zinc	

minerals (xanthate,
cyanide, copper vitriol,
lime, pine oil)
Flotation of pyrite
(xanthate, Tragol,
liquid glass)
Flotation of barite
(oleic acid), see No,25
as well

EXOGENIC

Weathering deposits

Sedimentary

Weathering crust deposits

- | | | | |
|----|--|---|--|
| 33 | Eluvial-deluvial
placers
Au, Pt, W, Sn
Quartz, gold, platinum,
scheelite, wolframite,
cassiterite, barite, etc. | Washing
Table separation,
sluicing,
jigging
Magnetic and
electrostatic separation
(conductors:
wolframite and
cassiterite)
Cyanation
Amalgamation
Gold and platinum
trapping in hydraulic
traps, on fluffy sluice,
in mercury traps
Removal of sulfur,
arsenic, phosphorus,
antimony, bismuth in
... with downstream
leaching, precipitation
and flotation of
tungsten | Flotation of gold
(xanthate, aerofloat 15,
pine oil) |
| 34 | Feruginous laterites
fe (Mn, Ni, Co, Cr)
Limonite (manganese
oxides, nickel silicates,
chromite, asbolan) | Washing
Roasting - magnetic
separation
Flotation (fatty acids,
mixture of cride tallow
oil and still residues,
liquid glass, H ₂ SO ₄ ,
mixture of crude tallow
oil and fish oil)
Back flotation

Oxidizing flotation
with downstream
leaching, cementation
and flotation of copper
Flotation of
manganese-cobalt | Flotation of olivine
from placers
Dressing of chrome-
containing laterite ores
by alkaline roasting
(drying, agitation with
waterless soda,
nodulizing, roasting of
pellets, water leaching,
aluminium hydroxide
precipitation and
steaming)
Magnetic separation
(H=1000 Oe), reducing
roasting (wood coal),
magnetic separation
(H=5000 Oe) |

		minerals (sodium oleate, oleic acid, soda)	
		Flotation of chromite minerals	
		(aerocyanamides 708 and 824, mixture of crude naphtha and diesel oil, H ₂ SO ₄), see No.26 as well	
36	Aluminous laterites Hydrates (alumosilicates, iron hydrates, etc.)	Rable separation Heavy-media separation Magnetic separation Flotation (fatty acid collectors)	Flotation of slime in magnetic field Electric flotation Flotomagnetic separation in column type machine
36	Silicate nickel ores Ni (Co) Nickel hydrosilicates, nickel-bearing clays (asbolan)	Washing flotation of nickel minerals (oleic acid, tallow oil, carbonic acids) Magnetic separation Roasting - magnetic dressing	Magnetic separation in superstrong fields
		<i>Infiltration</i>	
37	Infiltration ores Fe, Mn, Cu, U-V Limonite, sphaeroiderite, pyrolusite, psilomelane, cuprite, chalcocite, roscoelite	(See Nos.26, 31) Nitrate leaching and extraction of rare-earth elements are applied in dressing of monacite ores after electric separation and flotation (mixture of organic solvents of di-(2-ethylhexyl) phosphoric acid and tributyl phosphate	See Nos.26 and 31
		Sedimentary deposits	
		<i>Mechanical sediments</i>	
	Placers (alluvial, delta, marine, glacier, etc.)	Washing Jigging, table dressing,	Flotation of of titanazircon minerals in neutral and low-alkaline medium
38	Alluvial and marine placers W, Ta-Nd, Zr, Fe, Ti Diamonds Gold, platinum, tin, cassiterite, scheelite, wolframite, tantalocolumbite, zircon, diamonds, magnetite, ilmenite	sluicing, ject concentrator and screw separator dressing Sluices with mechanical disintegration and classification of sands at start (washeries with barrels and scrubbers, kulibins with hydraulic cradle and ... devices	(fatty acids and salts, oxidized recycle, oxidized petrolatum, sulfate soap, naphtha oil) Foam separation of marice sands with ilmenite, rutile, zircon

with scrubber drums)	selected to concentrate
and in the middle of	MHD separation
the process	Gravity flotation
(counterflow dugouts, subsluices)	
Magnetic separation of bulkgravity cocentrate (high-magnetic fraction: iron, magnetite, pyrrhotite, magnetic platinum; medium-magnetic fraction: wolframite, hematite, garnets, ilmenite, columbite, limonite, tourmaline, ferberite; low-magnetic fraction: monacite, light garnets, tourmalines, pyroxenes, epidote, chromite)	
Electrostatic separation (conductors: wolframite, rutile, chromite, tantalite, ilmenite; nonconductots: garnet, zircon, monacite, xenotime), staurolite and tourmaline are separated from nonconductors by magnetic method	
Flotation of bulk titanozircon concentrate (oxidized recycle, oleic acid, sulfate soap, soda, liquid glass, starch, tallow oil, naphtha soap, soap stock, sodium alkylsulfate, oxidized petrolatum, IM-11)	
Flotation of zircon from rutile, ilmenite, monacite, silimanite, cassiterite, chromite (hot soap solution, sodium oleate and stearate, re-pulping by cold water, sulfuric	

acid, mixture, of
methyl alcohol and
eucalypt oil, hydrogen
gas and naphtha soap,
copper vitriol, lome)
Flotation of zircon
from rutile (naphtha
soap, oleic acid, soda,
liquid glass, lime,
 Na_2SiF_6)
Selection of diamonds
by jigging, manual
sorting, in mercury
traps, by
amalgamation, in tube
separators, cyanation
Radiometric soring

Chemical sediments

	Sediments from colloid solutions	see Nos.23 and 31	Foam separation Electric flotation
39	Sedimentary iron ore fe (Mn, P, V) Limonite, chamosite, siderite (manganese hydroxides, kerchenites, barite, sulfides)		Flotation in magnetic field, MHD separation
40	Sedimentary manganese Pyrolusite, psilomelane, manganite, rhodonite, rhodochrosite, manganocalcite	Washing Jigging Magnetic separation Flotation ("white water" - mixture of motor oil, acedol and alkali, distilled tallow oil, emulsion oil, still residues, ..., liquid glass, mixture of white water and soap, sunflower hydrofuse, solid fatty acids and alcohols, white eater paste, segezh foamer) Flotation of manganese from slime (mixture of crude tallow oil, solid fatty acids and emulsion oil, liquid glass, mixture of soap, distilled tallow oil and sulfanol, soda) Foam separation (liquid glass, emulsion	See No.31

		of emulsion oil, diesel oil, soaped still residues and crude tallow oil, fuel oil, OPSB, xanthate), see No.31 as well	
41	Sedimentary bauxite Hydrates, aluminosilicates, chamosite, iron hydrates	Washing Table dressing Flotation of disthene (oleic acid, tallow oil, H ₂ SO ₄ , liquid glass) Flotation of andalusite (oleic acid, soda, starch and sulfide lye) Flotation of sillimanite (oleic acid and salts, alkylsulfates, still residues from distillation of synthetic fatty acids and alcohols), see also No.35	Foam separation Production of Al ₂ O ₃ by leaching of bauxite according to Bayer method at high temperature, see No.35 as well
43	Sedimentary phosphorite Phosphorites, apatite, carbonates	Jigging Flotation of phosphorites from sedimentary sandstones (fatty acid collectors, kerosene, solar oil, soda, liquid glass) Back flotation (amines, soda, kerosene)sulfuric acid, Flotation of ferruginated carbonates (fatty acids, sulfuric acid, phosphoric acid, tallow oil, liquid glass), see also No.6	Gravity flotation (soda, fuel oil, tallow oil)
	Biochemical sediments	Radiometric sorting	Extractive flotation Electric and ionic flotation
43	Sedimentary V, U, Mo-bearing shales Metallorganic compounds:oxides, sulfides	Jigging, table separation, screw separation, hydrocyclone separation Selective separation Heavy-media separation Flotation of carbonates (soda, organic colloid R-633, palm oil, fuel	

		oil, aerofros-63) Flotation of sulfides, organic matters and limestone with downstream roasting, leaching of uranium with acid; flotation tailings are delivered to soda leaching Flotation of uranium- containing minerals with downstream acid, soda or carbonate leaching, presipitation of uranium, recovery by ion exchange method, extraction by organic liquids Flotation of copper, iron-containing, lead and nickel minerals from cake after uranium leaching Hydrometallurgy	
44	Sedimentary sulfide copper and lead-zinc ores Cu (Pb, Zn) Chalcopyrite, bornite, chalcocite, galenite, sphalerite, barite	See Nos.17 and 25	see Nos.17 and 25
METAMORPHOGENIC			
Metamorphized			
45	Metamorphogenic iron ores Fe Magnetite, martite, hematite, limonite, quartz (alkaline amphiboles, aegirine)	See Nos.4, 26 and 34	See Nos.4, 26 and 34 Gravity flotation, flotation jigging (crude tallow oil soap, crude and distilled tallow oil, solar oil) Foam separation of nonmagnetic minerals
46	Metamorphogenic manganese ores Mn Braunite, jacobsonite, manganese garnets, hausmannite, rhodonite, pyroxenes, magnetite	See Nos.31 and 40	See Nos.31 and 40
47	Metamorphogenic gold-uranium-bearing conglomerates Au, U	Table dressing, sluicing, screw separation, jigging Ore sorting	See Nos.33, 38 and 43

	Gold (Os, Ir, diamonds, zircon, chromite)	Heav-media separation Fatty surface dressing (fish oil, soda) Direct cyanation Amalgamation Electric separation for -6 mm size (H=25 kV) Flotation, see also Nos.33, 38 and 43	
		Metamorphic	
48	Metamorphogenic andalusite-cyanite-sillimanite shales	Table separation Heavy-media separation Magnetic separation Flotation (emulsified mixtures of fatty acids, solar oil, alkylsulfates, sulfuric acid, oleic acid emulsion, liquid glass, starch, lead nitrate, distilled tallow oil emulsion, synthetic carbon acids (C ₁₀ - C ₁₆), see also Nos.35 and 41)	See Nos.35 and 41

4.8.2. Statement of Mining Process Problems of Ore Dressing

Natural mineral complexes feature genesis, mineral composition and other geological-minegalogical parameters examined hereinbefore. Diversified ore-dressing problems can be solved by comparison of properties of minerals which ore is composed of. Table 4.20 indicates the stages of solving some dressing problems. It is evident from the table that though solution stages may differ they can be solved by common methodic and mathematical methods.

System analysis involves maximum account of interaction between projects under study and solutions using tools of decision-making, simulation and optimization. It permits analysis of the process at different modifications of decomposition which results in its being applied as unique methodological approach both in on-line control, engineering, planning and study for dressability and in acquisition and assessment of apriori information.

Envisaging interrelation of forecast problems and generality of dataware, we shall make up a schedule of data application and handling in mineral dressing (Fig.4.22).

While considering the following four forecast types: (1) mineral product quality forecast, (2) technological demand forecast, (3) production process and equipment forecast, and (4) technoeconomic indicator forecast, we understand that data of geological prospecting are the information source for the first forecast. The second forecast type is supported by the information of virtually any type except data on performance of existing undertakings, the third forecast type calls for information on processes and equipment of existing plants, results of studies for dressability as well as bibliographic and patent information which is input into forecasting from information retrieval system on technology. Geological prospecting data and plant performance are the information for developing the fourth forecast type.

The schedule shows that these forecasts are used in long-range planning, dressability studies, process improvement, development of computerized design and process control systems.

Information support structure must be in line with initial data on characteristics of ore entering the dressability study. They include genetic deposit type, mineral composition, petrographic composition with impregnation estimate. According to this, information support structure is split into retrieval of dressing methods for this ore type and retrieval of separating methods for certain minerals depending on particle size.

Table 4.20. Dressing problem solution stages

Solution stage	Dressability study	Engineering of concentrator flowsheets	Prediction of technoeconomic indicators of dressing	Control
0. Statement of problem and selection of aim	Achievement of results which is limited by theoretical possibilities, process criteria	Development of engineering assignment by subsystems. Economic criteria	Prediction of results. Technoeconomic criteria	Achievement of preset or optimal indicators for small finite time. Output parameters of equipment and schemes.
1. Acquisition of information	Mineralopetrographic and phase analysis of ore. Retrieval of analogues and potential methods of dressing	Gathering of reference and experimental data on equipment and modes. Identification of analogues	Gathering of statistical information on technoeconomic indicators and monthly plant calculations	Sensors, registrators and recorders installed for analysis of content of components in liquid slurry phase, ore and dressed products, machine performance.
2. Primary information processing	Selection of scheme of study on mineralogical and phase analysis data. Planning of experiments on identification of significant parameters	Definition of variety of potential scheme variants including an optimal one	Rejection of unrepresentative data. Estimation and distribution of costs by operation	Identification of technological ore types. Calculation of random function characteristics and approximation of parameter distribution, calculation of efficiency criteria

3. Control and correction of data	Planning of experiments based on search data for finding of optimal process modes	Calculation and estimation of scheme of variant indicators	Make-up of initial data arrays with correction on mineral product quality	Verification of stationary state of time drift of parameters and estimation of delay in process
4. Process simulation	Statement of extremum experiments and calculation of dressing models based on planned experiments	Construction of mathematical models on vector of aim functions and restrictions	Calculation of models of distributing costs and effect of mineral product quality	calculation of equations of concentration of parameters, models and processes
5. Optimization	Calculation and experimental check-up of optimal process modes	Synthesis of optimal schemes	Optimizing calculation of planned indicators	Calculation of optimal process parameter values, modes for obtaining optimum, values of output parameters of subsystems optimizing the system
6. Decision-making	Make-up of dressing scheme based on models of individual processes	Selection of optimal scheme	Approval of planned or optimal indicators	Comparison of variants optimal in different criteria and selection of process mode by criteria vector
7. Verification of efficiency and optimality of solution	Experimental check-up and correction of dressing scheme developed	Engineering of scheme selected	Agreement of indicators with external restrictions	Estimation of efficiency of preset optimal mode, arrangement of optimization system self-learning

Taking into account application of computers for information accumulation, retrieval and analysis, requirements of system approach in solving prediction problems, dressability studies, engineering, and control, the problems enlisted below are posed:

(1) classification of dressing information by type of ore deposits, technological processes, process intensification methods, mineral dressability based on physical

optical properties and luminescence, natural and induced radioactivity, solubility of minerals in inorganic solvents, dressability using bacterial leaching method and antecedent alteration of mineral properties by means of thermal effects, and by floatability;

(2) acquisition and presentation of technological information in a table form, correction, supplementation and processing;

(3) construction of systems of selecting rational schemes of ore dressability studies;

(4) study of possible application of available information in practice during choice of schedules of dressability investigations, processing technology improvement, on-line dressing process control and long-range planning.

The interrelated consideration of information on dressing processes and mineral dressability affords development of a formalized system of selection of rational ore dressability study schedules and directions of technological improvements with regard to up-to-date requirements to dressing circuits.

4.8.3. Information Support of Ore Dressing Problems

Multi-aspect problems of technological mineralogy, enormous mass of unsystematized information and potential of applying the same information in different tasks (investigation, engineering, development of computerized control systems, etc.) calls for elaboration of a united system of information support.

Statement of this question is connected with transition from conventional methods of information accumulation and analysis to presentation of information in a formalized form which is classified and easily coded for input into computer memory. Information must support solution of several interrelated tasks:

- identification and classification of mineral complexes subject to separation,
- selection and synthesis of innovative processes of mineral separation,
- synthesis of ore dressing flowsheets with optimization by stages of ore preparation, dressing and final processing,
- control of dressing process based on variable-structure models,
- identification and alteration mineral properties for extraction of valuable components from ores using different physical and chemical actions.

Classified information accumulated in a certain way affords solution of the whole number of a priori prediction problems.

Sophistication and variety of ore complexes, flowsheets and methods of dressing involve increase in dressability study scope. However, the mass nature of these studies have not brought about their standardization so far, and consequently the possibility of using their results for generalization, classification and diagnostics of ores.

From this viewpoint a unique value is attributed to a priori estimation of mineral product dressability, account and application of all potential methods of valuable component extraction. When new ore is studied or a technology is improved, not only up-to-date processes and machines should be used but also promising methods of their combination, possible application of physical and chemical actions intensifying mineral complex separation processes must be borne in mind.

This problem is posed not only when a dressability study plan is made up and it is necessary to take into account any promising processing schedule subject to be experimentally verified but also when economic planning questions are settled. In the last case it is of great importance to make tentative estimation of mineral resource reserves, among them, promising ones, and predictive reserves for which investigation samples cannot be obtained so far and expensive detailed studies have no sense to be carried out. [17].

In so doing, it is required to have a prompt *apriori ore dressability estimation* which permits, let it be approximately, a forecast of possible processing scheme and process parameters.

A system of predicting mineral product processing technology cannot be created without close interconnection of all links of such a system, and in the first place the connection with computerized systems of information retrieval, engineering and control.

A predictive system is difficult to be developed which is predetermined by absence of similar elaborations and standardized system of dressability studies, nonavailability of information on dressability of mineral variants and peculiarities of each ore deposit nature. Nevertheless urgency of the problem and a high up-to-date investigation level permits a statement to be made that the problem of *apriori* dressability prediction and forecast of ore dressing technology development can be gradually solved.

Data on minerals and separating processes allows a number of classifications to be given, promising new process synthesis methods to be identified, technological development in connection with mineral product quality forecast to be envisaged.

An attempt to link a genetic and dressing classifications of deposits may turn out to be useful not only to geologists but also to dressing engineers. Promising combined and hydrometallurgical processes which are more and more used in mineral processing technology, different methods of action on mineral (bacterial, thermal, electrochemical, ultrasound, etc.)...

We have tried to present the basic material in a table form suitable for further coding and input into a computer. It can be a basis for developing an algorithm of *apriori* selection of process flowsheets.

A number of handicaps associated with sophisticated nature of predicting ore dressability and mineral behaviour alteration can appear during the elaboration of a dressing circuit. Numerous examples of deviations of ore from normal behaviour in the dressing process can be cited here. However it must be taken into account that almost always a reason for such deviations connected with physical, mineralogical or geological ore peculiarities can be found. A complex of preliminary studies including mineralogical, fractional, granulometric ore analyses, and certain investigations of physical properties of minerals which the ore is composed of permit an investigation schedule to be outlined.

It must be noted that prediction of mineral dressability keeps behind similar investigations to a considerable extent in applied fields, in particular, in geology and mineral mining. Forecast of promising areas of mineral search, deposit mining systems, and other problems seem to be easier for formalized computer analysis.

Selection of rational schemes of ore processing with maximum account of all information accumulated is essentially important with modern scopes of deposit mining and mass dressability investigations. It may be reliably guaranteed by application of an information retrieval system of ore dressability since subjective experience of a researcher is not always adequately full.

A variety of scheme modifications can be made up based on existing methods. The schemes will differ in the operation order and the operations proper. In this connection there appears a necessity of preliminary substantiated choice of schemes due to be checked up with a view to shortening a stage of experimental study. There are no definite rules of scheme selection, a correct choice depends on researcher's experience, availability of information on methods and techniques of dressing similar raw materials, achievements in dressing technology in general.

An *apriori* estimation of dressability which affords prediction of possible processing scheme and process parameters can be made based on application of

information on dressing practice and process investigation of similar ores as well as on patent information in order to establish the most promising directions of studies.

A considerable statistical and experimental material on a majority of industrial minerals, operation of concentrators and research laboratories which is generalized and input in computers will permit several scheme variants to be marked from which one scheme is selected and tuned.

With mineralogical analysis data available, it is possible to apply scales of mineral dressability by different existing methods: gravitational, magnetic, electrostatic, flotation and hydrometallurgical. Minerals distributed based on properties applied in dressing by any method affords them to be grouped so that the minerals which will be selected to an individual product on this or that machine will turn out to be in one block. A differentiated classification of minerals by floatability can be used in the basis of a flotation dressing scale. Each scale should be superimposed by a number of conditions, restrictions and characteristics corresponding to each method, machine or economic factors. Three main variants in dressability may be chosen: as much as possible full extraction of one valuable component, selection of maximum quantity of barren rock at minimum grinding rate or maximum extraction of all valuable components to bulk concentrate with maximum separation of barren rock. The operations enlisted below are chosen for each of the variants.

By analogy with the task posed it must be pointed to the gains of *computer diagnostics* and information retrieval in medicine which object is a human organism: a system, in any case, no less complex than ore deposits. When applying to medical diagnostics practice, two main distinctions of the system under examination must be borne in mind: (a) in ore dressability diagnostics optimization is established by the task not to omit an effective dressing circuit even in case experimental scope is enlarged by check-up of a large number of schemes, (b) in ore studies statistical sampling is substantially narrower with a smaller number of diagnostical symptoms than in medicine.

A unique character of a majority of deposits makes it problematic to give an accurate ore identification by mineralogical and petrographic properties and dressability. Availability of a large number of symptoms and mineral properties unidentified during routine mineralogical studies has a substantial effect on their behaviour in dressing. The role of genetic mineral peculiarities are more than once stressed in dressing studies. Moreover, there are no standardized methods for dressability studies which permit results of all investigations to be applied as initial information for diagnostics.

Diagnostics practice in medicine, machinebuilding, biology makes it possible to give shape to basic concepts also in mineral processing technology. First of all, an computerized system of technical diagnosis must not exclude a man and his subjective experience from the process of decision-making but on the contrary must be developed based on man-machine dialog in which the machine is entrusted with retrieval of information in accumulated practice memory, computations and sampling of possible variants according to the rules of combination theory.

Accordingly, the diagnostic process must be constructed as a dynamic procedure including primary diagnosis and recommendation on preliminary investigations, clarified diagnosis with account of results of these investigations, detailed investigations, final diagnosis and making of design solutions.

Different *optimization criteria* which are responsible for each stage logics are put forward at different stages. At the last stage diagnostics is incorporated as a constituent part into the development of a process control algorithm depending on disturbing actions connected with possible deviations in quality of entry material. This circumstance gains a particular value owing to the modern trend of simultaneous engineering of process flowsheet and computerized process control for the flowsheet.

The most significant aspect in constructing the diagnostics system is arrangement of algorithm self-learning, i.e., deliberate improvement of diagnostics quality as experience is accumulated by the diagnostics system.

The technical diagnostics subsystems to be examined are as follows: accumulated memory which generalizes process experience gathered, logical-mathematical search of possible schemes by preset parameters of material or composition, computation of statistical dependences, material balances and dressing flowsheets.

First of all, initial information on material composition and ore dressability must be formalized in order to be input into the computer memory. One memory section is given to a coded list of minerals encountered in industrial deposits. Each mineral has correspondence to certain physical properties used in dressing processes, namely: density, magnetic susceptibility, conductivity, luminiscence, radioactivity, etc.

During description of a particular deposit codes of appropriate minerals, mineral content in a sample and impregnation size are input into the computer. Each impregnation type is in line with a certain list of processes and assessment of possible recovery rate when different dressing methods are applied.

According to dressability scales, material composition of ore is analysed, yield of fractions and mineral content in them are computed depending on content in original ore and granulometric composition of ground ore. Dressability scales are made up only for gravitational, magnetic and electric dressing processes. Mineral floatability class and bulk concentrate yield are established for flotation processes.

In many cases flotation extraction of minerals depend not only on floatability of this or that mineral but also on composition of associate components as well as on genesis, impregnation, availability of isomorphous impurities in the mineral and other factors. All this significantly complicates study of ore dressability, choice of modes and agents.

Main and auxiliary flotation collectors and controllers which application promotes transition of mineral to foam or chamber product are chosen in accordance with the mineral floatability table. After agents are chosen, several agent modes for investigations are elaborated.

The second diagnostics task is search of a precedent of dressing ore of this type acknowledged in industrial practice or dressability studies. With this view in mind encoded parameters of material composition of familiar ores are compared with relevant parameters of new ore composition. For this first of all a genetic deposit type is defined, and then an analogue is found within this type scope.

Statistical analysis and computing methods of evaluating process indicators according to balance models can be used, with system operation practice accumulated. In the first place, equations of interrelation between content of certain components in ore and recovery of metals to concentrates can be constructed for some ore types.

The block-diagram of the apriori selection of ore dressing technology is shown in Fig.4.23.

The pattern of technology selection is grounded on data of geological and mineralogical sampling which include mineralogical characteristics with structure-texture and quantitative parameters indicated (mineralization nature, ore and nonmetallic mineral composition, mineral content, impregnation type and size, granulometric composition).

Further on genetic class and ore formation type together with mineral complex are identified by geological data. Existing and promising methods of dressing the ore are identified and prototypes of similar ore dressing are found by formation in accordance with the table named "Genetic types of ore formations, minerals complexes and dressability".

Within the genetic type, completeness of coincidence of new ore and the precedent may be assessed by two parameters: congruence of percentage of unextractable minerals in ore, for example, with an accuracy of up to 90 %, and list of extractable minerals. A precedent retrieval algorithm must be tuned during system operation and assessed by statistical indicators of connection between material composition parameters and potential process flowsheets. Most probably, there may be applied methods of pattern recognition, initial state and method correspondence graphs, linear decision functions.

In parallel to genetic formation analysis, mineral complex dressability is studied which includes analysis of minerals introduced into the complex by scales of dressability by gravitational, magnetic and electric methods, evaluation of potential of dressing by special methods based on physical properties of minerals (emissivity, lustre, colour, transparency, radioactivity, luminiscence, hardness, fragility, shape, etc.). In accordance with the floatability table, a floatability class is selected, and main and auxiliary collectors, foamers, controllers and modifiers are chosen which application promotes ...

A technology is predicted based on apriori data obtained and several process flowsheets for experimental check-up are chosen.

When promising methods of dressing ores of similar composition are examined, recommendations on application of methods of intensifying existing dressing processes are elaborated.

Examples of generating scheme variants are outlined below.

Example 1. The genetic type of the deposit is endogenic, magmatic, liquation, copper-nickel sulfide ores. The initial information on ore is given in Table 4.21.

Table 4.21. Characteristic of copper-nickel ore

Mineral	Content, %	Impregnation	Note
Pyrrhotite	9.8	Aggregates of irregular shape, some part of rounded shape 0.05-3.6, sometimes to 5 mm, 0.07-0.126 mm predominate	Intergrowth with chalcopyrite and ilmenite; ilmenite inclusions: 0.042-0.8 mm
Chalcopyrite	1.1	Segregations of irregular elongated shape, sometimes veinlets. 0.017-1.44 mm; 0.02-0.05 mm predominate	Intergrowth with pyrrhotite, sometimes with ilmenite
Pentlandite	0.71	Xenomorphic segregations: .02-0.04 mm bands; flame-like segregations: 0.016-0.07 mm, 0.01-0.03 mm dominate; nest aggregations along the margins of pyrrhotite : 0.02-0.05 mm	Segregations are confined to cracks in pyrrhotite grains
Ilmenite	4.9	Grains of rounded laminated shape: 0.084-2.3 mm, 0.2-0.4 mm dominate; 0.08-	Ilmenite grains are corroded with pyrrhotite

		0.25 mm in nonmetallic rock	
Magnetite	0.2	Grains from hundredth parts tp 0.36 mm	Closely associate with ilmenite, more seldom with pyrrhotite
Pyroxenes	61.12		Fine impregnation of sulfides
Micas	9.24		
Feldspars	0.95		
Galenite, sphalerite, pyrite	Below 0.5		
Serpentine	0.56		Fine impregnation of sulfides
Amphiboles	0.45		
Barite	0.25		
Aggregates: pyroxenes, amphiboles, feldspars	9.73		

Figure 4.24 shows the distribution of minerals by density and magnetic susceptibility. It is evident that the group of sulfide minerals can be selected to a heavy fraction during separation for density of 3.8 g/cm^3 . Ilmenite, magnetite and a part of pyroxenes of close density which constitute the basic rock mass will be selected to the same group. Density separation is low-efficient because of fine impregnation of sulfides.

Magnetic method may be recommended only in final processing since nickel-containing pentlandite is not effectively separated from ilmenite and biotite. Large losses of pentlandite and chalcopyrite will take place during antecedent magnetic separation. Electric methods of dressing are not applicable in this case as well because of the similarity of electric properties of many minerals in the separable group and fine impregnation requiring very fine milling for opening of constituents.

Available minerals have no specific properties adequately manifested for special dressing methods to be applied, in particular, radio or photometric sorting, dressing for colour, lustre, etc.

Here an extract from the table of dressability of genetic ore types (formation *) regarding the applied dressing methods is given:

(a) flotation of bulk copper-nickel concentrate (xanthates, aerofloat, foamers, carboxymethylcellulose, copper vitriol, soda, trisodium phosphate, liquid glass) with bulk concentrate delivered to selection (with/out steaming at 80°C);

(b) bulk flotation with production of copper-nickel concentrate delivered to metallurgical operations,

(c) flotation of nickel minerals (ethyl xanthate, mixture of butyl and amyl xanthates, pine oil, copper vitriol, liquid glass, carboxymethylcellulose,

(d) magnetic separation with selection of pyrrhotite concentrate and downstream flotation selection of copper and nickel minerals, stage-by-stage selective flotation for production of copper and nickel concentrates.

Table 4.22 gives the extract from the mineral floatability table. Several plants of different countries are chosen as prototype plants at which sulfide copper-nickel ores are processed; the technological specification is presented in Table 4.23.

Table 4.22. Extract from mineral floatability table

Mineral	Collector	Foamer	Controller	Activator	Depressant
Pyrrhotite	Xanthates, alkyltrithiocarbonates. Oxidized fish oils	Aerofloat, OPSB, T-66, etc.	H ₂ SO ₄ H ₂ S Na ₂ CO ₃	CuSO ₄	
Chalcopyrite	Xanthates, dixanthatide, thiocarbonilide, thiophosphates, alkylsulfates, dithiocarbamates, dodecylsulfate. Minerecs. Cresyldithiophosphoric acids. Hydrocarbons (for large aggregations)	Pine oil, terpene oil, T-66, OPSP, cresyl acid, MIBK, etc.	CaO H ₂ SO ₃ H ₂ SO ₄	H ₂ SO ₃ AgNO ₃	Na ₂ S NaCN other cyanides, cellulose ethers
Pentlandite	Xanthates, dixanthatides, thiocarbonilide, thiophosphates, alkylsulfates, dithiocarbamates, carbons (for coarse aggregations). Minereks. Aerofloats 15, 25 at pH above 7	Pine oil, terpene oil, T-66, OPSB, pyridine bases. Cresyl acid.	CaO H ₂ SO ₃ H ₂ SO ₄	H ₂ SO ₃ AgNO ₃	
Pyroxenes	Oleic acid at pH 8-9. Soapstock (with aegirine flotation)				pH above 11 and below 7
Feldspars	Fatty acids, secondary aliphatic amines with C ₅ -C ₁₄ or their mixture. Oleic acid (after activation)			Rare-earth metal cations, fluorides	
Micas	Amines, petroleum oils, cresyl aerofloat, oleic acid with lead salts, hexadecylsulfate, indanes, alkylindanes		H ₂ SO ₄	Lead salts	Glue, starch, milk acid, tannin, etc.

Table 4.23. Technological characteristic of prototype plants

Country (plant)	Mineral composition of processed ore	Content in ore, %		Concentrate produced	Content in concentrate, %		Recovery to concentrate, %		Agent consumption, g/t	Brief outline of scheme
		copper	nickel		copper	nickel	copper	nickel		
Canada (Cenishi)	Chalcopyrite, pentlandite, NiOcontaining pyrrhotite, platinum, gold, silver, serpentine, asbestos, garnierite	0.76	0.5	Bulk copper-nickel	8.5	4.2	89.3	67.0	Isopropyl xanthate 130, daufros 140, guartek, 500, copper vitriol 190, pH 9-9.2 (without controller)	Main, two recleaner and three control flotation operations
Finland (Kotalahti)	Pentlandite (2-3%), pyrrhotite (5-7%), chalcopyrite (1.2%), pyroxenite, quartz, calcite	0.29	0.74	Nickel Copper	29.26	5.84	62.3	93.0	Sulfuric acid 6400, ethyl xanthate 59, TEB 129, lime 1060, CMC 43	Main bulk, two recleaner and control flotation; agitation with lime and dextrine, main copper, two recleaner and control flotations

Austalia (Kambalda)	Pyrrhotite, pentlandite, pyrite, chalcopryrite	Nickel Pyrrhotite United nickel	0.925	7.0 1.0 11.55	NA	NA NA NA	Ethyl xanthate 800, maize flour 400, sulfur for sulfurous gas 90, TEB 100	operations Magnetic separation; flotation of magnetic fraction with nickel pyrrhotite concentrate produced; treatment of nonmagnetic fraction by sulfurous gas and flotation of nickel minerals at pH 5.5
CIS	Pyrrhotite, pentlandite, chalcopryrite, magnetite, serpentine, talc, olivine, chlorite, actinolite, micas, calcite. Nickel silicate 15-20%	Copper-nickel	2-3	5-6	73-75	73-76	Soda 1020, xanthate 125, aerofloat 10-36, copper vitriol 10-55, CMP 400-540, iron vitriol 55	Intercycle, main, three recleaner, control and two middlings flotation operations

Note: NA - non-available..

Judging from the material obtained, it is recommended to extract copper and nickel minerals by flotation according to direct selective and bulk-selective dressing circuits using butyle xanthate and aerofloat, alcohol foamer, copper vitriol and soda as main agents, with downstream recovery of pyrrhotite by magnetic separation.

For additional tests it is recommended to study promising methods, namely, roasting of low-grade nickel ore in a reducing atmosphere in the presence of chloride, and flotation of additional recovery of nickel. Wood coke or hard coal and other matters of about 44 μm (65 %) on size with a consumption of no more than 3.5 % of ore weight can be used as reductants, with potassium or calcium chlorides used as chlorides. After roasting flotation is carried out, with addition of amyl xanthate, foamer, copper vitriol and a small quantity of coke fine for higher recovery of fine nickel and iron.

High-frequency treatment of nickel-pyrrhotite product in an electric condenser field is also proposed as promising investigation trend.

Two schemes of stage-by-stage selective and bulk-selective flotation, with downstream extraction of pyrrhotite for each scheme by electromagnetic separation, were elaborated as a result of the studies. Both schemes were applied to produce high-quality copper concentrates, copper-nickel concentrates suitable for either hydrometallurgical or pyrometallurgical processing, and high-quality pyrrhotite concentrates. Fig.4.25 (a and b) shows the process flowsheets of copper-nickel ore processing which were elaborated as a result of the experimental investigations/

Example II. The ore is represented by pyroxene-amphibole-garnet scarns and, to a lesser extent, mica shales with scheelite, wolframite and cassiterite in association with quartz (Table 4.24). The rocks have been intensively destroyed, being clay material in some cases. As to genetic type, the deposit is attributed to an endogenic group, a postmagmatic category, a scarn class, the formation of ore bearing scarns.

Table 4.24. Mineralogical characteristic of tungsten-containing ore

Mineral	Content, %	Mineral	Content, %
Scheelite	0.3-0.7	Quartz	17.5-27.0
Wolframite		Dolomite	6-9
Tungstite		Pyroxenes	4-5
Cassiterite		Hornblende	2-5
Hematite	0.2-2	Actinolite	0.5-2
Magnetite	1.5-5.7	Amphiboles (alk.)	0.5
Fluorite	7-8	Garnet	4.5-6
Muscovite	3-6	Calcite	4.4-4.5
Chalcopyrite	0.2-0.5	Fluorite	0.5-2
Pyrite	1.5-3	Siderite	1.5-3
Sphalerite	0.5-0.6	Phlogopite	1.5-2
Arsenopyrite	-0.9	Biotite	2-5
Iron hydroxides	2-9.8	Feldspar	1.5

The distribution of minerals by density and magnetic susceptibility is indicated in Fig.4.26 where it is evident that the separation for density of about 5.5 g/cm^3 will permit selection of arsenopyrite, wolframite, scheelite and cassiterite. However the efficiency of this separation will be low as the valuable minerals among them scheelite, are grouped in very fine fractions. When separated for magnetic properties, three products can be selected. Magnetite will go to the magnetic fraction, while wolframite, siderite, chalcopyrite, hematite, iron hydroxides which have medium and low magnetic properties can be separated to an individual product. A part

of biotite, amphiboles and b\horblende, together with ferruginated garnets will be also extracted to the same product. The other minerals will go to the nonmagnetic fraction.

As there is a considerable amount of slimes in the ore, a magnetic method can be recommended only at the stage of final dressing operation. Electric separation applied as a rougher dressing method will be also inefficient for the same reason.

Below is given an extract from the table of dressability of genetic ore types in recovery of iron-containing minerals.

Washing, magnetic separation: oxidizing roasting with downstream recovery of copper by leaching-precipitation-flotation process (xanthate, flotation oil, pine oil, lime). Extraction of tungsten-molybdenum-minerals: table separation, flotation of molybdenum, flotation of sulfides, flotation of scheelite (oleic acid or substitutes, kerosene, soda, wetting agent D-40, quebracho, steaming (liquid glass). Jet flotation of scheelite. Flotation of scheelite from barite (alkylsulfates in acidic medium). leaching of apatite and calcite (industrial HCl), lime neutralization, lime residue is delivered to soda pressure leaching.

Table 4.25 shows the extract from the table of mineral floatability.

Table 4.25. Extract from table on floatability of minerals

Mineral	Collector	Foamer	Controller of medium	Activator	Depressant
Scheelite	Oleic acid and soaps in alkaline medium, alkylsulfates after activation in acidic medium, dodecylammonium chloride. Unsaturated fatty acids with carbon atom number of 20-24 and soaps, products of condensation of fatty acids with organic amine-containing acids, taurine, etc.	Terpineol, aerosol OT (with carbon acid emulsion)	Na ₂ CO ₃ Na ₂ SiO ₃ NaOH	Lead cations during flotation with alkylsulfate, zinc cations at pH 7, aluminium cations during flotation with amines, pH 2-12, steaming with liquid glass	Na ₂ S ₂ O ₃ NaFe(CN) ₆ Na ₂ AsO ₄ Na ₂ CrO ₄ polyphosphates and potassium iodide during flotation with amines, lead cations at pH 2-6
Wolframite	Oleic acid at pH 7 and 10, alkylsulfates, Cupferron, petroleum oils	Alcohols, OPSB	Alkalies, soda, sulfuric acid	Bivalent manganese salts	Na ₂ SiO ₃ in flotation with alkylsulfate, iron vitriol
Cassiterite	Fatty acids at pH 7-8, alkylsulfates at pH below 6, long-chain alkylsulfates, primary amines and tetrasubstituted ammonium salts at pH above 11	Alcohols, cresol, etc.	Smoothed water, liquid glass	Drying, desliming, acid washing	H ₂ PO ₃ , CaO, NaOH metaphosphate, tannin, nitrates, salts of iron, lead, copper, barium, etc.
Hematite	Fatty acids, tallow oil,		Soda, sulfuric acid	Phosphate,	Liquid glass.

	petroleum sulfonates, alkylsulfates, vetluzhsky oil, monononyl or dinonylphosphoric acids and salts in flotation from quartz, naphta soap			polyphosphate of sodium. Desliming	Fluorides, starch, cations of lead, manganese, copper, ligninsulfate
Magnetite	Carboxylic acids and soaps, tallow oil, petroleum sulfonates, dodecylamine, vetluzhsky oil		Soda, sulfuric acid	Lead nitrate	Aluminium intrate, zinc sulfate, iron cations, lime, starch
Fluorite	Fatty acids and soaps, alkylsulfates, aerosol OT, aerosol MA, cationic agents		Soda	Phosphate of sodium, polyphosphate	Liquid glass, starch, fluoride, hydroxyl ion, cations of heavy metals
Muscovite	Fatty acids, amines (pH 4-6), indanes, alkylindanes: additional collectors in flotation with aliphatic amines		Sulfuric acid	Lead nitrate	Startch, glue, milk and tannin acids, aluminium sulfate
Chalcopyrite	Xanthates, dixanthogenides, thiocarbanilide, thiophosphates, alkylsulfates, minercs	Pipe oils, terpeneol	Lime, sulfuric and sulfurous acids	Sulfuric acid	Sodium sulfide, cyanide, OH ion, mixture of $ZnSO_4$, Na_2CO_3 , $Na_2S_2O_3$, SO_2 + NaCN
Pyrite	Xanthates, aerofloats, fatty acids in acidic medium	Pine oil, ONSB, OPSM	Soda, lime, sulfuric acid	Na_2S , Na_2CO_3 , H_2SO_4 , Na_2SiF_6	CaO , NaCN, Na_2S , $Na_2Cr_2O_7$, $KMnO_4$, K_2CrO_4 , cellulose ethers
Sphalerite	Xanthates,	Pine oil, pyridine	Lime, sulfuric and	Copper vitriol, cations	Sodium sulfide,

	dithiocarbamates, dioxanthogens, aerofloats, mercaptocarboxyl acid ethers, amines, crude tallow oil, aeropromoter 3477	bases, OPSB, OPSM, etc.	sulfurous acids	of silver, lead, antimony	cyanide, sulfurous gas, Congo red agnet
Arsenopyrite	Xanthates	OPSB, etc.	Soda, copper vitriol, alkali	Copper vitriol and mixture with alkali	Lime at pH above 11, oxygen, potassium manganate pH above 11 and below 7
Pyroxenes	Oleic acid at pH 8-9, soap stock				
Quartz	Fatty acids and naphtene acids, amines	Alcohols, pine oil	Alkali, liquid glass, sulfuric acid, hydrofluoric acid,; peeling	Cations of calcium, ironm aluminium, iron and aluminium sulfates	Liquid glass, cyanide
Dolomite	Oleic acid at pH above 10, alkylsulfates	Pine oil, alcohol foamers	Lime, alkali, soda, liquid glass		Alum, starch, mahogany extract, calcium chloride

A plant at which scarce tungsten-molybdenum ores are processed is chosen as a prototype. The dressing schedule includes a molybdenum and tungsten cycle which is composed of rougher, six cleaner and five control operations. Coarse scheelite concentrates are finally processed with steaming by liquid glass. The following agents are used: in the molybdenum cycle - soda, butyle xanthate, transformer oil, kerosene, terpineol, sulfurous sodium, cyanide, liquid glass; in the scheelite flotation cycle - soda, oleic acid, liquid glass which is supplied to the first cleaner operation and steaming.

Copper, molybdenum and three scheelite concentrates are produced at the plant. The recommendation made on the basis of the information obtained is to apply flotation separation of ore with preliminary extraction of sulfides and the tungsten-containing minerals using downstream magnetic separation for selection of iron concentrate.

It is proposed for supplementary studies to check potential methods, for example, selective flocculation and flotation of ultra fine scheelite (below 10 μm in size). This method involves flocculation of slurry which density is 0.2 or 1 % of solid with $6 \cdot 10^{-4}$ M of sodium oleate and 10^{-4} M of sodium silicate at pH 10 for 1 h with an agitation velocity of 700 rotations per minute and flotation with preliminary slurry conditioning for 2 min with foamer supplied. In accordance with the studies scheelite recovery is about 80 % (uncollected: 20-30 %).

When the stage of additional extraction of cassiterite from the ore is included into the investigation program, it is recommended to apply the collector of ether phosphate or its salt of alkaline, alkaline-earth metal or ammonium $(\text{RO}(\text{C}_n\text{H}_{2n}\text{O})_m) - \text{RO} - (\text{OH})_{3-x}$, where R is the hydrocarbon radical of $\text{C}_8\text{-C}_{20}$, n is 2; 3 or 4; m is from 1 to 8; x is the mean statistical value in the range from 1 to 2. The preference is given to compounds with hydrocarbon radical including lauryl, oleyl, cetyl or stearyl group. The collector concentration depends on tin content, being in average (in mg/l) from 0.01-0.2 part of initial tin content, i.e., with 10 % tin content in ore the collector consumption is $10 - 0.01 = 0.1$ and $10 \cdot 0.2 = 2$, or from 0.1 to 2 mg/l.

4.8.4. Mineralogical Typification and Ore Dressability

Mineral composition varies virtually at any deposit in some areas to some extent so that certain horizontal and vertical zonality can be identified. The zonality is expressed in a regular change of different ore minerals, alteration of quantitative ratios between them and rock-forming minerals, sometimes in variation of mineral forms of identical ore elements, changes in ore structure and texture, ore impregnation size, different impurity elements emerged in minerals. Naturally, ores from different deposit areas will behave in the technological process in a different way.

It is approved to identify certain *ore types* by mineral composition based on preliminary technological studies. However average samples present the ore of the entire deposit incompletely. The ore from different areas will be delivered to the plant at different times. The technology will have to be modified as applied to changes in ore composition as the ore will be delivered from deeper horizons or from the deposit flanges. Changes in ore composition or processability lead to a dramatic fall in recovery rate or in quality of the finished product.

In this connection it is necessary to establish a spatial distribution of different ore types and their quantitative ratio together with structure-texture peculiarities and,

ultimately, their processability. This can be done by means of detailed mineralogical volumetric mapping, working-out of mineralogical (ore mineralogical-petrographic) and mineralogical-technological maps and plans.[99].

In detailed geological mapping mineralogical-petrographic maps are made up in cases when several mineral parageneses with which different ore minerals can be associated may be identified at the deposit. If the deposit contains several ore minerals differing in processability it is required to make up maps showing distribution of individual ore minerals. For example, at the Tyrnyauz scarce tungsten-molybdenum deposit, besides scheelite, molybdenoscheelite which behaves during flotation otherwise as compared with scheelite.

It is also necessary to define availability of components harmful to technology, besides basic ore minerals, for some deposits. For instance, when deposits presented by silicified, sericitized and chloritized granophyres with polymetallically rare-metal mineralization are mapped, it is important to know the amount of random siderite and its spatial distribution because it gets into the ore concentrate, a great quantity of iron oxides and hydroxides hindering the routine operation is generated during sintering of siderite with soda and downstream leaching. When deposits presented by rare-metal granates with tantalum mineralization are mined, it is also required to be in the know of amount and distribution of random wolframite since it gets into one concentrate with columbite-tantalite.

Besides identification of composition and number of useful ore and harmful minerals as well as total mineral rock composition, it is of value to get familiar with size of ore impregnation and regularity of impregnation variation in space.

The results of mineralogical mapping can be used technological evaluation of deposits. Microtechnological tests of mineral products and ore dressability studies can be carried out directly in situ on small-volume samples.

Small-volume technological trials and mapping include a complex of investigations of spatial variability of material composition, physico-mechanical and processing properties of ore which is performed on a considerable (tens or hundreds) number of process samples small in weight. The samples may be presented by group prospecting specimens weighing up to 50 kg which are selected from drill cores or channels during opening sinking. These studies are carried out at the detailed prospecting stage when main ore types have been identified and dressing schedule and mode concepts have been elaborated based on representative samples. The dressing schedule is checked up and the variability of processing properties of the ore from different areas and deposit horizons is identified on small-volume group samples taken uniformly over the prospecting pattern. The spatial reference of indicators obtained on these small samples and tailored to the mineral composition affords spatial location and mapping of technological ore grades differing in dressability.

On identification of different types and geometry of ore the cases depicted below are possible.

1. The ore of all types identified in mineral composition is dressed according to one schedule, and concentrates produced are processed according to one scheme. In this case all mineralogical-petrographic types belong to one technological type of ore.

2. Mineral ore types behave differently during dressing processes while the process flowsheet is developed for the medium-composition ore. Under these

circumstances it is required to blend ore of different types in the relevant ratio so that the ore of medium composition enters the plant.

3. The ore of different types is dressed according to one schedule, with the concentrates processed variously. It is necessary to separate the ore of different technological types for their selective final processing. Concentrates of different ore types are processed according to different technology.

4. The ore of types differing in composition is dressed according to different schedules. The ore of different technological types must be mapped in order to provide for selective processing.

5. The ore of some types cannot be dressed and processed at all. It should be mapped, and the reserves must be attributed to the off-balance ones. If the ore of these types is located inside the ore outline this must be taken into account by introduction of ore content ratio during calculating reserves.[56].

If ore types differ in quantitative ratio of extractable components, a spatial mathematical model of the deposit can be constructed. Sometimes a similar model is composed for the deposit under mining, and parameters of processing ore from different areas are accumulated in the model of dressability of the deposit which affords prediction of dressing results, optimal make-up of ore charge, presetting of the process for a certain ore type, etc.

Variable material composition of ore provokes a lot of problems in process control at concentrators which mode is preset for a certain medium composition and a certain ratio of mineral components.

Ore composition is the key uncontrollable factor in the vector of dressing process disturbances. Heterogeneity of ore mass to be processed prevents an optimal dressing process mode from being kept. Essential variations in ore quality have a negative effect of dressing parameters, and deviations of metal content in concentrates in turn impair metallurgical process indicators.

Owing to the above a trend towards maximum blending of initial material has emerged in plant engineering. When the process mode is made more stable, it brings about a great effect because losses connected with the non-optimal “medium” process mode for each particular ore type are reduced.

From the other hand, a technological process optimal for this ore type brings about some effect in comparison with the “medium” mode for the blended ore. In so doing, there is a particular ratio of optimums of selecting technological types and their blending which depends on the approved control system and frequency ratio: changes in initial ore types and possible resetting of the process.

From this viewpoint the problem of ore typification for the deposit is governed not only by geological-mineralogical variability of the deposit but the available process control system as well. If there is one process flow at the plant without in-line ore type detectors, the possibility of recognizing technological ore type is extremely limited, the resetting of the process once in several months predetermines a very rough differentiation of ore types and a necessity of maximum blending during mining. If there are several process flows in which individual ore types can be processed together with a possibility of differentiating ore types in-line, higher process parameters may be achieved than for the blended ore.

Process experiments on dressability of ore samples with definite typomorphic differences have become of great value from the viewpoint of technology as well as for establishing some purely mineralogical regularities in a number of control cases. These studies aimed at geological-technological mapping and development of process control systems at a concentrator with an in-line ore type change are correspondent with definite mineralogical peculiarities for the most part isomorphic and morphological. Statistical methods widely applied in similar studies afford establishment of factor relations between mineral parameters and optimal dressing mode. An effect of physical actions on mineral properties (magnetic, electric, chemical) is of unique value. Magnetizing roasting of oxidized iron ore, thermal decrepitation of lithium ore, chemical and bacterial leaching of copper, uranium and other ores have been developed. A temperature effect on decarbonization of minerals is made use of in processing of phosphorites and some other calcite-containing mineral resources, in particular, tantalum-niobium ores.

Of the greatest effect are the variability of mineralogical and texture-structure parameters of ore on flotation process, and the influence of crystallochemical peculiarities of minerals, isomorphous impurities, conductivity type on mineral interaction with flotation agents and floatability.

The notion of ideal crystals cannot be a model of adsorption of chemical agents by actual minerals. Genetic mineral peculiarities responsible for concentration, composition and charge of isomorphous impurities, vacancies and structural defects of other types along with physical and physicochemical properties have a decisive effect on flotation.

Variable floatability of mineral variants is connected with genetic and processing properties. A significance of redox processes in adsorption of flotation agents, and participation of defects in adsorptive processes affecting flotation were defined. Processing properties and selective flotation of minerals can be controlled by means of chemical, electrochemical, thermal, radiation and other actions.

We shall examine the possibilities of flotation process control based on *identification of type modifications* exemplified by the Norilsk copper-nickel ores.[99].

The compact copper-nickel ores polymetallic in composition. The essential minerals of the ores are pyrrhotite (*Po*), chalcopyrite (*Cp*), talnakhite (*Tlh*), moihukite (*Mk*), cubanite (*Cub*), pentlandite (*Pnt*). The minerals encountered in various combinations compose sophisticated natural associations each of which features specific inherent content of valuable components and forms of segregation of carrier mineral of these components as well as different set of valuable minerals of each component. If chalcopyrite, talnakhite and moihukite are comparatively close in copper content, cubanite is approximately half as lean as again that. The above copper minerals have different physical properties. In accordance with the proven process flowsheet of flotation dressing the minerals are arranged in floatability as follows: the *Cp*, *Tlh*, *Mk*, *Cub*, the *Pn* nickel minerals, nickel-bearing pyrrhotite, pyrrhotite.

The ores of various mineral associations within each deposit compose the complexly built beds and sizable bodies. Five mineral types of the ore are distinguished among the compact ores of deposit I. They are essentially pyrrhotite, pyrrhotite-cubanite series, chalcopyrite and talnakhite-cubanite series, essentially chalcopyrite and mixed chalcopyrite-talnakhite. The composition of deposit II ores is somewhat more complex (Fig.4.27) but it can be reduced to similar groups: two primary - chalcopyrite-pyrrhotite

and essentially chalcopyrite (including the ore intensively enriched by chalcopyrite-like minerals of talnakhite, moihukite, etc.), and two other ones which present different stages of cubanitization of these ores. The deposit I ores are peculiar in that talnakhite and moihukite are more abundantly manifested, and that mineral compositions intermediate between pyrrhotite and chalcopyrite types proper are available.

Table 4.26. Statistical data on content of principal minerals in copper-nickel ore delivered to dressing

Mineral	Variation ratio, %	Correlation ratio					
		<i>Po</i>	<i>Cp</i>	<i>Cub</i>	<i>Pnt</i>	<i>Mt</i>	<i>Hp</i>
Pyrrhotite (<i>Po</i>)	16.3	1	-0.09	-0.26	0.54	0.11	-0.69
Chalcopyrite (<i>Cp</i>)	16.0		1	-0.28	-0.03	0.12	-0.31
Cubanite (<i>Cub</i>)	38.3			1	0.01	-	-0.24
Pentlandite (<i>Pnt</i>)	13.8				1	0.04	-0.59
Magnetite (<i>Mt</i>)	13.2					1	-0.18
Nonmetallic (<i>Nm</i>)	32.1						1

Note: Correlation ratios differ from zero with a reliability of 0.95 at the absolute value $r \geq 0.26$.

The studies of pyrrhotite ore mineral composition of both deposits showed that the high variation ratio of mineral content is preserved in the slurry. The multiphase nature of distribution curve series (Fig.4.28) and the absence of correlations among individual mineral content prove different types of technological mixtures.

The mineral composition of daily ore delivery was studied using methods of taxonomy and principal components. The studies showed that despite random character of actual mixtures their totality is broken to four steady and one intermediate types of technological associations (Fig.4.29). The comparison of average figures and standard deviations testify to their substantial diversity in symptom space and distribution density close to normal in all associations.

In order to interpret associations the mineral composition of all samples transformed by the method of principal components was presented as a component diagram in the plane of two weight-first factors showing the main portion of the system dispersion (Fig.4.30). It is evident that the factor structure is close to that for natural types (Fig.4.29) but is not identical.

It was found that association II may be approximated with a natural pyrrhotite body, association III is a mixture of the latter with chalcopyrite and talnakhite-moihukite ores while association IV is a mixture with cubanite-pyrrhotite ores. Association I is the most intimate mixture of all natural types. The component diagram also manifests that the leading internal trend in all the associations is connected with impoverishment by nonmetallic minerals but is accompanied by some antagonism of pyrrhotite and cubanite together with greater pentlandite importance in the two first associations, and another

trend transversal to the above one which is predetermined by antipathy of cubanite against chalcopyrite and magnetite.

That the above associations are technologically expedient to be identified is confirmed by the fact that their replacement in time takes place gradually. The examination of decade deliveries display that they are fairly uniformly presented by the three first associations (Fig.4.31). The fact that there is no association IV in the examined period can be explained by processing of less cubanite ore but one cannot disregard its possible appearance. The studies by the method of canonical correlation permitted an evaluation of significant correlation between databases of technological associations identified and dressing parameters (0.53).

It means that the conventional statistical approach to simulation of connection between the material composition and the dressing mode is unsuitable for dressing process control.

At the first stage the control system must rest on identification of technological-mineralogical types and on content of chemical elements at the second stage, especially in ores of complex composition, when the ore may have different dressability with identical content of some element.

Ore type is recognized not by regressive dependencies on element content but by identification of component ratios. This identification, as evident from Fig.4.30, can be fairly clear.

In so doing, the results presented can be the basis for improvement of a computerized system of flotation process control using a mathematical model. Natural factors, besides technological ones, will be incorporated into the model. This will permit to find the most profitable values of controlling actions with a view to achieving optimal process parameters in real time under the conditions of varying types of technological associations. Interactive process control will afford in-line transformation of correlative ore quality function with low-frequency oscillations excluded, hence possible stability and higher dressing parameters are achieved.

4.8.5. Structural Peculiarities of Concentrators

A sophisticated problem in many unknowns is to develop an efficient and economical dressing schedule. This calls for an attentive comparison of many often-contradictory data as well as an experimental study. The difficulties of this study is associated with that a complex of dissimilar minerals having variants and different compositions even within one deposit. Here allowances must be made for comprehensive dressing with output of several concentrates or one concentrate of minerals differing in properties but containing one and the same element.[11].

The presentday dressing methods offer a great number of schedules differentiated in operations and sequence. Bearing in mind that the possibilities of experimental schedule control are very limited, the preliminary justified choice is a vital constituent of the study.

The dressability study can be broken up into several successive stages when a definite objective interconnected with other stages is pursued by each stage.

The objective of the *first stage* is selection of barren rock maximum with minimum of crushing by any simple and cheap technique. This stage is necessitated by that

when a deposit is mined by high-productive methods (open-pit working, bulk caving system, placer opening) a considerable amount of rock contains no valuable minerals. The dump tailings of the first dressing stage are perceived to contain no more valuable component than tailings of a concentrator without a similar preliminary dressing operating. However higher-grade tailings of the first stage may be economically justified since the high concentration rate at this stage not only substantially lowers the overall processing costs but permits higher recovery rate to be attained in downstream operations as well. Gravitational dressing processes are for the most part applied at this stage. They are heavy-media separation, jigging, sluicing (and dressing in other machines as well), sometimes magnetic separation, bulk flotation of sulfides, and, lately, bacterial leaching.

The objective of the *second stage* (sometimes it is the first one) is to prepare raw materials for subsequent dressing: maximum opening of valuable minerals with potential application of one or other dressing method.

Here it must be kept in mind, on one hand, potential losses of valuable components with slimes during grinding at next stages and, on the other hand, valuable mineral impregnation size. Besides grinding, the preparatory stage may incorporate magnetizing, sulfation or other roasting and conditioning of slurry prior to flotation (aeration, peeling-off, treatment with agents). The size of particles attributed to slime is a function of dressing method and mineral resource type: (3-1)mm in heavy-media separation, (0.5-0.1) mm in jigging, (0.1-0.05) mm in table concentration, (0.1-0.05) mm in magnetic separation, 0.1 mm in flotation. This stage affords the highest dressability of entry stock to be achieved by methods which will be applied at the next (third) stage).

The *third stage* of the study includes identification of an optimal dressing mode for production of rough concentrate. The objective of the stage is maximum recovery of all valuable components and the problem of comprehensive ore processing is solved. The parameters of dressing machines of rougher operations are evaluated in accordance with this objective.

The *fourth stage* is aimed at clarifying the possibility of producing finished products of preset quality (prime concentrates), type and mode of finishing operations are established, necessity and possibility of chemical and metallurgical methods to be used for processing of middlings.

Gravitational and magnetic methods are the simplest, most economical and fairly effective in case of mineral impregnation is not very fine. Of particular high production rate are gravity methods, like jigging, heavy-media and screw separator dressing. As a rule 6-8 mm material is dressed in heavy media, and 0.6(8) + 0.5 mm material is jigged. Gravity dressing of below 2 mm material is carried out in a stream flowing along the inclined plane (concentration tables, screw separators, sluices, cone separators, troughs, etc.). Off-shore sands, tin, diamond-bearing and rare-metal ores are dressed in screw separators. Jigging is one of the widely-used gravitational dressing methods due to fairly high efficiency with low capital investments and operating costs. Prior to jigging mineral product is usually deslimed. Jigging exhibiting definite advantages against heavy-media dressing falls behind the latter in dressing efficiency.

Gravity dressing methods are mainly improved by means of vibrations imposed or ultrasound applied which intensify the process by destroying structured suspensions. Here high stability of dispersive medium is provided, without delamination of weighting compounds (which is vital to heavy suspensions), and heavy fractions rapidly precipitate

as a result of lower medium viscosity. A number of new machines have been developed on the basis of vibrations: vibrating separator, vibrating sluice, vibrating concentrator; high-frequency vibrations and ultrasound treatment applied also increase efficiency of jigging and table concentration. There are proposed aerosuspension dressing and application of ultrasound in centrifugal dressing.[84].

Several innovative gravitational machines are offered. They are turbocyclone, shaking sluice, worm separator and classifiers of new design. There was an attempt to dress finer fractions by gravitational methods after pretreatment with flocculants.[84].

Magnetic separation is used in dressing of magnetic and low-magnetic ores. Dry magnetic separation and electric separation after dry grinding (aerophore, jet, ball-less) are very effective. Polygradient separation is also an effective method of reextracting low-magnetic minerals in dressing of rare-metal ores.[85].

Three directions of increasing efficiency of magnetic separation may be singled out: rise of separating forces (magnetic and centrifugal), higher field intensity, neutralization of surface forces causing adhesion flocculation.

Magnetic separation is heading in direction of new separators designed and new projects involved. As there is iron present in extractable or associate minerals the latter can have low-magnetic properties and be dressed in ultrasonic separators with high magnetic fields (for example, copper, asbestos, tungsten, cassiterite, kaoline, limonite and phosphate ores). Magnetic separation is more and more widely applied in finishing of rare-metal ore concentrates.

Full-scale separators with up to 20,000 Oersted intensity field have appeared. New designs are being developed, in particular, on superconductors in which field intensity can be an order of magnitude increased. This will permit wider range of ores to be dressed, higher accuracy and efficiency of separation.

Various designs of polygradient (ball) filter separators are being developed and put into practice.

New designs of a jet electromagnetic separator, a multi-stage separator with demagnetizing of material after each stage, a rotating double magnetic field separator for dry dressing of iron ore are offered. An electromagnetic hydrocyclone with a magnetic field concentrator which affords 8-9 times lower field intensity in iron ore dressing was tested.

Material dressability can be improved by reduction magnetizing roasting as well as processing in high-frequency magnetic field.

Magnetic flocculation on carrier with downstream magnetic separation of flocs is offered in dressing of fine fractions.

Separation in isodynamic magnetic fields where change in magnetic force affecting minerals is continuous in different areas of the working separator zone is applied (in laboratory conditions as yet) at present. Isodynamic electromagnetic separation is intended for parting of minerals in a magnetic field of required heterogeneity with an intensity maximum of about 18,000 Oe. The isodynamic field is provided for by a special configuration of pole tips. Minerals of 1 to 0.05 mm in size with similar magnetic susceptibility, for instance, olivine and pyroxene, glauconite and garnet, phlogopite and hornblende, hematite and staurolite, calcite and phlogopite, etc., can be separated. The material to be delivered to separation must be classified and dedusted.[85].

Innovative dressing methods are magnetohydrodynamic (MHD) and magnetohydrostatic (MHS) separation: processes of separating solid mineral particles for density, magnetic susceptibility and electric conductivity. The material is separated due to the effect of ponderomotive forces acting on the particles from the side of separating fields or liquids.

MHD separation is performed at joint action of crossed electric and magnetic fields on electrolyte owing to the ponderomotive Lorentz force appeared here. Electric current passes the electrolyte in MHD separation. MHS separation takes place when a heterogeneous magnetic field affects the paramagnetic liquid owing to the ponderomotive force of the magnetic field. Electric current does not pass the paramagnetic liquid in MHS separation. The process of separating particles in magnetic and ferromagnetic liquids and electrolytes may be used at considerable contrast of gravitational properties and small contrast of magnetic properties. Methods of magnetic and ferrohydrostatic separation supplant conventional gravitational processes in dressing of nonmagnetic ores from -20 to +0.2 mm in size because these methods have separating efficiency nearing the ideal one, and their application affords an order of magnitude higher productivity per unit of area.

Electric dressing methods may be used individually for direct dressing and in combination with magnetic, magnetizing roasting and other methods.

Greater efficiency of electric separation is achieved preliminary treatment of material surface, for instance, triboadhesive, mechanical and radiation effects. Another way is material treatment with agents, mainly organic surfactants: fatty acids, amines, milk acid, chloroacetic acid, etc. An electrostatic concentrator applied for fluidized iron and other ores is a promising version.

Nowadays flotation is applied for extraction of approximately one hundred of minerals (the total tonnage of processed mining products is more than 650-700 mln tonnes per year, besides coal and iron ore). Flotation is likely to keep its leading position in the non-ferrous metals ores processing technology. The application scope is widening. It is used in dressing of several metallurgical products, fly ash of power plants, chemical products, for treatment of waste water, soluble salts and even for separation of bacteria. New flotation types are being put into practice. They are columnar and foam flotation, electric flotation, ion and emulsion flotation, etc. which will widen the application scope of this dressing method.

Conditions of flotation separation of any mineral can be selected for any mineral complex in theory. Mineral floatability much depends on flotation conditions, fraction size, presence of other minerals, etc.[76,91,92].

Slimes of 0.05 mm in size are inefficiently dressed by gravitational methods, and flotation is the main method of dressing them. Techniques of selective flotation of slimes are different: some are grounded on aggregating assisted by flocculants, emulsions of apolar agents, agents, others are based on peculiarities of hydrodynamics. Relevant size of air bubbles is required to selective flotation of slimes. Special flotation cells, for instance, columnar machine, were developed. Besides, fine particles can be extracted by electric flotation. Aerofloccular flotation is a process which combines aggregating of particles and emanation of gas from solution.

The key trends of further flotation improvement are connected with higher selectivity and wider range of selectively floated particle size.

Control of flotation process and rise in its selectivity are based on detailed study of physicochemical composition of characteristics of slurry, different physical and physicochemical actions applied to slurry during preparation and flotation.[96].

The vital directions of the study are methods of supply, pretreatment and preparation of agents. Effective techniques are supply of agents to grinding plants, individual conditioning of sands and slimes, aerosol supply of agents with air to flotation cells.

Widely applied will be different ways of preparing ore, slurry and agents for flotation by means of physical actions: photon and radioactive rays, ultrasound effect and thermal treatment. In some cases thermal treatment permits better parameters of ore flotation. Pre-roasting is used for carbonate manganese and nodular phosphorites

Dramatic field of improving flotation technology is the study of particle size. Possible ways of flotation dressing of coarse particles and slimes are being looked for. The interrelation of particle size with adsorptive properties involves the necessity of elaborating unique modes of slurry processing with agents. The method of individual treatment of sand and slime fractions with agents and downstream joint flotation is the simplest and promising one.

Combined processing schedules, for example, flotation and hydrometallurgy, will be more often used as the size of floatable particles is reduced. Extractive flotation and ion flotation exemplify such combination of processes.

The value of agent form (molecular or ionic) and conditions of supplying agents, especially, slightly soluble collector agents, is identified, the latter are supplied in the most active and suitable form (emulsions, pastes) and in the form of combinations from two or more agents often belonging different functional groups.

Flotation results depend on a range of agents and their efficiency to a considerable extent. An agent mode improved by more purpose-designed (selective) agents applied permits reduced agent consumption and higher recovery rate and product quality.

Inorganic agents account for about 15 % (35-40 names). The problem of search for new and more effective flotation agents will remain one of the important tasks in future development of flotation. Progress in chemistry of complex compounds and physical chemistry allows a supposition to be made that already in the years ahead there will be elaborated the basic concepts of "designing" flotation agents (in particular, collectors) with required properties. Encouraging works in this field have been already conducted.

A great number of new agents, mainly collectors, is offered for flotation. Already known agents are being put into production, and their application scope is being widened. Among the latter there must be noted IM-50, polyethylene glycols, polyglycerin ethers, amines, various fractions of fatty acids and soaps, sulfonated petroleum products and other collectors, as well as depressants and controllers based on fluorides. Of interest from new agents are collectors as follows: butyl ethers of fatty acids for carbonate fluorite-quartz ores, hydrochloride thiuram-3-chlorobutane-2 for sulfide and gold-bearing ores. H-alkylsulfosuccinamates for cassiterite, sulfocarboxylic acids for apatite, chlorinated and dehydrochlorinated fatty acids for iron oxides, ethylene oxide for sulfide polymetallic ores, isoamyl ether of isonicotinic acid for gold and chalcopyrite, tallactam-6 for hubnerite, hydrogenated olefin products for coal and compounds based on furan series for polymetallic ores. Polyesters of different acids, ethers of monohydric and dihydric alcohols, etc. were patented as collectors.

Substantial changes have become evident in designing of flotation cells. Columnar flotation cells have several advantages in production rate and separation parameters as well as in convenience of additional slurry treatment in flotation process by different effects: magnetic, radiation, ultrasound, etc. Magnetic flotation with/out carrier had been tested in a columnar machine on manganese slimes and was a success. New designs of flotation machines are used for treatment of waste water using ion flotation of sediments and ultrafine particles. Machine elements (chamber shape, foam removal technique, impeller, etc.) are being modified. A specialized flotation cell combined with a hydrocyclone has been offered. [92].

Full-scale implementation of columnar ion, floccular, segregation, electrolytic flotation, foam separation, selective flocculation permits an expansion of size range for particles suitable for flotation dressing both towards size enlargement and towards slime flotation with simultaneous increase in recovery of valuable components from ores and their additional extraction from industrial solutions and waste water.

In the last decades extensive investigations on intensification of flotation process by imposition of energetic effects (electrochemical, vibrating, ultrasound, thermal, etc.) on flotation systems have been carried out.

Distribution of slurry flows in flotation flow has a great influence on dressing results. It was more than once intimated that yield of foam product in intermediate operations and division of flotation front between operations are of vital importance, sometimes even greater one than optimization of agent mode.

In engineering an optimal flotation cascade it is required to keep in mind heterogeneity of products in separability with identical compositions. In each particular case the relationship between composition and separability of middling product may be obtained experimentally or by statistical processing of trial results. Some required kinetic regularities, dependence of separation results on slurry flow passing the flotation cell, etc. can be also obtained by means of experiments.

Being aware of statistical data for a certain ore type, one can engineer a cascade adequately close to an optimal one. The control of this cascade at variable quality of entry material can be gained by redistribution of flows of middling products, foam and foamless, or by redistribution of chambers among stages. In this sense flotation cascade are more flexible than in other separating processes.

In so doing, optimal flotation schedules must be grounded, first, on calculation of flotation kinetics for each cascade step which depends on mode process parameters, floatability and flows; second, on minimum impoverishment of products during agitation in a flotation cascade (keeping in mind different floatability and not valuable component content).

Obviously there is an optimal distribution of flotation chambers among operations (rougher, cleaner and recleaner) when at the plant the recovery rate will be maximum with the preset concentrate quality. This chamber distribution is possible when products with close floatability are agitated at stages. An indirect indicator of optimal schedule layout with different distribution of flotation front among stages may be total recovery to prime concentrate at stable agent mode and entry material quality.

Optimization of the process arranged according to the concept of separating cascade is connected first of all with regulation of output and quality of flows produced at individual dressing stages. Product yield and quality are interrelated in dressing of ore

and coal materials. This relationship is characterized by dressability curve. Theoretically possible quality of products and recovery of valuable components can be evaluated for each output of dressed product. Dressing curves which pass a little below do not virtually coincide with dressability curves because flotation separation is less effective than heavy-media separation.[18].

In some cases output increase brings about a drastic reduction in concentrate quality at a small rise in output. In other cases recovery drastically grows with a small deterioration of concentrate quality. The most representative dressability characteristics are the function of material distribution by flotation activity and its parameters.

If the flotation kinetics of particular schedule stages is defined at the optimal agent mode, there is a clear flotation front optimal with these process kinetics in each operation, i.e., the number of flotation cells is distributed in an optimal way. Being ware of the content in the entry ore, an approximate recovery and concentrate yield with quality of foam product in each chamber can be estimated by the kinetic equation.[91].

At some flotation plants various turn schedules, jet flotation modifications, etc. were adjusted in practice. Evidently these schedules are efficient just in case they are nearer to the perfect cascade than the conventional ones. In turn it is established by ore nature, relative rate of different composition aggregate flotation, etc.

4.9. Interaction of Conversion Stages. Production Combination

The efficiency of a mine & concentrator depends not only on the ore extraction efficiency in the mining operations and the recovery rate for the valuable component at the concentrator but on parameters connecting the mining and concentrating operations. The recovery to concentrate, the concentrate quality, the prime cost of ore processing and especially the prime cost of the product made at the plant are substantially controlled by the original ore quality, in particular, by the valuable component content in the ore, impurities detrimental to the dressing technology, blending rate, sequence of delivery of various ore grades to the plant, etc. The ore quality is in turn rely on the parameters of mining operations. Here the prime cost of the run-of-mine ore is the lower the higher the impoverishment is. Ore standards are established with the help of economic & mathematical simulation. Of concern is the interaction of the mining and dressing cycles in the plane of setting up optimal parameters of ore impoverishment during mining, ore output and processing tonnage (the optimal production rate of the plant), evaluating allowable limits of ore impoverishment by impurities of barren rock, clay minerals, filling concrete, etc. In the majority of cases ore blending which can be performed both during mining and directly before dressing as well improves process parameters. If there is no in-line monitoring and process control blending permits the more appropriate selection of optimal processing conditions.

A prognostic dressability map for individual deposit areas is required in order to arrange blending in mining or ore output by grade (for establishing the optimal process dressing conditions for each ore grade).

Methods of rapid control of material composition are of vital value to dressing process control and better process parameters. Alongside this the methods also afford in-line control of mining operations. The joint examination of mining and dressing cycles

based on common economic criteria will make it possible to raise economic efficiency of mining & processing operations.

To link mining and dressing is especially promising from the viewpoint of economics and environment control. Among these processes one must intimate underground (in particular, bacterial) leaching, extraction of valuable components dissolved in marine water, dressing in a natural basin.

The multi-component composition of raw materials of virtually any deposit calls for such a combination of processes during processing which involves the most comprehensive (in number of extractable components) and complete (in recovery rate and utilization of components) processing of ore. It may be exemplified by combined dressing & hydrometallurgical processes which comprehensive ore processing is associated. Process flowsheets of a lot of concentrators fail to provide for recovery of all valuable metals as well as nonmetallic resources which are irrevocably lost in waste.

Several *types of non-ferrous and rare metals deposits* are distinguished.

(1) Within the industrial outline of deposits identified by a single ore mineral there are other useful minerals which can be extracted to selective ore bulk concentrate during comprehensive dressing. The examples of the like complex deposits are deposits of polymetallic ores, rare-metal pegmatites containing spodumene, beryl, tantalite and cassiterite, tungsten-molybdenum deposits containing beryl and zinnwaldite concurrent with wolframite and molybdenite. Of primary importance for involvement of similar complex deposits into industrial usage is the elaboration of an economically rational dressing circuit. Here it must be kept in mind that the majority of the like deposits can be profitably mined only if all valuable components are comprehensively extracted.

(2) In ore deposits there are minerals of not only iron and non-ferrous metals but nonmetallic minerals which can be employed by the industry. For instance, rare-metal pegmatites may be the source of ceramic materials, pyrochlore of lime and apatite, polymetallic ores of barite, etc.

(3) Ore mineral contains several valuable components. In this case all components which are further divided in metallurgical operations are extracted to concentrate as a result of dressing. These minerals may be exemplified by fergusonite, euxenite and priorite which contain rare earths of itrium group, niobium, tantalum and scandium; loparite which contains niobium, tantalum, rare earths of cerium group; phosphorites which contain uranium, rare earths, fluorite together with phosphate raw materials; sphalerite, which often contains cadmium, indium, germanium besides zinc. It must be noted that when establishing the industrial outlines of the deposit not only the principal valuable component but useful components which accompany the principal one as well must be incorporated.

The ratio between the costs of valuable constituents may vary in a wide range. Whether or not it is of necessity to extract valuable components is dictated by an economic estimate. In some cases the value of associate components is very essential (Table 2.27).

Relevant estimations must be made for each process flowsheet with due regard to shortage and significance of finished products, established wholesale prices, cost of individual process operations, etc. In some cases an innovative technology which affords a profitable extraction of all valuable components is required to be developed.

Table 4.27. Specification of some non-ferrous metal ore complexity

Ore type	Essential components	Associate valuable components	Percentage of associate components in total value of raw materials
Polymetallic	Pb, Zn,, Cu	S, Cd, Au, Ag, In, Te, Ga, Ge, Bi, Sb, Hg, Co, Ba, Se, Tl	38
Copper	Cu	S, Au, Ag, Cd, Re, Se, Te	44
Copper-zinc	Cu, Zn	S, Au, Ag, Cd, Se, Te, In, Tl, Ge	50
Copper-molybdenum	Cu	Mo, S, Au, Ag, Re, Se, Te, Cd	45
Oxidized nickel	Ni	Co	24
Sulfide nickel	Ni, Cu	Co, S, Pt, Pd, Ru, Os, Ir, Au, Ag, Se, Te	34
Bauxite	Al	Ga, V	15
Nepheline	Al	Na, K, Ga, Si	28
Alunite	Al	Na, K, Si, S, Ga, V	44

Combined processing of mineral products is a cross between methods and processes of derassing and metallurgy for more efficient separation of components.

This is achieved by combination of physical fields in one machine (a combined process) or in a straight-away arranged machine row (a combined process flowsheet). These dressing circuits as a rule include gravity separation (heavy-media dressing, jigging, screw separation, sluicing, etc.) and then magnetic separation or flotation. Similar schedules are applied in dressing of rare-metal ores (gravitation - magnetic or electric separation - flotation).

The most widely-used combined derassing processes are gravity flotation: table concentration (diamond ores), jigging flotation (rare-metal ores). Besides, magnetic field sorting (magnetite, titanomagnetite ores), flotation in magnetic, high-frequency current, vibration or ultrasound fields.

If prime concentrates cannot be produced by dressing methods or their combination, comprehensive processing with hydro or pyrometallurgical final operation is used. Hydrometallurgical final operation is performed by means of leaching of deleterious components from concentrates, for example, phosphorus or silica from iron, manganese, tungsten concentrates. Deleterious components can be also removed by the pyrometallurgical process (for example, concentration of useful components can be substantially increased by roasting of carbonatite ores due to CO₂ combustion. Roasting permits a change in magnetic properties of minerals (magnetizing roasting of oxidized iron ores) for downstream magnetic separation and floatability of certain minerals as well (phosphorites). A special pyrometallurgical flotation schedule is used in processing of copper-nickel ores. Another unique schedule of processing these ores is bulk-selective

flotation with nickel-pyrrhotite concentrates produced which undergo pressure oxidizing leaching with downstream flotation of sulfur.

Ion flotation belongs to combined dressing & hydrometallurgical processes. Combined schedules afford the highest recovery of valuable components from mineral products and purity of concentrates.

Elaboration of combined schedules does not mean a simple uniting of processes but requires their functions to be redistributed. For instance, advance in hydrometallurgy permits selective flotation circuits to be avoided and replaced by bulk flotation circuits because pure selective monometallic concentrates can be produced by hydrometallurgical methods, application of chloride sublimation during roasting to cement clinker (Waelz slag -?) brings about higher recovery of metals.

Chemical metallurgical methods can be applied for dressing of original ore proper and different dressing products as well as dressing tailings in some cases. These methods make it possible to solve many problems of complex utilization of raw materials and certain associated but essential problems, like extraction of valuable components from mine water and treatment of industrial sewage.

Different types of roasting (oxidizing, reducing, chloridizing, sulfatizing, carnonizing, etc.), different types of leaching, among them bacterial one, recovery of valuable components from solutions using ion exchange, extraction, ion flotation, etc.

The objective of roasting is to intensify the difference in properties of extractable components, transformation of this or that component into a more or less extractable form.

Magnetizing roasting is applied in dressing of hard -to-dress iron and manganese ores, calcination in dressing of phosphorite and rare-metal ores, chloridizing and sulfatizing roasting in dressing of hard-to-dress rare-metal ores.

Different types of leaching are of vital importance in chemical and hydrometallurgical methods of dressing. In particular, leaching of copper with downstream cementation and flotation are applied in dressing of hard-to-dress ores. Chemical and microbacteriological (bacterial) leaching are more and more widely applied in dressing of hard-to-dress copper and uranium ores.

The development of complex ore processing flowsheets must follow the way of linking the widely-used (conventional) methods of dressing with pyro and hydrometallurgy (sorption, extraction, flotation of sediments, reliminary roasting of ore with downstream dressing). In the progress of such flowsheets one may mark the following trends: primary dressing with dump tailings produced and downstream chemicometallurgical treatment of concentrates and middlings; production of prime concentrates and hydrometallurgical processing of tailings, bacterial, underground and heap leaching with downstream sorption, extraction and flotation of metals from solutions; preliminary chemical or thermal treatment of ores with a view of partial recovery of valuable components or their conversion to the state which provides efficient dressing.

Putting-into-practice of new hydrometallurgical methods of pressure leaching, sorption from slurries and solutions as well as combination of flotation and hydrometallurgy allows lower cost of processing of raw materials, solution of comprehensive processing problem, reduction of ore and concentrate deviations and avoidance of selective flotation.

As the scope of industrial application of hydrometallurgical technology in production of sulfide concentrates is widened, circuits of selective flotation will be replaced by circuits of bulk flotation with downstream production of pure selective monometallic concentrates by hydrometallurgy. In so doing, recovery of valuable components and complexity of utilization of raw materials will be increased and redundant operations at concentrators will be reduced. The routine practice of producing rich concentrates of copper, lead, zinc, tungsten, molybdenum and other metals with downstream pyrometallurgical processing is accompanied with substantial losses of metals with tailings. The higher the metal content in concentrate is, the greater loss of the metal with tailings. Since metallurgical engineers are in need of concentrates in which metal content is 50-70 per cent, If pyrometallurgical processing of rich concentrates is applied, metal content in slag remains to be higher than in the original ore, and the total metal losses are no less than 20-30 per cent.

A radically different process flowsheet is more efficient. Only the easy-to-dress part of valuable minerals can be extracted to rich concentrates. The ore residues are used for lean middlings to be produced which contain several metals and lean tailings suitable to production of building materials. The middlings, maybe, together with pyrometallurgical slags enter hydrometallurgical processing, and the entire complex of valuable components is stag-by-stage extracted from them. (Fig.4.32). Here the recovery rate in the dressing cycle is increased to 90-95 per cent, the recovery rate in the hydrometallurgical cycle is 95-98 per cent, and the total metal losses to waste are reduced to 7-20 per cent.

In this way there may be solved, for example, problems attributed to processing of the Ural copper-zinc ores: dumps of pyrite residues containing non-ferrous metals will disappear, the chemical industry will receive elementary sulfur instead of pyrite concentrates for production of sulfuric acid which will substantially simplify the production cycle at chemical plants, problems of atmosphere sanitation together with improvement of labour conditions and increase in labour productivity will be radically solved while recovery of essential and associate metals will grow 7-10 per cent, reaching 99-97 per cent in metallurgical operations.

The key concept of waste-free technology is extraction of complex of valuable components in one process. For example, the process of producing glass, cement clinker, ceramic tile, agglomerate and other types of building materials is connected with heating of material to 1200-1400 °C. Sublimation of a majority of metals as oxides or chlorides is possible at this temperature, it is required only to select appropriate additions to burden and install machinery for trapping of sublimates.

The ratio of metal losses during mining, dressing and metallurgical operations (Table 4.28) indicates that there is a definite interaction of total recovery and recovery at each conversion stage. Recovery should be optimized with due regard to the cost of material processing at each conversion stage.

Table 4.28. Recovery (%) of mineral resources (valuable components)

Mineral resource	Mining	Dressing	Chemico-metallurgical	Total figure
			1	

			operations	
Copper ores	92	87	96	77
Lead-zinc ores	90	80	95	68
Nickel ores	95	90	84	76
Tungsten-molybdenum ores:	95	76	-	72
W				
Mo	95	83	-	79
Tin ores	92	64	96	57

In connection with drastic sharpening of ecological problems environment control is an essential requirement to the technology of mineral processing. From this viewpoint on must consider the most promising schedules those with closed water circulation and development of waste-free dressing technology with complete utilization of the entire raw materials entering the process. Problems of water treatment with associated extraction of valuable components and organic impurities gain a primary value.

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