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METALLOGENESIS AND MINERAL ORE DEPOSITS

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PREFACE

The leading scientists in the many different fields of geology were invited by the Organizing Committee to present a paper on a specific problem in present-day geological science at the 27th International Geological Congress. The published proceedings of the Congress consist of twenty-three volumes. Each volume is dedicated to a particular aspect of geology. Together the volumes contain all of the contributions presented at the Congress.

The Organizing Committee is pleased to acknowledge the efforts of all of the participating scientists in helping to produce these proceedings.

Professor N. A. BOGDANOV
General-Secretary of the
Organizing Committee

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PERIODICITY OF ORE FORMATION IN GEOLOGICAL HISTORY

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It is a common knowledge that the most important endogenic mineralization takes place under geosynclinal conditions. Consequently, a major part of endogenic ore deposits is found to occur within geosynclinal-fold systems. Such systems are a natural result of the Earth's crust development and provide a basis for subdivision of its history into geologic-metallogenic epochs. Metallogenic epochs are represented by regularly recurring sequences of events that give rise to a syclicity in geological history, though the overall trend in the Earth's crust development remains progressive and irreversible. Each epoch begins with a long-term accumulation of the rockforming material under conditions of Earth's crust extension associated with basaltoid magmatism, and terminates with a brief pulse of tectonic compression accompanied by granitoid magmatism. The epochs of the Earth's crust development are marked by intensive tectonic deformation, metamorphism and granitoid magmatism. The subdivision of geological history into the epochs forms a basis for its tectono-magmatic and metallogenic analysis. This is fundamental for the Phanerozoic, and it is being applied to this purpose by the prominent Precambrian geologists.

The difficulty stems from an insufficient certainty existing in distinguishing the tectono-magmatic and corresponding metallogenic epochs of Precambrian history. However, the data from numerous works on this subject enable to define such epochs within the oldest interval of geological history as well. There are altogether eleven epochs distinguished in the history of the Earth's crust development: Greenland (5,000-3,800 m.y.), Kola (3,800-2,800), Belomorian (2,800-2,300), Karelian (2,300-1,800), Gothian (1,800-1,500), Grenville (1,500-1,000), Baikalian (1,000-600), Caledonian (600-400), Hercynian (400-250), Kimmerian (250-100), Alpine (100-0).

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METALLOGENESIS AND MINERAL ORE DEPOSITS

Tectono-magmatic and metallogenic epochs are called differently; we have adopted the most widespread definitions and their synonyms. Although the boundaries of epochs lie near some age steps, they (boundaries) are placed with various degree of deviation by every different investigator; we follow the majority of geologists in placement of the boundaries, though the latters need, probably, further correction. There is evidence for suggestion that the defined epochs are universal enough to occur all over the globe, though they exhibit themselves inadequately in different places, and their boundary age values may shift up and down.

A remarkable feature about all the tectono-magmatic epochs, except for the oldest Greenland epoch, is that a complex of basaltoid rocks, derived from a mantle source, is formed during the early stage while during the late stage a complex of crustal granitoids is developed, with specific ore deposits being associated with each complex. Thus, the early basaltoid and the late granitoid deposits make up two groups of endogenic ore deposits distinguished within a framework of the metallogenic epochs. The typomorphic basaltoid deposits are known to consist of deep-seated formations including the magmatic titanomagnetite, chromite, platinoid deposits and the near-surface formations characterized by massive sulphide deposits. The typomorphic granitoid deposits embrace the groups of pegmatites, albitites, greisens as well as hydrothermal formations of plutonogenic and volcanogenic classes.

The following step-by-step characteristic of endogenic ore deposits is no generalization. Rather, it is based on the most representative well-dated examples from the world ore provinces.

Greenland epoch covering the time span between 5,000 and 3,800 m.y. B.P. coincides in full with the Lunar Period of geological history. This is considered to be non-geosynclinal, non-platform, non-granitic, non-ore, and, hence of no interest for the geohistorical metallogeny.

Kola (Saamian, Transvaal) epoch covering the time span between 3,800 and 2,800 m.y. B.P. corresponds to the Nuclear Period and marks the onset of formation of the oldest, usually highly metamorphosed endogenic ore deposits. They clearly fall into two groups, namely, the basaltoid deposits related predominantly to greenstone belts, and the granitoid deposits associated with granite-gneiss domes.

The basaltoid group constitutes the deposits deep-seated and near-surface in origin. The deep-seated category is represented by relatively small in size, about 3,500-m.y.-old magmatic chromite deposits found in anorthosites of Greenland, Scotland, South Africa, and India. The Kambalda (Australia) and Moncha-Tundra (Kola Peninsula) nickel-copper sulphide deposits having the age about 3,000 m.y. as well as similar (about 3,400-m.y.-old) deposits of Zimbabwe may also be assigned to this category. The oldest massive sulphide deposits having the age of 3,400 to 2,600 m.y. in North America, 3,400 m.y. (Big Stubby) in Australia, 2,900 m.y. (Abitibi) in Canada, and 3,400 m.y. in South Africa are associated with volcanism of the Kola epoch. Numerous greenstone-belt-hosted gold ore deposits such as the 3,200 to 2,800-m.y.-old Kalgoorlie and other deposits of Australia, 2,800-m.y.-old Kolar deposits of India, 3,500 to 2,900-m.y.-old Porcupine, Kirkland, Kerr Edison and other deposits of Canada, Morro-Velho deposit of Brazil, and 3,000 to 2,900-m.y.-old deposits of Sierra Leone fall into the same category. The most ancient iron formation deposits including the world's oldest (3760±70 m.y.) ore deposits of Isua in Greenland, and iron formations of Abitibi in Canada tend to be related to basalt volcanic series of the Kola epoch.

The granitoid group is typified by the oldest pegmatites of metamorphogenic origin. Their representatives are muscovite pegmatites of the Anabar Massif and Dzhugdzhur Range, 3,500 to 2,900-m.y.-old natrolitic Li-Ta-Nb-bearing pegmatites of Western Australia and Brazil, and 3,350 to 2,600-m.y.-old pegmatites of Africa.

<u>Belomorian (Kenoran, Rhodesian)</u> epoch covering the time span between 2,800 and 2,300 m.y. B.P. encompasses the first half of the Protogeosynclinal period and corresponds to the time of initiation of the ancient geosynclines crosscutting the platforms. The ore deposits

of geosynclinals and ore deposits of platforms are distinguished in this epoch.

The early basaltoids consisting most frequently of insignificant in size masses of peridotitic, gabbroic, plagiogranitic and volcanic basaltoid rocks, converted by metamorphism into pyroxene-amphibole-biotite gneisses, are very conspicuous within protosynclinal systems of the Belomorian epoch. Associated with them are small magmatic deposits of chromites of the South-Africa type, titanomagnetite of the Otanmäki deposits (Finland), small 2900 to 2500-m.y.-old iron-ore taconites of Norway and Sweden, and unimportant 2,750 to 2,650-m.y.-old massive sulphide deposits of the North-America type. In addition, the late Belomorian granitoids are ubiquitously recorded, with first occurrences of allochthonous granites being noted along with predominant autochthonous granite-gneisses. These are chiefly characterized by pegmatite deposits such as ceramic pegmatites of Karelia, rare-metal 2700-2500-m.y.-old pegmatites of Canada, South Africa, Madagascar, Western Australia, and India. The iron-bearing 2,600 to 2,400-m.y.-old skarns of the Aldan Shield also belong to this category.

The platform ore deposits are just starting to emerge during this period as well. Magmatic 2,700 to 2,500-m.y.-old chromite deposits occurring in dunite of the Great Dyke (Zimbabwe) and less important 2,500-m.y.-old copper-nickel sulphide deposits within the Thompson Greenstone Belt of the North America Platform are associated with tectono-magmatic activity of the Belomorian epoch. The unique 2,750-m.y.-old gold uranium conglomerates of Witwatersrand in South Africa is a salient example of the exogenic platform ore deposits of this type.

Karelian (Svecofennian, Hudsonian, Eburnian) epoch covering the time span between 2,300 and 1,800 m.y. B.P. marks the climax and waning stages of the protogeosynclinal activity. This epoch is also characterized by the ore deposits both geosynclinal and platform types.

Early basaltoids composed of volcanites (converted into schists, amphibolites and leptites), small masses of dunites, peridotites, pyroxenites, plagiogranites as well as the bodies of somewhat later normal granites and the latest leucocratic alkaline granite are ubiquitous among geosynclinal units. Small 1900-m.y.-old chromite and rare apatite-magnetite ore deposits of the Kiruna type in Sweden are associated with basaltoids. Geosynclinal basaltoid volcanism of the Karelian type is responsible for the world's largest deposits of iron formations including those of the Great Lakes region (Canada and the USA), Venezuela, Brazil, Hamersley area of Australia, Krivoy Rog, Kursk Magnetic Anomaly (both in the USSR) as well as for metamorphogenic 2300 to 1600-m.y.-old iron and manganese ores of India. Well known massive sulphide deposits including the 1,700-m.y.-old Broken Hill and Mount Isa deposits of Australia, the 1,900-m.y.-old Boliden deposits of Sweden, the 2,300 to 1,800-m.y.-old Outokumpu and other deposits of Finland, 1,900 to 1,700-m.y.-old deposits of North America and 2,200 to 2,000-m.y.-old deposits of Karelia. Muscovite and muscovite-rare metal 1,800-m.y.-old pegmatites of the White-Sea region and coeval mica pegmatites of the Mama Belt (Siberia) are associated with the Karelian granitoids. Included into this group, though tentatively, are the hydrothermal deposits exemplified by the 2,000-m.y.-old silver Cobalt deposits in Canada and by the 1,800-m.y.-old and semicontemporaneous gold deposits associated with black schist successions of Homestake (USA) and Sukhoy Log (Siberia); the latter are considered by some geologists as being metamorphogenic.

Skarn (1,800-1,700-m.y.-old) tin and tungsten deposits of Karelia relate to the late orogenic leucocratic granitic of the rapakivi type. Large ore deposits were forming under platform conditions of Karelian time. They include magmatic 1950-m.y.-old chromite and platinoid ores of the Bushveld lopolith of South Africa, magmatic copper-nickel sulphide deposits having the age of 2,000 to 1,800 m.y. within the Sudbury massif of Canada and 1,770 m.y. within the Pechenga massif of the Kola Peninsula, linear near-fault zones of the feldspathic metasomatites, chiefly after albitites, with 2,000 to 1,800-m.y.-old uranium, tantalum, niobium and beryllium mineralization of the Russian, Siberian, and North America platforms, cupriferous 2,300-m.y.-old Palaboro carbonatites of South Africa. Both the formation and distribution of these deposits were controlled by major faults related to protoactivation of the Karelian platforms. This epoch saw also the formation of stratiform 2,100 to 1,800-m.y.-old cupriferous sandstones of Central Siberia (Udokan) and uranium-bearing 2,200-m.y.-old Elliot-Lake conglomerates of Canada.

Gothian (Elsonian) epoch covering the time span between 1,800 and 1,500 m.y. B.P. corresponds to the Intergeosynclinal period of the history of Earth's crust development. A break in endogenic ore formation corresponds to this period marked by a suspension in active development of the Earth's crust. Geological literature is lacking of any record of endogenic ore deposits dated by a Gothian age. Some geologists (for example, Yu.G. Staritsky) who have studied extensive Precambrian rock complexes point straightforwardly out that during this epoch ore deposits were not being formed (this particular case is pertinent to the Siberian platform). For lack of areas of distinct geosynclinal regime, no geosynclinal ore deposits have been revealed. Only exogenic ore deposits associated with erosion of granitic topographic highs and the deposition of the detrital sediments in the adjacent depressions were formed within platforms. It was just the way of formation of the Jabiluka, Ranger and other large uranium deposits (Australia) occurring in 1,700-1,600-m.y.-old sedimentary sequences rich in organic matter, and of the known primary copper-cobalt, uranium and lead-zinc singenetic stratiform deposits in terrigenous, about 1,500-m.y.-old, rocks of Katangian System of the Zambia-Zaire ore belt; these deposits were repeatedly modified, which led to formation of epigenetic ore concentrations ranging in age from 840 to 520 m.y.

Grenville (Early Baikalian, Satpuran, Kibarian, Minassian) epoch covering the time span between 1,500 and 1,000 m.y. B.P. opened the geological events of a new geosynclinal period. Although it is distinguished clearly enough by folding and granitization of the age of 1,000 m.y., the information on its special features, magmatism and metallogeny is extremely limited due to two reasons. First, the Grenville epoch is believed to be embryonic and poorly expressed in the history of geological events; second, it is seldom to be differentiated from the following Baikalian epoch because investigators usually apply a combined description to the areas of distribution and to the compositional features of rock formations belonging to both epochs. Nevertheless, even the scanty data available allow to draw a conclusion that geosynclinals of the epoch under consideration were limited in distribution and in maturity. They were dominated by the early basaltoid magmatism consisting chiefly of volcanic facies with which rare 1,340-m.y.-old massive-sulphide and pyrite-pollimetallic deposits of the Sullivan type are associated. Similar deposits are also found within 1,400 to 1,100-m.y.-old volcano-sedimentary complexes of the USA and Canada. There are no significant deposits related to the Grenville granites. The probable exceptions are the 1,180-1,150-m.y.-old Ilimaussaq rare-metal alkaline complex of Greenland and pegmatites described by L.N. Ovchinnikov et al. without mentioning the locality of their occurrence.

Baikalian (Assyntian, Cadomian) epoch covering the time span between 1,000 and 600 m.y. B.P. saw already a mature geosynclinal development. The part of geosynclinals that had ceased to exist prior to the Palaeozoic is now traced by independent geosynclinal-fold zones; the other part within which geosynclinal conditions continued to operate in the Phanerozoic is now recorded by the Baikalian geosynclinal formations found at the base of the geosynclinal-fold belts formed during subsequent epochs of geological history. Independent Baikalian geosynclinal formations are mostly confined to the margins of the East-European, Siberian, Indian, African, China, and Australian platforms, but are also known within inner parts of platforms, for example, in Timan-Pechora region. They are composed of thick sedimentary-volcanogenic sequences undergone metamorphism and granitization at the end of their accumulation; inner ophiolite belts and peripheral miogeosynclinal zones with granitoids are distinguished.

Two groups of endogenic ore deposits are clearly defined. The early group associates with basaltoids of both deep-seated and near-surface facies; the late group is associated with granitoids. The deep-seated basic rocks, for example, serve to be host rocks to the 950-m.y.-old Egersund titanomagnetite deposit of Norway, similar 850-m.y.-old Lawrence River deposits of Canada, and, probably, the deposits of the Kusa area in the Urals. North America's massive sulphide deposits aged 800 to 600 m.y. as well as Kholodninskoye (1,000-900 m.y.) and Gorevskoye (970-870 m.y.) pyrite deposits of Siberia are associated with basalt-liparite formations.

The most typical products of the Baikalian granitoids are pegmatites and greisens containing tungsten, tin, tantalum, niobium, lithium. They range in age from 1,000 to 800 m.y. and are known from Egypt, Uganda, Transvaal, India, Australia. The knowledge of Baikalian platform endogenic ore deposits is sketchy; nevertheless, the known 1,000 to 700-m.y.-old lead-zinc mineralization in carbonate sequences of Northern Canada suggests that such ore deposits might have been formed.

<u>Caledonian epoch</u> covering the time span between 600 and 400 m.y. B.P. brought to completion the geosynclinal development in the regions of independent Caledonian folding (such as, for example, Altay-Sayany region of the Soviet Union or Coastal region of Norway and Great Britain) and preceded further development in the regions of successive geosynclinal regime. This epoch is characterized by intensive activity during the early geosynclinal stage and by weakly-developed orogenic tectonics and magmatism of the late stage. Nevertheless, it is possible to distinguish within its limits not only basaltoid magmatism and metallogeny of the geosynclinal stage but also the manifestations of granitoid magmatism and metallogeny related to orogenic stage and to platform environment.

Basaltoid magmatism of Caledonian epoch was of onesided nature. Deep-seated ultrabasic and basic intrusions and associated deposits of chromites and titanomagnetites are of extremely sparse occurrence; somewhat more conspicuous are basalt magma acid derivates represented by plagiogranites and plagiosyenites with iron-skarn deposits,