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Hypergene Metallogeny of the Urals

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Abstract—The presented overview of hypergene metallogeny of the Urals is largely based on original data of the author. All bauxite, Co–Ni oxide–silicate, and high-grade ferromanganese our deposits, gold, platinum, and diamond placers, as well as brown coal, kaoline, refractory, and other economic-grade mineral deposits, currently mined in the Urals are hosted in hypergene zones and related hypergene blankets of different ages. Prospects for diverse mineral deposits are estimated with a special emphasis on thermal hypergene deposits (Ni, Au, and others) that are atypical for the Urals but favorable for mining under conditions of the market economy owing to the presence of high-grade ore bodies.

BASIC DEFINITIONS

Hypergene metallogeny is a branch of general metallogeny focused on the study of formation conditions and spatial distribution of hypergene mineral deposits (Mikhailov, 2000a).

Hypergenesis is a term proposed by A.E. Fersman in 1922 instead of the grammatically wrong English term *Supergenesis* (Greek root and Latin prefix). In the modern Russian geological literature, hypergenesis is understood as the whole entity of processes and phenomena in the subsurface section of the Earth's crust, i.e., within the hypergene zone (*Prognoznaya…*, 1998; Mikhailov, 2000a).

Hypergene zone (sphere, after Fersman) is a subsurface section of the consolidated lithosphere, where rocks exposed on the day surface or seafloor tend to equilibrate with environment as a result of the impact of both exogenic and endogenic agents.

The consolidated land or seafloor surface locally overlain by products of the proximal redeposition serves as the upper boundary of the hypergene zone. The lower boundary commonly coincides with the biological cycle boundary and is established by the waning of photo- and chemosynthetic effects. This is accompanied by sharp depletion in oxygen, respective change in Eh (partly pH) of environment, and suppression of some processes (hydration, colloid formation, and hydrolysis) (*Prognoznaya…*, 1998).

The most intense hypergene alteration extends to a depth of several tens or hundreds of meters. Locally (commonly, in mountainous regions), one can observe a weak hypergene alteration related to the surface water that can penetrate down to a depth of few kilometers along karst passages, faults, and cataclastic zones.

The hypergenesis zone is characterized by the formation of specific rocks and hypergene bodies (Table 1) as a result of complex interaction of various energy and material sources rather than the mechanical mixing of products of exogenic and endogenic processes (*Izuchenie…*, 1995; (*Prognoznaya…*, 1998).

The hypergene zone incorporates all bauxite deposits of the world, numerous deposits of Ni and Co–Ni oxide–silicate ores, high-grade iron ore (>60% Fe), high-grade manganese oxide and peroxide ores (>48% Mn), and high-grade rare earth ore (REE content up to 100 kg/t or more), and the largest deposists of uranium, gold, diamond, and various nonmetallic minerals (phosphorite, kaolin, salt, bentonite, and so on).

Deposits in the hypergene zone are commonly characterized by favorable technical and economic mining parameters. The present-day hypergene zone is the environment of human habitat and the object of economic activity.

Hypergene blankets are formed during a long-term stabilization of large geological structures and identified as hypergene rock associations often corresponding to formations or sequences. In the Russian literature, periods of hypergene blanket formation are commonly defined as epochs of weathering crust or hypergene rock and ore formation. These epochs are usually confined to particular physicogeographic provinces (e.g., the Late Triassic epoch of hypergene rock and ore formation on the eastern slope of the Urals, the Early Carboniferous epoch of hypergene rock and ore formation at the Russian Plate, and so on).

Study of the evolution of hypergenesis in the Earth's geological history indicate that all hypergene processes, as well as related bodies and blankets, inevitably change in time. These changes proceed in a stepwise manner. Therefore, the Earth's history can be divided into (1) Precambrian–Early Paleozoic, (2) Middle–Late Paleozoic, and (3) Mesozoic–Cenozoic stages (epoch groups) of hypergene rock and ore formation. The most dramatic change in composition, structure, and metallogeny of hypergene blankets took

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Table 1. Typification of hypergene bodies

Type of hypergenesis	Hypergene body		Genetic group			Typical hypergene products
Surficial	Weathering crusts		Eluvium			Red cap, laterite, structural (pseudomorphous) bauxite, ocher, and clay with relict structure and texture
	Gossan					Cavernous brown ironstone with malachite, azurite, and manganese hydroxides; jarosite and other sulfates in arid and Polar regions
	Caprock					Cavernous limestone with sulfur, gypsum, anhydrite, occasional bitumens, iron hydroxides, borates, and other minerals as relicts of salt and sulfate protoliths
	Infiltration crusts		Illuvium			Caliche, silcrete, and alm; carbonate, siliceous, and sulfate crusts
	Products of proximal redeposition	Karst bodies	Karst (exokarst)			Karst breccia, mixed silt, clay, and leached cavernous bedrock
			Speleokarst			Stalactite, stalagmite, mineral wax, marble onix and others
		Fluvial bodies, block slope, spot medallions of freezing-out	Proluvium, colluvium, cryogenic blanket, and landslide			Unsorted, poorly rounded pebbles, breccia, sand with rubble, clayey conglomerate, and cryoclastopelites
		Paleosol	Continental deposit of primitive desert			Polymineral metamorphosed rocks, sericite–berthierine schist, and silicate diasporite
Underground	Paleoaquifer (stratal oxidation zone), roll		Aquifer			Clayey, limonitized, Mn-bearing, carbonate, sulfate, and other colmatolites
	Coal fire site		Underground fire site			Burnt rocks, sulfur efflorescences, alunogen, ammonium chloride, and bitumens
Thermal	Exohydrothermal vein, stock, column, lens, thermal window, and depression		Zone of the ascent of thermal water and fluids			Kaolinite and sericite argillic-altered rocks with chalcedony, opal, quartz, pyrite, and other sulfides; Au-bearing kaolinite–sericite marshallite with high-temperature quartz, occasionally with ferromanganese hydroxides and REE; secondary quartzite with diaspore and alunite
	Hydrothermal, solfataric, and fumarolic crusts		Exohydrothermal field	Climate	Humid	Opal–kaolinite rocks, often with quartz and iron hydroxides; siliceous–clayey geiserite (often with iron hydroxides) and fumarolic deposits
					Arid	Hydrothermal zeolites, smectite with chalcedony and quartz nodules, sulfates and iron hydroxides
	Hydrothermokarst bodies		Hydrothermokarst (endokarst)			Corrosion avalanche breccia cemented by various exohydrothermal materials, often with sulfides of Fe, Cu, Pb, and Ni
Submarine (halmyrolysis)	Halmyrolitic crusts and products of their redeposition		Hydroeluvium			Palagonite basalt, submarine tuff, and tuffite; bentonite beds
	Submarine gossan					Hematite–quartz and chlorite–hematite rocks, pelitolites, and hematitized hyaloclastites; lenticular bodies of base metal oxide ore, often with gold

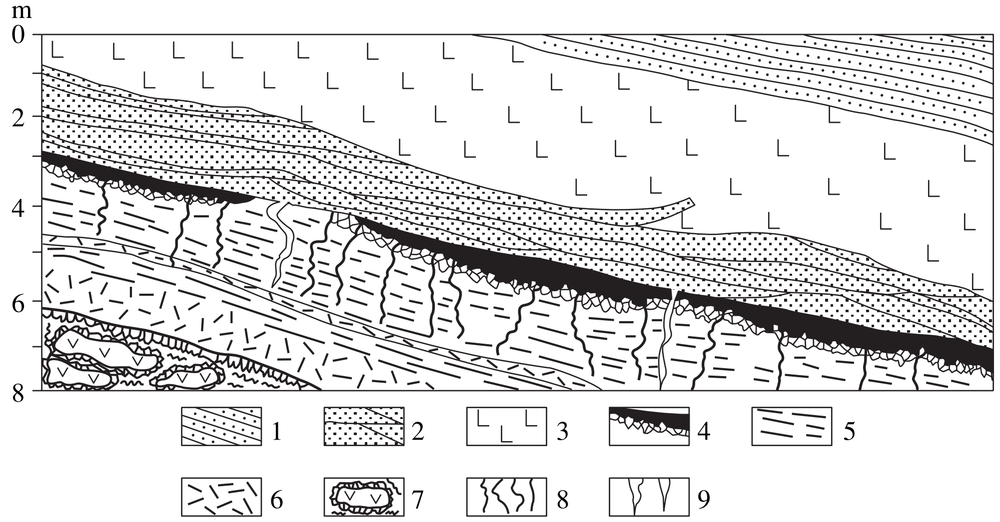

Fig. 1. Section of the Waterval Onder clayey paleosol (paleosopralite) on the 2200-Ma-old Hekpoort basalt, (Retallak, 1986). (1) Bedded clayey quartzite; (2) cross-bedded quartzite; (3) diabase sill; (4) black sericite schist; (5) yellowish olive-gray sericite schist; (6) greenish gray granular quartz–berthierine rock; (7) basalt (weathered in Cenozoic time) with fresh cores; (8) Mn- and Fe-bearing veinlets and gouge along jointing; (9) neptunic quartzite–sandstone dike.

place in the Devonian as a response to the appearance of vegetation. “No other more permanently acting and, thus, more powerful chemical force (in terms of consequences) is known on the Earth’s surface than the living organisms taken as a whole” (Vernadsky, 1989, p. 21).

1. PRECAMBRIAN–EARLY PALEOZOIC HYPERGENESIS

Since lithosphere, atmosphere, and hydrosphere already existed in Precambrian, their boundaries were the places of rock alterations and deposition of hypergene products.

Many dozens of localities with Precambrian weathering crusts are described in the literature and unpublished reports (see works of V.K. Golovenok, A.D. Dodatko, O.S. Koryakin, E.A. Kulish, A.D. Savko, V.A. Sokolov, K.I. Heiskanen, V.M. Chaika, V.S. Shub, and others). Comparison of these weathered rocks with Phanerozoic (more precisely, post-Silurian) hypergene blankets reveals a significant difference between them in composition, thickness, development area, and other parameters (Mikhailov, 1986, 1991; *Izuchenie…*, 1995).

The issue of Precambrian hypergene rocks has recently attracted much attention in South Africa, Canada, Australia, and other countries. Hypergene products on Precambrian shields are known as paleosols (Ollier, 1984). This term is usually translated into the Russian as ancient (buried) soils or weathering crusts.

However, most of the paleosols known abroad (see the works of M.J. Edelman, R.W. Foster, A.Z. Gray, D.E. Grandstaff, H.D. Holland, M.M. Kimberlay, G.J. Retallak, E. Zbinden, and others) actually are *complexes of proluvial, talus, and eluvial deposits accumulated on the surface of primitive (vegetation-free) Precambrian and Early Paleozoic deserts.* The paleosols are confined to hiatuses and mark the beginning of a new sedimentation cycle. The thickness of paleosols commonly does not exceed a few tens of meters. Some thicker layers related to the stratigraphic and structural unconformities also may be regarded as paleosols.

The composition, structure, and formation conditions of paleosols was scrutinized in (*Izuchenie…*, 1995). Let us briefly consider the Waterval Onder paleosol developed on the 2200-Ma-old Hekpoort basalt (Fig. 1). Ollier (1984) referred this paleosol to as a Precambrian weathering crust. At the same time, based on the study of paleosol mineralogy, Retallak (1986) stated that quartz–berthierine rocks and sericite schists in this paleosol are a basal unit of the Dwalhenkel Formation rather than ancient soil or saprolite. This unit (clayey paleosol) is 4.5 m thick and includes several continental facies of vast flat-bottom valleys.

Metallogeny of Precambrian paleosols drastically differs from that of the genetically akin post-Silurian deposits.

Products of Precambrian hypergenesis (weathering crusts or paleosols) were intensely studied by geological organizations of the former Soviet Union since the late 1960s. As a result, it has been established that they are completely devoid of laterites and related bauxite, Co–Ni ore, high-grade Fe, Mn, REE, and kaolin deposits. However, they have a high potential for uranium, base metal, and gold deposits of the unconformity type often localized within ancient aquifers, as well as for gold, rare metal, and other deposits of thermal hypergenesis (Mikhailov, 1991; *Izuchenie…*, 1995; and others).

Precambrian and Lower Paleozoic Hypergene Blankets in the Urals

Several long-term hiatuses are known in Precambrian and Early Paleozoic of the Urals. In the 1970s, Sigov and Shub studied the issue of prospecting for bauxite ores in the Urals. Based on the overview of available materials devoted to continental hiatuses, they identified the following levels of possible hypergene blanket formation in Precambrian and Lower Paleozoic sections: (1) Early Proterozoic level at the pre-Uralides–Uralides boundary corresponding to the Taratash Complex–Ai Formation hiatus (2700–1700 Ma); (2) Middle Riphean (pre-Zigalga) level with the upper age limit at about 1400 Ma; (3) Late Riphean (pre-Zilmerdak) level with the upper age limit at ~1050 Ma; (4) Vendian level (base of the Asha Formation), and (5) base of the Cambrian or Ordovician-Silurian where Cambrian is missing (Sigov and Shub, 1975; *Boksitonosnye…*, 1987).

All efforts to find guides for bauxite or at least laterite formation at these levels turned out to be unsuccessful. Researchers found only some signs of karst bauxite formation at the surface of the Lower Riphean Bakal Formation (carbonate rocks) exposed in open pits of the Bakal iron ore deposit (Sigov and Shub, 1975).

The Bakal Paleosol

We studied the Bakal iron ore deposit in 1993–1994 (Mikhailov, 1995) and obtained results substantially refining the character of continental hiatus between the Lower Riphean Bakal and Middle Riphean Zigalga formations and the metallogeny of the related hypergene blanket.

The hiatus is clearly fixed by abrupt compositional change of rocks and angular unconformity corresponding to the Bakal tectonic phase. Black shales and carbonate rocks of the Bakal Formation are overlain by sandstones and conglomerates of the Zigalga Formation with “rewash shales,” i.e., various rocks commonly regarded as redeposited products of the pre-Zigalga weathering crust (Anfimov *et al.*, 1989) at the base.

In the Novyi Bakal open pit, the thickness of rewash shales does not exceed a few dozen centimeters and increases to 15 m along the road toward the Petlin open pit, where they make up a persistent 50-m-thick unit which is denoted by index PR_{2Bas} (basal unit of the Zigalga Formation) in field documents. This unit includes greenish gray conglobreccia with chlorite–sericite cement and quartz–sericite schist interbeds. Subrounded and angular fragments of quartz–chlorite–sericite schists and sporadic fragments of hydrothermally altered acid volcanics occur along with quartz pebbles. Abundant dissemination of sulfides (pyrite, chalcopyrite, and galena) and relicts of pyroclastic material are locally observed in the cement. Some samples are enriched in Au and Pd (up to 0.5 and 0.016 g/t, respectively) that stand out against the background clarke value.

Analyses performed in laboratories of the VSEGEI (St. Petersburg) revealed that the rewash shales markedly differ from black shales of the Bakal Formation in composition.

First, they are characterized by dull grayish green color (with greenish and pale gray hues) as a result of the prevalence of sericite with significant chlorite admixture (up to 10%). The organic matter is completely lacking, but tiny pyrite crystals are always present. The rewash shales have a chlorite–sericite rather than quartz–hydrosericite composition, as was previously determined (Sigov and Shub, 1975). This is responsible for relatively high contents of alumina (20–27 wt %) and potassium oxide (6–9 wt %), Mg admixture, and low L.O.I. value mostly related to the sulfide sulfur ignition.

Another distinguishing feature of rewash shales is a wide range of trace elements including REEs and Au.

The enrichment of shales in alumina as an argument in favor for their involvement in weathering crust (Sigov and Shub, 1975) can hardly be accepted as valid, especially with respect to the Riphean section of the southern Urals. For example, the sideroplesite ore at the Bakal deposit is normally characterized by a high silica module. Ore intervals with a thickness of hundred of meters and $Al_2O_3/SiO_2 = 0.87–1.70$ are common here.

In our opinion, the available data refute the eluvial genesis of rewash shales and argue in favor for their assignment to Precambrian paleosols formed in primitive deserts (Perel’man, 1966).

The metallogenic specialization of the Bakal paleosol is characterized not only by elevated Au, Pd, and REE contents but also by the development of a specific iron oxide (turgite) ore.

Various types of hydroxide ores are recognized among the Bakal brown iron ore. According to A.V. Krasnopolskii, M.N. Dobrokhotov, A.E. Malakhov and others, these ores formed in Mesozoic and Cenozoic. The brown iron ore is divided into turgite and limonite groups.

The turgite ore is mainly composed of hydrohematite. The massive “karandash” (“pencil”) variety is characterized by bluish black color and cherry streak. The loose “chernotal” variety is dark red-brown.

The turgite ore is enriched in Mn (up to 2%) and depleted in water and Ti. The average iron hydroxide content is 60–80% (occasionally, 90%).

The turgite often retains the relict texture of parental sideroplesite ore. “The replacement of siderite ore with turgite is especially intensive in diabase dike fields. The diabase dikes, which cut the turgite ore, are commonly transformed into bright green foliated quartz–sericite rocks mainly consisting of sericite, chlorite, quartz, and pyrite dissemination” (Solov’ev, 1951, p. 276).

Beginning from the late XIX century, almost all researchers noted the following essential fact: The brown iron ore includes hydrothermal minerals, such as pyrite, chalcopyrite, galena, albite, rock crystal, and barite (Anfimov *et al.,* 1989). According to the observations made by Ushakov (1934), quartz, barite, and partly sulfides remain unaltered in the oxidized mass.

The size of sulfide segregations varies in a wide range. Pockets of massive crystalline galena, up to 500 kg in weight, with secondary anglesite and cerussite on the surface were found in 1947–1948 within the ocherous and cavernous brown iron ore (Solov'ev, 1951).

Facts mentioned above suggest that the replacement of sideroplesite ore with turgite predated the hydrothermal activity related to subvolcanic minor intrusions of the Bakal phase; i.e., the replacement started no later than in Early Riphean.

Thus, the scenario of turgite orebody formation in the Riphean (Bakal) paleosol may be interpreted as follows.

The hillocky topography of the Bakal area during the Early–Middle Riphean continental hiatus formed in a primitive desert environment characterized by the lack of vegetation, elevated surface temperature, and deficiency in the surface moisture. The meteoric water drained into intermontane depressions and evaporated or penetrated into aquifers without retaining at the surface. The lithomorphic relief with stable quartz–sericite schists on the hills and less stable carbonate rocks in depressions controlled the formation of basal unit of the transgressive Zigalga Formation, i.e., the paleosol consisting of allochthonous quartz pebbles and sand and autochthonous conglobreccia with fragments of quartz–sericite schists. The carbonate rocks were dissolved by aggressive groundwaters derived from depressions in topography. As a result of the absence of vegetation, these waters were saturated with oxygen and responsible for the formation of Riphean stratal oxidation zones.

The formation model of stratal oxidation zones as specific aquifers is elaborated conformably to Neogene–Quaternary uranium deposits localized in arid climatic belts of the partly or completely isolated basins in regions affected by moderate tectonic reactivation (Maksimova and Shmariovich, 1993, p. 18). These authors call attention to the following fact: “Duration of the stratal oxygen infiltration may vary from tens and hundreds of thousand to a few million years, i.e., within four orders of magnitude. As a rule, these values are significantly greater than the typical duration of syngenetic sedimentary or endogenic epigenetic (hydrothermal) deposit formation. Therefore, stratal infiltration deposits may be defined as deposits of long-term process” (Maksimova and Shmariovich, 1993, pp. 24–25).

Thus, the turgite orebody probably began to form in the Bakal paleosol in stratal oxidation zones during the Early–Middle Riphean hiatus.

The Kozhima Paleosol

Another no less significant area of paleosols is situated on the western slope of the Subpolar Urals at the headwater of the Kozhima River in the field of Riphean–Vendian volcanosedimentary complexes (pre-Uralides). These rocks are overlapped with a sharp angular unconformity by only slightly metamorphosed terrigenous–carbonate rocks of the Middle–Upper Cambrian and Ordovician.

The paleosol consisting of continental, often high-alumina rocks known as the Al'kesvozh Sequence (Formation ?) lies everywhere at the base of Uralide section as a thin basal unit. This unit attracts attention, first of all, owing to the discovery of high-grade gold occurrences in the 1980s (Ozerov, 1996). In addition, occurrences of uranium, rare earth elements, and silicate diasporite have been discovered in basal units in the same territory.

Unfortunately, the descriptions presented in papers, preprints, monographs, and dissertations contain many controversial, often geologically crude statements. Therefore, geology and economic potential of the Kozhima Au-bearing district remain ambiguous (see works of V.S. Ozerov, Ya.E. Yudovich, M.P. Ketris, L.I. Yefanova, and others).

According to Ozerov, the Paleozoic section in the Kozhima area begins with “Early Cambrian metamorphosed lateritic (weathered) rocks.... The sericite–chlorite–paragonite schists are products of the metamorphism of subore weathered basic rocks that postdated the erosion of laterites, formation of erosion depressions, and their partial filling with terrigenous materials. The weathered rocks are overlain (commonly only within wide pre-Paleozoic fault zones) by Late Cambrian–Early Ordovician lateritic conglomerates varying from 0.9 to 2.68 m in thickness” (Ozerov, 1996, pp. 28–29). Taking into account the regional development of the lateritic weathering crust, Ozerov outlined the Early Paleozoic Ural bauxite-bearing formation. Thus, the meaning of weathering crust in the interpretation of Ozerov remains ambiguous.

According to the commonly accepted definition, the *weathering crust* is a geological body composed of eluvium, i.e., autochthonous products of the strong surficial alteration of rocks left *in situ.* Hence, the notion of redeposited weathering crust is meaningless. Any kind of redeposition of eluvium or other rocks leads to the formation of colluvium, talus, proluvium, and alluvium, eventually, resulting in the deposition of lacustrine, marine, and oceanic sediments. If we accept ideas developed by Ozerov, Yudovich and others, virtually the Earth's entire sedimentary cover should be regarded as a redeposited weathering crust!

The notion of Lower Paleozoic Ural bauxite-bearing formation is an obvious misunderstanding. The history of the term *bauxite* is relatively short but rich in controversial statements (see works of G.I. Bushinskii, Yu.K. Goretskii, D.V. Nalivkin, and others). In the

1970s, Bushinskii, one of the oldest explorers of bauxites, recommended to reject this term at all in geological works and replace it by terms *allite* and *allitic rocks* (Bushinskii, 1975). He suggested that the term *bauxite* should be restricted to the widely used in Russia and abroad notion of the *ore for alumina production.* At present, when our country has to import the bauxite ore, this interpretation of term *bauxite* brings about additional confusion in the Russian geological literature, because aluminum industries of developed and importing countries have different requirements to the bauxite ore depending on technological, economic, and other factors. For example, only rocks containing >55% Al_2O_3 and <5% SiO_2 were referred to as bauxites during the exploration of the huge Boke deposit carried out by the Bauxite du Medi Co. in the Republic of Guinea. At the same time, during exploration of the Bokson deposit in the former USSR, rocks containing >37% Al_2O_3 and <23% SiO2 were regarded as bauxite ore based on “Temporary quality requirements of the Ministry of Geology”. Moreover, although the State Standard, which existed in the former Soviet Union, defined bauxite as an ore used for the production of various industrial materials (including alumina), exploration of each new deposit was based on special requirements to the ore quality, i.e., individual definition of the term *bauxite*. Consequently, L.S. Rudashevskii from the All-Russia Aluminum–Magnesium Institute (VAMI) went so far in his PhD dissertation in the mid-1970s as to define bauxite as “a rock that can be used for alumina production at a cost of no more than 150 rubles per ton.” In 2002, the price rose to US $180–190 per ton (Kozlovskii, 2002). From the geological point of view, the above definition is absurd, although it is quite acceptable for technologists or economists.

We believe that it is necessary to return to the original definition of bauxite as a residual or sedimentary rock largely consisting of aluminum hydroxides (gibbsite, boehmite, and diaspore) with some admixture of goethote, kaolinite, hematite, chamosite, and titanium dioxide. Bauxites are formed during the lateritic weathering of aluminosilicate rocks accompanied by intense removal of alkali metals, alkali earths, and silica.

According to the classification of aluminous rocks and based on the composition and position in the section, diaspore segregations (boles) found at the Kozhima paleosol base and subsequently studied in detail by Bogatyrev *et al.* (1996) can be defined as silicate diasporite (a chemogene rock), which is formed during the percolation of high-alumina hydrothermal solutions into the near-bottom layers of water reservoirs and has no relations to bauxite (Mikhailov *et al.*, 1979). It should be noted that the Kozhima paleosol as a basal unit of the Paleozoic section is very indicative of geology and geological history of this region.

The consideration of Precambrian and Early Paleozoic hypergene processes in the world shows a complete lack of conditions favorable for the formation of lateritic blankets, gossans, and related bauxite, kaolinite, high-grade iron, manganese, and phosphorus deposits. This implies that prospecting for these mineral deposits in Precambrian and Lower Paleozoic rocks of the Kozhima territory is unreasonable. At the same time, the Kozhima paleosol may be prospective for hypergene deposits of the unconformity type, orebodies of thermal hypergenesis, and ancient aquifers hosting U, Au, and REE ores.

2. MIDDLE–LATE PALEOZOIC HYPERGENESIS

The terminal Middle and Late Devonian periods were characterized by the development of land plants along the marine coasts. This process became most active in the Early and Middle Carboniferous when the stenozonal hygrophilous plants migrated from maritime plains toward the continents and occupied large tectonic depressions. The bloom of land vegetation was likely accompanied by the generation of organic acids and extensive involvement of colloidal mineral and organomineral systems in hypergenesis. This, in turn, substantially changed physicochemical parameters of the hypergene environment. The accumulation of moisture at water divides, abrupt increase in the underground runoff, respective chemical and physicochemical removal of dissolved materials, their hydration, and hydrolysis served as the major factor responsible for the appearance of a new type of hypergene formation (weathering crust). The composition and structure of weathering crusts as bioinert systems of humid regions strongly depend on climate and geomorphological environment. The most complete chemical differentiation of protolith observed under conditions of hot and variable humid climate is terminated with the formation of lateritic horizon. The latter may retain relict structure of protolith, but it largely consists of alumina minerals, and iron, manganese, and titanum oxides. The lateritic weathering crusts first appeared only in the Devonian and became widespread over the world in the Mesozoic.

Two Paleozoic (Middle–Late Devonian and Early Carboniferous) epochs of hypergene rock and ore formation are recognized in Russia and CIS. The formation of bauxite, iron ore, coal, refractory minerals, Ti, REE, and gold placers, and phosphorite deposits are related to these epochs.

Middle–Upper Paleozoic Hypergene Blankets in the Urals

The Urals underwent an active tectonic rearrangement in the Paleozoic accompanied by orogeny, volcanic eruptions, and emplacement of multiphase intrusions.

Numerous local hiatuses with a specific hypergene regime were marked in the Middle and Late Paleozoic in various territories of the Urals. The Middle Devonian, Late Devonian, and Early Carboniferous hiatuses are most significant in terms of the Paleozoic hypergene metallogeny. Hypergene blankets related to these hiatuses are localized within strictly definite tectonic domains.

Middle Devonian (Eifelian and Givetian). The Eifelian and Givetian bauxite-bearing rock complex of the North Ural bauxite district (NUBD) is related to the Middle Devonian hypergene blanket in the northern eugeosynclinal domain on the eastern slope of the Urals. This complex is traced as a discontinuous belt from the Karpinsk district to the Shchuchinsk Synclinorium in the Polar Urals. Economic-grade deposits are known in the Severouralsk, Ivdel, and Karpinsk districts (*Boksitonosnye…*, 1987). Bauxite formed here on the reefal limestone surface of the coastal island. It should be noted that economic-grade bauxite deposits are confined to the irregular surface of limestones of karstic or reefal origin. In both cases, bauxite replaced sediments enriched in volcanic materials. No signs of the lateritic weathering of volcanics coeval with limestones and occurring on the coastal land were found as yet (*Boksitonosnye…*, 1987).

In 1960, Vinokurov and Gutkin described the weathering crust on porphyries and agglomerate tuffs in the Cheremukhovo deposit area. The weathering crust, up to a few meters thick, is composed of slightly altered spotted red-brown bedrock. In the upper part of the section, feldspars are replaced by the secondary chlorite, hydromica, opal, halloysite, and iron hydroxides (Vinokurov and Gutkin, 1960). It cannot be ruled out that a paleoaquifer at the boundary between carbonate and volcanic rocks was taken for the weathering crust.

When describing the bauxite-bearing sequence, the above authors noticed a local enrichment of bauxite in magnetite and titanomagnetite. They wrote that “some ore samples from cores, open pits, and mines contain as much as 70–80 vol % of magnetite and titanomagnetite” (Vinokurov and Gutkin, 1960, p. 118).

Upper Devonian (Frasnian–Famennian). Another bauxite-bearing rock complex related to the Upper Devonian hypergene blanket is situated in the southern miogeosynclinal domain on the western slope of the Urals within the South Ural bauxite district (SUBD) that differs in geology from the NUBD counterpart (*Boksitonosnye…*, 1987).

The rock complex is divided into two bauxite-bearing associations (the major lower Frasnian Pashiya association and the subordinate upper Frasnian Orlov association) confined to continental hiatuses within the Upper Devonian carbonate sequence. The bauxite bodies commonly occur as stratiform lodes a few meters in thickness. The bauxite ores in the SUBD were deposited under conditions of smoothed relief in wide valleys with gentle slopes. The ore quality is lower than that in the NUBD. The secondary chamosite and kaolinite are abundant. Bauxite is replaced in the lateral direction with coastal-marine boehmite–diaspore–hematite ores typical of platform regions.

The so-called Kara bauxite is important for understanding the Middle Paleozoic hypergene environment.

The Kara district in the Polar Urals occupies middle reaches of the Kara River at the junction of the Pai Khoi Anticlinorium and the western slope of the Polar Urals. A bed of coaly–siliceous–clayey limestone with numerous drag microfolds overlies the Givetian biohermal dolomitized limestone. All known silicate diasporite (“bauxite”) occurrences in the Kara River basin are localized as lenticular bodies of dark gray, almost black diaspore–chloritoid rock in the lower section of this bed (Mikhailov *et al.*, 1979). The ore lenses are 2–15 m long. Their thickness varies from 10–15 cm to 3–5 m. They are overlain by a thick (>400 m) sequence of gray platy clayey limestone of the Frasnian age.

The careful examination of the section points to the complete lack of geological guides indicating the continental hiatus. The contact between Givetian and Frasnian bears all signs of hydrothermal alteration (quartz–calcite and quartz–feldspar veins with sulfide mineralization and quartz–calcite–fluorite veinlets) and dynamometamorphic impact (occurrence of moissonite, chloritoids, muscovite, and others) superimposed upon both host rocks and lenticular diasporite segregations (macronodules ?).

Absence of evidence for hiatus and obvious indications of endogenic impact upon the contact zone testify to a low probability of relations of diasporite bodies with the continental hiatus and lateritic weathering. It looks more likely that the acid high-alumina hydrothermal solutions seeped in deeps of water reservoirs. Alkaline water in the reservoirs served as pH hypergene barrier, where the alumina compounds readily precipitated.

In other words, the Kara bauxite is silicate diasporite formed as a product of submarime thermal hypergenesis (Mikhailov *et al.*, 1979; *Boksitonosnye…*, 1987).

Early Carboniferous (Tournaisian and Visean). In contrast to the adjacent Russian Plate, the Ural region is characterized by a very weak manifestation of the Early Carboniferous epoch of hypergene rock and ore formation as a result of orogeny and related cooling.

Only, the regional pre-Visean and pre-Tournaisian hiatuses, which control chemallite occurrences at the Kolchima Uplift (western slope of the northern Urals, the Krasnovishersk district) and the Zhuravlikovo kaolin deposit in the central Urals (*Boksitonosnye…*, 1987; Mikhailov, 1982) attract attention.

The Krasnovishersk district, where geological explorations were carried out several times to find the Lower Carboniferous bauxite, is most interesting.

Chemallites were recovered by boreholes at the Storozhevsk prospect in lower reaches of the Kolchima River and close to the Lower Tulymka River area. They are observed as olive-green brittle claylike quartz–gibbsite–kaolinite rock with Al_2O_3/SiO_2 =

0.72–0.83. White and yellow halloysite pockets with pyrite dissemination are clearly discernible in chemallites overlying limestones of the Tournaisian Kynovo Unit.

In terms of composition, occurrence mode, and age, chemallites from the Krasnovishersk district correspond to the well-known bauxites of the Moscow district of the chemallite group (Mikhailov, 1982, 1988).

The recently developed concept of the participation of hypergene processes in the formation of massive sulfide base metal deposits is of certain interest for the interpretation of hypergene blankets in the Urals. The generalized model of iron oxide formation with a special emphasis on submarine gossans was proposed in (Maslennikov *et al.*, 1989 and *Geologo-geneticheskie…*, 1993).

3. MESOZOIC–CENOZOIC HYPERGENESIS

Mesozoic–Cenozoic hypergene rock and ore formation is most diverse and productive in the world. Hypergene blankets of this time host the major part of mined mineral deposits.

Mesozoic and Cenozoic Blankets in the Urals

Mesozoic and Cenozoic hypergene blankets in the Urals are subdivided into the following three groups: Upper Triassic, Cretaceous (Aptian–Turonian), and Paleogene (Oligocene). The Neogene–Quaternary sedimentary cover, which overlies older rocks virtually everywhere, merit a special consideration.

Upper Triassic group. The Triassic Period as a whole is characterized by highstand of the Ural Orogen and wide development of subarid climate in both the Urals and adjacent territories. Erosional-tectonic depressions along the eastern slope of the Urals and the vast Orsk Basin are the only exceptions.

The lateritic weathering crust formed here at that time only at the walls of depressions that started to subside in the Late Triassic (Volchanka, Veselovka–Bogoslovka, Lyul'ino basins). No signs of lateritic weathering are noticed within the older basins (Mikhailov, 1998).

The Late Triassic hypergenesis was most widespread in the Tanalyk Depression of the western Orsk Basin. The Upper Triassic Khalilovo Sequence underlies here the Jurassic cover with coal-bearing sediments (Mikhailov *et al.*, 1998). This sequence includes different hypergene formations, including lateritic (bauxite-, Co–Ni-, and Mn-bearing) weathering crusts and proluvial and deluvial iron ores with Ni, Co, and V. The ore-bearing karst is extensively developed in certain areas where the Khalilovo Sequence overlaps the karstified limestone surface.

Late Triassic hypergene blankets are characterized by the development of thermal hypergenesis, in particular, within the Main Ural Fault zone with high-grade Ni deposits (Ufalei group, Akkerman deposit, and others). Gold deposits (Kirov and others) are known in fault zones at the boundary between the Magnitogorsk Trough and East Ural Uplift (Mikhailov, 1999).

Cretaceous (Aptian–Turonian) group. Cretaceous hypergene blankets are widespread throughout the Urals. They are developed as weathered rocks, gossans, karst and fluvial deposits, various bauxite, manganese, nickel, and gold ores related to the thermal hypergenesis, placers of titanium minerals, and so on.

The most complete and paleontologically substantiated Cretaceous hypergene sections are typical of the Transural peneplain (Southeastern Urals) mostly covered with the Cretaceous eluvium and products of its redeposition on land.

The thickness of the preserved hypergene blanket generally does not exceed a few dozen meters and reaches 200 m or more in some karst depressions and erosional-tectonic depressions. It should be noted that this thick cover is not commonly shown on geological maps. Its presence is only indirectly suggested by hypergene ore occurrences.

Numerous nearly meridional erosional-tectonic valleys filled with products of the proximal redeposition of commonly ore-bearing Cretaceous and Paleogene eluvium attract a special interest in the Urals (Guzovskii, 1971). These valleys often follow fault and crush zones in the basement associated with occurrences of thermal hypergenesis and ore-bearing karst.

Hypergene ore bodies are generally shown on the mineral resource and metallogenic maps as a part of deposits in the basement, resulting in substantial errors in hypothetical resource estimates. For example, Silurian and Devonian Mn-bearing rocks including several manganese deposits are commonly recognized in the Magnitogorsk Megasynclinorium. Actually, only the Cretaceous and, probably, Cenozoic oxidation zone (hypergene blanket, gossans) are of economic importance at these deposits. The Silurian and Devonian volcanosedimentary rocks contain only manganese silicates and carbonates having no economic significance (Mikhailov, 2001).

Oligocene group. The Aptian and Turonian reactivation of hypergene processes in the Urals gave way to the period of relative tectonic quiescence and slow marine transgressions from both the West Siberian and Russian plates. The rejuvenation of tectonic activity, relief formation, and weathering took place only in the late Paleogene. The hypergene blanket of this age markedly differs from the older blankets. First of all, Oligocene lateritic crust and related bauxites are absent in this region. In contrast to alumogoethite-containing hydroxides in Triassic and Cretaceous weathering crusts, iron hydroxides from the Oligocene eluvium lack the aluminum admixture.

The Oligocene hypergenesis is often superimposed upon older hypergene blankets with the formation of complex weathering profiles of ambiguous age. However, there are all grounds to state that hypergene alterations in the Oligocene developed rather actively. This is supported by the abundance of highly mature rocks (kaolinite clay, clayey marshallite, and quartz sand) containing stable heavy minerals.

Minerageny of the Oligocene hypergene blanket is diverse and characterized by the specific behavior of several ore and major elements. As a result of high geochemical mobility, iron hydroxides occasionally make up complete goethite pseudomorphs in quartz veins and limestone. Oligocene oolitic iron ore deposits with reserves of hundreds of million tons and economic placers of titanium and zircon minerals formed in the Transural region. Manganese behaves like iron, and manganese hydroxides concentrate in the upper zone of the Oligocene weathering crust and gossans as incrustations and pisolites. Manganese compounds occasionally absorb Co, Ni, Au, and PGE.

The Paleogene section is also characterized by high geochemical activity of silicon. Silicon readily migrated in the upper units of eluvial profiles and beyond them. Thus, thick silification zones appeared in the Oligocene. Chert beds formed in the coeval sedimentary sequences.

The karst topography continued to form in the Oligocene, and the depth of karst depressions locally reached hundreds of meters. Gold and rare metal placers are known at the bottom of such depressions.

Present-Day Mineral Potential of Hypergene Blankets in the Urals

The active development of mineral resources in the Urals began in the 18th century. Mainly high-grade iron ores hosted in Mesozoic and Cenozoic hypergene blankets were mined in the first two centuries. They included martite and pebble ores on the Blagodat, Vysokaya, and Magnitnaya Mountains (Fe 60% or more); turgite and hydrogoethite ores in the Bakal district (Fe 50–55%); hydrogoethite ores with Ni, Co, and V in the Orsk–Khalilovo district of the southern Urals; high-grade manganese oxide ores (40–45% Mn), bauxite ores in Cretaceous and Devonian hypergene blankets, and eluvial and karst Co–Ni ores in the Ufalei and Rezh districts of the central Urals (up to 2.0–2.5% Ni); copper, base metal, and gold ores in gossans at the massive sulfide deposits; brown coal fields; and numerous Neogene–Quaternary high-grade placers of gold, platinum, diamond, chromites, titanium minerals, gem stones, and decorative stones.

As the high-grade but commonly small (in reserves) hypergene deposits and placers became exhausted, large deposits of primary (endogenous) ores with a lower grade were put into operation (e.g., iron ores of the skarn magnetite, magnetite, and titanomagnetite types, as well as sideroplesite and pistomesite ores; siliceous–carbonate manganese ores; base metal massive sulfide, gold–sulfide, and gold deposits and so on). These deposits occur at a depth of tens and hundreds of meters.

Under the present-day conditions of the transition of the Russian industry to open market system and conversion of the State mining enterprises into joint-stock companies, the majority of mining plants in the Urals dealing with Fe, Mn, Al, Cr, Ni, Cu, and Au ores have lost the State subsidies and become noncompetitive on the world market. Several ore processing enterprises have been forced to import raw materials from abroad or transport them from Russian deposits situated many hundreds of kilometers from consumers (iron, manganese, and bauxite ores).

Iron ores. In the 1990s, 5 Bt of iron ore were registered on the State balance in the Ural region. If 10 Bt of hypothetical resources are added, the Uralian metallurgic industry should apparently be provided with iron ores for hundreds of years. However, the situation is not so simple. Now, the Magnitogorsk metallurgical plant, one of the largest in the Urals, is operating on ores imported from the northern Kazakhstan (Kachar deposit) and the Kursk Magnetic Anomaly (30% of ore consumption). The Orsk-Khalilovo plant (NOSTA) has also changed over to ore transported from distant sources. These dramatic changes are caused by the fact that 75.5% of the identified reserves in the Urals fall on the low-grade (Fe 16.6%) titanomagnetite ore of the Nizhnii Tagil district. The average grade in skarn magnetite deposits of the Urals is no higher than 2% Fe. Only 29% of iron ore reserves can be used without dressing (Table 2).

The situation is especially alarming in the old town of Bakal bounded more than 200 years ago on the basis of local iron ore deposits. Approximately 1 Bt of Riphean siderite (pistomesite–sideroplesite) ores and 100 Kt of brown iron ores in the polychronous hypergene gossan were registered on the State balance in the 1990s. Initially, only high-grade brown ironstones with 50–55% Fe were mined. However, when the miners had to deal with the Riphean siderite, this ore turned out to be a refractory mixture of sideroplesite and pistomesite containing 10–15% MgO (Table 2). The high-grade brown iron ore should be added as a deoxidizer for fusing the Bakal siderite. To date, such brown iron ore deposits, which were discovered and explored may years ago, are virtually exhausted throughout the entire Urals.

The high-grade brown iron ores are only known in hypergene blankets. They are also necessary for the Orsk–Khalilovo metallurgical plant specially constructed for reworking the Ni-, Co-, and V-doped brown iron ores from the Khalilovo and Khabarny ultramafic massifs in the southern Urals.

Such ores may be discovered in hypergene blankets in other areas of the Urals, such as the Buruktal and Sakharinskii ultramafic massifs (Ni-rich brown iron ores (structural ochers), which are stripped in open pits of this area and dumped, contain 40% Fe) and margins

Table 2. Composition of economic iron ores in the Urals

The 1930s–1940s (Great Soviet Encyclopedia, 1952)					The 1990s (State balance, 1991)			
Ore type	Fe %	L.O.I., %	Ore minerals	Note	Ore type	Fe %	Ore minerals	Note
Pebble ore	61.1	2.4	Hematite, hydrohematite	Mount Magnitnaya	Skarn magnetite	25–36	Magnetite	Mount Magnitnaya
Martite	61.9	0.8	Hematite	Mount Magnitnaya	Kachkanar and Gusevogorsk titanomagnetite	15–17	Magnetite, titanomagnetite	Mount Magnitnaya
Half-martite	55.0	2.5	Magnetite, hydrohematite	Mount Vysokaya	Skarn magnetite	20–30	Magnetite	Mount Blagodat
Kusa titanomagnetite	46.2	0.6	Titanomagnetite	TiO_2 – 12.5% V – 0.35% Cr – 0.22%	Bakal siderite	31.6	Sideroplesite, pistomesite	MgO – 10–15%
Khalilovo brown ironstone	40.9	8.5	Goethite, hydrogoethite	Ni – 0.66% Cr – 1.27%	Brown ironstone	40–45	Goethite, hydrohematite	Reserves are limited
Pebble ore	55.2	3.93	Hematite, hydrohematite, goethite	Mount Blagodat				
Martite	64.1	1.8	Hematite	Mount Blagodat				
Bakal limonite	53.2	12.72	Goethite, hydrogoethite	MnO – 1.0%				
Bakal turgite	61.0	4.8	Hydrohematite, goethite	MnO – 3.0%				

of the exhausted Magnitnaya, Vysokaya, Blagodat, and other open pits where the reappraisal of preserved nodule and martite ores would also be reasonable.

Deposits of high-alumina iron ores in the Urals also deserve attention. Technology of their processing for the production of alumina and high-quality cast iron was developed by Odokiĭ (1984). The high-alumina ores include Ni- and Co-doped brown iron ores of the Khalilovo type, Upper Devonian hematite–diaspore pisolitic ores in the southwestern SUBD framework, as well as hundreds of million tons of Cretaceous sedimentary Co- and Ni-doped pisolitic iron ores in the Serov district of the northern Urals.

Manganese ores. Numerous Mesozoic–Cenozoic manganese oxide caps developed on Mn-bearing rocks of variable composition, genesis, and age served as sources for metallurgical plants in the Urals in XVIII–XIX centuries. Historical records bear information about the mining of high-grade pyrolusite–cryptomelane ores along the banks of the Sos'va River composed of Paleogene low-grade siliceous–carbonate manganese ores deposited in the coustal-marine environment. Mesozoic–Cenozoic manganese oxide caps of the Sapal deposit (central Urals) were also mined. In the south (Orsk region), hypergene oxide ore was mined at the Faizula, Yalimbet, and other small deposits confined to exposures of Devonian Mn-bearing volcanogenic siliceous rocks. However, since the early XX century, when the unique Nikopol (Ukraine) and Chiatura (Georgia) deposits were put into operation, the mining of manganese ore in the Urals drastically decreased and reached just 0.3% of the total amount of manganese ore mined in Russia by the beginning of World War I (Sustavov, 1997).

Deposits in the Ukraine and Georgia remained the main source of Mn for the rapidly growing metallurgy of the Soviet Union in the 1930s. All efforts of the Geological Survey of the Soviet Union to find alternative Mn sources in the Urals were unsuccessful. They usually resulted in the discovery of ore occurrences (small subeconomic deposits?) or the formulation of recommendations coupled with the estimation of hypothetical resources.

A paradoxical situation arose in the Urals by the end of XX century. In 1999, the total amount of hypothetical resources of manganese ore estimated by E.S. Kontar and K.P. Savel'eva was 580 Mt. These authors also stated that "together with the speculative resource potential of so far insufficiently studied levels and areas, the total amount of undiscovered resources in the

Table 3. Characteristics of manganese ore reserves

Country and ore type	Proven reserves	Mn in crude ore	Mn in market ore	Prevalent ore minerals
Australia	300	38–50	50–55	Pyrolusite, cryptomelane, less abundant manganite and nsutite
Brazil	200	30–40	50–53	Cryptomelane, pyrolusite, manganite, lithiophorite, braunite
Gabon	400	40–55	48–60	Pyrolusite, cryptomelane, manganite
India	100	25–50	40–50	Pyrolusite, manganite, braunite, cryptomelane, hausmannite
South Africa	1000	25–55	48–52	Pyrolusite, manganite, braunite, hausmannite, cryptomelane
Ukraine, oxide	200	20–23	38–48	Manganite, cryptomelane, pyrolusite
Ukraine, carbonate	1000	18–22	–	Rhodochrosite, manganocalcite
Georgia, oxide	30	25–35	45–50	Pyrolusite, cryptomelane
Georgia, carbonate	140	18	–	Rhodochrosite, manganocalcite
Russia, oxide	7.5	27	Up to 40	Cryptomelane, vernadite, manganite, pyrolusite
Russia, siliceous–carbonate	160	16–20	Up to 22	Rhodochrosite, manganocalcite, oligonite
including the Urals				
oxide	1.5	25–30	Up to 40	Cryptomelane, pyrolusite, manganite, braunite, hausmannite
siliceous–carbonate	40	17–21	Up to 25	Rhodochrosite, manganocalcite, oligonite

Note: Ore reserves are given in Mt; Mn content, in %.

region (without taking into account the potential of the Pai Khoi–Novaya Zemlya province approaches 1 Bt" (Kontar *et al.*, 1999, p. 112). Researchers of the All-Russia Research Institute of Geology and Mineral Resources of the World Ocean (VNIIOkeanologiya), who discovered the Pai Khoi–Novaya Zemplya Mn-bearing basin, estimated its potential at several tens of billion tons (Platonov *et al.*, 1992). At first glance, since the annual consumption of manganese concentrate by the Uralian metallurgic industry amounts to several hundreds of thousand tons, the situation seemingly looks quite good. However, in the light of incorporation of Russia into the world economy, the actual state of affairs with the manganese ore base in the Urals is far from safe.

Metallurgy of the developed countries is largely based on hydroxide manganese ores mined from large and giant deposits localized within the present-day tropical belt of the Earth. The comparison of these ores with identified reserves in Russia (Table 3) demonstrates that our reserves are smaller and dominated by siliceous–carbonate (silicic module $M_{Si} = 1–2$) and carbonate–siliceous ores ($M_{Si} < 1$) that are not used abroad. The low Mn content, occasional, high grade of metamorphism, and enrichment of ore in S and P are additional unfavorable factors.

Study of manganese ore sources in the Urals (Mikhailov, 2001) led to the following conclusions.

(1) Conditions and environments favorable for the formation of large and high-grade manganese deposits, similar to those in the present-day tropical belt (South Africa, Brazil, Gabon, India, and others) were not developed in the geological history of the Urals. Therefore, the Uralian metallurgic industry must either use the lower-quality domestic ore with its subsequent complicated dressing or rely on the import of high-quality ore (Table 3).

(2) Small economic-grade manganese ore deposits and manganous caps pertaining to the Mesozoic–Cenozoic hypergene blankets may be discovered in the Urals. Intensely crushed and readily weathered rocks with very high contents of various manganous minerals (Mn-bearing limestone, marble, dolomite, tuff, carbonatized tuffaceous breccia, tuffite, skarn, and so on) are the best protoliths for these blankets.

Manganous ore caps are easily formed under conditions of hot and humid climate in regions with a dissected, medium- and low-mountainous topography. Such environments existed in the Urals in Late Triassic, Cretaceous, and Oligocene.

These periods were also characterized by the development of Mn-bearing karst. Review of works of E.A. Baskov, D.I. Pavlov, and other researchers devoted to karst deposits in the world shows that karst manganese deposits are formed under the impact of both meteoric and deep-seated polygenetic (sedimentary, infiltrational, regenerated, and metamorphic) waters (Varentsov, 1996; Mikhailov *et al.*, 1998).

Thus, we believe that prospecting for high-grade oxide ores in manganous ore caps confined to Mesozoic–Cenozoic hypergene blankets is among the most important and realistic geological tasks aimed at providing the Uralian metallurgic industry with manganese ores. It is expected that these deposits will not be large in reserves (hundreds of thousand or a few million tons). They should contain 30–35% Mn in the form of pyrolusite, cryptomelane, and manganite. The Cretaceous Transural peneplain, Zilair Plateau, and the northern Orsk Basin are the most prospective territories.

Experience of long-term prognostic research shows that the most productive Mn-bearing caprock occurs in the present-day depressions beneath the Neogene–Quaternary sedimentary cover that prevents them from erosion. In this case, the caprock is spread over the loam cover and pebble placers with fragments of high-grade manganese oxide ores are formed.

The metallometric geochemical exploration of Mn is efficient in areas partly or completely covered by loose sediments, such as the southern and central Urals. Manganese anomalies (0.5–1.0%) occupying areas of a few hundred meters may serve as prospecting guide for the Mn-bearing caprock.

Alumina ores. Alumina (Al_2O_3) is an intermediate mineral product derived from various raw materials and used for obtaining different final products. The alumina recovery technology is elaborated for virtually all high-alumina rocks (Mikhailov, 1982), but only bauxite and nepheline ores are used in practice as alumina sources. These ores must contain no less than 25–27% Al_2O_3 and 15–17% $Na_2O + K_2O$. Previously, the plant built in Kirovobad, Azerbaijan treated alunite to obtain alumina, potassium sulfate, and sulfur acid. Alumina is primarily used for the production of aluminum in metallurgical works.

Despite the similarity with bauxite in alumina content and silicic module, all other aluminous rocks are recognized under special names (Mikhailov, 1988). To date, bauxites, silicate diasporites, and chemallites are known in the Urals, but only bauxite is of economic importance.

Bauxites (bauxite ores). Bauxites and bauxite-bearing sediments occur in the Urals in both the folded basement and sedimentary cover. Economic bauxite ore deposits are localized only in the hypergene blankets of the Middle Devonian eugeosynclinal, Upper Devonian miogeosynclinal, Upper Triassic subplatformal, and Cretaceous platformal bauxite-bearing complexes (*Boksitonosnye…*, 1987).

The structure, composition, formation conditions, and economic significance of bauxite-bearing complexes are scrutinized in the above monograph. Therefore, we shall discuss below mainly prognostic estimates of the entire Ural section for bauxite ore.

The current state of affairs concerning the provision of alumina plants in the Urals with domestic raw materials is extremely grave. Mining of Mesozoic bauxites ceased long ago and mines in the SUBD are abandoned. Mines in the NUBD actually situated in the West Siberian lowland have reached a depth of more than 500 m, and their deep horizons lie 200–300 m beneath the sea level in kartified carbonate rocks. Expensive measures required for preventing groundwater inflow markedly depresses the efficiency of mining. The Bogoslovka and Ural alumina plants have to transport compositionally different and lower-quality ores from Timan and modify the technological process.

In this situation, forecasting and prospecting for alumina mineral deposits should be resumed.

In the monograph mentioned above, the characteristics of bauxite potential of the Urals is based on data retained to outcrops, workings, and boreholes within a depth interval of approximately 1 km. Materials concerning the deeper levels are speculative and based on the extrapolation of surface data taking into account usually equivocal geophysical results. For example, as follows from the description of the Middle Devonian bauxite-bearing complex (*Boksitonosnye…*, 1987), favorable conditions for the formation of economic deposits existed in Eifelian and Givetian only on the eastern slope of the northern Urals. Efforts to find bauxites in the southern area including the Turgai Trough were unsuccessful. However, this by no means implies that bauxites do not occur there, because only the shallow-seated parts of Devonian sections have been examined.

Prospects for bauxite mineralization in areas north of Ivdel, i.e., on eastern slopes of the northern, Subpolar, and Polar Urals, which are located in the northern zone extending from deposits of the NUBD to ore occurrences in the Shchuchinsk Synclinorium, are somewhat better substantiated. In the 1970–1980s, this poorly studied territory was explored by geologists from the following regional geological surveys: Polyarnouralgeologiya (S.D. Petrov, I.V. Maksimov, V.P. Teplov and others); Uralgeologiya (O.A. Tkachenko and G.A. Bol'shun); All-Russia Research Institute of Geology (R.I. Eroshevskaya and B.M. Mikhailov); Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (B.A. Bogatyrev); and All-Russia Institute of Mineral Resources (S.K. Gipp and M.V. Voinov). Based on new data, they suggested that the belt of Middle Devonian bauxite deposits extends further northward. Unfortunately, these promising investigations ceased due to collapse of the Geological Survey of the former Soviet Union.

In the basal unit of the lower Eifelian Takatin Formation on the western slope of the central Urals, Eroshevskaya found clayey rocks with minerals of free alumina. Unfortunately, these investigations were terminated.

Table 4. Principle parameters of the mineral base of oxide–silicate nickel ores in the world

Country	Ni reserves, Mt	Ni mining, kt	Ni content in ore, %
Cuba	18.000	40.0	1.10–1.16
New Caledonia	11.700	121.0	2.10
Indonesia	2.960	88.2	1.60
Philippines	0.370	3.5	2.10
Columbia	0.450	24.0	2.60
Russia (active reserves in the Urals)	~0.500	8.0–10.0*	1.0–1.2

Note: * Based on (Proshin and Gorelov, 1997).

Bauxite potential of the Sakmarian (Lower Permian) reef limestone remains a debatable issue. Many Uralian geologists believe that Permian rocks are not prospective for bauxites because of the arid climate that existed in Permian Period. At the same time, Permian bauxite deposits are known in Turkey, Iran, Afghanistan, Korea, and Vietnam. It cannot be ruled out that the opinion of Uralian geologists is wrong. In particular, the sharp contact of the Sakmarian light gray (with crimson spots) reef limestone with the Artinskian dark gray platy dolomite and carbonate shale attracts the attention. The surface of Sakmarian reef limestone is karstified, and the general environment is quite similar to that in the Middle–Upper Devonian bauxite-bearing sections. Based on the review of archive data, G.A. Bol’shun and N.V. Fedorov established that previous geologists had reported various forms of bauxite and allite blocks and outcrops at this contact. The data reported by P.V. Lazarev are apparently very reliable. In order to check the report submitted by V.D. Nalivkin concerning the development of bauxites, he trenched the contact between the Sakmarian reef limestone and Artinskian dolomite near the Settlement of Yaroslavka (Duvin district, Bashkyrtostan) and found that the allite unit at the contact contains 32.98% Al_2O_3 and 16.8% SiO_2.

The subplatformal and platformal bauxite-bearing complexes are rather comprehensively studied to a depth of 150–200 m (*Boksitonosnye…*, 1987; Savel’eva, 1997; and others). However, vast areas in the Transural region with promising bauxite occurrences at a great depth remain to be assessed. The bauxite potential of the western limb of the Magnitogorsk Synclinorium in the Lower Carboniferous carbonate rock field is incompletely evaluated so far. We should check karst holes filled with the deficient (Ca-free) electrocorundum bauxite in this area. In particular, several Cretaceous bauxite-bearing karst depressions were found on the right bank of the Ural River (Lower Orlovka tributary basin). The exposed bauxite lenses contain as much as 60% Al_2O_3 and 1.5–1.8% SiO_2. The total reserve of high-grade ores is estimated at 0.5 Mt (Nozdrin, 1959). The near-surface bauxite orebodies (approximately 100–300 kt) situated in the developed regions are of economic importance.

Bauxite resources in the world are as much as several tens of billion tons. Russia is one of the few countries that import bauxite or alumina for the operation of aluminum plants. To date, we do not have feasible substitutes for bauxite. However, in the case of unexpected situations, the bauxite and nepheline ores may be replaced by alunite ores and synnyrites, which are abundant in Russia. At worst, kaolin, anorthosite, and some other high-alumina rocks, which have been tested for the technology of alumina recovery (Odokii, 1984), can be used.

Nickel ores. The Urals with their 11% of total Russian Ni reserves (Kozlovskii, 2002) is second to the Talnakh–Noril’sk district in terms of ore source for the Russian nickel industry. Plants processing the typical Uralian cobalt and nickel oxide-silicate ores have been built in Orsk, Ufalei, and Rezh. All of the known nickel deposits are confined to the Mesozoic hypergene blanket that includes polygenous and polychronous rocks related to ultramafic dunite–harzburgite massifs.

The Uralian nickel ores are compositionally similar to Cenozoic Ni-bearing laterites in the Earth’s present-day tropical belt, which contain more than 70% of the world nickel resources. However, no direct analogues of Ni-bearing laterites are known in Russia and, probably, elsewhere in the CIS. The Uralian hypergene nickel ore deposits are older formations related to substantially different tectonic and paleogeographic environments. It is evident from Table 4 that the Uralian ores are characterized by lower grade and worse technological parameters. They require special methods of forecasting, prospecting, and evaluation (Mikhailov, 2002).

At present, the Buruktal deposit is the main source of ore for the South Ural nickel plants (SUNP). The Sakharin deposit is at the preparation stage. The Serov deposit (Elov open pit) provides the Ufalei and Rezh plants with nickel ore. All deposits are situated 240–500 km from the consumers.

The Buruktal deposit, the largest complex Fe–Co–Ni deposit in Russia, is related to the eponymous ultramafic massif in the eastern Orenburg region (240 km east of Orsk). The ultramafic massif and ore deposit were studied by many geologists (Edelstein, 1956; Nikitin, 1962; Grigor’eva and Sheshukova, 1969; Vershinin, 1996; Mikhailov, 2000b; and others).

The massif is intensely deformed and crosscut by different-aged crush and fault zones. Abundance of tectonic zones favored the development of thermal metamorphism with the formation of tremolite, chlorite, and talc. The subsequent tectomagmatic reactivation in Early Mesozoic resulted in the thermal hydrolysis of rocks within the entire hypergene zone.

The Buruktal deposit includes seven ore sectors. The major reserves and the open pit put in operation in 1978 are related to the sector N_3 area (Table 5).

Table 5. Characteristics of economic ores in the Buruktal deposit

Metal	Deposit as a whole		N_3 ore sector					
	Ovchinnikov (1998)		Approved by the SCR of the Soviet Union (1 May 1968)		TEA, Gipronikel, 1992		Open pit (N_3 ore sector), 2000–2001	
	reserves, kt	content, %	reserves, kt	content, %	reserves, kt	content, %	content, %	
							plant	storage
Nickel	1377.0	0.97	1032.0	0.89	715.196	1.11	in blocks 1.1–1.2 ~1.15	0.9–1.03
Cobalt	121.37	0.06	96.769	0.084	67.404	0.105	–	
Tentative (adjusted) nickel	$\frac{2226.59}{(\mathrm{Ni}+7\mathrm{Co})}$	1.39	$\frac{1639.476}{(\mathrm{Ni}+7\mathrm{Co})}$	1.3	$\frac{782.6}{(\mathrm{Ni}+\mathrm{Co})}$	1.21	–	
Naturally doped iron ore	892 kt		1.3 Mt of ore with 35% Fe, 0.45% Ni, and 0.034% Co				to storage (ore with 25–28% Fe)	

Note: (SCR) State Commission for Reserves; (TEA) technical and economic assessment.

The deposit was explored in the 1950s when the information concerning Co and Ni reserves could not be published. Demand and prices for metals were dictated by the defense industry and subsided by the government.

The first estimation of reserves was approved by the State Commission for Reserves in 1968. The cutoff grade of conditional nickel ($\mathrm{Ni_c}$ = Ni% + 7Co%) was accepted as 1.3% within a rock block. The minimum economic ore grade was 0.6% Ni and 0.05% Co. The attendant iron ore reserve (1.3 Mt) with 35% Fe, 0.45% Ni, and 0.034% Co were also taken into account (Table 5). In the 1950s, the construction of a plant was started at the Settlement of Svetloe 7 km from the Buruktal deposit in order to process complex ore of the deposit by electromelting with the recovery of Ni and Co.

However, in the early 1960s, nickel works in the Urals (particularly, at the Buruktal deposit) were abruptly reduced and then almost completely abandoned due to the discovery of the Talnakh deposit (Noril'sk district, northern Siberia), one of the largest Cu-Ni ore deposits in the world.

After the revolution in 1958, Cuba, one of the leaders in nickel reserves, became the main supplier of nickel concentrates to the Soviet Union. Workshops of the future Buruktal plant were redesigned for processing these concentrates and included into the SUNP management.

In the 1990s, nickel plants in the Urals were transformed into joint-stock companies, and the State subsidy was terminated (Stukalov and Muftakhov, 1996).

In addition, these plants also suffered severe losses due to the uncontrolled export of scrap nickel that partly compensated for the low Ni grade in domestic ore.

Before 1991, the group of deposits in Kempirsai located 80 km south of the SUNP served as main ore source. After breakdown of the Soviet Union, these deposits turned out to be in Kazakhstan. Attempts to create a joint Russian–Kazakhstan company for mining these deposit failed mainly due to the exhaustion of the Kempirsai deposits that were intensely mined over the last fifty years.

In the 1990s, specialists of the Gipronikel Institute analyzed the state of the SUNP mineral resource base and supported the proposal to use the Buruktal deposit as the major ore supplier. The technical economic assessment elaborated in 1992 under the supervision of chief specialist A.A. Bugaev provided for substantial changes in the parameters approved by the State Committee for Reserves of the Ministry of Geology of the Soviet Union in 1968 (Table 5). The main point of these changes consisted in the drastic decrease in cobalt contribution to the end product cost and the simultaneous increase in the average Ni grade to 1.1%.

Although, the Gipronikel proposals have not yet been considered by the Russian State Commission for Reserves, they are now applied (with some modifications) in the intense mining of the Buruktal deposit since the late 1990s. This complex Fe–Co–Ni deposit is currently mined as a virtually pure nickel deposit with the total Ni reserve of 715.196 Kt (Table 5).

Let us discuss additional specific features of ores in the Buruktal deposit area.

Based on orebody morphology, all nickel ore deposits in the hypergene zone are divided into the stockwork and stratal (weathering crust and laterite blanket) types (Fig. 2).

Veined ("tectonic") deposits in New Caledonia containing 6–10% Ni were the first economic hypergene

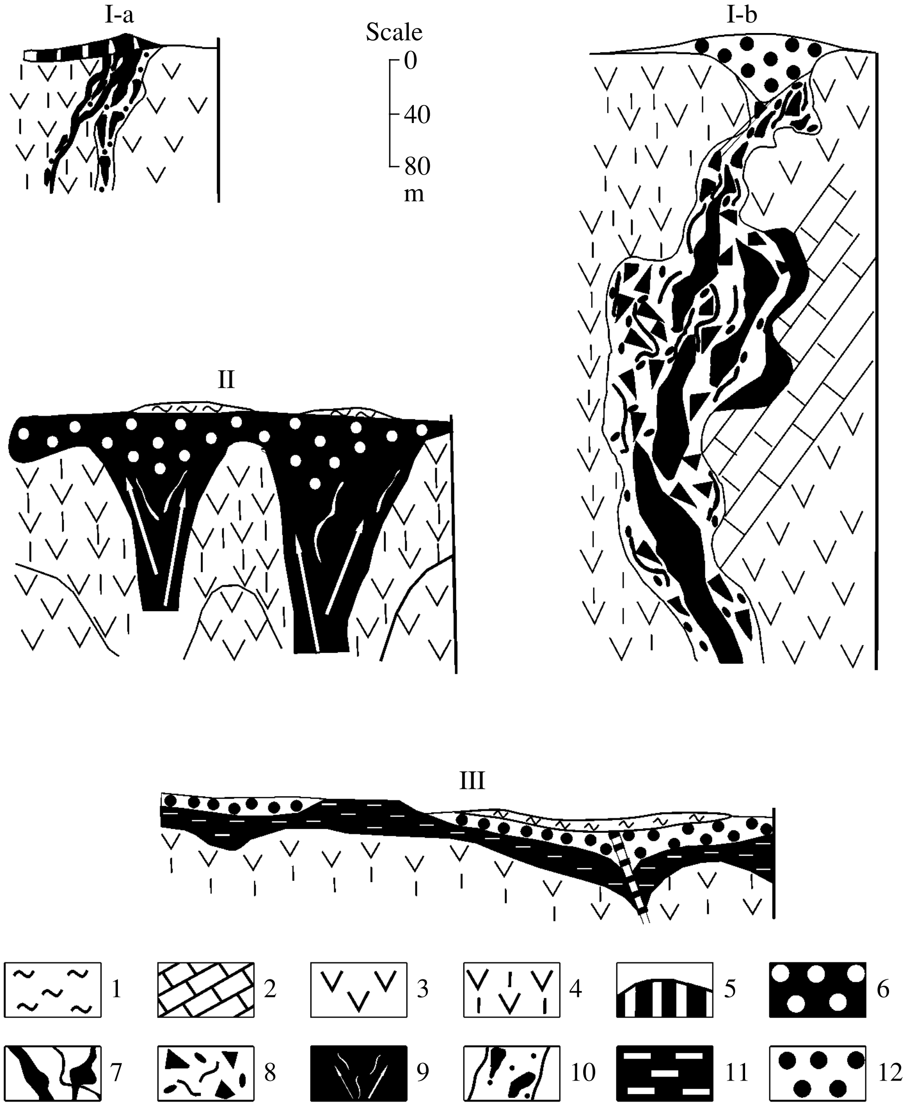

Fig. 2. Various morphological types of hypergene nickel orebodies. (I) Veined type: (Ia) Boa Kain area, New Caledonia (Glasser, 1903); (Ib) Cheremshanska lode in the Ufalei deposit, central Urals (Mikhailov, 1997); (II) stratal–veined type, a part of profile XIX, N_3 ore sector of the Buruktal deposit, southern Urals (Mikhailov, 2002); (III) stratal type, sector of the Kempirsai deposit, Mugodzhary Mountains (Grigor'eva and Sheshukova, 1969). (1) Loam and sandy loam; (2) limestone; (3) serpentinite; (4) hydrated serpentinite (locally ore-bearing); ore types: (5) Ni-bearing laterite (Ni 1.4–2.0%), (6) Co–Ni ocher (Ni 1.1–1.3%, Co 0.05–0.10%), (7) quartz–garnierite (occasionally limonitized nodular and lenticular) ores (Ni 3–5%, occasionally up to 10–15%); serpentinite melange with Ni hydrosilicates (Ni 0.9–2.0%); (9) severely hydrated serpentinite–talc–chlorite clayey rock with relict texture of serpentinite (Ni 1.5–2.5%); (10) hydrated, silicified, and limonitized serpentinite with nickel hydrosilicates (Ni 1.5–3.0%); (11) nontronite clay (Ni 0.7–1.3%); (12) barren siliceous ocher.

nickel deposits to be mined at the beginning of XX century (Glasser, 1903). High-grade ores of these deposits occur as veins and linear stockworks, up to 10–20 m thick, in crush zones within ultramafic massifs. Boreholes traced the ores to a depth of 100–200 m. Nickel in veined ores is concentrated in garnierite associated with quartz, chalcedony, opal, carbonates, iron oxides, and products of serpentine hydrolysis. The average ore composition is as follows (%): SiO_2 42.5, Fe_2O_3 15–20, MgO 20–30, and NiO 5–10.

The Chusov lode in the Cheremshan deposit of the Ufalei group is a typical example of veined (stockwork) thermal hypergene deposit in Russia. This deposit has been mined to a depth of 240 m and penetrated by boreholes to 400 m. The Ni content at the hole bottom is 4% (Fig. 2).

Ore stocks of the Akkerman deposit in the southern Urals belong to the same type. In the 1940–1960s, they were mined to a depth of 20–40 m and abandoned due to the strong groundwater inflow.

However, the main world resources of hypergene nickel ores are related to eluvial deposits of the Earth's present-day tropical belt (New Caledonia, Cuba, Brazil, Indonesia, and others). The ores occur as layers, commonly 2–5 m and occasionally 10 m thick, confined to ochreous–clayey zones of lateritic blankets. The Ni content in these ores commonly does not exceed 1.4–1.6%.

The unique character of the Buruktal deposit as compared with other hypergene deposits of the world consists in the following features.

(1) The nontronite zone, commonly rich in Ni, is lacking.

(2) The siliceous ocher (2–6 m) and underlying hydrated serpentinite zones serve as the main carriers of Ni and associated Co.

(3) The siliceous ocher zone is characterized by low Ni and high Co contents (0.7–0.9% and 0.10–0.15%, respectively).

(4) The hydrated serpentinite zone has a complex structure. Orebodies of variable thickness therein consist of hydrated, commonly whitish or light gray serpentinite with a network of greenish brown thermal-metasomatic ore veins. They are also hydrated and crosscut by the inherited fracturing of the massif. The thickness of veins varies from 1 to 3–5 m and reaches 10 m in bulges. The veins are largely composed of the serpentinite–talc–chlorite aggregate with manganese hydroxides, abundant magnetite dissemination, and opal, chalcedony, and quartz veinlets. The minerals contain 3–6% Ni and up to 0.15% Co (Grigor'eva, 1969; Vershinin, 1996). At the same time, the Ni content in the hydrated serpentinite is only slightly higher than the clarke value (0.3–0.5%, on the average).

Thus, if the hydrated serpentinite zone is mined by the continuous face method, the average Ni content in ore turns out to be 0.7–0.9% and the ore cannot efficiently be processed by the blast smelting technique applied at the SUNP. Therefore, the selective mining technique was applied in the open pit of Orebody N_3 in 2000–2001. The ore was divided into three groups directly at the pit face: (1) economic-grade ore with an average Ni content of 1.1–1.2% (cutoff 1.03%), (2) low-grade ore with 1.03–0.9% Ni, and (3) tails with <0.9% Ni. The economic-grade ore was transported to the plant, while the low-grade ore was stored as tailing (Table 5).

It is evident that this mining system leads to a significant loss of metals and mineral resources discovered by geologists in the 1950s–1970s.

Our observations in the functioning open pit suggest that the Buruktal deposit should not be considered a stratal eluvial deposit representing the Ni-bearing weathering crust.

Drastic inhomogeneity and frequent alternation of ore compositions within the hydrated serpentinite zone hamper the geometrization of the ore blocks and efficient mining. High-grade ores makes up nearly vertical stocks, which are exposed as greenish brown spots at the surface of trimmed benches. These stocks are traced at the Buruktal deposit to a depth of 60–80 m and known in the literature as weathered rock pockets (Grigor'eva, 1969; Vershinin, 1996). These stocks should actually be regarded as former conduits for hydrothermal solutions and their discharge zones (Fig. 3).

Thus, the Buruktal deposit is a specific morphological and genetic type of stratal-vein thermal-hypergene nickel mineralization. Exploration and mining of such deposits must be performed with the consideration of their specific features (Mikhailov, 2000a, 2002).

The Serov deposit (Elov open pit) is situated on the eastern slope of the northern Urals and related to the Kola ultramafic massif. The deposit can be divided into several equant areas including the most prospective Elov area, where the open pit was put into operation in the late 1980s.

Based on the study of exploration borehole cores, the majority of researchers concluded that the Serov deposit is a fragment of Triassic–Jurassic weathering crust that was significantly altered in the Late Jurassic and Early Cretaceous by "strong infiltrational-metasomatic processes with the formation of atypical rock and mineral assemblages in the weathering crust, such as chamosite rocks containing a variable amount of relict minerals inherited from the Triassic-Lower Jurassic residual crust and newly formed (Middle Jurassic-Lower Cretaceous) magnetite, siderite, manganosiderite, millerite, and marcasite" (Kononova *et al.*, 1974, p. 163).

Examination of the open pit in 1994 and study of the collected samples allowed us to doubt the validity of the commonly accepted genetic model of the Serov deposit. We suggest that the upper part of the nearly vertical linear stockwork, which is about 200 m across and genetically similar to ore stocks in the Ufalei and Akkerman districts, rather than Ni-bearing weathering crust is exposed in the Elov open pit (Mikhailov, 2000a).

In other words, we deal here with the subsurface part of a Ni-bearing hydrothermal system that existed during the Early Mesozoic tectonomagmatic reactivation on the eastern slope of the Urals.

Reduced hydrocarbonate (gley) hydrothermal solutions ascended along the deep fault zone filled with intensely crushed rocks (serpentinite melange) and induced hydrolysis and metasomatic alteration of serpentinite, resulting in the formation of the specific mineral assemblage of Ni-rich serpophyte, chamosite, chlorite, millerite, garnierite, and other nickel hydrosilicates, along with talc and carbonates (see works of V.M. Grigor'eva, E.N. Kuzemkina, and L.I. Kononova). The ore-forming hydrothermal solutions locally poured onto the surface and made up organic-free fumarole blankets. The Ni-enrichment of sediments

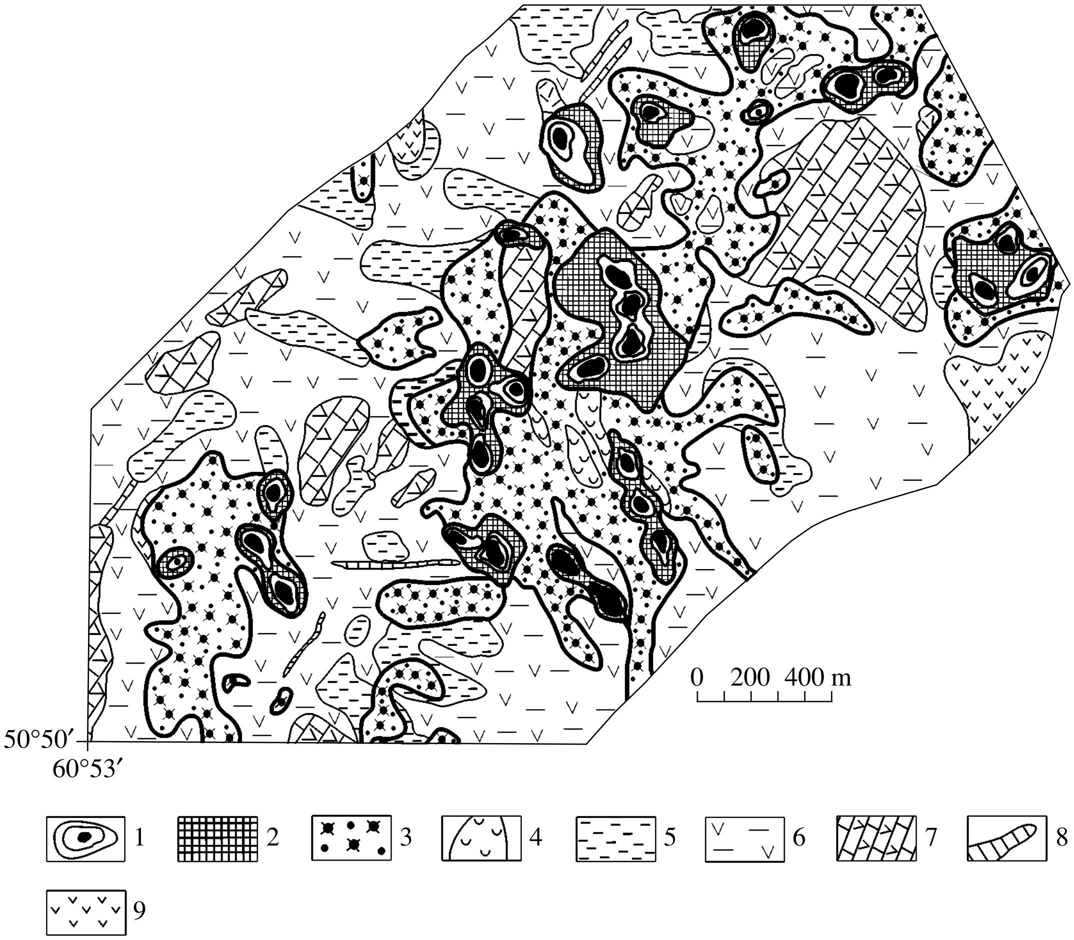

Fig. 3. Lithological map of the Late Triassic fumarole field (southwestern part of sector 3 in the Buruktal deposit). Modified after V.E. Vdovina, O.S. Gerasimenko, and I.G. Zyuzina in 2000–2001. (1) Ore stocks penetrated by boreholes to a depth of 80–120 m; (2) talc–chlorite–serpentinite rock (product of serpentinite reworking by Ni-bearing hydrothermal solutions, i.e., ore-bearing fumaroles; (3) Co- and Ni-bearing ocher and siliceous ocher; (4) silicified and limonitized leached serpentinite; (5) serpentinite replaced by nontronite (often ore-bearing); (6) intensely hydrated (steamed) light gray (whitish) serpentinite (occasionally Ni-bearing); (7) carbonated serpentinite; (8) (hydrated mainly diorite) dikes; (9) serpentinite.

was caused by the percolation of hydrothermal solutions in the serpentinite melange.

If our suggestions are correct, the search for high-grade nickel ores should be focused on fault zones, which crosscut the ultramafic massifs, such as the Main Ural Fault and regional faults bordering the Magnitogorsk and Tagil sinclinoria, rather than lateritic weathering crusts.

Gold potential of hypergene blankets. Hypergene blankets are geological bodies most enriched in gold. The related alluvial, talus, proluvial, eluvial, and karst placers of various ages yielded the major mass of the gold in the Urals. The composition, structure, and economic significance of placers are discussed in several publications. Therefore, only a debatable issue concerning the recognition and evaluation of gold deposits related to thermal hypergenesis (Mikhailov, 1999) is considered below.

Several large deposits of fine-dispersed free gold were recently discovered in Meso–Cenozoic hypergene blankets over the world. Host rocks at these deposits commonly consist of quartz–muscovite schists with paragonite, chlorite, and lenticular limestone interlayers. The primary low-grade stringer-disseminated gold–sulfide ore mineralization is generally unsuitable for industrial dressing with cyanidation. The Kirov and Svetlin (southern Urals), Vorontsov (central Urals), and Katalambi-Yu (Subpolar Urals) deposits can be referred to this type (Rindzyunskaya *et al.*, 1995; Savel’eva, 1997). Orebodies in these deposits are composed of clayey kaolinite–sericite rocks with occasional paragonite. The finely dispersed gold occurs in free form as small particles (<0.3 μm), while the newly formed hypergene gold of high fineness makes up thin films and globules. Such hypergene ores (Au 5–10 g/t or more) are most suitable for the processing with cyanidation.

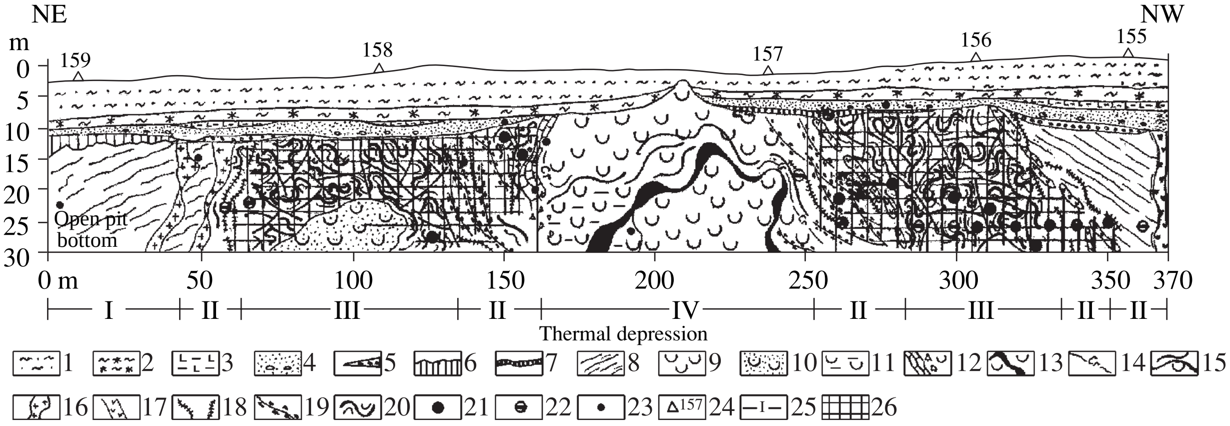

Fig. 4. Cross section of the open pit at the Kirov deposit. (1) Pliocene and Quaternary brownish gray loam and sandy loam (locally loesslike); (2) Pliocene Zhilandy Formation (reddish gray calcareous loam with gravel and rubble lenses); (3) Miocene Aral (Svetlin) Formation (greenish gray lumpy clay with manganese oxide selvages and sporadic ferromanganese nodules, gravel and rubble at the base; (4) Oligocene Chilikta Formation (?) (brownish yellow clayey silt and fine-grained sand, layers of limonitized sand and pebbles at the base; (5) Upper Triassic (?) conglomerate and conglobreccia consisting of varisized quartz and limonitized silicified rock pebbles and quartz and carbonate cement; (6) Cretaceous light gray to white kaolinite clay with relict structure of schists (eluvium of Lower Carboniferous carbonaceous quartz–mica schists); (7) Upper Triassic gray quartzite with sporadic siderite inclusions; (8) Lower Carboniferous slightly hydrated and partly silicified carbonaceous quartz–sericite schist, siltone, sandstone, and tuffite; (9) white marshallite with nodules of milky white quartz; (10) yellowish white silty marshallite; (11) clayey kaolinite–sericite marshallite; (12) loose and crushed limestone with sponge spicule imprints (locally silicified); (13) gray and dark gray wavy marshallite interlayers; (14) thin discontinous interlayers of Cr-bearing smectite clay; (15) thin (occasionally filiform) interlayers of gray smectite clay; (16) hydrated (locally silicified) diorite dikes; (17) hydrated and locally silicified (mainly diabase) dikes; (18) quartz veins and veinlets; (19) intense detachment zones accompanied by limonitization of rocks and formation of brown limestone geodes and concretions; (20) intensely hydrated and deformed carbonaceous quartz–mica schists (with numerous fractures and detachments) transformed into pale gray clay locally containing abundant pockets of secondary quartz, sporadic carbonate crystals, and clots of colloform isotropic material (often bear economic gold mineralization); Au content, g/t: (21) >0.5, (22) 0.1–0.5, (23) 0.01–0.1; (24) intersections of borehole profiles; (25) thermal depression zones (from margin to center): (I) slightly hydrated carbonaceous quartz–mica schists with limestone lenses (bioherms and reefs), (II) zone of hydrothermally altered dikes framing the thermal depression, (III) gold ore zone, (IV) reef transformed into marshallite; (26) gold orebody.

Orebodies in these deposits are commonly referred to eluvial, linear fissure, and contact karst types of Au-bearing weathering crusts. However, such classification is doubtful.

All open pits at these deposits are circular (in planview) in compliance with the morphology of nearly vertical hydrated Au-bearing stocks traced by boreholes to a depth of a few hundred meters. The stocks often reveal crosscutting relationships with carbonate rocks. In some cases, they are completely hosted in schists.

In the 1980s, a team of geologists studied the ore potential of hypergene zone within the framework of scientific program conducted by the Ministry of Geology of the Soviet Union. They recognized the thermal hypergenesis as a special set of processes and events that occur near the Earth's surface under the impact of thermal fluids (Table 1). Hypergene bodies formed in such cases commonly represent the upper portions of hydrothermal systems. Their ore potential is governed by the supply of respective chemical elements with thermal solutions and their precipitation at hypergene barriers as a result of temperature and pressure decrease, organic and colloidal sorption, pH and Eh changes, and so on (*Izuchenie…*, 1995; *Prognoznaya…* 1998).

The model of thermal hypergenesis was first applied to the Kokpatas and Chul'boi gold deposits in central Asia (*Izuchenie…*, 1995). In 1998–1999, this model was used for the genetic interpretation of the Kirov gold deposit in the northeastern Orenburg region at the East Ural Uplift–Magnitogorsk Trough boundary.

The Kirov deposit is hosted in the Lower Carboniferous carbonate–coaly–terrigenous sequence filling the eponymous graben. Orebodies are related to a tectonic zone that reactivated periodically until the Neogene and Quaternary. The bedrocks contain only a low-grade mineralization (0.1–0.5 g/t Au) in thin pyritized zones with quartz veinlets. The economic mineralization (5–10 g/t Au or more) is confined to the linear kaolinite–hydromica weathering crust traced to a depth of more than 300 m.

Open pit at this deposit reached a depth of 30 m by the autumn 1998. Study of the pit walls and collected samples revealed the following relationships (Fig. 4).

In the northeastern sectors of the pit, the Neogene–Quaternary sedimentary cover (4–12 m) is underlain by a marshallite-free kaolinite–sericite and sericite body (about 70 m thick) with nodules and small lenses of quartz. E.V. Tolmacheva estimated the temperature of quartz nodule formation as a few hundred degrees. The marshallite body is a hydrothermally altered Lower

Carboniferous reef. The relicts of unaltered organogenic limestones are retained at the northwestern termination of this reef. The reef is overlapped by a 0.5-m-thick layer of gray high-temperature α-quartz replaced with Upper Triassic (?) conglobreccia in the lateral direction.

A 30-m-wide slightly mineralized crush zone with small quartz veinlets and limonite segregations is localized at the contact of reef with country rocks. Schists, siltstones, and sandstones are severely hydrated and enriched in the secondary quartz. The contact zone locally contains 20–25% Fe_2O_3, 4% K_2O, and ~1% Na_2O.

The aforementioned features obviously rule out the formation of mineralized rocks within a weathering crust.

Further, one can see an orebody largely composed of strongly folded, hydrated, metasomatically silicified schists, with finely dispersed free gold (up to 20 g/t). The chemical composition of the ore is as follows (wt %): SiO_2 53–57, TiO_2 1.6–2.0, Al_2O_3 23–26, Fe_2O_3 2–3, MnO 0.01–0.03, MgO 0.15–0.50, CaO 0.2–0.3, Na_2O 0.8–2.0, K_2O 3–4 and L.O.I. 5–8. The orebody thickness is 20–60 m.

The orebody is bounded on the outer side by dikes and quartz veinlets. Slightly deformed, less hydrated, and Au-free carbonaceous–siliceous sericite schists, siltstones, and sandstones crop out beyond this contact zone. The eluvial sequence is absent in the deposit area.

The available data and their comparison with other similar deposits show that ore mineralization at the Kirov deposit formed in two stages.

(1) In the Late Paleozoic (Middle-Late Carboniferous), a thick fault zone appeared along the eastern margin of the Magnitogorsk Synclinorium. This was accompanied by the formation of amplitude-variable dislocations, long tectonic melange zones, regional silicification, low-grade sulfide–gold mineralization, and emplacement of dikes.

(2) Ore-forming hydrothermal centers originated in Late Triassic at the final stage of tectonomagmatic reactivation along ancient fault zones as nearly vertical stocks with circular cross sections (thermal windows) that served as conduits for the ascent of ore-bearing solutions and delivery of gold (probably, as chloride complexes) to the hypergene zone. High-gradient thermal depressions, up to 100–150 m in diameter, originated near the day surface in oxidation zones as a result of decrease in pressure and temperature and interaction between exo- and endogenous processes. These depressions were favorable for the evaporation, intense hydrolysis, differentiation of material and the formation of economic-grade gold deposits.

The Kirov deposit is an example of gold mineralization in thermal depressions. The main prospecting guides for such deposits are as follows: (1) localization within hypergene zone, (2) the presence of ancient fault zones that crosscut rocks with superimposed silicification and low-grade gold mineralization (>0.01 g/t Au); (3) the presence of Early Mesozoic thermal depressions and windows that penetrate the fault-line melange and provide intense hydrolysis at a depth of tens or hundreds of meters.

CONCLUSIONS

Overview of hypergene metallogeny largely based on the original data gained by the author suggests that economic deposits formed in hypergene blankets of various ages are most important constituents of the raw mineral base in the Urals.

The hypergene deposits are generally diachronous. Their formation encompasses the entire cycle from sedimentation and syngenesis to the subsequent stages of dia-, cata-, and epigenesis and completed at the stage of hypergenesis. The highly evolved rock complexes formed at the latter stage serve now as hosts for high-grade iron, manganese, nickel, gold, and alumina, and other mineral deposits.

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