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General features relating to the occurrence of mineral deposits in the Urals: What, where, when and why

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ABSTRACT

This study of metallogeny of the Urals is strongly tied up with a stage-by-stage geodynamic analysis of the orogen. The analysis includes a revised understanding of geodynamic development of the Timanides (development of a deep sedimentary basin since the Mesoproterozoic, ocean formation and subduction in the Neoproterozoic and collision in the Late Ediacaran). For the Uralides, a new interpretation includes relationships between Tagil and Magnitogorsk arcs, arc–continent collision in the Late Devonian, subduction jump in the Early Carboniferous, and thrust stacking in the Late Carboniferous to Permian. Attention is paid to metallogeny of the platform (Middle Jurassic to Paleogene) and neo-orogenic (late Cenozoic) stages. For the first time an effort is made to consider the role of mantle plumes and superplumes in the geodynamic development and metallogeny of this fold belt. Many deposits are polygenetic, and different stages of their formation belong to different geodynamic stages and substages, therefore the deposits becoming additional geodynamic indicators themselves.

1. Introduction

The Urals, one of the world's oldest mining provinces, dating back to the Bronze Age, is producing great amounts of raw materials, making up about a quarter of total value of all Russian mineral resources (Koroteev, 2004) — while it occupies less than 2% of territory of the country. Many deposits were mined out, but the region still has large resources.

This paper analyzes metallogeny of the Urals on the basis of plate and mantle plume tectonics, as well as on ideas of ore-forming processes leading to formation of individual deposits.

The primary aim is to understand the principal features that are responsible for the presence and siting of deposits and occurrences. First of all, the deposits must be mapped and tied up to characteristic geological formations. But the general structural map of a fold belt with symbols of deposits on it is still not a metallogenic map, though it may be declared to be such. In fact, it is just a map showing the actual position of deposits. The tectonic settings of regions are changing with time, and therefore we need to understand the position of deposits in relation to the structures that existed during their formation. This requires recognition of post-mineral structural evolution caused by thrusting and other faulting in relation to stages and substages in the tectonic evolution of the region, as well as affiliation to particular structural zones and understanding of the role of climate constraints for every substage.

Using specific magmatic and sedimentary complexes, hosting and accompanying the deposits, as geodynamic indicators, it will be possible to tie up every deposit to a geodynamic setting and active structure at a particular time interval — a continent, rift, mid-oceanic ridge, island arc, a specific zone of an orogen, or even a plume. After that, the genesis of deposits is to be taken into account, such as different hydrothermal processes, skarns, SEDEX and many others. In case of supergene deposits (bauxites, lateritic nickel, base and precious metal gossans, placers, coal, etc.), a climatic ambience and epeirogenic movements must be also taken into account. In some cases, deposits can be polygenetic. Finally, there are man-made deposits (described as “technogenic” by Rubinstein and Barsky, 2002 and many others in Russia): accumulations of mineral substances, which were considered as waste from mining, dressing, metallurgical and other operations, and suitable for commercial use for extraction of metals and other valuable components. The importance of such deposits is growing with time, in agreement with the noosphere concept of Vladimir Vernadsky (Vernadsky, 1944). The latter suggested a theory that the noosphere is the third in a succession of phases of development of the Earth, after the geosphere (inanimate matter) and the biosphere (biological life). Just as the emergence of life fundamentally transformed the geosphere, the emergence of human cognition fundamentally transforms the biosphere (and geosphere).

2. Structural divisions of the Urals

The structural subdivisions of the Uralides (Puchkov, 2010a, 2013b) are a reference frame for Uralian geology including the stages before

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and after establishment of these zones. From the west to the east, they are (Fig. 1):

A) Preuralian foredeep, filled with Permian molasse;
B) West Uralian zone, with a predominant development of intensely folded and westward-thrust Paleozoic shelf and bathyal (passive margin) sedimentary sequences;
C) Central Uralian zone, with exhumed Precambrian complexes;
D) Tagil–Magnitogorsk zone, limited from the west by the Main Uralian Fault (MUF), with mostly Paleozoic ocean floor and island arc formations, including Platinum-bearing Belt (PBB) of concentric-zonal mafic–ultramafic massifs;
E) East Uralian zone, containing a combination of Precambrian and Paleozoic oceanic and island arc complexes, welded along the Main Granite Axis (MGA);
F) Transuralian zone, composed of pre-Carboniferous complexes, probably accretionary in origin, unconformably covered by the Lower Carboniferous calc-alkaline volcanic rocks of the Valerianovka arc.

The first three zones are attributed to the so-called “paleocontinental sector” of the Urals, while the other three are “paleo-oceanic”. The Paleozoic oceanic and island-arc formations in the paleocontinental sector are known only in thrust klippes. While these formations are predominant in the paleo-oceanic sector, it also hosts subordinate microcontinental blocks. The important divide between the two sectors is marked by the Main Uralian Fault (MUF), an east-dipping zone of serpentinitic melanges and blastomylonites, traceable in seismic sections to a depth of 30–40 km (Puchkov, 2013b).

3. The stages of development and structural complexes of the Urals

The geodynamic development of the Urals can be subdivided into several major stages, each characterized by a specific style of processes and their own structural pattern. The magmatic, metamorphic and sedimentary processes and complexes of each stage (and substage) typically overlie and overprint the previous ones. Additional complication exists in the cases of thrust and nappe development. The major stages are as follows (Fig. 2) (Puchkov, 2010a, 2013b):

a) The Archean to Paleoproterozoic (Pre-Timanides) crystalline basement of the East European platform under the western part of the Southern and Middle Urals;
b) The Meso- to Neoproterozoic complexes of the Timanides, with their external part developed mainly as a deep and wide sedimentary basin as a result of several successive mantle plume and rifting events prior to final late Precambrian collision and orogeny, and their internal part, which inherited oceanic, microcontinental, subductional and accretionary complexes of a complete Wilson Cycle;
c) The Cambrian to Early Jurassic Uralides, primarily products of the Paleouralian Ocean, which was opened as a result of the Late Cambrian to Ordovician epicontinental rifting and subsequent oceanic spreading and closed through subduction in the Late Ordovician to Early Carboniferous, followed by collisions in the late Paleozoic and Early Jurassic, of another complete Wilson Cycle;
d) Jurassic to Miocene platform complex, formed when the orogen was finally eroded to a hilly country and then to a peneplain, with related deep weathering;
e) Late Cenozoic neo-orogenic complex, formed when new orogenic deformations started and new mountains rose along some tectonic lines of the Uralides.

Each complex has its zoning, and each zone reveals its own metallogeny.

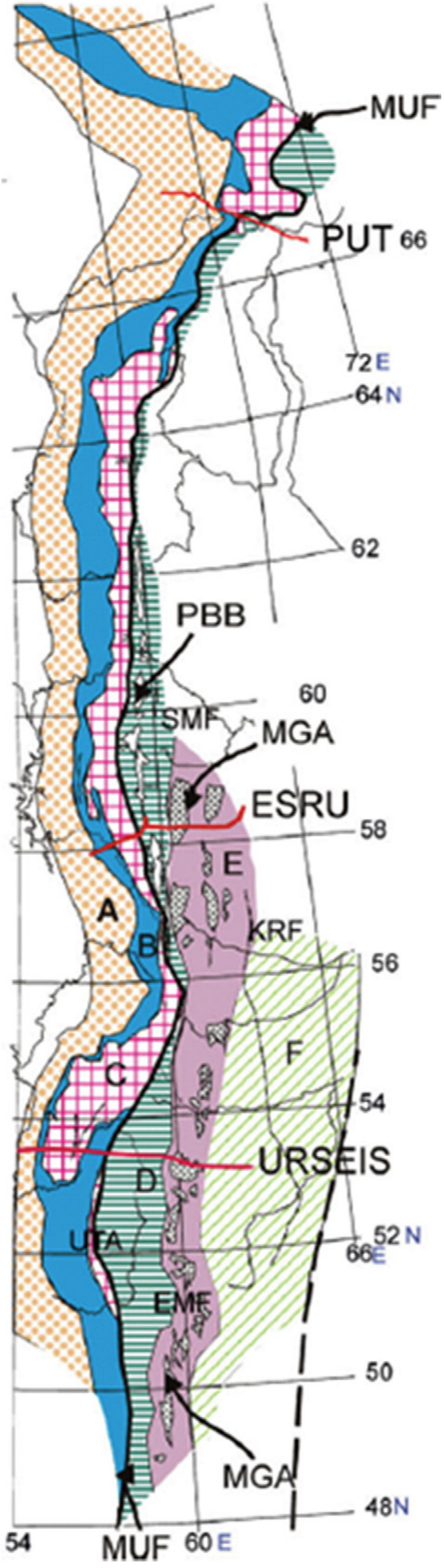


Fig. 1. Structural zones of the Uralides. MUF — Main Uralian Fault, EMF — East Magnitogorsk Fault, SMF —Serov–Mauk Fault, KRF — Kartaly Fault. Seismic profiles: URSEIS, ESRU and PUT (Polar Urals Transect). The other letter symbols are explained in the text.

3.1. The Archean to Paleoproterozoic basement

The metamorphic complexes of this stage belong to the crystalline basement of the paleocontinental sector of the Urals. They are exposed in the rather small Taratash and probably in some other small massifs. In seismic sections, it is traceable to the east until the middle of the Magnitogorsk zone to a depth of ca 30 km. The basement consists of

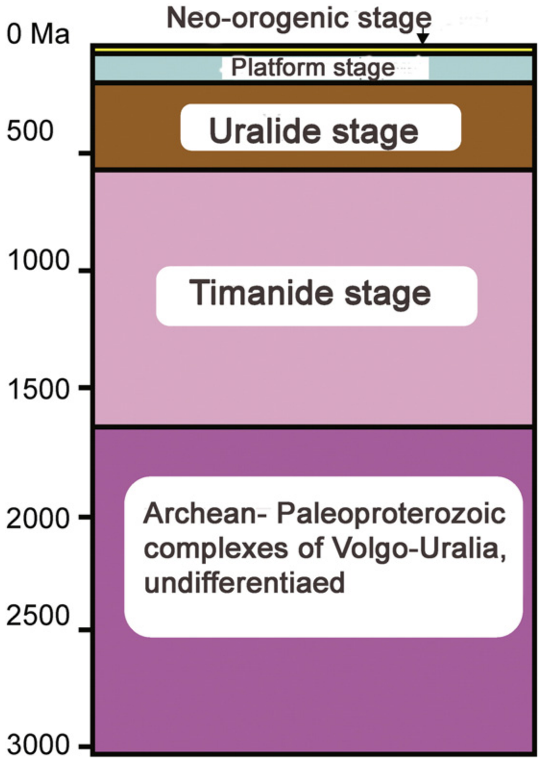


Fig. 2. Stages and structural complexes of the Urals.

para- and orthometamorphic rocks, regionally metamorphosed to granulite and amphibolite facies, and more locally, in shear zones, displaying a retrograde, low-grade metamorphism. According to isotopic data (Krasnobaev et al., 2011; Ronkin et al., 2012), the oldest U–Pb age of zircons from granulites is 3504 ± 210 Ma, and the youngest isotopic age of greenschist metamorphism is 299 ± 43 Ma. The youngest age for the amphibolite metamorphism and granite formation is close to 1800 Ma. In the Polar Urals, Archean rocks are not recognized and probably do not exist, but Paleoproterozoic rocks are inferred in the most metamorphic core domes, based on rare U–Pb ages.

Quartz–magnetite deposits of disputable genesis (primarily sedimentary, or metasomatic), some of them fairly large, like *Kuvatal*, are known within the Taratash block (Ovchinnikov, 1998). They are very difficult to date. But in any case, the amphibolite facies metamorphism, affecting the deposits, took place here before ~1800 Ma (Krasnobaev et al., 2011). Due to deep position of the crystalline complex, its metallogeny does not attract much attention.

3.2. Timanides (Meso- and Neoproterozoic)

The Timanides were formed during the Timanian orogeny (600–550 Ma) in place of the Pechora oceanic basin and a continental margin of Baltica craton (Puchkov, 2010a). They strike parallel to the Uralides in the South and Middle Urals, but acquire a northwest strike in the Sub-Polar and Polar Urals and continue into the crystalline basement of the Timan–Pechora basin (Fig. 3). Puchkov (2010a) proposed two parts in the Timanides: the Externides, belonging to the pericratonic part of Baltica, and the Internides, created in place of the Pechora Ocean, its microcontinents and island arcs. Owing to differences in orientation between the Timanides and the Uralides, the Meso- to Neoproterozoic complexes in the Polar and Sub-Polar Urals do not exhibit much resemblance to those in the South and North Urals (Fig. 3). In the Central Uralian zone of the Polar and Sub-Polar Urals, the relics of Neoproterozoic oceanic and subduction complexes are present, which is not the case in the areas to the south. For this reason, the metallogeny of the South, Middle and North Urals strongly differs to that of the Sub-Polar and Polar Urals.

3.2.1. Metallogeny of the Externides

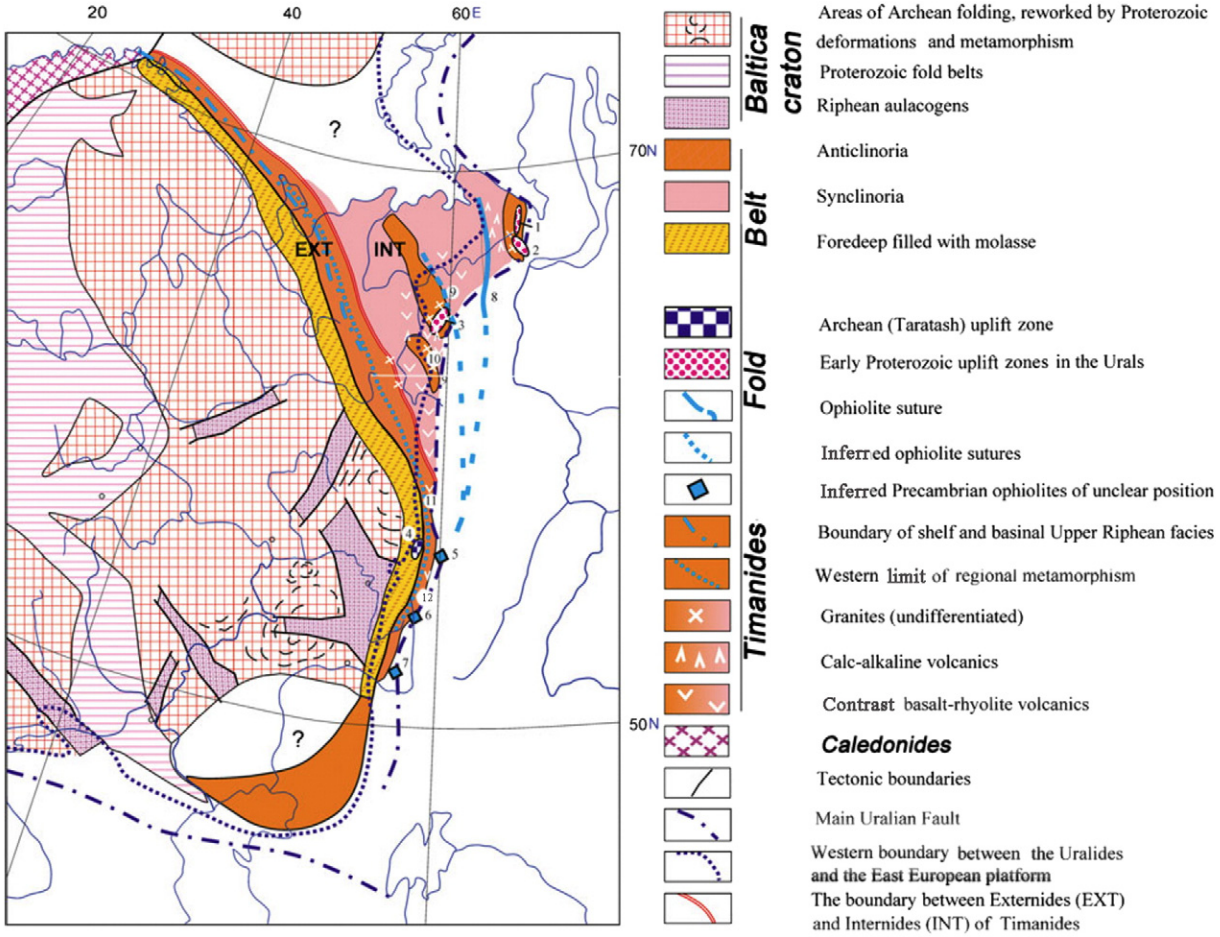
Being restricted to the South and Middle Urals (Fig. 4), the stratified Riphean (Meso- and Neoproterozoic) mafic–ultramafic complexes host titanomagnetite (with vanadium) deposits (*Kusa–Kopan group* of intrusions in the South Urals and *Yubrishka* in the North Urals); high-alumina chromites with PGE (*Sarana group* of deposits in the Middle Urals) (Ovchinnikov, 1998). The Proterozoic sedimentary formations in the South Urals reveal the most complete sequences, up to 15 km thick. They form a deep and vast sedimentary basin, catagenetically transformed with hot expulsion of waters, squeezed out of the sediments, along with an iterative rifting events. These processes could be responsible for formation of a series of stratiform, epigenetic, hydrothermal–sedimentary low–middle-temperature deposits. The richest of them are *Satka* (magnesite), *Bakal* (siderite) ore clusters, *Suran* (sellaite–fluorite) and smaller deposits of the same type in the Lower and Middle Riphean (Mesoproterozoic) carbonate sediments. There is also a series of smaller barite, barite–polymetallic and polymetallic deposits and occurrences, probably of SEDEX type with a later hydrothermal overprint in the Upper Riphean (e.g., *Kuzha*, *Verkhnyaya Arsha* and others) (Ovchinnikov, 1998; Maslov et al., 2001).

In the Bashkirian Meganticlinorium, there are also well known gold–sulphide–quartz lode deposits of the *Verkhneavzyansk group*, hosted in the Riphean schists. Along the western and northern periphery of the Beloretsk dome (12 in Fig. 3) in the South Urals, Mesoproterozoic black shales were reported to contain gold, gold–palladium and palladium–gold–REE mineralization (Ovchinnikov, 1998; Kovalev et al., 2013; Snachev and Puchkov, 2010). Probably the same type of mineralization is developed in the Middle Urals (*Kedrovka* occurrence of metasomatically altered rocks with quartz and quartz–carbonate veins in the Neoproterozoic carbonaceous schists as an example) (Zoloev et al., 2001). This prospective zone can be traced for a great distance along the western slope of the South and Middle Urals and is attributed tentatively to the same type as the Sukhoi Log deposit, which is treated by many researchers as metamorphogenic–hydrothermal (Wood and Popov, 2006). More or less confidently, to this type is attributed the *Ashka* deposit in this zone (Sazonov and Velikanov, 2010).

In the mineralized zones of Bashkortostan, black shales were influenced by high-temperature (up to 500 °C) fluid (Kovalev et al., 2013). The concentrations of precious metals correlate with intensity of alteration (Zoloev et al., 2001). One cannot be sure that all mineralization is Precambrian in age as it is also recorded in Ordovician and Silurian rocks and could be iterative (Zoloev et al., 2001; Ovchinnikov, 1998).

Gold and platinum also form noticeable concentrations in hematite-enriched matrix of basal conglomerates of the Mashak Formation of the Bashkirian meganticlinorium at the *Shatak* range (Kovalev et al., 2013).

Mineralization in the Bashkirian meganticlinorium was studied recently with application of new precise methods of isotopic dating and characterization of mineralizing fluids. In particular, a new model of formation of magnesite deposits was suggested, as a result of interaction of primarily hot, cooling (440 to 85 °C) brines, probably of evaporite nature, with porous brecciated dolomites soon after their deposition (Krupenin et al., 2013). Formation of Bakal siderites, according to isotopic and mineralogical data, was also connected with the action of <250 °C fluids (Maslov et al., 2001). The U–Pb (baddeleyite) age of the Main Bakal dyke was constrained as 1385.3 ± 1.4 Ma (Ernst et al., 2006). It was noted (Maslov et al., 2001) that the thermal influence of the dyke initiated an intense brucite replacement of the hosting magnesite, which leaves only a small time window between the origin of the Lower Riphean Bakal Formation and the dyke intrusion, contemporaneous with the Mashak volcanism. The siderites of Bakal were formed much later, at the Middle to Late Riphean transition (1010 ± 100 Ma Pb–Pb isochron from the least altered siderites; and 1090 Ma according to Th–Pb method) (Maslov et al., 2001). The ages of the latest



Numbers in the scheme: 1–4 — Archean and Paleoproterozoic blocks: 1 — Marun-Keu, 2 — Kharbey, 3 — Nyartinsky or Nikolayshorsky (core of Khobeiz dome) and Nerkayu, 4 — Taratash and Aleksandrovsky; 5–7-fragmented and metamorphosed ophiolites on the both sides of the Main Uralian Fault: 5 — in the Ilmeny-Sysert dome, 6 — in the Maksiutovo complex, 7 — in the Ebeta complex; 8, 9 — Proterozoic ophiolite sutures: 8 — Manyuku-yu suture in the Engane-pe uplift, 9 — inferred Dzelya – Parus-shor suture; 10, 11 — anticlinoria: 10 — Mankhambo, 11 — Vogulsky (Kvarkush) ,**12-Beloretsk thermal dome**

Fig. 3. Structural scheme of the Timanides.

overprinting hydrothermal processes, including barite and polymetallic mineralization, correspond to the Latest Riphean (Arshinian): 615 ± 6 Ma (Rb–Sr), 632 ± 12 and 610 ± 6 Ma (K–Ar) (Maslov et al., 2001). Because of this, and in contrast to the above-described Middle Riphean deposits, the barite-polymetallic occurrences are hosted in the Lower and Middle Riphean, as well as in the Upper Riphean sequences.

In the Suran low-temperature (230–50 °C) hydrothermal deposit, several types of fluorite were recognized. The purest optical fluorite is the latest and is dated as 1219 ± 120 Ma (Sm–Nd isochron) (Maslov et al., 2001), which suggests a link to the Mashak magmatism (see below).

Therefore, one can recognize three main metallogenic epochs: the beginning of the Middle Riphean, beginning of the Late Riphean and the end of the Riphean.

In fact, this territory was part of the Riphean platform. The most important metallogenic factor here could be a widely distributed thermal–magmatic (rift, plume or both) Mashak episode at ca 1380 Ma, corresponding to a mantle plume event of a subglobal scale (Puchkov et al., 2013; Puchkov, 2013a) (Fig. 5). This magmatism activated mineral formation in the deep sedimentary basin of the Externides. Layered mafic intrusion of the Kusa–Kopan complex, as well as the Berdyaush rapakivi pluton, have the same age as Mashak (Krasnobaev et al., 2006; Ronkin et al., 2005). Recently, the Sibirka carbonatite, situated not far to the east of the Berdyaush pluton, was dated as 1350–1360 Ma (Kholodnov et al., 2014), and therefore this carbonatite may also belong to the same episode.

Among the Neoproterozoic mafic complexes that may be attributed to mantle plumes, one can mention layered pyroxenite-gabbro intrusions. One of them, the Sarana intrusion, hosting the chromite deposit of the same name, is dated as ca 745 Ma, which is close to the Arshinian volcanic event in the Bashkirian meganticlinorium and trachybasalts in the 1 — Kipchak borehole in the adjacent East European platform (726–709 Ma). They are close in age to 725–715 Ma Franklin and Irkutsk Large Igneous Provinces (LIPs) (Ernst et al., 2015). Another layered intrusion, hosting *Kiryabinka* 680 ± 3.4 Ma sulphide copper mineralization (Krasnobaev et al., 2013), has its age equivalents in the Middle Urals. These Neoproterozoic magmatic formations may also represent fragments of concealed LIPs (Puchkov, 2013a,b). Therefore, most metallogenic processes in the Externides can be associated with mantle plumes. Less important for metallogeny, but still deserving attention, could be the Timanide orogenic activity in the late Ediacaran. It can be correlated with metamorphism and must increase eastward.

3.2.2. Metallogeny of the Internides

The Internides, exposed in the northern parts of the Central Uralian zone (Figs. 3, 4), are characterized by the presence of epicontinental rift-related volcanics, ophiolites, calc-alkaline volcanics and subduction-

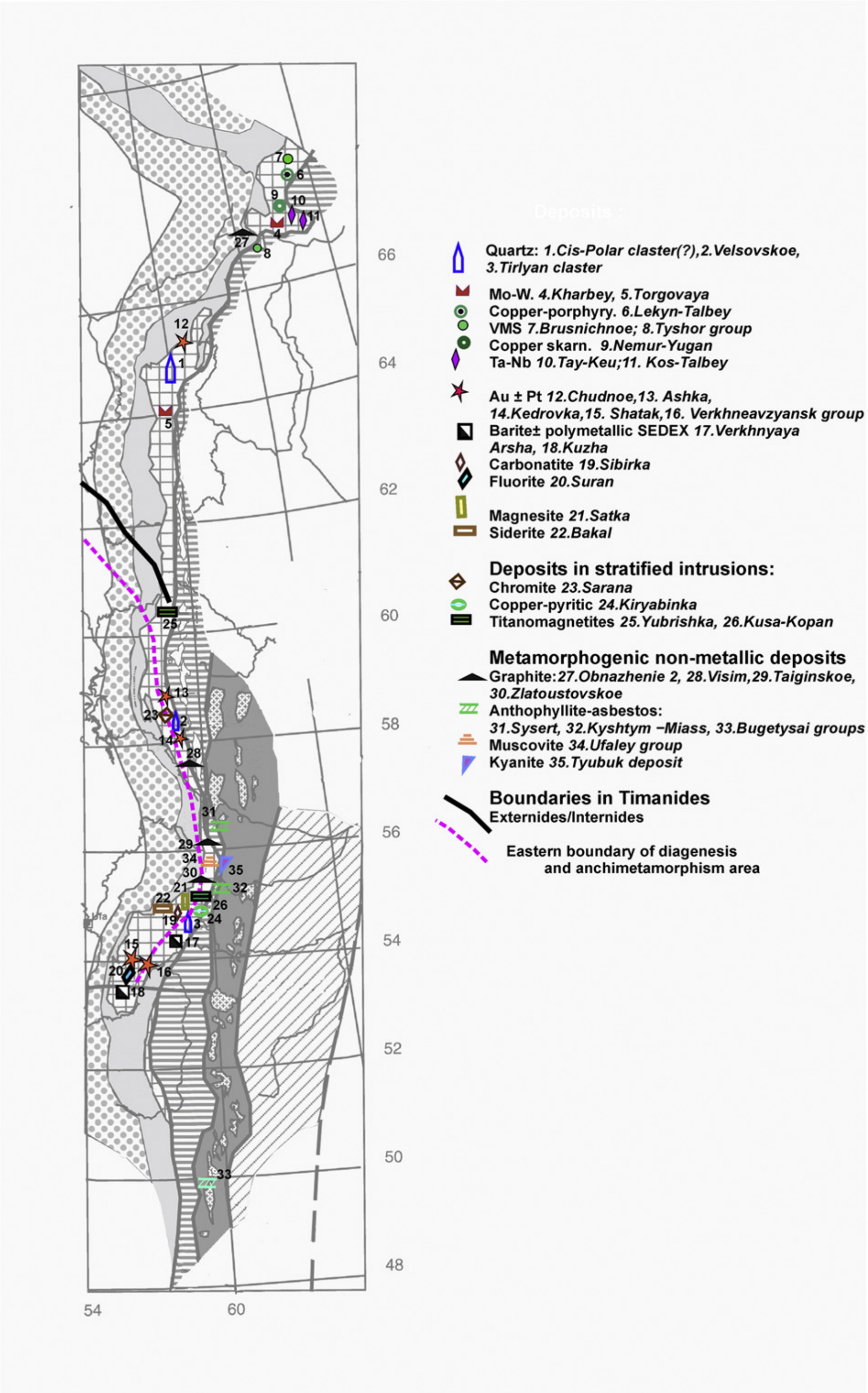


Fig. 4. Complexes and ore deposits of the Timanides. Here and in the following schemes the deposits of the same type are listed in the order from the north to the south and from the west to the east.

collisional granites (Puchkov, 2010a). Therefore, the metallogeny of this zone in the north is very different, to the southern parts. VMS deposits and occurrences are found here, belonging to the Cu-VMS *Tyshor group* (*Verkhniy Elets*, *Montalor*, *Tyshor*), as well as polymetallic-VMS (*Brusnichnoe* and others), copper-skarn (*Nemur–Yugan*), porphyry molybdenum–copper (*Lekyn–Talbey*) occurrences (Prokin et al., 1992; Dushin, 1997; Kontar' and Libarova, 1997). Molybdenum–tungsten deposits of the Polar and Sub-Polar Urals (*Kharbey*, *Torgovaya*) are related to the Precambrian granite intrusions and accompanying hydrothermal to greisen-hydrothermal processes (Yushkin et al., 1997; Ovchinnikov, 1998). The Precambrian complexes of the Polar Urals also contain deposits in relation to albitites, in particular, Ta–Nb deposits at *Tai-Keu*, *Kos-Talbey* and others (Es'kova, 1976; Zoloev et al., 2004). However their ages could be Paleozoic (see below).

In the Sub-Polar Urals, in the upper reaches of the River Kozhim, the *Chudnoe* Au–Pd–REE deposit of unusual type was discovered in the Upper Riphean rhyolites (Ovchinnikov, 1998; Goldin et al., 1999; Dodin et al., 2001). Unfortunately, reliable isotopic ages are absent.

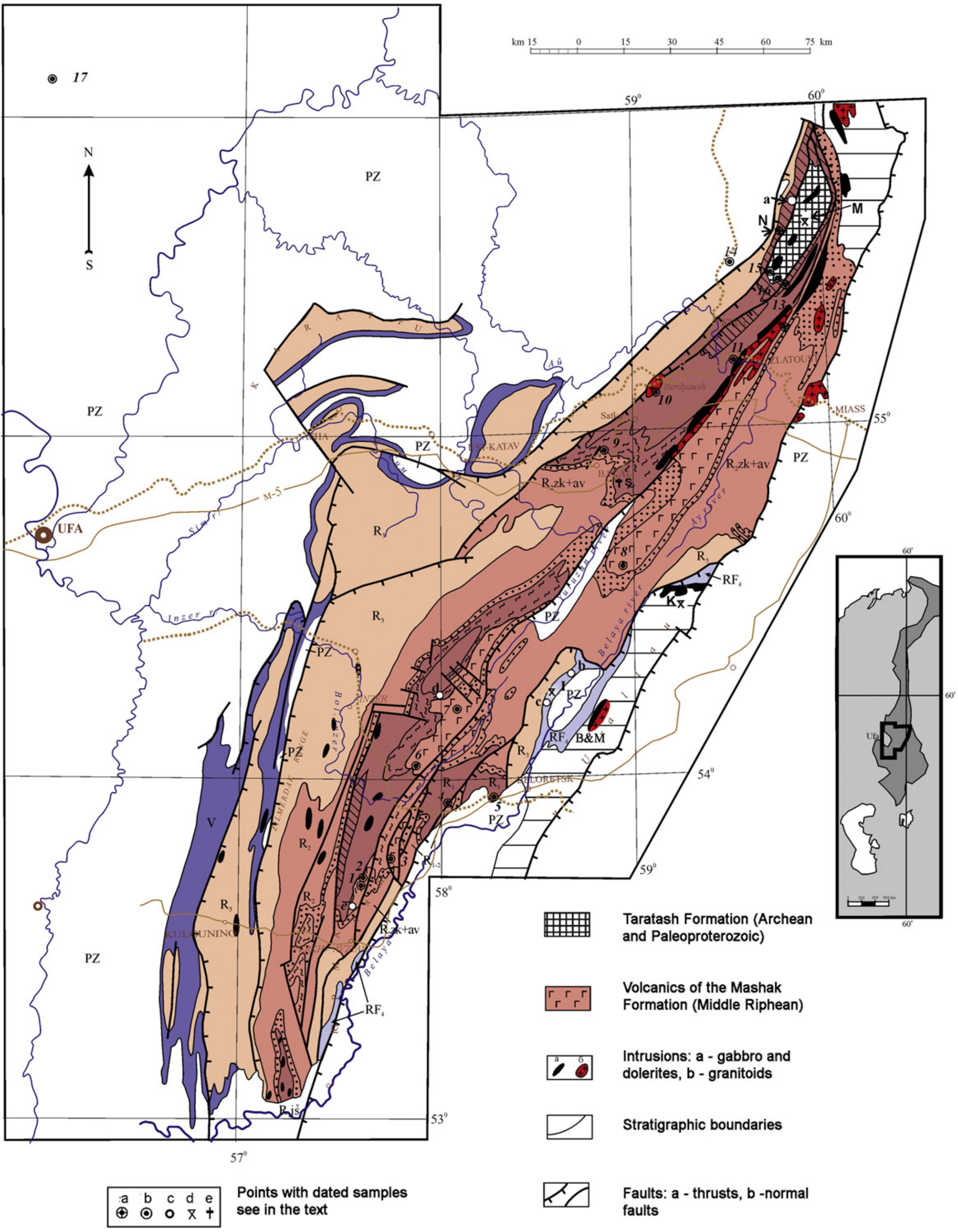


Fig. 5. Suspect plume complexes of the Bashkirian meganticlinorium. Points with dated samples of the Riphean (Meso- and Neoproterozoic) on the geological map of the Bashkirian meganticlinorium. RF_1 — Lower, RF_2 — Middle, RF_3 — Upper, RF_4 — Uppermost Riphean; V — Vendian (ca. Ediacaran). PZ — Paleozoic. Dated magmatic rocks: a — Navysh, b — Mashak, c — Ushat, d —Arshinian, e — Sibirka carbonatites. Letters: N — Navysh subformation of the Lower Riphean, S —Sibirka Middle Riphean carbonatite complex. Arshinian magmatic complexes of the Uppermost Riphean: I — Igonino basalts; M — Misayelga layered complex, K — Kiryabinka layered intrusion. B&M — Barangulovo and Mazara gabbro-granite complexes. Points where the Mashak Formation and its comagmatic rocks are dated: 1 — Shatak Range; 2— Shatak Range; 3 — Karagas-3 borehole, basalts; 4 — Akhmerovo granites; 5 — eclogites of the Beloretsk complex; 6 — rhyolite of the Dunansungan Mnt.; 7 — rhyolite, Kuzyelga river, Mashak Range; 8 — Berezyak river, Kuvash complex; 9 — main Bakal dyke; 10 — Berdyaush rapakivi granites and associated rocks; 11 — Kusa–Kopan mafic intrusion; 12 — Ryabinovo granites; 13 — Kusa dolerite sill; 14 — rhyolite dyke of Bagrusha river, 15 — dyke in the quarry, the left bank of Navysh river; 16 — dolerites in the valley of Maly Navysh river; 17 — dolerites in the 183 Menzelino–Aktanysh borehole. Paleozoic Ordovician/Silurian dolerite, trachydolerite magmatic rocks of the Ushat complex: a — Ushat brook, b, c — Tirlyan syncline, d — Mashak Range, e — Shatak Range.

Summarizing the metallogeny (sensu stricto) of the Timanides, the differences between mineral deposits in their southern and northern parts of the Central Uralian zone prompt a conclusion on difference of their geodynamic settings.

Not so sharp are differences between the groups of southern and northern deposits of a non-metallic type, which are in many cases metamorphogenic (Ovchinnikov, 1998; Eremin, 2007). It must be noted that the outer and inner parts of Externides differ in the grade of metamorphism. For example, as it was shown for the Archangelskoe–Beloretsk transect of the Bashkirian meganticlinorium (Matenaar et al., 1999), the finite thermal grade in the outer part of the Externides shows diagenetic to lower anchizonal conditions, while anchi- to epizone-greenschist and more locally amphibolite facies conditions (with eclogites) are characteristic for the inner part. The same tendency is in the Kvarkush anticlinorium (Rusin, 1996). In the Internides, the metamorphism varies mostly between the greenschist and amphibolite facies (Keylman, 1974; Timonina, 1980). Elevated grades of metamorphism are characteristic also for the East Mugodzhary complex (although its attribution to Timanides is conditional). Of the metamorphogenic deposits, situated to the east of the outer Externides, one may mention graphite (*Obnazhenie 2*, *Visimskoe*, *Taiginskoe*, *Zlatoustovskoe*). Deposits of anthophyllite-asbestos are mostly products of metamorphism of ultramafic rocks of Internides (*Sysert*, *Kyshtym–Miass*, *Bugetysai groups*). Parallel to the trend of these metamorphic rocks, in the Middle and Southern Urals are also located numerous deposits of kyanite (disthène) — e.g. *Tyubuk* deposit and abrasives (garnet, corundum, emery). The Ufaley and Sysert–Ilmenogorsk metamorphic complexes host muscovite deposits, but they may belong to the Uralide stage. The same problem is with the age of rock crystal (quartz) deposits, hosted by the Precambrian complexes: *Cis-Polar claster*, *Velsovskoe group*, *Tirlyan claster* of deposits in the northwestern part of the Bashkirian meganticlinorium and others. They may belong, at least partly, to the collisional stage of the Uralides (see below).

3.3. Uralides

Development of the Uralides corresponds to classic Wilson Cycle and comprises epicontinental rifting in the latest Cambrian to Early Ordovician, formation of the Paleouralian Ocean with its continental passive margins and eastward-dipping subduction zones in the Late Ordovician to Late Devonian, arc–continent collision in the Late Devonian, formation of the Nevada-type (?) (see later, Section 3.3.5 of the paper) subduction zone in the Early Carboniferous, continental collisions in the Late Moscovian to Permian, Triassic mantle plume/rifting episode and, finally, new collision in the Early Jurassic. Every substage of the cycle is characterized by a specific array of magmatic and sedimentary complexes and their own zonation (structural and, consequently, metallogenic).

After the Timanian orogeny in the Vendian (Ediacaran) and a short-lived platform stage, when a peneplain was formed, a stage of epicontinental rifting started, which smoothly evolved into an oceanic spreading in the Middle Ordovician, with simultaneous formation of passive continental margins, of which only one margin can be recognized in the modern Urals. Starting with the latest Ordovician, subduction can be recorded in the Tagil island arc.

The accumulation of thick Ordovician terrigenous and volcanic “graben” (riftogenic) formations was preceded by processes of peneplaining, weathering and placer formation. The position of Baltica at the lower latitudes (Svyazhina et al., 2003) promoted these processes. Ancient, basal weathering crust with gold mineralization and elevated concentrations of beryllium, germanium, gallium and REE, established as the Alkesvozh Formation (Yudovich et al., 1998a) (Fig. 6) and gold-bearing conglomerates (ancient placers), were found in the north of the Urals (Goldin et al., 1999; Nikulova, 2013).

3.3.1. Metallogeny of the Ordovician epicontinental rifting

Mineralization (Fig. 6) is represented in the Polar and Sub-Polar Urals by cupriferous sandstones (*Kosyu* and *Manita-Nyrd* deposits) and barite-polymetallic stratiform deposits (*Saurey*), associated with Ordovician riftogenic volcanic rocks — probably associated with mantle plume activity. In the western slope of the Middle Urals are the stratiform polymetallic and copper-polymetallic ores of the *Ufaley* uplift (Shirobokova, 1992; Dushin, 1997; Yushkin et al., 1997; Prokin, 2002). Quite unexpected was the discovery of halite in the *1 East Lemva* borehole: a ca 300 m thick evaporites at a depth of 2700–3000 m, associated with the uppermost Cambrian to Lower Ordovician sandstones in thrust structures of the Lemva zone. The appearance of salt can be explained by a graben character of the depositional environment of these sediments, where half-isolated basins and hot climate created favourable conditions for evaporite accumulations. The intense thrusting at the late Paleozoic orogenic stage concealed these evaporitic formations.

After the rifting stage, since the Middle Ordovician till the Early Carboniferous, several geodynamic settings coexisted, partly replacing one another in time and space: *oceanic*, *passive continental margin*, *subduction* and *continent–island arc collision.*

3.3.2. Metallogeny of the Ordovician to Early Carboniferous passive continental margin and plumes

In the sedimentary successions of the passive continental margin, rift formations are followed by purely sedimentary formations demonstrating a transition from shelf to continental slope (Puchkov et al., 1988; Puchkov, 2000, 2002) (Fig. 7).

Shelf sediments contain (or produced) hydrocarbons (*Vuktyl* gas condensate and many others in the Devonian to Lower Permian), coal (*Edzhyd–Kyrta* deposit, *Kizelovskiy* basin of the Visean age) and bauxite (South Uralian bauxite area in the Frasnian), some minor stratiform copper–zinc mineralization (*Ilych* occurrence) (Fig. 8). The Lower Devonian (pre-Emsian) erosion and weathering controlled formation of diamondiferous paleoplacers in the west of the Middle to North Urals, which means that kimberlites or other sources of diamonds must be present immediately to the west of the Urals, under the Paleozoic sediments. In the bathyal successions, the most important are stratiform barium and manganese deposits. Here, the most typical are *Khoila* (Ba) and *Parnoka-Yu* (Mn, Fe) deposits of the Lemva zone. Khoila is classified as a hydrothermal–sedimentary deposit (Yushkin et al., 2002). As for Parnoka-Yu, there are direct analogies with the Atasu type of epigenetic Fe–Mn deposits of Kazakhstan. Along with that, one must take into account that these deposits and similar occurrences are concentrated in “geochemical horizons” of deep-water sediments, enriched with the mineral component (Yudovich et al., 1998b), possibly enhanced by cold methane “seeps” with deposition of barite at deep-water continental margins (Torres et al., 2003).

The fluorite province of Pai-Khoy and southern part of Novaya Zemlya island is traced to the western slope of the Polar Urals (Yushkin et al., 2007).

Late Ordovician to Early Silurian subalkaline magmatism and carbonatitic metasomatism in the Middle Urals have led to formation of rare metal (Ta, Nb) deposits of the *Ilmeny–Vishnevye Gory* ultramafic–alkaline (miaskite)–carbonatite complex (UACC). The substrate of the complex is represented by Paleoproterozoic (ca. 1800 Ma) Selyankino gneisses. The early phase of the complex was thought to be represented by alkaline–ultramafic Buldym complex, dated by zircons (U–Pb: 662 ± 14 and 543 ± 7.1 Ma) and Sm–Nd isochron (602 ± 24 Ma) (Baneva and Rusin, 2014). But soon enough A. Rusin joined to a more argumented opinion (Krasnobaev et al., 2015) that the Buldym massif is Lower Silurian in age (433 Ma). According to Nedosekova (2012 and references therein), dating of zircons from miaskites corresponds to the early stages of crystallization of miaskite–carbonatite complex at 446–420 Ma (Late Ordovician to Early Silurian); the younger clusters of zircons correspond to later tectonic stages of the region development during Middle-Late Devonian, Lower Carboniferous and Permian–Triassic stages and belong to the superimposed metamorphic processes. These processes led to anatexis, pegmatite formation of several types (Popov and Popova, 2006), metasomatism and mineralization, in particular, the formation of famous precious stones of the Ilmeny State Reserve. It is a good example of iterative style of mineralization processes.

I suggest that the initially magmatic Ordovician/Silurian Ilmeny–Vishnevye Gory complex is the trace of a mantle plume, affecting the continental margin (like in the Montreal area), tied up to the

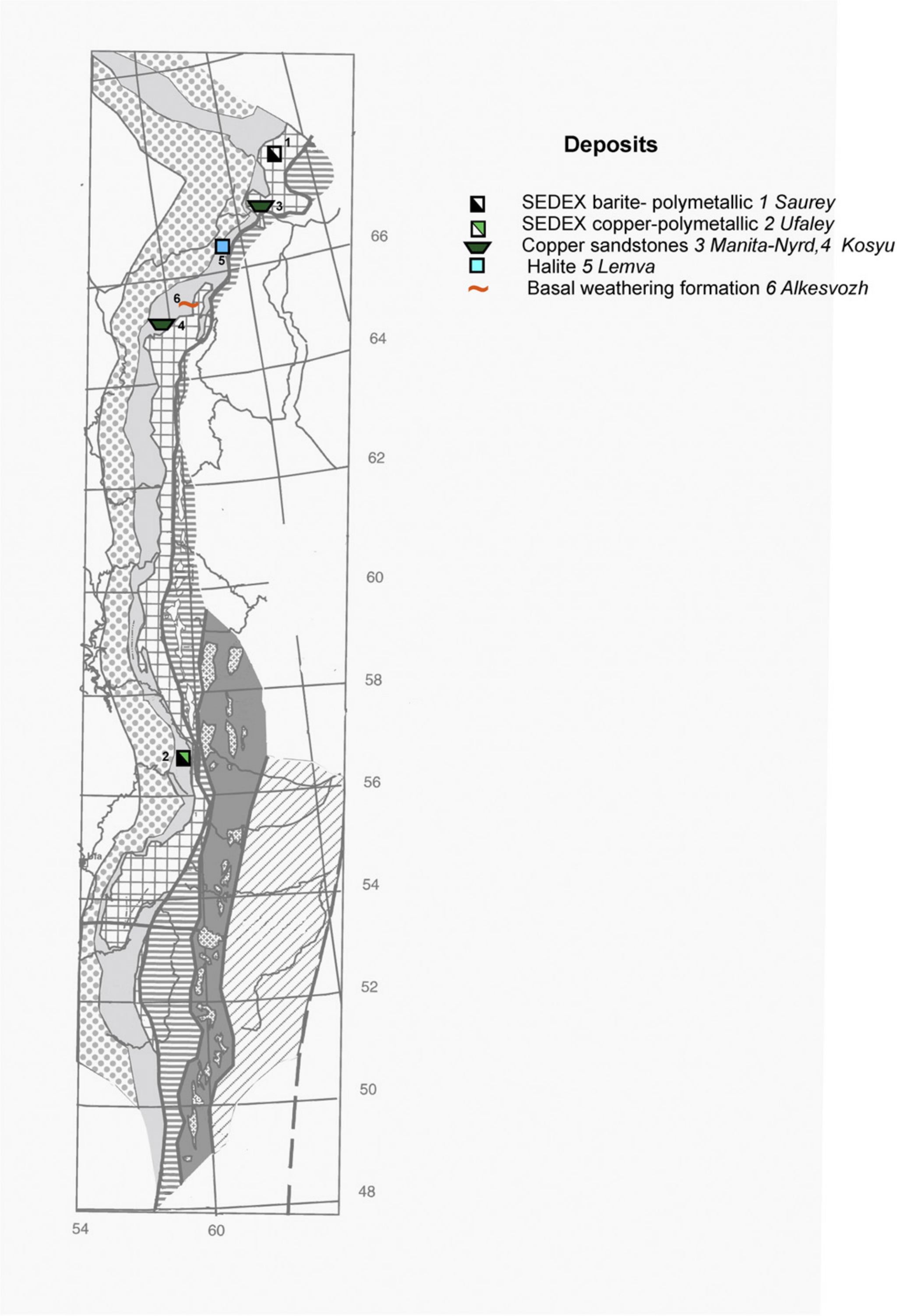


Fig. 6. Ordovician rift complexes and associated ore deposits of the Urals.

opening of a new ocean (Puchkov, 2010a). Trachybasalts of the same age occur immediately to the west, in the Bashkirian meganticlinorium (Puchkov et al., 2011).

In the western slope of the Middle Urals this magmatic stage was manifested as syenite-porphyries of the Verkhneserebryanski complex (age — 447 ± 8 Ma, U–Pb, zircons, SHRIMP (Petrov, 2006).

Similar processes probably took place in the Polar and Sub-Polar Urals, in particular, in the *Turupya* syenite-hosting zone of mineralization in the Ordovician deposits. Along with K–Ar Late Paleozoic ages, in the north of the Urals were obtained the Late Ordovician to Early Silurian Rb–Sr and U–Pb ages (420–460 Ma, like in the Vishnevye Gory) for granites, hosting rare metal mineralization: Kharbey, Tai-Keu (see above), and also *Man'-Khambo*) (Udoratina and Larionov, 2005).

Another mantle plume event can be reconstructed for the Devonian magmatism on the western slope of the Urals (Puchkov, 2012). A vast area of the East European craton, including its eastern margin,

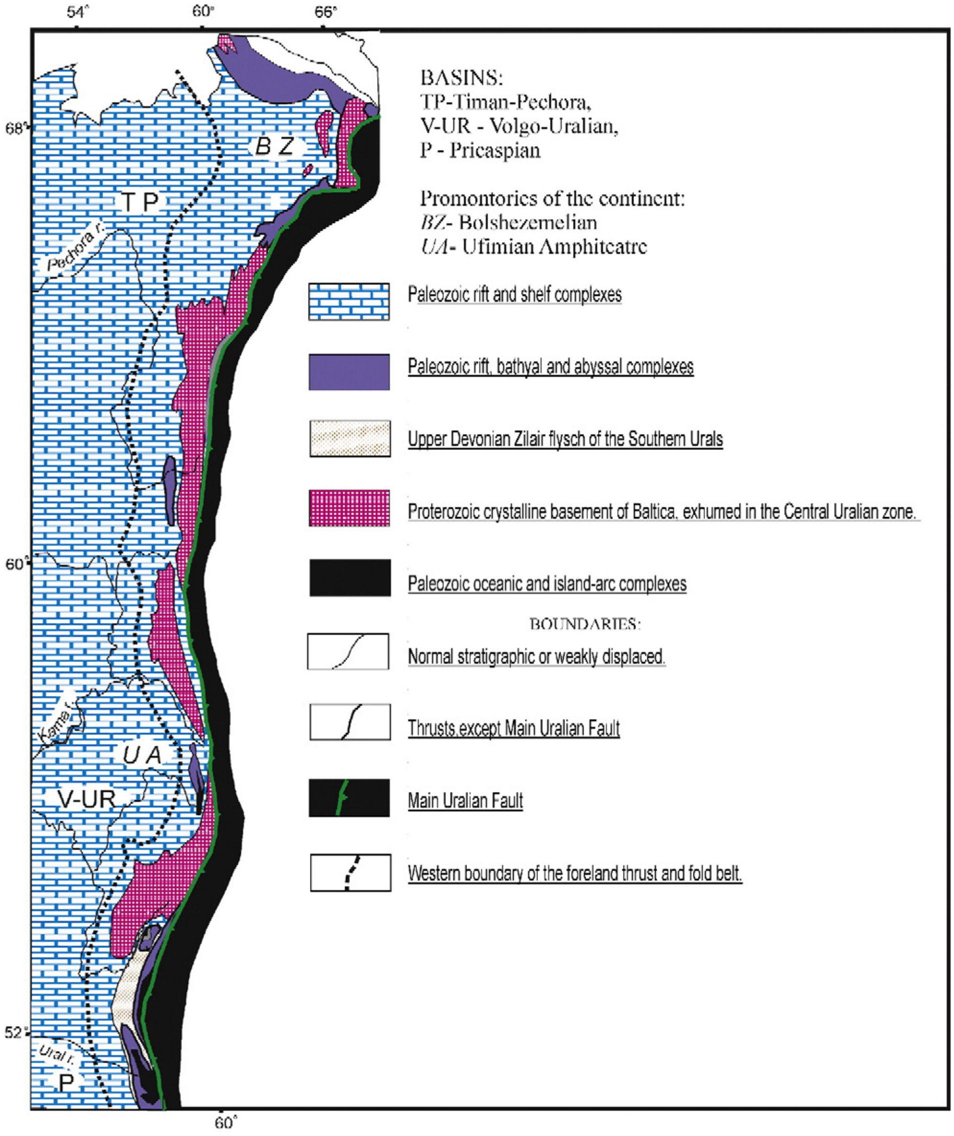


Fig. 7. Sedimentary complexes of the Paleozoic passive margin of the Urals.

experienced a dissipated Devonian rifting, with alkaline basalt magmatism, which are defined as the Kola–Dnieper LIP (Puchkov, 2002, 2013a; Ernst and Bell, 2010).

The lengthy (more than 2000 km) Urals–Novaya Zemlya belt of Devonian dolerite dykes, sills and effusive rocks (Puchkov, 2012; Puchkov et al., 2016) is part of this LIP (Fig. 9). Goldin et al. (1972) reported that larger sills associated with the Devonian Uralian dyke swarm are differentiated. In some rare cases, the length of sills reaches 5–10 km, and they are up to 100–250 m thick. For instance, large differentiated bodies were mapped in the north (Sub-Polar Urals and Pay-Khoy). In typical cases these differentiated bodies include picrite, biotite-bearing olivine gabbro, olivine-free gabbro-dolerite, essexite-diabase, quartz dolerite and monzonite. They contain magmatic titanomagnetite (e.g., Tima-is Range) and pyrrhotite–pentlandite–chalcopyrite lens-like bodies (in Pai-Khoy) at the bottom parts of the intrusions (Yushkin et al., 2007). Kimberlites could associate with this belt. Exposed kimberlite bodies are very rare in the north of the Urals (and rather doubtful), but Devonian (Emsian) diamond-bearing sandstones were formed as ancient placers probably as a result of erosion of Devonian or older kimberlites in the areas of the platform situated close to the Middle Urals, now concealed under the sedimentary cover of the platform.

A "shadow" longitudinal zone was suggested under the northern part of the South Urals, where alkaline and subalkaline magmatic formations are concentrated (carbonatites of the Ilmeny–Vishnevye Gory complex, as well as Sibirka deposit, Berdyaush and other plutons) (Levin et al., 1997). Perhaps, the lithosphere under this zone had an ability of producing alkaline complexes. In development of this idea, I propose an existence of much more extensive zone ("corridor") of such type (Fig. 9), with the Khibiny alkaline complex having their continuation in the Archangelsk kimberlite fields, and further on, to the east, to the kimberlites and carbonatites of the Timan and probably to concealed kimberlites of the easternmost part of the platform close to the North Urals.

3.3.3. Metallogeny of Paleozoic ophiolites

Ophiolites are very widely developed in the Urals (Savelieva et al., 2006a). In the orogen, huge fragments of oceanic lithosphere are preserved in large massifs, such as *Syum-Keu*, *Ray-Iz*, *Voykar*, *Kraka* and *Kempirsay*. The ophiolites host chromium and PGE (in chromites), Cu–Zn VMS (Cyprus, or Dombarovka type, such as at Letnee and Osennee) (Fig. 10) and gold (e.g., *Zolotaya Gora*). But formation of these deposits did not stop at the oceanic stage and may belong to the

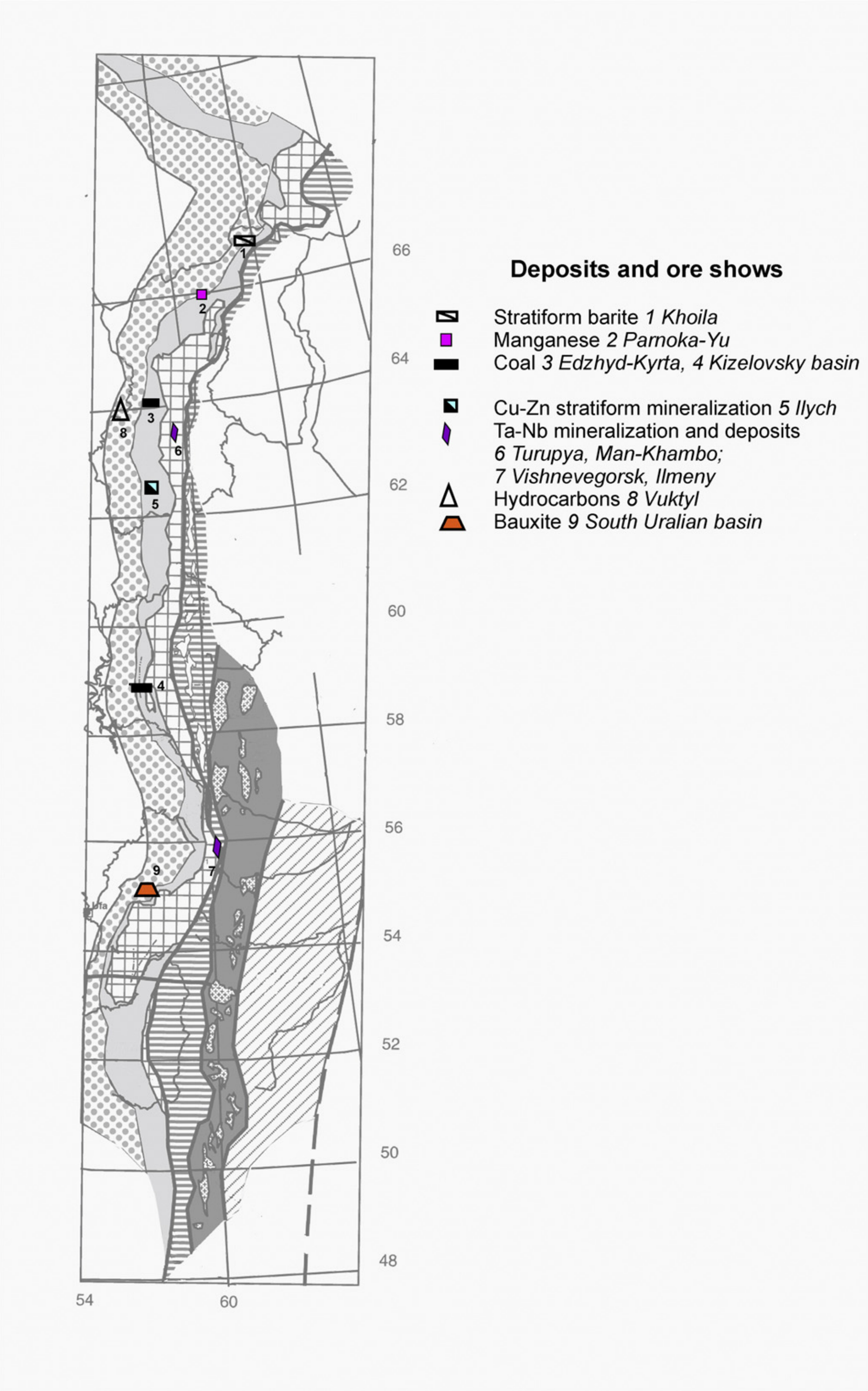


Fig. 8. Ore deposits of the Paleozoic passive margin of the Urals.

later (subduction or collisional) stages — like in case of Zolotaya Gora (Fig. 13).

The largest concentrations of chromite are associated with ultramafic restites: they are usually hosted by dunites, surrounded by harzburgites and lherzolites. Small deposits are sometimes concentrated in dunites of the layered dunite–wehrlite–clinopyroxenite complex (*Kliuchevskoy Massif*). But the majority of large deposits are by-products of large-scale mantle depletion, which took place both at MOR and island-arc settings. It must be taken into account that island arc volcanism resulted mainly from partial melting of a supra-subduction mantle wedge. Therefore, subduction participated in reworking of dunite–peridotite part of ophiolites and in ore formation. As it was shown (Melcher et al.,

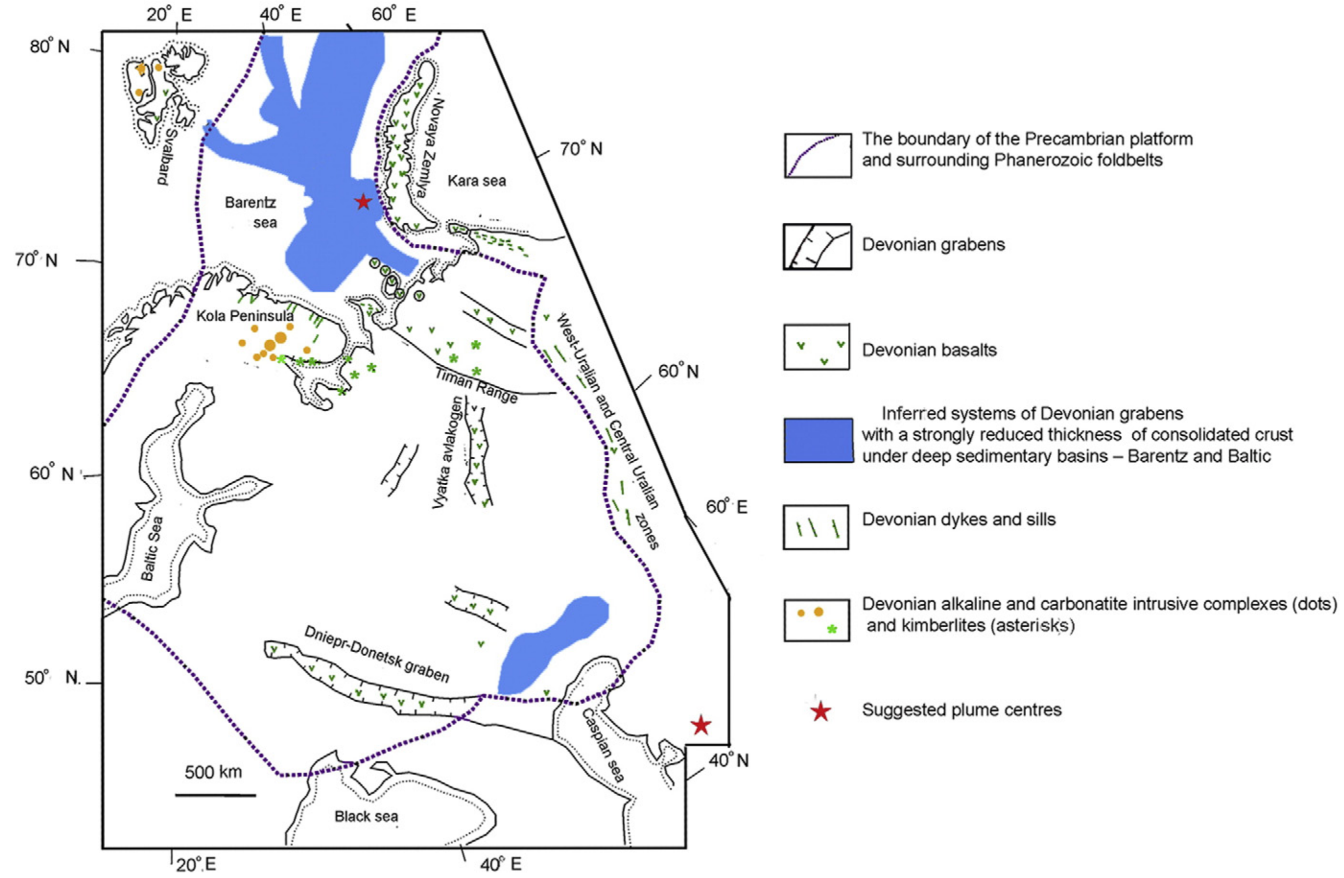


Fig. 9. Devonian dyke complexes of the paleocontinental sector of the Uralides in context of the Kola–Dnieper LIP (Ernst and Bell, 2010; Puchkov, 2010a, 2012, 2013a; Terekhov et al., 2012).

1999), subduction participated in reworking of peridotites of ophiolites and concentration of richest chromite deposits with refractory PGE (Os, Ir) of the *Donskoy group of deposits in the Kempirsay massif* in the South Urals, although small deposits in the northern part of the same massif did not reveal any subduction-related signature. Smaller chromite deposits of the Urals are known in the *Ray-Iz*, *Khoila*, *Kraka group*, *Akkarga* and *Khabarnyi.*

It must be also taken into account that the ultramafic (restite) part of ophiolite, together with their chromites, belongs to the mantle which can be much older than the upper, mafic part of the ophiolites, formed as a result of partial melting of the mantle. The zircons in the Voykar chromites were dated as Ediacaran (ca. 585 Ma), i.e., pre-Uralide (Savelieva et al., 2006a,b). The chromites in the Ray-Iz massif contain diamonds, advocating for a deep, sublithospheric mantle origin with participation of a plume, transporting them close to the Moho (Yang et al., 2014).

Ophiolites contain also some non-metallic syngenetic and epigenetic deposits, such as jaspers of a high aesthetic value. The Southern Urals has more than a hundred deposits and occurrences of jaspers, *Kalkan* and *Orenburg group* among the most famous.

3.3.4. Metallogeny of the Ordovician to Late Devonian (Early Carboniferous in the north) Guberlya, Tagil, Magnitogorsk and Transuralian island arcs

The main zones of calc-alkaline magmatism correspond to three main subduction zones, which developed in a succession, superseding one another: Tagil (Late Ordovician to Early Devonian); Magnitogorsk (Early to Late Devonian or Lowermost Carboniferous in the North); Valerianovka (Early Carboniferous, up to the Early Bashkirian) (Fig. 11). However, one cannot be sure about the island-arc origin of the latter — it could be an active margin of a specific type (see below).

Recently, a successful attempt was made to return to an idea of the Guberlya island arc in the South Urals (Fig. 11A). The arc, preserved mostly in the Sakmara allochthon, is Middle to Upper Ordovician in age, changing upwards into Llandoverian cherts and oceanic basalts (Ryazantsev, 2012). The arc series consists of an Ordovician basalt–rhyolite formation hosting the VMS deposits of the *Mednogorsk group* (*Blyava*, *Yaman-Kasy*, *Komsomolskoe*).

In the East Uralian zone, traces of independent Transuralian island arc (probably allochthonous) are found (see below) (Fig. 11B).

The island arc formations of the Urals host most of its VMS deposits, which contain a considerable part of copper, zinc, lead and gold endowment of the region (Fig. 12). The deposits are hydrothermal, mostly due to the activity of “black smokers” (Maslennikov and Zaykov, 1998). The most well-preserved deposits belong to the Tagil–Magnitogorsk zone. Some of them are large and even giant, lens-like and often multistage. In the Southern Urals, these are Devonian *Uchaly*, *Sibay* (mined out), *Podolsk*, *Yubileynoe*, *Gay* and others. Among these, Gay hosted the largest copper endowment in excess of 6.5 Mt of metal.

The weakly deformed Silurian deposits are present also in the North Urals (*Shemur*, *Valentorsk* and others). Their primary morphology is also rather simple: they represent massive lens-like ore bodies, often arranged in several levels, with long aprons of clastic sulphide taluses along the bedding of host rocks. In some cases, the massive ore preserved sulfidized “oasis” fauna and hydrothermal vents (Maslennikov et al., 1995). But in some cases, the ores and host rocks of deposits are strongly deformed, metamorphosed and even overturned, where they are affected by collisional overprint. Such are deposits of the *Degtyarsk* and *Mauk* groups (Ovchinnikov, 1998). Some deposits are situated in allochthons, transposed into “alien” tectonic and metallogenic zones (e.g., *Safyanovka* deposit and above-mentioned Mednogorsk group).

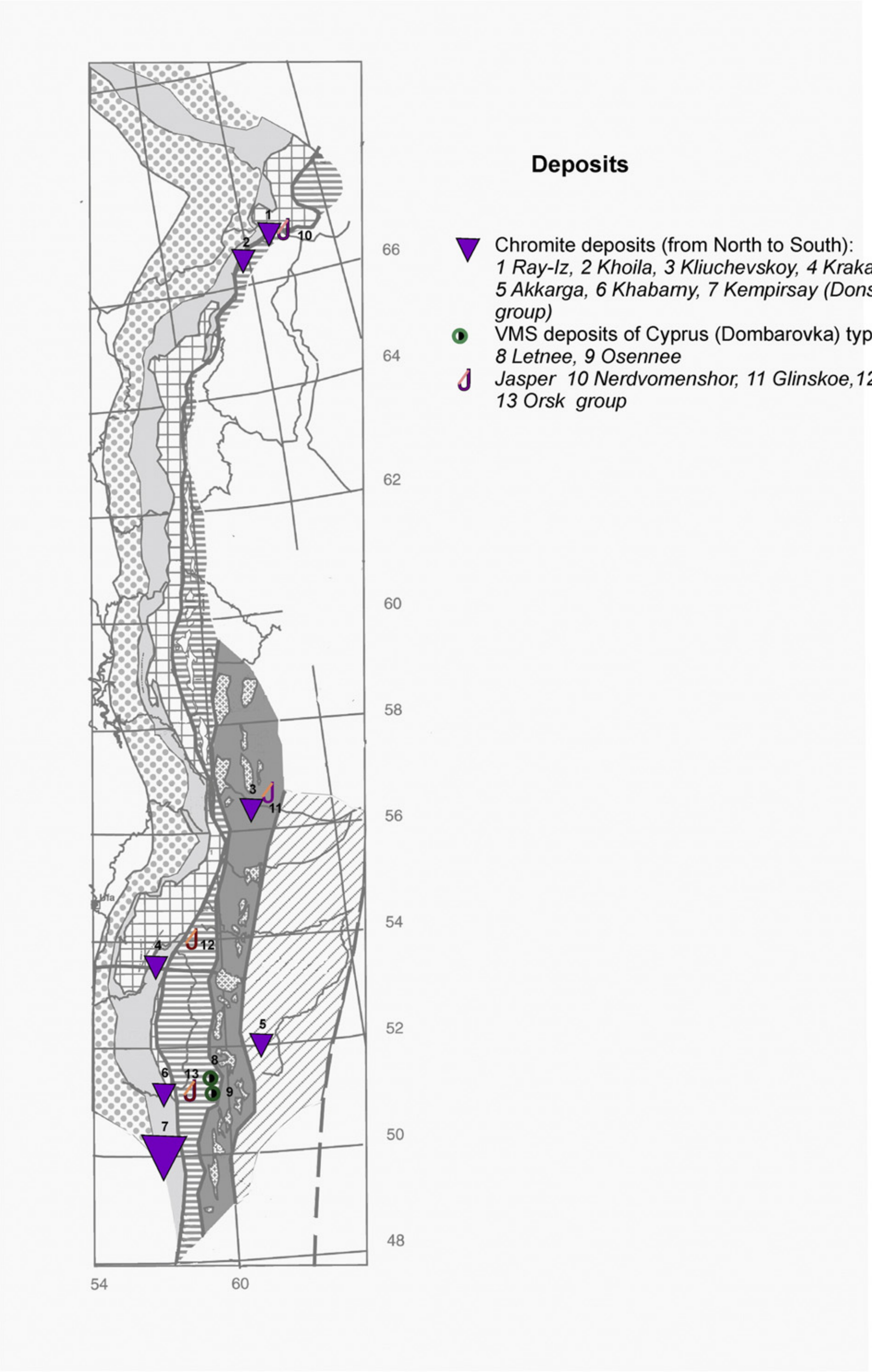


Fig. 10. Mineral deposits hosted by ophiolites.

Not specially dwelling upon well-argumented classification of the Uralian VMS deposits (Seravkin, 2002b; Herrington et al., 2002, 2005), their composition is correlated closely with the composition of host volcanics. The basalt–rhyolite volcanics contain Cu–Zn-pyritic deposits of the Uralian type, while differentiated calc-alkaline volcanics host Au–Ba–Cu–Zn-pyritic deposits of the Baimak (Kuroko) type. These deposits are of hydrothermal–sedimentary genesis, when sea waters, penetrating into the oceanic crust, were heated close to magmatic chamber, leaching the metals on their way back to the sea floor where they appeared as "black smokers" (Maslennikov and Zaykov, 1998).

A specific type of sulphide Cu–Ni–Co VMS mineralization is traced along the MUF in the South Urals. The most famous are *Ishkinino*, *Ivanovka* and *Dergamysh* deposits (Ovchinnikov, 1998). Their Ni–Co specialization is explained by the above-said rule: the mineralogy of sulphides correlates with the type of host rocks. In this case, the host rocks are predominantly mantle ultramafics, while the upper part of the ophiolite succession is strongly reduced. Some time ago, they were thought to be analogues of hydrothermal fields of the Middle Atlantic Ridge at its low latitudes, like Rainbow and Logachev, and attributed to the specific Atlantic type. At a later stage, it was shown that they were formed in the forearc setting (Jonas, 2003; Nimis et al., 2005; Zaykov et al., 2009).

The VMS deposits are accompanied by metamorphic aureoles that are useful as indicators of prospecting targets. They also may contain

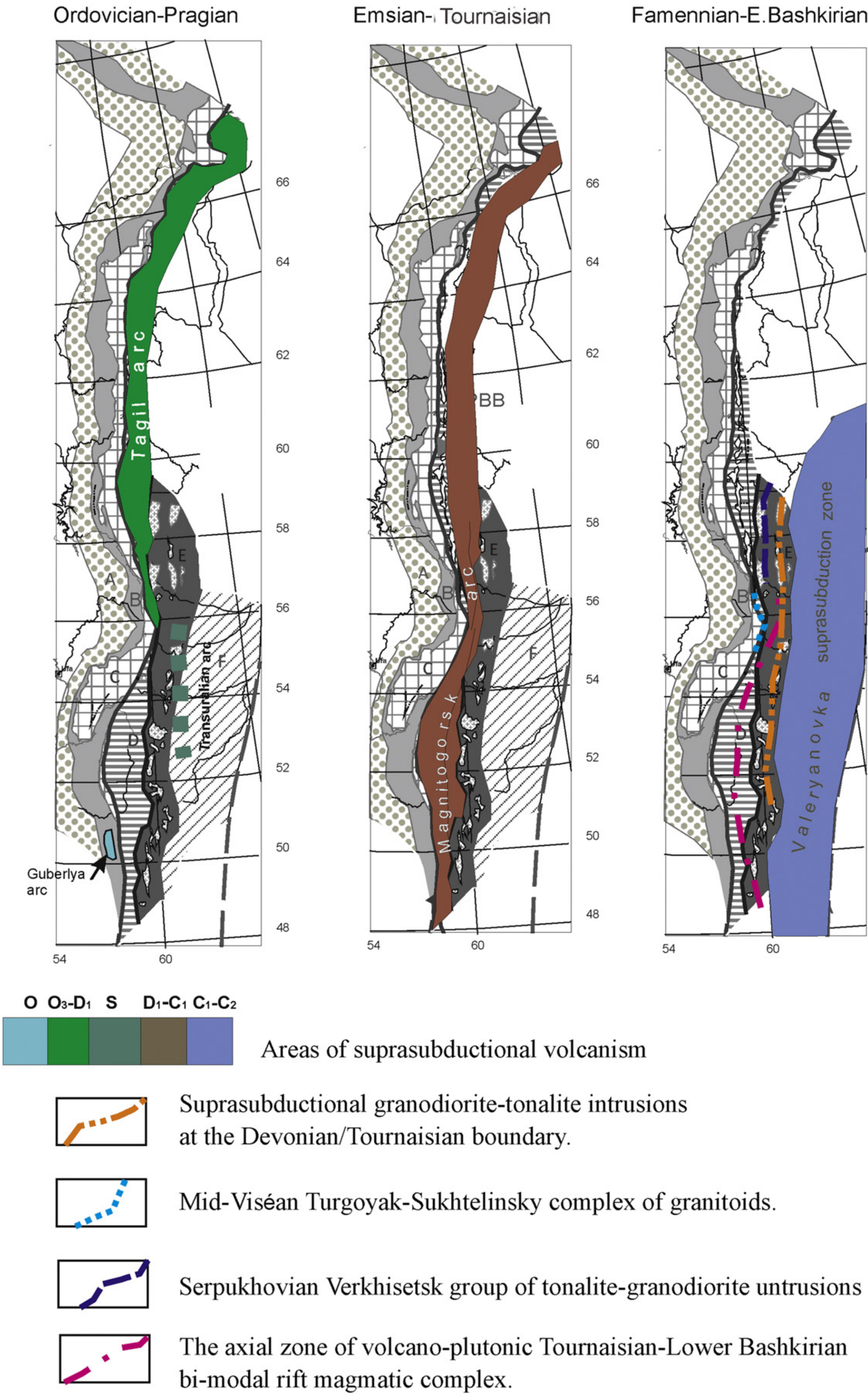


Fig. 11. Paleozoic subduction complexes of the Uralides.

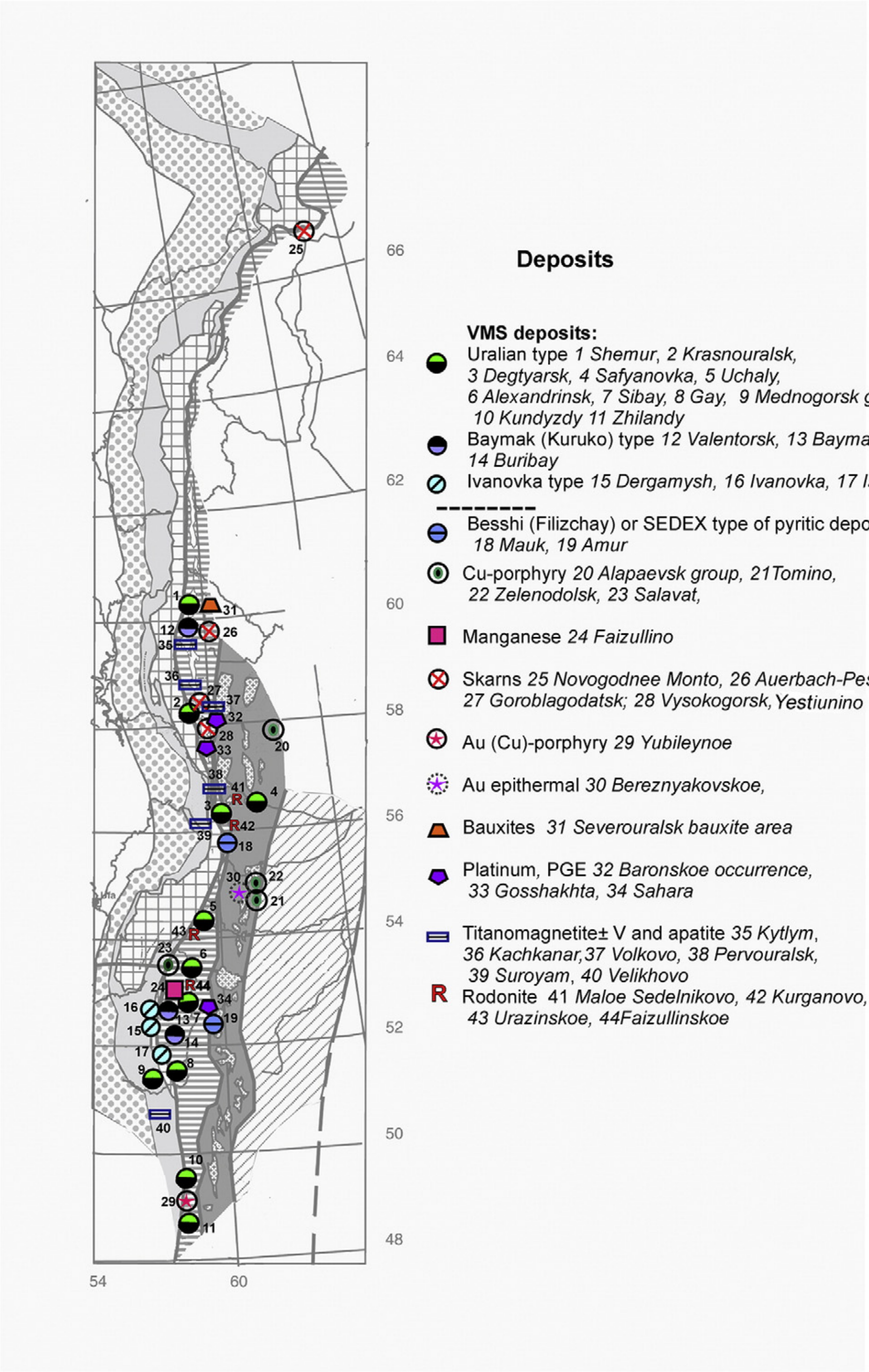


Fig. 12. Mineral deposits hosted by early subduction complexes (Ordovician–Upper Devonian).

pyrophyllite deposits, like *Kul-Yurt-Tau* in the Southern Urals (Zaykov and Udachin, 1991).

The iron–manganese mineralization in cherts, mainly of Middle Devonian age, in the Magnitogorsk zone was probably a result of sea-floor deposition from hydrothermal sedimentation, more distant from volcanic centres and of lower temperature (e.g., *Faizullino* and many others). Formation of rhodonites (unique *Maloe Sedelnikovo* and large *Kurganovo* in the Middle Urals; Faizullino and many others in the South Urals) is related to these hydrotherms, but metamorphism of primarily manganese–carbonate and opal material at 450–500 °C is a necessary condition of their origin (Brusnitsyn, 2000).

Along with the VMS deposits, there are several other types of sulphide mineralization in relation to island arcs. Among them is the *Amur* polymetallic deposit, represented by stratiform sulphide mineralization (mainly zinc) hosted by Devonian black shale–carbonate sedimentary unit with rare volcanics of supra-subductional origin. Traditionally, the deposit was attributed to a Filizchay (Besshi) type of pyritic deposits, but now there is a tendency to regard it as a SEDEX type. In fact, no direct connection with volcanics was demonstrated (Novoselov and Belogub, 2008; Snachev et al., 2015).

In the Magnitogorsk arc, there is a *Salavat* porphyry Mo–Cu deposit (Grabezhev and Belgorodsky, 1992). Two porphyry copper occurrences

(*Voznesensk* and *Karagaikul*) belong to the same arc, though Early Devonian diorites, gabbro, gabbro-diorites and other intrusive rocks, hosting the sulphides, are blocks in the serpentinite melanges along the MUF (Kosarev et al., 2014). The *Yubileinoe* Au–(Cu) porphyry deposit in the Mugodzhary must also be mentioned as belonging to the same arc (Shatov et al., 2005).

The genesis of the porphyry copper system is usually discussed in relation to a "diorite" model. Grabezhev and Ronkin (2011) noted that such ore-magmatic systems are developed in all volcanic (subduction-related) zones of the Urals. The U–Pb SHRIMP-II dating of zircons from diorites confirms in general the geological data on eastward younging of ore systems from the Late Silurian to Lower and Middle Devonian sequence in the Tagil–Magnitogorsk zone, to the Famennian to Lower Carboniferous sequence in the East Uralian megazone and mid-Carboniferous (K–Ar method) in the Valerianovka zone in the easternmost Urals. The *Tominsky* porphyry Cu deposit of Late Silurian age (428 ± 3 Ma) seems to be an exception in the western part of the East Uralian megazone (Uvelka zone). Genetically and spatially close to it, the *Bereznyakovskoe* deposit, often attributed to a gold epithermal type is also Silurian in age: 427 ± 6 Ma (Grabezhev et al., 2013). The Silurian age is also suggested to the nearby Cu-porphyry Birgilda deposit by Romashova (1984) These data have an additional confirmation of Late Silurian mineralization of the Uvelka zone: zircons from the *Zelenodolsk* porphyry copper deposit also yielded a Late Silurian age (Grabezhev et al., 2016). These data are an additional proof for existence of the Silurian subduction zone (Fig. 12A) in relation to the Transuralian arc (Puchkov, 2009, 2010b, 2013b). The Silurian porphyry deposits are indicators for tracing the arc here, although it may be allochthonous.

The Lochkovian to Upper Devonian island arc (probably part of the Magnitogorsk arc) is traced in the eastern part of the East Uralian volcanic zone of the Middle Urals, and its metallogeny is characterized here by presence of a 100-km-long *Alapaevsk–Sukhoi Log zone* of porphyry copper and porphyry molybdenum–copper occurrences and small deposits, with U–Pb (SHRIMP II and LA-ICP-MS) ages of zircon, ranging from 411 ± 3 to 397 ± 4 Ma (Grabezhev et al., 2014b).

The intrusions of the Platinum-bearing Belt (PBB) in the Tagil arc in the Middle and North Urals are composed of dunite, pyroxenite, gabbro, gabbro-amphibolite and granites forming large concentric-zonal massifs. Some researchers attribute them to the Alaskan type, but for the sake of political correctness, it would be better to call it the Ural–Alaskan type, because in the Urals, they are studied much better. The massifs have hot protrusive contacts with host Ordovician to Silurian island arc effusives, underlain by Ordovician ophiolites.

Two main complexes (under different names) were established in the PBB (Efimov, 1984; Fershtater, 2013). The older one (DCG complex) consists of dunite, clinopyroxenite and gabbro (tilaite). The younger one and more uniform predominantly consists of gabbro-norite (GN complex), represented mostly by large bodies of gabbro with relics of primary ophitic two-pyroxene gabbro-norites. These two complexes make more than 90% of all PBB massifs. The PBB massifs differ from ophiolites in their concentric-zonal structure, with complete absence of harzburgites and characteristic chemistry (high-Fe dunites, high Sr in gabbro, higher concentration of incompatible elements and others). They are now believed to belong to the Early Paleozoic island arc (Ivanov and Shmelev, 1996; Yazeva and Bochkarev, 1993; Fershtater, 2013). However, the problem of their origin and age is probably far from resolution (Puchkov et al., 2014; Tessalina et al., 2015). First of all, the isotopic age data conflict with the idea of a single stage.

As for the GN complex, its Early Paleozoic supra-subductional nature is proven fairly well. The concentrations of the most petrogenic and incompatible elements permit to speak about their similarity to island arc tholeiites (Ivanov and Shmelev, 1996). The predominant Late Ordovician to Silurian (460–410 Ma) U–Pb isotopic ages of zircons from gabbro (Bosch et al., 2006) and the same age of predominantly island arc host rocks speak in favour of this point of view. But numerous results of Sm–Nd dating of the DCG complex conflict with this hypothesis. In particular, a series of papers was published during the last decades by Ronkin et al. (1997); Mægov et al. (2006); Popov and Belyatsky (2006); Efimov et al. (2010); Petrov et al. (2010) and others, suggesting that this complex is of Late Vendian (Ediacaran) or older age.

The belt received its name from native platinum that originally was produced mostly from placers. Platinum was supplied to these placers from chromite bodies of the nearby dunite massifs, part of the DCG complex. The restite versus melt-produced differentiate models were discussed for the platiniferous dunites. Recently, it was shown that primary, accessory chromites of the platiniferous Nizhny Tagil massif contain melt inclusions of high-temperature (up to 1430 °C) subalkaline picrobasalt magma (Simonov et al., 2013). But platinum is concentrated in late magmatic or rather postmagmatic (metasomatic) schlieren of secondary chromites, formed with presence of low-temperature fluids (Pushkarev et al., 2014).

The richest platinum placer, which yielded more than 100 t of the metal, is called *Isovskaya* (after River Is). Platinum was redeposited here from two adjacent dunite massifs — Veresovoborsky and Svetloborsky. The exploitation of primary deposits was not so profitable. Nevertheless, a rich pillar-like deposit of Pt-bearing chromites in dunites in the Solovyova Gora area of the Nizhny Tagil massif (*Gosshakhta*) was exploited successfully for many years and is now closed (Zoloev et al., 2001).

A special role as an active factor of ore mineralization in the belt was played by magmatic stratification and thermo-chemical activity of mafic–ultramafic zonal intrusions, forming transitions from magmatic segregations of vanadium-rich titanomagnetite in pyroxenites and gabbro to skarn-magnetite and more distant skarn-hydrothermal deposits in gabbro (Ovchinnikov, 1998). At that, the *Kachkanar* group of deposits can be a typical example of a vanadium-bearing magnetite mineralization in pyroxenites. To the same type belongs the *Kytlym* and other groups. Kachkanar titanomagnetite are characterized by Pd–Pt–Ru mineralization. The *Pervouralsk* deposit in the Revda massif differs from the Kachkanar ores, being localized in hornblendites, not in pyroxenites; the Pd–Pt–Ru–Au association of precious metals is somewhat different here (Zoloev et al., 2001).

Another type of mineralization, skarn-magnetite, is represented by large *Yestiunino* deposit at the contact with the Tagilo-Baranchinskiy gabbro massif. The magnetite in these skarns has untypically high TiO_2 concentration (0.84% on average). The third type, represented only by the *Volkovo* group, is hosted in layered gabbro and is represented, along with predominant titanomagnetite, by ilmenite, apatite, bornite, chalcopyrite and chalcocite (the latter three minerals are concentrated along the zones of superimposed tectonic reworking). The ores contain palladium, platinum and gold in uneconomic quantities. But with Volkovo group is connected the new Baronsky type of economic Au–PGE (Pd–Au–Pt) mineralization (*Baronskoe* Fig. 12 occurrence). The titanomagnetites, containing precious metals, are hosted by apatite-bearing olivine pyroxenites; the structure is complicated by a swarm of diorite and granite–aplite dykes, which influenced the distribution of ore mineralization (Zoloev et al., 2001).

Comparable associations of the platinum-bearing type are also developed in other massifs of the Urals, e.g., in the Khabarny massif. Titanomagnetites of the *Velikhovo* deposit in the gabbroids of the Sakmara zone resemble Kachkanar type (Ovchinnikov, 1998). These are allochthonous. The Pd–Pt metal association is known in the *Suroyam* massif, with the Ti–V-rich magnetites and apatite deposit of the same name in the Nyazepetrovsk allochthon (Zhilin and Puchkov, 2009). Allochthonous are some VMS deposits, such as Mednogorsk group in the West Uralian zone and Safyanovka in the East Uralian zone. Allochthonous are also the Kempirsay and Kraka chromite deposits of the West Uralian zone. Without understanding of the nappe structure, it is impossible to understand the localization of such deposits west of the MUF, because they are found in "wrong" places.

In the Magnitogorsk zone, presence of platinum was only confirmed in the *Sakhara* massif (Ivanov, 1997). Massive complexes of PBB type are suggested at some depth according to geophysical data (Ivanov and Vinnichuk, 2001).

In the Early Devonian, the development of the Tagil island arc was at its late stage with higher-alkaline volcanism. The group of skarn-magnetite deposits (such as *Vysokogorskoe* and *Goroblagodatskoe*) is connected with the subalkaline syenite, diorite and granodiorite intrusions, e.g., Tagil, Kushva and others (Ovchinnikov, 1998). Together with trachytes, trachyandesites of the Lochkovian-aged Turinsk Formation, they finalize magmatic succession of the Tagil zone.

After the Lochkovian (in the Pragian–Emsian), the active stage in development of the Tagil zone came to an end. The arc became divided into two zones. In the west (Petropavlovsk zone), volcanic activity was replaced by formation of the carbonate shelf with sub-equatorial lateritic weathering and bauxite deposition (*Severouralsk* bauxite field). In the eastern part of the Tagil arc (Turinsk zone), subduction-related magmatism of the Krasnoturinsk Formation was still going on, supplying volcaniclastic material to be weathered and turned into bauxites in the Petropavlovsk zone and giving birth to skarn-magnetite and copper-skarn mineralization in the Turinsk zone. I suggest that the extinct Tagil arc was by that time incorporated into the younger Magnitogorsk arc as a microcontinent (Fig. 12B).

Metallogeny of this stage is characterized here by presence of magnetite and copper-magnetite skarns. As an example, deposits of the Auerbakh–Turinsk ore field can be suggested. Skarn magnetites of the *Auerbakh–Peschansk* group occur among the Emsian Krasnoturinsk volcanogenic–sedimentary rocks (andesitic basalts, tuff sandstones, limestones), which were influenced by multiphase granitoid intrusions, forming a single volcano-plutonic association (Grabezhev et al., 2014a). *Turinsk* copper-skarn deposits are known at the southern periphery of the Auerbakh–Peschansk skarn group (Ovchinnikov, 1998; Grabezhev and Shardakova, 2004).

In the Polar Urals, a *Novogodnee Monto* gold-skarn deposit was discovered. It was shown that it is a polychronous and polygenetic deposit that originated primarily at a flank of the Schuchya zone as a middle Paleozoic typical magnetite skarn. Sulphide and quartz-sulphide mineralization with gold was formed as a result of a later hydrothermal alteration during the collisional stage (Trofimov et al., 2005).

3.3.5. Metallogeny of early collisional (Late Devonian) and late subductional (Early Carboniferous–Bashkirian) stages (Fig. 13)

In the Late Devonian, collision between continental passive margin and Magnitogorsk island arc took place in the South Urals (Brown and Puchkov, 2004; Puchkov, 2009, 2010b). The stage was accompanied by some economic mineralization (e.g., rutile (*Shubino*), quartz (*Ivanovka*), metamorphosed VMS deposits, jadeite and gold, inside and adjacent to the MUF zone).

Still unsolved is the problem of the diamond potential of the eclogite–glaucophane Maksyutovo complex. Notwithstanding some positive indications (rare finds of diamond crystals) and X-ray patterns, the estimations of pressure after mineral barometers usually did not exceed 1.5–2 GPa (Leech and Ernst, 2000 and others), which is too low for diamonds to form. However, data were published concerning the aggregates of a nanocrystalline diamond in eclogites (Bostick et al., 2003), indicating a possibility of recognition of the Kumdykol-type diamonds in northern Kazakhstan, as well for its analogues in the north of the Urals.

HP–LT metamorphism, related to the arc–continent collision, could have led to formation of the *Kechpel* jade (jadeitite) deposit at the expense of a plagiogranite vein in peridotites of the Voykar ophiolite massif in the hanging wall of the MUF. The *Pusyerka* jade (jadeitite) deposit in the western endocontact of the Syum-Keu peridotite massif occupies the same position The jade-nephrite (*Nerdvomenshor*, *Miass*, *Kozma–Demiansk*) and talc (*Miass group*) deposits were also formed within the MUF or close to it, as a zone of stress-metamorphism, permeable for fluids into the mafic–ultramafic complex. (Efimov and Potapova, 1992; Dushin et al., 2000, 2001; Salikhov et al., 2010).

Of non-metallic deposits, there also must be mentioned such decorative stones as listwanites (*Ieremel*, *Mindyak* deposits) and decorative serpentinites (*Bazhenovo*, *Shabry*, *Nurali group*, *Mindyak*, *Kuvatovo*) (Ovchinnikov, 1998; Salikhov et al., 2010).

A special problem is *Yuluk* group of pyritic deposits in the Uraltau Range, associated with the Maksyutovo complex. Probably, these are metamorphosed hydrothermal–sedimentary deposits of the Magnitogorsk arc, involved into the accretionary complex of the Uraltau antiform during the Late Devonian collision.

Puchkov (2009) demonstrated that the MUF was diachronously formed during the continent–island arc collision in the Late Devonian in the South Urals to the Early Carboniferous in the North Urals. Collision and accretion of the continent continued into the Late Carboniferous after a jump of the subduction zone and formation of either ensialic island arc or a Nevada-type active margin in the east of the Urals.

The skarn-magnetite deposits of the *Sokolovo–Sarbay* group (*Sokolovo*, *Sarbay*, *Kachar*, and others) in the Transuralian zone and in the Magnitogorsk area (*Gora Magnitnaya*), Cu-skarn-porphyry mineralization (*Tarutino*, *Novonikolaevskoe*) and several Cu-porphyry, Au–Cu-porphyry deposits in the Transuralian zone (*Varvarinskoe*, *Mikheevskoe* and others) accompanied this process (Fershtater et al., 1984; Poltavets, 1991; Grabezhev and Belgorodsky, 1992; Grabezhev et al., 2004; Seravkin, 2002a,b).

The skarns of the Sokolovo–Sarbay group contain a resource of 3 Gt of iron oxide. The magnetite deposits are developed dominantly as metasomatic replacement of limestone, but also, to a lesser extent, of volcanic rocks, Visean and Serpukhovian in age. According to Hawkins et al. (2017), analysis of Re–Os isotopes in molybdenite indicates formation of the sulphide mineral assemblage at 336.2 ± 1.3 Ma, whilst U–Pb analyses of titanite from the skarn alteration assemblage suggests skarn alteration at 326.6 ± 4.5 Ma. It leaves practically no time gap between the sedimentation, volcanism and ore formation. The geodynamic context is a subject of discussion: see Ivanov et al. (1986), who proposed the rift nature of the deposits and Poltavets (1991) who advocated their suprasubductional position (in fact, they may belong to subduction-related rift?). As for the Gora Magnitnaya deposit, it was certainly formed in a rift setting (Fershtater et al., 1984).

Tevelev et al. (2005) demonstrated that the Carboniferous volcanics of the eastern zones of the Urals, from Magnitogorsk to Valerianovka, have mixed geochemical signatures of supra-subductional and intraplate (riftogenic) magmatism, and this is typical for continental margins of Nevada or Californian type (this type originates when a mid-oceanic ridge is subducted under a continental margin (Breitsprecher and Thorkelson, 2009; Cole and Stewart, 2009).

The termination of the island arc development was accompanied by formation of the Carboniferous coal basins, both in the eastern and western zones of the Urals.

3.3.6. The continent–continent collision stage (Fig. 14)

Continent–continent collision began in the Late Bashkirian time, when all of the oceanic lithosphere was completely subducted. It led to the formation of the Uralian orogen and Preuralian foredeep. Intense thrust stacking and formation of the crustal root have resulted in anatexis and emplacement of Permian granites. Together with transpressional style of deformation (Znamenskiy et al., 2015), it created elevated heat and fluid production, partial melting in the lower crust and abundant fluid conduits in the upper crust, which was favourable for intense metasomatism, hydrothermal activity and formation of specific deposits.

In the Central Uralian zone, Alpine-type veins with different kinds of quartz were formed. The north of this zone is well-known for numerous deposits of piezoelectric and optic quartz, forming the Sub-Polar rock crystal province (*Parnuk*, *Pelengichey*, *Skalistoe*, *Khasavarka* amethyst, and others), with *Zhelannoe* and *Puiva* deposits exploited during recent years (Yushkin et al., 1997). The processes of their formation may

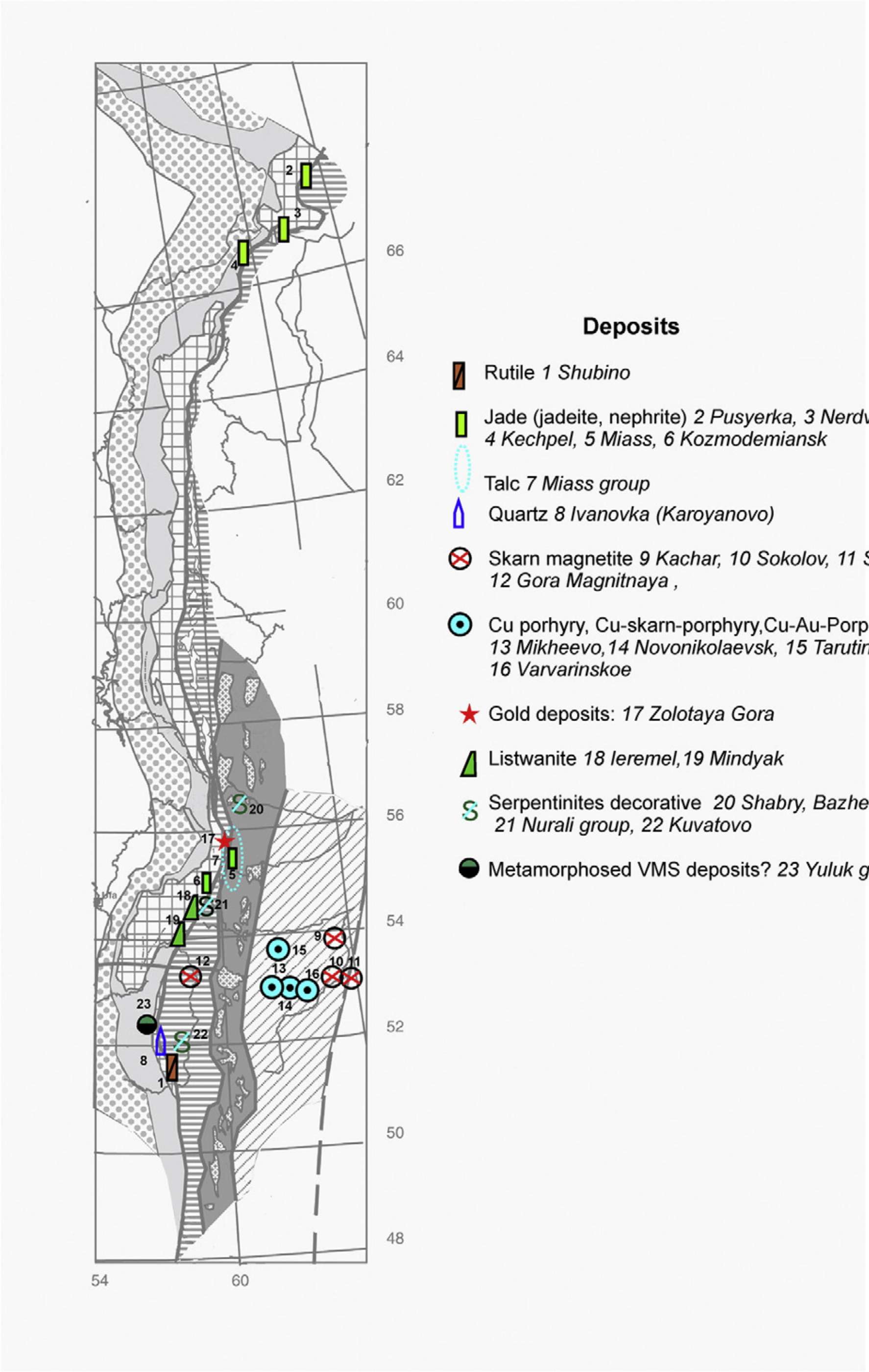


Fig. 13. Mineral deposits hosted by early collisional (Upper Devonian–Lower Carboniferous) and late subduction (Lower Carboniferous — Bashkirian) complexes.

belong to both Timanian and Uralian orogenic stages, though Zhelannoe is hosted by the Lower Ordovician quartzites and therefore certainly belongs to the Uralides. The high-quality metamorphogenic granulated quartz is associated with collisional zones of crushing, particularly in the *Ufalei* area of the Middle Urals (Savichev, 2005). Quartz veins with crystals (or granulated quartz) are associated with quartzites or (more often) with granites: *Murzinka–Aduy with its Vatikha amethyst deposit*, *Syrostan*, *Kachkar* (*with Svetlinskoe and other deposits*), *Dzhabyk*, and *Suunduk groups* — in this case, they are certainly of Carboniferous–Permian age).

A possibility of transformation of rare metal deposits at the collisional stage was discussed above.

In the MUF and some other suture zones, metasomatism and formation of quartz–gold deposits were active, controlled structurally by strong transpressional deformations and generation of heated fluids of metamorphic and magmatic type (Znamenskiy et al., 2015), e.g., *Murtykty*, *Orlovskiy*, *Sredneubalinskiy* and *Mindyak* deposits.

In the Tagil–Magnitogorsk megazone is the *Vorontsovskoye* gold deposit, sometimes attributed to the Carlin type (Sazonov et al., 2001). The deposit is situated near the Devonian Auerbakh gabbro-diorite pluton, with its suite of skarn deposits. But its genesis (at least during the late stages) can be linked to 300 Ma collision. It is localized under a thrust fault, at a contact of limestones and tuffites. Gold is associated with As,

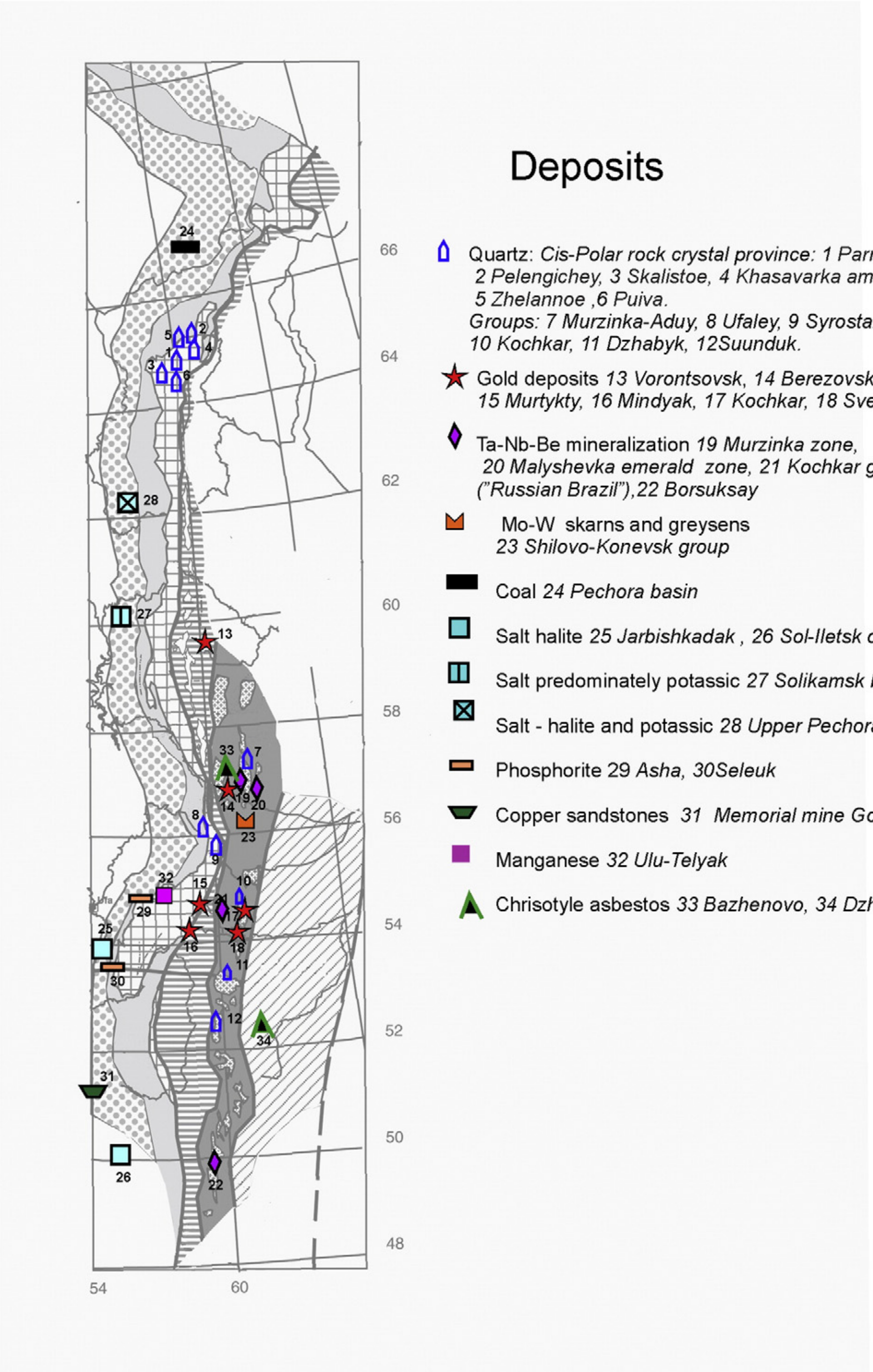


Fig. 14. Mineral deposits hosted by continent–continent collision complexes (Upper Bashkirian–Upper Permian).

Sb, and Hg and is hosted by highly variable skarns to metasomatic argillites.

In the East Uralian zone at the collision stage, in the Late Carboniferous and Permian time, a formation of the Main Granite Axis of the Urals took place. Permian anatectic granites were added here to the Late Devonian–Early Carboniferous supra-subduction intrusions of the granite–tonalite series (Bea et al., 2002). This magmatic activity was accompanied by zonal metamorphism, hydrothermal alteration, formation of quartz veins (Dzhabyk area, where the most important is the *Astafievskoe* deposit (Ovchinnikov, 1998)), gold deposits (*Kochkar*, *Svetlinskoe*, *Berezovskoe*); in their history, gold–quartz lodes, accompanied by rare metal deposits and precious stones, were produced in several steps (e.g. Polenov et al., 2013) during the final stage. The latter can be traced along the entire length of the MGA, but the most abundant are the two zones of mineralization at the exocontacts of the Late Permian Murzinka–Adui granite massif, connected with a late-stage accumulation of fluids, formation of greisens and pegmatites. The western *Murzinka zone* is represented by the Late Permian rare metal pegmatites with precious stones (topaz, beryl, alexandrite) (Prokin, 2002). The eastern Emerald (*Malyshevka*) zone represents a combination of pegmatite fields (Popov et al., 2008), with deposits of emeralds, beryl and alexandrite, rare metals (Ta–Be, W–Mo) and others.

At the continuation of the MGA to the south, deposits of skarn, greisen and pegmatite type are developed in endo- and exocontacts of

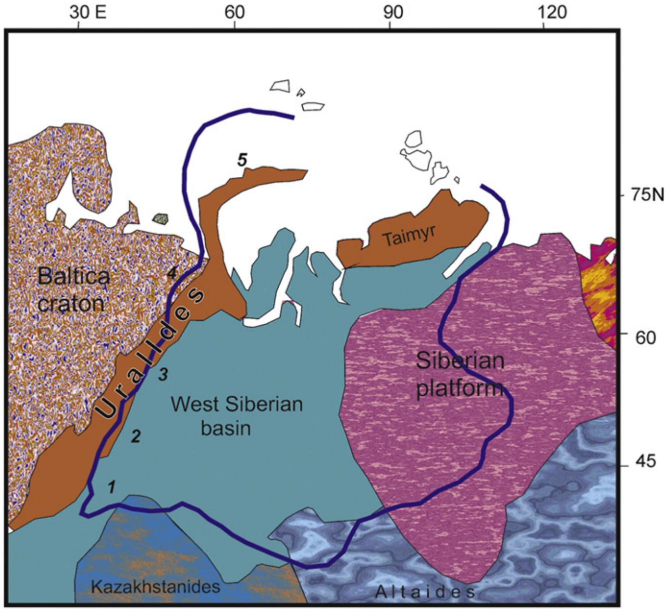


Fig. 15. Triassic basalts in the context of the Uralo-Siberian superplume. Contours of the Urals–Siberian Triassic superplume are shown by a thick line. Triassic flood basalts in the Uralides (Puchkov, 2010a): 1 — Kushmurun uplift, 2 — grabens of the Chelyabinsk and Kamensk–Uralsk regions; 3 — Severososvinsky graben, 4 — traps of the Kosyu–Rogovskoy, Korotaikha depressions and Chernyshov Range; 5 — Triassic basalts and small intrusions of the Novaya Zemlya.

middle-sized granite massifs of the *Shilovo–Konevsk* group. Further south, the small rare metal occurrences accompany a majority of the MGA granite massifs (Chelyabinsk, Kochkar, Dzhabyk, Suunduk) (Ovchinnikov, 1998). The Kochkar group of occurrences of precious stones was given a name of "*Rusiian Brazil*" (Kolesnichenko and Popov, 2008). Rare metal mineralization is described also in the southern end of the East Uralian megazone (*Borsuksay* deposit, associated with miaskites) (Es'kova, 1976).

It is quite probable that metamorphogenic–metasomatic processes, accompanying formation of the MGA, led to development of rich deposits of chrysotile–asbestos (*Bazhenovo*, *Dzhetygara* and others). The early stages of their formation could be connected with granite–tonalite intrusions of the previous (subduction) epoch, while the late stages were related to the granites (Efimov, 2000).

The Preuralian foredeep, formed during the Permian collisional stage, hosts hydrocarbons, coal, salt, cupriferous sandstones and manganese. The distribution of many of these deposits along the foredeep was controlled by climate (salt and cupriferous sandstones in arid climate, and coal — in colder and wet conditions of a humid climate of the Northern Hemisphere). Cupriferous sandstones are widely distributed in the Cis-Urals and were exploited since the Bronze Age (Gorny village near Orenburg as an example). Now they are all abandoned. The ore bodies are numerous, but small in size, not suitable for modern mining technologies.

Of halite deposits, the *Jarbishkadak* deposit in the South Urals must be mentioned as the largest and most productive, as well as very famous and large deposits of halite in *Sol-Iletsk* and of potash in the *Solikamsk* basin of the Perm district. At its prolongation to the north is the *Upper Pechora* basin, with considerable reserves of halite, magnesial and potassic salts, still not exploited. Coal deposits are concentrated further North, in the Pechora coal basin.

The Lower Permian deep-water deposits of the foredeep contain layer- and concretionary-type phosphorites (e.g., *Seleuk*). In the *Asha* area, among shallow-water sediments, are small phosphorite deposits, connected with Permian weathering of phosphorus-bearing rocks (Chuvashov and Yakovleva, 2008).

Ulu-Telyak manganese deposit in the Southern Urals is represented by magnesial carbonates, but commercial reserves are connected here with the supergene oxidized ores.

In the Triassic period, collisional processes have stopped, and the mode of tectonic activity has changed. Apart from coal deposition, it was characterized by an intense flood basalt volcanism, probably connected with the widest Early Triassic Siberian superplume event (Fig. 15) (Dobretsov et al., 2001; Reichow et al., 2009; Puchkov, 2010a). In this connection, a high possibility of discovering the Norilsk-type deposits in the Uralian part of the superplume is promoted by some workers (Zoloev, 2001).

The Triassic mineragenic processes in the Urals are practically not studied. In particular, a problem of primary sources of diamonds, connected with this plume is not resolved. Dykes and explosion pipes of alkaline–ultramafic composition are described in the Kvarkush anticlinorium and Chernyshov Range in the South Urals. They were dated tentatively as the Late Triassic to Early Jurassic and therefore could be connected with the Siberian mantle plume (Krasnobaev et al., 1993; Lukianova et al., 1997; Rapoport and Barannikov, 1997; Surin, 1999; Zoloev et al., 2006). On the other hand, Ar–Ar dates of the lamproites of the South Urals range between 303.2 ± 3.8 and 308.4 ± 3.8 Ma, e.g., are not connected with the plume (Pribavkin et al., 2006). In the Sub-Polar Urals (Khartes area), kimberlites were found; in the MUF zone on River Sertynya, K-alkaline lamproites and kimberlite-like tuff breccias contain diamonds (Golubeva and Makhlaev, 2004; Zoloev, 2001). But still there is no real breakthrough in this problem.

Before the Middle Jurassic, the last (Cimmerian) phase of thrust-and-fold deformations took place. After that, erosion of the orogen went on very quickly and ended with formation of a peneplain, which means an establishment of the platform stage.

4. The Middle Jurassic to Paleogene platform complex (Fig. 16)

The beginning of the platform stage is accompanied by formation of shallow Jurassic coal basins (*Orsk-Tanalyk and Severnaya Sos'va*) in the South and Sub-Polar Urals (Volkov et al., 1961; Lider, 1964). In general, the stage was characterized by poor erosion, weathering (partly lateritic), karst formation, fluvial drainage and burial of river valleys, with flow directions, indicating the absence of a single Uralian watershed. Periodic sea transgressions never covered all the Urals, but also indicated an absence of even lower Uralian range (Papulov, 1974).

These processes were accompanied by accumulation of a series of sedimentary deposits along the sea shore lines, in buried Jurassic and Cretaceous river valleys, in karst cavities, above limestones, salts and sulphates. As a result, many small bauxite deposits were formed, which belong collectively to an East Uralian bauxite-bearing region; various alluvial and near-shore placers — gold- and platinum-bearing, titanium-zircon and others. Among placers of the Urals were gigantic, with 150-year history of exploitation (*Isovskoy group* that produced more than 100 t of platinum; *Miass Gold valley* with 125 t of gold) (Sigov, 1969; Popova, 2002; Shilo, 2002). Placers (*Krasnovishersk group*, Korablev, 2002) on the western slope of the Middle Urals contain gem-quality diamonds. Many famous placer areas are now exhausted (for example, the resources of placer gold in Bashkortostan do not grow for many years). On the other hand, some of the placer areas were discovered not so long ago. A rich *Kozhim* gold placer area was discovered in the North Urals in the 1970s, though later its economic prospects were restricted, because it was declared to belong to a territory of the Kozhim Natural Reserve (Yushkin et al., 1997; Dodin et al., 2001; Popova, 2002).

On the western slope of the Middle Urals, the diamond placers are controlled by ancient valleys (Sigov, 1969; Papulov, 1974). By the end of the XX century, an extensive discussion unfolded around presence of diamond deposits of tuffisite type in the same region (Chaikovskiy,

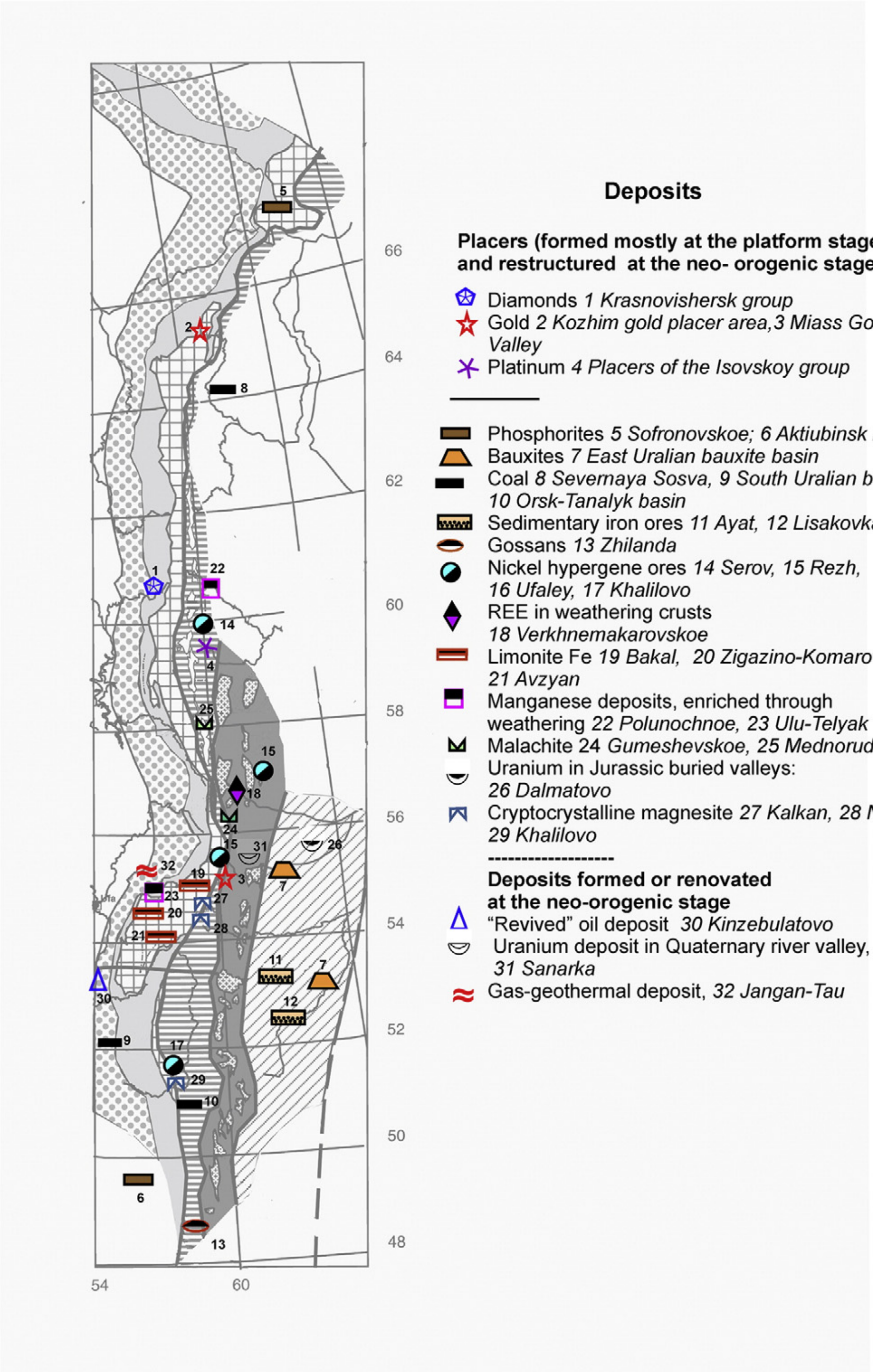


Fig. 16. Mineral deposits of the platform stage of development in the Urals.

2002). Their age is thought to be Mesozoic to Cenozoic (up to Quaternary). However, this point of view has a strong opposition. According to Malakhov (2000), the oldest placers of diamonds here (Lower Silurian Kolchim and Lower Devonian Takata formations) put an age limit to the source of primary deposits.

Very large and easy to extract, extensive sedimentary iron deposits were controlled by swampy lowlands and shore lines of the West Siberian Sea in the Late Cretaceous (e.g., Ayat deposit) and in the Oligocene (Lisakovka deposit). Analogous near-shore position had the Polunochnoe manganese deposit (Ovchinnikov, 1998).

A formation of Aktyubinsk phosphorite-bearing basin along the southernmost Urals was connected with a shallow Cretaceous sea (Bespaev and Miroshnichenko, 2004).

Deep weathering also produced gossans, which were developed on top of VMS deposits and produced tonnes of free gold, often with bonanza concentrations. For example, the *Zhilanda* VMS deposit in the

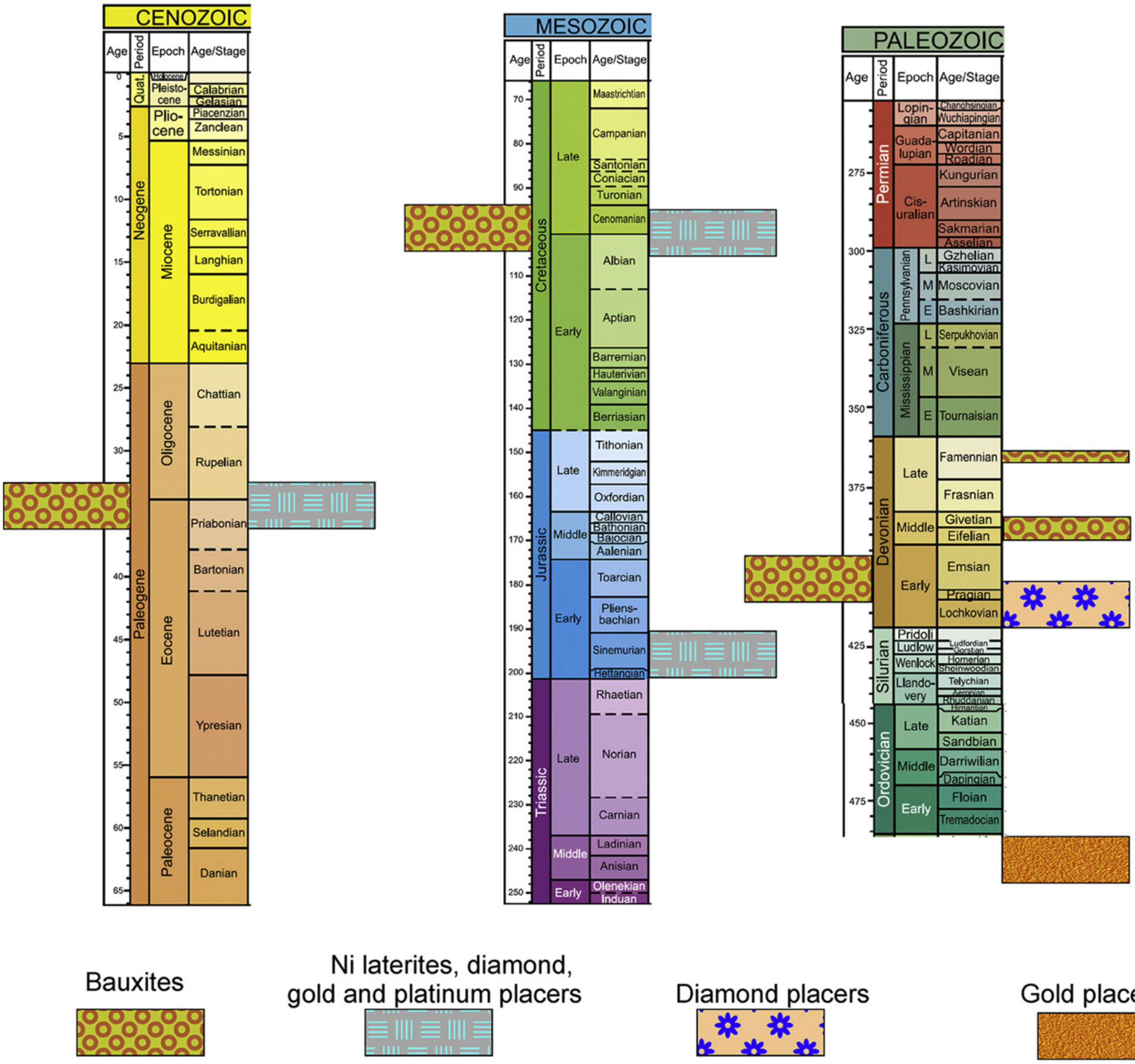


Fig. 17. Major weathering epochs in the Urals and associated mineralization.

Mugodzhars was exploited only for gold, with a tonne of gold taken from gossans, and sulphides left untouched.

Lateritic nickel ores are connected with weathering of serpentinites, commonly along their disjunctive contacts with karstified carbonates (*Serov*, *Rezh*, *Ufaley*, *Khalilovo* and other groups). Naturally alloyed iron ores are widely developed along the MUF mélange. Such are the Khalilovo limonite deposits, enriched in Mn, Cr, Ni and Co (Ovchinnikov, 1998). Deposits of a cryptocrystalline magnesite were formed due to leaching and infiltration processes upon ultramafic rocks: *Kalkan*, *Nurali*, *Khalilovo* (Eremin, 2007; Salikhov et al., 2010).

Of other supergene deposits, the *Gumeshevskoe* malachite deposit near the town of Polevskoy and the *Mednorudyansk* deposit of the Vysokogorsk ore field, must be mentioned. Malachite in both cases was formed in the supergene zones of copper skarn deposits (Ovchinnikov, 1998; Grabezhev, 2010) with active role of limestones as a substrate for karst and source of carbonate.

Karst was also important for localization of some other supergene deposits, such as a series of small coal deposits of the *South Uralian basin* in the south of the Preuralian foredeep, which are situated in depressions, formed during the Miocene over salt domes and ridges (Yachimovich and Adrianova, 1959).

A special type of REE deposits is represented by weathering crusts on gneisses and granites of the South and Middle Urals. The REE were absorbed by clay minerals and partly concentrated as secondary minerals such as cherchite. As an example, the *Verkhnemakarovskoe* deposit, situated to the east of the Sysert anticline, can be mentioned (Savelieva, 1997; Zoloev et al., 2004).

The weathering was a factor of enrichment of primarily poor deposits. *Sofronovskoe* phosphorite deposit in the Polar Urals was formed during the supergene enrichment of primarily poor phosphate-bearing shelf sediments, and gold was accumulated along with phosphorite (Kozmin, 2000).

Enrichment, as a result of weathering, led to formation of a series of small limonite deposits upon shales and siderites in the Bashkirian meganticlinorium (*Zigazino–Komarov*, *Avzyan* and others). Manganese deposits, such as Ulu-Telyak, Polunochnoe and a series of deposits in the Magnitogorsk zone, were also partly enriched as a result of their oxidation.

In the Jurassic, epigenetic uranium (with REE) deposits were formed in the buried valleys (Dalmatovo in the Kurgan district and others) (Khokhryakov, 2004).

5. The Late Cenozoic neotectonic (neo-orogenic) complex

The time when the Ural Mountains began uplifting again came in the Pliocene (Puchkov and Danukalova, 2009). It is most important as the time of placer final formation. Once created during the previous epochs, placers could not simply disappear, dissipate or shift horizontally under influence of a deep erosion, but could be just redeposited into new transversal valleys (Shilo, 2002). On the other hand, the importance of this epoch for formation of placers should not be overestimated. The previous, platform stage, with its long epochs of weathering, river transportation and near-shore sediment differentiation was much more productive.

In compliance with the above, in the areas of intense syn-orogenic erosion of the Urals, one can expect presence of only “secondary”, redeposited placers; the “primary”, predominantly Mesozoic placers are preserved at lower topographic levels; they occur in the Transuralian areas. In turn, the Mesozoic placers are attracted to an intersection of ancient valleys and zones of primary mineralization. Thus, the most usual gold-placer primary sources are thought to be quartz lodes (Koroteev and Sazonov, 2005).

The reworked placers are not the only type of deposits formed during the neotectonic epoch. For example, in the Quaternary time in the Chelyabinsk area was formed the uranium deposit of a new type (*Sanarka*), situated in a river valley over a weathering crust of granites (Khokhryakov, 2004).

The neotectonic stage had a special effect on redistribution of liquid and gaseous deposits (oil, gas, condensate, mineral and drinking water and, as a special case, formation of thermal gases of *Jangan-Tau*) (Puchkov and Abdrakhmanov, 2003).

The velocity of movement of oil and condensate could be considerable. As it is shown for the exhausted oil deposits, after some period of rest, they can show a partial recovery of resources (*Kinzebulatovo* oil deposit in the South Urals and some deposits of Chechnya in the Greater Caucasus).

The dynamics of underground waters of the Urals and adjacent territories experienced a great influence of orogenic processes (the modern Urals plays a manifold role as a repository of fracture waters, regulator of water distribution, influencing water pressure in the basins around the Urals). Nevertheless, the most important stage of formation of water chemistry in the Volga–Urals basin was the extensive Early Permian halogenesis. The surficial waters in the early Permian basin became very dense, due to high concentration of salts. This caused an intense density inversion and quick and strong salification of deep horizons of the basin. The brines were stratified and metamorphosed during the Meso- and Cenozoic times. The penetration of brines into the Proterozoic and Paleozoic (pre-Kungurian) strata also caused a metasomatic dolomitization of limestones with increase in their filtration capacity (Popov et al., 2015), which was important for formation of hydrocarbon plays.

The last, but not the least, are the man-made, “technogenic” deposits, formed as a result of human mining activity. Very often, gigantic waste dumps and tailings of beneficiation plants of active mining enterprises contain useful components that can play now, or in the future, a role of new deposits, though currently they produce a negative impact on atmosphere and water. Even waters formed under waste heaps in some cases may attract attention not only as an environmental menace, but also as a mineral source (Puchkov et al., 2006; Akhmetov, 2010; Kovalev et al., 2015). It is in agreement with the idea of Vladimir Vernadsky (1944), who proposed that a man created around him a noosphere — a sphere of interaction between the mankind and the nature (see also Introduction).

6. Discussion and conclusions

Based on the previous chapters of the paper one can conclude that the metallogeny of the Urals was controlled in the first instance by the following factors:

1) *Geodynamic settings prevailing during a particular stage in a particular zone where a deposit or its precursor was formed.* This factor is the most important when a deposit had been formed in an *interplate* zone. The geodynamic analysis is effective when it is made in a context of plate tectonics and needs a special attention to the geodynamic indicators. This was successfully developed during the last decades (e.g., Mitchell and Garson, 1981; Dobretsov and Buslov, 2011; Richards, 2015), but there are always some new facts and ideas to be added to the picture (Puchkov, 2006, 2010a and this paper).
2) *Position of the prospective deposits in relation to the modern structure.* As it was said, localization of mineral deposits depends on their affiliation to a structural stage and a particular structural zone in it. However, the superimposed deformations may distort or conceal initial relationships.
   In particular, it was the reason why metallogeny of the southern and northern parts of the Central Uralian zone are so strikingly different. High amplitude thrusts (nappe-type) also distorted primary zonation, and, as a result, a deposit finally finds itself in a “wrong” place. Such are the positions of the Kempirsay and Kraka chromite deposits, Blyava group and Safyanovka VMS deposits and Suroyam titanomagnetite deposit (Zhilin and Puchkov, 2009; Puchkov, 2010a; Ryazantsev, 2012).
3) *Mineralization in intraplate settings in relation to LIPs and probably induced by mantle plumes and superplumes.* This factor was also a subject of great interest (Pirajno, 2004). In the Urals, a systematic analysis of plume events was initiated by the author of this paper. As it was shown above, the Externides of the Timanides and western structural zones of the Uralides were formed in intraplate settings at the margin of the East European craton.
   Metallogeny of Mashak event can be used as an example of plume action. The magmatic complexes of the South Urals, dated as 1380–1385 Ma, can be correlated with their analogues in the East European craton, Timan, Greenland, Siberia and Laurentia, encompassing a very large LIP or a superplume (Puchkov et al., 2013). In the South Urals, mineral deposits, associated with these magmatic complexes, host titanomagnetites, carbonatites, gold, magnesites and siderites.
4) Both *orogenic and epeirogenic movements* led to the burial or exhumation to a depth amenable to exploration and exploitation of the deposits. The example is the Taratash complex, which is exposed in the uplift of crystalline basement at the eastern margin of the East European craton. From the Taratash uplift, the basement plunges very quickly to the east to a depth of >30 km under the western limit of the Magnitogorsk zone.
5) *Intensity of subduction and orogenic reworking of primary complexes through deformation, metamorphism and anatexis, resulting in formation or upgrading of deposits.* For example, gold deposits of the MUF were formed in two stages, and only the second stage was really productive (Znamenskiy et al., 2015). Still a more evident example is the formation of chromite deposits of the Kempirsay massif, which starts at the oceanic stage, but is iterated at the stage of subduction, with a more prolific effect (Melcher et al., 1999). Two-stage formation of chromian spinel is described also for dunites of the PBB (Simonov et al., 2013; Pushkarev et al., 2014). The origin of gold-enriched gossans at the expense of sulphide deposits, rich (oxidized) manganese deposits at the expense of poor primary accumulations, etc., were also mentioned. An iterative character of a deposit development or a transition from a

precursor to an industrial deposit had been demonstrated here on many occasions.

6) *Climatic*, *tectonic*, *lithological and geomorphological characteristics*, *controlling genesis and burial of supergene deposits in the territory and throughout sections* (Figs. 14, 16, 17). In this way, most of the supergene nickel deposits were formed in the Meso- and Cenozoic, owing to weathering of ultramafic rocks and karst formation. Importance of climate zonation is well demonstrated in the Permian time for the Preuralian foredeep (Fig. 14): the southern part of the Urals was situated in arid climate, favourable for formation of a large evaporitic basin with halite and potassic salt deposits, cupriferous sandstones and phosphorites, while in the north, the Pechora coal basin was formed.
7) *Epicontinental orogeny* (*not preceded by a Wilson cycle*), like the neoorogenic "revival" of the Urals mountains in the Neogene–Quaternary times (probably under a far-reaching influence of Alpine orogeny), modified the processes of exhumation, burial, transportation, erosional elimination or redistribution of deposits, formed at preceding stages of development.
8) *Formation of man-made* (*technogenic*) *deposits* as a consequence of mining activity of a man creates a new challenge to geologists, and its importance is notably growing in this century.

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