Russian Geology and Geophysics © 2019, V.S. Sobolev IGM, Siberian Branch of the RAS
Vol. 60, No. 4, pp. 369–385, 2019 DOI:10.15372/RGG2019030 Geologiya i Geofizika

A Model of Keyboard-Like Nonuniform Exhumation as a Possible Cause Zoning of Metallogenic Belts in Folded Areas (Eastern Transbaikalia and Southern Primorye)[1]

I.N. Kigai

Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, 119017, Moscow, Russia

Received 5 October 2017; accepted 15 June 2018

Abstract—Zoning of metallogenic belts is observed in folded areas of all metallogenic epochs from Precambrian to Cenozoic. The changes observed across the strike of folded areas on geological mapping are usually treated as geodynamic, petrometallogenic, or temporal specialization of corresponding belts (terranes) and zones. However, there are serious petrological reasons to expect a significant downward change in the basicity of magmatites and the composition of related mineralization in folded areas. The change may be caused both by relationships between the densities of magmas and country rocks and by relationships between the solidus temperatures of different magmas and the thermal gradient pattern on the magma ascent path. More basic magmatites and related mineralization should be detained at the deeper levels of the lithosphere because of the higher density and higher solidus temperature of magmas. During orogeny, the vertical differential movements of several adjacent terranes located between deep-seated faults can create keyboard-like structures composed of parallel belts variously uplifted and subsided, similarly to white and black keys of a piano. In belts and blocks of such structures more uplifted and then more subjected to denudation, the ore-magmatic complexes earlier located at deeper levels can expose at the surface. As a result, zoning of metallogenic belts can form, which is totally or only partly related to the metallogenic specialization of structure-facies zones and terranes. The possibility of this origin of zoning of metallogenic belts is shown with the use of geophysical data for two important ore-producing regions of Russia — eastern Transbaikalia and southeastern Primorye. The above model is proposed as one of the possible ways of metallogenic-belt formation in some other folded areas.

The author hopes that this work will stimulate a more profound analysis of the nature of metallogenic-belt zoning in the considered and other world regions with the use of modern geophysical methods. The use of the described regularities of the storied arrangement of magmatites of different basicity and oxidation states and genetically related hydrothermal ores may facilitate prospecting for ores of different metals and their 3D forecasting in keyboard-like structures of Phanerozoic orogens and ancient platforms.

Keywords: metallogenic belts, terranes, folding, orogeny, tectonometallogenic cycles, ore-magmatic storeys and levels, keyboard-like structures of folded areas, nonuniform exhumation, ore-magmatic assemblages, ore zoning

INTRODUCTION

Zoning of metallogenic belts is inherent in fold systems of all metallogenic epochs. The review of ore belts of the Soviet Union has been made by A. Fersman (1932) and K. Il'yin (1974). The wider global reviews belong to F. Blondel (1936), S. Smirnov (1946), V. Smirnov (1947, 1963), P. Kropotkin (1955), F. Turneaure (1955), G. Shcherba (1960), G. Tvalchrelidze (1972, 1985), I. Magakian (1974), L. Baumann and G. Tischendorf (1976), M. Itsikson (1979), V. Kotlyar (1983), E. Radkevich (1987), A. Mitchell and M. Garson (1981), A. Kovalev (1985), I. Abramovich (2010) and V. Starostin (2012). The metallogenic zoning conformable to modern plate tectonics concept has been disclosed (Zonenshain et al., 1990; Lehmann, 2004; Kigai, 2006, 2013).

The ore belts are located in various structural-formational zones, or terranes, and are extending subparallel to strike of fold systems.

Specialists in tectonics, petrology and metallogeny are usually considering the zoning of metallogenic belts in the 2D space accessible to geological mapping. All above mentioned authors usually treat the material changes observable across the structures as a geodynamic, petrological-metallogenic or temporal specialization of corresponding terranes and blocks.

In the scope of shallow depths covered by an erosion cut of a particular mountainous area or depth of underground workings and drilling penetration, the vertical ore zoning has been studied in detail by numerous researchers of ore deposits from different countries. The depths that could not be covered by shafts and drill-cores, basically serve as a study subject for geophysicists. For decoding the deep structure of terranes geophysicists use such methods as gravitational, seismic and magnetic, but all these methods until

[1] The paper was translated by the author.

E-mail adress: kigai@igem.ru (I.N. Kigai)

now have certain restrictions concerning interpretation of material composition of deep structures.

Due to nonuniform vertical movement of different zones and blocks during postfolding orogeny, the fold areas, alongside with multibelts structure, possess also a keyboard-like structure, in which the neighboring belts and blocks have been in a various degree uplifted (similarly to white and black keys of a piano), and the more uplifted zones were then partially more eroded than less uplifted or subsided "keys". And the horizontal zoning observable now in some cases can be a result of a greater exhumation of more uplifted "keys" relative to less uplifted or subsided ones. As a result, the magmatites and related mineralization of deep storeys of fold areas can be seen at the Earth's surface in earlier more uplifted and deeper eroded "keys". At the same time the similar ore-magmatic assemblages are expected to be found in deeper storeys of adjacent less eroded metallogenic belts.

The Phanerozoic metallogenic belts, considered here, usually represent large zones several tens of km wide and many hundreds of km long, and the roots of the deep-seated faults dividing them usually reach the mantle. Therefore, the subsided and uplifted "keys" (graben-synclinoria and horst-anticlinoria) can correspond to lowered and uplifted Moho and Conrad discontinuities and, accordingly, to increased and reduced thickness of the Earth's crust. Such distinctions can and should find reflection in gravitational, seismic and magnetic geophysical fields.

On the basis of seismic waves velocity change with depth, geophysicists usually assume the existence in the Earth's crust of the so-called Conrad discontinuity which, being defined by sharp change of primary seismic waves velocity (from 6 to 6.5 km/s), separates the essentially sialic ("granitic") top part of the crust from bottom one, composed presumably of rocks of basaltic composition. However, as a result of drilling the Kola superdeep well (12,226 m) in the Baltic shield, at a depth about 5 km where the Conrad discontinuity has been assumed to occur from geophysical data, and even deeper, until the drilling bottom, no distinct borders caused by change of rocks composition were found. In this Precambrian megastructure, the Conrad discontinuity has appeared to be density related rather than defined by the change of crustal rocks composition. It was a reflection of downward density increase and porosity reduction of rocks within a quite monotonous granite-gneiss unit (Kozlovskii, 1984).

Nevertheless, there are some petrological reasons to expect the essential downward change of magmatites' basicity and related ore composition. The change may be caused both by relationships between densities of different magmas and crustal rocks, and by relationships between the solidus temperatures of different magmas and the thermal gradient pattern on the path of the magmas ascension. More basic magmatites and related mineralization should be detained on deeper levels of the Earth's crust due to higher density and higher solidus temperature of those magmatites.

DEEP STOREYS OF ORE-MAGMATIC SYSTEMS

Within the limits of the Earth's crust, it is possible to suppose the existence of several thick ore-metallogenic **storeys** characterized by occurrence of certain types of magmatites and specific types of ore mineralization closely related with the magmatites genetically or spatially. Several ore-metallogenic **levels** can be defined (within the scope of each storey) comprising downward zonally arranged different ore-metasomatic assemblages (OMA), and ore types related to one or two magmatic series. Taking into consideration the present data on relationships between different ore types and magmatism (Ishihara, 1977, 1981; Kigai, 2011; etc.), and the common knowledge on densities and solidus temperatures of different magmatites, it is possible to presume the existence of the following storeys within the Earth's Crust (from bottom to top).

1. A first abyssal storey where a series of autochthonous magmatites are initially located along the Moho discontinuity, being composed in general by basic and ultrabasic rocks of calk-alkaline, alkaline, and agpaitic type.

2. A second abyssal storey where autochthonous series of granites and migmatites are initially formed being practically barren relative to any ore mineralization. This storey is initially localized at the bottom of the crust, possibly, being a little bit raised relative to the first storey.

3. A lower mesoabyssal storey where the allochthonous basic ore-magmatic series presumably represented by plutons of gabbro and ultrabasic composition with related magmatic Cu–Ni with PGE and/or chromite mineralization. It is supposed that water-enriched residual melts of such plutons of this and upper mesoabyssal storey give rise to basic dikes and sulfide mineralization of overlying storeys.

4. An upper mesoabyssal storey where mesocratic allochthonous ore-magmatic series are developed, being mainly represented by plutons of diorite, granodiorite, syenite and monzonite composition, that belong to magnetite or intermediate FMQ redox type. The ore mineralizations genetically related to those magmatites comprise skarn-related Fe (magnetite), B (ludwigite), W (scheelite), Mo (molybdenite, molybdoscheelite), Cu and vein-type Mo and Au ores.

5. A hypabyssal storey, where allochthonous granitoid magmatism prevails and related granitoid dikes with lithophile W (as wolframite), Sn, Ta, Nb, Li, Be and sometimes Mo mineralization. At the same level and above, the belts and swarms of basic, andesitic and lamprophyre dikes with temporally and spatially closely related Cu, Pb, Zn sulfide mineralization occur in connection to the residual melts of oxidized basites of mesoabyssal storeys. This mineralization is overprinting the granitoids and related lithophile mineralization to form sometimes concentric zonal patterns around granite stocks.

6. A subvolcanic storey with prevailing occurrence of volcanoplutonic series of different acidity: shallow rhyolite lopoliths, small stocks and dikes as roots for basalt, andesite and rhyolite sheets. The wide spectrum of mineralization is

related with them from Sn, W, Be to Cu, Mo, Au–Ag, and Sb, As, Hg, in particular giant Sn (Llallagua), Sn–Ag (Potosi, Oruro) deposits of porphyry type above zones of steep subduction (Lehmann, 2004) and giant Cu ± Mo ± Au porphyry deposits above zones of gentle subduction of Andean-type (Sillitoe, 1972).

7. A volcanic subsurface storey where volcanic processes and related minerals occur: borosilicate and base-metal skarn, epithermal Au–Ag deposits, deposits of native copper and mercury related to volcanoplutonic series of oxidized magmas of basic and mesocratic composition, and also Be mineralization and small deposits of metacolloidal "wood tin" related to ongonite and rhyolite effusive sheets.

As far as the melting within the mantle wedge and crust is initiated by the fluids rising from the asthenospheric mantle, the relative age of magmatites and related mineralization in above described storeys should become younger upwards. And it is possible that the ore-magmatic assemblages of the last three storeys form substantially later than those of the first four storeys, which will be considered at the end of this paper.

Vertical intervals of the specified storeys and corresponding geothermal gradient temperatures, most likely, should differ for the Earth's crust sections of different age and thickness. In fold areas with a typical crust 30–45 km thick, the volcanic and subvolcanic levels correspond to depth approximately 0–3 km, hypabyssal levels from 3 to 6 km, mesoabyssal from 6 to 12 km, abyssal more than 12 km deep. For the consolidated terranes of greater thickness, for example, in ancient shields, the depths of storeys should be most likely increased and the geothermal gradients usually reduced.

In a mantle wedge, the magmas of basalt and andesite composition are formed under influence of fluids derived from a subducting oceanic slab due to dehydration of serpentine, chlorite and white micas. These melts can ascend to the overlying mass of crustal sialic rocks but, as far as their solidus temperatures exceed 1100 °C, the bottom horizons of the crust are already cold enough for them to start their emplacement and crystallization at mesoabyssal storeys.

The rising fluids also promote formation of granite magmas at crustal bottom. The melts of autochthonous granitic magmas can buoyantly migrate upwards to cooler zones and create also initially water-undersaturated allochthonous plutons at a hypabyssal storey. During differentiation, such magmas are capable of generating water-oversaturated leucocratic and lithium-fluoric residual melts (Kovalenko, 1977; Zaraisky et al., 2009).

The melts, forming the dikes of basalts, andesites and lamprophyres, and the ore-bearing fluids paragenetically related with the dikes, derive from basic plutons whose larger part is already solidified. But their water-saturated residual melt can possess high pressure sufficient for breakthrough into overlying granite-dominated hypabyssal crustal levels. Existence of such high fluid pressure in residual basic melts is proved by presence in dikes of biotite and amphibole phenocrysts whose formation, according to experimental data (Burnham, 1997), requires the water content in melt, accordingly, to be no less than 3.3 and 2.5 wt.%. Additional evidence of basic dikes intrusion by the hydrorupture mechanism is their filling of steep faults of various strikes (strike wise, diagonal, and transverse) which is observable at different ore regions, including the Primorye territory and Transbaikalia.

When a residual basic melt is oversaturated with water-rich fluid, the skarns with magnetite, ludwigite, scheelite, copper and molybdenum mineralization appear in mesoabyssal storey. The same intermediate zone can host small stocks of granodiorite and monzonite and also some derivatives of alkaline basic magmas.

The basic dikes and related sulfide mineralization appear in the hypabyssal granitic storey above granitic plutons only after the complete solidifying of the plutons. This is evidenced by the fact that postgranitic basic dikes crosscut flat granitic plutons and carry with them the xenoliths of rocks underlying granites. Such evidence was published by O. Polkvoi (1950) for granitoids of Central Kazakhstan and by F. Shipulin (1956) for the Primorye territory. Following the dikes and alternating with their later generations, the base-metal sulfide mineralization of vein type is overprinting the granites and related tin and tungsten ores (Kigai, 1966; Dubrovsky and Kigai, 1974).

Multilevel zoning of smaller scale, within the limits of one from the described storeys, can be sometimes seen as a horizontal concentric ore zoning around intrusions (see, for example, (Kropotkin, 1957), and references in this paper). Such zoning has been described by many investigators, but it will not be considered here in detail. From the point of view of exploration and forecasting problems, the brightest examples of downward ore zoning are those of gradation from richest silver to great tonnage tin ores at the Potosi deposit in Bolivia (Suttill, 1988), the regular down dip change from copper ores to tin ores at deposits of Cornwall (England) and the San-Rafael deposit (Peru), the change from copper ores to molybdenum ones at Cu–Mo-porphyry deposits, and practically universal gradual downward change from Pb-rich ores through Zn-rich to Cu-rich ore at all genetic types of base-metal hydrothermal deposits, SEDEX included (Kigai, 2010b).

Let us look at how the non-uniform exhumation of keyboard-like structures model can be applied to two important ore regions of Russia.

EASTERN TRANSBAIKALIA

The Eastern Transbaikalia name is usually applied to an area which is now a part of the Transbaikal territory ("Zabaykalsky Krai"), composed in 2008 by the unification of the Chita Region and the Aginsky Buryat Autonomous District. According to views of former geosynclinal concept adherents (Shcheglov, 1968; Karpova, 1973; Radkevich, 1987), the most important industrial mineralization of wide minerogenic spectrum (Sn, W, Ta, Nb, Li, Mo, Au, Zn, Pb, U, fluorite) in Eastern Transbaikalia was formed in environments of tectono-magmatic reactivation of the continental plate, that is in "diwa" structures, after Chen (1965, 1988).

The tectonomagmatic reactivation concept is to some extent congenial to the modern magmatic plume tectonics concept. An analysis of geologic and isotope-geochemical data performed by some researchers has shown that the intraplate magmatism related to processes of deep geodynamics, that is to plume tectonics, has played an important role in the Phanerozoic in the formation of orogenic belts and metallogeny of Northeastern Asia and, in particular, of the Siberian Platform, including its folded framing (Yarmolyuk et al., 2000; Kuzmin and Yarmolyuk, 2014). The Eastern Transbaikalia comprises a part of the southern fold framing of the Siberian platform which has been rotating clockwise above the immobile Mongolian Plume during the Phanerozoic, up to the Jurassic and the Cretaceous. The activity of this plume (considered as a part of the African Belt superplume) gradually degraded during the Phanerozoic due to the sinking of the mantle plume generation level from the upper mantle to the bottom of the lower mantle (Yarmolyuk et al., 2000; Kuzmin and Yarmolyuk, 2014).

From the plate tectonics point of view, Eastern Transbaikalia comprises a central part of the Mongol-Okhotsk fold belt, named first by A. Fersman (1926). The Belt has been formed from the Triassic to the Jurassic in the place of a wide oceanic bay that intruded into the south of Siberia from the Pacific Ocean (Kuzmin and Filippova, 1979; Parfenov,

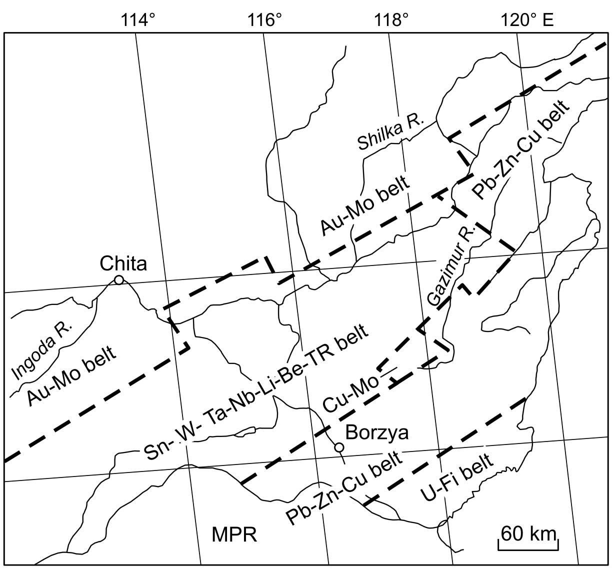

Fig. 1. A chart of metallogenic belts of Eastern Transbaikalia, composed on the base of S. Smirnov's (1944) map of distribution for 12 types of ore deposits: 1, Sn; 2, W; 3, Mo; 4, Li, Be, Ta, Nb, TR; 5, Ag–Pb–Zn; 6, Au; 7, Cu; 8, Fe; 9, Sb; 10, Hg; 11, Bi; 12, CaF_2. The borders of metallogenic belts and blocks were drawn taking into consideration the deposits location and orientation of river valleys reflecting position of fault dividing the belts and blocks with different mineralizations. Uranium was added to fluorite belt name after M. Skurskii (1996).

1984; Zonenshain et al., 1990; Parfenov et al., 2003) and also includes some adjacent parts of the Siberian and Mongolia-China continents. That wedge-like bay is sometimes named the Mongol-Okhotsk ocean.

As a result of subduction of the oceanic plate, first underneath the Mongolia-China continent and then below the Siberian continent (before the Early Jurassic), and due to the Siberian continent's clockwise rotation, the ocean initiated a scissors-like closing starting from the west (Mongolian) end, and was closed in Eastern Transbaikalia by termination of folding in the Middle Jurassic.

The northern boundary of the belt is clearly indicated by the Mongol-Okhotsk suture, which was split around the Onon island arc sigmoidal block into two branches (Zorin et al., 1998a). These authors used the results of a geophysical transect to analyze the geological development of the Mongol-Okhotsk belt on the base of the plate tectonics concept and subdivided the belt into three zones: the Aga–Borzya, Onon and Daur-Hentiyn ones. Each of the first and the third zones comprise several metallogenic belts defined by other researchers.

Other papers of the same authors (Zorin et al.,1998b, c) are devoted to the spatial distribution of some ore mineralization. The gold deposits are mostly related to Middle-to-Late Jurassic collisional magmatism of mantle origin and are therefore located closer than 60–80 km to both branches of the Mongol-Okhotsk suture. The mineralization of rare metals (Sn, W, Ta, Nb, Be, Li) does not show such tendency of relationship with the suture, being related to subaluminous crustal granites, which were controlled by younger faults of the second order (Zorin et al., 1998c) and, perhaps, also by the still a bit warm Mongolian plume.

The first metallogenic division of Eastern Transbaikalia has been defined by S. Smirnov (1936, 1944) who has found (looking from NW to SE) the existence of gold-molybdenum, tin-tungsten and base-metal belts in this region (Fig. 1). Yu. Bilibin (1961) has added to S. Smirnov's scheme a gold-scheelite belt, which did not found reflection in the subsequent schemes as it is not a long belt and is represented by few small blocks which complicate the structure of other belts. But one of such blocks contains two world-class deposits—the Bugdaya Mo–W–Au–Cu stockwork deposit of porphyry type and the Bystrinskoye Cu-Au skarn deposit (Kovalenker et al., 2011, 2016). M. Skursky (1996) in addition to that has added a short uranium-fluorite belt, a former part of the base-metal belt on its southeastern flank.

Additionally, the metallogenic belts' zoning of Eastern Transbaikalia has been considered by P. Kropotkin (1955), V. Kormilitsyn (1959, 1960, 1973), V. Kozerenko (1960, 1963, 1981), D. Gorzhevsky and V. Kozerenko (1965), V. Kormilitsyn and A. Ivanova (1968), G. Menaker (1971, 1972, 1976, 1986, 1990), G. Knyazev (1967, 1972), A. Kanishchev (1971, 1977), A. Kanishchev and G. Menaker (1971, 1972, 1973), P. Komarov and I. Tomson (1995), V. Kotlyar (1983), B. Rybalov (2002), and V. Gordienko et al. (2013).

Within the Eastern Transbaikalian part of the Mongol-Okhotsk belt, the last folding, which had been terminated in the Middle Jurassic, has been followed (like in typical fold regions) by the orogeny (mountain building) with transtensions and differential vertical block movements. The orogeny in such a meaning (not synonymous to "folding") has been considered by some geosyncline concept adherents who worked in IGEM RAS (Favorskaya et al., 1969; Tomson et al., 1992). Later the plate tectonics partisans have been describing, relative to the Mongol-Okhotsk belt, "the Early Cretaceous transtensions and the orogen's destruction, presumably related to a gravitational instability of the crust thickened due to orogenic dislocations" (Mazukabzov et al., 2004). The transtensions resulted in some zones in rifting and exhumation of central parts of the crust to form the gneiss cores and narrow half-grabens filled with continental, sometimes coal-bearing, sediments combined with the effusion of bimodal volcanics (Zorin et al., 1997, 1998a; Mazukabzov et al., 2006). Notwithstanding that the rift depressions were bordered by rather gently dipping normal faults, perhaps inherited from the thrust faults, with the dip from 5° to 40°, these normal faults outcropped the rocks from their lower plate. But the scale of vertical normal faulting of zones and blocks could be rather large because the horizontal displacement along the faults was estimated to be as large as 20–25 km (Zorin et al., 1998b). And there were some indications that the faults can become steeper and even nearly vertical down dip (Parfenov et al., 1982).

Yu. Komarov (1996, 1998) has divided a metallogenic cycle into four periods with the mineralization specific for each of them (enclosed in brackets): **preorogenic** (stratiform deposits and basic-ultrabasic ore-bearing complexes), **orogenic** (metamorphic and skarn-type Au and Fe deposits), and two post orogenic periods—**early destructive** (principal vein-type rare-metal, Au and base-metal mineralization), and **late-destructive** (epithermal Au–Ag, Hg and fluorite mineralization) periods.

We propose an advanced variety of such a classification with the distribution of ore-magmatic assemblages distribution among such periods of tectonometallogenic cycle (Table 1). The start of the early destructive period in Eastern Transbaikalia (change from collisional environment and orogenesis to transtensional rift tectonics), perhaps corresponded to the boundary of the Middle and the Late Jurassic (161 Ma) or to the boundary of the Jurassic and the Cretaceous (145 Ma).

The isotopic age determinations for the Eastern Transbaikalia mineralization has been carried out by many researchers (Komarov and Tomson, 1975; Syritso, 2002; Smolyanskii and Bogomolov, 2011; Borisenko et al., 2012; Chernyshev et

Table 1. Principal types of exhalative-sedimentary and ore-magmatic complexes created at different periods of a single tectonometallogenic cycle (division of the cycle—modified after Yu. Komarov (1998))

Periods of metallogenic cycle	Types of mineralization	Ore-producing magmatites						
		Ultrabasic plutons	Basic plutons and dikes	Carbonatites	Granodiorite, monzonite, syenite	Pegmatites	Granite types	
							Magnet.	Ilmen.
Prefolding*	SEDEX, Pb–Zn	–	–	–	–	–	–	–
	VHMS, Cu–Zn–Pb	–	+	–	–	–	–	–
	Cr, Pt,	+	–	–	–	–	–	–
	Cu–Ni–PGE	–	+	–	–	–	–	–
	Ta–Nb–REE	–	–	+	–	–	–	–
Folding and orogenesis	Orogenic Au	–	–	–	+, RM	–	+, RM	–
	Fe skarns,	–	–	–	+	–	+	–
	W–Cu–Mo skarns	–	–	–	+	–	+	+
Erosion with the removal of upper storeys of the most elevated belts and blocks is possible at this interval of time								
Postorogenic early-destructive	Vein-type Au	–	+	–	+	–	+, (PG)	–
	Mo veins	–	–	–	–	–	+	–
	Ta, Nb, Li	–	–	–	–	+	+	–
	Be	–	–	–	–	–	+	–
	Sn–W veins	–	–	–	–	+	–	+
	Borosilicate skarns	–	+	–	–	–	–	–
	Cu–Pb–Zn skarns and veins	–	+	–	–	–	–	–
Late-destructive	Cu–Mo–(±Au)-porphyry	–	–	–	+	–	+	–
	Sn–Ag-porphyry	–	–	–	–	–	–	+
	Epitherm. Au–Ag	–	+	–	–	–	–	–
	Hg, Sb, As	–	+	–	–	–	–	–
	U, fluorite	–	+, (U,Fl)	–	–	–	+, (U)	–

Note. RM, regional metamorphism; PG, plagiogranites. The boundary between fO_2 of magnetite and ilmenite types (series, after S. Ishihara) of magmatites corresponds to FMQ buffer. For more details see (Kigai, 2011).
*These mineralization types can be regarded also as overprinting relative to previous tectonometallogenic cycle.

Table 2. Isotopic ages of Late Mesozoic endogenous ore deposits of Eastern Transbaikalia

Ore deposit	Ore	Mineral	Isotope pair	Age, Ma	Reference
Early Cretacious mineralization					
Solonechnoe	Fluorite	Adularia	K–Ar	113 ± 3	(Komarov and Tomson, 1995)
Baley	Au–Ag	Adularia	K–Ar	120 ± 5–114	(Andreeva, 1971)
Abagaitui	Fluorite	Adularia	K–Ar	122 ± 5	(Komarov and Tomson, 1995)
Kamenskoe	Pb–Zn	K-feldspar	K–Ar	123 ± 7	(Komarov and Tomson, 1995)
Dedovogorskoe	Sn–W	Muscovite	K–Ar	125 ± 5	(Komarov and Tomson, 1995)
Etyka	Ta–Nb, Sn	Zinnwaldite	K–Ar	125 ± 5	(Komarov and Tomson, 1995)
Belukha	W	Muscovite	K–Ar	127 ± 5	(Komarov and Tomson, 1995)
Spokoininskoe	W	Muscovite	K–Ar	130 ± 5	(Komarov and Tomson, 1995)
Novo-Shirokinskoe	Pb–Zn–Au	Sericite	K–Ar	133 ± 5	(Komarov and Tomson, 1995)
Strel'tsovskoe	U	Pitchblende	U–Pb	135.5 ± 1	(Chernyshev et al., 2016)
Davenda	Mo	Sericite	U–Pb	139 ± 7	(Komarov and Tomson, 1995)
Orlovka	Ta–Nb	Zircon	Rb–Sr	139.9	(Syritso, 2002)
Zun-Undur	Sn–W	Muscovite	K–Ar	141 ± 5	(Komarov and Tomson, 1995)
Garsonui	Fluorite	Fluorite	Sm–Nd	141 ± 6	(Smolyansky and Bogomolov, 2011)
Zhipkoshin	Sb–Hg-Au	Sericite (ore)	Ar–Ar	142.5 ± 1.5	(Borisenko et al., 2012)
Kazakovskoe	Au	Sericite	K–Ar	143 ± 8	(Komarov and Tomson, 1995)
Spokoininskoe	W	Muscovite	K–Ar	144 ± 5	(Komarov and Tomson, 1995)
Darasun	Au	Metasomatites	K–Ar	144 ± 10	(Pakhol'chenko et al., 1987)
Garsonui	Fluorite	Muscovite greis.	K–Ar	145 ± 8	(Komarov and Tomson, 1995)
Late Cretacious mineralization					
Kozlovskoe	Au–Pb–Zn	Sericite	K–Ar	147 ± 6	(Komarov and Tomson, 1995)
Balei	Au–Ag	Sericite (ore)	Ar–Ar	149.2 ± 1.5	(Borisenko et al., 2012)
Etyka	Sn	Zinnwaldite	K–Ar	153 ± 7	(Komarov and Tomson, 1995)
Shakhtama	Mo–Pb–Zn	Molybdenite	Re–Os	159 ± 1	(Borisenko et al., 2012)
Darasun (berezites)	Au	Sericite	K–Ar	159.6 ± 1.5	(Chernyshev et al., 2014)
Middle Jurassic mineralization					
Darasun	Au	Amphibole	Ar–Ar	161.3 ± 6.1	(Borisenko et al., 2012)
Zhireken	Mo	Molybdenite	Re–Os	163 ± 1	(Borisenko et al., 2012)
Zhireken	Mo	Biotite	Ar–Ar	168 ± 1.9	(Komarov and Tomson, 1995)
Khapcheranga	Sn–Pb–Zn	Muscovite	K–Ar	166 ± 7	(Komarov and Tomson, 1995)
Early Jurassic mineralization					
Zheleznyi Kryazh	Mg skarn	Phlogopite	K–Ar	185 ± 8	(Komarov and Tomson, 1995)
Garsonui	Greisen	Muscovite	K–Ar	195 ± 10	(Komarov and Tomson, 1995)
Triassic mineralization					
Garsonui	Pyx skarn	Phlogopite	K–Ar	215 ± 9	(Komarov and Tomson, 1995)
Zheleznyi Kryazh	Mg skarn	Amphibole	K–Ar	221 ± 12	(Komarov and Tomson, 1995)
Zheleznyi Kryazh	Mg skarn	Phlogopite	K–Ar	245 ± 8	(Komarov and Tomson, 1995)
Devonian and Carboniferous mineralization					
Yakovlevskoe	Mg skarn	Phlogopite	K–Ar	360 ± 20	(Komarov and Tomson, 1995)

al., 2014, 2016; and others). The age information about the main ore deposits of the region are shown in Table 2.

It is known that at hypabyssal levels of the Earth's crust containing dolomites in the host rocks intruded by granites, a tectonometallogenic cycle usually starts with the formation of magnesium and later calcareous skarns with magnetite or scheelite ore followed by K-feldspar metasomatites with related Mo ore, then by greisens with related W, tourmalinites with Sn ores, and terminates with the base-metal, Hg and fluorite mineralization (Kigai, 1966, 2012). So, if we take the latest magnesium skarns of the Zheleznyi Kryazh magnetite deposit as the start of the late Mesozoic tectonometallogenic cycle of Eastern Transbaikalia, and the epithermal gold and fluorite deposits as the final products, we have a total length of the Cycle equal to 72 mln years.

As far as the deep faults dividing the large belts and blocks were transecting all the crust down to its bottom (which is evidenced by their serving as the channels for ascending basic magmas responsible for gold and base-metal mineralization of the region), the differential vertical movements of belts and blocks, naturally, were reflected in deep structure of the Earth's crust (ascension and depression of Konrad and Moho discontinuities) and on the surface (outcropping of more ancient rocks in more uplifted and therefore more eroded belts and blocks). In works of adherents of the geosyncline concept such surficial outcrops differences were reflected in the distinctions of synclinorium and anticlinorium structures.

Thus, D. Gorzhevsky and V. Kozerenko (1965) have defined in this region seven metallogenic belts.

1. The Shilka River zone of gold-molybdenum mineralization.

2. Northwest ***synclinal*** zone with tin deposits and lithium pegmatites.

3. A transitional zone of molybdenum—base-metal mineralization.

4. Eastern Transbaikalian Central ***synclinal*** zone of quartz-cassiterite and quartz-wolframite deposits.

5. Area of the Gazimur–Uryumkan ***uplifts*** with the base-metal deposits of complex composition.

6. Aginsky rigid median massif with the quartz-wolframite-cassiterite and Ta–Nb deposits.

7. Argun' River zone with lead-zinc, fluorite and uranium mineralization (This zone contains Paleozoic carbonate units and therefore it can be treated as a relatively ***uplifted*** structure. – I.K.).

From this description the location of belts with the lithophile (earlier named as rare-metal) mineralization in synclinal structures subsided relative to adjacent uplifted zones with chalcophile, basite-related metallogeny becomes evident.

An analysis of geophysical data carried out by Yu. Zorin (1967) shows that Sn–W-bearing late Mesozoic granitoids of Southern Transbaikalia are located in areas where the Earth' crust thickness is relatively greater, and the Argun' zone base-metal belt is known as an area of small crustal thickness and low landscape. This suggested that neotectonic structures are close to isostatic equilibrium.

In his detailed paper devoted to the analysis of geophysical data for Transbaikalia, G. Menaker (1976, p. 228) wrote: "the greatest location density of deposits of the lithophile group corresponds to areas with the maximum thickness of the Earth's crust (44–48 km) and the deepest position of a basaltic layer roof (19–22 km); whereas the density of chalcophile group deposits—to minimum thickness of the Earth's crust (40–42 km) and the shallowest location depth of basaltic layer roof (14–16 km)".

It follows from these data that elevated zones and blocks, if compared with subsided ones, have been eroded to depth of 4–6 km.

It is interesting that G. Menaker's notion that the blocks with the ore of chalcophile type, occurring in lowered parts of the terrestrial surface, can settle down both as adjoining laterally a lithophile mineralization, and simultaneously underlying it on a vertical section, especially in a rugged topography (Menaker, 1976, Fig. 82). This is verbally very close to the keyboard-like structures exhumation model, but G. Menaker related that feature to small-scale instances of badland, and did not take into consideration a possible influence of different belts exhumation, as we did here.

The above cited data are quite sufficiently corroborating the possibility of descripting the metallogenic zoning of late Mesozoic mineralization of Eastern Transbaikalia in terms of the of keyboard-like structures exhumation model of metallogeny offered here.

SOUTHEASTERN PRIMORYE TERRITORY

A more complicated case for analyzing relationships under consideration is perhaps the region of the southeastern Primorye territory. There the Cretaceous, Paleocene and Eocene mineralization of the Sikhote-Alin' fold region has been created under environments of active continental margin. There has been a gradual eastward growth of accretionary prism under conditions of alternating pure subduction and transform sliding of an oceanic plate, according to A. Khanchuk (2000). In the same direction, from the West to the East, the age of ore became younger from the Early Cretaceous to the Eocene. The Samarka, Zhuravlev and Taukhe terranes defined in the southeastern Sikhote-Alin' region (Fig. 2) (Golozubov and Khanchyuk, 1995; Golozubov, 2006), have been earlier known, accordingly, as the Main anticlinorium, Main synclinorium of Sikhote-Alin' and the Coastal anticlinal zone (Kropotkin, 1954; Radkevich, 1958).

In the Samarka terrane which is a fragment of an accretional prism, the upper Permian sedimentary rocks with inclusions of Devonian ophiolite mélange and olistostrome limestones occur. The turbidites and siltstone matrix of the mélange contains large olistoliths of cherts, limestones, basalts and radiolaria of Jurassic age (Kemkin and Khanchuk, 1992). The Early Cretaceous granites of this region have been formed under environment of transform continental margin (Khanchuk..., 2006; Kruk et al., 2014). Along the contacts of the oxidized granodiorites, plagiogranites and

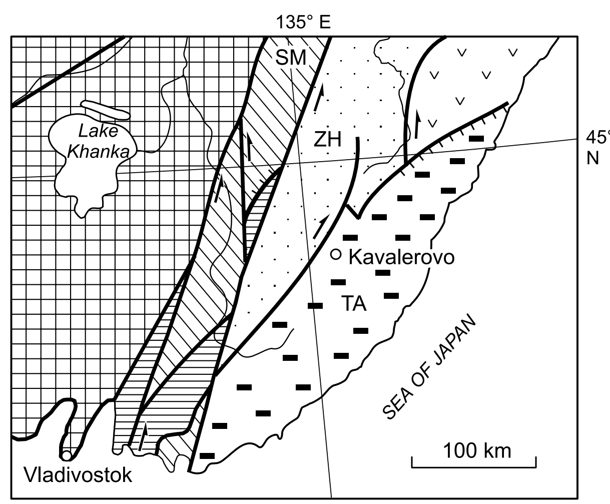

Fig. 2. Terrains of Sikhote-Alin' orogenic belt, after V. Golozubov (2006), abridged. The terrains shown right-hand from Khanka Lake: Samarka (SM), Zhuravlev (ZH) and Taukhe (TA). Their old names correspondingly are: Main Sikhote-Alin' anticlinorium, Main Sikhote-Alin' synclinorium and Coastal anticlinal zone, after P. Kropotkin (1954).

other mesocratic magmatites with olistostrome limestones, the Vostok-2 and Lermontovskoe skarn deposits have been created with scheelite-chalcopyrite mineralization in the Early Cretaceous with isotopic age 102 and 125 Ma, correspondingly (Gvozdev, 2010; Sakhno et al., 2012). But according to data from K. Sato et al. (2006), K–Ar dating of muscovite from greisenized granite and from high-grade scheelite ore of the Lermontovskoe deposit give the age 132 ± 7 Ma. The Malinovskoe gold and Lazurnoe porphyry copper deposits, located in the same terrane, have isotopic ages, correspondingly, 87 and 103.5 Ma (Sakhno et al., 2012a,b; Gvozdev et al., 2016). This mineralization, apparently, is typically representative of an exhumed second mesoabyssal storey.

The Zhuravlev terrane is composed at the surface mainly by Early Cretaceous turbidites, which contain plentiful chert debris, indicating the adjacent eroded Samarka terrane rocks as the feeding source (Malinovsky and Golozubov, 2011). The sediments have been overlain by covers of Late Cretaceous–Danian effusives and intruded by granitoid plutons of Early Cretaceous to Paleogene age. The tin mineralization associated with leucocratic differentiates of the last plutons is represented in this terrane by mineralization of prevailing tourmaline type (Dubrovskoe, Khrustal'noe, Iskra, Vysokogorka, Ternistoe, Silinka, Smirnovka, Arsen'evka, and other deposits) and rare greisen (Tigrinoe) and chlorite (Verkhnee deposit) types. According to data by A. Kokorin et al. (2001), the Vysokogorka deposit mineralization has been formed in three stages: (1) 105–75 Ma—minor tourmaline-cassiterite ore; (2) 75–50 Ma—greisens and Mo mineralization; (3) 45 Ma—main tin ore. For the Iskra tin deposit the ore formation age interval (from K–Ar dating) was found to be 72.2–61.6 Ma (Gonevchuk et al., 2005).

The easternmost Taukhe terrane has been composed by units of accretionary prism, into which the fragments of Late Devonian–Permian, Early Triassic–Late Jurassic, and Late Jurassic–Berriasian units of the paleooceanic plate (including upper terrigenous olistostrome parts) have been successively accreted, the younger units being accreted underneath the more ancient ones (Kemkin and Kemkina, 2000). In general, the sediments composing the Taukhe terrane are somewhat older than those of Zhuravlev terrane.

In the Taukhe terrane, within the limits of the Dal'negorsk district, the small stocks and dikes of basites (partially alkaline) and associated calcareous skarns with conjugated borosilicate and a lead-zinc mineralization occur. The age of younger dikes cross-cutting the datolite veins in 53–50 Ma (Dobrovol'skaya et al., 1990, 1993; Baskina et al., 2004, 2010).

According to data by Ratkin et al. (2016), all mineralization of the Dal'negorsk cluster has been created in two periods. The Dal'negorsk borosilicate skarn deposit was formed during the Campanian (early) period of ore-formation corresponding to the termination of deposition of the Turonian–Campanian mass of ignimbrites. At this time, a giant (>1 km^3) zone of grossularia-wollastonite skarns metasomatically replaced the lower part of a large vertical flat body of limestone. A zone of paleohydrothermal karst cavities in limestone was formed above the skarns. The walls of these cavities were covered with the thinly laminated nodules of datolite-ferrosilite-wollastonite-hedenbergite skarns (Ratkin et al., 1993). After that, these cavities were filled with the crystalline aggregates and druses of danburite, quartz and calcite, followed by basalt injection to form pipe-like body. According to V. Ratkin et al. (2016) and E. Dubinina et al. (2011), these magmatites correspond to basalts, which are overlain on the layer of ignimbrites of the Primorsky Group, terminating the Turonian–Campanian period of volcanism. The ilvaite-andradite-hedenbergite skarns with Pb–Zn mineralization and vein-type bodies of the same composition were emplaced in the Paleocene during the final period of the Maastrichtian–Paleocene volcanism. All skarn-type mineralization of the Dal'negorsk ore cluster were formed in 70–50 Ma time interval (Simanenko and Ratkin, 2008).

The granites at these deposits are presumed to occur on shallow depth in the form of small stocks which, being boron and sulfur-deficient, hardly could generate a large-scale borosilicate and sulfide mineralization, but served, possibly, as intermediate chambers for mass pre-ore outflow of Upper Cretaceous–Danian effusive dacites and rhyolites. O. Karas' et al. (2014) assume some role was played by granites in mobilizing boron, but all data in their possession does not allow to relate the borosilicate skarn ores with these granites.

However, the source of boron in a suprasubductional environment could be found in subducting slab serpentinites, which can be enriched in boron up to 200×10^{-6} g per gram (Pabst et al., 2011) and liberate boron at transformation of chrysotile to antigorite during the dehydration of the slab (Kodolányi and Pettke, 2011). Boron mineralization is typical of all Pacific fold rims.

According to radiometric dating, the Late Cretaceous–Paleogene metallogenic cycle was as long as 87 Ma. This figure is not seen as too large because even the Vostok-2 and Lermontov similar tungsten skarn deposits have isotope age difference of 30 Ma, being located at the same Samarka terrane. It is seen that the tin mineralization of the Zhuravlev terrane started formation a bit earlier than the boron and base-metal skarn mineralization of the Taukhe terrane, but the sulfide mineralization overprinting tin deposits is practically coeval with the sulfide assemblages of skarn deposits of the Taukhe terrane. It is quite possible that the mineralization of both terranes is the result of activity of fluids related to leucocratic and mesocratic magmatites of a single volcanoplutonic complex of the Late Cretaceous–Paleogene. But why the leucocratic magmatites and lithophile mineralization has been active only in the Zhuravlev terrane, perhaps can be explained by the thicker sialic unit in it, and the development of ore-bearing skarns only in the Taukhe terrane by the practical absence of limestone olistoliths in the Zhuravlev terrane. That can be considered as the host rock related specialization of these two terranes.

Table 3. A sketchy stratigraphic column of Late Cretacious–Paleogene volcanogenic pile of PrimoryeTerritory (modified after (Sakhno and Akinin, 2008))

System	Series	Stage	Thickness, m	Unit	Suite	Composition
Erosional unconformity						
Paleogene	Paleocene	Danian	300	Bogopol'skaya		Tuffs, ignimbrites, rhyolites
		Maastrichtian	370–1100	Samarginskaya		Andesites, andesite-basalts, andesite-dacites, rhyolites, dacites
		Erosional unconformity (?)				
Cretacious	Late	Campanian	240–1120	Kamenskaya		Ignimbrites, rhyolites,, tuffs and breccias of dacites and andesites
		Turonian, Coniacian, Santonian	510–3200	Primorskaya	Monastyrskaya Arzamasovskaya	Welded tuffs, ignimbrites, andesite-dacites (lavas)
Erosional unconformity						

Table 3 shows briefly the structure of the Late Cretaceous–Danian effusive complex of Primorye borrowed from the stratigraphic column of (Sakhno and Akinin, 2008). In this sequence more than 5 km thick, the basalts and andesite-basalts have been repeatedly alternating with dacites, rhyolites and ignimbrites. This is suggestive of possible long-term coexistence (at different levels of suprasubductional crust) of magmatic sources of melanocratic, mesocratic and leucocratic composition, which could alternately generate fluids responsible for different mineralization. The feeding channels of these volcanics have been detected at the Lifudzin (now Dubrovsky) tin-sulfide deposit as dikes of various thickness: primarily some thick pre-ore dikes of quartz-diorite-porphyry and hornblende-porphyry, then a small hidden leucogranite stock responsible for tin ore, and finally—thin pre-sulfide, intra-ore (dividing two sulfide stages) and post-ore dikes of hornblende- and plagioclase andesite-porphyry (Kigai, 1966). The K–Ar isotopic age of the leucogranites and quartz-biotite hornfels was found to be 58 ± 3 Ma, and that of the intra-ore and post-ore dikes—54 and 48 Ma (Kigai, 2010a).

The three described terranes of southern Sikhote-Alin' are bordered by deep-seated faults which initially were acting as sinistral strike-slip faults (Utkin, 1989, 2913). These faults are cross-cutting fold structures at an oblique angle, in the NNE direction, and are steeply dipping (Parfenov et al., 1982).

Modelling the deep structure of the Earth's crust of Sikhote-Alin' by gravimetric data, carried out by L. Bryansky (1984), has distinctly shown a deeper Moho discontinuity position beneath the Zhuravlev terrane relative to the Samarka and Taukhe terranes (Fig. 3). A. Petrishchevsky and Y. Yushmanov (2012) analyzing the geophysical data for Primorye territory, concluded that magmatic plutons of more basic composition occupy deeper levels of the Earth's crust.

So, the cited geophysical data as a whole correlate with our suggestions expressed in the form of the nonuniform exhumation of keyboard-like structures model of metallogeny.

The application of the model to the Primorye territory is a little bit complicated because the Early Cretaceous–Danian effusive sheets widespread here postdate the formation of skarn-scheelite and gold deposits of the Samarka terrane and early low-productive tin ores of the Vysokogorka deposit in the Zhuravlev terrane, but predate or are coeval with all major tin mineralization of the Zhuravlev terrane and with the skarn-borosilicate and skarn-polymetallic ore in the Taukhe terrane (Kokorin et al., 2001; Gonevchuk, 2002; Kigai, 2010; Ratkin et al, 2016).

The effusive strata of Maastrichtian–Danian age unconformably overlie folded and eroded sedimentary sequences: Lower Cretaceous turbidites in the Zhuravlev terrane and Triassic–Jurassic and the earliest (Valanginian–Berriasian) Early Cretaceous sequences in the Taukhe terrane. It follows from this, that the Taukhe terrane in the middle of the Early Cretaceous could be somewhat uplifted relative to the Zhuravlev one and eroded before the formation of base metal and borosilicate skarn ores of the Dal'negorsk district. During the effusives eruption, the Taukhe terrane could be even a little bit subsided due to isostatic compensation because of thick effusive sheets load. So abnormally abundant Late Cretaceous–Danian effusive rhyolites and dacites[2] can be considered, presumably, as an effusive equivalent of a major part of a hypabyssal granitoid ore-magmatic complex which could not form or have been eroded in this elevated block.

The transfer from orogenesis to destructive periods of tectono-metallogenic cycle in Primorye took place, perhaps, at the boundary of the Campanian and Maastrichtian ages of the Late Cretaceous (about 60 Ma), when 1 mln. years could be sufficient for denudation of several km from tops of highly uplifted zones and blocks of the young mountains of particularly the Samarka and the Taukhe terranes.

V. Baskina (1997) has attracted attention to an original symmetrical zoning of ore belts of the Primorye territory

[2] According to S.P. Solov'ev (1949) estimates, a ratio of areas occupied by acid (rhyolites, dacites) effusive rock sheets to those occupied by basic ones (andesites, basalts) is close to 1 : 1 in Primorye territory, whereas a similar ratio for all the USSR is close to 1 : 5. So it is evident the abnormally high occurrence of young (K_2–Pg) acid effusive rocks in Primorye.

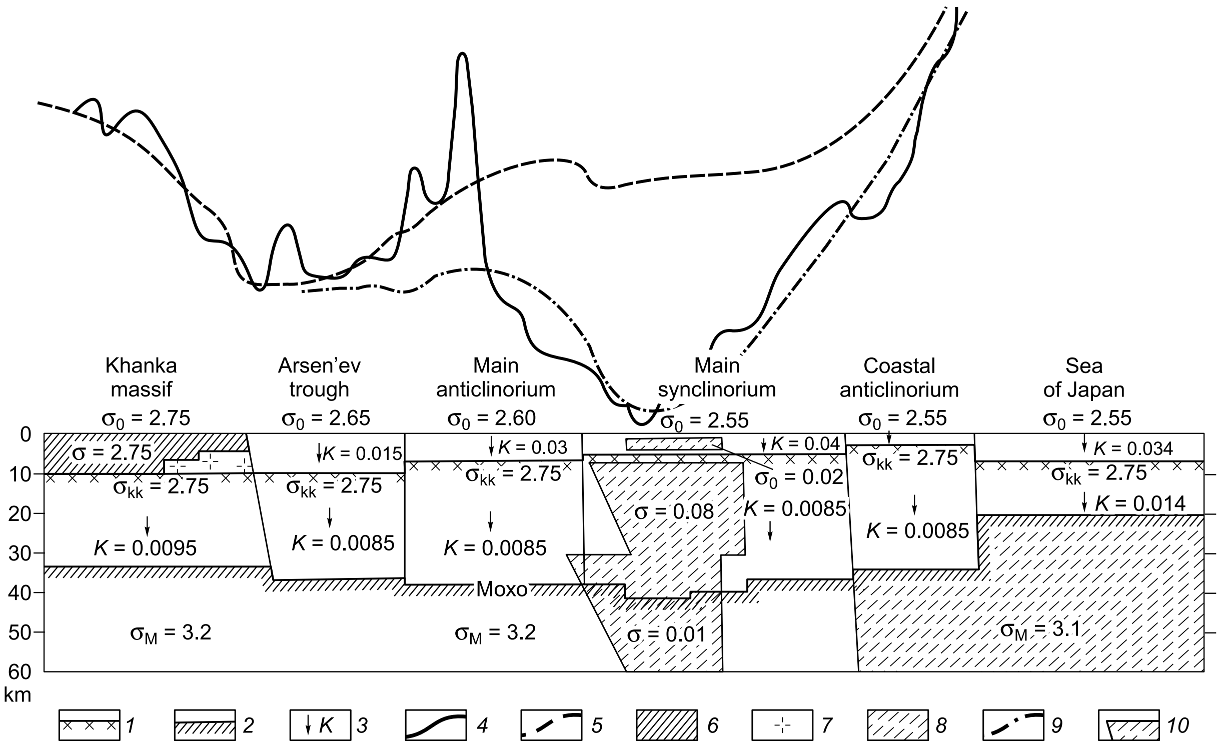

Fig. 3. Gravitational model of the Earth's crust along a section Spassk-Zerkal'naya (southeastern Primorye territory, Russia), after L. Bryansky (1984). *1*, Konrad discontinuity; *2*, Moho discontinuity; *3*, a direction and size of a density gradient; *4*, an initial curve of a gravity field; *5*, a curve of gravity field from a model's section without taking into account a local decompression of the Earth's crust and upper mantle in the Main synclinorium; *6*, metamorphic complex of Khanka massif; *7*, decompressed basis of Khanka massif; *8*, the decompressed mantle; *9*, a curve of gravity field from a models section taking into account a local decompression in the Main synclinorium; *10*, local decompression of the Earth's crust in the upper mantle and Main synclinorium. It is seen the Moho discontinuity subsidence beneath the Main synclinorium which mainly correspond to Zhuravlev terrain.

and Japan relative to the Sea of Japan (Fig. 4). It is known that in the pre-Miocene time when tin and base-metal mineralization of the Primorye territory and Japan has been formed, the Japanese Islands were a part of the eastern margin of Asia and were just the eastern continuation of the Sikhote-Alin' structures. The Japanese Islands comprise terranes of Permian, Jurassic, Late Jurassic–Early Cretaceous and Late Cretaceous–Paleogene accretionary prisms similar to those of the Primorye territory (Kropotkin, 1980; Mizutani and Kojima, 1992; Kemkin, 2006). Before the Sea of Japan rift opening, the western Sanin base-metal belt of Japan and similar eastern belt of the Primorye territory have been parts of one uniform belt, which was from both sides bordered by tin-tungsten belts. The axis of symmetry for this structure has been the Sea of Japan rift which has started opening only in the Miocene, but, probably, had been already active in Late Cretaceous–Paleogene. The strike-slip movements along this rift have been dextral (Parfenov et al., 2003), therefore the Japanese Islands have been displaced to the South from Primorye.

According to the model suggested here, the specified symmetric metallogenic zoning of the Primorye territory and Japan receives a simple explanation. The common base-metal belt of Primorye and Japan has been uplifted, eroded and then covered by Maastrichtian–Danian effusive rocks, beneath of which the skarn-borosilicate and base metal mineralization was formed or rejuvenated in Primorye and the base-metal ores formed in the Sanin belt of Japan. After that the base-metal belt was split into two parts by the Sea of Japan rift. Additionally, it is important to note that the symmetry of Primorye–Japan belts is not flawless, because the Sanin belt has no borosilicate mineralization. Moreover, the existence of the older tin-tungsten Sanio belt to the east from the base-metal Sanin belt (Fig. 4) is breaking the one-sided tendency of mineralization age decrease observable in the Far East of Russia and can be explained only in frames of the keyboard structure exhumation model proposed here.

It is known that the Pacific plate has been (during Cretaceous–Paleogene and continues nowadays) subducting beneath the east of Asia at a rather steep angle, 40°–45°. A flat-subducting Pacific slab should be inevitably and repeatedly broken at a place of abrupt change to steep dipping angle. The splitting of slab blocks during their sinking into the asthenospheric mantle results in formation of slab windows, making an opportunity for injection of the asthenosphere mantle hot melts into mantle wedge and further into the crust to provide there the formation of the rift and later the Sea of Japan back-arc basin (Fig. 5). Formation of slab

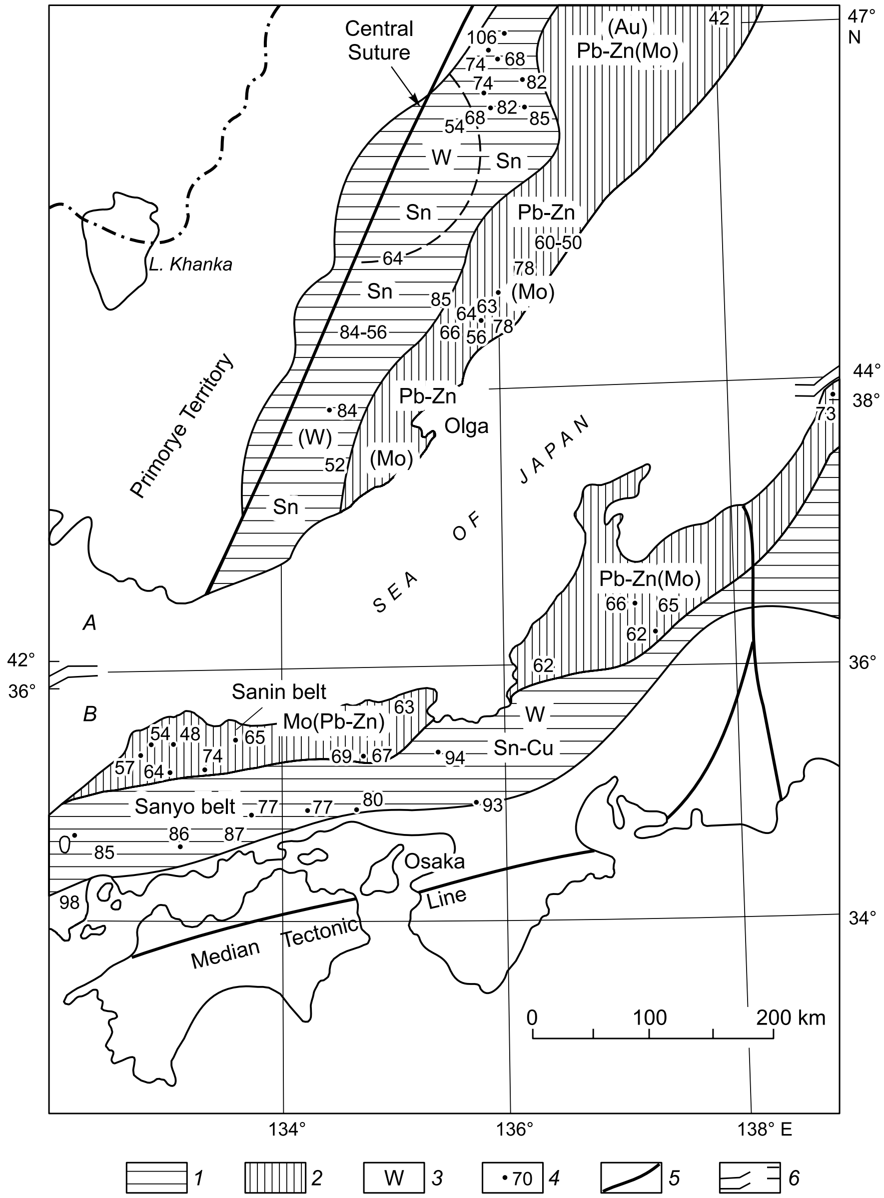

Fig. 4. The symmetric zonal arrangement of granitoids and associated mineralization relative to the Sea of Japan basin, after V. Baskina (1997). *A*, southeastern Primorye territory; *B*, Island of Honshu, Japan; *1*, belts of late Cretaceous granites of ilmenite type; *2*, belts of Paleogene granites of magnetite type; *3*, major metals; *4*, age of deposits (for Japan after S. Ishihara et al. (1988)); *5*, tectonic sutures; *6*, sites of parallels compression in order to get the Japan islands to one horizontal level with Primorye Territory.

windows allows the breaking of suprasubduction rocks during the orogenic uplift with the creation of uplifted and relatively subsided blocks of keyboard-like structures. Splitting of the upper part of the Pacific slab is well seen on the seismotomographic section of the Japanese sector of Eastern Asia (Fig. 6).

Mesozoic basic magmatism and related base-metal mineralization of the Primorye territory and Japan, if they existed, could undergo rejuvenation in the Paleogene, probably, in connection with the activation of plutonic processes near a growing rift that opened later in the Miocene to form the Sea of Japan back-arc basin.

The scales of relative vertical displacement of blocks in keyboard-like structures could be initially much larger than are seen now. They could be changed by isostatic compensation after covering some blocks by thick piles of volcanics.

CONCLUSIONS

The paper offers one of possible formation mechanisms of metallogenic belts zoning or some of its parts at some fold regions. The author guesses that the proposed model can be quite acceptable for description of belts zoning at

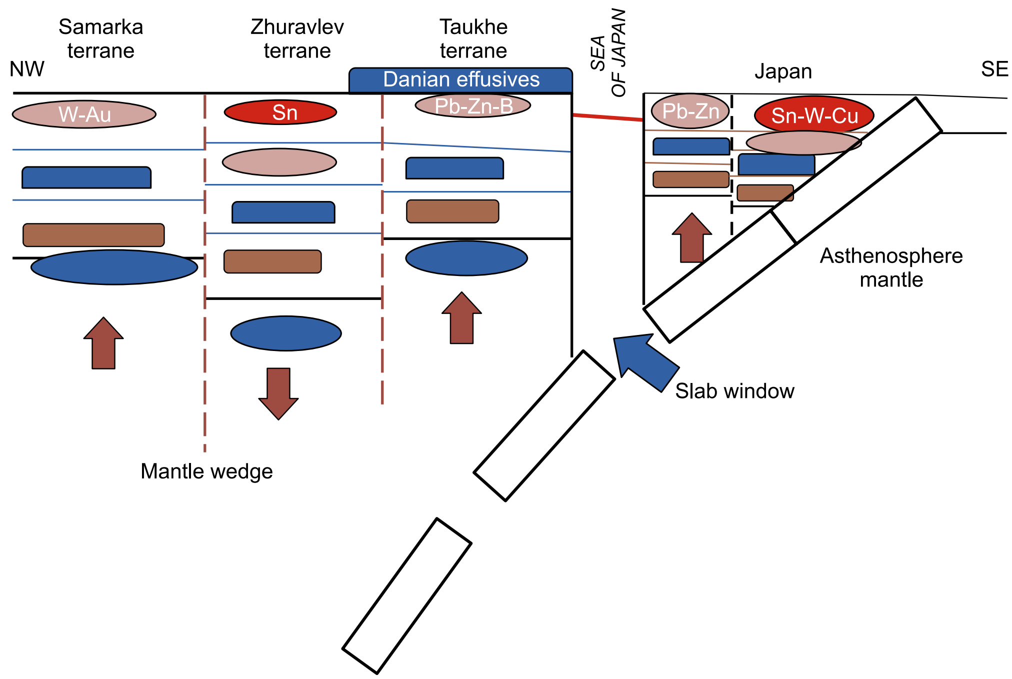

Fig. 5. A schematic section the Primorye–Japan keyboard-like orogenic structure in its modern state. The vertical scale is arbitrary. Explanations see in the text.

such suprasubduction areas, and also areas of tectonomagmatic activation of continental structures, where the dominating young mineralization of the latest minerogenic epoch is developed, as in Transbaikalia and the Primorye territory. During such final minerogenic activity lasting dozens of million years, the essential rejuvenation of magmatites and mineralization of previous minerogenic epochs may proceed with the formation of a full spectrum of ore-metasomatic assemblages from the earliest high-temperature (ore-bearing skarns, feldspar metasomatites and greisens) up to the latest

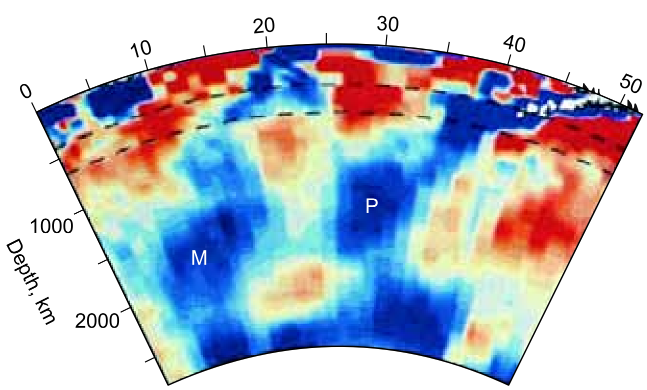

Fig. 6. Seismothomographic section of the Kuril–Japanese sector of Pacific plate subduction after Bijwaard et al. (1998). In the right top part the square allocates a part of the structure in which the fragments of solid immersing slab (white) in its top part are well seen. By letters of M and P, accordingly, are marked presumable ancient Mesozoic and new Paleogene slabs which are designated in view of typical 5–6 cm/yr rate of subduction and its start about 200 million years ago with subduction zone overjumping eastward at a boundary of Mesozoic and Cenozoic.

and low-temperature (base metal ores, mercury, fluorite) assemblages.

It is necessary to notice, that V. Kozerenko (1963, 1981), analyzing spatial distribution of *shallow* ore mineralization, has practically foreseen the basic thesis of the keyboard-like structures exhumation model, having written: "…various extent of deposits erosion within the limits of various areas can lead to specific lateral zoning which is as though a horizontal reflection of vertical ore zoning". But he never further developed this idea and did not specify what scale of zoning and what erosion scale he meant.

The location of lithophile mineralization in the belts and blocks with the thickest crust and negative Bouget anomalies, i.e., with the sunken Moho discontinuity, and the relation of mesocratic and chalcophile mineralization to zones of positive Bouget anomalies and thinner crust has been detected, besides Eastern Transbaikalia and the Primorye territory, in many other parts of the world. The positive Bouget anomalies have been found in regions with Au–Ag and Cu mineralization of Japan, at Java Island with the Cu, Au and Hg deposits, and on Cyprus with Cu deposits (Andreev, 1958). At the same time, the negative Bouget anomalies are typical of regions with the Sn–W mineralization—in the Russian Northeast (Chaikovskii, 1956), in Japan, Southeast China, Bolivia, western states of the USA (Andreev, 1958), in Central Kazakhstan (Kazanli et al., 1959), in the Kalba–Narym district and Gornyi Altai (Shcherba, 1960).

The keyboard structures model which is proposed here is capable to explain those regularities, if we suggest particularly that the chalcophile base-metal and Au–Ag epithermal mineralization of subvolcanic and volcanic storeys form at upper parts of elevated terranes and blocks after partial or complete erosion of a lithophile ore-magmatic storey. Such suggestion, as a matter of fact, implies the formation of above considered four basic storeys before or during the orogeny, but of all later ore-magmatic assemblages of lithophile, subvolcanic and volcanic storeys – only after vertical differential displacements and denudation of more elevated blocks and zones of the orogenic belt, i.e., during the destructive periods of metallogenic cycle, according to the terminology of Yu. Komarov (1998).

At the Dubrovsky (former Lifudzin) tin deposit in Primorye the ore formation during destructive period is corroborated by development of cassiterite-quartz-tourmaline mineralization at the time of normal faulting upon the faults of all strikes, i.e., during the all-round transtension generated by upwelling pressure (Kigai, 1966, 2010a). The pressure could be created by volume increase due to anatectic rock melting or injection of magma, which can explain a long ago known location of the magmatogene hydrothermal deposit clusters at the dome or diapir structures (Wisser, 1960; Favorskaya et al., 1972 (7 papers in this collection: by I. Volchanskaya, M. Favorskaya et al., I. Shapochka et al., I. Tomson and O. Polyakova, N. Kochneva, V. Nartikoev and M. Lepeshov, Yu. Mironov and N. Kochneva); Tomson et al., 1992). In Sikhote-Alin', such structures are looking like the windows, comprising sedimentary rocks and granitoids, within surrounding volcanic sheets of the Eastern Volcanic Belt (Kuperkonik, 1932; Ratkin et al., 2016).

The author hopes that this work will allow stimulating more profound analysis of the nature of zoning of metallogenic belts in regions of the world mentioned here and in others with the use of modern geophysical methods.

The use of the described regularities of vertical arrangement of magmatites of different basicity and oxidation state and genetically related hydrothermal ore may facilitate prospecting the ores of different metals, and also their 3D forecasting in keyboard-like structures of Phanerozoic orogenic belts and ancient platforms. That may become important when the necessity and possibility arise for ore mining from depths over 2.5 and 3.8 km attained at the Morro-Velho (Brazil) and Witwatersrand (South Africa) gold mines.

The author is grateful to two anonymous reviewers who have offered information on some relevant literature, before unknown to the author, and made some useful remarks which stimulated an essential revision of the manuscript and, perhaps, helped to make it better. He is also greatly thankful to professor V.I. Starostin (Moscow State University) for goodwill expressed after hearing the new model, to Dr. I.P. Kuzin (Institute of Oceanology of the Russian Academy of Sciences) for consultations concerning interpretation of geophysical data, and to Dr. V.V. Ratkin for kindly offering some his recent papers.

REFERENCES

Abramovich, I.I., 2010. Metallogeny [in Russian]. Geokart-GEOS, Moscow.

Andreev, B.A., 1958. Structural-metallogenic zones and gravitational anomalies. Dokl. Akad. Nauk SSSR 121 (6), 402–405.

Andreeva, M.G., 1971. The peculiarities of composition and distribution of mineral assemblages and the elements of zoning within the frames of the Baley ore field and its surrounding, in: Trans. TsNIGRI, Issue 96 (1) [in Russian], pp. 32–45.

Baskina, V.A., 1997. Mirror-image zonality of magmatism and ore deposits around the Japan Sea, in: Saxena, N. (Ed.), Recent Advances in Marine Science and Technology'96. Honolulu, USA, pp. 45–53.

Baskina, V.A., 2010. Role of exogenic fluids in formation of datolite ores at the Dal'negorsk skarn-borosilicate deposit, in: Proc. Sci. Conf. "New Horizons in Investigation of Magmas- and Ore-Formation Processes" [in Russian]. IGEM RAN, Moscow, pp. 396–397.

Baskina, V.A., Tomson, I.N., Arakelyants, M.M., Polyakova, O.P., 2004. Early Cretaceous alkaline basites and carbonaceous metasomatites of the Primorye territory. Dokl. Akad. Nauk 398 (5), 652–655.

Baskina, V.A., Arakelyants, M.M., Lebedev, V.A., 2006. A succession of endogenic formations in ore districts of Primorye and their K–Ar dating, in: Isotope Dating of Processes of Ore-Formation, Magmatism, Sediments Accumulation, and Metamorphism, Proc. 3rd Russ. Conf. (6–8 June 2006), Vol. 1 [in Russian]. IGEM RAN, Moscow, pp. 84–88.

Baumann, L., Tischendorf, G., 1976. Einführung in die Metallogenie, Minerogenie. VEB Deutsche Verlag Grundstoffind, Leipzig.

Bilibin, Yu.A., 1961. Main features of Mesozoic endogenic metallogeny of Eastern Transbaikalia), in: The Selected Papers, Vol. 3 [in Russian]. Izd. Akad. Nauk, Moscow, pp. 319–365.

Bijwaard, H., Sparkman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. J. Geophys. Res. 103 (B12), 30,055–30,078.

Blondel, F., 1936. La géologie et les mines des vieilles plateformes, in: Publ. du Bureau d'Etudes Geologiques et Minières Coloniales. Paris, pp. 194–214.

Borisenko, A.S., Spiridonov, A.I., Izokh, A.E., Prokopiev, A.V., Lebedev, V.I., Gas'kov, I.V., Zorina, L.D., Kostin, A.V., Naumov, E.A., Tret'yakova, I.G., 2012. Highly-productive stages of basic and granitic magmatism of North Asia: the estimates of their resource potential, a scientific substantiation of the criteria for prediction and search of the large deposits (Cu–Ni–Pt, Co, Au, Ag and rare-metal), in: Rundqvist, D.V., Bortnikov, N.S., Safonov, Yu.G. (Eds.), Problems of Minerageny of Russia [in Russian]. GTsRAS Publ., Moscow, pp. 237–252.

Bryansky, L.I., 1984. A gravitational models of the Sikhote-Alin fold area. Tikhookeanskaya Geologiya, No. 2, 52–61.

Burnham, C.W., 1997. Magmas and hydrothermal fluids, in: Barnes, H.L. (Ed.), Geochemistry of Hydrothermal Ore Deposits (3rd edition). John Wiley and Sons, pp. 63–123.

Chaikovskii, V.K., 1956. New data on the Pacific Belt. Sovetskaya Geologiya, No. 50, 134–149.

Chen Guoda, 1965. Diwa—a new type of epiplatform mobile region. Scientia Sinica 14 (10), 1478–1498.

Chen Guoda, 1988. Tectonics of China. Int. Acad. Publishers.

Chernyshev, I.V., Prokof'ev, V.Yu., Bortnikov, N.S., Chugaev, A.V., Goltsman, Yu.V., Lebedev, V.A., Larionova, Yu.O., Zorina, L.D., 2014. Age of granodiorite porphyry and beresites from the Darasun gold field, eastern Transbaikalia region, Russia. Geol. Ore Deposits 56 (1), 1–14.

Chernyshev, I.V., Golubev, V.N., Aleshin, A.P., Larionova, Yu.O., Gol'tsman Yu.V., 2016. Fluorite as an Sm–Nd geochronometer of hydrothermal processes: Dating of mineralization hosted in the Strel'tsovka uranium ore field, eastern Baikal region. Geol. Ore Deposits 58 (6), 447–455.

Dobrovol'skaya, M.G., Baskina, V.A., Balashova, S.P., Kenisarin, A.M., Arakelyants, M.M., Klimachev, L.A., Muravitskaya, G.N., 1990. A sequence of ore formation and the basic dikes of the Nikolaevsky deposit (Southern Primorye Territory). Geologiya Rudnykh Mestorozhdenii 32 (1), 85–97.

Dobrovol'skaya, M.G., Balashova, S.P., Zaozerina, O.N., Golovanova, T.I., 1993. Mineral assemblages and stages of ore formation at the lead-zinc deposits of the Dal'negorsk ore district (Southern Primorye Territory). Geologiya Rudnykh Mestorozhdenii 35 (6), 493–519.

Dubinina, E.O., Baskina, V.A., Avdeenko, A.S., 2011. Nature of ore-forming fluids of the Dal'negorsk deposit: Isotopic and geochemical parameters of the altered host rocks. Geol. Ore Deposits 53 (1), 58–73.

Dubrovsky, V.N., Kigai, I.N., 1974. Zoning of Tin-ore Deposits, in: Sokolov, G.A. (Ed.), Zoning of Hydrothermal Ore Deposits [in Russian]. Nauka, Moscow, Vol. 1, pp. 19–88.

Favorskaya, M.A., Tomson, I.N., Ivanov, R.G., Baskina, V.A., Volchanskaya, I.G., Dezhin, Yu.P., Kravtsov, V.S., Frikh-Khar, D.I., 1969. Relation of Magmatism and Endogenic Mineralization to Block Tectonics [in Russian]. Nedra, Moscow.

Favorskaya, M.A., Konstantinov, R.M., Tomson, I.N. (Eds.), 1972. Local Prognosis in Ore Districts of the East of the USSR [in Russian]. Nauka, Moscow.

Fersman, A.E., 1926. The Mongol-Okhotsk metallogenic belt. Poverkhnost' i Nedra 4 (3), 45–65.

Fersman, A.E., 1932. Prospects of Mineral Commodities Distribution in Territory of the USSR [in Russian]. Izd. Akad. Nauk SSSR, Moscow.

Golozubov, V.V., 2006. Tectonics of Jurassic and Early Cretaceous Complexes of the Northwestern Surrounding of the Pacific Ocean [in Russian]. Dal'nauka, Vladivostok.

Golozubov, V.V., Khanchuk, A.I., 1995. Taukhe and Zhuravlev terranes (Southern Sikhote-Alin)—fragments of the Early Cretaceous Asian margin). Tikhookeanskaya Geologiya 14 (2), 13–25.

Gonevchuk, V.G., 2002. Tin-Producing Systems of the Far East: Magmatism and Ore Genesis [in Russian]. Dal'nauka, Vladivostok.

Gonevchuk, V.G., Gonevchuk, G.A., Kokorin, A.M., Lebedev, V.A., Orekhov, A.A., 2005. New isotope-geochronological data and some genetic problems of tin mineralization of the Kavalerov district (Primorye territory, Russia). Tikhookeanskaya Geologiya 24 (6), 77–87.

Gordienko, I.V., Bulgatov, A.N., Orsoev, D.A., 2013. Geodynamic environments and metallogeny of the Sayan-Baikal mountain area. Otechestvennaya Geologiya, No. 3, 7–15.

Gorzhevsky, D.I., Kozerenko, V.N., 1965. Relation of Endogenic Ore Formation to Magmatism and Metamorphism: Introduction to Metallogeny of Endogenic Ore-Formation Processes [in Russian]. Nedra, Moscow.

Gvozdev, V.I., 2010. Ore-Magmatic Systems of Skarn-Scheelite-Sulfide Deposits of the East of Russia [in Russian]. Dal'nauka, Vladivostok.

Gvozdev, V.I., Dobroshevsky, K.N., Vakh, A.S., Goryachev, N.A., Stepanov, V.A., Fedoseev, D.G., 2016. Malinovka deposit—a new type of gold mineralisation in Primorye, Russia: Geology, mineralogy, and genesis. J. Pacific Geol. 10 (1), 34–49.

Il'in, K.B., 1974. Regional Metallogeny of the USSR [in Russian]. Nedra, Moscow.

Ishihara, S., 1977. The magnetite-series and ilmenite-series granitic rocks. Min. Geol. 27, 293–305.

Ishihara, S., 1981. The granitoid series and mineralization. Econ. Geol., 75th Anniversary vol., 458–484.

Ishihara, S., Shibata, K., Uchimi, S., 1988. K–Ar ages of ore deposits related to Cretaceous–Paleogene granitoids. Bull. Geol. Surv. Japan 39, 81–94.

Itsikson, M.I., 1979. Metallogenic Zoning of the Pacific Segment of the Earth [in Russian]. Nedra, Moscow.

Kanishchev, A.D., 1971. On the possible causes of regional metallogenic zoning of Transbaikalia), in: Shakhov, F.N. (Ed.), Granitoid Massifs of Siberia and Ore Mineralization [in Russian]. Nauka, Novosibirsk, pp. 154–163.

Kanishchev, A.D., 1977. Primary factors of geochemical assemblages and vertical zoning of endogenic ore deposits. Geologiya Rudnykh Mestorozhdenii 19 (6), 80–99.

Kanishchev, A.D., Menaker, G.I., 1971. Chemical structure of the Earth's crust of the Central and East Transbaikalia. Geokhimiya, No. 1, 3–17.

Kanishchev, A.D., Menaker G.I., 1972. Experience of a quantitative estimation of informativity of schemes of metallogenic division of the Central and East Transbaikalia districts, in: Menaker, G.I., Sizikov, A.I. (Ed.), Ore-Bearing Potential of Mesozoic Geological Formations of Transbaikalia [in Russian]. Zabaikal. Filial Geogr. Obshch. USSR, Chita, pp. 71–85.

Kanishchev, A.D., Menaker, G.I., 1973. Quantitative estimation of informativity of schemes of metallogenic zonation of the Central and East Transbaikalia districts. Geologiya Rudnykh Mestorozhdenii 15 (6), 95–99.

Karas', O.A., Pakhomova, V.A., Ekimova, N.I., 2014. Granitoid massif of the Dal'negorsk borosilicate deposit in the Primorye region of Russia: The role of the intrusion in the formation of the boron mineralization. J. Pacific Geol. 8 (3), 213–223.

Karpova, E.D., 1973. Metallogeny of regions of tectonomagmatic activation, in: Grushevoi, V.G. (Ed.), Problems of Regional Metallogeny [in Russian]. Leningrad, pp. 62–101.

Kazanli, D.N., Popov, A.A., Antonenko, A.N., 1959. Deep Seismic Sounding in Central Kazakhstan). Vestnik Akad. Nauk Kaz. SSR, No. 4 (169), 26–36.

Kemkin, I.V., 2006. Geodynamic Evolution of Sikhote-Alin' and the Sea of Japan Region in the Mesozoic [in Russian]. Nauka, Moscow.

Kemkin, I.V., Kemkina, R.A., 2000. Taukhe terrane of South Sikhote-Alin': structure and formation environments. Geotektonika, No. 3, 71–79.

Kemkin, I.V., Khanchuk, A.I., 1992. New data on age of parautochthon at the Samarka accretional complex of South Sikhote-Alin'. Dokl. Akad. Nauk 324 (4), 847–851.

Khanchuk, A.I., 2000. Paleogeodynamic analysis of formation of ore deposits in Far East Russia, in: Khanchuk, A.I. (Ed.), Ore Deposits of Continental Margins [in Russian]. Dal'nauka, Vladivostok, pp. 5–34.

Khanchuk, A.I. (Ed.), 2006. Geodynamics. Magmatism, and Metallogeny of the East of Russia: in 2 Vols. [in Russian]. Dal'nauka, Vladivostok.

Kigai, I.N., 1966. The Lifudzin Tin Deposit and Some Problems of Hydrothermal Mineral-Forming Processes [in Russian]. Nauka, Moscow.

Kigai, I.N., 2006. The Earth's rotation related asymmetry of the North Pacific tectonics and metallogeny, in: 12th IAGOD Symp., Program and Abstracts [in Russian]. Moscow, p. 71, also CD with Extended Abstract No. 219, pdf.

Kigai, I.N., 2010a. The Dubrovsky deposit, in: Kozlovskii, E.A., Ledovskikh, A.A. (Ed.), Russian Geological Encyclopedia [in Russian]. Moscow, Vol. 1, pp. 534–535.

Kigai, I.N., 2010b. Zoning of Deposits, in: Kozlovskii, E.A., Ledovskikh, A.A. (Ed.), Russian Geological Encyclopedia [in Russian]. Moscow, Vol. 1, pp. 595–597.

Kigai, I.N., 2011. Redox problems in the "metallogenic specialization" of magmatic rocks and the genesis of hydrothermal ore mineralization. Petrology 19 (3), 303–321.

Kigai, I.N., 2012. Metasomatites associated with fluids of calc-alkaline magmas. Geokhimiya i Rudoobrazovanie 31–32, 56–66.

Kigai, I.N., 2013. The dependence of metallogenic style of suprasubductional zones from the angle of the slab dipping, in: All-Russ. Sci. Conference "Ore Formation Processes: from Genetic Concepts to Forecast of Ore Provinces and Deposits", Abstracts [in Russian]. IGEM RAN, Moscow, p. 41.

Knyazev, G.I., 1967. On systematization of the closed ore belts. Geotectonika, No. 2, 94–100.

Knyazev, G.I., 1972. The regularities of base-metal deposits location of East Transbaikalia), in: Trans. Dnepropetrovsk Mining Institute, Issue 58 [in Russian]. Nedra, Moscow, pp. 30–35.

Kodolányi, J., Pettke, T., 2011. Loss of trace elements from serpentinites during fluid-assisted transformation of chrysotile to antigorite—An example from Guatemala. Chem. Geol. 284 (3–4), 351–362.

Kokorin, A.M., Gonevchuk, V.G., Kokorina, D.K., Orekhov, A.A., 2001. The Vysokogorskoe tin-ore deposit: peculiarities of mineralization and genesis, in: Khanchuk, A.I. (Ed.), Ore Deposits of Continental Margins [in Russian]. Dal'nauka, Vladivostok, Issue 2, Part 1, pp. 156–170.

Komarov, P.V., Tomson, I.N., 1975. Temporal sequence of mineralization and plutonogenic minerogenic cycles on an example of Eastern Transbaikalia. Otechestvennaya Geologiya, No. 10, 26–35.

Komarov, Yu.V., 1996. On formation of mature continental crust at mountainous framing of Siberian platform), in: Logachev, N.A. (Ed.), The Lithosphere of Central Asia (Principal Results Investigation of the Institute of the Earth' Crust SB RAS in 1992–1996) [in Russian]. Nauka, Novosibirsk, pp. 27–30.

Komarov, Yu.V., 1998. Postaccretional and orogenic geodynamics and metallogeny, in: Proc. 2nd All-Russ. Metallogenic Conf. [in Russian]. Irkutsk, pp. 52–53.

Kormilitsin, V.S., 1959. Main features of Mesozoic metallogeny of Eastern Transbaikalia. Sovetskaya Geologiya, No. 11, 96–109.

Kormilitsyn, V.S., 1960. On ore belts of Eastern Transbaikalia. Bull. VSEGEI, No. 2, 45–52.

Kormilitsyn, V.S., 1973. The ore assemblages and the ore formation processes, in: On the Example of Transbaikalia [in Russian]. Nedra, Leningrad.

Kormilitsyn, V.S., Ivanova, A.A., 1968. The Base-Metal Deposits of the Shirokinskoe Ore Field and Some Problems of Metallogeny of Eastern Transbaikalia [in Russian]. Nedra, Moscow.

Kotlyar, V.N., 1983. Metallogeny and Prognosis of Ore Formation [in Russian]. Nedra, Moscow.

Kovalev, A.A., 1985. Mobilism and Geological-Prospecting Criteria (2nd edition) [in Russian]. Nedra, Moscow.

Kovalenker, V.A., Kiseleva, G.D., Krylova, T.L., Andreeva, O.V., 2011. Mineralogy and ore formation conditions of the Bugdaya Au-bearing W–Mo porphyry deposit, Eastern Transbaikal Region, Russia. Geol. Ore Deposits 53 (2), 93–125.

Kovalenker, V.A., Abramov, S.S., Kiseleva, G.D., Krylova, T.L., Yazykova, Yu.I., Bortnikov, N.S., 2016. The large Bystrinskoe Cu–Au–Fe deposit (Eastern Trans-Baikal Region): Russia's first example of a skarn-porphyry ore-forming system related to adakite. Dokl. Earth Sci. 468 (5), 566–570.

Kovalenko, V.I., 1977. Petrology and Geochemistry of Rare-Metal Granitoids [in Russian]. Nauka, Novosibirsk.

Kozerenko, V.N., 1960. Importance of structural-facial zones for metallogenic analysis on an example of Eastern Transbaikalia, in: Shatskiy, N.S. (Ed.), Regularities of Mineral Commodities Location [in Russian]. Izd. Akad. Nauk SSSR, Moscow, Vol. 3, pp. 441–459.

Kozerenko, V.N., 1963. On primary horizontal zoning of endogenic deposits), in: Problems of Postmagmatic Ore Formation, Vol. 1. Czech Acad. Sci. Publ. Prague, pp. 109–113.

Kozerenko, V.N., 1981. Endogenic Metallogeny [in Russian]. Nedra, Moscow.

Kozlovskii, E.A. (Ed.), 1984. The Kola Superdeep [in Russian]. Nedra, Moscow, 1984.

Kropotkin, P.N., 1954. A brief sketch of tectonics and paleography of southern part of the Soviet Far East, in: Shatskiy, N.S. (Ed.), Problems of Geology of Asia [in Russian]. Izd. Akad. Nauk SSSR, Moscow, Vol. 1, pp. 736–764.

Kropotkin, P.N., 1955. Concerning belts ore zoning in ancient fold areas. Sovetskaya Geologiya, No. 43, 43–60.

Kropotkin, P.N., 1957. A concentric (temperature) zoning and genetic relation of ore mineralization to intrusions. Sovetskaya Geologiya, No. 58, 74–92.

Kropotkin, P.N., 1980. Problems of geodynamics, in: Peyve, A.V. (Ed.), Tectonics in the Research of the Geological Institute [in Russian]. Nauka, Moscow, pp. 176–247.

Kruk, N.N., Simanenko, V.P., Gvozdev, V.I., Golozubov, V.V., Kovach, V.P., Serov, P.A., Kholodnov, V.V., Moskalenko, E.Yu., Kuibida, M.L., 2014. Early Cretaceous granitoids of the Samarka terrane (Sikhote-Alin') geochemistry and sources of melts. Russian Geology and Geophysics (Geologiya i Geofizika) 55 (2), 216–236 (276–302).

Kuperkonik, V.V., 1931. The base-metals of the Far-East territory, in: Nekrasov, B.P. (Ed.), Proc. 4th All-Union Conf. on Nonferrous Metals, Issue 3: Base-Metals [in Russian]. Moscow–Leningrad, pp. 174–181.

Kuzmin, M.I., Filippova, I.B., 1979. History of the development of the Mongol-Okhotsk belt in the Middle–Late Paleozoic and the Mesozoic, in: Zonenshayn, L.P., Sorokhtin, O.G. (Ed.), Structure of the Lithosphere Plates [in Russian]. Moscow, pp. 189–226.

Kuzmin, M.I., Yarmolyuk, V.V., 2014. Mantle plumes of Central Asia (Northeast Asia) and their role in forming endogenous deposits. Russian Geology and Geophysics (Geologiya i Geofizika) 55 (2), 120–143 (153–184).

Lehmann, B., 2004. Metallogeny of the Central Andes: geotectonic framework and geochemical evolution of porphyry systems in Bolivia and Chile during the last 40 million years, in: Khanchuk, A.I. (Ed.), Metallogeny of the Pacific Northwest: Tectonics, Magmatism and Metallogeny of Active Continental Margins, Proc. Interim IAGOD Conf. [in Russian]. Dal'nauka, Vladivostok, pp. 118–122.

Magakian, I.G., 1974. Metallogeny: Principal Ore Belts [in Russian]. Nedra, Moscow, 1974.

Malinovsky, A.I., Golozubov, V.V., 2011. Lithology and depositional settings of the terrigenous sediments along the transform plate boundaries: Evidence from the Early Cretaceous Zhuravlevka terrane in Southern Sikhote-Alin. J. Pacific Geol. 5: 400. DOI: 10.1134/S1819714011050058.

Mazukabzov, A.M., Donskaya, T.V., Gladkochub, D.P., 2004. Late Mesozoic geodynamics of Transbaikalia, in: Sklyarov, E.V. (Ed.), Geodynamic Evolution of the Lithosphere of the Central Asian Mobile Belt (from Ocean to Continent), Vol. 2 [in Russian]. Irkutsk, 2004, pp. 24–26.

Mazukabzov, A.M., Gladkochub, D.P., Donskaya, T.V., Sklyarov, E.V., 2006. Geodynamics of Formation of "Transbaikalian" type of troughs, in: Geodynamic Evolution of the Lithosphere of the Central Asian Mobile Belt (from Ocean to Continent), Vol. 1 [in Russian]. Irkutsk, pp. 229–231.

Menaker, G.I., 1971. Methods of a quantitative estimation of metallogenic schemes (on an example of Transbaikalia), in: Problems of Regional Geology and Metallogeny of Transbaikalia, Issue 6 [in Russian]. Chita, pp. 58–64.

Menaker, G.I., 1972. A model of regional accommodation of ore deposits in a vertical section of the Earth's crust of the Central and East Transbaikalia, in: Menaker, G.I., Sizikov, A.I. (Eds.), Ore Capacity of Mesozoic Geological Formations of Transbaikalia [in Russian]. Zabaikal. Filial Geogr. Obshch. SSSR, Chita, pp. 63–70.

Menaker, G.I., 1976. Development of methods of volumetric forecasting and estimation of territories' ore potential on the basis of geological-geophysical methods, in: Ivanov, V.V., Meituv, G.M. (Eds.), Prediction of Potential Ore-Bearing Areas, [in Russian]. Nauka, Moscow, pp. 195–245.

Menaker, G.I., 1986. Structure of the upper mantle and a space-temporal migration of tectono-magmatic activation processes in Pribaikalye and Transbaikalia), in: Sarin, L.P. (Ed.), Problems of Geology and Metallogeny of Chita Region [in Russian]. Geolfond RSFSR, Moscow, pp. 5–17.

Menaker, G.I., 1990. Tectonosphere and metallogeny of Transbaikalia from a geohistorical viewpoint. Geologiya Rudnykh Mestorozhdenii 32 (1), 21–36.

Mitchell, A.H.G., Garson, M.S., 1981. Mineral Deposits and Global Tectonic Settings. Academic Press, London.

Mizutani, S., Kojima, S., 1992. Mesozoic radiolarian biostratigraphy of Japan and collage tectonics along the eastern continental margin of Asia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 96 (1–2), 3–22.

Pabst, S., Zack, T., Savov, I., Ludwig, T., Rost, D., Vicenzi, E.P., 2011. Evidence for boron incorporation into the serpentine crystal structure. Am. Mineral. 96 (7), 1112–1119.

Pakhol'chenko, Yu.A., Zorina, L.D., Plyusnin, G.S., 1987. First Rb-Sr ages for the metasomatites of the Darasun ore field in Transbaikalia. Dokl. Akad. Nauk SSSR 295 (5), 1219–1223.

Parfenov, L.M., Natal'in, B.A., Vrublevskii, A.A., 1982. Role of faults in forming tectonic structures of the South Far East, in: Kuznetsov, V.A. (Ed.), The Faults and Endogenic Mineralization of the Baikal-Amur Region [in Russian]. Moscow, Nauka, pp. 21–33.

Parfenov, L.M., 1984. The Continental Margins and Island Arcs of Mesozoic Structures of the Northeast of Asia [in Russian]. Nauka, Novosibirsk.

Parfenov, L.M., Berzin, N.A., Khanchuk, A.I., Badarch, G., Belichenko, V.G., Bulgatov, A.N., Dril', S.I., Kirillova, G.L., Kuzmin, M.I., Nokleberg, W.J., Prokopiev, A.V., Timofeev, V.F., Tomurtogoo, O., Yan', Kh., 2003. Model of the orogenic belts formation in Central and Northeast Asia. Tikhookeanskaya Geologiya 22 (6), 7–41.

Petrishchevsky, A.M., Yushmanov, Yu.P., 2012. Metallogeny of deep structures of the Earth's crust in Southern Sikhote-Alin: Evidence from gravity data. J. Pacific Geol. 6 (5), 369–381.

Polkvoi, O.S., 1950. The formation of vein-like rocks of felsic intrusions (the Central Kazakhstan), in: Trans. Geological Institute of the USSR, Issue 107 [in Russian]. Moscow, pp. 53–63.

Radkevich, E.A., 1958. Metallogeny of South Primorye (Trans. IGEM AN USSR, Issue 19) [in Russian]. IGEM AN USSR, Moscow.

Radkevich, E.A., 1987. Regional Metallogeny [in Russian]. Nedra, Moscow.

Ratkin, V.V., Khetchikov, L.N., Gnidash, N.V., Dmitriev, V.E., 1993. Paleohydrothermal karst as the most important factor of forming the Dal'negorsk borosilicate deposit. Tikhookeanskaya Geologiya, No. 2, 97–108.

Ratkin, V.V., Simanenko, L.F., Eliseeva, O.A., 2016. Typing of deposits and the resource potential of lead-zinc and borosilicate ores of the Dal'negorsk ore district (Sikhote-Alin'). Otechestvennaya Geologiya, No. 4, 1–13.

Rybalov, B.L., 2002. Spatial distribution of Late Mesozoic ore deposits in Eastern Transbaikalia (Russia). Geologiya Rudnykh Mestorozhdenii 44 (4), 354–368.

Sakhno, V.G., Akinin, V.V., 2008. First U–Pb dating of volcanics from the East Sikhote-Alin belt. Dokl. Earth Sci. 418 (1), 32–36.

Sakhno, V.G., Gvozdev, V.I., Alenicheva, A.A., Prasolov, E.M., Zarubina, N.V., 2012a. Granitoid magmatism of the Lermontovskaya and Vostok-2 tungsten ore-magmatic systems: U–Pb (SHRIMP) dating and isotope characteristics ($^3He/^4He$) of ores. Dokl. Earth Sci. 443 (1), 308–315.

Sakhno, V.G., Gvozdev, V.I., Safronov, P.P., Rostovsky, F.I., Tsurikova, L.S., 2012b. Late Mesozoic and Cenozoic epochs of magmatism and ore-formation of the Far East: criteria of prognosis for high-tonnage porphyry-copper and silver mineralization on the base of isotope-geochemical studies, in: Rundqvist, D.V., Bortnikov, N.S., Safonov, Yu.G. (Eds.), Minerogenic Problems of Russia [in Russian]. Moscow, pp. 301–322.

Sato, K., Rodionov, S.M., Vrublevsky, A.A., 2006. Lermontovskoe Tungsten skarn deposit: the oldest mineralization in the Sikhote-Alin orogen, Far East Russia. Resour. Geol. 56 (3), 257–266.

Shcheglov, A.D., 1968. Metallogeny of the Autonomous Activation Regions [in Russian]. Nedra, Leningrad.

Shcherba, G.N., 1960. Contribution to the problem of rare-metal ore belts, in: Shatskiy, N.S. (Ed.), Regularities of Mineral Commodities Accommodation, Vol. 3 [in Russian]. Izd. Akad. Nauk SSSR, Moscow, pp. 541–549.

Shipulin, F.K., 1956. On the small intrusions of Southeast Primorye, in: Trans. IGEM AN SSSR, Issue 3 [in Russian]. IGEM AN SSSR, Moscow, pp. 42–113.

Sillitoe, R., 1972. A plate tectonic model for the origin of porphyry copper deposits. Econ. Geol. 67 (2), 184–197.

Simanenko, L.F., Ratkin, V.V., 2008. The Partizan Skarn-Base-Metal Deposit: Geology, Mineralogy, Genesis [in Russian]. Nauka, Moscow.

Skurskii, M.D., 1996. The Bowels of Transbaikalia [in Russian]. Chitageologiya, Chita.

Smirnov, V.I., 1947. The ore belts, in: Problems of Theoretical and Applied Geology [in Russian]. Moscow, Vol. 1, pp. 5–10.

Smirnov, V.I., 1963. An Essay on Metallogeny [in Russian]. Gosgeoltechizdat, Moscow.

Smirnov, S.S., 1936. A scheme of Eastern Transbaikalia metallogeny. Problemy Sovetskoi Geologii 6 (10), 246–265.

Smirnov, S.S., 1944. An Essay on Metallogeny of the Eastern Transbaikalia [in Russian]. Gosgeolizdat, Moscow–Leningrad.

Smirnov, S.S., 1946. About a Pacific ore belt. Izvestiya Akad. Nauk SSSR, Geol. Ser., No. 2, 13–28.

Smolyanskii, P.L., Bogomolov, E.S., 2011. Structural-morphological and REE geochemical control of the correctness of Sm–Nd dating for fluorite formation in the Garsonui deposit, eastern Transbaikalia. Petrology 19 (3), 297–302.

Solov'ev, S.P., 1949. Principal features of distribution and structure of magmatic rocks in Sikhote-Alin' and some petrologic problems. Zapiski VMO 78 (3), 187–194.

Starostin, V.I., 2012. Metallogeny (2nd edition) [in Russian]. Universitet–Knizhnyi Dom, Moscow.

Suttill, K.R., 1988. Cerro Rico de Potosi. Eng. Min. J., No. 3, 50–53.

Syritso, L.F., 2002. Mesozoic Granitoids of Eastern Transbaikalia and the Problems of Rare-Metal Ore Formation [in Russian]. Sankt-Peterburg. Gos. Univ., St. Petersburg.

Tomson, I.N., Kravtsov, V.S., Kochneva, N.G., Kurchavov, A.M., Seredin, V.V., Seliverstov, V.A., Tananaeva, G.A., 1992. Metallogeny of the Orogens [in Russian]. Nedra, Moscow.

Tvalchrelidze, G.A., 1972. The Ore Deposits of the World: The Mediterranean Belt [in Russian]. Nedra, Moscow.

Tvalchrelidze, G.A., 1985. A Metallogeny of the Earth's Crust [in Russian]. Nedra, Moscow.

Turneaure, F.S., 1955. Metallogenetic provinces and epochs. Econ. Geol. 50th Anniversary Volume, 1905–1955, Vol. 1, 38–98.

Utkin, V.P., 1989. Strike-Slip Dislocations, Magmatism and Ore Formation [in Russian]. Nauka, Moscow.

Utkin, V.P., 2013. Shear structural paragenesis and its role in continental rifting of the East Asian margin. J. Pacific Geol. 7 (3), 167–188.

Wisser, E., 1960. Relation of Ore Deposition to Doming in the North American Cordillera. Geol. Soc. Am. Memoir, Pap. 77.

Zaraisky, G.P., Aksyuk, A.M., Devyatova, V.N., Udoratina, O.V., Chevychelov, V.Yu., 2009. The Zr/Hf ratio as a fractionation indicator of rare-metal granites. Petrology 17: 25. DOI: 10.1134/S0869591109010020.

Zonenshain, L.P., Kuz'min, M.I., Natapov, L.M., 1990. Tectonics of Lithosphere Plates of the USSR Territory: in 2 Vols. [in Russian]. Nedra, Moscow.

Zorin, Yu.A., 1967. On distribution of Late Mesozoic intrusions and tin-tungsten mineralization in relation to deep structure of the Earth' crust within the southern part of Transbaikalia. Geologiya i Geofizika, No. 5, 122–125.

Zorin, Yu.A., Belichenko, V.G., Turutanov, E.Kh., Mazukabzov, A.M., Sklyarov, E.V., Mordvinova, V.V., 1997. Structure of the Earth' crust and geodynamics of the western part of the Mongol-Okhotsk belt. Otechestvennaya Geologiya, No. 11, 52–58.

Zorin, Yu.A., Belichenko, V.G., Turutanov, E.Kh., Kozhevnikov, V.M., Sklyarov, E.V., Tomurtogoo, O., Hosbayar, P., Arvisbaatar, N., Biambaa, Ch., 1998a. Terranes of Eastern Mongolia and Central Transbaikalia, and the development of the Mongolia-Okhotsk fold belt. Geologiya i Geofizika (Geology and Geophysics) 39 (1), 11–25 (8–21).

Zorin, Yu.A., Zorina, L.D., Spiridonov, A.M., Rutshtein, I.G., 1998b. Geodynamics of the Transbaikal segment of the Mongol-Okhotsk fold belt and distribution of ore showings of gold, in: Proc. 2nd All-Russ. Metallogenic Conf. [in Russian]. Irkutsk, pp. 257–258.

Zorin, Yu.A., Belichenko, V.G., Rutshtein, I.G., Zorina, L.D., Spiridonov, A.M., 1998c. Geodynamics of the western part of the Mongol-Okhotsk fold belt and the tectonic position of gold ore showings in Transbaikalia. Geologiya i Geofizika (Geology and Geophysics) 39 (11), 1578–1586 (1578–1585).

Yarmolyuk, V.V., Kovalenko, V.I., Kuzmin, M.I., 2000. North-Asian superplume in the Phanerozoic: magmatism and deep-seated geodynamics. Geotektonika, No. 5, 3–29.

Editorial responsibility: A.S. Borisenko