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GEOCHEMICAL IMPLICATIONS OF THE RELATIONSHIPS BETWEEN ORE FORMATIONS AND MAGMATISM, AND THE EARTH'S CRUST STRUCTURE

(Figs. 12)

Abstract: There is a certain file of empirically established interrelations: ore formation — ore-bearing geological formation — deep-seated structure of the Earth's crust and upper mantle and its imprint on the morphological structure of the relief.
Metallogenetic zoning related to the successive change of geological and ore-bearing formations in time and space is in many ways determined by the generation and development of Benioff type deep fault zones on the boundaries of oceanic and continental plates.
The general zoning sequence of lithophyllic, chalcophyllic and siderophyllic ore formations is similar to the sequence of ore-geochemical zoning of an ore-bearing district, a field and an individual deposit, including halos.
In a wide range of zoned differentiation of the ore-bearing formation. the concentration of mineralization has only a definite narrow interval of petrogenic component ratios. This interval corresponds to the definite deep-seated section of the Earth's crust and therefore to the hypsometric relief level.

Резюме: Существует определенная цепь эмпирически установленных взаимосвязей: рудная формация — рудоносная геологическая формация — глубинное строение земной коры и верхней мантии и его отражение в морфоструктуре рельефа.
Металлогеническая зональность, связанная с закономерной последовательной сменой геологических формаций во времени и пространстве, во многом определяется зарождением и развитием глубинных разломов типа зон Беньофа.
Общий зональный ряд литофильных, халькофильных и сидерофильных рудных формаций в элементном выражении аналогичен ряду рудногеохимической зональности рудного района, поля и отдельного месторождения, включая ореолы.
В широком диапазоне зональной дифференциации состава рудоносной формации концентрация оруденения занимает только определенный узкий интервал соответствует определенному глубинному разрезу земной коры и в связи с этим — и гипсометрическому уровню рельефа.

The analysis of regional metallogenic zoning in provinces with prolonged unidirectional or polycyclic geosyncline and orogenic development shows a certain file of empirically revealed relationship: ore formation — ore-bearing geological formation — the deep-seated structure of the Earth's crust and upper mantle — the morphostructure of the surface topography.

Metallogenic and geological zoning in the Urals — Kazakhstan-Tien Shan region and in the south-western framework of the East Siberian Platform reflects unidirectional sequence of events during growth and evolution of

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the Earth's crust from oceanic to continental environment, the sequence of several magmatic series from ultrabasic to felsic rocks and from normal to alkaline rocks (Fig. 1).

The process occurred predominantly in the Devonian and Carboniferous and elapsed in different places with various velocity and intensity (Peive—Yanshin, 1980).

The ophiolitic complex of oceanic and transitional stages related to marginal zones is accompanied by chromite, platinum, copper and nickel ores hosted by ultrabasic and basic intrusive rocks. In the Urals region belts of massive sulphide Cu- and Cu-Zn ores, Au sulphide and iron ores follow each other

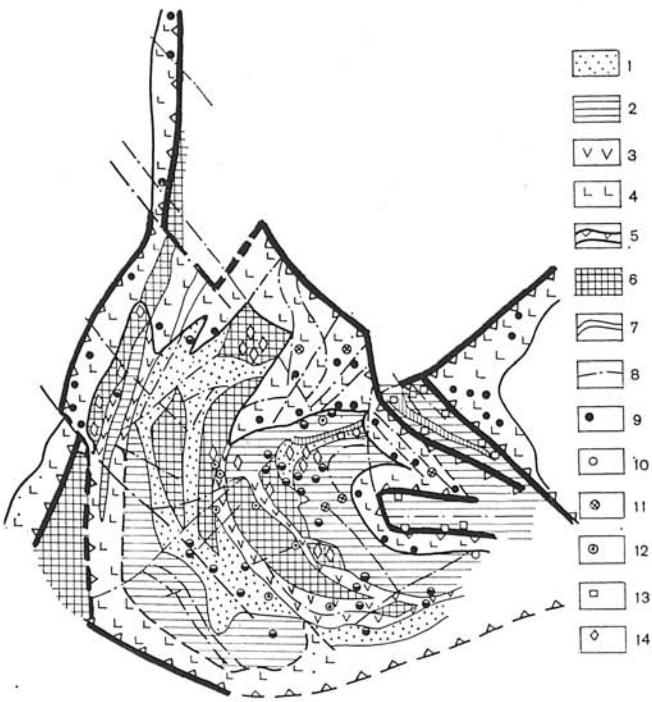

Fig. 1. The diagram shows structural-formational and metallogenic zoning of Kazakhstan and its framework (based on the data represented by Esenov—Kayupov et al., 1974).

Explanations: 1 — miogeosyncline zones; terrigenous-carbonate and carbonate formations with Fe-Mn and Pb-Zn ore mineralization; 2 — geosyncline zones with calc-alkaline (andesitic and rhyolitic) volcanics which host Cu(Mo)-porphyry, Ba-Pb-Zn and Fe-Mn ore mineralization; 3 — major intracontinental volcanogenic troughs with Ba-Cu-Zn ore mineralization; 4 — eugeosyncline zones on oceanic and transitional crust with massive sulphide and iron ore mineralization; 5 — boundaries showing distribution of massive sulphide and associated ore mineralization; 6 — geoanticline zones and median masses with rare metal ore mineralization; 7 ophiolitic zones with Cu, Co-Ni and Cr ore mineralization; 8 — faults; 9—14 — ore deposits; 9 — massive sulphide; 10 — barite-copper-skarn; 11 — copper (molybdenum)-porphyry; 12 — cupreous sandstones; 13, 14 — rare metal.

with appreciable overlapping. The belts are associated genetically with differentiated basaltic and andesitic formations.

In the Central Kazakhstan block essentially basaltic and andesitic-basaltic massive suplhide-bearing formations are replaced in places by andesitic volcanic zones with porphyry copper deposits, next by zones with stratiform barite--copper-lead-zinc ores and further on by terrigenous and terrigenous-carbonate lead-zinc and iron-manganese ore formations. Antimony-mercury ores and cupreous sandstones occur in the centre of the plate; rare metal granitic mineralization is confined to the cores of the structures represented by median masses (E s e n o v—K a y u p o v, 1974).

In the Eastern Kazakhstan and South-Western Altai an ophiolitic complex with Cu-Ni and chromite ores is replaced laterally and upwards (in cross--sections) by a zone with Au and As-Sb mineralization in sandstones and shales containing minor basaltic intrusions, and then by a granitic-rare metal zone related to flyshoid formation. Further on there is a zoned complex of massive sulphide base metal, Au-Ag and iron ores related to basalt-rhyolite and andesite (basalt-andesite) formations of regular petrochemical variations.

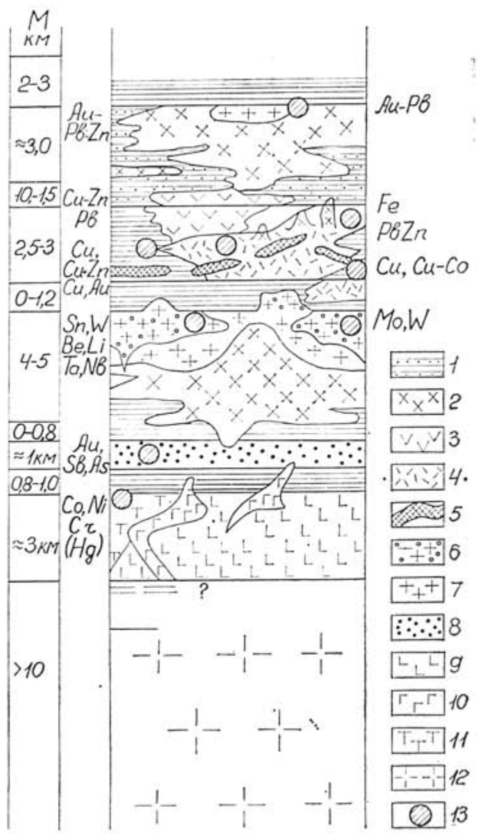

Fig. 2. Geological-geochemical column of the South-Western Altai.
Explanations: 1—5 — geological formations: 1 — terrigenous and terrigenous--carbonate; 2 — gabbro-granodioritic-granite; 3 — basalt-andesite; 4 — basalt-rhyolite; 5 — gabbro-diabase (dikes, minor intrusions); 6 — rare metal greisen and pegmatite fields; 7 — rare-metal granites; 8 — Au-Sb-As mineralization; 9 — basaltoids; 10 — gabbroids; 11 — ultrabasic rocks; 12 — granitic-metamorphic layer; 13 — ore deposits.

Such spatial sequence of geological and ore formations is consistent with the billowy rhythmic growth of the crust thickness, and primarily of its granitic-metamorphic layer (O v c h i n n i k o v—B a r a n o v, 1974).

The regional geologic-geochemical mapping in the Eastern Kazakhstan and in the South-Western Altai shows spatial consistency and persistence of thicknesses of the metallogenic zones, their vertical and lateral sequence, rhythmic alteration of geosyncline and orogenic type of basaltic and granitic magmatism (Fig. 2).

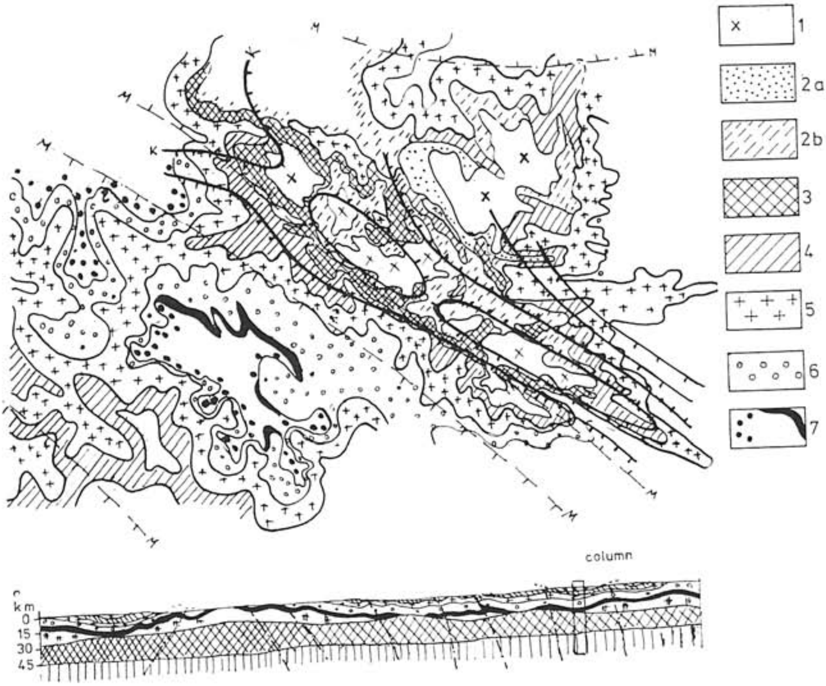

Fig. 3. The structure of geologo-geochemical zoning of Eastern Kazakhstan and South-Western Altai.

Explanations: 1 — area of the gabbro-granodiorite-granite formation; 2–7 — ore-bearing zones. 2a — lead-zinc and lead, 2b — zinc-lead-iron ore; 3 — complex copper-lead-zinc; 4 — copper, copper-massive sulphide; 5 — granite-rare-metal; 6 — arsenic-antimony — gold ore; 7 — copper-cobalt-nickel-chrome (green specks). Contour lines denote Moho discontinuity (M) and in part (for Rudnyi Altai) Conrad discontinuity (K). Metallogenic zones, Moho and Conrad discontinuites are also shown in the cross-section.

There is a stable conformity of metallogenic zones which have very twisting and gently sloping boundaries (Fig. 3).

The volumetric structure of the metallogenic zoning is connected to an appreciable degree with the successive stratification of volcanic and sedimentary metal-bearing formations. Subsequent magmatic and metamorphic processes gave rise to some regeneration of the earlier ores.

Lateral zoning is especially contrasting in the outer areas of basaltic volcanism and related massive sulphide ores.

In the general zoning series of massive sulphide ore formations which is characterized by increase of acidity and degree of magmatic differentiation two groups can be distinguished: the first is tholeiitic group (ultrabasic, basic, basaltic, basaltic-andesitic, rhyolitic-basaltic and rhyolitic-andesitic-basaltic formations) and the second, calc-alkaline group (andesitic, basaltic-rhyolitic, rhyolitic formations) (Fig. 4) (O v c h i n n i k o v—B a r a n o v , 1978).

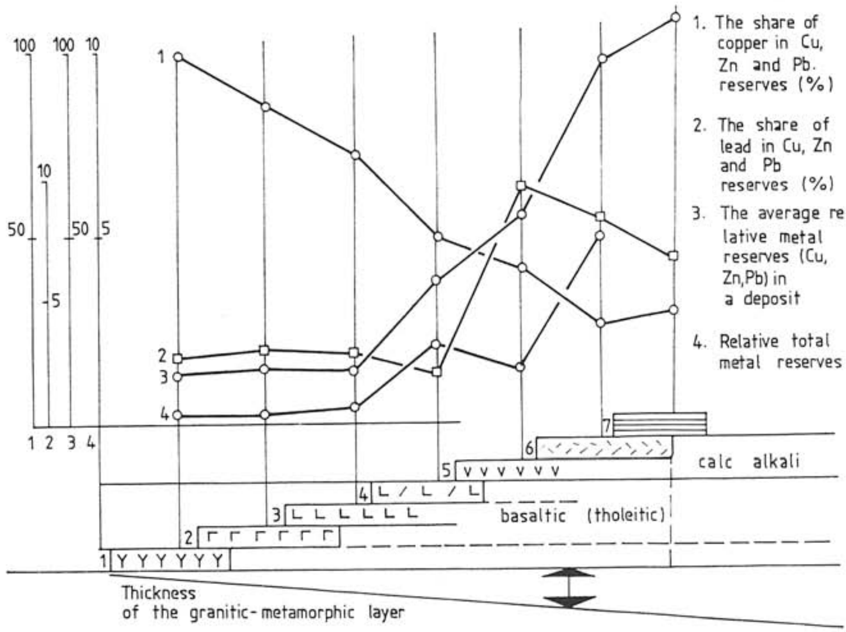

Fig. 4. Zoned series of massive sulhpide-bearing formations and their metallogenic parameters.

Explanations: Formations: 1 — ultrabasic; 2 — gabbroic; 3 — basaltic; 4 — andesitic -basaltic; 5 — andesitic; 6 — basaltic-liparitic (liparitic); 7 — terrigenous (terrigenous--carbonate).

The share of Cu in the total reserves of Cu + Zn + Pb, (I) the mean relative reserves of metal in a deposit (3) and relative total reserves of metal in various formations (4) are shown as a function of the thickness of granitic-metamorphic layer.

The type of ore mineralization changes with the increase of the thickness of granitic-metamorphic crust layer; the share of copper drops and the share of lead in the base metals total increases, sulphur-metal ratio in reserves and contents decreases, the mean and the cutoff metal reserves of a single deposit increase and so do the specific ore content and the bulk of disseminated mineralization (B a r a n o v—O v c h i n n i k o v, 1980).

The variations of the thickness of granitic-metamorphic layer (the depth of Conrad discontinuity) in longitudinal sections of some provinces are directly correlated with ore composition, for examle, with the copper share in Cu, Zn and Pb reserves (Fig. 5).

Two main formational groups corresponding to two types of geosynclines are distinguished by mean ratios of reserves and average metal contents in ores as much as crustal abundance of these elements differ in basic and igneous rocks (Fig. 6). The ratios of reserves and contents of all elements in the Urals

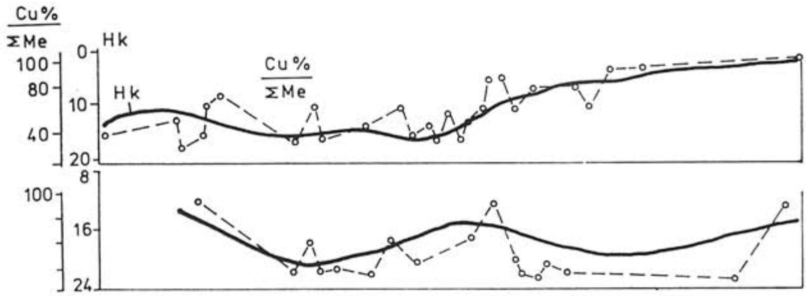

Fig. 5. Relationship between massive sulphide ore composition and deep-seated structure of crust. The share of Cu in the total reserves Cu + Zn + Pb is shown on the longitudal vertical projection as a function of the Conrad discontinuity.

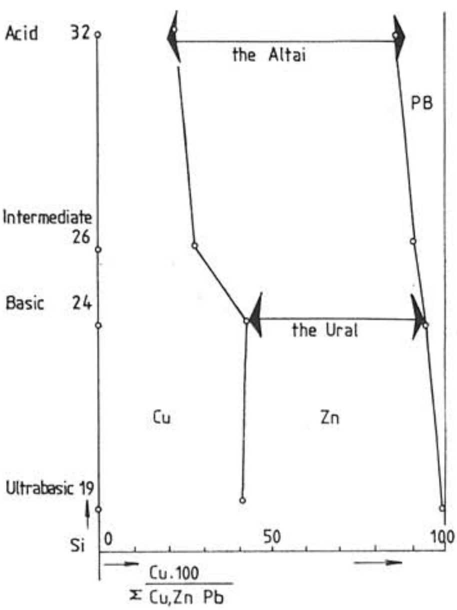

Fig. 6. Relationship between metal reserves (Cu, Zn, Pb) in massive sulphide ores and mean metal contents in main igneous rock types (after A. P. V i n o g r a d o v).

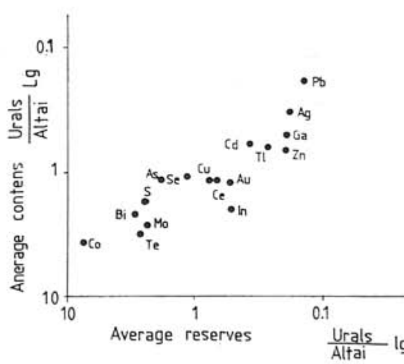

Fig. 7. Relationship between mean contents (C) and reserves (r) of chemical elements in massive sulphide deposits of Altai (A) and the Urals (U).

and Altai type ores are consistent with general regional zoning series of elements which are characteristic of geological processes at different levels of the matter organization (Fig. 7). Thus the ratio of element concentration at different levels of this zoning series (basaltic and rhyolitic) reflects the degree of crust maturity and the thickness of its granitic-metamorphic layer.

Each massive sulphide ore province and an individual ore-bearing formation are characterized by a clear lateral zoning of volcanics and ore composition. Thus the variation of Cu, Zn and Pb contents in the Rudny Altai ores is clearly

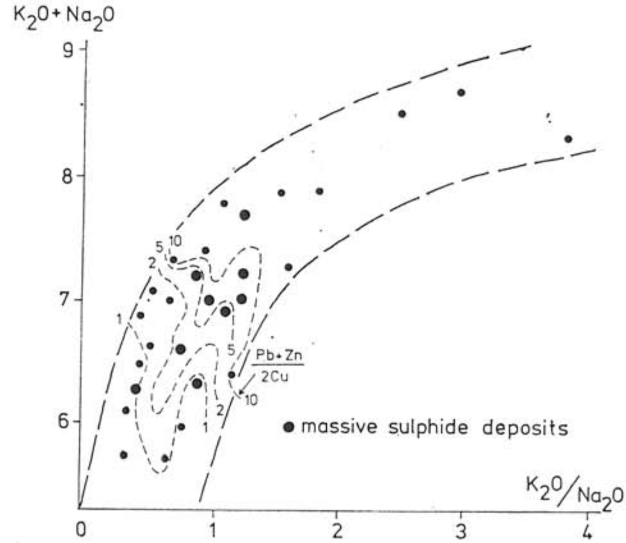

Fig. 8. Dependence of the contents and concentration of mineralization on K_2O and Na_2O contents in rhyodacite-rhyolite (Altai).

correlated with the change of potassium-sodium alkali ratio in subvolcanic rhyolites. The range of K_2O/Na_2O is relatively wide (0.2—4.0) but the position of economic ore mineralization corresponds only to a comparatively narrow interval which is close to clarke values for rhyolites. When the alkali content is lower and sodium predominates, then sulphur-rich massive sulphide base metal ores appear; with predominance of potassium, ore mineralization becomes sulphur-poor, essentially lead-zinc in composition. Iron deposits are associated with alkaline and potassium rhyolites (Fig. 8).

The hydrothermal alteration near massive sulphide ore mineralization develops in such a manner that in sodium-rich part of the formation the share of sodium, and in potassium-rich part, that of potassium, increases.

Thus the petrochemistry of magmatic rocks and, primarily, the alkali contents are good indicators for the relationship between ores and the deep-seated crust structure.

Petrochemical data help to trace the boundaries and to clear up the various features of the inner facies structure of ore-bearing formations which give rise to very long (many hundreds of km) and narrow (tens of km) ribbon-like bodies in massive sulphide ore provinces (Fig. 9). Not only linear but also ring and arc deep faults are important for the structure of formation. These faults are likely to have a great general significance for the distribution of magmatic formation during geosyncline and orogenic evolution. Arc and ring faults are fairly well established by morphostructural analysis of surface topography and by interpretation of space images. The faults are to some degree imprinted on the Moho surface structure (B a r a n o v—D i d e n k o, 1982).

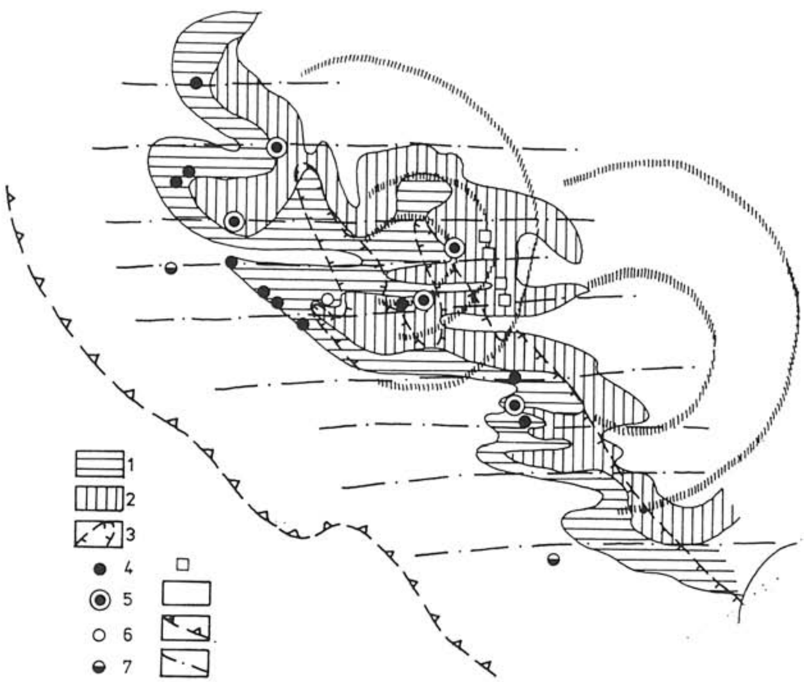

Fig. 9. The position of ore deposits within the structure of petrochemical (facies) zoning of basalt-rhyolite formation in the Altai.
Explanations: 1 — essentially sodic (Na_2O and K_2O) part of the basalt-rhyolite formation; 2 — essentially potassic (K_2O and Na_2O) part of the basalt-rhyolite formation; 3 — anticlinorium-synclinorium boundaries; 4—7 — ore deposits; 4 — massive sulphide base metal (sulphur-rich); 5 — base metal (Pb-Zn) and Pb (sulphur-poor); 6 — Cu--massive sulphide; 7 — Au-Ag- ore occurrences; 8 — Fe deposits; 9 — complex geochemical aureoles; 10 — Zavaritsky — Benioff Palaeozoic; 11 — transform deep faults; 12 — arc (ring) deep faults.

As shown in Fig. 9 the most contrasting lateral zoning and the highest ore concentration accompanied by complex geochemical aureoles are related to concentric areas. Cylindric and conic faults zones are assumed to be the deepest channels which connect mantle and crust.

Ore-geochemical and petrochemical zoning of massive sulphide ore provinces is expressed in the relief. Many provinces exhibit vertical hypsometrical zoning

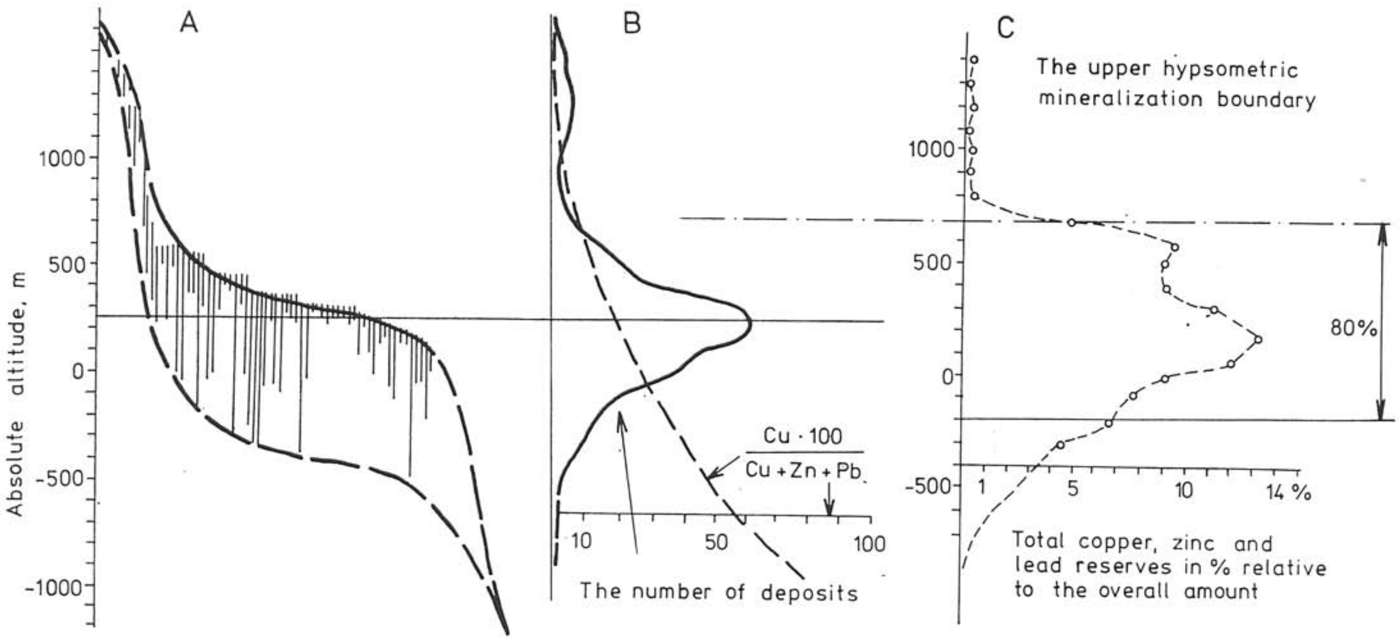

Fig. 10. An example of hypsometric zoning within massive sulphide ore province. *Explanations:* A — vertical extent of ore mineralization in deposits; B — amount of deposits (black line); the share of Cu in the total reserves Cu + Zn + Pb; C — total reserves Cu + Zn + Pb. Note that 80 % reserves of these metals are concentrated within a certain hypsometric interval about 1 km in extent.

of mineralization with different levels of metal concentration. An example of such hypsometrical zoning for massive sulphide ores is shown in Fig. 10. The explanation of the relation can be found in the long-term inheritance of the ore-bearing level position in the interrelated structure of deep-seated crust and surface topography. The relation provides good explanation of the model of structure and development of active ocean-continent boundaries along the marginal deep fault (Benioff zone) combined with transform, arc or ring fault systems (Fig. 11).

The ore-bearing magmatic source is located in the deep-seated mantle part of the Benioff zone. Above it massive sulphide ore-bearing formation forms which change its composition and thereby the ore composition depending on

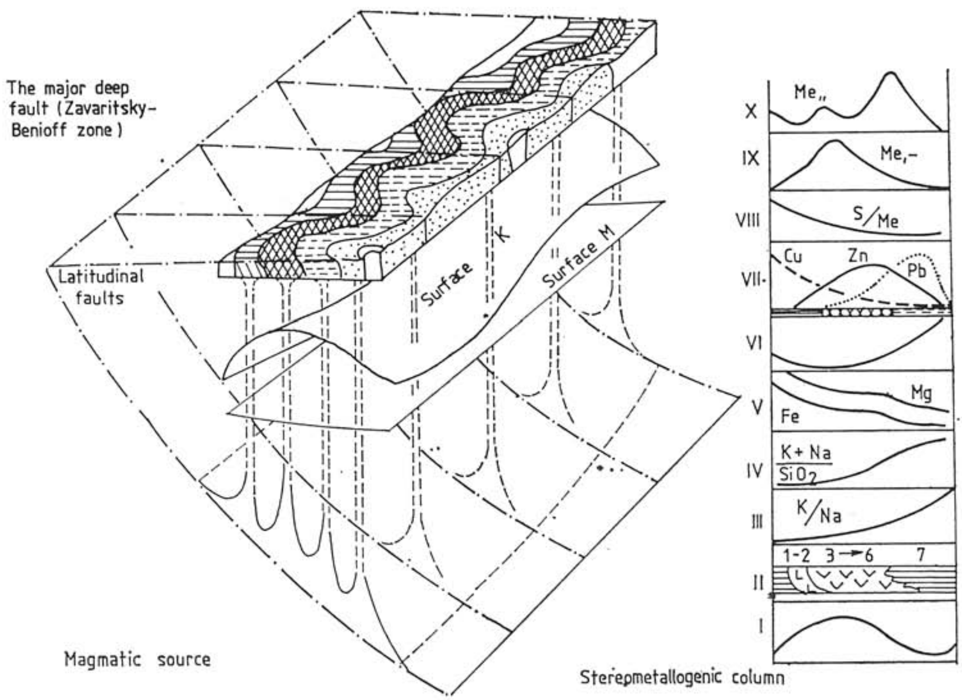

Fig. 11. The model of volumetric metallogenic (stereometallogenic) relationships and regional zoning of the massive sulphide ore provinces.

Explanations: The following features are shown in the figure: the major deep fault (Zavaritsky–Benioff zone), transversal (transform) faults; metallogenic zones (coloured): green — Cu, Cu-massive sulphide, red — Cu-Pb-Zn, blue — Pb-Zn, brown — Fe. Stereometallogenic column (to the right) shows relationships between features I–X. I — deep structure, C. discontinuity; II — complex of geological formations: 1–3 — ultrabasic, gabbroic, basaltic, 4 — differentiated basaltic, 5 — andesitic, 6 — rhyolitic, 7 — terrigenous, terrigenous-carbonate; III–V — petrochemistry of magmatic rocks from the ore-bearing formation; VI — surface topography; VII — metal content; VIII — sulphur-metal ratio within aureoles and ores; IX–X metal reserves in ores (two types of provinces).

the depth of the fault zone and magma formation (Smirnov, 1974, 1978; Ovchinnikov—Baranov, 1978).

A part of the ore-bearing formation is the most productive, and in this way appears a narrow lateral ore level within the ribbon-like zone; the position of this level is inherited in the Earth's crust and relief.

The stereometallogenic (volumetric metallogenic) column (Fig. 11) shows relations of (from bottom to top):

I — deep-seated structure of crust (structure of Conrad discontinuity); II — zoned geologo-formational series; III—V — petrochemical zoning of the ore-bearing formation (complex of formations); VI — structure of the Recent relief; VII—VIII — variations of metal and sulphur contents in ore and geochemical anomalies; IX—X — structures of distribution of the total metal reserves for different types of crust environment (oceanic and continental).

The structure of geochemical zoning within massive sulphide ore provinces suggests paleoreconstruction of the Benioff zone position during ore formation.

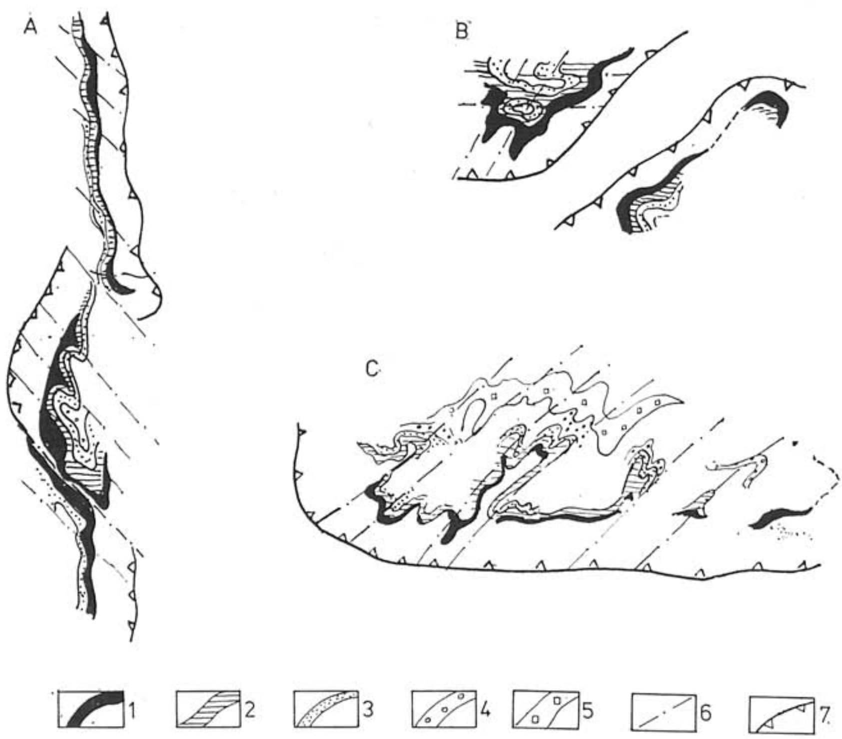

Fig. 12. Examples of a structure which is typical of regional geochemical zoning of massive sulphide ore provinces.

Explanations: A — the Urals, B — Quebec, C — Altai. Geochemical zones of ore mineralization in shares of Cu in total reserves Cu + Zn + Pb; 1. 100—75 %; 2. 75—50 %; 3. 50—20 %; 4. 20—0 %; 5. iron ore deposits zone; 6. transversal (transform) deep fault zones; 7. assumed positions of the palaeoseismofocal zone (Zavaritsky-Benioff zone).

The simplest technique used for the reconstruction is based on contour lines denoting copper share among base metals. Fig. 12 shows regional geochemical zoning for several ore provinces.

No petrological model has been so far accepted for different magmatic series. Rb/Sr isotopic evidence points to mantle source of magmas and metals for magmatic rocks which are hosts for Cu-Ni, chromite, massive sulphide and Cu-Mo ores.

The crust origin of the granites which host Sn, W and rare metal deposits does not rule out the primary enrichment of the metals in sedimentary geosyncline formations and its subsequent regeneration during polygenesis. This assumption explains the sequence and conformity of different chalcophile, siderophile and lithophile metallogenic zones and the rhythmic-billowy growth of the granitic-metamorphic layer.

The distribution of trace elements including metals in volcanics of different tectonic setting shows that the ore content of geological formations is determined primarily by the depth and geodynamic conditions during melting of mantle substratum which is the source of ore matter. It is reasonable to believe that metallogenic zoning connected with rhythmic-billowy growth of crust, especially its granitic-metamorphic layer, is related to regular increase of the depth of mantle ore source.

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