

## Multilevel Structure of Ore-Magmatic Columns in Large Ore Deposits

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Received March 5, 2005

Mining of large deposits and prospecting for separate ore occurrences at deep levels has provided new data on the deep structure of ore-magmatic columns and variation in the mineralization types replacing each other with depth [1]. For example, veinlet-disseminated ores of the porphyry type are localized at relatively deep levels of copper, molybdenum, tin, tungsten, and gold deposits. At a hypsometrically higher level, they are replaced by ores of the vein type. Simultaneously, the type of deposits also changes toward quartz and polysulfide ones. Vein ores represent differentiates of porphyry mineralization matter.

Let us consider the structure of ore-magmatic systems at different deposits (Fig. 1). Vertical transition from one ore type to another is rarely observed. Therefore, in order to reconstruct a multilevel vertical ore column, we used the data on different deposits located at different erosional and stripping levels within the same ore district or node.

In the Primor'e region, tin deposits of different types are widespread [2]. Vein bodies of the cassiterite–sulfide association dominate in the Shcherbakov deposit. Direct relationships between sulfide and quartz–cassiterite veins are observed only in the Mayakovskii area of the deposit. The cassiterite veins usually associate closely with granitoids, which are not exposed by erosion in the Shcherbakov deposit. Veins of the cassiterite–quartz association are superimposed on the cassiterite–sulfide ones to form common orebodies. The deeper erosional level of this ore district incorporates the Tigrinoe deposit located on western slopes of the Sikhote Alin Ridge. The greisen orebody is hosted in leucocratic granites, which are separated from hosting terrigenous sequences by the aplitic fringe. The quartz–cassiterite vein system occurs in terrigenous rocks

located above the granite stock. A cassiterite–sulfide vein system is located farther from the massif. Orebodies occurring at different levels in these deposits provide the opportunity to reconstruct the multilevel ore-magmatic column of tin mineralization in the Primor'e region. Results of the comparison of greisens from the lower level and the overlying vein system indicate that sulfide and quartz veins represent differentiates of greisen mineralization and correspond to greisens in the bulk composition. There are grounds for expecting that a stock of leucocratic granites with greisen mineralization occurs at the deep level of the Shcherbakov deposit. Signs of the presence of leucocratic granites and quartz ores are known in several deposits of the Primor'e region.

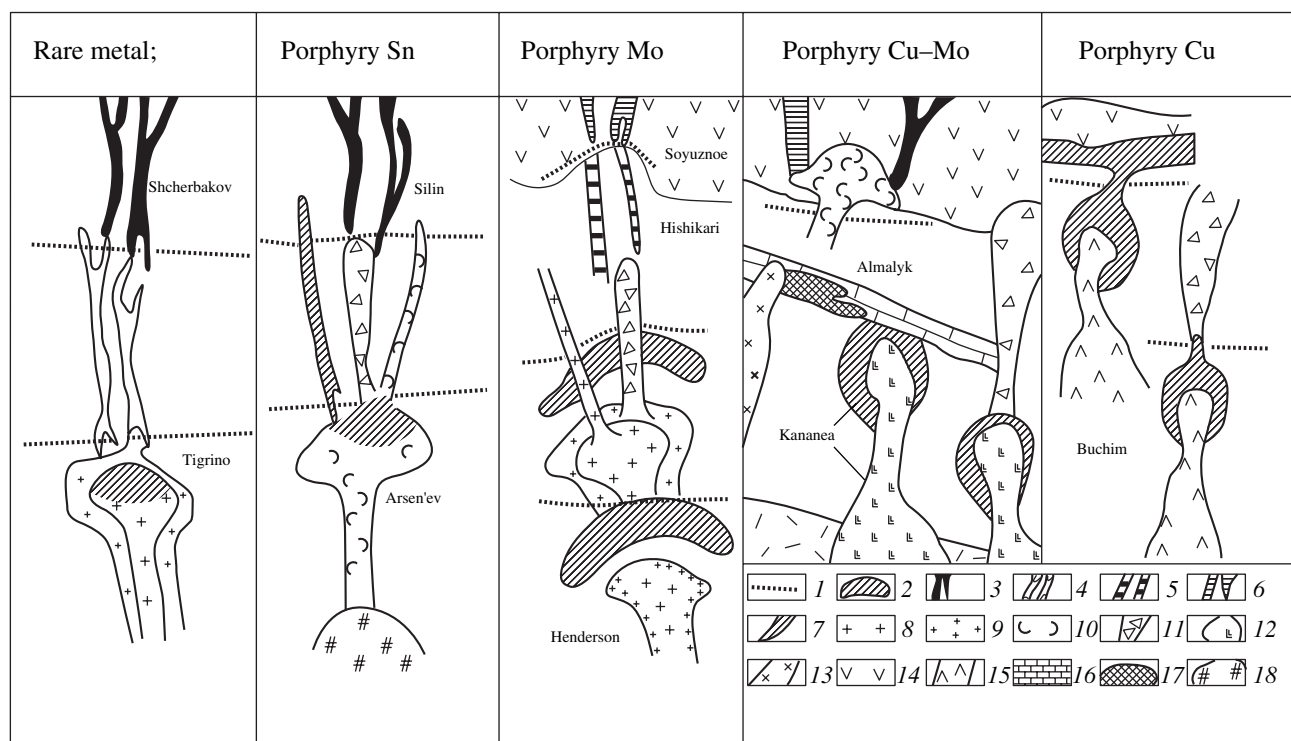
Thus, the ore-magmatic column of tin ore deposits in the Primor'e region consists of three levels (Fig. 1). The upper, middle, and lower levels of this column are localized in terrigenous rocks, hornfelses, and leucocratic granites, respectively.

Other tin orebodies are grouped around rhyolite stocks and they compositionally correspond to the cassiterite–silicate association. The Arsen'ev deposit exemplifies these orebodies. Its lower mineralization level is represented by a stockwork of the rhyolite-hosted cassiterite–porphyry association enclosed in intrusion and dikes. The middle level hosts mineralized breccia and chlorite–cassiterite veins. The upper level includes sulfide veins of chlorite–galena–sphalerite composition. One may suppose that the middle and upper levels of mineralization in this deposit are also related to the differentiation of ore material of the cassiterite–porphyry association.

An intricate multilevel structure is assumed for the ore-magmatic column with the porphyry molybdenum stockwork at the base (Fig. 1). Its reconstruction is based on factual data from the Climax and Henderson deposits (United States) [3]. The upper part of the column hosts gold–silver deposits similar to the Soyuznoe (Primor'e region) and Hishikari (Japan) deposits. The geochemical survey carried out at the Soyuznoe deposit showed that the ore field is characterized by a wide distribution of tungsten and molybdenum halos and by the development of molybdoscheelite, scheelite, and

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**Fig. 1.** Models of the multilevel structure of ore-magmatic columns in large deposits (based on data from [3–6]). (1) Boundaries between mineralization levels; (2) ore-bearing stockwork; (3) sulfide veins; (4) quartz–rare metal veins; (5) low-grade gold–silver veins; (6) high-grade gold–silver veins; (7) cassiterite–silicate veins; (8) leucocratic granites; (9) aplitic fringes in leucocratic granites; (10) rhyolite–dacite subvolcanic bodies; (11) ore-bearing breccia; (12) monzonites; (13) granodiorites; (14) andesites; (15) latite stocks; (16) limestones; (17) polymetallic skarns; (18) granites.

molybdenite. The leucocratic granite dike is also known to occur in the gold–silver deposit. This allows us to assume that the lower part of the ore-magmatic column is structurally similar to that in the Henderson and Climax deposits [3]. The ore-bearing stockwork probably resembles an inverted cup (Fig. 1). If the ore-bearing massif was formed in several phases, then it is possible that every stock is accompanied by a stockwork lode. The upper level is characterized by the development of vein quartz–gold–silver mineralization. If vein mineralization is localized near the contact between a volcanic sheet and terrigenous rocks, two systems of gold–silver veins are formed. One of them occurs in volcanics and is composed of low-grade ores, while high-grade ores are localized above the volcanic sheet in basal terrigenous rocks. Thus, volcanics play the role of a screen. This ore-magmatic column demonstrates distinct zoned patterns. Its lower level incorporates the stockwork with scheelite mineralization that is replaced downward by the molybdenite one. The upper level is dominated by vein gold–silver mineralization. This column represents a summary section based on data from different deposits. The hypothesis of a multilevel structure implies the possibility of deep prospecting drilling.

The porphyry copper column demonstrates distinct zoned patterns, which are observable in large deposits,

such as the Almalyk (Uzbekistan) and Kanansa (Mexico), and in the Basins and Ridges Province (Nevada, United States) [6]. Using the Buchim deposit in Macedonia as an example, one can reconstruct the ore-magmatic column for this type of deposit. Stockwork orebodies are concentrated around latite stocks and some of them are superimposed by tubes of breccia with hematite cement. These tubes can serve as indicators of latite stocks and stockwork mineralization at deeper levels. Carbonate sequences host skarns. The upper level is represented by disseminated ore lodes of the “mantle” type in andesites.

Ores from the Maisk and Carlin deposits are characterized by certain common features [7]. Recent facts and observations confirm this similarity and allow us to propose the multilevel model (Fig. 2). The uppermost level of Carlin-type mineralization is observed in the Alshar deposit (eastern Macedonia), where mineralization is distinctly related to volcanic activity. The ore zone formed beneath the screen of alkaline volcanics. Similarly to the Carlin trend (Nevada, United States), the near-surface level (above 500 m) hosts jasperoid metasomatic ores with native mercury, arsenic, cinnabar, realgar, orpiment, and thallium minerals. Epithermal deposits of the Divide, Gatchell, Cortez, and Tuscarora types (Nevada) formed at the same level [3]. Core from the interval of 700–1000 m of the deep (over

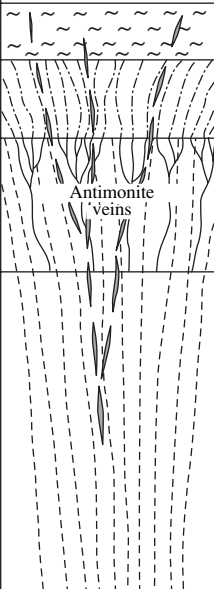
Depth, m	Vertical mineralization zoning	Characteristic minerals	Deposits	
100–200		Realgar, cinnabar, thallium minerals, antimonite	Alshar, Lukhumi, Carlin, Cortez	
200–300		Quartz, chalcedony, hematite, pyrite, marcasite, antimonite		
300–900		Pyrite, marcasite, antimonite	Gold Strike, Gold Quarry	
900–3000		Disseminated gold–sulfide mineralization zone	Pyrite, arsenopyrite	Maisk, Nadezhdinsk, Kyuchus, Olimpiada, Bakyrchik, Kokpatas, Donlin Creek, Ashanti, Forestville
3000–5000			Arsenopyrite	

Fig. 2. Model of vertical zoning in disseminated gold–sulfide mineralization.

1000 m) structural borehole drilled within the Carlin trend shows the presence of acicular arsenopyrite in addition to the main gold-bearing minerals (As-pyrite and marcasite) [8]. Carlin-type disseminated ores from this level are virtually indistinguishable from ores of the Maisk deposit. Several deposits with disseminated gold–sulfide (pyrite–arsenopyrite) ores have been discovered at flanks of the world’s largest Bingham porphyry copper deposit [9]. Consequently, the formation depths of porphyry copper and gold–sulfide disseminated mineralization are comparable. Deep structural boreholes drilled at the Maisk and Nadezhdinsk deposits demonstrated that disseminated ores are continuously developed from the surface to depths of 1200 and 1500 m, respectively. According to computer modeling, orebodies from deep levels (800–1000 m and deeper) of the Maisk deposit are characterized by an almost twofold decrease in the average As content (from 1.5 to 0.8–0.7%) as compared with higher levels and by similar Au concentrations (10–11 g/t). This fact can probably be explained by the decrease in the content of disseminated As-pyrite in orebodies, which is accompanied by an elevated Au content in the acicular arsenopyrite.

Thus, the following zoning can be assumed for disseminated mineralization (Fig. 2). Jasperoid metasomatic ores with native mercury, arsenic, cinnabar, realgar, orpiment, and thallium minerals are developed at the near-surface level (up to 300 m). The interval of 300–1000 m is composed of ores of the so-called Carlin type represented by disseminated gold-bearing pyrite–marcasite mineralization. Disseminated pyrite–arsenopyrite ores occur at the hypabyssal level (1500–3000 m) and

arsenopyrite-rich ores occur at the lowest level. Consequently, the total mineralization interval can be as wide as 3000 m or more. Such a significant vertical interval of disseminated mineralization is probably explained by the specific ore formation conditions in zones of tectonomagmatic activation, which are unexplainable in terms of zoned hydrothermal ore formation. Therefore, we proposed the hypothesis of the initial hydrocarbon fluidization of host rocks [11]. The proposed model explains the absence of large Carlin-type deposits in other gold ore provinces of the world in terms of the substantially high degree of erosion in these regions.

Comparison of the above-mentioned ore-magmatic columns shows that the lower level is usually characterized by lodes associated with intrusions of stockwork ores and greisens. The initial composition of these disseminated ores governs the composition of veins and lodes at higher levels. The bulk mineralogical composition of orebodies from the upper level is close to that of ores from the lower level due to the differentiation of complex ores of the lower level. Thus, cognate ore associations are united in ore-magmatic columns, and deposits of the lower level govern the basic associations.

The defined regularities made it possible to specify substantially a complex of prognostic–prospecting criteria. Models of the multilevel structure can be used for regional and deep mineralization prognosis. The ore-magmatic columns can be considered as classification “blocks” whose type is determined by the basic formation.

## ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 03-05-64095, 03-05-64334, and 04-05-64359) and Program no. 2 of the Earth Sciences Division of the Russian Academy of Sciences.

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