

## Anomaly Geochemical Fields in Siberian Hydrothermal Gold Deposits

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**Abstract.** The composition and internal structure of geochemical fields associated to hydrothermal gold deposits within the Siberian territory were investigated. The concentric zonal structure of ore-forming geochemical fields embracing accumulations of Au, Ag, Bi, Pb, Zn, Cu, Te, As in ore bodies and their adjacent locations, and Ni, Co, V, Cr, Mn, Ba, Ti – within the external margin of gold ore formations were determined. The thermometric properties of gas-fluid inclusions in minerals of hydrothermal gold deposits were described. The results specified not only high-mineralized but also weakly-salted fluids are involved in the formation of the deposit. The latter is subjected to both retrogressive boiling and the mechanisms of direct and reverse osmosis. In this case, ascending and descending fluids produce eddy fluxes during Earth rotation, where minerals of different composition are formed in this flow path. Produced spiral mineral-geochemical fields can be observed on satellite images as hierarchy circular pattern system. Both the analysis of anomalous geochemical field structure and satellite images make it possible to predict the ore bodies of different grades in complicated landscape geological conditions.

### 1. Introduction

The target problem in modern applied geochemistry involves such a fact as the low efficiency of existing geochemical methods used in mineral exploration. The reason is the depletion of easy-to-discover deposits, outcropping as primary and secondary dispersion haloes of tracer-element mineralization. Today, the prospecting of new deposits is being conducted in complicated landscape geological conditions where ore bodies are detectable only at great depths, and associated anomaly geochemical fields outcrop only as fragments, which, in its turn, is difficult to structure without additional information. Personal understanding of a geologist plays the major role in this case. This, however, does not foster reliable results and forecast. Current research is governed by the new geochemical data interpretation methods for mineralization forecasting in complicated landscape geological conditions. Anomaly geochemical fields develop during the formation of thermal fluid ore-generating systems, that is why, additional information on the development of hierarchic geochemical field system is based on the result investigation of gas-fluid inclusions preserved in hydrothermal minerals [1-3]. Temperature, composition and fluid salinity varies consistently in time and space, due to such phenomena as retrogressive boiling, direct and reverse osmosis and the blending of juvenile and vadose waters. Fluid migration scale during ore emplacement causes not only significant chemical rock composition alterations, but also changes its physico-mechanical properties. These alterations can be observed in the geochemical field structure and are recorded as line and circular patterns on spectro-zonal satellite images. Circular pattern hierarchy is easily identified within any landscape



geological conditions, which, in its turn, makes it possible to use these patterns in ranking ore-forming geochemical fields and predicting future mineral deposits.

## 2. Methodology

The investigation of anomaly geochemical field structure accompanying gold - ore deposits was based on V. Voroshilov's method [4]. Geochemical field ranking was performed within the framework of the existing Russian gradation: ore body- deposit- ore field- ore cluster- ore district.

In microthermometrical investigation of gas-fluid inclusions in minerals, the following research tools were used: computer measurement package designed on the basis of microthermo-chamber MDSG600 ( produced by “Lincam, England), microscope “Axio Imager” (Germany), with a set of long-focus lens (maximum amplification 50x), video-camera and administrative computer ( all investigations were conducted in Laboratory of Natural Research Methods of Rocks and Ores at Department of Geology and Mineral exploration, Tomsk Polytechnic University). These facilities are used to measure the temperatures of the transition phases in real time within the interval of -180 - +500° C, to observe corresponding increases and to obtain digital micro photos. Measurement error is not more than 0.5° C.

Geological interpretation of spectrozonal satellite images was conducted by the geoinformation systems Erdas Imagine and ArcGIS. Interpreted data was retrieved from geological, depth-geophysical and geochemical information. Within the framework of the investigation, spectrozonal resolution images of high and low resolution Modis, Landsat ETM+ were used, as well as radar data- SRTM and Aster Global DEM. Processing, interpretation, analysis of satellite data and the modeling of geological and ore-geochemical systems have been conducted in accordance with the recommended and approved guidelines [5].

## 3. Results and discussion

Within the investigated deposit there are three basic developed gold-ore formations: (1) gold-polysulphide-quartz, (2) gold-skarn and (3) gold -(arsenic)- sulphide. The geochemical field of gold-bearing pyrite-polymetallic Rudni Altai deposits, traditionally associated with gold-sulphide formation, was investigated.

Quartz-veined gold-ore deposits are widely found in the Altai-Sajansk fold and for quite a perceptible time they have been the major geological-industrial type of lode mineralization. These deposits are spatially associated to magmatic massifs of diorite-granodiorite composition, accompanied by beresite-type wallrock alteration having similar mineralogical composition and close geochemical properties. Anomaly geochemical fields of gold-polysulphide-quartz formation have concentric zonal structure with Au, Ag, Bi, Pb, Zn, Cu, Te, As accumulations located within the interior zones. There are also three spatial isolated associations within this interior zone: (1) Au, Ag, Bi, Te; (2) Au, Pb, Zn, Cu; and (3) Au, As. These three industrial gold- bearing associations can be found in major field deposits. In small ore occurrences the high gold concentrations are associated with Ag, Bi, and Te in geochemical fields, due to poor polymetallic and arsenic mineralization.

Ore bodies' periphery is characterized by the formation of Cr, Ni, Co associations in beresite, which, in its turn, is conditioned by poor gold-bearing pyrite impregnations. In small occurrences with poorly-developed zoning this association combines with polymetallic and arsenic associations.

Anomaly geochemical fields of gold-skarn formation deposits of different mineral types, in general, are similar and can be characterized as concentric structures with centripetal zoning. Au and other trace elements accumulate in ore bodies of which associations slightly vary depending on the mineralization type. External ore body boundaries, involving slight pyrite and pyrite-magnetite mineralization, can be found in all deposit types of Co, Ni, Cr, V associations, whereas, Ba, Mn, and sometimes Ti accumulate longwise ore-controlling faults.

Gold sequentially accumulates in pyrite with arsenic pyrite, then with galena and chalcopyrite and finally with tellurides and sulphosalts in association with late copper sulfide. Every subsequent process involves the gold redistribution and relative gold accumulation in late associations.

A typical gold-(arsenic) sulphide ore formation is Olimpiad deposit in Yenesei ridge. The anomaly geochemical field has a pronounced concentric structure typical of hydrothermal deposits: ore-channel structure, where external ore bodies' periphery is distinguished by Ni, Cr, V associations, while gold and groups of associated trace elements concentrate within the internal zone. Arsenic and antimony are found in the Olimpiad deposit, whereas Ag, Cu, and W, to a far smaller degree. Wallrock micaceous-carbonate-quartz metasomatites involve Mn and Ba accumulations.

The more increasingly the hydrothermal process the more distinct the spatial isolation of geochemical associations. In areas of intensive mineralization reduction there are overburden associations.

Similar zoning is observed in other large-volume gold-vein deposits in black-shale formations. In particular, in the Bakirchiksk ore district deposit (Kazakhstan) an intimate gold to As, Sb, Ag and W correlation was established, which is governed by massive gold associations with early pyrite-arsenic-pyrite mineralization [6]. Polymetallic association is a less gold-bearing lode, while Co, Ni, V and Ba have a negative correlation to gold and is spatially confined to the ore body periphery.

Gold-sulphide deposits in Patom crater black-shale formation have a structurally similar anomaly geochemical field [7].

The gold-bearing deposit geochemical field of the sulphide-polymetallic formation has not only similar features of all hydrothermal deposits, but also its own specific characteristic features. In the Rudni Altai sublateral ore-controlling irregularities are detected by the anomaly concentrations of Ti, V and Mn. Areal volcanism which is observed in a geochemical field as associations of H Ni, Cr, Co (basaltoid volcanism) and Mo, Sn (acid volcanics) was formed in the intersection with tectonic structures of NW strike slip. According to the metallogenic behavior these structures could be classified as ore clusters. Anomaly Cu, Pb, Zn, Ag concentrations confined to these structures highlights the location of individual ore fields and deposits. In particular, gold-silver deposits are peripherally located in geochemical fields of ore clusters. In this case, rather intensive geochemical haloes are associated with basaltoid volcanism, while gold-silver mineralization is associated with acid volcanics, well-defined in volcanic depressions. Industrial gold and silver concentration deposits expose a rather high concentration of Ba, Ag, As, Au, Sb, and Te.

Thus, ore-genetic geochemical fields of hydrothermal gold-ore deposits have a concentric zoning structure with gold accumulations in the central section of this anomaly structure. The chalcophilic trace element groups of gold mineralization and their quantitative correlations significantly vary, however, for each individual deposit type, typical geochemical associations can be defined reflecting the gold-bearing mineral assemblage compositions. For example, Kuznetsk Altai gold-polysulphide-quartz formation, these are Au-Cu-Pb-Zn-Ag-As; Yenesei Ridge gold-(arsenic) sulphide formation – Au-As-Sb-W; and Gorny Altai gold-copper skarn deposits - Au-Cu-Ag-Bi.

The spectrum of siderophilic and lithophilic elements forming the anomaly concentrations in the geochemical fields of hydrothermal gold deposits are, generally, single-type and include Ni, Co, V, Cr, Mn, Ba, but rarely Ti. In most cases, these elements have a distinct spatial antipathy to gold and its associated chalcophilic elements.

On scale of ore clusters and districts those elements indicating ore-generating magmatism: Mo, Be, Y, Sn are of scientific importance. The anomalies of these elements often exhibit a spiral ring structure and are confined to magmagenic ring structures with a diameter of tens kilometers. Spiral structures of anomaly geochemical fields are often plotted on a deposit scale, as well as individual ore bodies [8]. Self-similar variable ranking geochemical fields indicate their versatile formation mechanism and the possibility of applying the structures of geochemical fields in predicting ore bodies.

There are two basic problems accompanying this prediction technique:

(1) geometrizing zonal plotted poly-elemental geochemical fields; and (2) ranking multi-phase ore-genetic geochemical fields in complicated landscape geological conditions.

Mathematical procedure in geometrizing anomaly geochemical fields has been developed for many years and at present there are 4 methods to implement different approaches in objectively solving this problem [4]:

1) defining quasi-homogeneous spatial regions (cluster analysis observation, artificial neural networks);

2) identifying stable element associations and analyzing their positional application (factorial, discriminate, regressive methods);

3) calculating indexes of total intensive re-distribution of chemical elements ( mineralization intensity, geochemical spectrum dispersion, ranking dispersion);

4) calculating zoning indexes based on the universal vertical geochemical zoning concept or centrifugal-centripetal differentiation of elements within the hydrothermal process.

Integrated application of all these methods minimizes the human factor in geometrizing the anomaly geochemical fields and advancing objective prediction of mineralization according to the geochemical data.

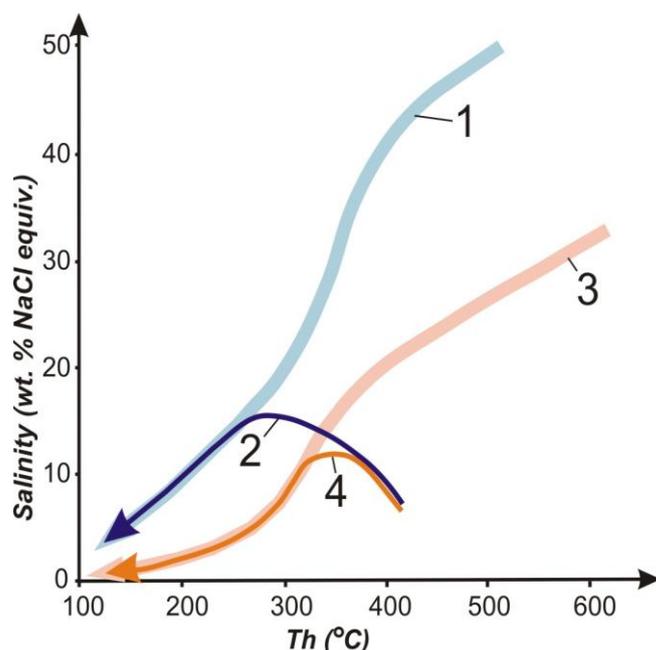
In complicated landscape geological conditions where the anomaly geochemical fields are only fragments, to structure them by using above-mentioned methods is sometimes unsuccessful. In this case, an independent ranking criterion for geochemical fields is necessary which could be a geological feature closely associated with the deposit formation itself and would be identified in any landscape geological environment.

Such features could be detected ring structures (those interpreted from spectral-zoning satellite images) with a natural hierarchy. To understand what the interrelation between anomaly geochemical fields and ring structures is, the temperature evolution pattern and fluid salinity during hydrothermal deposit formation was examined.

The examination of preserved gas-fluid inclusions in minerals show that after the separation of aqua-saline fluid from magma, its salinity increases from 45 to 60% (NaCl equivalent) due to periodic boiling, and then gradually decreases in proportion to solution temperature drop, correlating to NaCl saturation curve [2,3,9–11].

During boiling, the separated vapor-gas mixture condensates into a high-temperature (350–400 °C) low-mineralized solution. Its salinity initially increases, but at the temperature of 270–300 °C it decreases. This can be explained by the fact that at the initial mineralization stage the high fluid pressure promotes the so-called phenomenon- reverse osmosis, i.e. solution dewatering in low permeable country rocks. The retrogressive boiling processes also further the entrance of low-mineralized waters into the environment. During penetration these non-equilibrium hot waters ( in balance to rocks) being enriched by country rock components (Co, Ni, Cr, Fe –from mafic minerals; Mn – from carbonates) migrate further alongwise weakened zones, forming in the surrounding rocks upward flows. In time, these solutions, receding from the main channel, then cool, blend together in the downward flows and escaping from above-mentioned elements form their geochemical anomalies, being typical of the hydrothermal system frontal zones.

Ore formation during the initial mineralization stage could not be associated with solution dilution, but possibly be associated with the sharp pressure variations as a result of tectonic movements. In the process of fluid pressure drop as a result of solution intensity decrease, the reverse osmosis inevitably becomes a direct one. Critical osmosis pressure boundary depends on the concentration gradient and correlation between fluid pressure and lithostatic load. As seen in Figure 1 fluid pressure inversion occurrences begin at solution temperature decrease to 270-300° C and solution salinity of up to 13-18 mass% of NaCl equivalent. At this moment the water inflow from the environment and the salinity reduction (up to 2-5 mass% of NaCl equivalent) start against the mineral formation temperature drop. This process is embodied in the geochemical ore features. Particularly, pyrite and arsenic-pyrite accumulating during solution flow inversion and significantly enriched by Co and Ni imported from the host rocks.



**Figure 1.** Salinity and homogenization temperature evolution of gas-fluid inclusions in quartz hydrothermal deposits (in accordance to data from [1–3, 9–13]): (1) gold-copper-porphyry; (2) quartz-gold-sulphides and gold-sulphides; (3) in prograding skarns; and (4) in retrograding skarns.

Downward fluid flows affected by Corioli forces form cyclones controlling the hydrothermal product distribution, in which the structure of emerging anomaly geochemical fields is embodied in.

In spite of the deposit mechanism diversity of ore mineralization, the eddy fluid flow would lead to the concentric (ring) distribution pattern of trace element mineralization anomalies. These changes in rock composition affect their physico-mechanical properties and influence the spectral features and vegetation composition, which, in its turn, can be observed as new formations on satellite images. Based on experimental data, the regular spatial correlation between multi-phase anomaly geochemical fields and detected ring structures (observed on satellite images) have been pervasively revealed [8]. It can be highlighted that most detected ring structures, principally magmatogene, are the results of emerging eddy fluid flows.

#### 4. Conclusion

Investigation results of gas-fluid inclusions in hydrothermal minerals show the extensive process development of retrogressive boiling, direct and reverse osmosis, blending of juvenile and vadose waters during ore formation. As a result the system of upward and downward fluid flows, the interaction of which promotes the concentric zoning structure of emerging geochemical fields.

Geochemical fields of hydrothermal deposits have a concentric- zonal structure with Au, Ag, Bi, Pb, Zn, Cu, Te, As accumulations in the central anomaly structure zone, while Ni, Co, V, Cr, Mn, Ba, Ti – in the external margin of gold-ore bodies.

Under conditions of Earth rotation the upward and downward fluid flows form rotating-cyclones and anti-cyclones. In this case, ore-genetic geochemical fields have a spiral structure. These changes in rock composition affect their physico-mechanical properties and influence the spectral features and vegetation composition, which, in its turn, can be observed as new formations on satellite images. Thus, hydrothermal systems and associated geochemical fields include cause-effect and positional correlation with detected ring structures.

Therefore, the natural hierarchy of ring structures, interpreted from space data, could be used as an independent tool in ranking ore-genetic geochemical fields.

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