The physical-geological model of the epithermal Au-Ag deposit (Chukotka) on the basis of the integration of geophysical and geochemical investigations

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Introduction
There are a lot of medium and large gold-silver epithermal deposits concentrated in the Far East of Russia. As a rule, the richest ores belong to LS-type, with dominance of quartz-vein ore [Hedenquist, J.W. Arribas, A.R. and Gonzalez-Urrien E., 2000]. Separate ore veins with the thickness of several meters can have up to 1 km in length and consist of 10-15 tons of gold. If these veins are satellites of the large already workable deposits, their exploration can be economically justified even in case of their being covered by more than 100 meters of volcanic rocks. The prospecting of such objects (3 meters thickness vein on the 100 meters of depth) is a complicated geological-prospecting task and, at the first sight, none of separate geophysical method can cope with it.

In 2013 the authors were given a target to determine the northern extension of the known vein zone on the large ore cluster within the Okhotsk-Chukotka volcanic belt (Figure 1a). This low-sulfidation epithermal quartz vein with the thickness of 3 meters has a high concentration of gold (15-20 ppm). The vein locates inside the intermediate-mafic Late Cretaceous lavas and covered by 100-130 meters of mafic volcanic rocks with layers of ash tuffs.

To determine the position of the displaced northern part of the vein, the 5-component measurement of the natural variable electromagnetic field was applied by the authors. It allowed implementing two independent methods simultaneously: audiomagnetotellurics sounding (AMT) [Berdichevsky and Dmitriev, 2008] and magnetovariational profiling (MVP) [Rokityansky I.I., 1982]. In addition, the induced polarization (IP) and resistivity methods were applied, which could

**Figure 1a.** The position of the investigation region on the tectonic scheme of Russia (by Tceysler V. M.). **Figure 1b.** The geological scheme of the investigated area with the position of AMT, MVP and IP stations.
not find the vein zone covered by conductive tuff layers. According to the results of 2D inversion of AMT-MVP data, the geoelectrical cross-sections were constructed and the position of the northern extension of the vein was forecasted which was confirmed by drilling in 2014. The methods of AMT-MVP field work and data analysis were more thoroughly described in the early authors’ work [Ermolin E., Ingerov O., Savichev A., 2014].

The target of the current work is a demonstration of the geophysical method features (AMT-MVP, ground gravity and magnetic survey) by means of which the covered thin vein zone can be determined. The authors suggest calling these features ‘geophysical-structural criteria’ of the epithermal ore. The physical-geological model of epithermal gold-bearing quartz vein is positioned by the authors as the main result.

The geological model and supposed physical properties
At present the geological model of epithermal LS-deposit assumed by the authors is the following:
- the source of the fluids as a magmatic rock body felsic-intermediate composition is necessary (it usually locates on the deposit periphery);
- the presence of the channel for fluids migration is required (the zone of the deep fault);
- the availability of hard rock block is needed to ore fluid crystallization within a thin zone, rather than dissipate in reservoir rocks;
- epithermal veins are accompanied by zone hydrothermal-metasomatic alterations (quartz-adulatory alteration and propylitic lateral zones).

The large fault zones usually correspond to geological block contacts and might be clearly reflect in gravity and magnetic anomaly fields. The zones of the propylitic and quartz-adularia alteration are poor in magnetite relatively to host medium [Sillitoe R., 2010]. Correspondingly, alteration zones are described as the zones of decreasing magnetic susceptibility. It is very likely that the vein and the area of quartz-adularia alterations around it will be both characterized by high resistivity. Therefore, the data analysis of the AMT-MVP, ground gravity and magnetic surveys will allow to detect some geophysical field features above the known vein.

Geophysical data analysis
The features of the geophysical response of the vein zone shown in figure 1b divided into two groups: I. - instance of ore controlling fault; II. – instance of the ore bodies and the alteration zone around them.

I. Instance of ore controlling fault
The magnetotelluric impedance phase is the most stable parameter in AMT method. The map of this parameter at the 300 Hz frequency has been shown in the figure 2a. The area is divided into two approximately equal parts (East and West) by sub-meridional strike gradient zone. The mentioned gradient zone marks the position of the boundary of two blocks and corresponds to the fault. This fault instance is obvious on the total horizontal gradient of the Bouguer map (gravity data transformation) as the contrast positive anomaly (Figure 2d). 350-400 m to the west to it another zone of high gradient zone of Bouguer anomaly appears. According to figure 2d, the known veins are located within the gradient zone with the width of 350-450 m. The general zone strike is near 20 degrees, whereas separate local anomalies on figure 2d have from -10 to 30 degrees strike.

II. Instance of the ore bodies and the alteration zone around them
On figure 2a the central elongated sub-meridional zone of impedance phase of low values attracts special attention. It is located to the east of the fault. The zone consists of three segments which displace to 120-300 m to the east relative to each other from the south to the north. The central segment is connected with the quartz gold-bearing vein. Its position had been known before AMT field works (summer 2013). The position of the northern and the south-western phase anomaly segments corresponds to the position of the determined after drilling (after AMT work) veins. The local anomalies of horizontal telluric tensor (Fig. 2b) also reflect the veins and quartz-adularia alteration position.
Figure 2. AMT-MVP parameters map (a-c): magnetotelluric effective impedance phase at 300 Hz (a); Altitude of horizontal telluric tensor at 300 Hz (b); Tipper phase at 9000 Hz and 800 Hz (c). Total gradient of Bouguer anomaly (d). The results of lithogeochemistry data analysis (e,f).

The ore zone appearance in geophysical fields allows to optimize drilling. The width of the anomalies on the impedance phase map (Fig. 2a) and on the horizontal telluric tensor map (Fig 2b) are from 200 to 300 m. For prospecting boreholes projection the using of the map of the tipper phase (MVP parameters) has been suggested by the authors. The anomalies on this map are more local and contrast. Crossing over the center of the anomaly body the tipper phase change the sign [Ermolin, E. Ingerov O., Ingerov I. 2011]. The zones of high gradient corresponding to the geometric center of the body on the plan are observed on the phase map. The position of the central part of the ore vein appears at 9000 Hz (Fig. 2c) as the area of the sharp alteration of the sign. The northern (dropped) part of vein zone better appears at the 800 Hz frequency.

The analysis of the parameters graphs and geoelectrical cross-section along line#2 have been shown in figure 3. The position of the quartz-adularia mineralization appears on the geoelectrical cross-section as the high resistivity area (Figure 3-III, blue-purple area within 0760-1000 stations on the altitude from 450 to 200 m). Gold-bearing veins are concentrated inside the area of the peak resistivity values (the purple area). The zone has a deep channel which also appears as the isolator for the depth of at least 1 km. The suits of ash tuffs, which cover the ore zone appear as low resistivity layers at the altitudes from 600 to 400 m.
Figure 3. Geophysical data comparison.


Ground magnetic survey was done by using GSM-19t proton magnetometers (“GEM Systems” Toronto, Canada). The station separation was 50 m. The circum-ore zone of alteration clearly reflects in the anomaly magnetic field (Figure 3-I, red-blue line). On the ore zone the overt bi-polar anomaly is observed.

The isolines of effective magnetization (result of the ground magnetic survey inversion) have been drown on the geoelectrical cross-section. The negative values have been shown with red lines.
while the positive values have been shown with blue. The zone of quartz-adularia mineralization appears as the contrast area of negative values of effective magnetization. By analogy with resistivity values, the zone of low values has a deep channel and an eastern dip.

Besides the geophysical data analysis, the geochemical data analysis has been done by the authors.

**Lithogeochemical survey** by secondary dispersion halo had been done on the investigated area before 2013 in 1:10000 scale. The re-interpretation of its results has been carried out by the main component of the factor analysis which showed the most important geochemical assemblages. The distribution of the main ore assemblage Au-Ag-As-Mo has been showed on the figure 2e (the factor weights of chemical elements showed by superfix). The poly-element anomaly consisting of three segments detects the position of the known veins. The described anomalies are similar to anomalies of the impedance phase (Fig. 2a) and horizontal telluric tensor (Fig. 2b). The upper ore Hg-Sb-As assemblage parameter has been shown in figure 2f. The intensive anomaly is observed on the map (Fig. 2f) to the north-east of the vein known before 2013. This indicates that the ore zone in the North is located structurally in a lower position than in the South. As result, the ore Sb-Hg-As aureola in the North has saved from erosion.

Following the results of geochemistry survey, the classical for epithermal deposits geochemical zoning has been determined [Sillitoe R., 2010]: the regular alteration of the chemical element associations are observed from the South to the North: bottom-ore (Mo±Cu) → ore (Au-Ag-As) → upper-ore (Sb-Hg).

**Physic-geology model**

The integrated analysis of discussed above data has shown that the ore controlling fault and the know veins zone with the thickness of 3 m covered by 100-meters shield are clearly visible in geophysical fields.

The ore control faults (blocks boundaries) appears as the zones of:
- increased gradient of the gravity anomaly in Bouguer reduction;
- increased gradient of the magnetotelluric impedance phase.

Quartz-adularia mineralization around vein appears as the zones of:
- increased values of resistivity. The zone has a deep channel;
- decreased values of the effective magnetization;
- decreased values of the effective phase of magnetotelluric impedance;
- increased values of horizontal telluric tensor.

Thin vein bodies appear as the zones of:
- high gradient on the tipper phase map.

The above features can be called “geophysical structural-prospecting criteria”. The classical zoning was determined (confirmed) on the basis of geochemistry survey: bottom-ore (Mo±Cu) → ore (Au-Ag-As) → upper-ore (Sb-Hg). The described geophysical and geochemical features reflect the physical-geological model of epithermal quartz-vein LS-deposit.

**Conclusion**

As results of integrated analysis of geophysical and lithogeochemical survey data the North extension of know ore vein was predicted. The prognosis was confirmed by drilling in 2014.

The physic-geology model of epithermal quartz-vein gold deposit has been described by authors. This model can be used by geologists and geophysicists in future prospecting surveys. For searching of gold-bearing quartz veins in Chukotka the following suit of geophysical methods has been suggested by authors: audiomagnetotelluric sounding (AMT), magnetovariational profiling (MVP), ground gravity and magnetic surveys. The selected suit of methods studies natural fields and very productive in the Extreme North. It doesn’t require attraction a lot of workers and doesn’t create any environmental impact. The using of the high productive ground gravimetric survey with 125x250 m grid allows to cover large areas. It allows determining the general structural features of the area. Ground detailed magnetic survey in 10x40 grid and AMT-MVP with 40 meters step and

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250-400 meters lines separation should project on the promised by geochemistry data and structural criteria areas.

**Acknowledges**

We acknowledge the support of the Mining Community in Chukotka for access and the opportunity to publish.

**References**


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