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Correlation of Epithermal and Geothermal Deposits (an Example of Mutnovsky Geothermal Area, Southern Kamchatka)

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ABSTRACT

Mutnovsky geothermal area is located within the Mutnovsko-Asachinsky volcanic center in South Kamchatka, which is a part of the presently active Eastern Kamchatka volcanic belt. During the last five millions years three large epithermal gold-silver deposits (Rodnikovy, Mutnovsky, and Asachinsky), hydrothermal springs, geothermal deposits, and more than 25 ore manifestations with gold reserves of up to 100 tonnes, and silver reserves of up to 1,000 tonnes were formed here. Magmatic, volcanic, and hydrothermal activities accompanying the ore forming process are still continuing in this area. The largest high-temperature hydrothermal systems of South Kamchatka (Koshelevsky, Pauzhetsky, and North-Mutnovsky) make a reliable basis of the geothermal energy of the Southern Kamchatka and Petropavlovsk-Elizovo cities. Mutnovsky Au-Ag-polymetallic deposit is a typical near-surface hydrothermal volcanic vein system with reserves of 14 tonnes of gold, about 455 tonnes of silver, and about 150,000 tonnes of zinc, lead, and copper. However, the silver resources may potentially reach up to 6,000–9,000 tonnes. The Mutnovskoe Au-Ag-polymetallic deposit and the Mutnovsky geothermal deposit are located alongside each other.

1. INTRODUCTION

Kamchatka Peninsula is one of the largest structural elements of the Kurile-Kamchatka island arc. It is located in the northeast of the Pacific Ring of Fire. Thus, only during Quaternary time about 300 volcanoes were formed in Kamchatka segment of the Kuril Kamchatka island arc. Among which 31 active volcanoes of Russia and more than 150 groups of recent hydrothermal springs of different sizes are located in Kamchatka (Liessman et al., 1994).

Mutnovsky geothermal area occupies the northern part of Southern Kamchatka. This area is known for its active magmatic, volcanic, geothermal, hydrothermal, and ore-forming processes. It started to develop in the Miocene and is still active in the present day.

During the last five millions years three epithermal gold-silver deposits (Rodnikovy, Mutnovsky, and Asachinsky) and more than 25 of ore manifestations with reserves of up to 100 tonnes of gold and 1,000 tonnes of silver were formed here. The estimated reserves of South Kamchatka territory are about 250 tonnes of gold and 10,000 tonnes of silver. Concentration of such quantities of gold and silver is the direct result of activity of the paleohydrothermal ore-forming systems (Lattanzi et al., 1995).

The active giant volcanoes such as Gorely, Mutnovsky, Zheltovsky, Ilinsky, Koshelevsky, and Kambalny are also located in South Kamchatka. A number of hydrothermal springs are located in the vicinity of these volcanoes. These are the largest high-temperature hydrothermal systems of Kamchatka (Koshelevsky, Pauzhetsky, and North-Mutnovsky), which make a reliable basis for the geothermal energy potential of the Southern Kamchatka and Petropavlovsk-Elizovo cities.

Geothermal energy is the most prospective line of economic development in Kamchatka. Pauzhetka is the first geothermal power station in Russia with an initial power of 5 MWt. It started operation in 1966 and its power increased to 11 MWt in 1979. Three geothermal power stations successfully operate in Kamchatka at the present time. In addition to the Pauzhetka station, the Verkhne-Mutnovsky pilot station (12 MWt) started operation in December 2000, and the Mutnovsky 1 station (50 MWt) in September 2002. New stations are being built at the Mutnovsky geothermal deposit of the North Mutnovsky high-temperature geothermal system, which is the largest geothermal system of Kamchatka. The energy resources are estimated as $71.28*10^{18}$ J.

This study is focused on the correlation between the geothermal deposit and the now-extinct epithermal gold-polymetallic system. Mutnovskoe geothermal deposit provides information on how metals are transformed, as well as on the main mechanism causing metal deposition.

2. CORRELATION OF EPITHERMAL MINERALIZATION AND GEOTHERMAL DEPOSIT

The ore-forming processes in some epithermal gold-silver (e.g., Rodnikovoe) and gold-silver-polymetallic deposits (e.g., Mutnovskoe) continue on the present day.

The Mutnovsky geothermal field is situated 70–75 km southeast of Petropavlovsk-Kamchatsky, on the volcanic plateau at elevations of 700–900 m a.s.l. and is localized in the central part of this system **(Fig. 1)**. The Mutnovsky geothermal system (Mutnovsky geothermal district; after Okrugin, 1995) is extremely diverse as it concerns the present-day volcanic and post-volcanic activity. Three field groups are recognized: (1) fumarolic fields of the active Mutnovsky and Gorely volcanoes, (2) thermal fields and water-vapor springs of the North Mutnovsky volcanic tectonic zone, and (3) thermal fields and ascending hot springs in river valleys (Okrugin, 1995; Kiryukhin, 1998). The largest heat occurrences in Dachny, North Mutnovsky, and Perevalny contain the main heat carrier resources and are localized within the North Mutnovsky volcanic tectonic zone. This zone is a graben-like basin controlled by a large meridional fault (Lonshakov, 1979; Kiryukhin, 2002). A combination of meridional zone of tectonic dislocations with diagonal NW and NE faults and latitudinal faults together with lithological screens provide favorable conditions for hot water and vapor accumulation.

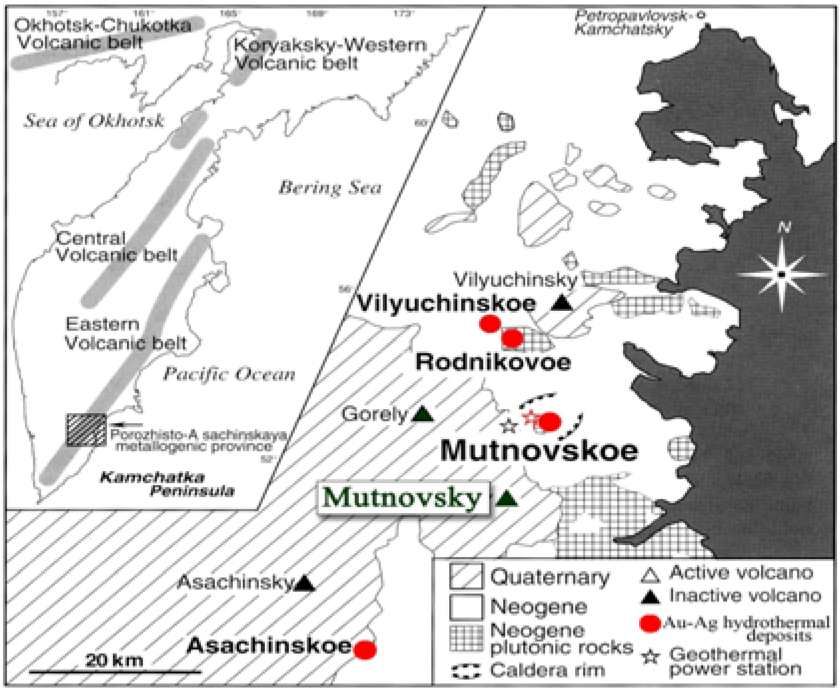

Figure 1: Geological map of South Kamchatka showing the location of the Mutnovskoe precious metal and geothermal deposit (Takahashi et al., 2006).

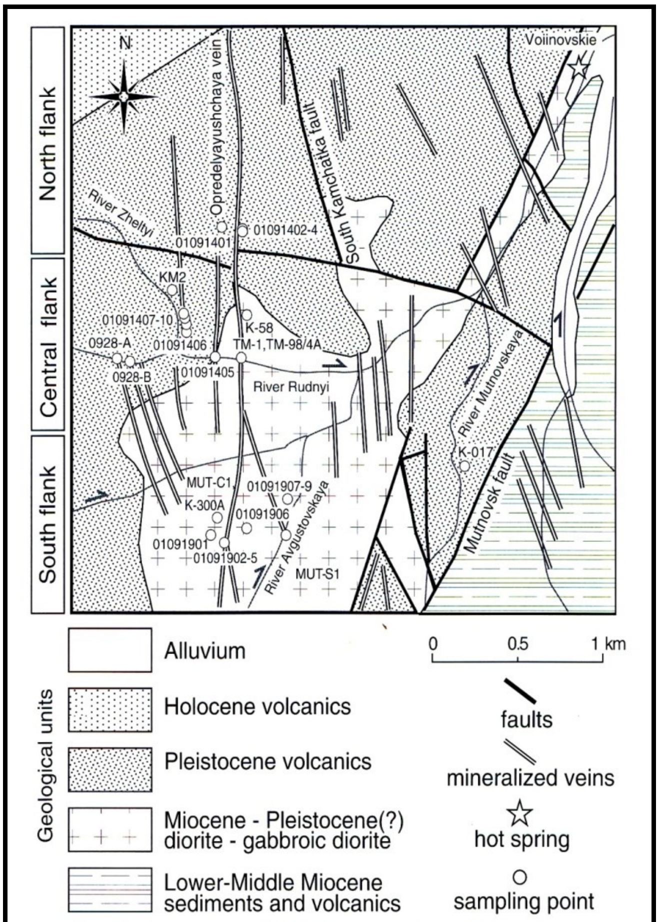

Fig. 2 Geologic map of the Mutnovskoe deposit (after Lattanzi et al., 1995).

Figure 2: Geological map of the Mutnovskoe deposit (Takahashi et al., 2006).

2.1 Au-Ag-Polymetallic Mutnovsky deposit

The Mutnovsky complex gold-polymetallic deposit is a typical near-surface hydrothermal volcanic vein system with reserves of about 14 tonnes of gold, about 455 tonnes of silver, and combined zinc-lead-copper reserves of up to 150,000 tonnes. However, the total silver resource in Mutnovsky is estimated to be around 6000–9000 tonnes. The deposit is located 10 km south of the active Mutnovsky volcano.

Mutnovskoe deposit and other ore deposits discovered in South Kamchatka have not been studied along either along their strike or dip orientations. It is not inconceivable that some of the veins are located close to the feeding system of the volcano. The distance from the main ore body of the Mutnovskoe ore deposit to a productive well of the Mutnovskoe geothermal deposit (vapor temperature of up to 230°C) is about 1.5 km.

The structure of ore zones and ore bodies of the deposit is a combination of the main on setter vein (massive vein) and series of fledged veins (vein swarms). They are focused in sub-meridional direction and have steep hades close to vertical. They spread over an extent of more than 2650 m, vertically falling up to 500 m **(Fig. 2)**. The veins were formed mainly by compounds of silica (quartz, chalcedony, opal) with sulfides of zinc, lead, and copper. The veins were formed from hydrothermal solutions with temperatures between 198°–282°C **(Fig. 3)**. The ages of the ore veins vary from 1,100,000 to 30,000 years (Takahashi et al., 2002; Takahashi et al., 2007).

The deposit is situated in the middle reaches of the Mutnovsky and Gorelovsky rivers, originating on the northern slope of the Mutnovsky volcano. The deposit is localized between the Rodnikovy Au-Ag deposit and the North Mutnovsky geothermal deposit **(Fig. 2)**. Geological exploration studies were carried out during 1975–1981. About 20 boreholes were drilled and many workings at the surface were driven and sunk.

The Mutnovsky deposit differs from typical epithermal deposits and cannot be assigned either to the low- or high-sulfidation vein types (White and Hedenquist, 1995; Hedenquist et al., 1996). Here, the orebodies are composed of mineral assemblages of both low-sulfide (gold-quartz with carbonates) and base-metal sulfide (Cu, Pb, Zn sulfides and Sb, As, Ag, Te sulfides together with silver and gold tellurides) types. In terms of geology, mineralogy, and geochemistry this deposit is very similar to the Toyoha Ag- and In-bearing Pb–Zn vein deposit, the largest deposit of this type in Japan (Hamada and Imai, 2000).

The most studied part of the deposit is its central part. The ore bodies make up a stockwork vein zone of 3 x 4 km in size, which comprises a nearly vertical thick stem vein (Determining Vein), a few smaller auxiliary veins, and numerous variably-oriented veinlets. About 80% of the reserves is confined to the Determining Vein, which reveals a complex internal structure with an en echelon arrangement, virgations, up to 20–30 m-thick bulges, and pinches. The vein is traced for 2,650 m along the strike and the vertical range of ore mineralization reaches to 400 m. The 1,1100 m-long northern segment of the vein zone is composed of low-sulfide ore and contains the main Au reserves. The southern segment (1,600 m-long) consists of a base-metal sulfide ore and is distinguished by a deeper erosion level. The host rocks exposed in river canyons are represented by intrusions varying in size and morphology, with compositions of gabbro, gabbro-diorite, and dolerite. Most of these intrusions may be regarded as the feeding systems and the shallow-seated magma chamber of the Zhirovsky ancient volcano. It should be noted that these rocks were not drilled by a large number of wells at the northern flank, as well as by Borehole 13c along the southern flank. Basic and intermediate tuffs, silicic lithic and crystal tuffs, and subordinate thin lava flows of basalt to rhyolite composition serve as host rocks. The ore is characterized by a combination of banded, colloform-banded, crustiform-banded, cockade, massive, and stringer-disseminated structures, and brecciated ore is typical. The mineral composition of ore is diverse. Ore minerals are commonly zoned and reveal a non-uniform distribution. Two sphalerite varieties, one containing up to 10–12 wt.% Fe and another with up to 10.5 wt.% Mn, may be seen in the same specimen (in the central part of the deposit). Sphalerite with zonal Fe and Mn distribution occurs together with this mineral revealing zoned patterns of Cd (up to 6.5 wt.%) and In (up to 9.7 wt.%) contents. The zoned fahlore, with variable As, Sb, and Ag contents, is associated with freibergite (as small inclusions in galena) and goldfieldite (as inclusions in sphalerite), which contains as much as 26.5 wt.% Ag and up to 2.3 wt.% Se. Zoned As-bearing pyrite is also typical. The As content in some zones of this mineral may be as high as 10.0–10.5 wt.%. Native gold with complex dendritic morphology is very fine-grained (10–150 µm). The largest grain (1.2 mm in size) was found in the base-metal sulfide ore. The Ag content in this grain varies from 29.5 to 41.5 wt.%. Local domains are practically devoid of Ag, but contain up to 2.5–3.0 wt.% Hg.

The inhomogeneous structure of ore is likely caused by its formation under hypabyssal conditions, and a wide variation of *PTX* parameters serves as additional evidence for its young age. The ore retained its pristine appearance without undergoing subsequent modification and alteration.

The specific features of the Mutnovsky deposit are as follows: (1) diverse composition and facies appearance of Quaternary volcanic rocks related to the East Kamchatka volcanic belt, (2) relatively good preservation of the Pliocene–Pleistocene volcanic edifice due to shallower erosion levels, (3) wide variation of mineralogical and structural features of ore and wide range of trace element contents in pyrite, sphalerite, fahlore, alabandine, and carbonates, (4) enrichment of ore in Mn and various modes of manganese occurrences from its own mineral phases as incorporated into sulfides and even sulfosalts, (5) elevated contents of As, Sb, Hg, and especially Cd (as much as 125 ppm in the bulk vein and 6–7 wt.% in sphalerite), In (90–130 ppm in the bulk orebodies and up to 9–11 wt.% in sphalerite), and Ag (freibergite-type fahlore, hessite, and Au and Ag tellurides), (6) abundant argillic and sericitic alteration along with a deficiency in adularia; sericite is the main potassium concentrator (as much as 6–8 wt.%), whereas adularia is distributed unevenly varying from single grains to fine aggregative disseminations, (7) enrichment of ore and altered wall-rock in Hg (up to 50–2000 ppb), (8) long-term and large-scale ore formation with appreciable contribution of the recently formed hydrothermal minerals.

Table 1. Mineralogical composition of primary ores and precipitation from the hydrothermal brine at the depth of 1,000–1,200 m (opaque minerals which were found in ore and brine).

Silicates	Sulfates	Sulfides, sulfosalts
adularia $K[AlSi_3O_8]$	anglesite $PbSO_4$	pyrite FeS_2 with As
albite $Na[AlSi_3O_8]$	anhydrite $CaSO_4$	marcasite FeS_2
epidote $Ca_2FeAl_2[Si_2O_7]O(OH)$	alunite $KAl_{13}[SO_4]_2(OH)_6$	sphalerite ZnS with Fe
prehnite $Ca_2Al[AlSi_3O_{10}](OH)_2$		chalcopyrite $CuFeS_2$
kaolinite $Al[Si_2O_5](OH)_4$	Exotic phase	galena PbS
muscovite $KAl[AlSi_3O_{10}](OH,F)_2$	calomel HgCl	alabandine MnS
jllite $(Al(OH)_2((Si,Al)_2O_5))*K(H_2O)$	bromargyrite AgBr	argentite Ag_2S
pyrophyllite $Al_2[Si_4O_{10}](OH)_2$		cinnabar HgS
chlorite $(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$	Oxides	arsenopyrite FeAsS
mordenite $(Ca,Na_2K_2)[AlSi_5O_{12}]_2*7H_2O$	quartz SiO_2	pyrrhotite FeS
	rutile TiO_2	proustite Ag_3AsS_3
Carbonates	magnetite $FeFe_2O_4$	pyrargyrite Ag_3SbS_3
calcite $CaCO_3$	titanomagnetite $FeTiO_3$	stephanite Ag_5SbS_4
manganocalcite	hematite Fe_2O3	stibiopearceite-arsenopolybasite $(Ag,Cu)_{16}$ $(As,Sb)_2S_{11}$
rhodochrosite $MnCO_3$	pyrolusite MnO_2	bornite Cu_5FeS_4
	hausmannite Mn_3O_4	luzonite $Cu_3(As,Sb)S_4$
Rare falhore	jacobsite $MnFe_2O_4$	famatinite SbS_4Cu
tetrahedrite $Cu_{10}Fe_2Sb_4S_{13}$	manganite MnOOH	enargite Cu_3AsS_4
tennantite $Cu_{10}Fe_2As_4S_{13}$		bournonite $CuPbSbS_3$
freibergite$Ag_{10}Zn_2Sb_4S_{13}$	Native	colusite $Cu_{13}As_4S_{16}$
goldfieldite $Cu_{12}SbTe_3S_{13}$	native gold Au:	mawsonite $Cu_6Fe_2SnS_8$
zandbergite (9 % Zn)	high karat gold (Au >75 %)	stannoidite
	electrum (25<Au <75 %)	$Cu_8(Fe, -Zn)_3Sn_2S_{12}$
Tellurides	native arsenic As	stannite Cu_2FeSnS_4
hessiteAg_2Te	native sulfur S	diaphorite $Ag_3Pb_2Sb_3S_8$
coloradoite HgTe		owyheite $Ag_2Pb_5Sb_6S_{15}$
altaite PbTe		

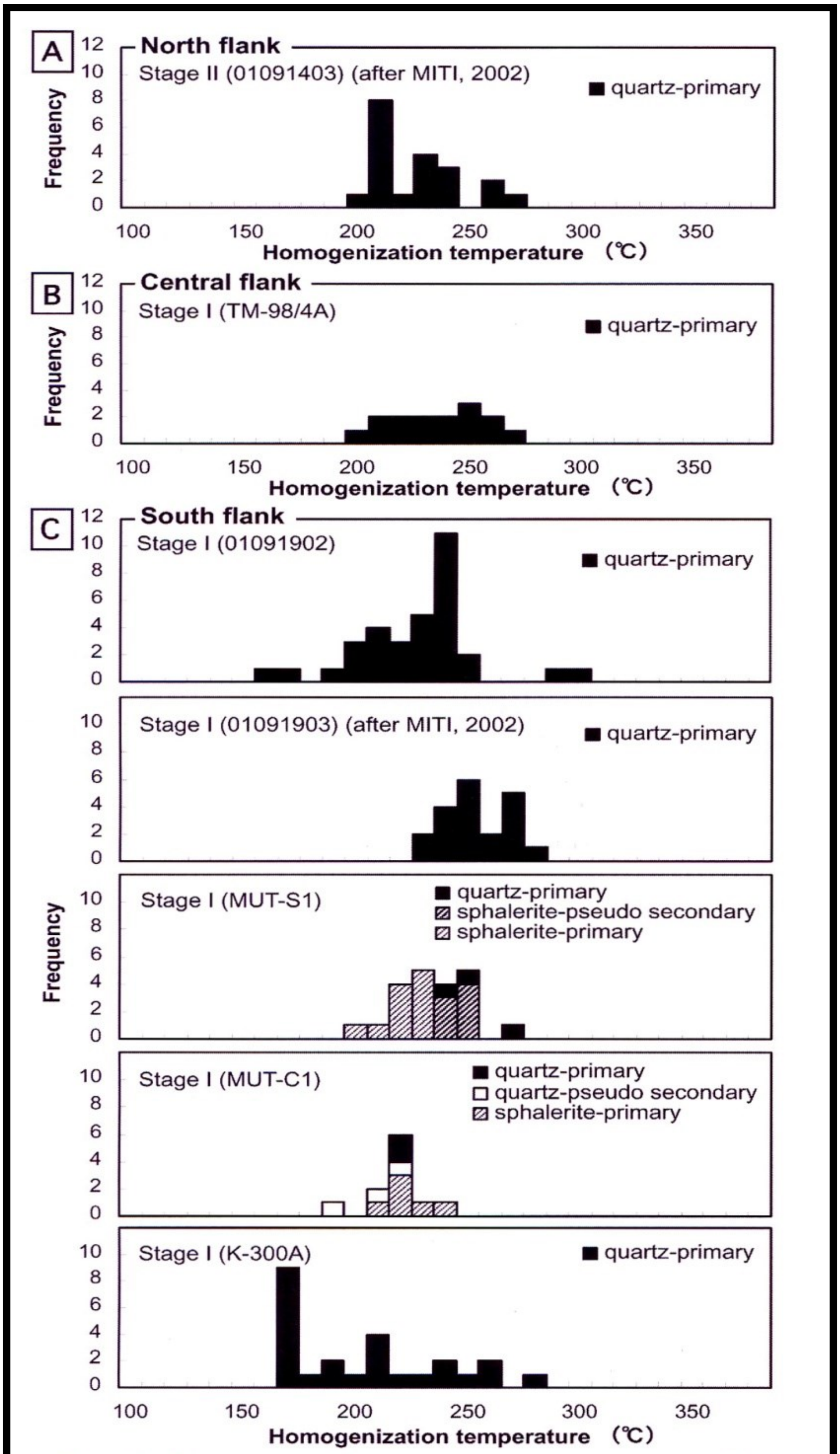

Fig. 12 Histograms of homogenization temperature of fluid inclusions at the Mutnovskoe deposit.

Figure 3: Homogenization temperatures of fluid inclusions.

Epithermal veins and ore bodies of Mutnovskoe epithermal Au-Ag-polymetallic deposit were formed from a hydrothermal solution (overheated fluid) that was at the same temperatures as indicated by fluid inclusions data. These were low-concentrated solutions. Main metals such as gold, silver, zinc, and lead were precipitated from a boiling fluid.

In the area of the Mutnovsky deposit there are some groups of hot springs (Voinovsky, Ore, Perevalnye), which contain sediments of sulfides with native metals.

2.2 Mutnovsky geothermal deposit

During exploration of the Mutnovskoe ore deposit several drilling wells as deep as 230–250 m intersected zones of hot dry rocks (with temperatures of up to 200°–270°C). The distance from the main ore body of the Mutnovsky deposit - vein zone "Defining" to the productive wells of the Pilot GeoPS (North-Mutnovsky geothermal deposit) is about 1,200-1,500 m. Geological and economic limits of the ore deposit are unknown.

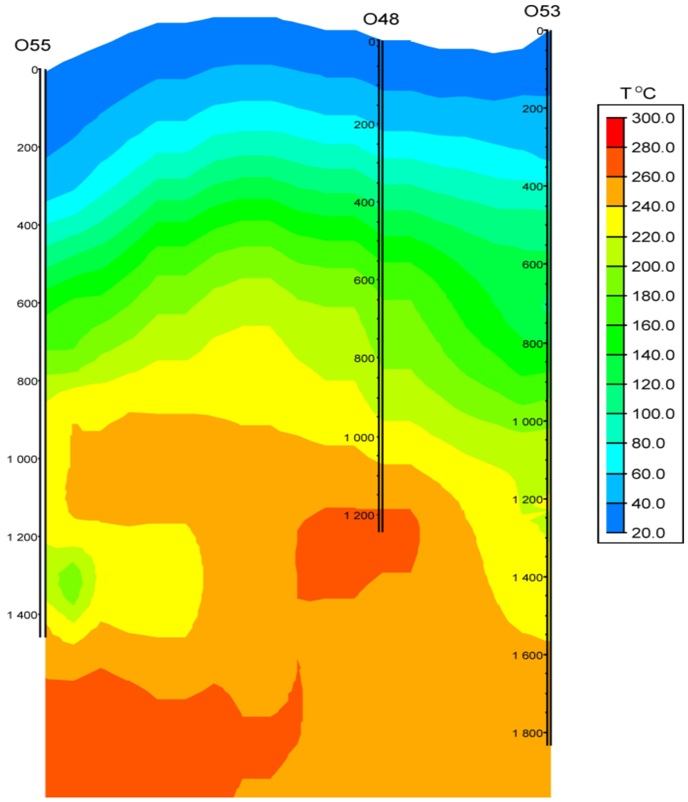

Figure 4: Temperature field along the drill well 55 at the Mutnovskoe geothermal deposit.

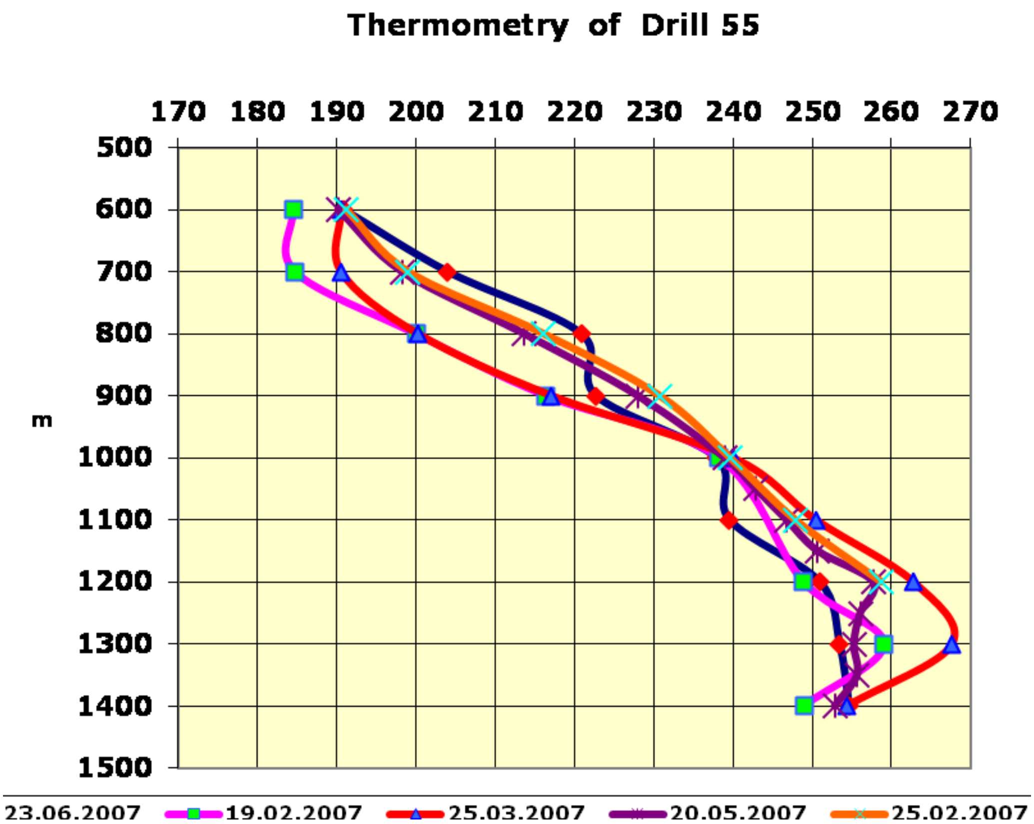

Figure 5: Temperature versus depth plot of drill well 55.

The temperature of a steam-water mixture (a heat-carrier) of the productive wells of the Mutnovsky geothermal deposit is comparable with the temperatures of ore-forming solutions of the Mutnovsky gold-polymetallic deposit. In the zones of hydrothermal alteration, areas of sulfidation (pyrite, chalcopyrite, and sphalerite) and silicification with veins of ore minerals are found in the immediate vicinity of the geothermal reservoirs. The steam-water mixture is supersatured with silica, which during degassing is precipitated in the form of white amorphous compounds around the wells, forming the fields of 100–500$м^2$.

In the hot springs of North-Mutnovsky hydrothermal system (Active group, Dachny, Medvezhji, and Utiniy) sulfides of iron, copper, lead, zinc, and mercury were precipitated. Sulfide layers with thicknesses of about 20 to 30 cm were formed in the North-Mutnovsky hot springs. Mineral precipitation in the drill wells of Mutnovskoe wells are similar to that are found in the Mutnovskoe epithermal veins (Table 1).

3. CONCLUSIONS

A comparison of these two geothermal and epithermal precious metal deposits has raised the following questions: Where to draw a geological line for the distinction between ore and geothermal deposits? And does this geological line exist today?

Probably a steam-water mixture of a geothermal deposit is one of the components of the hydrothermal ore-forming system. The process of epithermal gold-silver ore formation continues, and in 50,000 years the geothermal reservoirs of the Mutnovsky geothermal deposit will freeze and grow by silica. Silica will begin to devitrify, forming quartz, opal, chalcedony, and geothermal reservoirs will be indistinguishable from gold-silver quartz veins.

Ore zones and ore bodies of epithermal Au-Ag deposits are lithified (died or got cold and filled with crystallized SiO_2 to quartz) geothermal reservoirs. Let us imagine that we had the chance to re-drill wells in the same places 200 or 500 years later. What will these boreholes intersect? Will they be the same geothermal fluid-filled reservoirs with temperatures of about 180°–260°C, or will they be adularia-chlorite-sulfides-gold enriched quartz veins? These questions are still open.

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