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Thermal Waters Circulation During the Formation of Ore Deposits

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Abstract: The paper analyzes processes leading to the formation of gold-bearing sulphide deposits. The study was based on the data available for the territory of Ukraine and other regions. The deposits in question are shown to be associated with post-geosynclinal activation as postulated by concepts of the advection-polymorphism hypothesis. The nature of ore-bearing fluids is analyzed. Even on the ocean bottom helium isotopy points to the presence of mantle components in the fluid. Metamorphogenic and magmatic fluids are obviously involved in the process. An abnormally fast growth of permeability in fault zones during the activation period is shown to have contributed to the formation of deposits. The existence of metalliferous and barren phases of hydrothermal activity is explained. Thermal models of deposits are constructed and diagnostic criteria for their identification determined. The main features of the deposits are associated with faults through which mineralized deep waters circulate. In young deposits, these are: 1. Increased content of metals in soil and plants. 2. Intense heat flow anomalies. 3. High helium isotope ratios, indicating an active process in the Earth's mantle. 4. Zones of high electrical conductivity in the crust and upper mantle. 5. Near the faults, positive anomalies of the gravity field are formed, associated with the transformation of rocks under the influence of heating. The search for gold-bearing sulphide deposits should be continued, considering that the reserves already explored in Ukraine guarantee commercially viable production of over 10 tons of gold per year.

Keywords: Thermal Waters, Hydrothermal Deposits, Heat Flow Anomalies, Thermal Models, Geothermometers

1. Introduction

In addition to the pattern of substance transfer in the course of geothermal deposits' formation, the paper also focuses on sources of fluids and material filling ore zones. The origin of the nonmetallic portion in the filling is clear enough: The environment comprises sufficient amounts of silicates and carbonates. Required amounts of ore material can also be derived from host rocks. It is far more complicated to model the processes of its capture by the fluid, followed by its transport and settling. The source of the fluid is particularly problematic. The isotopy of oxygen in its composition often points to its surface origin. This type of origin is beyond doubt if we are talking about hydrothermal systems on the ocean bottom. Yet, even in this specific case, helium isotopy points to the presence of mantle components in the fluid. Metamorphogenic and magmatic fluids are obviously involved in the process.

The purpose of the study is to prove that concepts of the advection-polymorphism hypothesis regarding deep-seated processes in the Earth's tectonosphere can be applied to exploring the formation of certain types of mineral deposits. The questions listed above also need to be answered in the study.

The paper discusses gold-bearing sulphide deposits in light of the possibility to examine them in terms of the data known to the author for the territory of Ukraine. Without challenging H. P. Taylor [47], Jr.'s statement to the effect that "each mineral *deposit* seems to be a unique phenomenon, and this makes it difficult to expand the results of investigations devoted to the nature and evolution of the hydrothermal metalliferous fluid or fluids, which is especially true in relation to most hydrothermal *vein deposits"* [10], let us just indicate that the processes analyzed below are also characteristic of other types of hydrothermal mineralization and not of them alone.

Over 40 percent of the world's gold reserves are associated with gold-bearing sulphide ores [25]. Gold is primarily present as finely dispersed inclusions within sulphides (pyrite, pyrrhotine, arsenopyrite, chalcopyrite, etc.). In that sense, sulphide ores do not differ from ores of magmatic sulphide Co-Ni-Cu deposits. By way of example, commercial-grade sulphide ores in the Norilsk Region usually contain about 1-2 grams of gold per ton.

This type of mineralization and such deposits are encountered in various regions of Ukraine. They are viewed as products of the hydrothermal process (the skarn portion is often inaccessible due to the limited erosional truncation [35]. Mineralization usually accompanies steep faults producing fractured zones. In the Transcarpathian Region, this occurs within poorly lithified primary igneous-sedimentary strata. In Donbass, the extent of host rocks' lithogenesis is much higher [18]. On the Ukrainian Shield, it reaches greenschist of amphibolite facies. Precambrian and Cimmerian manifestations of this type of mineralization took shape in similar rocks both on the Ukrainian Shield and in the Donets Basin. It is only in the Precambrian, especially in the Archean, that basic formations prevailed in the volcanogenic portion of the deposits. Consequently, during any stretch of geological history the gold-bearing sulphide type of mineralization occurred throughout northern Ukraine from the Donets Basin to the Transcarpathian Region.

2. Formation of Ore Bodies

Over recent decades, thousands of publications have been dedicated to this topic. We will only briefly mention the basic principles of the pattern in which ore material is mobilized by thermal springs, and is then transported and deposited. Applications of the advection-polymorphism hypothesis, advanced by this author, are only concerned with several aspects of the process – its depth range, speed, and thermal model.

The data referred to below were quoted from studies published by [4-6, 10, 11, 23, 32, 36, 37, 39, 41, 45, 46, 51, 52].

Models based on the data of actual ore fields show that rocks, which directly host ore deposits or those contained in the stratum sequence, could well be the source for ores. For ore deposits under study to form, no excess in percent abundance of elements within parent rocks is required. In the case of polymetallic deposits, the most likely source of metals and sulphide sulphur are granites, including those with minor concentrations of sulphide sulphur.

The mobilization area for ore components is local in character and, for that reason, ore bodies of the relevant type are categorized as medium or even small [5]. In order to accumulate 10^6 tons of ore (a fairly large deposit of Cu, Pb, and Zn) from a granite block with a 4-5 km wide pane, we might need to extract about 7 percent of metal from that block [10]. It is common knowledge that sulphides and arsenides in metals are favorable for the accumulation of gold [4, 10]. Moreover, they do not necessarily originate from the same rocks as sulphide metals do. Average gold concentrations in dissimilar types of rocks do not vary significantly: Ultrabasic rocks – 5-6, basic rocks -- 4, intermediate rocks -- 4, acid rocks -- 4-5, and syenites – 4 (in 10^{-9}) [10].

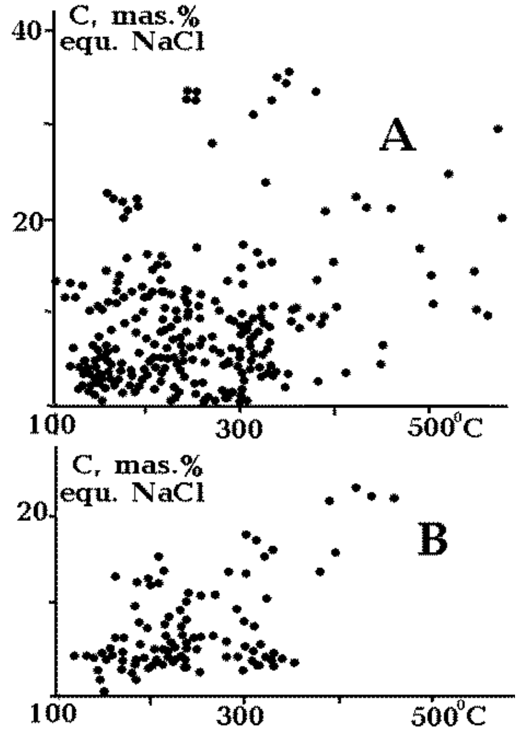

Figure 1. *Correlation between salt concentration and homogenization temperature of gas-fluid inclusions (A) within ore minerals of polymetallic deposits in various regions of Russia [41] and (B) in the Dzhimidon and Sadon ore fields (Northern Caucasus) [22].*

The fluid, which transports the ore-forming material, attains a chloride concentration, which is higher by an order of magnitude than normally observed in the melt. It may actually reach 40-50 grams per liter (we are talking here about typical values, whereas much higher concentrations can also be encountered). As the temperature decreases, some chlorides of K and Ca escape due to the transformation of rocks around the fluid circulation channel. The total concentration decreases as the relative amount of NaCl grows [10, 11]. Such chloride solutions are quite efficient in extracting metals from the parent rock.

Figure 1 shows that the most common concentrations of salts are in agreement with the above evaluations and match results of the compilation performed by this author in the determination of electrical conductivity of ore-bearing thermal springs [12]. The dependence of the concentration on temperature is not directly visible due to the strong effect of the dissimilarities among other factors. (Figure 1A). Information available on one specific deposit makes it possible to detect the said dependence (Figure 1B).

The use of samples of relatively low-temperature waters (enabling mass sampling) makes it possible to prove that the techniques for calculation of fluid composition are valid [5] – see Figure 2.

The chloride (chloride-carbon dioxide) fluid is part not just of deposit-forming solutions. It is also involved in the formation of saline sedimentary rocks, which preceded manifestations of gold-bearing sulphide mineralization in the Transcarpathian Trough, Folded Carpathians, and the Donets Basin. The time frame for the existence of such fluids is also extensive: There are reasons to believe that solutions, which formed Precambrian deposits on the Ukrainian Shield, were actually chloridic [16]. There also are indications of the presence of chlorine in solutions within rock complexes containing gold in the Dharwar Craton (India) and in the Siberian Platform's Aldan-Stanovoy Shield [40, 45]. This is notwithstanding the fact that the age (Archean) and composition of host rocks (greenschist belts just like those making up the Mid-Dnieprovian Block of the Ukrainian Shield – [16] differ sharply from those in the Carpathians and in the Donets Basin.

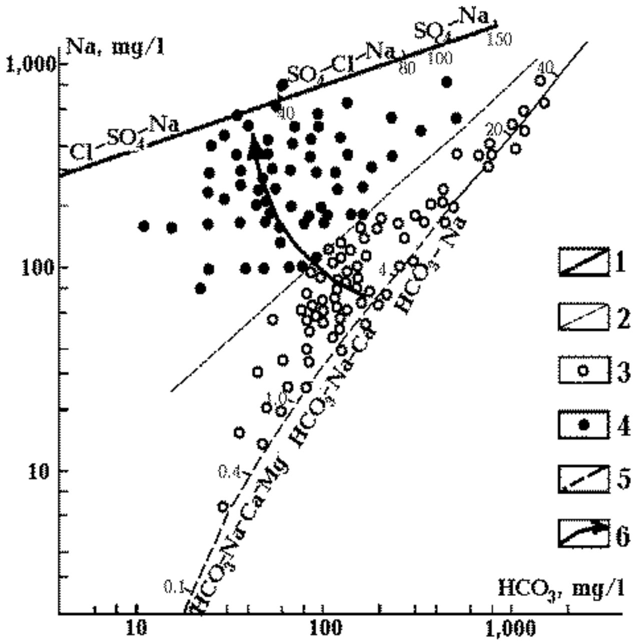

Figure 2. Estimated and measured (in subsurface thermal waters) concentrations of components in the solution as illustrated by the diagram of HCO_3^- + Na^+ [5].

1 – graph showing estimated equilibrium concentrations of components in a solution comprising 350 mg/l chlorine and interacting with a granite rock (50°C, P_{CO_2} --102.0; P_{H_2} – 10-13.9; P_{H_2S} – 10-20 Pa); 2 – graph showing estimated equilibrium concentration of components in the water interacting with granite (50°C, P_{CO_2} – 102.0 Pa); 3 and 4 – concentrations of components in thermal waters of crystalline rocks in the USSR and Bulgaria: 3 – HCO_3-Na in water, 20-80°C; 4 – SO_4(Cl)-Na in water, over 50°C; 5 – interface between thermal water varieties; 6 – direction of increase in the SO_4^{-2} concentrations and water temperature. The graphs bear marks indicating change in geochemical types of equilibrium solutions and rock/water ratios adopted in the calculations.

The effect of host rocks on the rate of sulphide deposition, more specifically, the intensity of reaction between the solution and the host rocks, was analyzed. For example, in a simple isothermal scenario, disregarding the effect of previous portions of the solution, 45 percent of zinc separate out as a result of cooling. In the case of reaction with granite, tuff breccia, or mica schist, the figure will be 83 percent, and if amphibolite or crystalline schist are involved, the amount will be 99 percent. The reaction brings about considerable changes in the solution pH in correlation with the rock's acid-base characteristics. More complicated scenarios of events were also studied, in particular, those in which the temperature in the system changes vertically [6]. The studies involved a "granite-fluid" system made up of 15 independent components. The model of water fluid comprised 79 particles, including 26 ore elements. Potential solid phases comprised 52 minerals, including rock-forming, metasomatic, and metallogenic ones. Estimates of dissociation constants for complex compounds were used in accordance with versions of Ryzhenko's equation [39]. Energies of aqueous solution particles were taken into account *on the* basis of the Helgeson-Kirkham-Flowers (HKF) model.

In the opinion of the majority of experts, the aqueous fluid responsible for the formation of mineral deposits (see below) is mixed in origin – surface and profundal waters of various origins are involved in the process. The types of barriers and their relative roles at various stages of mineralization were analyzed in detail for the above composition of the aqueous fluid. At the physicochemical level of modelling, the geochemical role of hydrodynamic barriers has been substantiated.

The concentration of sulphide sulphur in leaching solutions amounts to n.10^{-2-3} m (where m stands for solution molality). This is sufficient for the formation of ore elements' sulphides once the conditions change. There is no need to consider a different source of sulphide sulphur capable of forming the bulk of sulphides in veined polymetallic deposits [5, 50], analyzed a scenario of the mineralization process, and her results are provided in Figures 3 and 4. As shown below, those results were obtained within a range of genuine conditions.

It may generally be surmised that studies performed so far have proven quite substantially the concept regarding the process of formation of deposits of the type in question within the frameworks of a system comprising sources of profundal and surface waters, the parent rock, and the site of ore deposition.

The potential for the formation of a deposit depends on the duration of the process (the quantity of "waves," implying total replacement of the fluid in the interstitial space of the ore deposition site).

The duration of hydrothermal systems' existence on continents amounts to 1-100 thousand years [10, 46]. A conclusion has been drawn for vast basins: "... thermal waters… can transport and deposit sulphides of metals, but such a process is too slow to be able to produce commercially significant deposits. … for deposits to form, favorable conditions must prevail over at least millions of years rather than just over tens of thousands of years…" [11]. Commercially significant mineralization requires dozens of the aforementioned "waves."

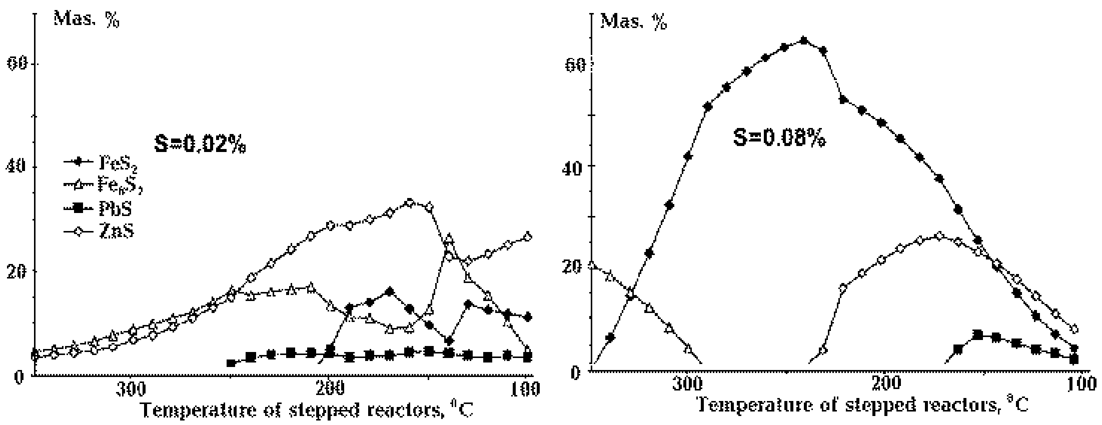

Figure 3. Bulk contents of minerals at the upslope of the vein (from higher to lower temperatures) at wave 15 for models with initial conditions: 420°C and 0.1 GPa.

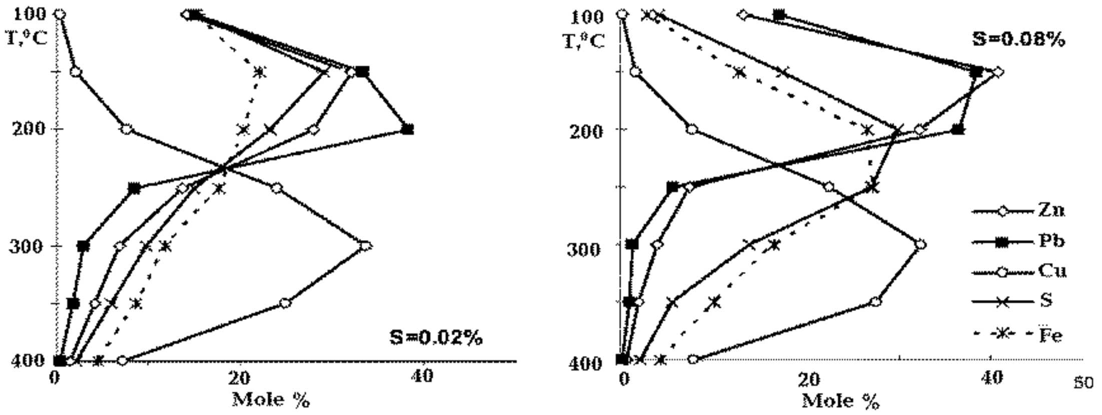

Figure 4. Deposition of metals and sulphur (mole percentage of the bulk amount of the deposited element) versus temperature intervals along the upslope of model veins.

3. Endogenous Conditions and the Mantle Stage of the Process

The fact that the process of mineralization is confined to a certain stage in the evolution of the region, characterized by a certain type of endogenous conditions, in conformity with APH concepts, fully predetermines the pattern of heat and mass transfer, as well as the thermal model. The type of conditions can be ascertained for Phanerozoic deposits. According to the evidence available to the author, such conditions developed at the stage of post-geosynclinal activation. The deposits formed 1) following the Alpine folding in the Carpathians and Balkanides of Slovakia, Ukraine, Romania and Bulgaria; 2) during the post-Hercynian (Cimmerian) stage of activation that affected the Donets Basin and the Scythian Plate of the northern Caucasus. No such deposits formed in zones of 1) recent and Cimmerian activations in the regions of Ukraine's Precambrian platform, 2) Hercynian rift of the Dnieper-Donets Depression, and the Pripyat Through; 3) recent activation in the Hercynian and Cimmerian geosynclines of the Scythian Plate, and 4) the Hercynian geosyncline of the Donets Basin.

In terms of the APH concepts, a typical situation at a relevant moment of geological history implies mantle material transport from a shallow residual asthenosphere into the crust. This results in partial melting within the median portion of the crust along with acid magma upwelling to depths of around 10 km [17, 46]. Less frequent and fast-cooling intrusions to even smaller depths also occur. The depth interval from 30 km to top portions of acid intrusions undergoes fluidization. The fluids may reach the surface (provided that there are no lithological screens) above the intrusions through permeable zones of the faults. All those phenomena take place against the background of crustal rocks already heated up and metamorphically reworked during the geologically recently completed geosynclinal process.

This pattern implies the presence of an active mantle stage, the possibility of material mobilization by fluids not just from the intrusive granite body alone, the emergence of an intensive heat flow (HF) anomaly not just above the permeable zone through which the fluids rise, and so on. It generally matches common concepts [23].

Helium isotopy in the groundwater of ore fields points to the presence of a mantle stage. Its numerical characteristic is normally expressed by the formula $R = (^3He/^4He).10^8$. The background value of R for the crust indicating the absence of a mantle component is about 2. In Ukraine's Transcarpathian Trough, where young gold-bearing sulphide deposits of the Beregovo ore field are situated, R reaches 200-300 [19]. The mantle helium identifier cannot be traced in waters of ancient deposits. It may, however, be discovered in rocks that have retained helium for long periods of time. Such data are in short supply. Results for the superdeep Kola Peninsula borehole can be referred to as an example of such a situation (Figure 5). A unique experiment performed there [21] encompassing rocks at all depths ranging from 0 to 12 km, made it possible to detect an anomaly with R of up to 10-12 against the normal background. An analysis of the disturbance showed that the anomaly is associated with profundal fluids, confined to the Luchlompolsky fault zone, which washed the rocks there during the Proterozoic time. Sulphide gold-bearing ores, which formed over the time span of several Proterozoic activations, were found within the aforementioned depth range. Ore formation is not always accompanied by R anomalies. Ore zones penetrated by the borehole at the depth of about 1.8 km are marked by helium isotopy in crustal rocks (Figure 5).

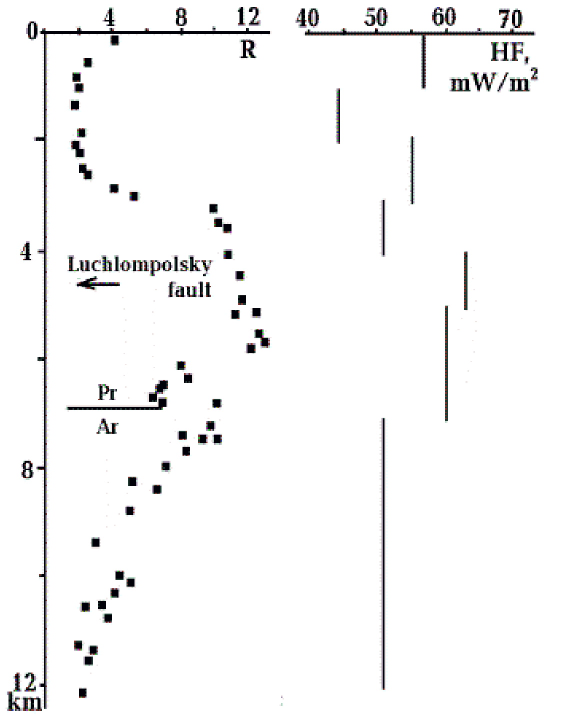

Figure 5. *Helium isotopy in rocks exposed by a superdeep borehole in Kola Peninsula [21].*

We cannot, however, rule out an alternative interpretation of the R distribution pattern observed in the superdeep borehole-3. An elevated (by about 10 mW/m^2) heat flow value was detected within the depth range with anomalous values of R (Figure 5). It is possible that we are dealing with a disturbance in R associated with a recent circulation of profundal fluids using the same channels as the Proterozoic ones. Unlike the latter, contemporary fluids on shields are not potentially ore bearing (see below).

4. The Origin of Water in Ore-bearing Solutions

Before we proceed to compiling a fluid balance, we need to be aware of the amount of water required for the formation of a deposit. To handle this task, we need more information than is currently available. Over the period of time it takes to form a deposit, the amount of water rushing through it should be equivalent to a water column of about 1-2 km. It may be assumed that most of it is not "removed from circulation" during convection in a fissured medium. Much of that water spilling onto the surface returns back to the convection cell. There is evidence on conformity between oxygen isotopies in thermal springs, geysers, and surface water streams [2]. Consequently, the process of deposit formation over 50-100 thousand years requires much less water.

In conditions prevailing in Ukraine, surface water infiltration to a depth of about 1 km over 100 thousand years amounts to 0.5-1.0 km. The above numbers apply to the sedimentary basin. Considerably less water percolates through the crystalline crust even to larger depths.

In our calculations of the amount of metamorphogenic water, we used the following information: 1. The data on the distribution of metamorphic facies versus depth in the crust of the Ukrainian Shield [16]; 2. The data on the average content of water in rocks of dissimilar metamorphic facies [48]; 3. The data on temperature variations in the crust of recent activation zones by comparison with the crust of the Precambrian platform and geosyncline [14]. The resulting "water table" equivalent height is 150 meters. The water in question forms following additional crustal metamorphism in a single-event activation zone. It is preceded by a process, similar in character, which concluded the geosynclinal cycle 10-50 million years ago. It is likely that a portion of the geosynclinal fluid in the crust is still in place. We are talking about a regional crustal reworking not restricted to the local area of deposit formation. It is likely that this set forth conditions for the formation of specifically ore-bearing fluids [34]. The layer immersed in fluidization is very thick – up to 25 km. At depths larger than 30 km, metamorphism of rocks in the granulite or eclogite facies also takes place, although it is not accompanied by any appreciable water discharge.

Our estimates apply to a completely crystalline crust. A thick sedimentary layer may at least double the amount of water forming in the process.

The regional body under study is not quite noticeable in terms of seismic-wave velocities' anomaly. This is due to the low concentration of the fluid (less than one volumetric percent). There are, however, occasions when it can be detected in the Donets Basin and in the Transcarpathian Trough in amounts sufficient for causing anomalies in electrical conductivity, and such anomalies are discovered more frequently.

The shallow acid intrusive body itself can also contribute to a fluidization of the medium. In many cases, deposits are confined to it. According to the data for the Donets Basin Nagolny Ridge, which has been explored in detail, the intrusive body beneath the ore-bearing area is about 5 km thick [1]. By the period of Cimmerian activation, the content of water in the magma that produced it can be assessed in terms of the data published by Menaker [33] -- see Table 1.

Table 1. *Contents of components in the ore-bearing solution within magmas [33].*

Components	Contents (weight percent)		
	Oceans	Geosynclines	Rifts
Basic rock melts			
H_2O	0.4-0.5	1.9	1.6
Cl	0.3	1.2	2.6
S	0.8-1.2	0.9	0.9
CO_2	0.3-0.4	0.6	2.0
Acid rock melts			
H_2O		2.2	3.6
Cl		0.8	1.7
H_2O		2.2	3.6
CO_2		0.4	0.2

The endogenous conditions in the regions, as shown in Table 1, are in line with APH concepts. It is but obvious that crustal and mantle magmas in continental regions carry much more water and chlorine than do mantle magmas in oceans. The latter are represented by magmas of both mid-ocean ridges and troughs.

The intrusive body mentioned above may contain 400-450 meters of water. This implies that the area above it can well be particularly prone to vigorous circulation of the ore-bearing solution. It should largely be confined to a highly permeable narrow fault zone (see below). This may promote entrainment of solutions from adjacent areas overlying the intrusive body into the heat and mass transfer process.

Some manifestations of hydrothermal activity are believed to be amagmatic [34]. Geological and geophysical data pertaining to Ukraine's zones of recent activation suggest that this is only formally true. There are no manifestations of magmatism in the Donets Basin today. Yet, the extensive hydrothermal activity there is accompanied by numerous indications of a deep-seated process, including the formation of a partially melting zone in the crust and upper mantle.

The data presented above, even though they may be incomplete, make it possible to believe that sufficient amounts of ore-bearing solutions may form without any involvement of hypothetical intensive fluid jets around the mantle. Some of those fluids penetrate the crust and may reach the surface. However, there is no relevant evidence that might point to their large volumes. Proceeding from qualitative considerations, the scenarios of fluid transport from the upper or lower mantle or from the core/mantle interface [27] should so far be considered unsubstantiated.

5. Thermal Models for Ore Zones

Evaluations of energy requirements for the formation of an average-size deposit of the type in question produce values of about 10^{12} J. Bearing in mind the data on the process listed above, we might agree with such an estimate. We cannot, however, accept the claim that this value exceeds, by thousands of times, the energy transported by the heat flow over the same period of time [46]. In all geological processes, transport of thermal energy is a major one, whereas the remaining elements of the phenomenon are secondary in terms of energy.

Let us consider the above statement as applied to our specific case. Some authors believe that it takes hundreds of years for individual ore veins to form and thousands of years in the case of ore fields [46]. Let us assume that an average deposit formed within 1,000 years and that it occupies an area of 100 by 100 meters. The average energy requirement per unit area will amount to 3 mW/m^2, which is lower than the background heat flow by at least one order of magnitude.

Actual heat flow anomalies matching the process can be registered in that same Transcarpathian Trough in the area of the Beregovo gold-bearing sulphide deposits (Figure 6). The example of the Velyka Bigan deposit is not isolated. Similar disturbances also occur at the Muzhiyevsky and Shayansky deposits (outside the Beregovo ore field). However, the background in those regions is not known sufficiently well, and the anomalous value of the heat flow (close to that for Velyka Bigan) was determined inaccurately.

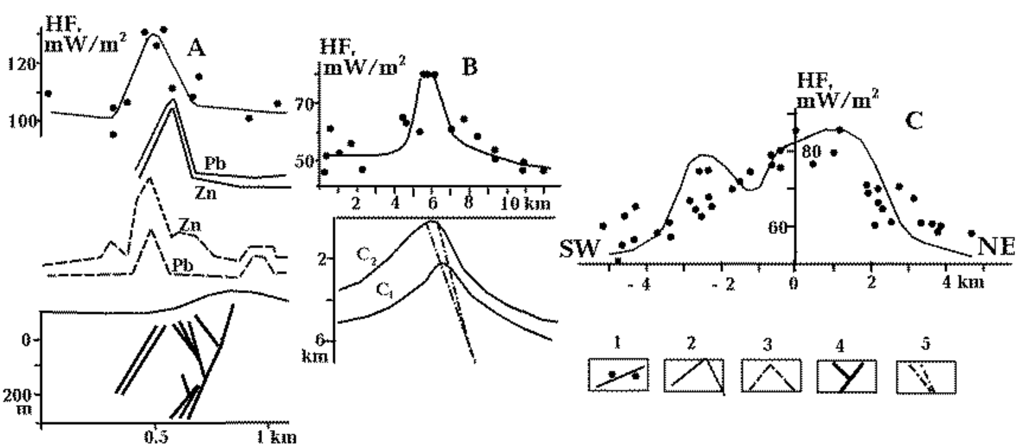

Figure 6. *Heat flow distribution at the (A) Velyka Bigan deposits in the Transcarpathian Trough [7], (B) on the Mykhaylivsky deposit situated at the Donets Basin major anticline [1], and (C) at the deposits of the Donets Basin's Nikitovsky ore deposit [15].*

1 – Heat flow (dots marking experimental values; lines – estimated values); 2 and 3 – metallometric data (2 – in the soil, 3 – in plant ashes); 4 – ore-bearing zones; 5 – Major anticline axial fault.

Heat flow anomalies in numerous zones of recent activation in Ukraine display the same intensity (about 25-35 mW/m^2) despite the fact that, outside the Carpathians, they are not associated with any ore deposits. This also applies to heat flow disturbances in Cimmerian deposits of the Major anticline (Figure 6) and the Donets Basin's Nagolny Ridge, as well as to Precambrian deposits on the Ukrainian Shield [16]. The situation on the Nikitovsky ore field is also worth mentioning. Eight deposits of cinnabarite (with a conspicuous content of gold) have been registered there. They form clusters in three areas of the central part of the anticline and at its limbs [26]. The current heat flow pattern (Figure 6) can be explained, approximately, by arranging in those areas anomalies calculated for the contemporary circulation system on the Mykhaylivsky deposit.

It may therefore be presumed that activation events of dissimilar age use the same permeable zones for transporting fluids upwards. It is, however, post-geosynclinal activations alone that produce genuine ore accumulations. Yet, small deposits of sulphides, frequently containing traces of gold, are present in zones of aforementioned activations that occurred outside of the post-geosynclinal stage. At the same time, in young ore fields, such as the Transcarpathian Trough, there exist small hydrocarbon deposits, which are common for zones of recent activation of troughs with the basement age ranging from Precambrian to Hercynian. The fluids that originated during those almost barren periods are characterized by appreciably smaller concentrations of chlorides; instead, significant amounts of fluorine have been detected there [28, 29, 42-44].

Interpretation of heat flow anomalies, which conformed to areas with vigorous circulation of fluids (Figure 6 and others), proceeded in the form of searching for parameters of a convection cell whose effect, if added to the heat flow normal for the region (at the moment of the cell inception) would make it possible to account for the observed pattern. The thickness of the convecting layer – the distance between the Earth's surface and the top of the intrusive body – was assumed to equal 7 km. Aleksandrov et al. [1] described the applied heat transfer scenario in greater detail. For explaining the anomaly, it was necessary to assume the presence of a narrow convection cell (just several hundred meters in width) with a very large Nusselt number implying an unusually high permeability of rocks within the layer – about 5.10^{-13} m^2 and the thermal field stabilization time of about a few tens of thousands of years. In the case of the Cimmerian activation in the Donets Basin, the calculations were rendered somewhat complicated by the need to take in account the about 2 km thick virtually impermeable Permian clay stratum in the upper portion of the profile.

Bachler et al. [3] reported similar calculations for one of the Rhine Graben's faults. They arrived at virtually the same parameters for the hydrothermal system (the width of the permeable zone amounting to 200 meters, the depth of the bottom – 5.5 km, the fault zone permeability – 5.10^{-13} m^2, and the thermal field stabilization time – 77 thousand years). In all cases, the intensity of the heat flow anomaly of up to 20-40 mW/m^2 at the conventional observation depth (500-1,000 meters) could be accounted for.

The permeability of rocks in the Donets Basin's Major anticline that was determined at normal laboratory conditions matches their low porosity of about 1 percent in the topmost portion of the profile further decreasing to 0.5 percent or lower in the rest of the sedimentary stratum [1].

In order to explain the observed thermal effect, we would need a permeability value larger than that calculated in terms of porosity by approximately 2-3 orders of magnitude. An analysis of the effect of the temperature and pressure increase with depth on permeability precludes the possibility of such an effect [50]. This characteristic property in the percolation-related increase of permeability prevails in all scenarios of this type that are associated with thermal springs in activated areas. Local seismicity inherent to all activated zones is a physical factor of percolation [9, 38].

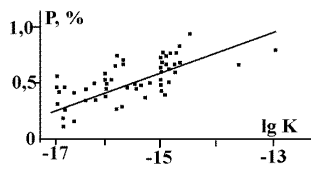

***Figure** 7. Correlation between permeability (K) and porosity (P) of rocks according to Sharapov [41].*

An alternative viewpoint assumes that an increase in permeability is associated with periodical short-term increase in porosity due to recurrent injections, under high pressure, of magmatic material from a deep-seated magma chamber into a near-surface one [8]. The fissures tighten up in between injections.

The thermal anomalies analyzed so far are similar in terms of intensity, even though the thickness of fissured zones in the Donets Basin is much greater than in the Transcarpathian Trough or on the shield.

Thermal models for the Earth's interior in the central portion of the cell (along the axis of the "thermal dome") relate to deposits for which geothermal data are available thereby making it possible to monitor the results of measurements. Differences between estimated models are partly due to variations of the Earth's surface temperatures during various periods of geological history versus current temperatures. During the Mesozoic period, the temperature was by 20°C higher that at present, and when deposits in the Ukrainian Shield formed (about 2,000 million years ago) it presumably was higher than now by 40°C. Figure 8 illustrates results of comparisons.

There is an obvious match between estimated (based on the scenario of the process adopted in accordance with APH concepts) and experimental data. The thermal models turn out to be quite similar for deposits of dissimilar age.

Let us compare the data on the distribution versus depth of temperatures at which minerals in ore deposits formed, on the one hand, and information for vast thermal water basins (in many cases, conjugated with areas of ongoing or recent magmatism) as presented in various publications, on the other [10, 11, 41] (Figure 9).

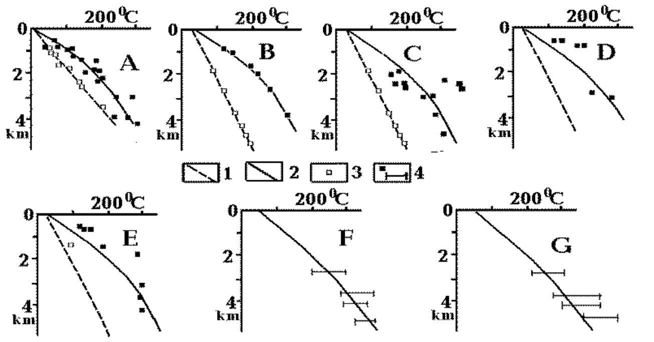

Figure 8. Comparison between estimated temperature patterns (1 and 2) and the data of geothermometry studies on sulphide deposits of the (A) Transcarpathian Trough [53]; (B) Major anticline of the Donets Basin [1]; (C) Nagolny Ridge [24, 26]; (D) Ore manifestations at the periphery of the Donets Basin; (E) Nikitovsky and Sadonsky ore areas [22, 26]; (F) Klintsy ore field; and (G) other deposits in the central part of the Ukrainian Shield [31].

1 – Beyond thermal domes, 2 – within thermal domes, 3 and 4 – the data of geothermometry measurements (3 – beyond thermal domes, 4 – within thermal domes).

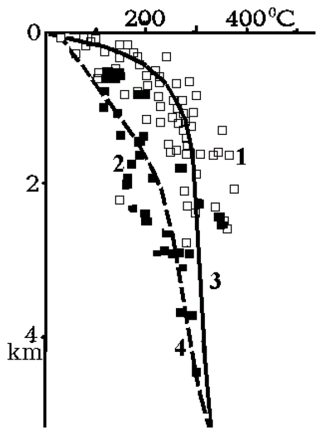

Figure 9. Distribution with depth of temperatures at which minerals in ore zones and thermal springs formed.

1, 2 – experimental data (1 – thermal springs, 2 – ore zones); 3 and 4 – estimated models for convection cells (thermal springs, 4 – ore zones).

The estimated distribution of T for thermal-water basins is characteristic of a situation with a nearly adiabatic gradient in the main portion of the cell and with a strongly pronounced upper boundary zone. In a similar lower boundary zone, the temperature must be close to the solidus for granite. We must be talking here about free convection prior to crystallization of the melt. It appears logical in this particular case to assign the role of a geodynamic barrier to the thin upper boundary zone. Assessments of the duration of the period of melt conservation near the top portion of the intrusive body indicate that it is much shorter than would be necessary for the deposit to build up. Its main part emerges during the next period of time when the temperature at the top of the intrusive body is below solidus.

The intensity of heat transfer in a thermal water basin within an igneous area enables us to explain with high precision, in particular, the colossal heat flows that cannot be accounted for with the help of a magmatism model in the subduction zone [20].

6. Compaction of Rocks Within a Thermal Dome

The heat-up within a deposit and in adjacent rock masses may affect the rock density. In the case of formation of an ore deposit in crystalline structures, the effect would be small. By way of example, on the Klintsy deposit at the center of the Ukrainian Shield, densities of altered rocks do not differ from those of unaltered ones. The effect of ore zones proper is insignificant. Owing to a detailed gravimetric survey performed in the area, we were able to compare the topographies (Figure 10) of the estimated and observed fields.

There is no Δg anomaly. The observed weak (relative to the estimated graph) negative anomalies might be due to existing less compact permeable zones marked by elevated heat flow values.

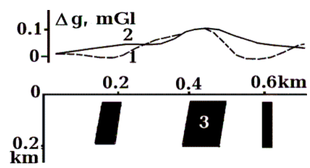

Figure 10. Distribution of the observed (1) and estimated (2) anomalous gravitational fields above ore zones (3) in the Klintsy deposit.

In rocks of the sedimentary stratum, even if katagenetically altered like Carboniferous deposits in the Donets Basin, the heat-up effect in the thermal dome is quite noticeable.

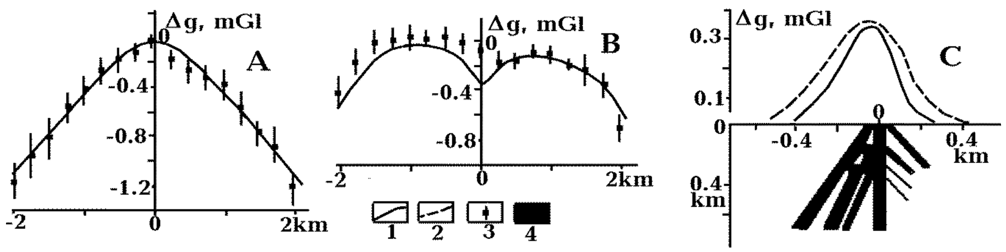

Figure 11. Estimated and observed gravitational fields at the Major anticline of the Donets Basin (after removing the regional background). A – is the anticline field beyond the dome; B – the field within the thermal dome; C – gravitational effect of the ore-bearing zone.

1 – Estimated Δg values; 2 – difference between the observed field and the effect of the thermal dome at the Mikhaylovsky deposit; 3 – mean values of the observed field; 4 – the ore zone.

The fact that the ore area in the Major anticline had been thoroughly covered by geological and geophysical surveys facilitated the construction of a density model for the area. Katagenetic transformations of rocks under the effect of an intensive heat flow occurred there as early as during the pre-folding period, so that the formation of the anticline with very steep beds (up to 70-80°), as well as upheaval and erosion exposed compact rocks at the surface. The estimated effect of the anticline in its central part (Figure 11A) is in fairly good agreement with the observed field. This proves that the choice of correlation between the anomalous density and the extent of katagenesis at dissimilar temperatures was correct. In the area of the deposit, the above effect is reinforced by an additional effect caused by an acid intrusive body (the density of its rocks is lower than that of the host rocks) and by the permeable fissured zone through which the fluids rise thereby producing the present heat-flow anomaly. The estimated field appears to be somewhat lower than the observed one (Figure 11B). When we compare this difference to the estimated effect of the ore zone (Figure 11C), it becomes obvious that they are similar both in shape and magnitude. Consequently, a sufficiently accurate and detailed survey makes it possible to use the resulting gravitational field as a diagnostic tool for tracing a deposit.

7. Electrical Conductivity Anomalies

It might be of interest to analyze geoelectric models for potentially prospective areas. We do not just mean traditional techniques involving resistivity and induced polarization techniques that are useful for shallow depths. Results obtained with the help of deep geoelectric studies could throw additional light on the problem.

The bodies causing anomalous conductivity, as assumed by the scenario of the process, are larger than the deposits proper by orders of magnitude. They are at least typical of ore-bearing areas. There is only one region in Ukraine where deposits currently form – the Transcarpathian Trough. It is, however, not suitable for detecting associated electrical conductivity anomalies. Throughout the territory of the structure, and beyond it, an extraordinarily strong anomaly prevails. It is characteristic of the entire activation zone and not just of the area of ore genesis. In all likelihood, apart from fluidization, it bears features of graphitization in some crustal areas of the region.

The Donets Basin with its gold-bearing sulphide deposits is suitable better than other such regions for studying electrical conductivity anomalies. Bodies with low specific resistivity (ρ) may in this case be associated with ore deposits proper (mainly of Cimmerian age) and with magma-fluid systems of recent activation zones. They are unlikely to hold ore deposits. Yet, in a number of cases, Cimmerian processes using the same permeable fault zones most certainly took place there.

Cimmerian mineralization does not produce large bodies that could be discovered with the help of a dense grid of regional geoelectric studies. Besides, an appreciable electrical conductivity of a medium impregnated with ore can only be a result of the ore minerals there forming large concentrations. The data shown in Figure 12 indicate that percolation-related decrease in the value of ρ occurs when the content of ore minerals in the rock is about 30 percent.

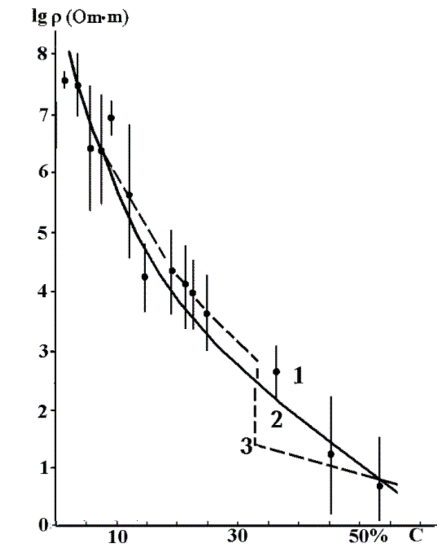

Figure 12. The ρ value as a function of C (concentration of ore inclusions in rocks).

1 – Experimental data; 2 and 3 – potential results after drawing an averaging graph (3 --with percolation variations of the parameter).

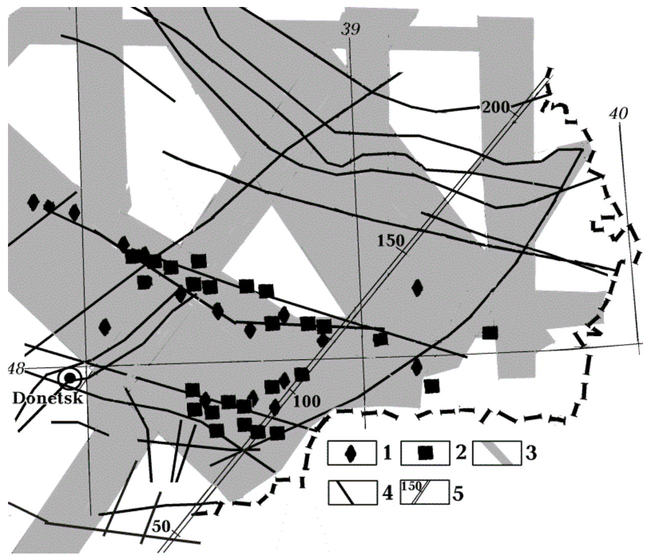

Figure 13. Cimmerian mineralization zones in eastern Donets Basin.

Deposits and ore occurrences: 1 – mercury; 2 – polymetal complexes; gold; antimony; molybdenum [42]; 3 – fault zones activated over recent three million years [49]; 4 – Cimmerian and older faults [30]; 5 – the profile along which a geoelectric section was constructed [13] – Figure 14.

Low resistivity values could be due to graphite nodules. In the Donets Basin, however, this kind of impregnation does not occur (abnormally low ρ values in coal can only reflect a metamorphism reaching the level of anthracite). Nor is graphite in other areas of Ukraine associated with the type of mineralization in question. Thus, fluidal and magmatic bodies alone remain conductive media in the crust and mantle beneath ore fields (Figure 9). Judging by heat flow anomalies (Figure 6), given the present circulation of profundal fluids, the process uses the same permeability channels as during the Cimmerian time. Anyway, heat flow anomalies associated with activated faults are much more common (Figure 6 and Figure 13) than ore aggregations that could be of commercial interest. Recent activation produces very few ore deposits. It may well be that the process is still at a pre-mineralization stage in the thermal water basin. Therefore, studies of conductive bodies in the tectonosphere of the Donets Basin are likely to be of significance only as far as our understanding of the process of recent activation is concerned.

Figure 14 depicts a two-dimensional geoelectric model of the crust and upper mantle beneath the Donets Basin plotted along the profile running across the Donets Basin at its eastern periphery within Ukraine.

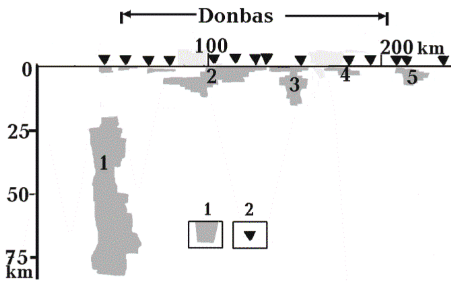

Figure 14. *Bodies with elevated electrical conductivity in the crust and upper mantle beneath the Donets Basin along the transverse profile (Figure 13).*

1 – Conducting bodies with ρ below 20 Ohm.m; 2 – magnetotelluric probing sites.

The pattern of conductive bodies' position may be interpreted as an indication of dissimilar periods of time during which individual activations took place. Shallow-lying conducting zones (2-5), which approximately match the position of faults and are situated close to them, do not correspond to bodies at the lower crust or upper mantle levels. It may well be that temperatures at the lower levels are already relatively low. Conductor number 1 took shape later and is overheated (partly molten and comprising fluids) at the lower level. The upper level there is just starting to form.

The depth of the base of shallow-lying conductors 2-5 is about 8±4 km. This is close to predicted.

Consequently, activation and formation of hydrothermal deposits are accompanied by the emergence of electrical conductivity anomalies.

8. Conclusions

Our analysis of certain aspects regarding the origin of hydrothermal gold-bearing sulphide deposits has enabled us to prove that the process is in agreement with concepts of the advection-polymorphism hypothesis and to throw light on those aspects of the phenomenon that cannot be readily accounted for outside the APH concepts.

1. The fact that the deposits formed during the period of post-geosynclinal activation, more specifically, during the period of crystallization of associated shallow-lying intrusive bodies.
2. The presence of a mantle level in the activation process.
3. Assessment of energy consumed by the process and the origin of that energy.
4. Percolation-related increase in the medium permeability is required for the formation of deposits and what triggers that increase.
5. Thermal models for deposits were calculated, and the results match experimental data.

It is shown that geothermal (paleogeothermal), gravimetric, and geoelectric data can be used as prospecting criteria. The search for gold-bearing sulphide deposits should be continued, considering that the reserves already explored in Ukraine guarantee commercially viable production of over 10 tons of gold per year.

References

[1] Aleksandrov, A. L., Gordienko, V. V., Derevskaya, Ye. I., et al., 1996. Deep-seated structure, evolution of fluid-magma systems, and prospects for endogenous gold occurrence in the southeast of Ukraine's Donets Basin. Kiev: Institute for Fundamental Research, 74 pages (in Russian).

[2] Babinets, A. Ye. and Vetshteyn, V. Ye., 1967. Results of studying O^{18} contents in some genetic varieties of natural springs. Problems of hydrogeology and soils engineering, Kiev, Naukova Dumka, p. 11-21 (in Russian).

[3] Bächler, D., Kohl, T., and Rybach, L., 2002. Characteristics of the upper crust convective flow in the Rhine graben: Application to the Gamma fault at Landau (Germany). The Earth's thermal field and related research methods. Moscow: RUPF, p. 10-11.

[4] Borisenko, A. S., Borovikov, A. A., Zhitova, L. M., et al., 2006. Composition of magmatogenic fluids, factors of their geochemical specialization and metal-bearing capacity Geology and Geophysics, No 12, p. 1308-1325 (in Russian).

[5] Borisov, M. V., 2000. Geochemical and thermodynamic models for vein-type hydrothermal ore deposits. Moscow: Nauchnyy Mir, 360 pages (in Russian).

[6] Borisov, M. V. and Shvarov, Yu. V., 2010. Effect of rocks adjacent to the vein on the efficiency of hydrothermal ore formation. Geochemistry, No 9, p. 996-1001 (in Russian).

[7] Boyev, N. I., Gordienko, V. V., and Kutas, R. I., 1977. On heat flow anomalies related to sulphide deposits. Geophysical Journal, issue 79, p. 73-77 (in Russian).

[8] Fournier, R., 1999. Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment: Economic Geology, Vol. 94, p. 1193-1211.

[9] Galimov, Ye. M., 1973. Carbon isotopes in petroleum geology. Moscow: Nedra, 384 pages (in Russian).

[10] Geochemistry of hydrothermal ore deposits. Vol. I, 1970, Ed. H. Barnes. Moscow: Mir Publishers, 544 pages (in Russian).

[11] Geochemistry of hydrothermal ore deposits. Vol. II, 1982. Ed. H. Barnes. Moscow: Mir Publishers. 623 pages (in Russian).

[12] Gordienko, V. V., 2001. The nature of conductive bodies in the crust and mantle. Geophysical Journal, No. 1, p. 29-39 (in Russian).

[13] Gordienko, V. V., 2015. Essential points of the advection-polymorphism hypothesis. NCGT Journal, No. 2, p. 112-134.

[14] Gordienko, V. V., 2016. Deep-seated processes in the tectonosphere of geosynclines. NCGT Journal, No., 1, p. 6-31.

[15] Gordienko V. V., Gordienko, I. V., Zavgorodnyaya, O. V., et al., 2002. Thermal field on the territory of Ukraine. Kiev: Znaniye Ukrainy, 170 pages (in Russian).

[16] Gordienko, V. V., Gordienko, I. V., Zavgorodnyaya, O. V. et al., 2005. The Ukrainian Shield (Geophysics, deep-seated processes). Kiev, Corwin press, 210 pages (in Russian).

[17] Gordienko, V. V., Gordienko, I. V., Zavgorodnyaya, O. V., et al., 2011. Ukrainian Carpathians (geophysics, deep-seated processes). Kiev: Logos. 128 pages (in Russian).

[18] Gordienko, V. V., Gordienko, I. V., Zavgorodnyaya, O. V., et al., 2016. Donbass (geophysics, deep-seated processes). Kiev: Logos, 159 pages (in Russian).

[19] Gordienko, V. V. and Tarasov, V. N., 2001. Recent activation and helium isotopy on the territory of Ukraine. Kiev: Znannya, 102 pages (in Russian).

[20] Hochstein, M. P., 1995. Crustal heat transfer in the Taupo Volcanic Zone (New Zealand): comparison with other volcanic arcs and explanatory heat source models. Journal of Volcanology and Geothermal Research, Vol. 68, Nos. 1-3, p. 117-151.

[21] Ikorsky, S. I., 1977. On distribution patterns and duration of hydrocarbon gas accumulation in rocks of the Khibiny Alkaline Massif. Geochemistry, No. 11, p. 1625-1634 (in Russian).

[22] Khetagurov, G. V., Vasilyeva, T. V., Shchepetova, L. V., et al., 1986. Geotectonic, mineralogical, and geochemical studies in the Arkhon-Unal Interfluve area, Ordzhonikidze: North Caucasus Ore Mining and Smelting Institute, 138 pages (in Russian).

[23] Krivtsov, A. I. and Makeyeva, I. T., 1981. Ore material sources in endogenic deposits. Moscow: VINITI, 132 pages (in Russian).

[24] Kurilo, M. V., 1980. Conditions that contributed to polymetallic mineralization of the Donets Basin Nagolny Ridge. -- Author's abstract for the PhD degree in geological and mineralogical science. Kiev: Kiev State University, 25 pages (in Russian).

[25] Kuzmin, V. I., Bolokhontseva, S. V., Ozhogina, Ye. G., et al., 1999. Mineralogical techniques for exploration and assessment of mineral ore deposits. Moscow: VIMS, 195 pages (in Russian).

[26] Lazarenko, Ye. K., Panov, B. S., and Gruba, V. I., 1975. Mineralogy of the Donets Basin. Kiev: Naukova Dumka, Vol. 2, 502 pages (in Russian).

[27] Letnikov, F. A., 2006. Fluid-related conditions during endogenic processes and issues related to the origin of ore. Geology and Geophysics, Vol. 47, No. 12, p. 1296-1307 (in Russian).

[28] Lukin, A. Ye., 1997. Lithological and dynamic factors in oil and gas accumulation in aulacogen basins. Kiev: Naukova Dumka, 224 pages (in Russian).

[29] Lukin, A. Ye., 2004. Deep-seated hydrogeological inversion as a global synergic phenomenon: Theoretical and applied aspects. Paper 1: Phenomenology and the nature of deep-seated hydrogeological inversion. Geological Journal, No. 4, p. 53-70 (in Russian).

[30] Map of fractured zones and major zones of lineaments in the southwest of the USSR, 1988. Ed. N. A. Krylov. Moscow: Ministry of Geology, USSR (in Russian).

[31] Marchenko, A. G. and Bratchuk, O. M., 2008. Stages of ore mineralization, mineral associations, and parageneses in the Klintsy ore zone. Proceedings of the National Institute for Geological Studies (UkrDGRI), Ukrainian Academy of Sciences, No. 1, p. 83-92 (in Ukrainian).

[32] Marsden, J. and House, I., 2006. The chemistry of gold extraction. Colorado: Society for Mining, Metallurgy, and Exploration, 655 pages.

[33] Menaker, G., 2011. Theoretical models in geochemistry and ore genesis. Chicago: Lulu Press, 271 pages (in Russian).

[34] Naumov, G. B., Berkliyev, T. K., and Mironova, O. F., 2011. Formation of hydrothermal ore-bearing solutions in oceans and on continents. Geology and mineral resources of the world ocean, No. 3, p. 28-44 (in Russian).

[35] Nechayev, S. V. and Naumov, G. B., 1998. Regional zoning of the Ukrainian Shield mineralization: Present-day plan and paleotectonic reconstruction. Geology of ore deposits, Vol. 40, No. 2. p. 124-136 (in Russian).

[36] Raffensperger, J. and Garven, G., 1995. The formation of unconformity-type uranium ore deposits. Coupled groundwater flow and heat transport modeling. Amer. J. Sci., Vol. 295, p. 581-636.

[37] Raffensperger, J. and Garven, G., 1995. The formation of unconformity-type uranium ore deposits. Coupled hydrochemical modeling. Amer. J. Sci., Vol. 295, p. 639-696.

[38] Romm, Ye. S., 1966. Filtration properties of creviced rock formations. Moscow: Nedra, 271 pages (in Russian).

[39] Ryzhenko, B. N., 1981. Equilibrium thermodynamics in hydrothermal solutions. Moscow: Nauka,. 191 pages (in Russian).

[40] Safonov, Yu. G., Genkin, A. L., Krishna, R., et al., 1988. Gold ore field in Kolar, India. Moscow: Nauka, 234 pages (in Russian).

[41] Sharapov, V. N., 1992. Evolution of endogenic ore-forming fluid systems. Novosibirsk: Nauka, 144 pages (in Russian).

[42] Shumlyansky, V. A., 1983. Cimmerian metallogenic epochs on the territory of Ukraine. Kiev: Naukova Dumka, 220 pages (in Russian).

[43] Shumlyansky, V. A., 2007. Tectonic conditions in the Cimmerian ore-formation epoch on the Eastern European Platform. Proceedings of the Institute of Fundamental Studies. Kiev: Logos, p. 50-68 (in Russian).

[44] Shumlyansky, V. A., Derevska, K. I., Dudar, V. T., et al., 2003. Lithogenesis and hypogene ore formation within sedimentary strata of Ukraine. Kiev: Znannya Ukrainy, 272 pages (in Ukrainian).

[45] Syasko, A. A., Grib, N. N., and Nikitin, V. M., 2006. Comparative analysis of Archean gold ore deposits. Nauka i obrazovanyie, No. 4, p. 58-65 (in Russian).

[46] Starostin, V. I. and Ignatov, P. A., 1996. Geology of mineral deposits. Moscow: Moscow State University. 477 pages (in Russian).

[47] Taylor, H. P., Jr., 1982. Geochemistry of Hydrothermal Ore Deposits, p. 232-233.

[48] Verhugen, J., 1962. Metamorphic reactions and metamorphic facies. Moscow: Izdatelstvo Inostrannoy Literatury, 414 pages (in Russian).

[49] Verkhovtsev, V., 2006. Recent vertical crustal movements on the territory of Ukraine and their relationship with linear and circular structures. Global energy, its geological and ecological manifestations, and scientific and practical utilization. Kiev: Kiev State University Press, p. 129-137 (in Ukrainian).

[50] Vitovtova, V. M. and Shmonov, V. M., 1982. Permeability of rocks at pressures of up to 2000 kg/cm^2 and temperatures of up to 600°C. Reports AS USSR, Vol. 266, No 5, p. 1244-1248 (in Russian).

[51] Volkova, M. M., 2009. Sulphide sulphur in host rocks and Pb-Zn mineralization (thermodynamic modelling). http://geo.web.ru/, p. 23-26 (in Russian).

[52] Yatsenko, G. M., Gayovsky, O. V., Slivko, Ye. M., et al., 2009. Metallogenic studies of gold within protoplatform structures of the Ukrainian Shield (Kirovograd Block). Kiev: Logos, 243 pages (in Ukrainian).

[53] Zatsikha, B. V., 1989. Crystallogeny and typomorphic characteristics of minerals in mercury and fluorite deposits in Ukraine. Kiev: Naukova Dumka, 192 pages (in Russian).