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Use of data magnetic susceptibility measurements in the thermometer deep processes

We obtain the connection between the magnetic susceptibility, the Gibbs energy of minerals and iron content of the mineral. The theoretical equation of communication is in good agreement with the experimental data. A relation between the temperature of formation of the mineral and its magnetic susceptibility. Knowing the temperature of formation of minerals makes it possible not only to determine the genesis of the deposit, but also to predict the shape of ore bodies. These equations connection between the temperature of formation of minerals and measured values in a particular method of geophysical studies contain a constant that must be determined empirically, using correlation analysis. If one examines the same geological object, the temperature of its formation is the same, then it is possible to define a constant through another one. Methods for assessing the geological formation temperature of the object proposed in this paper can be implemented by means of terrestrial or space without extracting the mineral from different depths of the Earth's crust.

Key words: mineral, magnetic susceptibility, temperature of formation, geophysics, genesis, deposit thermometer.

Introduction

In the field of thermometry underlying processes occurring in the Earth's crust and mantle, more than a hundred years ago and started to develop defined three main areas of research [1–5]:

- direct measurement of the temperature of lava, gas fumaroles and liquid thermal springs, as well as indirect judgments about the temperatures of the oxidation state of magmas xenoliths in igneous rocks and coking coal in the contacts with the intrusive rocks;
- the use of natural minerals and parageneses for judging the temperature based on the morphology of crystals, their structure, physical and chemical properties, as well as by growing crystals in artificial media with known physical and chemical parameters;
- thermometer underlying processes and modes of mineralization on the gas-liquid inclusions in minerals, which are the remnants of mineralizing fluids.

Geologic thermometry for inclusions

Historical overview of research on inclusion thermometry is given in [6]. Historically geological thermometry methods included the following: exact methods; approximation methods; unreliable methods; methods to be development [7].

Temperature homogenization biphasic liquid inclusions can be determined by the method of heating the stage or microscopic cracking method. The first is most effective when applied to a small number of large inclusions and the second — to a large number of fine particles.

The relative value of the gas bubble and inclusions can be measured under a microscope. It is suggested that the composition of the solution, we can calculate the temperature required. The approximate ratio of the temperature and pressure during formation of the host mineral can be obtained starting from the homogenization temperature biphasic liquids inclusions and P-V-T-water data.

When in two-phase aqueous inclusions present a significant amount of carbon dioxide, the temperature of the disappearance of a gas bubble can be extremely high or even completely inaccessible. The presence of carbon monoxide leads to reduction in the number of discontinuities as the rate of cracking. Due to the high prevalence of carbon dioxide is not usually considered, the change could be significant.

Temperature of the corresponding crystalline inclusions in minerals can be determined by optical methods, such as measurement of the degree of distortion of the crystal structure of the mineral host using birefringent having its cause mechanical stress or interferometry. The first method is more convenient for minerals that do not have cleavage, such as garnet and quartz, and the second — for the good minerals such as mica cleavage. If the effect of pressure on the establishment of compliance is large, the temperature suitable for different oriented anisotropic inclusions and various types of inclusions varies. In this case it is necessary to determine the temperature of compliance at different pressures is not to be found only temperature and pressure at which the match occurs in all types of crystalline inclusions. These values correspond to the temperature and pressure in the crystallization of the host mineral.

Currently, the newest achievement of physical experiment: Raman spectroscopy [8], nuclear quadrupole resonance spectroscopy [9], laser spectroscopy [10], mass spectrometry [11] and many others.

Mineralogical thermometry

In modern models of the genesis of ore deposits, along with the geological information it requires the involvement of data on physical and chemical conditions during the formation of ores and their subsequent transformations [12–14].

Currently, there are more than two dozen of geological thermometers. According to I.Oftedalyu scandium content of biotite increases in the series of rocks: igneous rocks poor in silica → rocks with a high content of silica regionally metamorphosed rocks → pegmatites. This is due to a decrease in the temperature of their formation, and the order of magnitude of the temperature for each class of rocks known enough. Scandium geothermometer I.Oftedalya in combination with other geothermometers can be successfully used to solve specific problems of thermometry rocks.

Method A.F.Baddingtona based on the decomposition of solid solutions and the distribution of the components between the coexisting phases, in this case — on the distribution of titanium between magnetite and ilmenite. More specifically, the titanium content should be considered in magnetite in equilibrium with ilmenite. No ilmenite it may be limiting for a given temperature and dependent on the overall composition of the rock. Based on numerous studies of A.F.Baddington concluded that the number of $Ti0_2$ magnetite associated with ilmenite, decreases with decreasing temperature education. A.F.Baddingtonom was offered a diagram showing the order of magnitude of the temperature expected for magnetite with different content TiO_2.

As geothermometer also draws part of pyrrhotite. The temperature and the volatility of sulfur are the points of intersection isopleths composition of pyrrhotite with pyrite-pyrrhotite line solvus (Fig. 1).

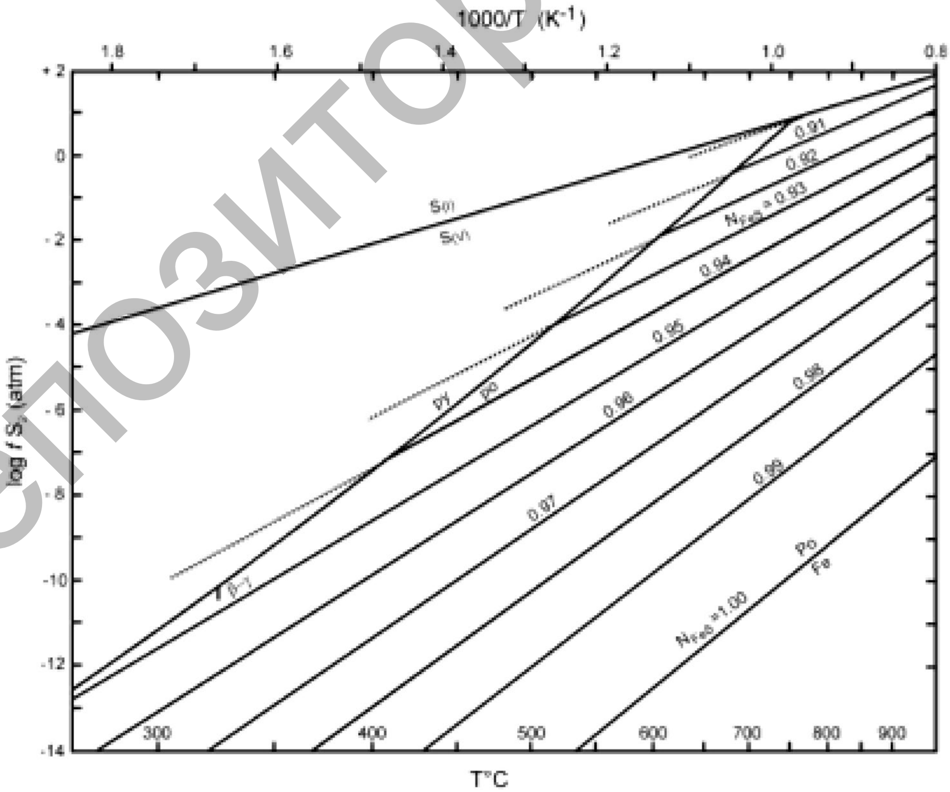


Figure 1. Composition of pyrrhotite in the iron-sulfur as a function of temperature and sulfur volatility [15]. NFeS — mole fraction in the system FeS–S_2

Some of the problems of geological thermometry

Mineral graphical method can only give a maximum temperature of formation of the association of each of minerals, but its use is always required to prove that they are not related to recrystallization or other events that may occur at temperatures that are totally different from the initial germination. Besides still reliable correlation between the shape of the crystals and their formation temperature still missing.

The experimental physical methods used various physical properties of minerals, but this method is suitable for judgments about certain temperature range, often far removed from the conditions of the natural mineral. The most important are the temperature of polymorphic transformations in enantiotropically pairs, but they require a cautious approach, because their true meaning is highly dependent on the pressure, the chemical composition of the medium of crystallization.

The melting points of many hydrothermal minerals are often higher than the temperature of their education (500–1000) ºC.

Temperatures dissociation and decomposition of minerals in very large extent depend on the unknown quantities we pressures at which they were allocated in nature, may indicate only that the possible temperature mineral was significantly lower than the decomposition of these minerals.

Of the physical methods is to use a reliable point of reversible transformations of minerals and decomposition temperatures and homogenization of solid solutions.

Geochemical methods of using the chemical composition of minerals, their synthesis and isotopic composition of their constituent elements, characterized by considerable diversity of approaches to the issue, but based only on qualitative indicators.

Magnetic properties of minerals

Earth's magnetic field and the magnetic properties of minerals have always been the object of extensive research [16–19].

All variety of magnetic properties of minerals determine the magnetic properties of magnetite ore can be divided into the following groups:

- The characteristics associated with the composition and crystalline structure of magnetite (Curie temperature (Tc), specific magnetization (**Js**)).
- Characteristics defined composition, crystal structure and the amount of the ferromagnetic (magnetic susceptibility, the residual saturation magnetization ($\boldsymbol{J}_{rs}$) coercivity force (**Hc**).

Igneous rocks are characterized by a wide range of values of the magnetic susceptibility — from a few to tens of thousands of units of 10^{-5} (Table).

Diagram of æ rocks (Fig. 2) on the content of ferromagnetic minerals C_{fm} divided into two parts.

For weakly magnetic rocks (æ = $(0–50)\cdot 10^{-5}$) regular connection between the magnetic susceptibility of rocks and the content of ferromagnetic minerals not found. The magnetic rocks (æ > $(50–100)\cdot 10^{-5}$) and the content of the ferromagnetic fraction more than 0.01 ferromagnetic effect is created mainly large grains of magnetite (titanomagnetite). These rocks observed correlation between æ and C_{fm}.

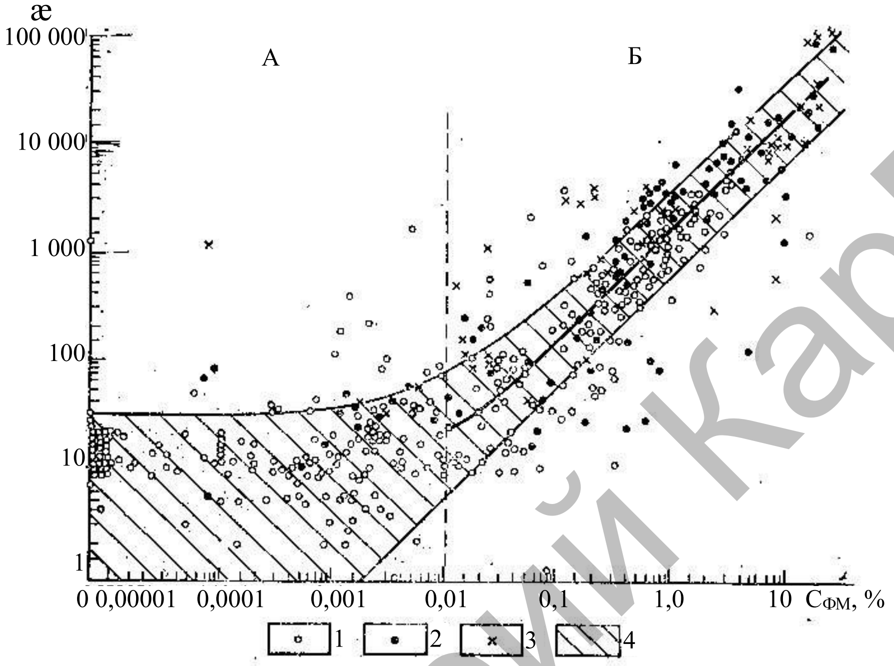
Table

Magnetic properties and standard Gibbs potential of certain minerals

Mineral	Formula	æ	J_s, A/m	$H_C\cdot 10^3$, A/m	$\Delta G^o\cdot 10^3$, kJ/mol
Magnetite	Fe_3O_4	8,8–25	$4,9\cdot 10^{-5}$	0,8–1,2	–1,015
Titanomagnetite	$xFe_3O_4(1–x)TiFe_2O_4$	$1,3\cdot 10^{-4}$	$(0,8–4,3)\cdot 10^5$	–	1,4–1,6
Trevor	$NiFe_2O_4$	6,3	$2,4\cdot 10^5$	–	–0,97
Jacobsen	MFe_2O_4	250	$3,2\cdot 10^5$	–	–
Magnesioferrite	$MgFe_2O_4$	10	$1,4\cdot 10^5$	–	–1,32
Maghemite	γFe_2O_3	3,8–25	$4,4\cdot 10^5$	0,8–10	~1,0
Hematite	αFe_2O_3	$(1,3–13)\cdot 10^{-3}$	$(1,5–25)\cdot 10^3$	550–640	–0,74
Pyrrhotite	FeS_{1+x}	0,13–1,30	$(1,7–7,0)\cdot 10^4$	1,2–8,8	–
Goethite	$\alpha FeOOH$	$2,5\cdot 10^{-4}$	$4,8\cdot 10^3$	56	–0,49
Siderite	$FeCO_3$	$(2,5–7,5)\cdot 10^{-3}$	–	–	–0,68

In view of the weak magnetic interaction of diamagnetic and paramagnetic minerals they create a magnetic effect is defined as the product of the susceptibility to volume concentration. Similarly, for the impregnation of ferromagnetic grains scattered early generation:

$$f\left(\text{æ}_n m_n\right)=\sum_1^n \text{æ}_n m_n,\ f\left(\text{æ}_{фм_1} m_{фм_1}\right)=\sum_1^n \text{æ}_{фм_1} m_{фм_1}$$



1 — granitoids; *2* — diorite and gabbro; *3* — ultramafic; *4* — Field correlation of theoretical calculations; *A* — class ferroparamagnitnyh rocks; *B* — the class of ferromagnetic rocks (magnetic susceptibility is given in 1,26 $\text{æ}\cdot 10^{-8}$)

Figure 2. Diagram of the magnetic susceptibility of the ferromagnetic fraction content in the intrusive rocks

Thermodynamics and magnetic properties of minerals

In [20] used the methods of nonequilibrium statistical thermodynamics to the analysis of the magnetic properties of minerals. Iron associated with magnetite, viewed as a system of non-interacting magnetic dipoles immersed in a thermostat, which is the host rock. Quantum transitions due to the interaction of magnetic dipoles with a thermostat, are dissipative unlike the interaction with the external magnetic field. Dissipative processes lead to the fact that the secondary field is always smaller than the primary. Since the magnetic dipoles subsystem communicates with the thermostat only energy, then the corresponding ensemble of particles to be canonical.

It was obtained relationship between the magnetic susceptibility and æ Gibbs energy G_T^0 minerals and iron content in the mineral

$$\text{æ}=\beta\frac{kT}{G_T^0}C_{Fe}^{мт}. \tag{1}$$

For the magnetite obtained by the equation of communication (*K* — factor of the display):

$$C_{Fe}^{мт}=72,2K,\%\,. \tag{2}$$

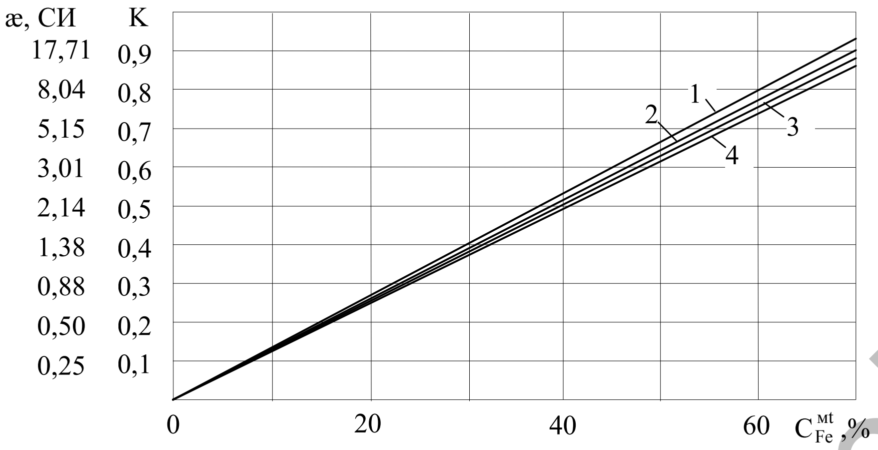
Figure 3 for the iron-ore deposits, the following experimental equation of communication:

$C_{Fe}^{мт}=75,1K\pm 2,32\%$ (Kentobe),

$C_{Fe}^{мт}=76,7K\pm 1,02\%$ (Sarbay),

$C_{Fe}^{мт}=77,5K\pm 1,70\%$ (Kurzhunkul),

$$C_{Fe}^{мт} = 79,5K \pm 0,98\% \text{ (Sokolovskoye).}$$



1 — Kentobe; *2* — Sarbay; *3* — Kurzhunkul; *4* — Sokolovskoye

Figure 3. Dependence of the magnetic susceptibility
and the coefficient of displaying the content of magnetite iron

The results obtained in [20] theoretical equation of communication (2) $C_{Fe}^{мт} = f(K)$ is in good agreement with the experimental ones given above. The maximum deviation from the Sokolovsky deposit ratio (2) is equal to 9.8 %. This may be due to the presence of titanomagnetite ores. Nevertheless, theoretical equation connection (2) is obtained from «first principles» is not attracted to the results of chemical analyzes. This makes it possible to make a preliminary assessment of stocks of iron magnetite.

Calculation of the experimental data in Figure 3 has given importance to $\Delta G^{o} = -1254$ kJ/mol, while the table value obtained by calorimetry as well $\Delta G^{o}_{tabl} = -1014$ kJ/mol, which gives the relative error equal to 11 %. This is quite satisfied with the result, considering that the correlations were based on the results of geological sampling slurry blasting holes with accuracy up to 10 %.

Study of relationship between magnetic susceptibility and chemical composition of rocks is difficult due to the lack of sensitivity to the chemical analysis of subtle changes that affect the magnetic properties of the rocks. Reliable results can only be obtained with a large statistical material.

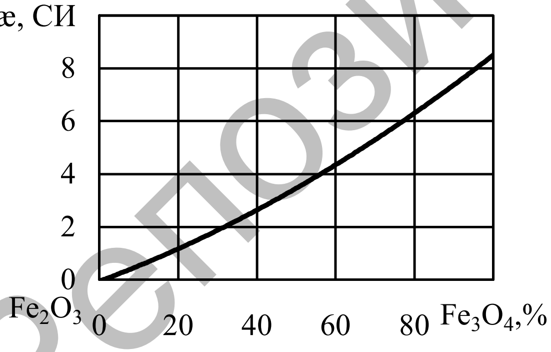


Figure 4. Dependence of the magnetic susceptibility
of the content of the component in the magnetite-hematite

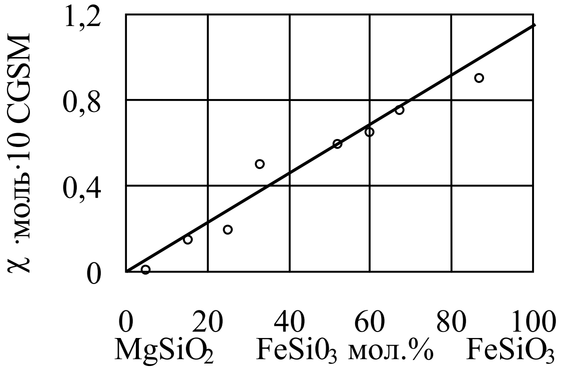


Figure 5. The dependence of the magnetic susceptibility
of the content of components in the system
$MgSiO_3$–$FeSiO_3$ (by T.Nagata)

For a binary mixture Gibbs energy is:

$$G_{см}^{0} = X_1 G_1 + (1 - X_1) G_2, \tag{3}$$

wherein X_1 — number of moles of the pure component 1; (1-X_1) _ number of moles of the pure component 2.

In view of (3), equation (1) takes the form:

$$\text{æ} = \beta kT \frac{1-X_1}{\left[X_1 G_1 + \left(1-X_1\right) G_2\right]}. \tag{4}$$

Consider the behavior of æ in a binary mixture of magnetite-hematite. Using the formula (4), this dependence is shown in Figure 4. For magnetite æ = 9,14, which lies within the values of Table 1. Figure 5 shows the experimental results (T.Nagata).

The character of both curves in Figures 4 and 5 close. Thus, to binary mixtures can reliably use the formula (4), to take into account the effect on the mineral composition of the method of magnetic susceptibility data.

From the formula (4) that the non-magnetic minerals with low energy Gibbs (G_1), will slightly affect the value of æ and thereby to determine the iron content in the ore.

Magnetic properties of minerals and the thermometer deep processes

In case of formation of ideal solid solutions:

$$G^0_{T,i} = RT_0 \ln X_i, \tag{5}$$

or:

$$G^0_T = RT_0 \sum_i \ln X_i, \tag{6}$$

where T_0 — the temperature of formation of the mineral.

For the two-component mixture of the solid solution forming temperature is as follows:

$$T_0 = \beta \frac{k}{R} \cdot N_A \frac{1}{\text{æ}} \; \frac{1-X_1}{\ln X_1 + \ln X_2}. \tag{7}$$

To estimate T_0 take the experimental data for a binary mixture $MgSiO_3$–$FeSiO_3$. When X_1 and X_2 = 0.4 = 0.6 value æ = $7 \cdot 10^{-3}$ and the ratio of (7) gives T_0 =766 K.

For the garnet and pyroxene-garnet skarns æ = $750 \cdot 10^{-5}$, allowing for the formation temperature T_0 = 640 K. The magnetite ore paragenesis with garnet T_0 range from 670 to 870 K, and with garnet and epidote — from 670 to 770 K. Our findings fit into the given temperature range that allows the use of a formula (7) to estimate T_0.

Application of magnetic prospecting more effectively on the fields of magnetic ores: ferruginous quartzites (magnetite difference), magnetite, titanomagnetite ores.

The magnetic rocks (æ> (50: 100)$\cdot 10^{-5}$ and the content of the ferromagnetic fraction> 0.01), a regular correlation between the magnetic susceptibility and the content of magnetite iron, which is the basis for magnetic testing of iron ore deposits.

Knowing the temperature of formation of iron minerals gives the opportunity not only to determine the genesis of the deposit, but also to predict the shape of ore bodies. In turn, the thermodynamic values of the currently known minerals identified with high accuracy in a wide range of temperatures and pressures.

Integration of geophysical methods in the thermometer deep processes

Integration of geophysical methods is one of the leading areas of scientific and technological progress in the exploration industry to help improve the efficiency of geophysical work at all stages, in prospecting and exploration of minerals [21–24].

The need for integration of geophysical methods is caused by two main factors: the ambiguity of the solution of inverse problems of geophysics to determine the nature of the geophysical anomalies and to assess the quantitative parameters of the desired object; the impossibility of using the geophysical method to obtain information about the basic parameters of the objects of study and the host medium.

The main objective of integration of geophysical methods — a unique solution set of geological problems with the definition of the basic parameters of physical-geological models of the objects and the host medium.

From equation (7) to obtain the magnetic exploration methods:

$$T_0 = C_1 \cdot \frac{1}{\text{æ}}. \tag{8}$$

To obtain electrical methods:

$$T_0 = C_2 \cdot \rho. \tag{9}$$

Where ρ — electrical resistivity of the investigated geological object.

To obtain exploration methods gravitational:

$$T_0 = C_3 \cdot \Delta g. \tag{10}$$

There Δg — gravitational acceleration anomaly.

To obtain seismic methods:

$$T_0 = C_4 \cdot \upsilon. \tag{11}$$

Here υ — velocity of propagation of seismic waves in the study of geological objects.

The above constraint equation (8)–(11) between the temperature of formation of minerals and measured values in a particular method of geophysical studies contain a constant that must be determined empirically, using correlation analysis.

The validity of the results will increase with the proximity of the results obtained by various geophysical methods.

If one examines the same geological object, the temperature of its formation is the same, then it is possible to define a constant through another one. For example, from the equations (8) and (9) we obtain:

$$C_1 = C_2 \cdot \rho \cdot æ. \tag{12}$$

Closing

Geologic thermometry methods used throughout the world and are constantly improving. Methods for assessing the geological formation temperature of the object proposed in this paper can be implemented by means of terrestrial or space without extracting the mineral from different depths of the Earth's crust. These methods can replenish the arsenal of modern geological thermometry.

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В.С.Портнов, С.А.Выжва, Н.В.Рева, В.М.Юров

Термометриядағы терең үдерістерге магнитті қабылдағыштық өлшем деректерін пайдалану

Мақалада магниттік қабылдағыштық, Гиббс энергиясы мен минералда темір пайдалы қазбалар арасындағы байланыс анықталған. Байланыстың теориялық теңдеуі эксперименттік деректермен жақсы сәйкестенеді. Минералды қалыптасу температурасында және оның магниттік қабылдағыштық арасындағы қатынасы алынған. Минералдар температурасын қалыптастыру тек қана генезис аймағын анықтап қоймайды, сонымен қатар кен органдарының пішінін болжайды. Геофизикалық зерттеулер, атап айтқанда, минералдар мен өлшенген құндылықтарды қалыптастырудың әдісі температура арасындағы мұндай теңдеулік байланыста корреляциялық талдауды пайдаланып, эмпирикалық жолмен анықталған болуы тиіс тұрақтылығы бар. Егер бір және сондай геологиялық объект зерттелетін болса, онда қалыптастыру температурасы бірдей, сонда басқа арқылы бірдей тұрақтыны анықтауға болады. Авторлар ұсынған объектінің геологиялық қалыптастыру температурасын бағалау әдістері жер қыртысының әр түрлі тереңдікте минералды өндірушісі жоқ жер үсті немесе кеңістік арқылы іске асырылуы мүмкін екендігі жайлы айтты.

В.С.Портнов, С.А.Выжва, Н.В.Рева, В.М.Юров

Использование данных измерений магнитной восприимчивости в термометрии глубинных процессов

В работе показана полученная связь между магнитной восприимчивостью, энергией Гиббса минералов и содержанием железа в минерале. Теоретическое уравнение связи достаточно хорошо согласуется с экспериментальными данными. Выделена связь между температурой образования минерала и его магнитной восприимчивостью. Знание температуры образования минералов даёт возможность не только определять генезис месторождения, но и прогнозировать форму образования рудных тел. Отмечено, что полученные уравнения связи между температурой образования минералов и измеряемой величиной в том или ином методе геофизического исследования содержат постоянную, которую нужно определять эмпирическим путем, используя корреляционный анализ. Если исследуется один и тот же геологический объект, то температура его образования одинакова, тогда можно определить одну постоянную через другую. Методы оценки температуры образования геологического объекта, предложенные в настоящей работе, могут быть реализованы наземными или космическими средствами без извлечения минерала с различных глубин Земной коры.