PROGNOSTIC RESOURCES OF MINERAL DEPOSITS BY GEOPHYSICAL METHODS

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In the framework of non-equilibrium statistical thermodynamics a relation between the concentration of component of the ore to its physical properties.On the basis of this communication formulas for calculation of the differentiated and predicted stocks of deposits of minerals are received on the basis of the geophysical data. Methods of magnetic investigation, electric investigation, gravitational investigation and seismic prospecting, and also nuclear physical methods are considered. A comparison of the calculated expected resources with proven for a number of fields in Kazakhstan.

The proposed method allows to perform predictive assessment of stocks of deposits in the early stages of prospects with using the results of geophysical methods, while it has a rapidity and to be sufficiently accurate.

Non-equilibrium thermodynamics, geophysical methods, and estimated resources, deposits of minerals.

Key words: nonequilibrium thermodynamics, the geophysical methods, predicted resources, deposits of minerals.

Since the early 50s of last century are being intensively developed direct geochemical methods for quantitative determination of probable reserves of ore. Of the thirty-year review of their development [1] that geophysical methods have traditionally belonged to the indirect methods of quantifying probable reserves of ore. Since then, the new basic idea does not appear, but the rapid development of computer simulation methods have forecast stocks based on mathematically and thermodynamically consistent use of geological and geochemical and geophysical data.

In the present work, we propose direct geophysical methods for a quantitative determination of probable reserves of mineral deposits (not just the ore). We use the method of analogies, but not in the sense in which it is used in geology. In geology it is based on knowledge of the geology and mineralization characteristics of the interactions of a deposit. We use the analogy between the physical scalar fields and characterize their parameters.

One of the most successful, in our opinion, forecasting models, determining ore reserves based on the concept of energy mineralization was proposed N.I. Safronov [2; 3]. Using the representation of the Boltzmann thermodynamic probability and its relation to entropy, Safronov N.I. an equation to calculate the differential for a given stock of ore content of the main element K:

$$P_K = \frac{E_K}{E_П} = \frac{1/K}{\sum_i K_i \ln K_i}. \qquad (1)$$

The numerator is the total energy consumption for the formation of ore grade *K* (Boltzmann); denominator is energy consumption per unit volume of the formation of ore grade *K* (on the thermodynamics of ideal solutions).

If the cost of energy for compression-rarefaction of minor elements, in comparison with the main metal, neglected, differentiated stocks *P* k per unit volume are defined as follows:

$$P_K = \frac{1/K_M}{K_M \ln K_M}. \tag{2}$$

Clarke is concentrations of the main metal.

To enter in the calculation of the metal into, account that the amount per unit volume is proportional to K m. Thus, the calculation of the metal:

$$P_K = \frac{1}{K_M \ln K_M}. \tag{3}$$

Application of statistical nonequilibrium thermodynamics to the analysis of geophysical data

To measure the physical properties of geological object to it impact-exist in any primary field (magnetic, electric, etc.) and measure the secondary field (response system), the magnitude of which carries information about the object. Since the process of interaction with the field of object generally occurs quite rapidly (particle relaxation time with ~10—12), it is clear that this process is far from equilibrium. On the other hand, the characteristics of the secondary field carry information about the object being in certain thermodynamic conditions, and possessing the thermodynamic parameters that are directly related to its structural, chemical and physical properties. Thus, with the help of non-equilibrium statistical thermodynamics can try to find a connection between the microscopic (quantum) processes of interaction of the primary fields (parameters that can control and change in a wide range) with the macroscopic characteristics of the geological object. This is the approach we have implemented and applied to the magnetic measurements [4].

Consider the iron that is associated with magnetite, as a system of non-interacting magnetic dipoles immersed in a thermostat, which is ore-hosting breed. Quantum transitions due to the interaction of magnetic dipoles with a thermostat, that will be dissipative (with probability P), in contrast to the interaction with external magnetic field (with probability F). Dissipative processes lead to the fact that the secondary field Z 2 is always smaller than the primary Z1.

Since the magnetic dipole subsystem communicates with the thermostat only energy, the corresponding canonical ensemble of particles will be (4). Statistical interpretation of the Boltzmann takes the form:

$$\frac{g_i P_{ij}}{g_j P_{ji}} = e^{\frac{E_j - E_i}{kT}}, \tag{4}$$

where g_i, g_j — statistical weights for levels E_i and E_j.

Then (5) becomes:

$$\frac{dS}{dt} = \frac{k}{2} P_{ij} \left(\ln f_i - \ln f_j \right) \left(f_i - \frac{g_i}{g_j} f_j e^{-\frac{E_i - E_j}{kT}} \right). \quad (5)$$

The canonical distribution function:

$$f_{ij} = \frac{1}{Z} e^{-E_{ij}/kT}. \quad (6)$$

The partition function:

$$Z = \mathrm{e}^{-G/kT}, \quad (7)$$

where G — the potential (free energy) Gibbs thermostat (host rocks) + system of magnetic dipoles (magnetite ore).

We assume that the configuration is not part of the Gibbs potential is linearly dependent on the concentration of N magnetic dipoles:

$$e^{-G/kT} = \sum_N h(N), \quad (8)$$

where $h(N) = \omega(N)`\, \mathrm{e}^{-G/kT}$; $\omega(N)$ is statistical weight.

Omitting the intermediate calculations, which are detailed in [4], we write the expression for the response function of a system of magnetic dipoles:

$$\Phi = \left(1 + \frac{2\Delta S}{k} \frac{\tau_p}{\tau} \exp\left(\frac{G^0/N}{kT} \right) \right)^{-1}, \quad (9)$$

where ΔS — change of entropy in the dissipative process; τ — relaxation time; τp — the lifetime of the excited state; G^0 — the thermodynamic potential of the thermostat; N — the number of magnetic dipoles in a unit volume of material; k — Boltzmann constant; T — temperature.

As the response function of the measured value can be taken in a particular geophysical methods (magnetic susceptibility, electric conductivity, etc.). To go to the mass concentration of iron associated with magnetite, use the formula:

$$N = N_A \cdot \frac{C_{Fe}^{мt}}{100\%}. \quad (10)$$

If the response function in (9) to take the ratio to display K in the method of artificial magnetization (or magnetic susceptibility), after linearization (10) and calculate all the variables, we obtain the following correlation equation for iron-related magnetite:

$$K = 13{,}86 \cdot 10^3 \frac{C_{Fe}^{мt}}{G^0}. \quad (11)$$

For magnetite, $G^0 = 1{,}014 \cdot 10^6$ J/mol–1.

For Kentobinskogo, Sarbai, and Sokolovsky, Kurzhunkulskogo fields experimentally obtained equation links allow you to define the content of iron in magnetite ores with an error not exceeding 2.3% abs. as a result of building quality (grade) plans horizons pits before drilling blast holes, which holds geological and geophysical testing. The construction of these plans allows you to manage mining operations to ensure the specified quality indicators of ore dilution and reduce losses.

Coupling equation (11) C_{Fe}^{Mt} = f(*K*), agrees quite well with the experimental ones. The maximum deviation for the deposit of Sokolowski (11) is 9.8%. This is due to the presence of titan magnetite in these ores and minerals, the Gibbs energy difference between the containing environment of each field. Nevertheless, the theoretical coupling equation (11) derived from first principles, not related to the chemical analysis makes it possible to assess the reserves of magnetite iron.

Using the log data of magnetic susceptibility for estimating undiscovered resources of iron ore

We make the association of ideas developed above with a model calculation of reserves.

Ores Safronova, N.I. [2]. For ideal processes change its internal energy and enthalpy is zero, and the free energy ΔF coincides with the Gibbs energy ΔG. Then:

$$\Delta F_n = \Delta G = K \ln K. \quad (12)$$

For the magnetic susceptibility of magnetite obtained by the expression (13):

$$g = \beta \frac{kT}{\Delta G_T^0} C_{Fe}^{Mt}, \quad (13)$$

where β = (2,4 + 0,7) · 10—2 units.

Given that the average content of iron in the Earth's crust $C_{Fe}^{н} = 4{,}65\%$ then (113) takes the form:

$$\ln K = 16\left(C_{Fe}^{к}\right)^2 \Big/ g. \quad (14)$$

Then, we can show from (11), (12), (13) and (14) that differentiated stocks of the metal has the following formula:

$$P_K = \frac{1}{\ln\left(q_1 g_{cp}\right)} \cdot 100\%, \quad (15)$$

where q_1 — is factor of 11 406, obtained based on the values $\beta, C_{Fe}^{Mt}, N_A, k, T$; $æ_{cp}$ — the mean value of the magnetic susceptibility of magnetite ore.

Sokolowski for the deposit, for example is the average value $æ_{cp} = 7{,}5$ ед. СИ, and (15) gives the iron content per unit volume and 8.81% for magnetite — 23.6%. N.I. Safronov for the same deposit was 11.359%, respectively, values and 26.06%. This is slightly different from our results.

In order to estimate the reserves using the relation (15), it is necessary to know the geometry of the ore bodies, their average magnetic susceptibility, and the volume content of magnetite in the ore. For most of the magnetite deposits in Kazakhstan, these parameters were determined [6]. Below, in Table 1 are calculated with these data, and (15) the resources of magnetite ores of some deposits of Kazakhstan.

Table 1

Resources of Kazakhstan deposits black iron ore, mln. tones

Deposit	Ore resources, mln.tones	
	Forecast	Explored [6]
Sokolovskoye	5 330	3 343
Sarbaiskoye	2 108	890,3
Kacharskoye	6 005	3 998
Second (basic orebody)	71,87	32,733
Third orebody	17,31	13,51
Kurzhunkulskoe	639,3	more than80

Table 1 shows that forecast resources of Sokolovskoye and Sarbaiskoye deposits amounted in sum to 7438 mln. tones and surveyed ones — 4233 mln. tones. N.I. Safronov supposes that the amount of unexplored reserves of these deposits comes up to 3—4 billion tones and it complies with our results. Alongside with previously known methods the advantage of the abovementioned calculation of black iron ore is rapidity of it along with satisfactory accuracy of its results. The method enable to calculate ore reserves within the limits of ore level and block area covered by measurements of magnetic susceptibility of ore in situ and also to carry out by — level quality assessment by means of determining an average value magnetic susceptibility.

Analogy method and analogy fields

There are significant amount of examples in physical science for successful use of analogy method and this forms background for conferring to analogy the status of being the one of the possible methods of scientific knowledge, it was brilliantly proved by G. Makswell [7]. Table 2 shows the analogy exists between values in different scalar fields.

Table 2

Analogy between values in potential fields [8]

Parameter	Electrostatic field	Current field	Magnetostatic field	Thermal field
Potential	U potential	U potential	Ω potential	T temperature
Gradient	E electric field intensity	E electric field intensity	H magnetic field strength	Grad Ttemperaturegradient
Constant, specified the properties of medium	ε dielectric permeability	σ conductivity	μ magnetic permeability	a temperature conductivity
fluxdensity	D dielectric density	j current density	B magnetic fluxdensity	q heat-flowrate
sourcestrength	ρecharge density	j electric current density	ρm magnetic masses density	Q heat source density
conductivity offield	C capacity	G electrical conductivity	Λ magnetic conductivity	λ heat conduction

The results of resistivity (p) measurements in different methods of electrical exploration can be used for calculation of forecast mineral resources.

By using analogy (table 2) for electrical exploration method we will get the following:

$$P_K = \frac{1}{\ln(q_2\sigma)} \cdot 100\%, \tag{16}$$

where σ — electric conductivity of mineral $(\text{Ohmm})^{-1}$.

By using previously got experimentally proved value q_1 for average values of magnetic susceptibility and by making (15) equal to (16), for the very same deposit it is easy to get the following

$$q_2 = q_1 g_{cp} \rho_{cp}, \tag{17}$$

where ρ_{cp} — the electrical resistivity average value of black iron ore.

This enables to calculate the q_2 figure which is equal to — 155121. The q_2 value the same as the q_1 one can be determined in a laboratory environment by determining the content of efficient element in ore by means of physical or chemical methods of analysis and measuring a counterpart in formulae (16) and (17). Table 3 illustrates the suggested method.

Table 3

Forecast differentiated coal resources of Karaganda coal basin basic series

Series	Specific resistance of coals, ρ (Ohm m) [Drizhd and others]	Differentiated coal Resources $P_к$ (%)
Dolinskaya	134,8	14,2
Tentekskaya	155,0	14,5
Karagandinskaya	145,1	14,3
Ashlyarinskaya	86,7	13,4

The thermodynamic analysis of magnetic susceptibility measurements results suggested by us was also used for gamma-gamma method. The difference is that Eγ gammas energy significantly overruns magnetic dipole energy therefore it is impossible in this case to ignore exp(Em/kT) component in formula for response function. Taking relative intensity scattered gamma radiation with Eγ energy as a Φ response function we get the following:

$$1 - \frac{I}{I_0} = -B \frac{C_{Fe}}{G^0 E_\gamma}, \tag{18}$$

where I — the intensity of gammas being recorded after diffusion; I_0 — intensity of gammas from source; $B = (kT)^2/C$, $C = 2\Delta S/k$ — constant for given element and a source of gamma emission; ΔS — entropy change when quantum jump from excited state toground state; $\Delta S = \overline{N} E_\gamma^2 / 2kT^2$, where $\overline{N}$ — average number of element atoms in mineral; G^0 — Gibbs energy of ferriferous mineral with total ferrum content of C_{Fe}.

The linear dependence of scattered intensity vs. C_{Fe} ferrum content follows from (18) that corresponds the experimental data.

In order to calculate the forecast resources along with the use of measurement results in gamma-gamma method it is enough just to do an analysis which similar to abovementioned and to use (18) formula. As a result, when q_4 = 809826, we get the following:

$$P_K = \frac{1}{\ln\left(q_4 I / I_0\right)} \cdot 100\%. \tag{19}$$

Forecast resources calculated with the use of formula (19) for a number of iron-ore deposits are shown on table 4.

Table 4

Iron ore and coal deposits of Kazakhstan resources, mln. tones

Deposit	Ore resources, mln. tones	
	Forecasted	Explored [6]
Atansore	51,6	55,9
Tlegen	19,3	12,0
Kuzgan	23,4	14,6
Sarytobe	35,9	20,0

We use the analogy between electric and acoustic systems given on table 5.

Table 5

Analogy between electric and acoustic variables and parameters [9]

Electric system	Acoustic system
Voltage *V*	Pressure P
Current *I*	Particlevelocity ν
Charge e	Biasing u
Inductance *L*	Medium density ρ
Capacity *C*	Acousticcapacitance $C_A = 1/\tau$
Resistance *R*	Acousticresistance R_A

We consider particle velocity υ to be interesting as it is the value measured by seismic exploration. For the forecasted resources of mineral raw material the following formula were got by use of seismic exploration data

$$P_K = \frac{1}{\ln\left(q_5\vartheta\right)}\cdot 100\%, \qquad (20)$$

where $q_5 = 26{,}03$.

As an example the results of forecasted differentiated resources calculation according to formula (20) are presented on table 6 for the resources of Karaganda basin coal series that have been already calculated on the base of electrical exploration data.

It is obvious that two methods comply against each other quite good within a limit of experimental error

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Determination of forecast mineral resources is economically important. The use of geophysical methods of exploration especially in situ (the method of forced magnetic biasing, the method of induced electric polarization etc.) enables significant savings in costs for exploration boreholes drilling. It also should be mentioned that the figure for the relevant physical value (magnetic susceptibility, specific resistance etc.) is determined by Gibbs energy value.

As is known the last mentioned is equal to G_0 = H – TS + PV, where H enthalpy defines ore and minerals metamorphism, S entropy determines its structural order, temperature and pressure — thermodynamical conditions of mineral formation process.

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ПРОГНОЗИРОВАНИЕ РЕСУРСОВ МИНЕРАЛЬНЫХ МЕСТОРОЖДЕНИЙ С ПОМОЩЬЮ ГЕОФИЗИЧЕСКИХ МЕТОДОВ

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В рамках неравновесной статистической термодинамики установлена связь между концентрацией полезного компонента в руде с ее физическими свойствами. На основе этой связи получены формулы для расчета дифференцированных и прогнозных ресурсов месторождений полезных ископаемых с использованием результатов геофизических исследований методами: магниторазведка, электроразведка, сейсморазведка и селективный гамма-гамма метод. Проведено сравнение рассчитанных прогнозных ресурсов с разведанными для ряда месторождений Казахстана.

Предложенный метод позволяет выполнить прогнозную оценку запасов месторождений на ранних стадиях разведки с использованием результатов геофизических методов, при этом он обладает экспрессностью и достаточной точностью.

Ключевые слова: неравновесная термодинамика, геофизические методы, прогнозные ресурсы, месторождения полезных ископаемых.