SUPERPARAMAGNETIC EFFECT OVER GOLD AND NICKEL DEPOSITS

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ABSTRACT

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The results of investigations of the superparamagnetic (SPM) effect, which takes place with the transient electromagnetic method (TEM) process, are discussed. Depending on the objective of the investigations, the SPM-effect can be considered either as a disturbance or as a useful tool. In this paper we consider some ways of suppressing SPM noise when conventional TEM investigations are carried out, and the application of SPM for mineral deposits exploration. Such an application is based on specific properties of subsurface rocks and soil samples above gold and nickel deposits. It is shown, that anomalies with relaxation time constants of SPM-processes are spatially correlated with the ore deposits. The nature of the anomalies can be connected with the presence of a mixture of elements in ferromagnetic minerals producing an SPM-effect. It is proposed that these elements have been brought to the surface by upgoing gas flows from the deep-lying ore-containing bodies and are characteristic in tectonic fault zones. The spatial peculiarities and supposed mechanism of their formation give us a possibility to use them as a tool for exploration of certain types of mineral deposits, such as those of gold and nickel.

KEY WORDS: magnetic viscosity, transient processes, electromagnetic prospecting, gold and nickel deposits.

INTRODUCTION

Some articles describing the effect of a superparamagnetic (SPM) response on transient electromagnetic (TEM) were published in the beginning of the '80s. This effect manifests itself most intensively in cases when closely located or coincident transmitter and receiver loops are used. The detected transient response contains a component with a short relaxation time that partially or fully masks the useful TEM signal. An SPM-effect in rocks is connected with processes of magnetic moment change of orientation of very fine grains (with diameters of a few Ångstroms) of ferromagnetic minerals in the initial stage after a sharp change of the exciting magnetic field. The study of rock samples producing this effect shows that the effect is connected with the phenomenon of magnetic viscosity, also known as superparamagnetic effect.

At present magnetic viscosity of rocks is recognized to be conditioned by fluctuations of the thermal energy that shift boundaries of domains along the acting field. Neel (1950) supposed that:

1. These fluctuations create an internal magnetic field which helps the domain's boundaries to overcome potential barriers,

2. Thermal activation processes have a hysteresis character. Under these assumptions viscous change of the remanent magnetization of rocks can be presented in the form (Stacey, 1963; Nagata, 1961)

$$J_{r1} = J_{r0} - S(Q + \ln t) \ , \tag{1}$$

where J_{r0} is the remanent magnetization just as the external magnetic field is turned off, S and Q are some constants. Correspondingly, the magnetic field at delay time t after shutdown is

$$H(t) = H_0 - NS(Q + \ln t) \ , \tag{2}$$

where N is a demagnetizing factor of a rock sample in the field's direction. The e.m.f. E in the receiving loop is proportional to $\sim \partial H/\partial t$, so $E(t) \sim 1/t$, and on a double logarithmic scale the graph of E(t) is a straight line with a slope of -1.

Lee (1981), Buselli (1982) and other investigators studied the effect of SPM on TEM results. Investigations of the SPM-effect allowed the main characteristics to be defined:

a) The most intensive SPM-effects exist in areas of effusive and volcanic-sedimentary rocks, superficial clay formations covering parent rocks are the most superparamagnetic;

b) SPM-effects can be measured in conditions of long-term permafrost and are usually located on the border of zones of thawing frozen rocks;

c) Significant SPM-effects are observed on glaciers;

d) As a rule, SPM is created by particles (with a radius $r \sim 10^{-9}$ - 10^{-7} m) of magnetite and maghemite.

Sometimes SPM-effects are treated as a frequency dispersion of a magnetic susceptibility of rocks (analogous to IP responses as a frequency dispersion of conductivity) (Tabbagh and Dabas, 1996). The transient characteristic (response to a step-type turn off of a magnetic field) of magnetic susceptibility χ_{SPM} is convenient for representing SPM effects obtained with TEM responses as a relaxation model.

$$\chi_{SPM}(t) = \chi_{SPM} \cdot K/t \ , \qquad (3)$$

where the factor K is

$$K = [\exp(-t/\tau_1) - \exp(-t/\tau_2)] \ / \ \ln(\tau_1/\tau_2) \ . \qquad (4)$$

The time constants $\tau_1 \gg \tau_2$ depend on many factors and they usually (for TEM) can be taken as $\tau_1 = 1$ s and $\tau_2 = 1$ μs. The slow rate of the characteristic transient decay in time as $E(t) \sim 1/t$ is a very important characteristic of SPM (since the induction process E(t) decreases not slower than $\sim 1/t^{5/2}$). For identification of the SPM response in recorded data, one can calculate the function $t_{\neg\Pi}$ E(t). On multiplying by time the late stages of the transient response containing an SPM component, a function that almost does not vary with time, is obtained.

Experiments (Barsukov and Fainberg, 1997) showed that observable SPM processes are slightly different from 1/t and can be approximated as $E \sim 1/t^{1+\delta}$, where $-0.2 < \delta < 0.2$. For coaxial circular antennas R (transmitter) and r (receiver), located above a superparamagnetic half-space at height h, the SPM transient is described by the formula:

$$E(t)/I = \mu_0 \cdot \chi_{SPM}(t) \ F(R,r,h) \ . \qquad (5)$$

The geometrical function F is

$$F(R,r,h) = (1/2)(R \cdot r)^{1/2} \cdot Q_{1/2}(x) \ , \qquad (6)$$

where $Q_{1/2}(x)$ is the Legendre function of order 1/2 with argument $x = (4h^2+r^2+R^2) \ / \ 2rR$.

In case of coincident configuration for $R = r$ and small values of $h/R \ll 1$, the geometrical function F is proportional to perimeter of the antenna

$$F(R,h) = (1/2)R \cdot \ln(R/h) \ . \qquad (7)$$

For $R = r$ and $h = 0$, F is equal to the inductance L of the antenna. For $r < R$ and $h = 0$, function F is equal to the mutual inductance M of the antennas. For a reduction of the radius r of the receiving antenna, the function

F sharply decreases in the interval $1 > r/R > 0.9$, and further approaches an asymptote proportional to the area of the receiving antenna:

$$F(r,h) \sim r^2 \quad . \tag{8}$$

Precise calculations of the transients for horizontal layered conductive and superparamagnetic media have shown, that the interaction of induction currents in the media and SPM-effects can be neglected, i.e., it is possible to consider these effects as additive.

REDUCTION OF SPM-EFFECT

To reduce the SPM-effect on the results of TEM soundings, three approaches are possible:

1) reducing the mutual inductance of antennas,
2) increasing the size of coincident antennas,
3) lifting the coincident antennas above the surface of the ground.

Variant 1

Use of the coaxial in-loop configuration is the most preferable one, because distortion of induction processes does not occur and the received data can be easily interpreted by conventional methods. However, even under the most favorable conditions the ratio of SPM-effects to induction can be improved only by 3.5 - 4 times, and that may be insufficient. For a remote small receiving antenna away from the side of a transmitter loop, the effect of attenuation is more significant; however, interpretation of the recorded transient at small and average times is extremely complicated with this geometry.

Finally, it is possible to use two identical antennas separated by some distance as transmitter and receiver loops, ensuring practically zero magnetic coupling (mutual inductance of antennas M). This method sometimes provides 50-100 times suppression of the SPM response; however, in real field conditions it is extremely time-consuming.

Variant 2

As was shown earlier, the signal in the coincident configuration is proportional to the square of the loop's area, of $\sim R^4$, while the SPM-effect at shallow depth of the bedding of magnetic layers is proportional to the perimeter of the antenna, or $\sim R$. Thus, with increase of the antenna's size from 25 to 50 m, the ratio between "useful" induction and "harmful" SPM-effects will increase by a minimum of 8 times ($\sim R^3$).

Variant 3

If the SPM-effect in a soil layer is not too large (in 80 % of the practical cases), application of small coincident antennas with a size not more than 50 × 50 m is a rather an effective way. It is effective both from point of view of quality of results, as from minimisation of the acquisition.

The raising of a 25 × 25 m antenna by 1 - 1.5 meters produces a reduction of SPM effects by 3-4 times and yields a TEM response practically without strong distortion. The effect of raising an antenna was investigated in detail by Buselli (1982). He demonstrated that the amplitude of the noise, arising when moving the receiver loop in the earth's magnetic field during the current pulses, does not exceed the 1μV level. This value is less than resolution of TEM-FAST system (manufactured by AEMR Ltd., The Netherlands), which we used for investigations of the SPM effect.

SPM OVER MAGNETIC DEPOSITS

Fig. 1 shows the apparent resistivity as a function of delay time measured with coincident antennas above terrigenous sedimentary rocks under permafrost conditions (of Norilsk, Taimyr Peninsula, Russia). At first sight the field data show the presence of a well-conducting horizon with $\rho < 10$ Ωm at rather large depth (h ~ 200 - 300 m). However, with a change of the antenna's size the curves $\rho(t)$ should coincide late in time, but that does not occur. Just this behavior indicates the presence of distortions of TEM processes by SPM-effects.

A superparamagnetic effect produced by a layer of frozen rocks at a depth of about 20 - 23 m can be used to locate thawing horizons which elude detection by any other method, except for geothermal researches in a well. In this case the SPM-effect was considered as a "useful" signal. The depth of bedding of the "SPM-layer" h was calculated using the ratio of signals at delay times t = 2 - 6 ms for different sizes of antenna [by analysing the function F(R,R,h)]. Taking into account that the induction processes in rocks with resistivities $\rho > 1000$ Ωm are some orders of magnitude less than SPM, the errors of estimation of h are determined only by the heterogeneity of distribution of magnetic minerals in the "SPM-layer".

As already noted, TEM has a restricted response (or in general is inapplicable) in highly resistive media or when using very small antennas, because the signals of TEM are proportional to $\sigma^{3/2}$ (where σ is the conductivity of the media) and to the square of the area of antennas. It is not possible, for example, to determine the conductivity of rock samples with this method.

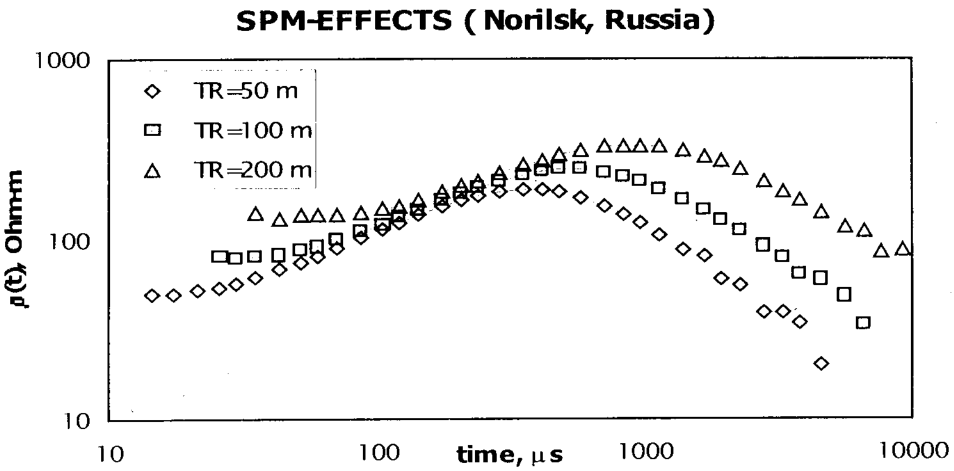

Fig. 1. Superparamagnetic effect over permafrost (for different diameter of transmitter loop) (Norilsk, Russia).

However, an SPM-effect is proportional to an inductance of the coincident antenna, i.e., for a small coil with n turns (or solenoid) with the core made from rocks, the signal E(t) is proportional to $\sim n^2R$.

An elementary demonstration of SPM measurements in laboratory can be done with a flat coil of n = 20 - 30 turns and a diameter of 5 - 7 cm, placed on a surface of a usual red brick. Despite the very high resistivity of Samel clay, after measurements with TEM-FAST instrument on the PC screen one can see a powerful signal E(t) ~ 1/t. Samel clay has intensive superparamagnetic properties. In Figs. 2 and 3 the results of measurements of magnetic and superparamagnetic susceptibility of samples of superficial deposits (sample W ~ 50g taken from depth 20 - 25 cm over the area of 12 hectares) are given. The investigations of the use of the SPM effect for exploration of gold - silver ore in scarns (Khakasia, Russia) were carried out with samples taken on a network of 10 m × 20 m. The magnetic susceptibility was measured with a viscometer, and SPM susceptibility with a solenoid with l = 100 mm, d = 12 mm, number of turns n = 200. The dried samples were used to fill the cavity of a solenoid with an internal volume of ~ 10 cm^3, and the measurements of SPM-signals were carried out with the TEM-FAST.

Estimations of χ_{SPM} in terms of SI units are made with eq. (3) (τ_1 = 1 s, τ_2 = 1 ms) with correction for the inductance of the solenoid. Comparing the data displayed in Figs. 2 and 3, four local χ_{SPM} anomalies (Fig. 3) can be noticed in the western part of the area. The subsequent drilling of boreholes has shown a sub-meridional mineral containing zone crossing all these anomalies.

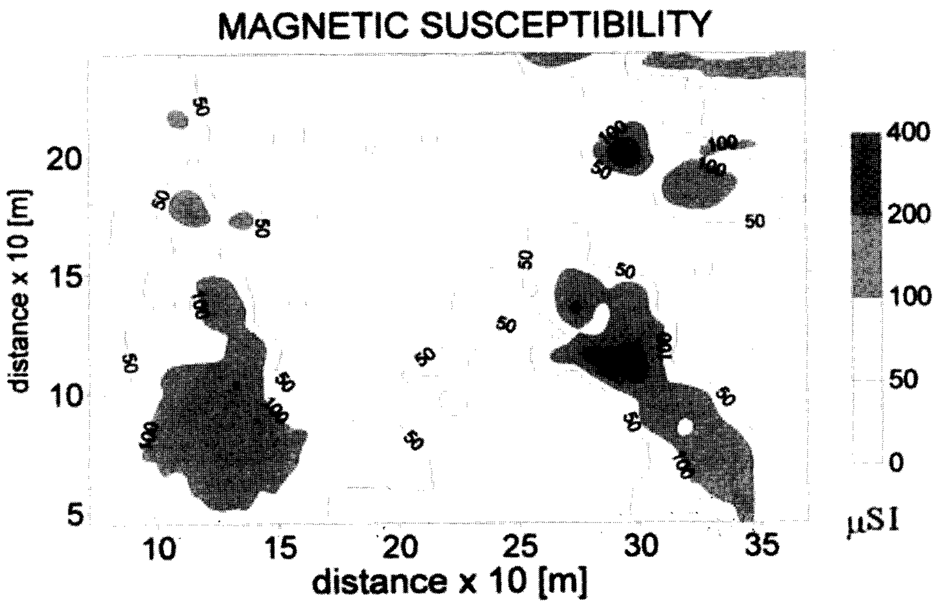

Fig. 2. Magnetic susceptibility of rock samples (Khakasia, Russia).

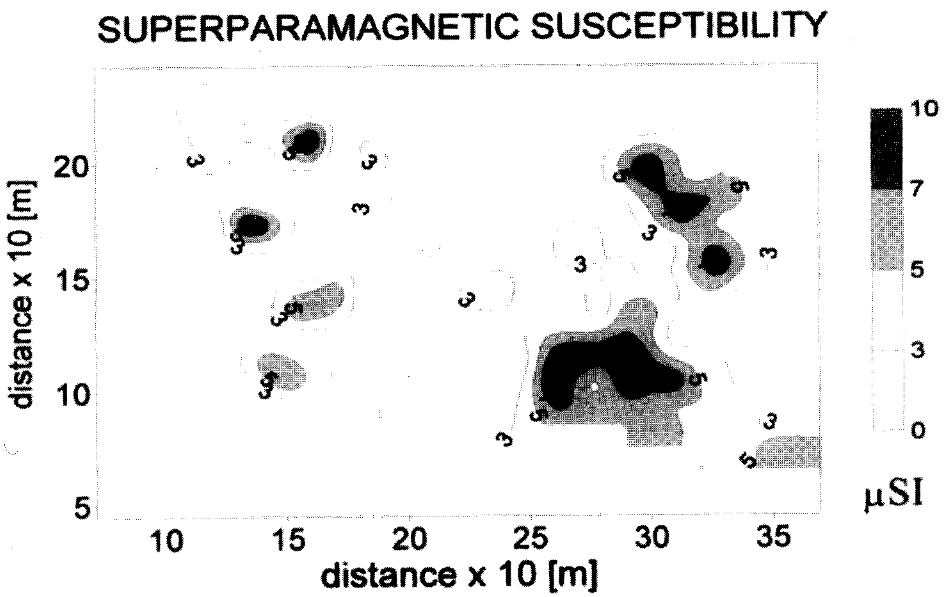

Fig. 3. Superparamagnetic susceptibility of rock samples (Khakasia, Russia).

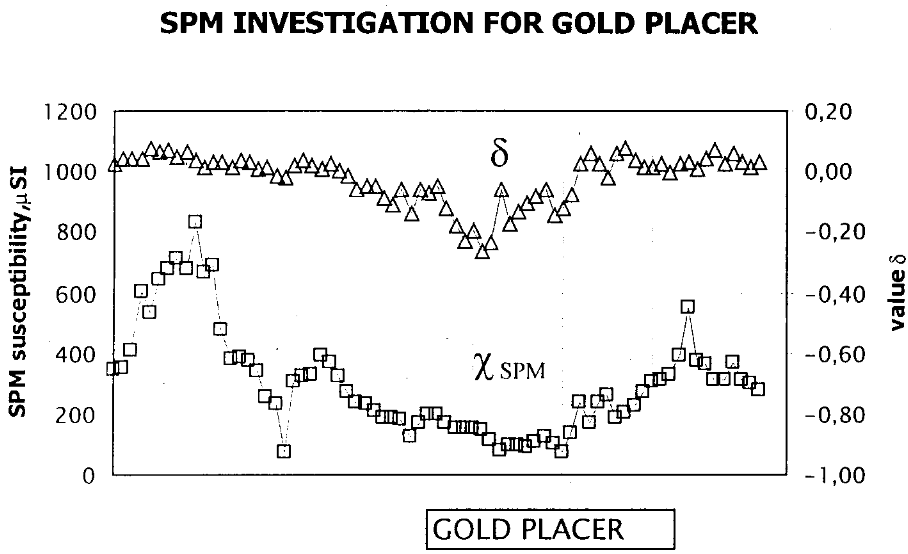

Fig. 4. SPM-effects over a structure with rich stream-gold.

In Fig. 4 the results of measurements of SPM-effects on a structure through rich stream-gold are presented. The deposit is located at a depth of about 40 metres and is covered by a layer of terrigenous sedimentary rocks. For the analysis, samples of superficial clay (Volume ~ 1.5 litres) were extracted from a depth of 20 cm and after drying were positioned in the cavity of a special high-sensitivity SPM-sensor manufactured as a hollow toroid. After measurements of SPM-susceptibility χSPM, an additional parameter δ which is the small increment in the power law index of the measurements E(t) ~ $1/t^{1+\delta}$ was determined.

The data recorded along the profile crossing a gold placer deposit (Chelyabinsk region, Russia) are shown in Fig. 5. Close correlation between the spatial distribution of χ_{SPM} and χ_{stat} testifies to the fact, that the relation of the concentration of small ferromagnetic grains with an SPM response and the concentration of larger particles changes weakly along the profile being in the limits of 1:3 - 1:4. However, these parameters do not correlate in space with the deposit zones and their nature, probably they are not connected directly with gold placers.

The plot of the δ profile presents obvious interest: above the blocks which do not contain gold there is $\delta > 0$, that is H′(t) decreases faster than 1/t, while $\delta < 0$ is observed above the ore deposit zones, where H′(t) decreases slower than 1/t.

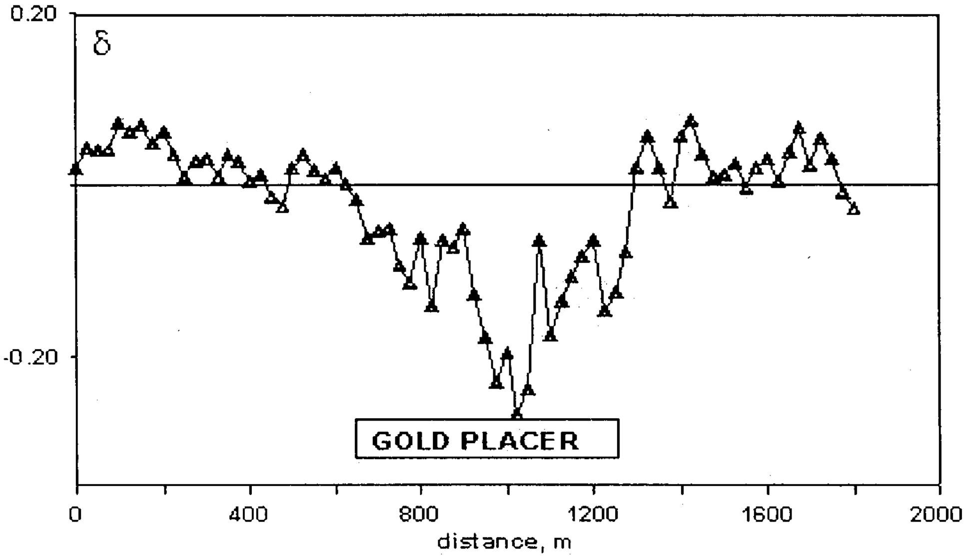

Fig. 5. δ-parameter measured along the profile crossing gold placer deposit (Chelyabinsk region, Russia).

In Fig. 6 the results of SPM-effect measurements above deep-lying intrusive nickel-containing bodies (Voronezh region, Russia) are presented. The χ_{SPM} profile does not correlate with the projection of the ore bodies. At the same time, the behaviour of the incremental parameter δ is the same as in the previous case: above the places where ore deposits exist $\delta < 0$, and on the contrary, $\delta > 0$ if there are no ore bodies.

It should be noted, that unlike the gold deposit where ore-containing blocks were overlapped by terrigene deposits of 20 - 40 m thickness, in the last case sub-vertically lying nickeliferous intrusive rocks were overlapped by terrigene deposits whose thickness was not less than 250 - 300 m.

The measurements of rock samples taken from different depths of both profiles showed that the values of χ_{SPM} and χ_{stat} up to two metres deep either increase slowly or do not change, and the δ parameter remains constant. Supposing that the recorded SPM-effects are produced mainly by magnetite-maghemite aggregates, it is possible to estimate the weight of grains which are in an SPM state to be 10^{-3} - 10^{-4}%; for hematite grains this value is 1.5 - 2 order of magnitudes larger.

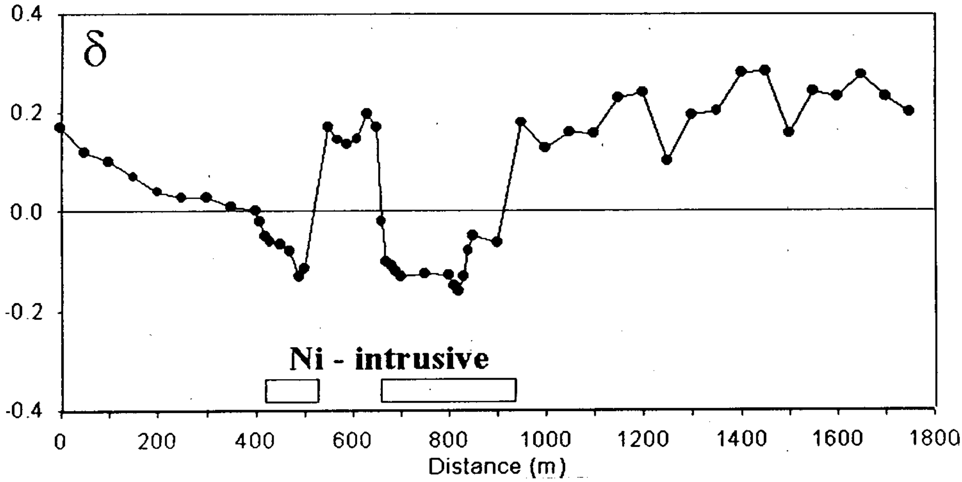

Fig. 6. δ-parameter measured above deep-lying intrusive nickel-containing bodies.

Taking into account both the data known before and those described above, one can suggest the following model of SPM anomaly formation. Grains of ferromagnetic minerals with a wide spectrum of sizes have been absorbed by clay fractions of terrigene rocks and have imparted to them rather intensive magnetic properties: the static magnetic susceptibility χ_{stat} can achieve a value of $3{,}000 \cdot 10^6$ SI units and even more.

DISCUSSION

In order to understand the behaviour of SPM effect over the mineral deposits, we have to understand the nature of the registered close spatial correlation between the measured rate of decay of SPM processes and properties of mineral deposits. There are two questions: 1) why the measured rate of decay differs from 1/t, and 2) what is a mechanism of transportation of mineral particles from deposits to sediments.

Averyanov (1965, 1967), Tropin and Vlasov (1966), and Tropin (1969) tried to improve the theory of magnetic viscosity of rocks. According to their theory, the energy of thermal fluctuations is expended not only in some work to overcome the energetic barrier, but in energy of magnetic field E_m in a volume of defects, exchange energy E_w and in energy of crystalline anisotropy E_k as well. Neel (1950) theoretically considered only the energy of magnetic field E_m. Tropin and Vlasov (1966) estimated the role of the exchange energy and demonstrated that for magnetite $E_w/E_m \sim 1$. This means, the process of the viscous demagnetizing depends on the rock's material.

A more sophisticated treatment of Neel's theory showed that the height of the potential barriers does not remain unchanged in time. The thermal fluctuations make the diffusion of extrinsic atoms and ions easier, and this can cause the height of potential barriers to gradual inconvertible change. Taking this factor into account results in a new relation for the magnetic field:

$$H(t) = H_0 - NS[Q + (\ln t - \delta)] \ , \tag{9}$$

where δ is a complex function depending on time. In simplified form

$$E(t) \sim \exp[-B \cdot \exp(-\beta t)]/t \ . \tag{10}$$

Here the factor $B \sim \chi_0/\chi_\infty$ characterises disalignment of magnetic susceptibility and $\beta \sim 1/\tau$, where τ is the constant of relaxation of the boundary layer's energy. It follows from (9) and (10) that the larger the disalignment of magnetic susceptibility B, the larger the decay E(t) differs from a straight line (on a logarithmic scale). The theory of magnetic viscosity of rocks is not completed yet. However, as was demonstrated above, a relation between the speed of decay of E(t) and viscous properties of rocks does exist.

Chunhan et al. (1997) experimentally investigated gas bubbles in which nitrogen, oxygen, argon and methane were the main constituents. These volatiles came mainly from the mantle by gas exhalation. Gaseous matters are continuously transferred from the depth to the surface by many factors, mainly by pressure effect. Studies of the gas dispersion halo revealed that the geogas flows can vertically transport metallic particles either in the condition of high temperature or in the state of atmospheric temperature. The analytical transmission electron microscopy technique (ATEM) discovered that the geogas composition includes Si, Al, K, Na, S and small amount of Fe, Mg, Ti, V, Zn, Au, As, Ba, Ca, etc. Specifically these elements form an SPM effect. Some successful examples of geogas prospecting show that the geogas anomalies present not only the above concealed mineralisations, but also above ore-bearing fracture zones (Kristiansson et al., 1990).

CONCLUSION

1. It is possible to measure SPM in samples of rocks in laboratory or directly under field conditions, using special portable sensors.

2. It is worthwhile to analyse data directly in the field to identify distortions caused by SPM-effects. If necessary, one should change the loop geometry to suppress distortions. Three characteristic attributes of SPM distortions should be remarked:

- the late stages of process are proportional to E(t) ~ 1/t,
- the resistivity $\rho(t)$ sharply decreases with delay time to a value lower than the known one,
- the curves $\rho(t)$ on late times for different size of antennas are parallel on a double logarithmic scale.

3. SPM-effects carry information about magnetic viscosity of the media under investigation. In some cases a SPM-effect can be used as a powerful tool for exploration for certain types of mineral deposits. The experiments showed that sometimes this new tool provides information about deposits buried at great depth, even in situations where conventional methods of electromagnetic sounding are inefficient or expensive.

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