Case History

Application of piezoelectric and seismoelectrokinetic phenomena in exploration geophysics: Review of Russian and Israeli experiences

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ABSTRACT

Systematic research of piezoelectric and seismoelectrokinetic phenomena in the context of exploration geophysics began in the former Soviet Union in the mid-1950s. These phenomena are manifested by electrical and electromagnetic (EM) processes that occur in rocks under the influence of elastic oscillations triggered by shots or mechanical impacts (hits). This paper presents a classification of piezoelectric and seismoelectrokinetic phenomena, which is based on the analysis of abundant theoretical, laboratory, and field data accumulated mainly by Soviet, Russian, and Israeli researchers. This classification divides the above phenomena into the following types: (1) the seismoelectrokinetic (electrokinetic) phenomenon E, which occurs in poly-phase media because of the mutual displacement of the solid and liquid phases; (2) the piezoelectric phenomenon, which occurs in rocks that contain piezoactive minerals; (3) the shot-triggered phenomenon, observed in rocks in the vicinity of a shotpoint or hit point; (4) the seismoelectric phenomenon I, manifested by the change of the electric current passing through rock; and (5) high-frequency impulse EM radiation, generated by massive base-metal bodies. This paper describes these five phenomena in detail — their nature, manifestation patterns, and registration techniques. Because the manifestation patterns of the phenomena differ in various types of rock, the phenomena can be used as a basis for geophysical exploration techniques.

The piezoelectric method is an example of a successful application of piezoelectric and seismoelectrokinetic phenomena in exploration geophysics. This method was developed in the former Soviet Union, and it has been applied successfully in mineral exploration and research in Russia and, recently, in the West. The method uses a new geophysical parameter: piezoelectric activity of rocks, ores, and minerals. It enables direct exploration for pegmatite, apatite-nepheline, sphalerite, and ore-quartz deposits of gold, tin, tungsten, molybdenum, zinc, crystal, and other raw materials. This method also differentiates rocks such as bauxites and kimberlites from host rocks by their electrokinetic properties.

INTRODUCTION

A number of electric and electromagnetic (EM) processes occur in rocks under the influence of elastic oscillations triggered by shots or mechanical impacts (hits). These processes are the result of polarization of rocks, changes in their conductivity, electrokinetic potentials, and magnetic and dielectric permeability. The processes can be divided into seismoelectric and seismomagnetic phenomena. Seismoelectric (piezoelectric and seismoelectrokinetic) processes in rocks are manifested by the occurrence of electric potentials as well as by changes in electric current that pass through the rocks.

According to our classification (Figure 1), in rocks under the influence of elastic vibrations or static pressure, five piezoelectric and seismoelectrokinetic phenomena arise:

1) The seismoelectrokinetic effect E arises as a result of polarization of rocks by relative displacement of solid and liquid phases and is observed mainly in sedimentary rocks. This effect is the basis for development of a seismoelectric method for searching for economic minerals differing in their electrokinetic properties (kimberlites, bauxites, water, hydrocarbons, some archaeological targets). A subset,

the electrokinetic sounding (EKS), is based on the physical fundamentals of seismoelectrokinetic effect *E*. EKS arises from the movement of pore fluids under seismic excitation and may have an essential importance in hydrogeologic investigations.

2) The piezoelectric effect arises as a result of electric polarization of piezoelectric minerals. This effect is the basis for a piezoelectric prospecting method oriented to search directly for pegmatite and apatite-nepheline deposits, ore-quartz gold deposits, tin, wolfram, molybdenum, mica, and rock crystal. The piezoelectric method can be used also in the search for polymetallic deposits of predominantly sphalerite composition.

3) The shot-triggered phenomenon is observed in rocks in the vicinity of a shotpoint or hit point. This effect is used in the piezoelectric method to mark the instant of elastic vibration generation.

4) The seismoelectric phenomenon *I* is manifested by the change of the electric current passing through rocks brought about by the passage of a seismic wave. This effect has not yet received broad application in applied geophysics.

5) High-frequency impulse EM radiation appears in polymetallic orebodies under the influence of elastic vibrations. The discovery of this phenomenon was used to develop the radio-impulse method of searching and prospecting for polymetallic deposits.

The effect of elastic vibrations in rocks produces almost all types of piezoelectric and electrokinetic phenomena, but the most important is piezoelectric activity of rocks, ores, and minerals. Other phenomena may be considered as subsidiary effects or noise.

Manifestation patterns of piezoelectric and seismoelectrokinetic phenomena vary in different types of rock, which makes these phenomena a potentially attractive basis for geo-

Figure 1. Types of piezoelectric and seismoelectrokinetic phenomena.

physical exploration techniques. The piezoelectric method is an example of the successful use of the abovementioned phenomena in exploration geophysics.

SEISMOELECTROKINETIC PHENOMENON *E*

The seismoelectrokinetic (electrokinetic) phenomenon *E* in rocks is manifested by the potential gradient resulting from the displacement of the liquid phase relative to the solid skeleton of the rock under the influence of elastic waves. The similarity of this phenomenon to potential produced by water flow in rocks suggests a similar origin for these phenomena (Fridrichsberg, 1995).

The electrokinetic phenomenon *E* in sedimentary rocks was first described by Ivanov (1940). He developed a filtration model based on the existence of a diffusion double layer at the solid/liquid phase boundary in sedimentary rocks. According to the filtration model, propagation of an elastic wave in sedimentary rocks causes mutual displacement of the liquid phase (electrolyte) and solid phase, which upsets the equilibrium state of the diffusion double layer. This generates a so-called filtration potential in rocks. This is an electric streaming potential *U*, and its instantaneous value at two points along the raypath of a compressional wave can be calculated using the Helmholtz-Smoluchowski equation (Probstein, 1994):

$$U_2 - U_1 = \frac{\varepsilon_f \zeta}{\eta_f \sigma_f}(p_2 - p_1), \tag{1}$$

where p_1 and p_2 are the instantaneous values of the fluid pressure, ε_f is the electric permittivity of the pore fluid, η_f is the viscosity of the pore fluid, σ_f is the electrical conductivity of the pore fluid, and ζ is the electric potential drop across the double layer of charge at the grain/pore-fluid interface.

Frenkel (1944) was the first author to propose a rigorous theory for how much the fluid pressure *p* changes in a compressional wave. His investigation was based on Ivanov's (1940) hypothesis regarding the electrofiltration nature of this phenomenon. Frenkel's (1944) estimates, written with more commonly used poroelastic moduli, predict that the electric field E_x that accompanies a longitudinal elastic wave propagating with displacement u_x in the *x*-direction is (Pride and Garambois, 2005)

$$\frac{E_x}{-\omega^2 u_x} = \frac{\rho_f \varepsilon_f \zeta}{\eta_f \sigma_f}\left(1 - \frac{\rho}{\rho_f}\frac{C}{H}\right), \tag{2}$$

where ρ_f is the density of the pore fluid, ρ is the density of the rock, and *C* and *H* are the elastic moduli related to the undrained bulk modulus K_U and Skepton's coefficient *B* as

$$C = BK_U,$$
$$H = K_U + \frac{4G}{3},$$

where *G* is the shear modulus of the rock.
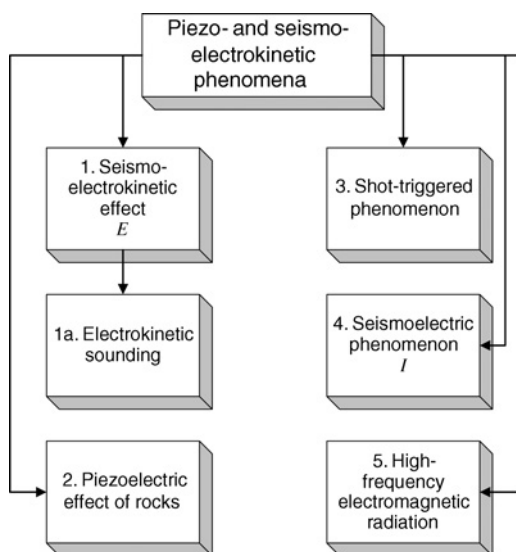
Under the restriction to isotropic monomineral grains, Gassmann (1951) obtained his known fluid substitution relations, which can be stated as

$$\alpha = 1 - \frac{K}{K_s},$$

$$B = \frac{\alpha}{\alpha + \phi \left(\frac{K}{K_f} - \frac{K}{K_s} \right)},$$

$$K_U = \frac{K}{1 - B\alpha},$$

where K is the drained bulk modulus (the bulk modulus when there is nothing in the pores of the rock). Although concern exists that $1 - \rho C/(\rho_f H)$ will conspire to be zero, it generally is on the order of one for most earth material. In this event, the electric fields that accompany a seismic wave are independent of the details of the pore space and grain packing and depend only on the fluid properties and the zeta potential. Even when there is some air in the pores, it is the water properties that are important, and one can use $\rho_f = 10^3$ kg/m^3, $\varepsilon_f = 80 \times 8.85 \times 10^{-12} \approx 10^{-9}$ F/m, $\sigma_f = 10^{-2}$ S/m, and $\eta_f = 10^{-3}$ Pa for estimates. A typical zeta potential might range from 10^{-3} to 10^{-2} V. It is safe to use 1 mV. Using these values, one finds that $E_x/v_x = 10^{-3} f$ in SI units for a typical water-saturated soil, where v_x is the particle velocity recorded by a geophone and f is the wave frequency.

The main message of equation 2 is that the electric field E_x moving along with a P-wave as part of the material response is directly proportional (without phase adjustments) to the particle acceleration in the x-direction. This fact has been verified experimentally by many investigators, including Garambois and Dietrich (2001).

To verify Ivanov's (1940) hypothesis regarding the nature of E in rocks, Volarovich and Parkhomenko (1955) conducted a series of laboratory experiments aimed at reproducing the E phenomenon in artificially moisturized rock samples. The experiments established that (1) a dry dolomite sample was not polarized by the elastic-wave influence and (2) after moisturizing, the same sample under the same influence produced electric potential at its edges. The potential polarity was independent of the measurement point. Its value was proportional to the pressure gradient.

The first field study of feasibility of piezoelectric and seismoelectrokinetic phenomena applications in exploration geophysics was carried out by Neishtadt and Osipov (1958, 1959). The measurements were conducted in sedimentary rocks and on a pegmatite deposit using a six-channel seismoelectric instrument prototype that later became a basic model for the 8SEF-2M commercial field instrument (Neishtadt et al., 1993). This field study revealed several characteristics of E.

First, manifestation of the contact phenomena at the electrode/soil boundary was studied. Measurements were conducted with variable electrode/soil contact areas (a different number of electrodes at each measurement point). It was established that changes in the contact area do not affect the measurement results. In addition, one of the electrodes was loaded with a weight of 80 kg. The results showed the electrode weight does not affect E's magnitude.

Second, the influence of the rock volume between the measurement electrodes was studied. Two types of screens were used for this study: continuous (large tin cans) and discrete (interconnected steel rods surrounding the measurement electrode). When the screens were connected to each other, a significant decrease in E was observed, which points to the fact that E was observed only in the rock volume sealed out by the screens. Disconnecting the screens from each other significantly weakened the screening effect. Increasing the screen diameter from 5 to 150 cm resulted in a 2.5-to-3.0-times increase of the E magnitude. The conclusion: E occurs in a finite volume of rock rather than at the electrode/soil contact.

Third, the feasibility of E detection with the use of induction sensors was established experimentally for the first time (Figure 2). This confirmed the EM nature of E.

Finally, time-distance curves for E and elastic waves were compared. The comparison showed that curves for E are similar to seismic curves but differ from them in the impulse magnitude and duration. The E curves show a better peak resolution and a stronger decrease with the distance from the shotpoint. The E impulses start 5 to 10 ms earlier than the seismic peaks. Arrival-time curves derived from the seismoelectric and seismic-field measurements practically coincide (Figure 3).

Martner and Sparks (1959) have used a standard seismic exploration instrument wherein one group of channels is connected to geophones and a second group is connected to electrodes. Seismic and electrokinetic signals from a single shot were recorded. The explosive mass was 0.4 to 7.5 kg, and the electrode spacing was 3 m. The magnitudes of seismoelectric signals derived from these experiments were in the range of tens of microvolts (μV). In our opinion, the results of this series of experiments were not affected by the direct current introduced into the ground, by the changes in the input resistivity of the amplifier, or by electrode type. Analysis was
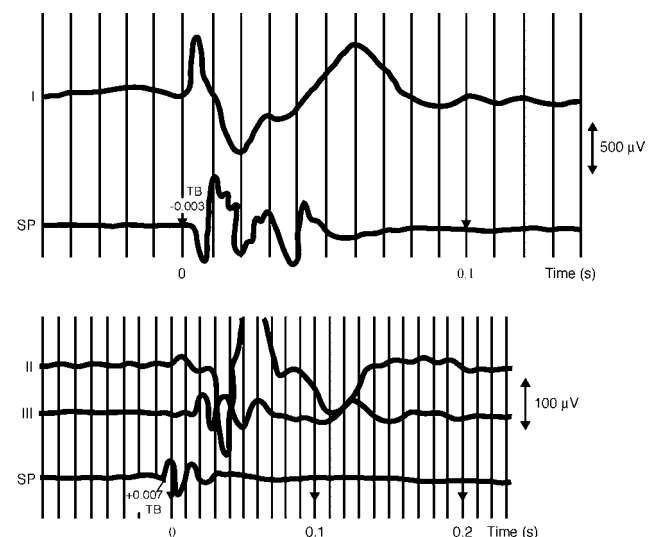

Figure 2. Registration of the electrokinetic phenomenon E with the use of an inductive frame hung above the soil. Electric potential in the inductive sensor located (I) 4 m and (II) 18 m from the shotpoint. (III) Electric potential at a pair of measurement electrodes wherein the distance between the shotpoint and the electrode closest to it is 18 m, and the spacing between the electrodes is 10 m. SP is the shotpoint, and TB is the time break.

carried out to determine properties of the near-surface, low-velocity material. Signals were recorded at a distance of 120 m from the shotpoint. Values of thickness derived for the low-velocity material from seismoelectric and seismic data showed good correlation with each other.

Parkhomenko and Tsze-San (1964) have studied the influence of water saturation on E in a series of laboratory experiments. Direct and inverse electrokinetic phenomenon magnitudes were recorded simultaneously using an ultrasound seismoscope. In dry samples of dolomite and till, the E magnitude was found to be near zero. With the increase of water saturation, the magnitude grew. When the optimal water saturation was reached, the magnitude value stabilized, then slowly decreased. It was established that the manifestation of E depends not on the total water saturation of the medium but on the bound-water content. Increase of the amount of free water does not affect the magnitude of E because this water does not participate in the formation of the electric double layer. The above experimental data confirmed the filtration hypothesis of Ivanov (1940) and the theoretical conclusions of Frenkel (1944).

Further investigations of E under laboratory conditions have been conducted by Tsze-San and Ziangirov (1965). Experiments were conducted in unconsolidated soils and sandstones. Dependencies of E on mineralogical composition, water saturation, grain size, and exchange cation composition of the medium were studied. These experiments established the following about E's magnitude:

- In unconsolidated water-saturated soils, it ranges from 1000 to 2400 μV.
- It decreases with a cation sequence of hydrogen > aluminum > magnesium > calcium > sodium.
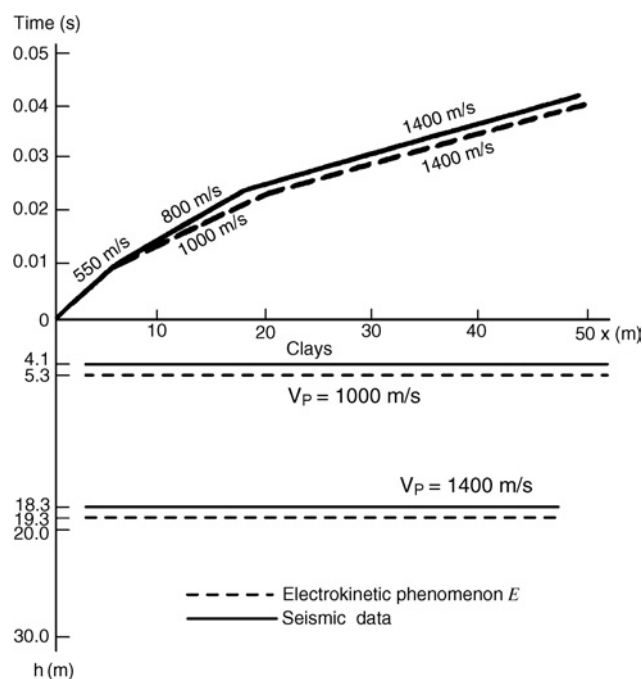

Figure 3. Combined arrival time and seismic section (Novosiverkii district, Leningrad region, Russia).

- It strongly depends on the absorbed cation type.
- It depends on the water saturation of the medium.

The above experimental results enabled the authors to propose a method of determining the concentration of bound water in the soil. The proposed method is based on the ability of bound water to completely compensate for electric charges at the surface of the soil particles.

Parkhomenko (1971) discussed electric processes that occur in two-phase porous media and which are responsible for E. The author also discussed laboratory and field experiments conducted by various researchers. Parkhomenko introduced a new parameter — seismoelectric modulus S — as a coefficient of proportionality between the mechanical force applied to a rock sample and the resulting electric charge at the sample surface: $Q = F/S$. Note that this parameter is an analog of the piezoelectric modulus (Neishtadt et al., 1986):

$$d = \frac{C}{F}, \tag{3}$$

where d is the piezoelectric modulus in coulombs/newton, C is the electric charge in coulombs, and F is the mechanical force in newtons.

Parkhomenko (1971) stated that further study of E will advance the current perception of electrokinetic phenomena and may lead to the development of a new geophysical exploration technique for determination of porosity properties of rocks. The author emphasized the importance of studying the behavior of E in various sedimentary rocks, its dependencies on medium saturation, chemical composition of the pore moisture, presence of oil, and the values of ζ-potential, apparent conductivity, and polarizability.

Migunov and Kokarev (1977) studied dynamic characteristics of E on limestone samples, aleurolites, and bauxites. The samples had high porosity, which increased the intensity of electromechanic energy transformation. Saturation of the samples measured 8% to 10%. It was established that the magnitude of E is one order of magnitude higher in the moisturized samples than in the dry ones. It was also established that the magnitude of E increased linearly with an increase in oscillation frequency. The E curves recorded by the inductive sensors had the same shape as those observed by regular electrodes. However, the magnitude of the recorded peaks in the former case was almost one order of magnitude lower than in the latter.

Parkhomenko (1977) established the following patterns in the behavior of E:

- The magnitude of E in saturated sedimentary rocks is directly proportional to the magnitude (energy) of the applied seismic field.
- The polarity of the first phase of the seismoelectric impulse depends on the gradient of the applied elastic field.
- Direct and inverse electrokinetic phenomena coexist in the same volume of rock.
- The magnitude of E is a function of several variables, the most important of which are the medium saturation, concentration of salts in the liquid phase, electrochemical properties of the solid phase, texture of the rock, and frequency

of the applied seismic field. The specific surface of the electric double layer is the key factor.

Kasim-Zade et al. (1987) established that the average value of E in kimberlites is one order of magnitude higher than that in the host (sedimentary and metamorphic) rocks. The anomalous seismoelectric properties of kimberlites may be because of the electrokinetic potential, which varies significantly, depending on the presence of radioactive inclusions and the ongoing reduction-oxidation (redox) reactions at the solid/liquid phase boundaries. They also established that the difference in seismoelectric activity between kimberlites and their host rocks persists and even increases at subzero temperatures. This may be the result of the influence of radioactive inclusions on the energetic state of the electric double layer as well as the exothermic character of redox processes.

In the course of a field trial reported by Kasim-Zade et al. (1987), a kimberlite pipe covered with 10 m of surface sediments was detected and delineated by surface seismoelectric measurements. The measurements were conducted with the use of the PAMZ-8 instrument.

In our opinion, the Kasim-Zade et al. (1987) results point to the feasibility of using the seismoelectric field technique in kimberlite exploration to verify seismic and resistivity anomalies.

Boulytchov (2000) observed the electrokinetic phenomenon E triggered by reflected seismic waves. Elastic waves were introduced into the ground by pneumatic hammer impacts (frequency of 1 kHz) and by a powerful piezoceramic vibrator. Stacking of the seismoelectric signals resulted in magnitudes of up to 200 μV. Measurements were conducted over sharp, seismically reflecting boundaries, 0.1 to 15 m deep. The observations enabled determination of the overburden thickness in a 10- to 12-m topographic depression. Boulytchov maintained that the applied technique can be used to delineate caverns in karsts. It would present an especially attractive choice in remote locations because of its simplicity and the portability of the required equipment.

Svetov and Gubatenko (1999) proposed a mathematical model that describes the manifestation of E for low-frequency oscillations in porous, saturated rocks. The authors proposed a four-step algorithm for calculating the electrokinetic component of the EM field: (1) Determine the displacement vector for the solid skeleton; (2) solve the fluid dynamic equations; (3) calculate the electrokinetic current; and (4) calculate the magnetic field induced by the electrokinetic current. Their paper offers equations for each step as well as boundary conditions for the equation solutions.

Ageyeva et al. (1999) conducted a laboratory study of E in a wide range of frequencies of the elastic field ($n \times 100$ Hz to $n \times 10$ kHz). This study resulted in a series of experimentally established dependencies between E magnitude and rock lithology, structure, and texture as well as the salt concentration in the pore moisture. In particular, four main dependencies were established. First, the value $\varphi[(\varphi = W/K)$—where W is the amplitude-frequency characteristics of the electric signals observed on receiving electrodes and K is the amplitude-frequency characteristics of the control piezoceramic sensor] — increased when raising the coefficient of saturation. Second, the seismoelectric signal increased 2 to 2.5 times when increasing the mineralization of porous solution

from 5 to 50 g/liter (this relationship for macroporous rocks is more significant than for fine-pore rocks). Third, increased porosity caused the φ factor to decrease. And fourth, the φ factor derived from permeability (especially its low values) has an ambiguous character.

Electrokinetic sounding

Electrokinetic sounding (EKS) is based on utilizing E. EKS arises from the movement of pore fluids under seismic excitation and may have significant importance in hydrogeologic investigations (for instance, depth of investigation using EKS may consist of many tens and even hundreds of meters) (Millar and Clarke, 1999; Rosid and Kepic, 2004). This technique has been the subject of study principally by Western scientists and is outside the scope of this review.

PIEZOELECTRIC PHENOMENON

The direct piezoelectric phenomenon is the ability of certain solid bodies to produce electric potential under an applied mechanical force — pressure, stretching, etc. This phenomenon was first observed in certain minerals by the famous French crystallographer Gaui in 1817 (Cady, 1946). Much later, in 1880, the Curie brothers rediscovered this phenomenon and studied its manifestations in quartz, tourmaline, and some other crystals (Curie, 1966).

The inverse phenomenon was observed in parallel with the direct piezoelectric phenomenon. The inverse phenomenon is manifested by the mechanical deformation of a crystal under the influence of an electric field. In other words, the direct piezoelectric phenomenon transforms the elastic mechanical energy to electric energy, and the inverse phenomenon performs the reverse transformation.

The direct piezoelectric phenomenon (Curie, 1966) is the electric polarization of certain crystals under stress. Most of these crystals are dielectrics; some are semiconductors. Polarization of these materials produces electric charges at specific elements of their surfaces. In an electrically conductive medium, the electric field produces the conductivity current and displacement current. According to Maxwell's first law, these currents generate a magnetic field:

$$\varepsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} = \mathrm{curl}\mathbf{H}, \qquad (4)$$

where ε is the electrical permittivity and σ is the electrical conductivity of the rock. That is why the piezoelectric phenomenon can be detected by measuring both the electric-field intensity $\mathbf{E}$ and the magnetic-field intensity $\mathbf{H}$.

Extensive experimental work resulted in establishing the main equation that describes the piezoelectric phenomenon

$$q = \delta\tau, \qquad (5)$$

where q is the surface density of the electric charge that occurs at a certain plane of a crystal plate under the stress τ, and δ is the piezoelectric modulus of the monocrystal of which the plate is made.

Equation 5 indicates that the electric-charge density is directly proportional to the applied mechanical force. In an isotropic medium when the mechanical force changes its direction by 180°, the charge polarity changes. In reality, the

piezoelectric phenomenon occurs in anisotropic media only. Therefore, the piezoelectric phenomenon is defined by a superposition of the vector of polarization intensity and tensor of mechanical stresses or deformation (Neishtadt et al., 1993).

Volarovich and Parkhomenko (1954) discovered a direct piezoelectric phenomenon in polycrystalline rocks in laboratory conditions. Later, Neishtadt and Osipov (1958) confirmed this effect in field conditions. This phenomenon is of critical interest in various areas of geology and geophysics. Based on it and some other seismoelectrokinetic phenomena, a new exploration technique — the piezoelectric method — was developed in Russia (Neishtadt 1961, 1966, 2000; Alexeyev et al., 1964; Mazanova et al., 1965; Volarovich an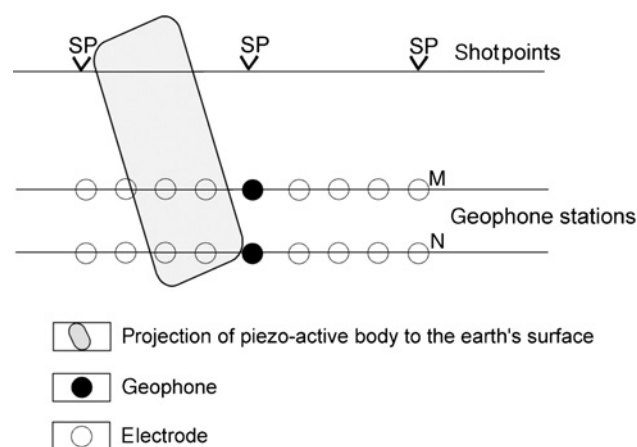d Sobolev, 1969; Neishtadt et al., 1993) and successfully applied in the West (Demin et al., 1992; Kepic et al., 1992, 1995; Maxwell et al., 1992a, 1992b; Russell et al., 1992, 1997; Butler et al., 1994, 1996; Pride and Haartsen, 1996; Haartsen and Pride, 1997; Mikhailov et al., 1997; Bishop and Emerson, 1999; Millar and Clarke, 1999; Garambois and Dietrich, 2001; Pride and Garambois, 2002; Butler and Russell, 2003; Zhu and Toksöz, 2003; Daley et al., 2004; Rosid and Kepic, 2004).

In the course of the field measurements at ore-quartz deposits in the polar Urals, Chukotka, and Yakutia (Russia) (Neishtadt et al., 1986), seismoelectric waves t_0 were observed, triggered by the interaction of an elastic wave on the boundary between frozen and thawed rocks. These waves were traced locally in the vicinity of patches of permafrost. Besides waves t_0, piezoelectric waves t_1 were observed at the deposits, associated with ore-quartz zones. Figure 4 shows an observation scheme for ground surveys using the piezoelectric method. The conventional piezoelectric measurements are performed using electrodes, while the geophones play a subsidiary role for monitoring intensity of the elastic oscillation generation and behavior of the initial seismic field.

Surface measurements at a gold-bearing quartz deposit at Ustnerinskoe (eastern Yakutia) showed that wave t_0 is omnipresent along the measurement profiles at 2 to 3 ms (Figure 5). Wave t_1 was generated by a refracted elastic wave and was registered at 4 to 8 ms. The average magnitude of this wave is 1600 to 1800 μV. The peak shapes of this wave show its piezoelectric nature corresponding to ore-quartz zones occurring at 7 to 8 m depth (Figure 5). By contrast, at a water-saturated and swampy site, wave t_0 was not observed, but E was recorded with a maximum magnitude of 1500 μv (Figure 6).

The distinctive features of the piezoelectric method are described in some detail in the piezoelectric method examples cited below.

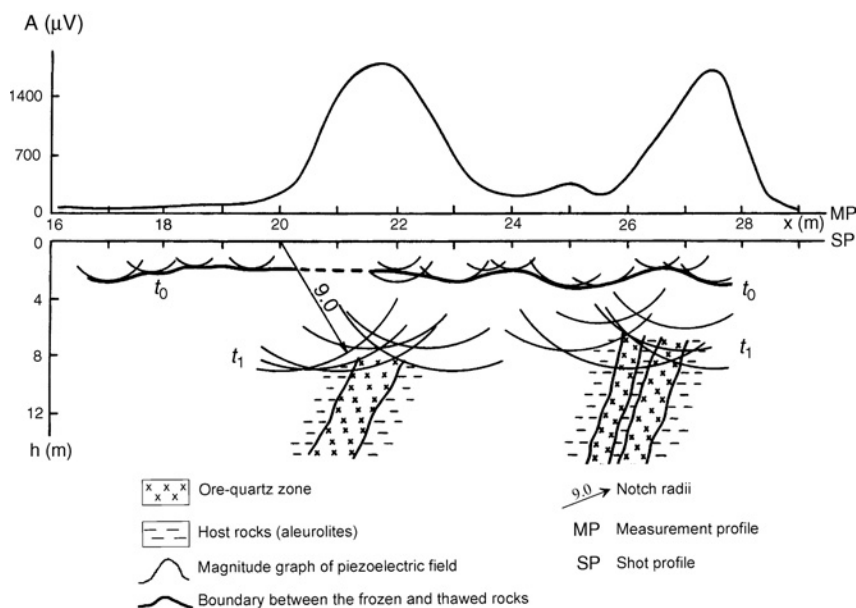Figure 4. Piezoelectric measurement array (surface traversing).

Figure 5. Piezoelectric measurements at a gold-bearing quartz depositat at Ustnerinskoe (Yakutia, Russia). The observed signals are the t_0-wave generated at the interface of thawed and permafrost ground and the t_1-wave generated by ore-quartz zones.

SHOT-GENERATED SEISMOELECTRIC PHENOMENON

The shot-generated seismoelectric phenomenon occurs in the vicinity of shot or hitting points in the beginning of elastic-wave excitation (Neishtadt et al., 1993). It is mainly the result of the nonlinear deformation of rocks and the ionization of the gaseous phase. The shot-generated impulse is detected by electrodes or induction coils positioned in the vicinity of the shotpoints (Figure 7).

The main characteristic of the shot-generated impulse is the identical peak at all registration channels. Both magnitude and duration of the peak increase significantly when shot in the air or in dry drill-holes. Under these conditions, the magnitude may reach tens of millivolts, and the duration may be 10 ms or more. The magnitude of the peak increases with shot strength, with no discernible quantitative correlation.

SEISMOELECTRIC PHENOMENON *I*

The seismoelectric phenomenon, or current change phenomenon *I*, is the result of changes of rock conductivity under stress.

Blau and Stathem (1936) proposed a geophysical exploration technique based on the use of *I*. Their seismoelectric instrument (Figure 8) included electrodes positioned in the ground (MN), batteries, a transformer, and an oscillograph connected to the secondary coil of the transformer. The authors proposed this instrument as an alternative to a seismograph in the reflected-wave mode. They pointed out that seismoelectric measurements observe an integral process in a certain volume of the rock, while a seismograph observes oscillations that occur at a point. The patent granted to the authors states that the artificial electric current can be suc-

cessfully substituted by the current that naturally occurs in the ground.

Thomson (1939) conducted a series of experiments aimed at a further study of *I*. These experiments confirmed that the current changes occur in a certain volume of rock rather than at the electrode/soil boundary. The author also noted that *I* is the result of the change in the contact resistivity between the rock particles.

Thyssen et al. (1938) continued the study of the nature of *I*. Their experiments showed that the magnitude of *I* does not depend on the mass of the electrodes. This conclusion was

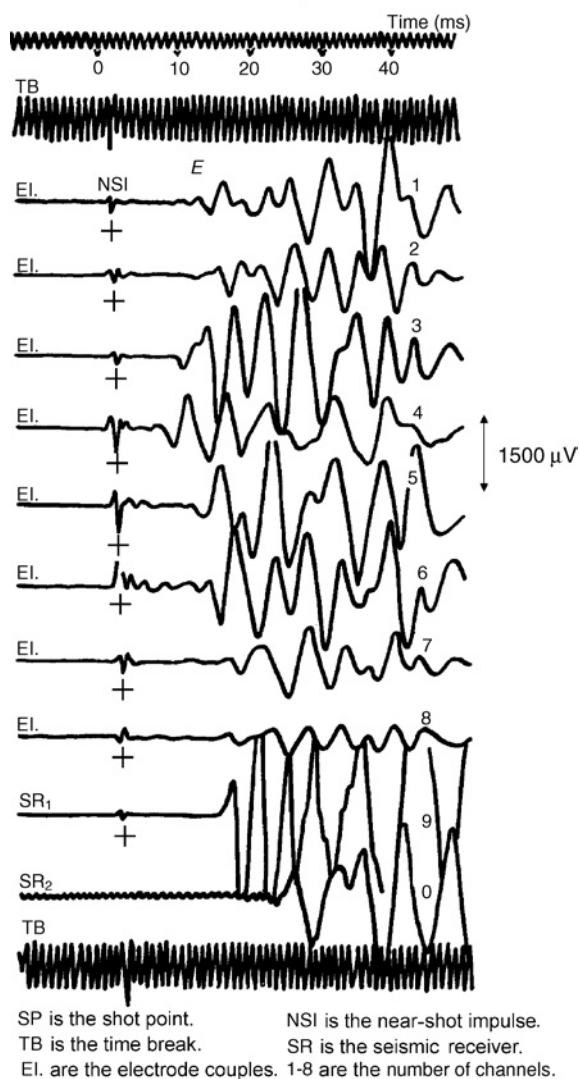Figure 7. Recording of the shot-triggered EM impulse.

Figure 6. Behavior of the elastic wavefield observed during the course of piezoelectric measurements at a swampy site (Ustnerinskoe deposit, Yakutia, Russia). Both electrode spacings and shotpoint distances are 20 m. The recorded signal is the electrokinetic phenomenon *E* generated at the interface of the water and solid phase.
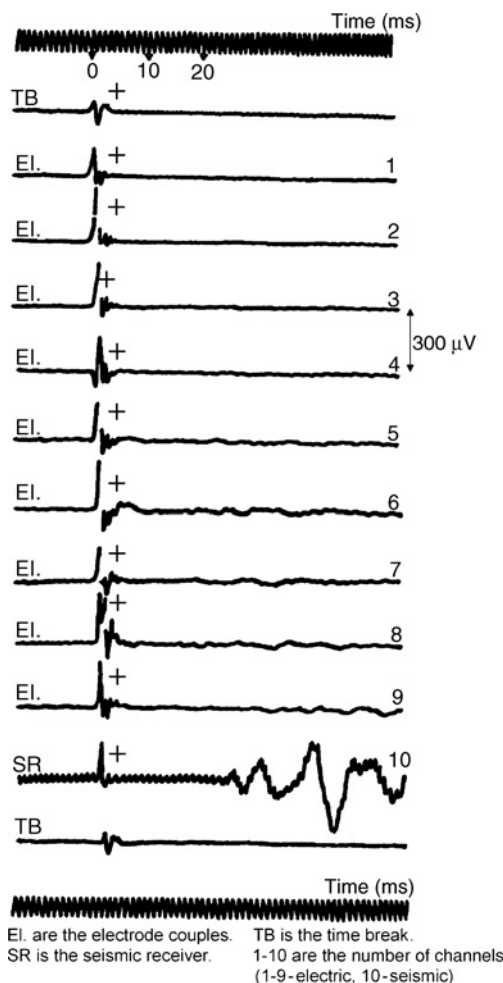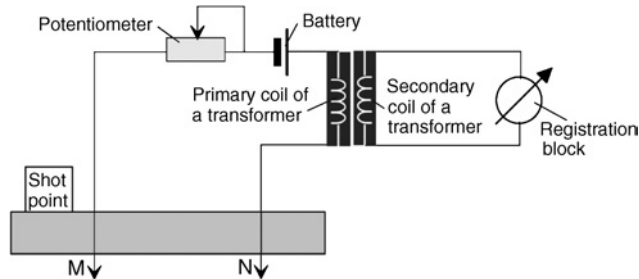

Figure 8. Schematic of a measurement device for detecting and recording *I*.

verified in the mass range of 10 to 40 kg. Another series of experiments studied the dependency of the method's sensitivity on the properties of the soil in which the electrodes were positioned. This series established that I occurs in the immediate vicinity of the electrodes. Moistening the soil in the near-electrode zone with saltwater (to moderate the contact resistivity) gradually decreased the I magnitude.

In the same paper, the authors described a series of experiments conducted on an electrolyte model. These experiments showed that with the increase of the electrolyte concentration, the magnitude of I first increases, then decreases. The magnitude also increases with the increase of the oscillation frequency. The authors maintained that the mechanical oscillations are not accurately reflected in the oscillograms and that the instrument they used was only good for recording the beginnings of the peaks.

Waters and Wen-Po (1939) carried out a series of experiments with a four-electrode array. This series confirmed yet again that the conductivity changes under the stress occur in a certain volume of rocks. The authors noted that the array designed for measuring I would not produce better results than a regular seismograph.

Ivanov (1949) established that I occurs because of the change of the electric conductivity of rocks in the near-electrode zone. The author stressed that the surface processes at the electrodes themselves contribute practically nothing to the phenomenon.

Loginov et al. (1977) reported an anomalously strong manifestation of I in the vicinity of sulfide ores, which later served as a basis for the method of induced seismoelectric potentials (Nazarnyi et al., 1989) designed for base-metal exploration.

HIGH-FREQUENCY IMPULSE EM RADIATION

High-frequency impulse EM radiation is generated by base-metal orebodies under the influence of elastic oscillations (Sobolev et al., 1982; Sobolev et al., 1984). This phenomenon served as a basis for a new exploration technique called the radio impulse method. Impulse EM radiation of the radio-wave frequency range differs from linear piezoelectric and seismoelectrokinetic phenomena in terms of intensity and frequency of the resulting electric field. The field produced by high-frequency EM radiation has an intensity two to three orders of magnitude higher than the intensity of fields generated by piezoelectric bodies. The field produced by the high-frequency EM radiation may read tens of millivolts per centimeter.

High magnitude and frequency of the observed EM signals enable detection of base-metal bodies at a distance of more than 200 m. That, as well as the feasibility of discerning between the different genetic types of base-metal deposits by the high-frequency impulse EM radiation measurements, makes this phenomenon a potential basis for an exploration technique. The main drawback is a relatively low reproducibility, which is because of the irreversible processes of redistribution of tension in the rocks, and the nonlinear EM field triggered by this redistribution.

PIEZOELECTRIC METHOD — EXAMPLES

The piezoelectric method is an example of the successful application of piezoelectric and seismoelectrokinetic phenomena in exploration geophysics. It is designed for direct exploration for minerals that differ from the host media in piezoelectric properties (Neishtadt et al., 1965; Neishtadt et al., 1973; Neishtadt et al., 1989; Volarovich et al., 1965). This method is employed in surface, downhole, and underground modes. It is used in exploration for pegmatite, apatite-nepheline, and ore-quartz deposits of gold, tin, tungsten, molybdenum, zinc, crystal, and other raw materials as well as kimberlite bodies. The piezoelectric method also has been applied successfully in prospecting for base-metal deposits of predominantly sphalerite composition. And it can be used also for detecting objects with different electrokinetic properties (such as kimberlites, oil-bearing rocks, and bauxites) by observing E.

Physical and geologic fundamentals

The piezoelectric method uses the direct piezoelectric phenomenon, which is manifested by the ability of certain geologic objects (containing piezoactive minerals such as quartz, tourmaline, sphalerite, and nepheline) to polarize under the influence of mechanical deformations caused by elastic waves. The field procedure includes three operations:

1) Excite the elastic field in rocks.
2) Record, amplify, and analyze the resulting piezoelectric and seismoelectrokinetic signals.
3) Interpret kinematic and dynamic characteristics of the recorded signals, which detects and delineates piezoactive bodies.

Geologic fundamentals indicate that quartz and pegmatite bodies are not necessarily comprised of oriented crystals of piezoactive minerals (Tatarinov and Karyakin, 1975). In most cases, piezoactive axes in quartz and quartz-pegmatite bodies are oriented randomly. The following mechanism for the piezoelectric phenomenon is assumed for rocks with a random distribution of piezoactive axes, where elementary volumes of the medium undergo deformation under the influence of a dipping elastic wave (Neishtadt et al., 1974):

- The elementary volumes are compressed for the r_x value along the x-axis (coinciding with the direction of the wave propagation).
- The elementary volumes are expanded along the y-axis and z-axis.

The values of expansion for small deformations of elastic medium are related to r_x as follows (Neishtadt et al., 1974; Tatarinov and Karyakin, 1975):

$$r_y = r_z = \frac{r_x}{2}, \tag{6}$$

where $r_x, r_y,$ and r_z are the components of relative deformation of an elementary volume along the x-, y-, and z-axes, respectively.

Relative deformation of the element of a piezoactive medium results in the electric charges q of different sign on the element's opposite boundaries. In a wide range of the applied force values, the value of q linearly depends on the relative

deformation:

$$q_x = er_x, \quad q_y = er_y, \quad q_z = er_z, \tag{7}$$

where e is the coefficient of proportionality, characterizing averaged piezoactivity of the element of medium.

Based on equation 7, a deformed element of a piezoactive medium can be described as a system of three dipoles whose axes are orthogonal and whose dipole moments are proportional to the relative deformations along the respective axes. Release of electric charges and the resulting dipole moments generate a rotating electric field in the surrounding medium. This is the field measured and recorded by the piezoelectric method.

An important element of this research method is the classification of rocks by their piezoactivity. An ongoing study of rock, ore, and mineral samples has been performed over several decades (Neishtadt et al., 1986; Neishtadt, 2000). Over the same period, a study of relative piezoactivity of orebodies and host rocks was conducted under field conditions (Neishtadt et al., 1989). Analysis of the above laboratory and field data resulted in a classification of rocks, ores, and minerals by their piezoactivity (Table 1). This classification includes four main groups:

I) Highly active — piezoactivity of samples is greater than 5.0×10^{-14} C/N.
II) Moderately active — piezoactivity of samples is $(0.5 - 5.0) \times 10^{-14}$ C/N.
III) Weakly active — piezoactivity of samples is lower than 0.5×10^{-14} C/N.
IV) Inactive — piezoactivity of samples is near zero.

The piezoelectric method's results are produced as maps, plans, and sections with the contours of piezoelectric and electrokinetic anomalies. The anomaly threshold values vary between sites depending on the specific geoelectric settings of the site as well as on the morphology and piezoactivity of the sought bodies.

Field applications

The piezoelectric method has been used in exploration for various economic minerals: gold, crystal, mica, tin, fluoric spars, rare metals, tourmalines, and base metals. At present, this method is a significant component of many complex exploration strategies (Neishtadt, 2000).

Recently, the MORION 2001 field instrument and a set of measurement and data interpretation procedures were developed in Israel (Neishtadt, 2002). The high sensitivity and S/N ratio of the MORION 2001 (Neishtadt, 2002), as well as new data-processing algorithms (Alperovich et al., 1997), significantly broaden application area of the piezoelectric method. Analysis of physical-archaeological models (Eppelbaum, 2000) suggests that this method can be applied successfully in archaeological investigations.

Case history 1

At a deposit of crystal-bearing pegmatites in the northern Ukraine, the piezoelectric method was applied to localize and delineate blind pegmatite bodies occurring in granites.

The pegmatite bodies at this deposit are of irregular isometric shape, several tens of meters across. Before the piezoelectric method was introduced, exploration for pegmatites at this deposit had been conducted by test drilling. Drillholes were 200 m deep on grids measuring 80×100 m and 40×50 m, and then later measuring 20×25 m. This approach had been rather expensive and unreliable; even relatively large targets (15–20 m across) could be missed.

A combination of geophysical techniques (piezoelectric method plus frequency-domain EM profiling) was applied. First, EM profiling was used to detect zones of low electric resistivity, which are often associated with the crystal-bearing pegmatite bodies in the area. Then the piezoelectric method was used to discriminate resistivity anomalies, detect pegmatite bodies in the interwell space, and delineate the discovered pegmatites (Figure 9). Shotpoints were located in drillhole 1, with sensors located in drillhole 2 (Figure 9). The distance between both shotpoints and sensor points was 10 m,

Table 1. Classification of some rocks, ores, and minerals by their piezoactivity d, 10^{-14}C/N

Piezo activity group	Rock/ore/mineral	d_{min}–d_{max}	d_{aver}
I	Quartz-tourmaline-cassiterite ore	0.8–27	15.7
	Antimonite-quartz ore	0.2–1.3	0.6
	Apatite-nepheline ore	0–5	0.9
	Galenite-sphalerite ore	0.2–7.7	3.2
	Ijolite	0.1–8	1.1
II	Melteigite	0.2–5	1.6
	Pegmatite	0.1–4.8	1.2
	Skarn with galenite-sphalerite mineralization	0.1–3	0.6
	Sphalerite-galenite ore	0.3–7.7	3.8
	Turjaite	0.9–4.8	2.1
	Urtite	0.1–32.5	3.2
	Juvite	0.2–5.4	1.8
III	Aleurolite silicificated	0–0.5	0.2
	Aplite	0–1.7	0.5
	Breccia aleurolite-quartz	0.1–0.4	0.2
	Gneiss	0–1.4	0.2
	Granite	0–1.6	0.4
	Granodiorite	0–0.2	0.1
	Quartzite	0–3.3	0.5
	Pegmatite ceramic	0–1	0.1
	Sandstone silicificated and tourmalinized	0.1–1.4	0.5
	Feldspars	0–0.4	0.1
	Porphyrite	0–0.3	0.1
	Ristschorrite	0.3–0.9	0.5
	Schist argillaceous	0–0.6	0.1
	Hornfels	0–0.4	0.2
	Skarn sphaleritic-garnet	0–1	0.3
	Skarn pyroxene-garnet	0–0.2	0.1
IV	Aleurolite, amphibolites, andesite, gabbro, greisens, diabase, sandstone	0–0.1	0
	Argillite, beresite, dacite, diorite-porphyrite, felsite-liparite, limestone, tuff, fenite	0	0

reducing to 5 m in the anomalous zone. Combined application of the frequency-domain EM profiling and piezoelectric method reduced drilling at the site and helped localize several pegmatite bodies.

Case history 2

At muscovite deposits in the Mamsko-Chuisky area (Irkutsk region, Russia), the piezoelectric method was used as the main tool for localizing blind bodies as well as for discriminating resistivity anomalies. Mica-bearing pegmatites are characterized by a secondary structure with replacement of quartz-muscovite association. Piezoactivity of pegmatites is almost one order of magnitude higher than that of the host rocks (gneiss). Field measurements using opposite arrays at a virgin site revealed seven distinct piezoelectric anomalies with relative magnitudes of 50–60 μV (Figure 10a). Geometry of the shot profiles and receiving arrays is presented in Figure 10b. Shooting the anomalous zone from two opposite sides relative to the receiving array essentially increases both the reliability of observed field interpretations and the dimensions of the study area. In the course of drilling the test borehole, six of the seven anomalies were found to be associated with pegmatite bodies. Below the seventh anomaly (third from the left in Figure 10a), a pegmatite body at a depth of 6 m was discovered by drilling.
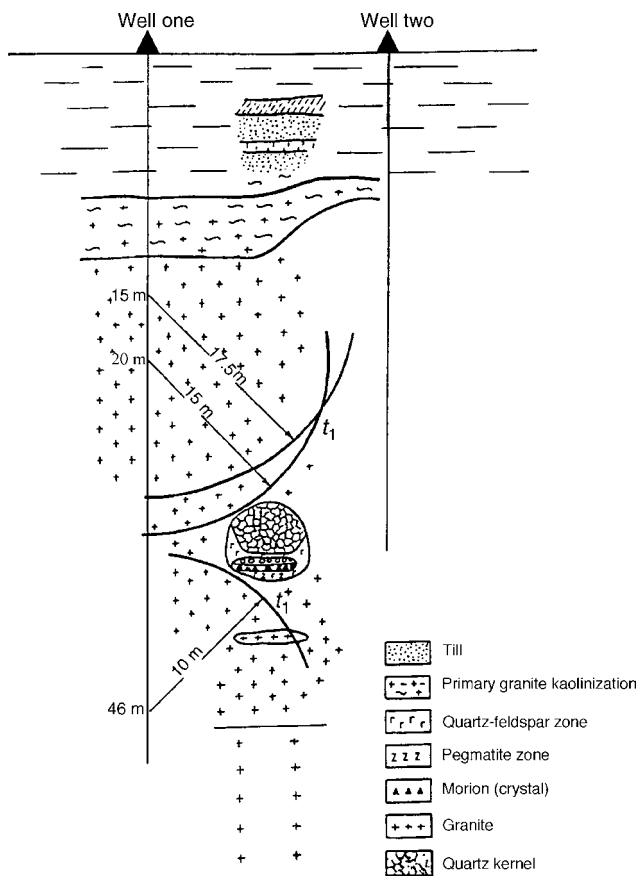
Case history 3

Electric and magnetic properties of base-metal ores with high sphalerite and chalcopyrite content are often very close to those of the host rocks. This makes conventional geophysical techniques virtually useless in exploration for these ores. At the same time, these ores are a natural target for exploration by the piezoelectric method since both sphalerite and chalcopyrite have high piezoactivity.

Laboratory piezoactivity measurements were conducted on ores and rocks from the Tishinskoe deposit in eastern Kazakhstan. Two ore zones of the Tishinskoe deposit were investigated. Ores from zone one had high sphalerite content; ores from zone two had high chalcopyrite content. The above measurements showed ore piezoactivity one order of magnitude higher than that of the host rocks. The data served as justification for field measurements.

At ore zone one, underground piezoactivity measurements delineated base-metal bodies located about 80 m from the blasting point. At zone two, underground piezoactivity measurements helped discover massive sulfide ore layers, which led to the delineation of base-metal bodies (Figure 11). These measurements were performed in the adits located 250 m below the earth's surface, where a few arrays of receiving electrodes, seismographs, and shotpoints were located at separation distances of 60 to 150 m. The interpretations from measurements were confirmed by test drilling.

Case history 4

Field trials of the MORION 2001 instrument were conducted at a gold-quartz mineralization site in southern Israel within the Precambrian terrain at the northern extension of the Arabian-Nubian shield (Gilat et al., 1993). The area of the archaeological site was located 5 km north of the town of Eilat in an area of strong industrial noise. Ancient river alluvial terraces (extremely heterogeneous at a

Figure 9. Application of the piezoelectric method in the downhole mode at a crystal-bearing pegmatite deposit at Volynskoe (northern Ukraine).
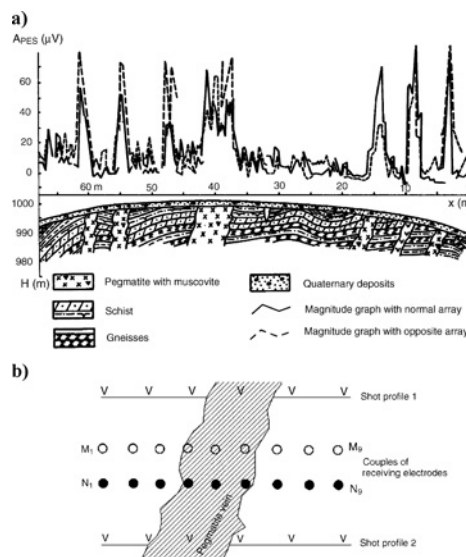

Figure 10. (a) Piezoelectric observations at a mica-bearing deposit (Mamsko-Chuisky district, Irkutsk region, Russia). (b) Geometry of shot profiles and measurement arrays.

local scale, varying from boulders to silt) covered the quartz veins and complicated their identification. Measurements conducted over a quartz vein covered by surface sediments (approximately 0.4 m thick) produced a sharp (500-μV) piezoelectric anomaly (Figure 12). Values recorded over the host rocks (clays and shales of basic composition) were close to zero.
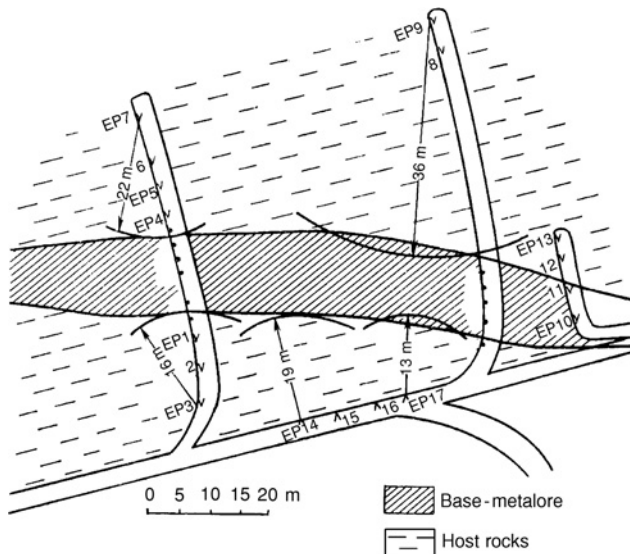

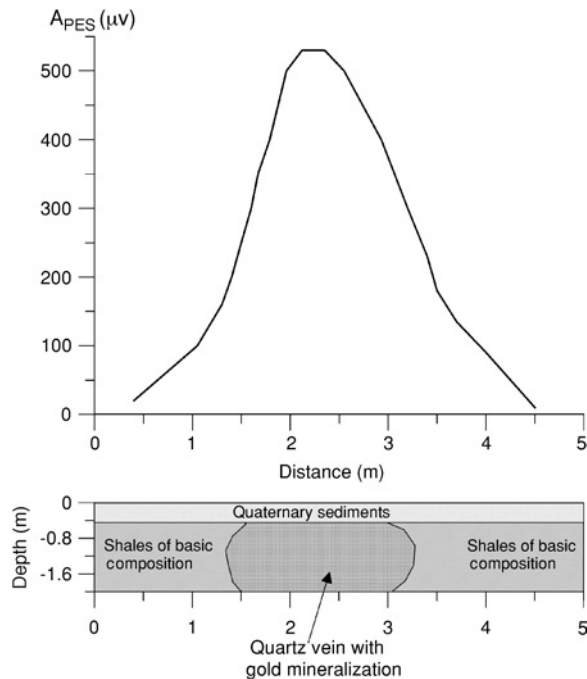Figure 11. Underground piezoelectric measurements at a base-metal deposit in eastern Kazakhstan.

Figure 12. Piezoelectric observations over a zone of gold-bearing quartz under alluvial sediments (southern Israel). Both electrode spacings and shotpoint distances are 5 m.

CONCLUSIONS

A classification of piezoelectric and seismoelectrokinetic phenomena in rocks has been presented. These phenomena are manifested by electric and EM processes that occur in rocks under the influence of elastic oscillations triggered by shots or mechanical impacts (hits). The classification describes these phenomena, detailing their nature and manifestation patterns. Because the manifestation of piezoelectric and seismoelectrokinetic phenomena differs in various rocks, these phenomena can be used as tools for geophysical exploration.

The piezoelectric method is an example of the successful application of piezoelectric and seismoelectrokinetic phenomena in exploration geophysics. This method uses a new geophysical parameter: piezoelectric activity of rocks, ores, and minerals. The geophysical technique enables direct exploration for pegmatite, apatite-nepheline, massive sphalerite ore, and ore-quartz deposits of gold, tin, tungsten, molybdenum, zinc, crystal, and other raw materials. This method also differentiates rocks such as bauxites and kimberlites from host rocks by using their electrokinetic properties.

In our opinion, this method deserves further development as the only geophysical technique that enables direct exploration for piezoactive minerals. A separate technique based on the high-frequency impulse EM radiation requires further research and development to take its place among commercial geophysical exploration methods.

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