Seismoelectric monitoring of producing oilfields: A review.

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ABSTRACT

Seismoelectric phenomena associated with seismic waves and activities have been observed in the laboratory and field for several decades. Geophysical techniques using active seismic sources such as reflection seismic can be modified to adapt the requirements for seismoelectric surveys and observations. Electrokinetic potential is a candidate mechanism to explain the seismoelectric phenomena observed in surveys using artificial seismic sources. Coupled electrokinetic signals are observed at the surface or in the borehole using grounded dipole antennas. Efficient power-line and telluric noise (using remote-referencing) reduction is essential to improve the weak amplitude of the seismoelectric signals. Preamplifier and analog notch filtering of the signals are valuable tools in this regard. Properties of pore fluids and solid matrix can be estimated using the linear relationship between seismic and its accompanying seismoelectric waveforms, which make the technique a possible tool for characterization of porous media. Simultaneous multi-component seismic recording will be a key contribution to estimate the rock and fluid properties of interest.

The delay traveltime concept associated with the seismoelectric signals generated by the positive holes mechanism makes it a plausible tool for monitoring seismically active environments undergoing natural or induced microfracturing such as producing oilfields. A processed pilot study using an array of pairs of grounded dipoles over an active area should be able to evaluate the ability of the technique in monitoring of the microfracturing process.

INTRODUCTION

Coupled electromagnetic and seismic wave phenomena have been observed in the laboratory as well as in the field for some time (e.g. Derr, 1973; Fujinawa and Takahashi, 1990; Kopytenko et al., 1993; Yoshida et al., 1997, Molchanov et al., 1998a,b). Unusual behaviour of electronic devices and luminous signals has been reported before and during earthquakes. Those problems and affects disappeared afterwards. These observations lead us toward a major measurable phenomenon, changes in electrical fields close to the surface due to changes in the stress field in the subsurface.

Some seismoelectric phenomena, such as piezoelectric effects in quartz deposits or the modulation of the resistivity of the earth by seismic stresses in the presence of uniform telluric currents, have sometimes been observed in geophysical exploration. In the early 1930s, it was known that an electromagnetic (EM) response was produced when a seismic source was ignited above a porous medium and the concept was discussed that this field conversion could be used as an exploration tool (Thompson, 1936). Until recently, the physics behind this phenomenon were not well understood. Pride (1994) succeeded in describing the conversion from acoustic energy into electromagnetic energy by a series of seven equations, based on the Biot and Maxwell equations with mechanical field equations coupling them (Pride and Morgan, 1991; Pride, 1994; Pride and Haartsen, 1996; Haartsen and Pride, 1997). A review of electrokinetic geophysics, including a historical background and multi-channel sounding techniques, has recently been given by Beamish and Peart (1998). Butler et al. (2002) conducted a field trial of combined seismoelectric and seismic reflection profiling to detect a sand aquifer at 40 m depth in a groundwater exploration. They used a very low noise preamplifier (Kepic and Butler, 2002) and an expanded recording system to detect weak signals. They suggested that the use of large dipole arrays, and seismic processing routines for the attenuation of coherent noise will play an important role in the development of the seismoelectric method as a tool for groundwater studies.

Garambois and Dietrichz (2001) showed theoretically that in the dominant seismoelectric effect, the electric field accompanying the compressional waves is approximately proportional to the grain acceleration, and the magnetic field moving along with shear waves is roughly proportional to the grain velocity. These relationships hold true as long as the displacement currents can be neglected (the diffusive regime). They also showed that the electric field is mainly sensitive to the salt concentration and dielectric constant of the fluid, whereas the magnetic field principally depends on the shear modulus of the grains and on the fluid's viscosity and dielectric constant. They suggest that the simultaneous recording of seismic, electric, and magnetic wavefields can be useful for characterizing porous layers at two different levels of investigation, near the receivers and at greater depth. Thompson and Gist (1993) presented the results of a study of deep exploration for oil and gas using seismoelectric effects. They used adapted data processing and common mid-point (CMP) techniques to produce a seismoelectric image of the subsurface from depths on the order of a few hundred meters. They concluded that seismoelectric signal could be detected from a depth of 300 m.

Detection and characterization of fractured zones using borehole seismoelectric measurements was investigated by Mikailov et al. (2000). They detected a very weak electrokinetic field (tens of microvolts), induced by pore fluid flow, after power-line and telluric signals were removed by remote referencing and notch-filtering. They showed that the normalized amplitudes of these electrical fields correlate with the fracture density log. According to their theoretical model, the normalized amplitude of the Stoneley wave induced an electrical field proportional to the porosity, and the amplitude versus frequency behaviour of this electrical field depends on the permeability of a formation around a borehole.

Zhu and Toksöz (2003) described crosshole seismoelectric measurements in small-scale laboratory borehole models with vertical and inclined fracture between source and receiver. They recorded not only the EM wave induced by the Stoneley wave excited in the fracture, but also the electric signals generated by the seismic wave arriving at the receivers. Using the latter, they claimed that a tomography image with the traveltimes extracted from the seismoelectric measurements can be constructed. They also showed that the crosshole seismoelectric measurements can more accurately detect and position the fracture between two boreholes than crosshole seismic tomography.

Ultra-low frequency (ULF) electromagnetic emissions in the range of 0.01-10 Hz produced by microfracturing electrification was suggested as a possible mechanism for EM emission before and after earthquakes (Molchanov and Hayakawa, 1995, 1998a,b).

In their model, they characterized a rock medium by the macroscopic dielectric permittivity and conductivity. They proposed that the microcurrent results from charge relaxation during microcrack opening and depends on the time-scale of opening and conductivity of the rock medium.

Takeuchi and Nagahama (2002) proposed hole and electron trapping centres as one of the probable origins of seismoelectromagnetic phenomena observed in fracturing and frictional sliding of quartz and granite under dry conditions. In their experiments they showed that the level of surface charge density on the fracture or frictional slip surface of quartz and granite could not be explained by the bound charge induced by the disappearance of piezoelectricity due to the release of stress. They suggested the hole and electron centres mechanism as a probable explanation why non-piezoelectric minerals or rocks generate electromagnetic phenomena.

Freund (2002) described a series of low (100 m/s) to medium (1500 m/s) velocity impacts to provide a physical basis for microfracturing electrification presented by Molchanov and Hayakawa (1998a). They illustrated that when dry gabbro and diorite cores are impacted a relatively low velocities, highly mobile charge carriers are generated in a small volume near the impact point causing electric potentials up to 400 mV. The same effect was observed when a dry granite block was struck at higher velocity. They observed that after the P- and S-waves passed, the surface of the block became positively charged, suggesting the same charge carriers as observed in low velocity impacts. They explained the phenomena based on the positive hole, e.g. defect electrons in the O^{2-} sublattice, travelling via O 2p-dominated valence band of the silicate minerals. They proposed that holes can be activated by low-energy impacts, and together with their related P- and S-waves, suggested that they can also be activated by microfracturing. If microfractures open and close in different parts of the rock volume in rapid succession, each generating a cloud of positive holes, fluctuations in charge carrier density are expected to produce current pulses, generating a wideband electromagnetic signal as described in Molchanov and Hayakawa (1998a).

PHYSICAL MODELS FOR THE GENERATION OF ELECTRIC CHARGES IN ROCKS

Even though there is still not a single comprehensive physical model to explain the elastic and electromagnetic coupled-wave propagation phenomena, the processes for the generation of electric charge in conjunction with elastic-wave propagation are fairly well understood. Historically, the known sources of electric charges on rocks can be categorized as electrokinetic (streaming) potentials, piezoelectricity, triboelectricity / triboluminescence, and contact electrification. Freund (2002) presented the positive holes mechanism as an alternative source of electric charge carrier.

Electrokinetic potentials occur naturally in all rock fluid systems when saline water and solvated ions of one sign move through porous rocks while the charge-balancing counter-ions remain adsorbed to the rocks (Corwin 1990; Bernabe 1998). Porous materials in contact with an electrolyte develop an electrical double layer and relative movement of the pore fluids results in a net displacement of charge across the double layer. Geophysical techniques can generate seismic body waves that stimulate electrokinetic coupling at the surface boundaries and can be observed using surface electric sensors.

The piezoelectric effect is one of factors for the model of seismoelectricity. Piezoelectricity describes the phenomenon that, when a stress is applied to certain crystals in specific crystallographic directions, opposite sides of the crystals becomes instantly charged (Finkelstein et al., 1973; Ikeya and Takaki, 1996; Yoshida et al., 1997). Anisotropic minerals, mainly quartz (SiO_2) demonstrates the piezoelectric effect. The electric potential variation over a standard cubic test sample is directly proportional to the stress change under time-varying mechanical load. In a stressed volume with quartz crystals in random orientation the piezopotentials tend to cancel.

Triboelectricity and triboluminescence describe phenomena that occur when crystals are abraded, indented, or fractured. On an atomic level, rapidly moving dislocations create exciton pairs, i.e. electrons and holes, which generate fractoluminescence by recombination of the exited electrons and holes. Advancing fracture wedges cause charge separation on either of the opposing sides. This mechanism is a candidate to explain why non-piezoelectric minerals or rocks generate electromagnetic phenomena.

Contact electrification is a fundamental process that occurs whenever two dissimilar materials are brought in contact. It arises even in insulators because, however low their conductivity, they will always have a nonzero density of electronic charges. Upon contact, charges flow across the contact point until the Fermi levels are equalized.

Each one of the above processes explains certain aspect of seismoelectromagnetic coupled wave phenomena under certain conditions, but no single mechanism has successfully described all aspects under a coherent physical model.

In the conventional model, it is assumed that the rocks themselves play only a passive role in electrical conduction and wave propagation since electronic charge carriers in rocks are of minor concern because most minerals are good insulators. Freund (2002) discussed another type of charge carriers in rock based on positive holes pairs. The author outlined a mechanism that converts O^{2-} to O^- under special local lattice conditions. An O^- in an O^{2-} matrix represents an electronic charge carrier, a hole or a defect electron. A series of laboratory experiments with low and medium velocity impacts conducted by the author illustrate that these kind of charge carriers can be activated by microfracture and seismic waves in dry igneous rock such as gabbro, diorite and granite. He concluded that the threshold for the generation of these charge carriers seems to be so low that the crackle of microfracturing in a rock volume under increasing stress is likely to have the same effect as that of impact. As microfractures open and close in rapid succession throughout such a rock volume, they emit acoustic wavelets. Each microfracture would generate positive holes, locally on a small scale, but in sum they would add up to a large charge cloud.

In the low velocity impact experiment, a cylindrical diorite core, 2 cm diameter and 10 cm long, was hit by a stainless steel ball (3 mm) projectiles at a speed of 100 m/s. Figure 1 shows an example of activation in a rock sample picked up by a contact ring electrode (channel 1), magnetic pick-up coil (channel 2), a plate capacitor at the back end (channel

3) and a photodiode at the front face (channel 4). The light blip (channel 4) marking the time of impact is probably due to triboluminescence, coming from electron-hole pairs generated by rapidly moving dislocations and their radiative recombination. From the small source volume the positive holes propagate outward as a charge cloud, causing positive potentials, EM and delayed light emission. The observations indicate that the charge carriers spread through the cores at a relatively high speed, in the range of 100–300 m/s.

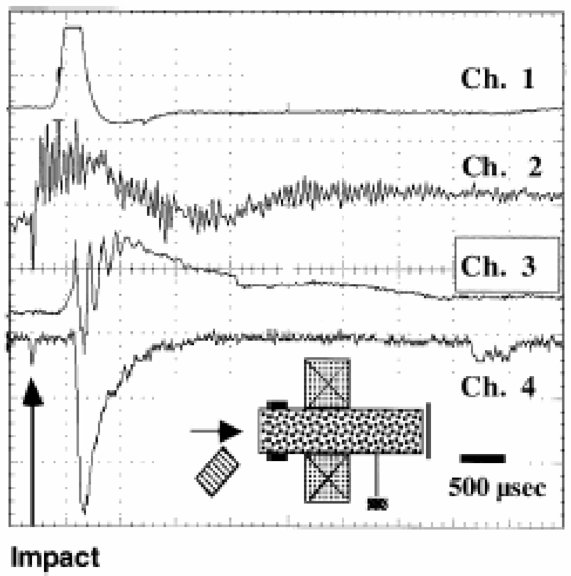

FIG. 1. A 100 m/s impact. Diorite core. Channel 1, ring electrode voltage, 400 mV; channel 2, EM emission, 10 mV; channel 3, back-end capacitor voltage, 20 mV; channel 4, front-end light emission, 500 mV. Vertical arrow marks the time of impact (source: Freund, 2002).

Figure 2 shows the voltage response of three capacitive sensors when a 25×25×20 cm granite block was hit by 6 mm steel ball in a medium velocity impact (1.46 km/s) experiment. The delay onset indicates that the middle and bottom coils register an electric charge moving through the block in the wake of the P- and S-waves and with their velocities of about 6 and 3.4 km/s, respectively. The same delay of the signals and propagation velocity was observed in an even higher impact experiment at 4.45 km/s, indicating that the delay time is not a function of the impact velocity.

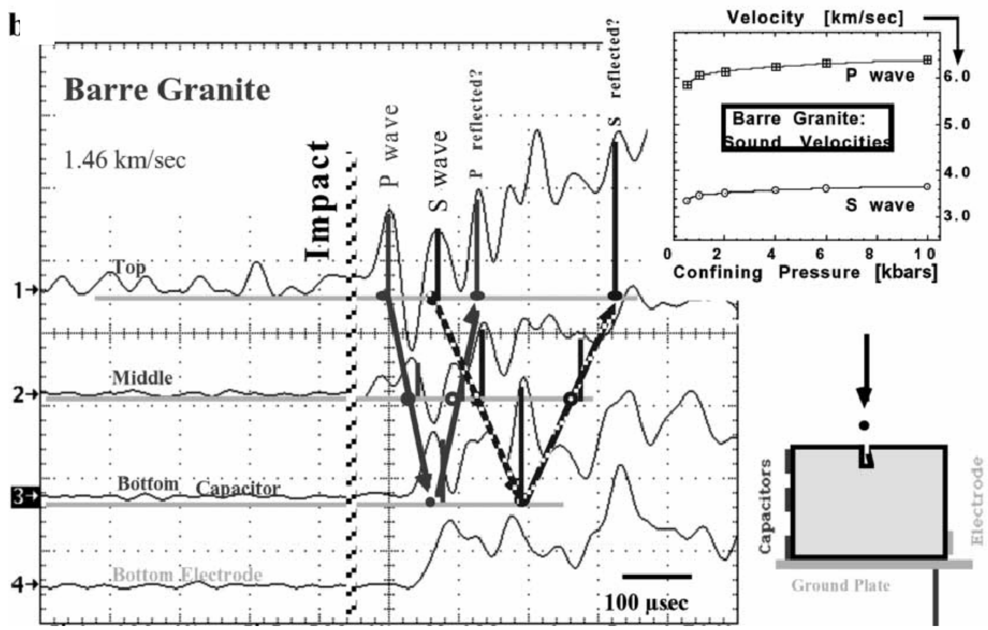

FIG. 2. The 1.46 km/s impact on the granite block. Initial arrival of the signals, at high resolution with tentative assignment of the short voltage pulses to piezoelectric signals arising from the passing of the incoming and reflected P and S waves. Inset shows velocities of the P and S waves in granite as a function of the confining pressure (source: Freund, 2002).

The impact experiments that indicate the electric charge carriers do indeed exist in dry rocks and can be activated by an impact and its related elastic waves, suggesting that they can also be activated by microfracturing. Wherever such moving and fluctuating charge clouds intersect the surface, an array of electric sensors can detect and monitor the electric discharge as an underground seismic event.

GEOPHYSICAL APPLICATIONS

Among different mechanisms for generating seismoelectromagnetic coupling response in the subsurface, the electrokinetic and positive hole mechanisms can be of interest in geophysical investigation. The delay traveltime concept linked to the seismoelectric emission of the converted body waves and also their close association with the exciting of elastic waves makes them a potential surface-sounding tool to produce images of the subsurface similar to seismic traveltime images. Interpretation of seismoelectromagnetic amplitude and waveforms in a shot record in conjunction with their seismic counterparts has potential to reveal information to characterize the properties of the solid phase as well as the fluids filling the pore space.

Electrokinetic measurements

Pride (1994) derived a complete set of equations that govern coupled seismic and electromagnetic wave propagations in a fluid-saturated porous medium expressing the coupling between mechanical and EM wavefields. By using a quasi-static approximation, $\sigma(\omega) >> \omega\varepsilon(\omega)$, where σ is the electrical conductivity, ε is the dielectric permittivity, and ω is the angular frequency, the displacement current can be neglected. The diffusive electromagnetic field, which holds for the low-frequency range used in seismic surveys, can be solved using plane-waves for an isotropic and homogenous whole-space (Garambois and Dietrichz, 2001), which results in an expression of electric (**E**) and magnetic (**H**) fields as a linear functions of the second derivative and first derivative of grain displacement **u**, respectively.

$$E_x \cong L\ddot{u}_x^P \text{, for P-waves.} \tag{1}$$

$$E_z \cong L\ddot{u}_z^P \text{, for P-waves.} \tag{2}$$

and

$$\sqrt{H_x^2 + H_z^2} = T\dot{u}_y^S \text{, for SH-waves.} \tag{3}$$

$$H_y = T\sqrt{\dot{u}_x^{2,S} + \dot{u}_z^{2,S}} \text{, for SV-waves.} \tag{4}$$

Equation (1) and (2) show that in-line (E_x, e.g. in surface measurements) and vertical (E_z, e.g. in borehole measurements) electric-field components accompanying the compressional waves are proportional to the horizontal and vertical grain accelerations, respectively. The proportional factor, L, or the ratio between the absolute value of electric field and grain acceleration, is a function of the salinity (i.e. electric conductivity) of the pore fluid and the relative fluid permittivity.

In equation (4) the proportional factor, T, relates the magnetic field H_y and composite grain velocity. This proportional factor principally depends on the pore fluid density, shear viscosity, fluid dielectric constant and to some extent to the porosity and shear modulus of the rock matrix.

According to electrokinetic theory, a survey including simultaneous measurements of multi-component seismic signals, three components of the electric fields, and three components of the magnetic fields allows calculation of the transfer functions between seismic and electric field, L, ($E_x / \ddot{u}_x^P$ or $E_z / \ddot{u}_z^P$) and seismic and magnetic field, T, ($\sqrt{H_x^2 + H_z^2} / \dot{u}_y^S$ or $H_y / \sqrt{\dot{u}_x^{2,S} + \dot{u}_z^{2,S}}$) through equations 1-4. A constrained inversion of these transfer functions that are a function of the saturating fluid's dielectric constant, electric conductivity, shear modulus of the framework of grains, porosity, viscosity, bulk density, and salt concentration could result in estimation of the properties of the pore-fluid and solid matrix. Using field experiments, Garambois and Dietrichz (2001) showed that the waveforms of the seismoelectric signals are consistent with the electrokinetic theory and that their amplitudes vary with the properties of the porous medium. The ability to reveal the properties of the pore fluid and rock matrix suggests that the technique can be used for detecting and monitoring characterization of evolving producing environment such as oilfield or contaminants in the subsurface.

The second electrokinetic effect induced by a seismic source is electromagnetic disturbances generated when a P-wave encounters a boundary where there is a contrast in mechanical or electrokinetic properties of the subsurface. As the seismic pulse impinges on the horizontal layer, circular regions of positive and negative displacement move outward along the layer from a point directly beneath the seismic source (Thompson and Gist, 1993). These circular regions are the Fresnel zones of the seismic wave. The first Fresnel zone is the portion of the horizontal layer reached by the seismic wave within one-half wavelength from the initial arrival. At later times, the seismic wave exhibits successive Fresnel zones. The EM radiation from each Fresnel zone can be represented by an electric multipole. The first Fresnel zone has dipole symmetry. The electric field falls off with distance *r* for higher order multipoles as l/r^{3+c} (c is positive integer), compared to l/r^3 for a dipole, so the electric field from the higher order Fresnel zones can be neglected.

According to the description given above, the geophysical signature of electrokinetic coupling due to vertical acoustic wave propagation will be that of a vertical electric dipole (VED) centred directly below the shot point (Beamish and Peart, 1998). Therefore, the electromagnetic oscillation will propagate to the surface at the speed of light. At a given depth, the time instant of coupling will occur at the one-way traveltime of the downgoing acoustic wave. Numerical modelling of the behaviour of the fields associated with a buried VED in a homogenous half-space shows that the maximum surface amplitudes will always be observed at an offset equal to half the depth of the source, which also corresponds to the signal with maximum S/N ratio. Analysis of the amplitude versus offset (AVO) of the electromagnetic waves and its Normal Moveout not only reveals the depth to the layer interface but also estimates the velocity of acoustic and EM wave propagations in the subsurface down to the reflector boundary. Modeling also predicts the phase reversal (180 degrees) of the field oscillations occurring about the plane of symmetry. This property is significant since all other remote sources of electromagnetic radiation (natural and man-made) would appear as in-phase oscillations across the local scale of the measurement.

Criteria to distinguish this type of signals from background noise and seismic arrivals can be listed as (Thompson and Gist, 1993):

- The converted signal arrives at the antennas at virtually the same time, independent of offset.
- The signal arrives in approximately one half the time required for a seismic arrival.
- The signal changes polarity on opposite sides of the shot point.

Joint seismic and seismoelectric surveys can be conducted by repetition of the seismic measurements over the seismoelectric profile or by simultaneous recording of the seismic and EM signals along two parallel lines either side of the shotpoints. In simultaneous measurements of the seismic and seismoelectric data, lines of geophones and dipole antennas must be horizontally offset a few metres to reduce risk of crosstalk between mechanical and electrical sensors by electrically isolating them from one another. A plan view of the layout of dipole antennas and geophones along seismic and seismoelectric profiles in a simultaneous survey is proposed in Figure 3.

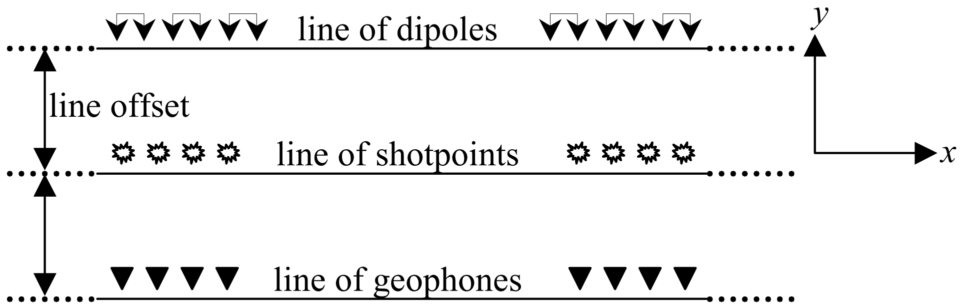

FIG. 3. Layout of grounded dipole antennas and geophones about the shotpoints in simultaneous recording of seismic and seismoelectric surveys.

Dipole antennas are stainless steel rods, several tens of centimetres long, driven into the ground. No special electrode type, e.g. non-polarizing electrode, is required since the behaviour of the recorded signal is independent of the electrodes (Beamish and Peart, 1998). Strength of the measured voltage is a function of the electrode separation of the dipole. However, the measured noise voltage scales with the antenna length. It imposes the fact that there will be an optimum length for an antenna. The noise level for a very short antenna may be limited by electrochemical electrode noise. Noise in a very long antenna may be dominated by environmental noise because the noise voltage increases in proportion to antenna length while the signal falls off away from the source. Therefore, the optimum survey arrangement will have the largest possible number of relatively short antennas, to optimize dynamic range, and a large number of sources, or a repetitive source like a vibrator, to stack out the effect of noise (Thompson and Gist, 1993).

In practice, any conventional multi-channel seismic acquisition system can be used for recording seismoelectric signals. The electric dipoles can be directly connected to the recording system through geophone cables; however, the quality and S/N ratio of the signals can significantly be improved by introducing analog notch filters and preamplifiers between the dipoles and acquisition system. Pre-amplification and filtering of the small amplitude of seismoelectric signals (μV to a few mV) is crucial in most seismoelectric surveys since a direct connection of the dipole antennas and recording system would result in noise levels an order of magnitude higher and capacitive loading of the seismic cable would reduce the bandwidth of the signal (Bulter, 2002; Kepic and Butler, 2002). In post-processing, the sinusoidal subtraction technique described by Butler and Russek (1993) or a two-zero, two-pole autoregressive moving-average notch filter (Dietrich et al., 1996) can be used to suppress the power-line frequency and its harmonics.

Simultaneous remote-reference telluric recording at a distant location of more than five electromagnetic skin depths, corresponding to the lowest frequency content of the observed seismoelectric signal, is essential to effectively detect and reduce the atmospheric noises. Mikhailov et al. (2000) described a simultaneous recording of the telluric noise on two perpendicular horizontal electrical dipoles on the surface during a borehole seismoelectric survey. They subtracted a linear combination of the two surface noise recordings from the measurements in the borehole. The coefficients of the linear combinations were chosen to obtain the best (least-squares) match between the noise records on the surface and in the borehole. They reported that this procedure increased the signal-to-noise ratio up to 50 times.

The accompanying seismic body waves are recorded by repetition or simultaneous measurements of elastic wave using high-frequency 3-component geophones located at, or with horizontal offset from, the centre of the dipoles (Figure 3). Sledgehammer blows or explosives can be used as the mechanical excitation of the medium. Multi-component geophones are required to compute the transfer function between seismic and in-line electric field recordings in a surface deployment of receivers (Equation 1). Recording the magnetic counterparts of the electric field, using a set of magnetic sensors in y-axis along the seismoelectric profile, extend this analysis to incorporate the other components of the body waves (Equation 4).

The electromagnetic skin depth set the scale for the useful depth of exploration. The EM skin depth (δ) for plane-wave approximation is a function of electrical resistivity (ρ) of the subsurface and the frequency content of the EM signal:

$$\delta(m) = 502\sqrt{\rho(\Omega m)/f(Hz)}\,. \tag{5}$$

For a given centre frequency of seismic and its accompanying seismoelectric data of 50 Hz and a subsurface electrical resistivity of 100 Ωm, the corresponding nominal EM skin depth is about 700 m. At a depth of five skin depths (3.5 km) the signal is attenuated by approximately a factor of 100. As a criterion, five times the skin depth was proposed by Thompson and Gist (1993) for the maximum achievable depth of investigation.

Positive holes measurements

The concept of positive holes as prominent charge carriers in dry rock, which can be activated by low-energy impacts and their attendant elastic waves, suggests that they can also be activated by microfracturing (Freund, 2002). The delay traveltime associated with the observed seismoelectric field in the impact experiments described by Freund (2002) in conjunction with the concept of electrification by microfracturing proposed by Molchanov and Hayakawa (1998a,b) advocates that seismoelectric signals generated by positive holes mechanism can probably be used for detecting and monitoring of the microfracturing processes and evolution. For instance, natural redistribution of the stress field over a producing oilfield due to depletion of the reservoir, or induced stress caused by steam injection or hydro-fracturing, can lead to opening and closer of microfractures which in turn results in the generation of body waves as well as seismoelectric signals. As a proposal, an array of pairs of orthogonal dipole antennas, separated by a few metres offset to eliminate risk of mutual induction, installed on the surface and spread over and beyond the area of interest could possibly detect and locate the tremors associated with the microfracturing in this kind of active zone. A schematic of such kind of array is illustrated in Figure 4.

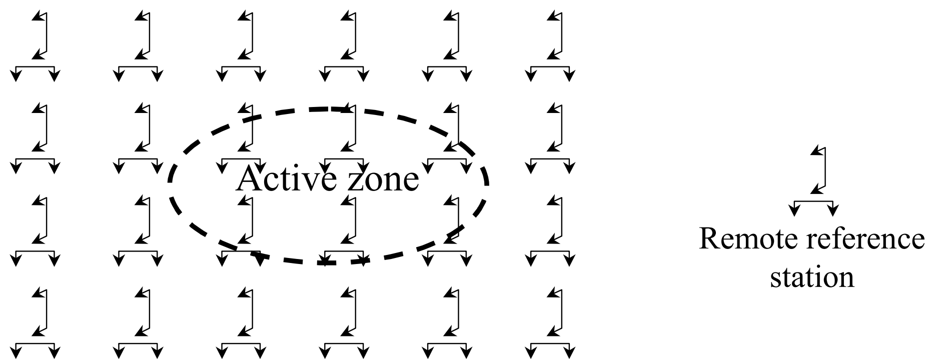

FIG. 4. Plan view illustrating the distribution of pairs of grounded dipole antennas over an active microfracturing zone.

A permanent array installation of the dipole pairs would possibly be able to monitor the evolution of the fracturing process. Similar to electrokinetic survey, pre-amplification, analog notch filtering and post-processing to reduce the power-line effect is required. A permanent remote reference station located at the distance of several skin depths is significant issue to reduce the telluric noise from the observation. Since the stacking technique cannot be applied in a randomly occurring fracturing process, a larger electrode separation of dipoles is required to increase the amplitude of the recorded signal. As a result, an effective reduction of the telluric noises becomes more critical. Vectorial measurements of the electric field using pair of grounded dipoles over a group of stations not only allows estimation of the total amplitude of the signal as well as the horizontal direction to the source of event, but also allows suppression of the noise from remote regions through spatial filtering.

Based on laboratory experiments, Freund (2000) claimed that a cluster of microfracture events can add up to a large charge cloud. Assuming a charge carrier density of 10 ppm, he estimated that an electric field of the order of 400,000 V/cm can be established across the flat surface during the fracturing process associated with earthquake event, which causes dielectric breakdown of the air and light emission. However, in applying the same mechanism as a geophysical tool for monitoring the small-scale microfracturing process, the generation of sufficiently strong seismoelectric signals that can accurately be identified from the background noises is a matter of concern. Microfracturing processes observed in geophysical investigation scales can be many orders of magnitude smaller, in terms of the numbers and amplitudes, than the fracturing caused by tectonic activity. A pilot study could explicitly aim to answer the question whether detection of such small seismoelectric signals originating from the microfracturing in the monitoring environments is practically plausible.

Finally, as a relatively unknown seismoelectromagnetic coupling effect, Karrenbach (1991a,b) and Karrenbach and Muir (1991) theoretically illustrated that elastic and electromagnetic coupling effects can change the velocity of naturally occurring rock in the range of a few percent. As they observed from the examples of quartz and Lead-Titanate-Zirconate, 3D slowness surface plots show significant difference in uncoupled and coupled wave propagation behaviour in a particular axis. It indicates that for descriptions of wave propagation, not only primary effects, such as anisotropic elasticity, must be considered but also secondary (coupling) effects be taken into account. They indicated that coupling phenomena may prove to be significant in geophysical applications such as enhanced oil recovery and detailed studies of hydrocarbonaceous target zones.

SUMMARY

Seismoelectromagnetic emission (vibration to radiation) and its linear relationship with the exciting elastic waves make them a potential exploration tool to produce images of the subsurface similar to seismic traveltime images. Using an array of dipole antennas and magnetic sensors the seismoelectromagnetic signals, originated by electrokinetic or positive holes mechanism, can be recorded as shot gather in conjunction with their seismic counterparts. Stacking and seismic processing routines might be used to attenuate undesired coherent noise such as that from power-lines. Recording the natural electromagnetic fluctuations at a remote site and subtracting it from the seismoelectromagnetic records can effectively suppress randomly occurring magneto-telluric noises. Seismoelectromagnetic records stimulated by electrokinetic potentials include EM waveforms traveling with their accompanying seismic waves as well as the EM impulses observed almost simultaneously across the array of surface dipoles. The latter corresponds to the one-way downgoing seismic traveltime, permitting a vertical sounding capability.

A comprehensive seismoelectromagnetic survey includes simultaneous measurements of multi-component elastic waves, electric fields, and magnetic fields. Any conventional seismic source and acquisition system can be used for generating and recording of the seismoelectromagnetic signals. However, pre-amplification of the small amplitude of seismoelectromagnetic signals is required in most surveys. Post-processing procedures of the data allows computation of the transfer functions between seismic and electric field (L) and seismic and magnetic field (T). These parameters are a function of the physical properties of the pore-fluids and rocks. A constrained inversion of the computed transfer functions could result in estimation of the properties of the pore-fluid and solid matrix.

The ability of seismoelectromagnetic surveys in not only producing images of the subsurface but also estimating the properties of the pore fluid suggests that the technique might be useful in detecting and evaluating of hydrocarbon reservoirs. It offers direct insight into subsurface fluid properties, which can be used, for instance, to discriminate between different liquid phases in an enhanced oil recovery and detailed monitoring of the reservoir.

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