Seismoelectric exploration

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Seismoelectric effects are electromagnetic signals that arise when seismic waves stress earth materials. At least four are of interest to geophysicists: (1) the modulation by seismic stress of the resistivity of the earth through which steady currents flow; (2) seismically induced electrokinetic effects analogous to streaming potentials; (3) the piezoelectric effect; and (4) highly nonlinear processes that generate high audio frequency and radio frequency impulsive responses in sulfides.

This method dates to the 1930s and has intrigued researchers in several countries in the succeeding decades. Soviet and Russian researchers have been active in this area since the 1940s and are responsible for the first measurements of the piezoelectric effect from quartz veins. In the late 1970s, G.A. Sobolev discovered unusual radio-frequency responses from sulfide ore bodies. This effect, which has obvious exploration potential, was originally referred to as PRRER but recent publications prefer the term RPE.

This paper describes three case studies illustrating the application of seismoelectric effects to shallow geophysics: the detection and delineation of a zinc-rich orebody at the Lynx Mine, British Columbia, Canada; the delineation of a quartz blow in the goldfields of the Bendigo mining district of Victoria, Australia; and the mapping of a shallow boundary between road fill and the underlying glacial till at the Malcolm Knapp Research Forest at Haney, BC, Canada.

Field procedures. Among the wide choice of sources for audio frequencies, we have successfully used a sledgehammer, a pneumatic tamper with stacking, a buffalo gun with 12-gauge or 8-gauge cartridges (usually blanks), blasting caps, and small explosives. For the excitation of radio-frequency responses from sulfides, there is a velocity threshold below which no signal is observed, and we

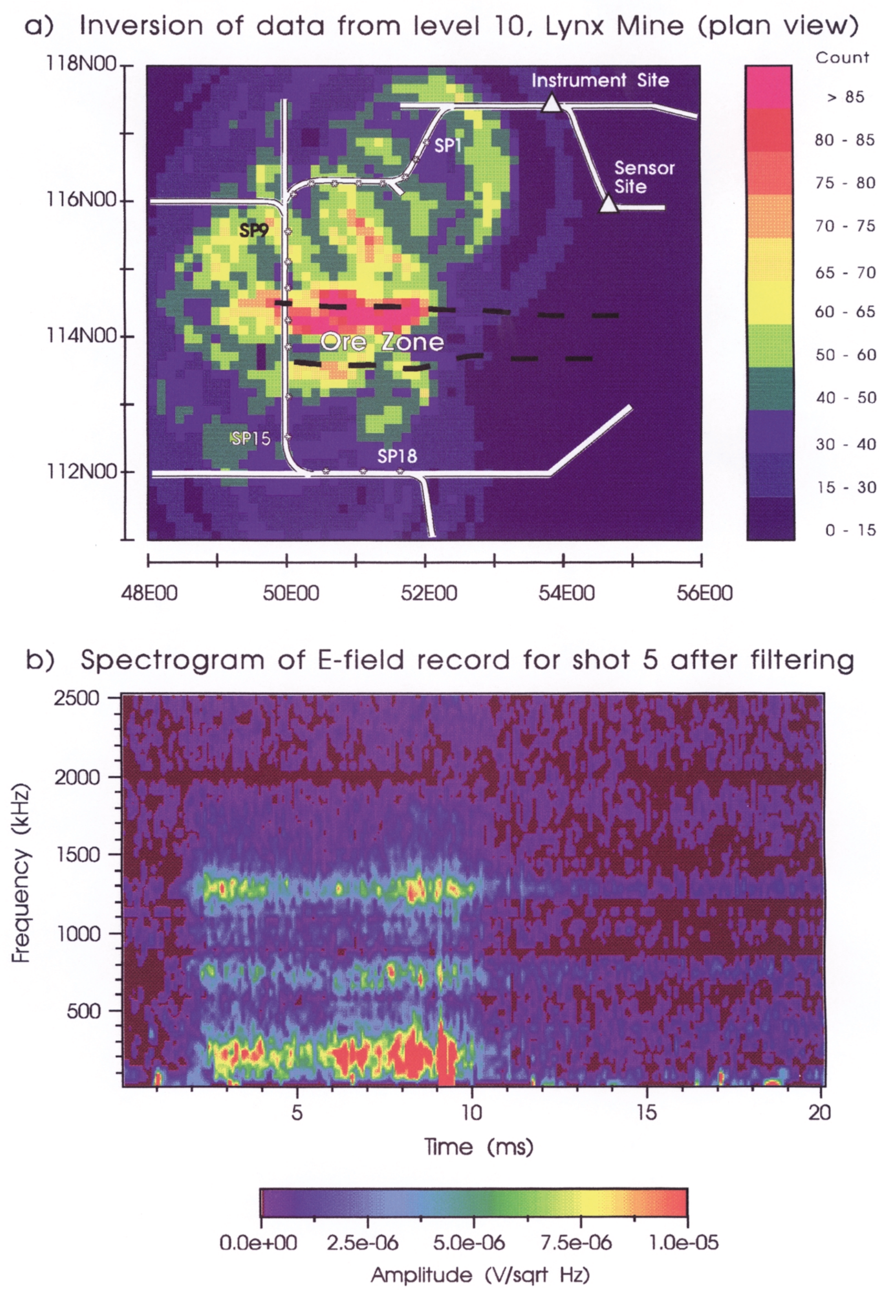

Figure 1. (a) Lynx tomography obtained with a narrow-band (1-60 kHz) acquisition system. Red is the inferred location of the main sphalerite deposit. This correlates with data provided by the operating company. The smallish red area to the upper left of the deposit is thought to be a zinc pillar left for structural support. (b) Lynx spectrum obtained with a broad-band (1kHz-5MHz) recording system. No energy was observed at frequencies higher than those plotted. Russian scientists have speculated that the dominant frequencies are characteristic of the composition of the ore.

have only been successful with high-velocity explosives such as pentolite boosters.

Almost invariably, power-line harmonics dominate raw field records and conceal the seismoelectric signal. These must be removed before interpretation. On occasion we have removed more than 20 harmonics. Otherwise, we have used relatively little processing although band-pass and notch filters and crosscorrelations have occasionally been useful.

A sulfide target. Signals from sulfides (RPE) are not very reproducible in arrival time nor in amplitude, but repeated RPE experiments give signals with similar amplitudes and generally appear at similar times corresponding to interaction with some part of the target. Nothing short of an explosive source excites the RPE mechanism, which is clearly nonlinear.

The Lynx mine is in the center of Vancouver Island. The orebody is a faulted and folded array of individual lenses along a strike length of 2700 m. The Lynx-Myra-Price horizon, in which the ore lenses occur, forms an asymmetrical anticline with ores on both the south side (S zone) and the north side (G zone).

Measurements on level 14 of the S zone were carried out in May and July 1992. They used high bandwidth EM sensors and preamplifiers (1 kHz-4 MHz), but the experiments were limited by the acquisition system to a bandwidth of 1-60 kHz. Each shot consisted of 0.22 or 0.45 kg pentolite primer placed in drill holes of 6 ft or 8 ft. Three magnetic sensors, two horizontal dipoles, and a vertical parallel plate dipole were deployed in a blind crosscut.

Several different signals were observed, but only "burst" signals were clearly induced by the blasts and these had many of the characteristics described by Sobolev. These results demonstrated that the orebody gave seismoelectric responses, but the configuration of the experiment did not permit an interpretation of the result.

After completing the above tests, we moved to level 10 where we could study the ore in the G zone with better shot distribution. Approximately 50 shots were fired at 18 locations, using 0.45 kg pentolite. At this level, there was only one variety of signal, the "spike", most

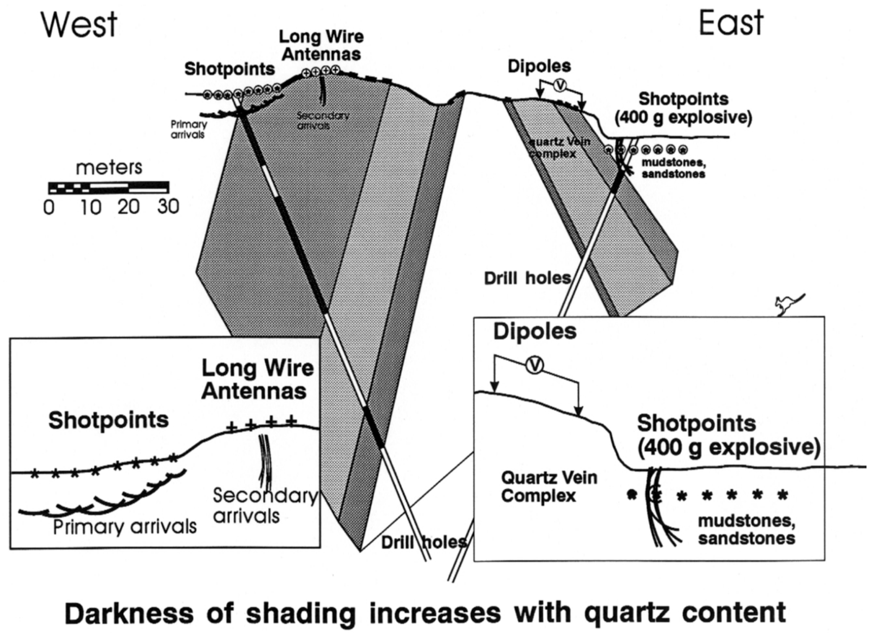

Figure 2. Interpretation of Humboldt measurements and comparison with assumed geology. The primary arrivals on the west side indicate a shallower contact than previously supposed, but it is consistent with borehole data and with occurrences of quartz observed while drilling shallow holes on that side of the structure. The secondary arrivals represent electric fields associated with the wavefronts and occur as the seismic wavefronts pass the antennas. To the east, the seismoelectric data are quite consistent with the assumed geology.

occurring 5-10 ms after the blast, or at distances of 30-65 m. A pseudotomograph was constructed by dividing the target region into equal cubic elements and counting the number of wavefronts that passed through each element at the observed delay time. Layers were averaged to obtain a two-dimensional interpretation as shown in Figure 1a.

Because it was quite important to test the Soviet claims that responses from sulfides extend to radio frequencies, we returned to the mine in 1994 with a data acquisition system capable of recording frequencies as high as 5 MHz. Both magnetic and electric field antennas were used.

The very high frequency nature of seismoelectric signals from sulfides was confirmed. Figure 1b shows clearly that the EM fields have much higher frequency content than the seismic input. Electric and magnetic field strengths can often reach 10 mV/m and 3 nT at a distance of 100 m. One very interesting result is that oscillations of approximately 1.3 MHz were quite reproducible from shot-to-shot and within each record. Such experimental results are consistent with the speculation by Russian researchers that each type of ore/mineral has distinctive spectral peaks.

We conjecture that the mechanism for producing RPE is linked with microfracturing, because there are many similarities to EM signals produced by the fracture of rocks in the laboratory. However, issues remain to be properly resolved, such as the role that sulfides play and the large amplitude of EM signals hundreds of meters from the source. Our laboratory experiments were not able to produce such remarkable signals from sulfides, presumably because of our inability to reproduce the field conditions.

A piezoelectric target. The Humboldt target north of Melbourne, Australia, is a massive quartz body exposed by extensive stripping and trenching. The deposit is a vein of nearly pure quartz, with a width exceeding 20 m, located in folded, weakly carbonaceous shale and silt. Samples of the quartz had large piezoelectric responses, greater than 5% of pure quartz. Three experiments were carried out at the site. The first, by Alan Boyle of CRA, revealed simultaneous EM arrivals at four long-wire antennas (about 50 m in length) positioned in a straight line close to the ground at 3-m intervals 6-15 m from the closest shotpoint.

Our research group carried out experiments in April 1990 and in August 1992. Both recorded clear seismoelectric conversions, presumably created by the piezoelectricity of the vein. The 1990 experiment approximately duplicated the conditions of the earlier CRA experiment, and used much of CRA's apparatus, including an analog recorder for data acquisition. Stacks of 1000 pneumatic jackhammer blows were collected for nine shotpoints at increasing distance, 0-27 m, from the exposed quartz. Crosscorrelations between seismic source and seismoelectric record revealed arrivals that were clear enough to outline a shallowly dipping quartz surface below our shot points. Although the boundary was much less steep than indicated by geologic cross-sections, it was quite consistent with the rather sparse data from cores. Moreover, in 1992 we observed quartz at the appropriate depths in several shallow drill holes.

In 1992, we had improved apparatus: better, more linear amplifiers that did not demodulate the ambient AM radio signals, digital recording systems that gave more more faithful field records, and explosive sources. We concentrated on the west side of the deposit and obtained results that were entirely consistent with previous geological interpretations and with core data. Figure 2 summarizes the 1992 results.

An electrokinetic test. At the Haney site near Vancouver, we have measured seismoelectric conversions that clearly originate at a shallow interface between pemeable, organic-rich road fill and the underlying impermeable glacial till. Detailed studies have shown that the conversion cannot be attributed to peizoelectricity or to resistivity modulation in the presence of uniform telluric currents. Seismically-induced electrokinetic effects or streaming potentials are considered the most likely explanation.

Electrokinetic effects arise in porous media because of the electric double layer that exists at a solid-liquid interface – a layer of ions adsorbed on the solid matrix, and a parallel, diffuse layer of counter-ions in the pore fluid. Because part of the

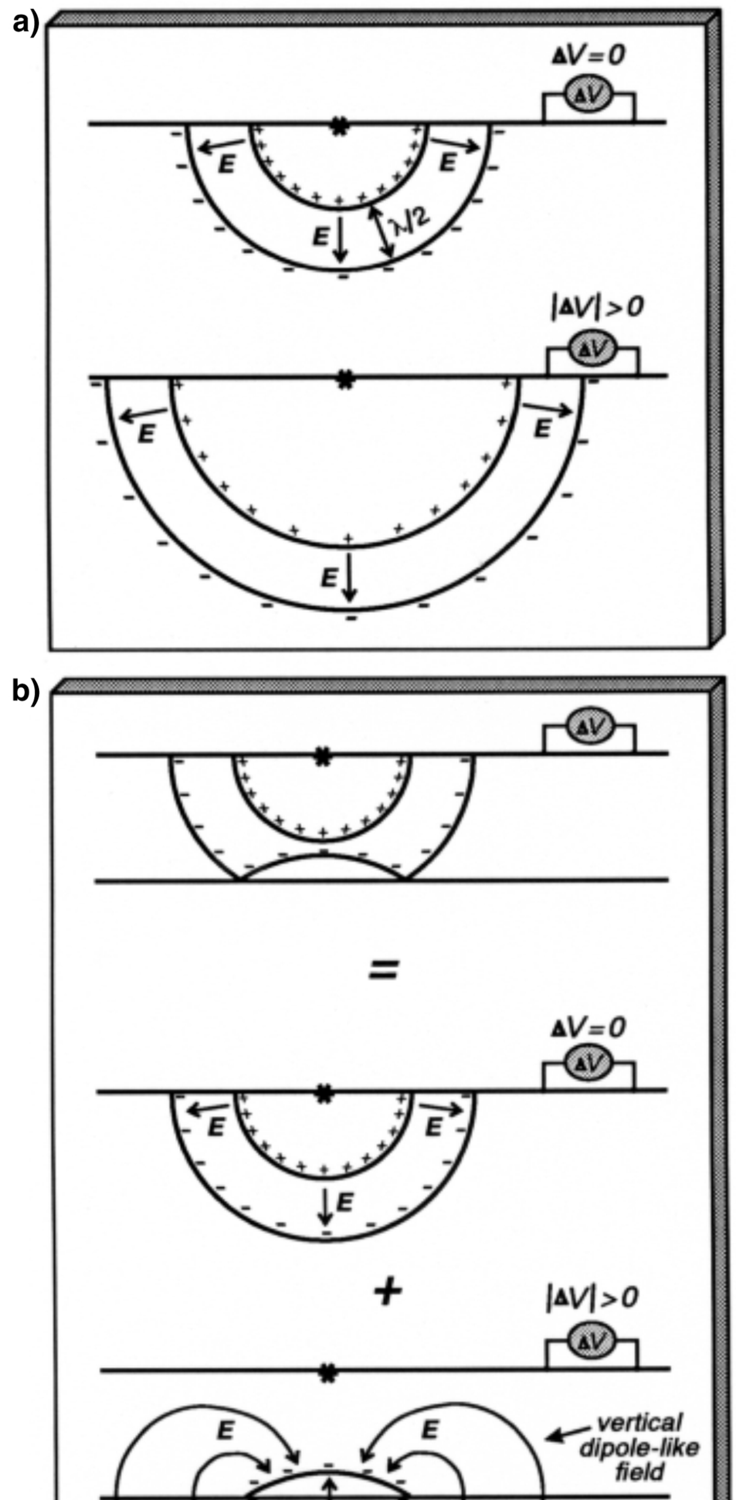

Figure 3. Conceptual modeling of two types of electrokinetic arrivals produced by a point source of seismic *P*-waves. Through electrokinetic coupling, regions of excess positive and negative charge form parallel to the peaks and troughs of the *P*-wave. The regions are here approximated by two shells separated by one-half of the dominant seismic wavelength. This charge separation produces electric fields which can be observed (a) when the *P*-wave passes by a receiver and (b) when the spherical symmetry of the charged region is broken by a boundary (here a perfect seismic reflector).

diffuse layer is free to move with the pore fluid, the flow of fluid relative to solid allows for the possibility of charge separation and the development of an (electrokinetic) electric field known as the streaming potential..

It is well known that compressional seismic waves are accompanied by relative motion between the solid and liquid components in a porous medium. The relative motion of liquid with its excess charge constitutes a streaming current that can generate electromagnetic fields. A complete treatment of this problem involves the solution of coupled electromagnetic and seismic wave equations. However, a reasonable understanding can be obtained by considering a simplified electrostatic model. It can be shown that a compressional wave produces regions of excess positive and negative charge parallel to the seismic wavefronts. This charge separation produces electric fields that are observable (1) as seismic wavefronts pass by a receiver, and (2) when the symmetry of a spherically spreading seismic wavefront is interrupted by a boundary. In the former, the seismoelectric signal exhibits the same velocity as the seismic wave. In the latter, it propagates as an electromagnetic wave and hence arrives nearly simultaneously at widely separated receivers.

The conceptual model is illustrated in Figure 3. Regions of excess negative and positive charge are represented by two shells carrying equal and opposite charge and separated by one-half of the dominant seismic wavelength. In homogeneous media, Figure 3a, it is straightforward to show that the electric field is confined to the region between the shells which travel at the compressional wave velocity. At a boundary, Figure 3b, the spherical symmetry of the charged wavefronts is destroyed. The resulting charge distribution can be modeled as the superposition of two simpler distributions, one of which produces a vertical dipole-like electric field that is everywhere nonzero. While the boundary shown here is a perfect seismic reflector, it could be a discontinuity in any property that affects the distribution of charge transported by the seismic wave. Such properties include fluid flow permeability, electrical conductivity, and the zeta potential of the

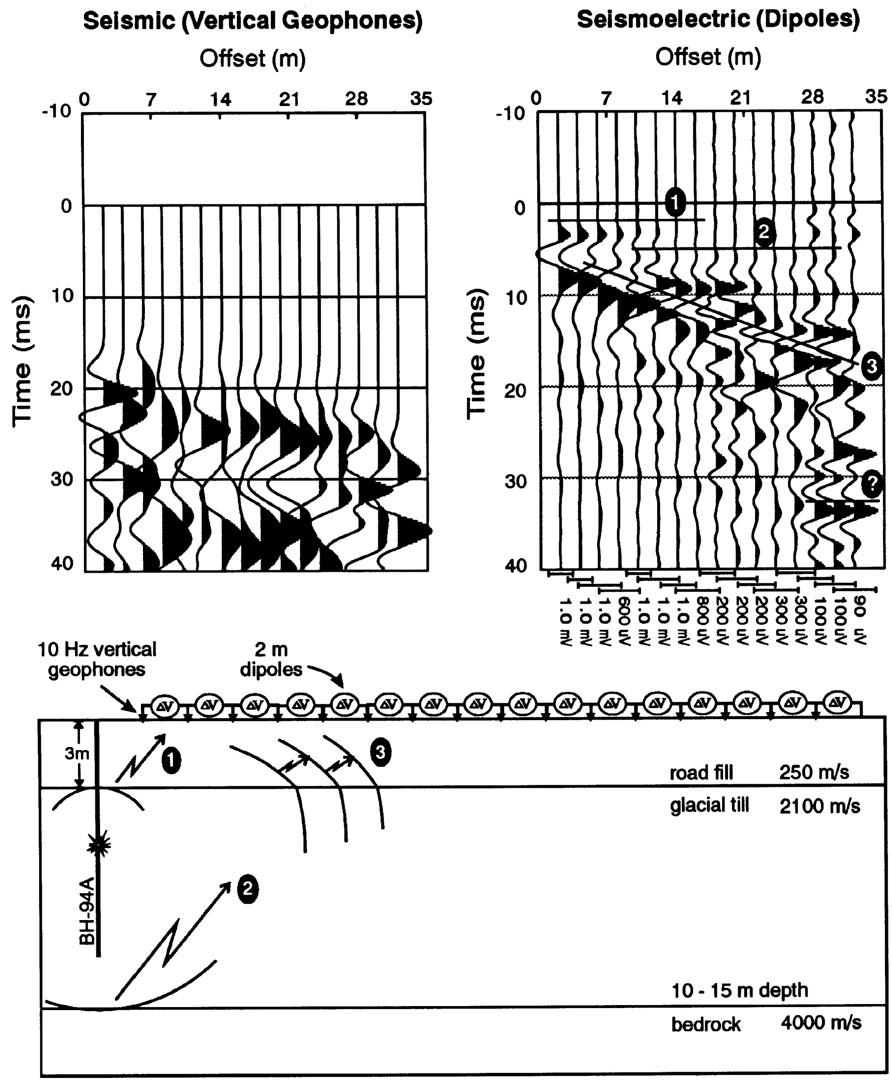

Figure 4. Comparison of seismic and seismoelectric arrivals at offsets of 2-32 m following detonation of a small charge below the fill/till contact at Haney. The cross-section illustrates the experimental layout and gives our interpretation for three coherent arrivals in the seismoelectric record. Trace amplitudes have been normalized for display purposes, but the true voltages measured across each 2-m dipole can be determined by use of the scale bars.

solid-fluid system, as well as the elastic constants.

Figure 4, representative of our 16 experiments at Haney, shows seismic and seismoelectric responses generated by a seismic source in a borehole. Both types of arrivals are clearly visible.

The cross-section in Figure 4 shows the experimental layout and the simplified site geology including the depth to bedrock and P-wave velocities. The shotpoint was at a depth of 5.5 m. Geophones and dipoles were deployed on the surface at offsets of 2-32 m. Because of the limited number of recording channels, four separate shots at the same depth were required to obtain the seismoelectric data. The seismic source in each case was either a safety fuse blasting cap or a cap plus a small (6-gram) booster. A 60-Hz notch filter and remote dipole subtraction were used to attenuate noise on the more distant dipoles. Powerline harmonics have been removed from the seismoelectric data, and 50-450 Hz Butterworth band-pass filter was applied to both data sets.

Three coherent seismoelectric arrivals were recorded prior to the arrival of seismic waves at the surface. This demonstrates that the electrical signals cannot be attributed to geophone crosstalk or to shaking of the dipole sensors. The seismoelectric data are also higher frequency. The difference in dominant frequency is attributed to the fact that the seismic waves had to travel through the soft, loose road fill before reaching the geophones at surface, whereas the seismoelectric fields, generated at or below the fill/till boundary, propagated through the fill material with much less attenuation.

Our interpretation of the three arrivals is also shown in Figure 4. Event (1) is generated as the seismic *P*-wave impinges on the fill/till boundary 2.5 m above the shotpoint. It is observed simultaneously by all dipoles out to about 16 m, and its arrival time (corrected for the delay introduced by the band-pass filter) is approximately 1.2 ms after detonation. This corresponds to the time taken by the *P*-wave to travel from the shotpoint to the fill/till boundary at the measured *P*-wave velocity of approximately 2100 m/s. Event (2) is also observed simultaneously over a broad range of offsets. In Figure 4 we have attributed it to a seismoelectric conversion produced at the top of bedrock. However, it is likely that a *P*-wave striking the fill/till boundary for a second time, after reflection from bedrock, also contributes to the signal. Event (3) differs from the other two in that it is not simultaneous. Instead, it exhibits a nearly linear moveout with an apparent velocity of approximately 2500 m/s. This signal is attributed to the electric field contained within theseismic P-wave as it passes beneath each dipole. As predicted by the conceptual model, its apparent velocity is in reasonable agreement with the measured *P*-wave velocity for the glacial till.

Conclusions. The seismoelectric effects of most interest for shallow engineering and environmental applications are those attributed to electrokinetic phenomena. Electrokinetic signals of two types, both related to the charge separation associated with a seismic wave in porous media, are evident in the data ob-tained at Haney, BC. The possibility of detecting the boundaries of formations with differing permeabilities or pore fluids will continue to drive research in this area. The case studies at Humboldt and Lynx Mine illustrate applications of seismoelectric phenomena to mineral exploration. Our results at Humbolt support Russian claims that quartz veins can be detected by their piezoelectric response. The data from Lynx Mine show the very high frequency nature of seismoelectric signals from sulfides and demonstrate the delineation of a sulfide ore zone. In all three case studies, we have been successful in making reasonable geological interpretations from the field measurements.

Suggestions for further reading. "Measurement of the seismoelectric response from a shallow boundary" by Butler et al. (GEOPHYSICS, 1996). "Field trials of a seismoelectric method for detecting massive sulfides" by Kepic et al. (GEOPHYSICS, 1995). "Electroseismic investigation of the shallow subsurface: Field measurements and numerical modeling" by Mikhailov et al. (GEOPHYSICS, 1997). "Geophysical applications of electrokinetic conversion" by Thompson and Gist, (*TLE*, 1993). LE

Acknowledgements: This research was supported by NSERC and five industry partners: BHP-Utah Mines, Cominco, CRA Exploration, Lamontagne Geophysics, and Placer Dome. We thank Westmin Resources for access to Lynx Mine.

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