GEOPHYSICS, VOL. 49, NO. 12 (DECEMBER 1984); P. 2178-2185, 8 FIGS.

Tests of piezoelectric and pulsed-radio methods for quartz vein and base-metal sulfides prospecting at Giant Yellowknife Mine, N. W. T., and Sullivan Mine, Kimberley, Canada

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ABSTRACT

In the summer of 1983, G. A. Sobolev and V. M. Demin of the U.S.S.R. came to Canada to demonstrate techniques using piezoelectrical and other mechanoelectrical effects for in-mine geophysical surveys. We performed field trials using Soviet and Canadian equipment in the Giant Yellowknife Mine, N. W. T., and the Sullivan Mine, Kimberley, B.C., Canada.

The principle of the technique involves detonating an explosive charge and subsequently measuring the strength and delay time of electromagnetic fields generated by excited minerals.

Ore grade gold zones at the Giant Yellowknife Mine occur within large quartz lenses in a shear zone in Archean volcanics. Our tests there produced strong signals in the 8 kHz range, which were very similar to piezoelectrical signals produced by quartz samples, in the laboratory at the University of British Columbia.

The Sullivan orebody is a 160 million ton iron-lead-zinc sulfide deposit lying comformably in Proterozoic rock. Our tests there yielded some very strong electromagnetic signals with frequencies as high as 350 kHz. The short delay times of these signals preclude any possibility that the signals were simple seismic phenomena generated at the antenna sites. Sobolev et al., (1982a, b) suggest that such high-frequency signals are produced by a highly nonlinear discharge phenomenon occurring at the grain boundaries of naturally occurring semiconductors such as galena, sphalerite, and pyrrhotite.

INTRODUCTION

The piezoelectric method of geophysical prospecting is in routine use in the U.S.S.R. for detecting and tracing quartz veins and pegmatitic bodies containing gold and other commercial minerals (Sobolev and Demin, 1980). A new mechanoelectrical effect arising in natural semiconductors has been discovered recently (Sobolev et al., 1982a, b) and is now being used in geophysical prospecting for orebodies containing galena, sphalerite, pyrrhotite, chalcopyrite, arsenopyrite, stibnite, molybdenite, cinnabar, and other sulfide minerals.

Suitable apparatus and field techniques have been developed for these two methods, but up to the present time the methods have been largely overlooked outside of the U.S.S.R.

The purpose of the present work was to test these methods in geologic situations found in Canada. This paper reports the results of experiments using the Soviet equipment and techniques in two Canadian mines.

BACKGROUND

Since the first researching of electromechanical effects in the earth, investigators in the U.S.S.R. have identified five separate electrical phenomena. One effect, called the "explosive electromagnetic impulse," is directly associated with the detonation of explosive material. Two seismoelectric effects have also been identified. The E-effect (also called the seismoelectric effect of the second kind) has been linked with moisture and ion motion in rocks (Ivanov, 1940; Neyshtadt and Osipov, 1962). Discovered later, the J-effect (Neyshtadt, 1970) likely arises from conductivity changes (caused by seismic stress) modulating telluric currents in the rock.

The piezoelectric signal as a geophysical effect is based on the familiar effect found in certain types of crystals (Volarovich and Parkhomenko, 1954; Volarovich and Sobolev, 1969; Sobolev and Demin, 1980). Observable piezoelectric effects in naturally occurring rocks are very rare, because random alignment of the piezoelectric crystals in the rock results in an overall cancellation of any large-scale electric fields. The method is limited to prospecting for quartz-bearing rocks (Neyshtadt et al., 1972; Sobolev and Demin, 1980).

More recently while performing piezoelectric method surveys, electromagnetic (EM) radiation of a new nature was

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found (Sobolev et al., 1980) having frequencies 10 to 100 times higher than the elastic waves from the explosion inducing the radiation. The effect has been called the pulsed radio-wave range of electromagnetic radiation (PRRER) and has been studied with respect to establishing its connection with specific types of orebodies (Sobolev et al., 1982a, b).

FIELD WORK

In June of 1983, G. A. Sobolev and V. M. Demin visited the University of British Columbia (UBC) for a period of four weeks. They brought with them equipment comprising three magnetic antennas, preamplifiers and equalizers, cables, a control module, and two PAL (phase alternate lines)[1] videotape recorders suitably cased for underground work in active mines.

[1]European Broadcasting Union television standard.

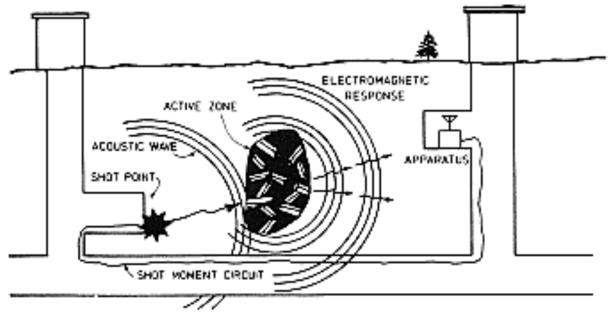
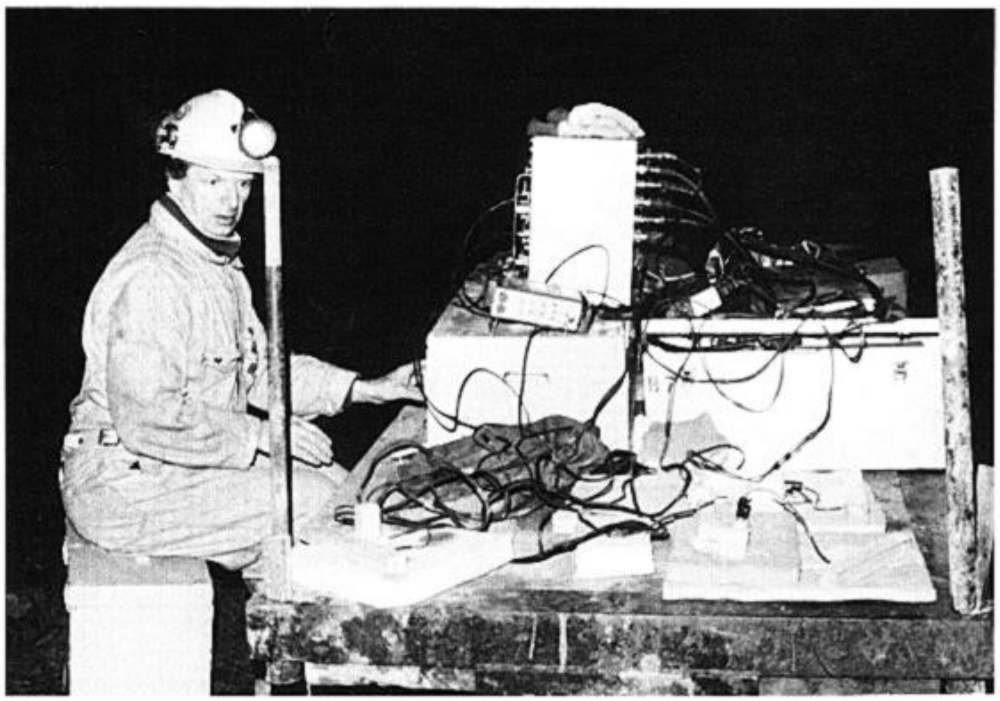


FIG. 1. Schematic drawing of exploration method, adapted from Sobolev (1982). An explosion causes an acoustic wave to propagate through the rock. The electromechanically active zone converts some of the acoustic energy to an EM field which is detected by magnetic antennas in the vicinity of the recording apparatus. The shot moment circuit provides a signal indicating the time of detonation.



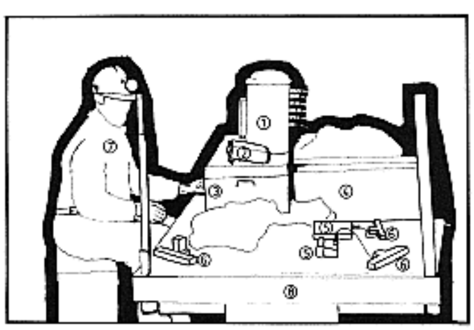


FIG. 2. The exploration apparatus as deployed and operated in the Giant Yellowknife Mine: (1) control module; (2) portable monitor oscilloscope; (3) videotape recorders in environmental enclosure; (4) battery boxes; (5) equalizers; (6) magnetic antennas (three pieces); (7) operator (Demin); (8) mining flatcar. Photo courtesy of E. Mosley of Newmont Exploration Ltd., Tucson, Arizona.

Total weight of the equipment brought from the U.S.S.R. was about 50 kg. For the field work, UBC provided supplementary equipment including batteries, mains power supplies, oscilloscopes and cameras, and tools. The two mining operations provided blasting apparatus, materials, and personnel.

The first week of Sobolev's and Demin's visit was spent at UBC interfacing and verifying the performance of the Canadian and Soviet equipment. For the second week we traveled to Cominco Ltd.'s Sullivan Mine at Kimberley, B.C., where we performed underground trials on three of the days. From Kimberley we traveled to Yellowknife, N. W. T., where we spent a week working in the Giant Yellowknife Mine. Again, we performed underground trials on three of the days. The last week was spent back at UBC processing and interpreting our collected data.

The actual underground experiment starts with the detonation of an explosive charge (Figure 1). The shock wave traveling through the rock compresses and thus energizes the reactive minerals in the orebody. The piezoelectric or semiconductor effect causes localized electrical currents to flow, setting up EM fields, which in turn are monitored by magnetic antennas (Figure 2). The EM signal is recorded on videotape for later analysis. Given the *P*-wave velocity, the delay time between detonation and reception of the EM signal will yield the distance between the shotpoint and the active zone. Many shotpoints are required to delineate the active zone. Spectral characteristics of the EM signal contain information about the mineralogy of the excited material (Sobolev et al., 1982a, b).

The tape recorders independently collect data in two frequency bands; a low-frequency band from 1–20 kHz, and a high-frequency band from 20 kHz to 3 MHz. A single antenna provides the low-frequency signal. Two equalized antennas provide the high-frequency signal. The amplitude-frequency characteristics of both channels are flat within their ranges.

The frequency ranges of interest are such that radio waves can easily penetrate several hundreds of meters of rock. The wavelengths involved are far too great for waveguide mode propagation in mine openings to be significant. Possibly the EM waves can interact with metal structures such as steel rails, pipes, or powerlines. Notwithstanding this, the principal information content of the signals resides in the arrival times. Since the EM signal travels instantaneously when compared with acoustic traveltimes, knowledge of the EM path is not important.

The tape recorders operate for a duration of about 30 s around each shot time, including a 10 s preamble during which the operator reads onto the recorders' voice channels shot identifier information and a countdown to shot time. The actual duration of signal recording lasts only a few milliseconds; thus tape usage is very inefficient. Since the total number of shots is small however (in our case typically five per day), tape consumption remains low.

In the laboratory individual shot data were identified by monitoring the soundtrack from the VTR. The ability of the VTR to "freeze" an image was used to display the shot data on an oscilloscope. We used a delayed time-base to measure the time between the shot moment and the onset of events. The individual events were expanded on the oscilloscope, photographed, then digitized for subsequent spectral analysis. In Soviet laboratories, direct digital signal analysis is more common.

QUARTZ DEPOSITS

Our experiments with quartz deposits were carried out in the Giant Yellowknife Mine. Here quartz lenses are situated in shear zones that cut Archean greenstones (Boyle, 1961). The lenses are flanked by characteristic alteration zones. The site we chose for the experiment was on mine level 250, in a drift running along the shear zone. The local rocks contain abun-

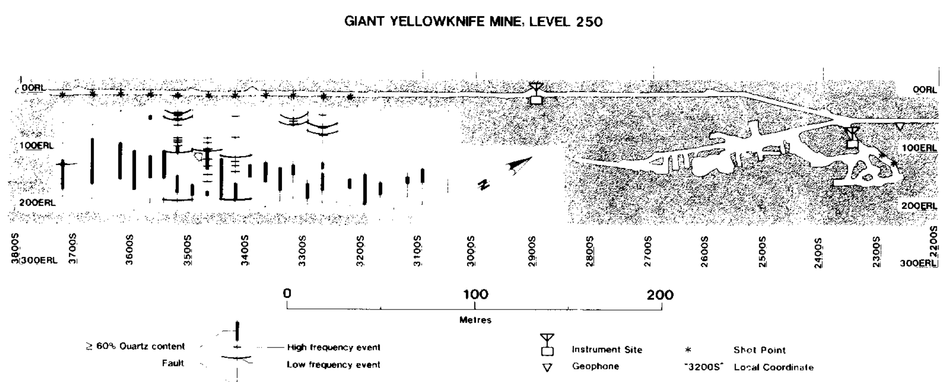


FIG. 3. Plan of the 2–11S drift of the Giant Yellowknife Mine which was used for our piezoelectric method trials. The figure displays shotpoints (asterisks), instrument and geophone sites, and interpreted results. Coring holes are marked as thin lines drawn into the east wall of the drift, between local coordinates 3 150S and 3 725S. Quartz contents greater than 60 percent are drawn as thickened regions on the drill hole lines. The remainder of the rocks are mainly greenstones with typically 5 to 15 percent quartz content. The strongest low-frequency responses have been plotted as broad arcs representing equidistant surfaces from their respective shotpoints. High-frequency responses have been plotted as narrower arcs. The open arrow indicates the signal which is displayed in detail in Figure 4. We believe the six low-frequency events nearest the opening to be associated with small quartz bodies not detected by the coring holes.

dant greenschist and such other minerals as (in order of decreasing relative abundance) chlorite, ankerite, quartz, albite, leucoxene, pyrite, arsenopyrite, including rare occurrences of tourmaline and apatite.

The quartz lenses contain quartz, arsenopyrite, pyrite, sulfosalts, sericite, ankerite, gold, and rare occurrences of tourmaline, apatite, and scheelite. The lenses have thicknesses up to several meters and are divided into layers of high purity quartz veins and of schists (Figure 3). The lenses have approximately vertical dip and sizes up to several tens of meters both vertically and along strike.

We located our shotpoints along one opening on level 250 of the mine (Figure 3). Each of our eleven charges contained about 1.5 kg of explosive material. The charges were placed in old coring holes which we stoppered at about 1.5 m from the wall. The shotpoints were uniformly spaced at about 15 m (exactly 50 ft) intervals.

We located the recording equipment at one of two sites, depending upon the blasting distance, some 200 to 400 m from the various shotpoints. Once set, the charges were detonated in sequence, five minutes between each shot. For precise determination of shot time, the apparatus sensed and recorded the destruction of a wire loop that was included with each charge. The use of electric detonators with a delay of 75 ms avoided interference from the signal used to detonate the explosive. Two separate shots (see Figure 3) provided seismic velocity data which yielded P-wave velocities of 6 400 $\pm$ 100 m/s. Examples of some of the received EM signals are shown in Figure 4.

The low-frequency response appears in Figure 4a, occurring 4.5 ms after the shot moment. This period is the delay time necessary for elastic waves to travel 29 m. The location of this signal is shown in Figure 3 and is marked by an open arrow. The high-frequency response from the same shot, shown in Figure 4b, is more complex. The delay time of the strongest signal, 4.3 ms, is slightly less than the delay time of the low-frequency signal.

Figures 4c and 4d show, respectively, the shapes and characters of the low- and high-frequency signals as displayed with appropriate resolution in time. One can see that, whereas the low-frequency signal has a quasi-sinuosidal form, the high-frequency signal shows a pulsed shaped with a step front and a gradual decay. This is in agreement with findings by Sobolev and Demin (Sobolev et al., 1982a, b) suggesting that two different mechanisms cause the two different signal types. Sobolev and Demin (1980) have established previously that quasi-sinusoidal signals arise in quartz veins as a result of the piezoelectric effect, and that pulsed radio signals (PRRER) appear at the boundaries of different natural semiconductors such as pyrrhotite, arsenopyrite, galena, sphalerite, etc. (Sobolev et al., 1982a, b). We have determined with spectrum analysis that the principal frequencies of the low-frequency signals are about 6–10 kHz, and of the high-frequency signals they are about 40, 90, and 350 kHz (see below).

Laboratory results at UBC have also demonstrated that natural quartz produces signals similar to those observed in our mine experiments (Figure 5) (Narod, 1982). 3 cm^3 samples of polycrystalline quartz taken from lenses in the Con Mine (in the same structure as the Giant Yellowknife Mine) show strong c-axis alignment and piezoelectric coefficients as high as 0.1 pC/N, only one order of magnitude smaller than that of a pure quartz monocrystal. This value, far in excess of that expected from randomly oriented crystals, is consistent with the results of Bishop (1981a, b) who reported the existence of piezofabrics, and is contrary to the results of Tuck et al. (1977).

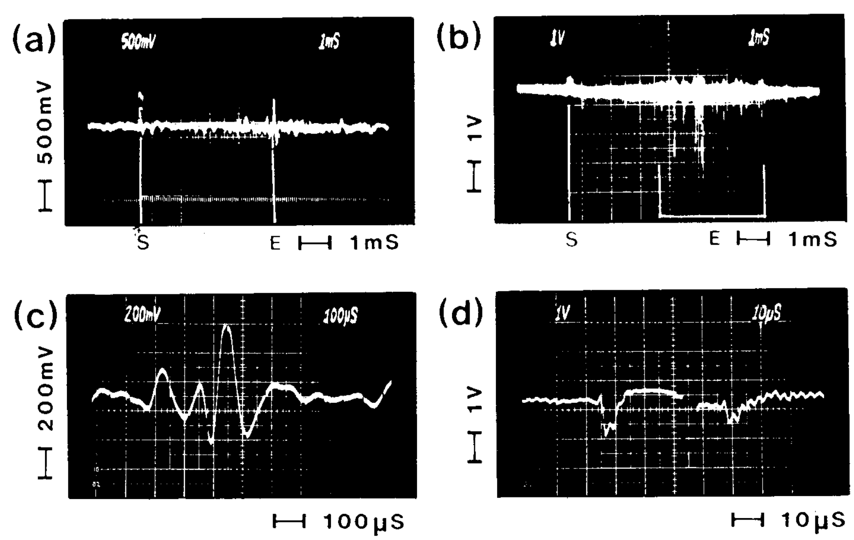


FIG. 4. Examples of EM signals recorded in the Giant Mine. These responses are indicated in Figure 3 by the open arrow. (a) Complete low-frequency record. Shot moment is indicated by a superimposed tone burst. The vertical scale is 500 mV/division and the horizontal scale is 1 ms/division; thus the principal event delay time (E-S time) is 4.5 ms. (b) Complete high-frequency record corresponding to (a). The vertical scale is 1 V/division. (c) Detail of low-frequency record event labelled E in (a). The vertical and horizontal scales are 200 mV/divison and 100 µs/divison. (d) Detail of high-frequency record. The vertical and horizontal scales are 1 V/division and 10 µs/division. Shotpoint tone bursts are indicated in (a) and (b) by S. Signals or periods of large signal activity are indicated by E.

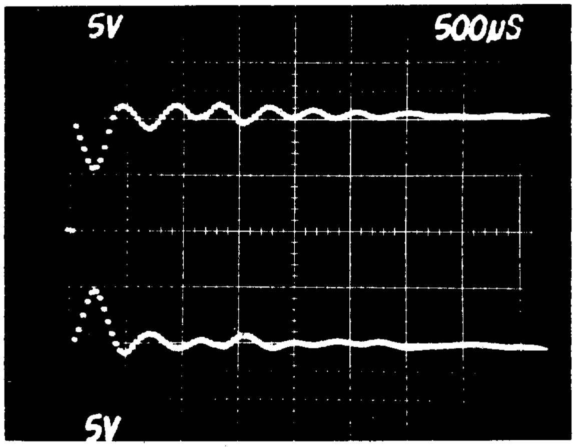


FIG. 5. Piezoelectric response obtained from Con Mine quartz, in a laboratory experiment. The lower trace displays the time series of applied stress. The upper trace displays the produced surface charge. Charge was sensed with a charge amplifier. The maximum charge developed had a magnitude of 18 pC at a force of 600 N, yielding a piezoelectric coefficient of magnitude 0.03 pC/N. The duration of the principal pulse was about 2 ms. The result is consistent with the findings of Bishop (1981a, b), and contrary to the results reported by Tuck et al. (1977). The quasi-sinusoidal form of the charge waveform is very similar to that of the low-frequency signal detailed in Figure 4c.

Many of the signals recorded in the Giant Yellowknife Mine look similar to those shown in Figure 4. We have plotted on Figure 3 the points of origin of the strongest ones, together with geologic information taken from drill core records. Low-frequency signals often arise on the boundaries of quartz lenses having greater than 60 percent quartz content by volume, whereas the high-frequency signals appear to come from both the quartz lenses and the schists. We can postulate that the high-frequency signals arise on the thin layers of pyrite, arsenopyrite, and other natural semiconductors scattered in the quartz lenses and in the alteration zone. Hence one can use only the low-frequency responses to delineate the quartz bodies. The three shotpoints nearest the end of the drift produced small signals with delay times of 2 to 3 ms, corresponding to a distance of 13 to 20 m. The sources appear to coincide with a fault, documented in the geologic data.

The magnitudes of the EM fields may be derived from the recording system calibration previously determined by Sobolev and Demin. Using this, the magnitudes of the low-frequency signals at the receiver from the quartz lenses were typically found to be 0.2 mV/m for a combination of shotpoint-to-quartz lens distance of about 30 m and a quartz lens-to-receiver antenna distance of about 300 m. Under the same condition high-frequency signals varied from 10 to 30 mV/m. The short duration of the tests did not allow us to obtain more detailed information regarding possibilities of distinguishing the different types of mineralization on the basis of amplitude, shape, and spectrum of the EM signals.

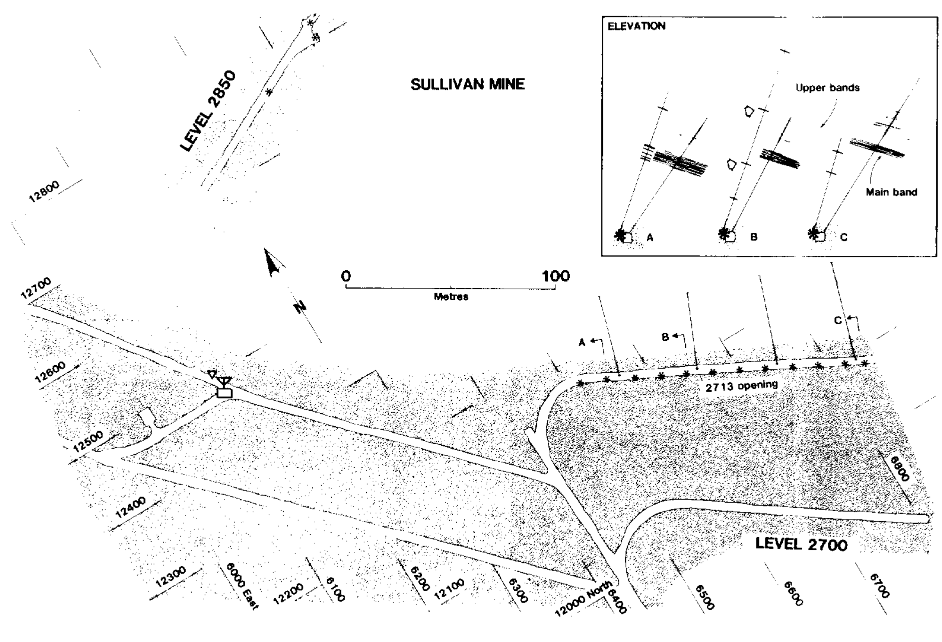


FIG. 6. Plan view of the 2713 opening of the Sullivan Mine, Kimberley, B.C. The symbols are the same as those used in Figure 3. Insert: vertical cross-sections along three drill holes. The main band ore is layered pyrrhotite, sphalerite, and galena. The upper bands are narrow sulfide bands separated by mudstone beds. The hanging and foot walls are predominantly mudstones and quartzwackes. The source locations for the high-frequency EM signals are marked on lines drawn normal to the dip of the orebodies. The two responses indicated by open arrows are shown in detail in Figure 7.

POLYMETALLIC-SULFIDE DEPOSITS

Our trials at a polymetallic-sulfide deposit took place at Cominco's Sullivan Mine, Kimberley, B. C. The Sullivan orebody is a 160 million ton, gently dipping, iron-lead-zinc sulfide lens which lies conformably in Proterozoic clastic metasedimentary rock (Hamilton et al., 1982). The footwall rocks are graded quartzwacke and mudstone beds 10 to 30 cm thick. The main mineral constituents are quartz, sericite, biotite, and some pyrrhotite laminations up to 1 mm thick occurring 5 to 15 m below the "main band" of the orebody.

The main band is 3 to 24 m thick and consists of a succession of fine-grained pyrrhotite, sphalerite, and galena beds. It is overlain by a succession about 20 m thick comprising 35 percent sulfide-rich layers in four bands intercalated with three sulfide-poor interbeds of mudstone and quartzwacke. The upper portion of the main band and the four overlying sulfide-rich bands contain thin, closely spaced interbeds of mudstone and quartzwacke which comprise about 20 percent of a typical band. The main band is about 35 percent of the total package of bedded ore, but it contains about 55 percent of the tonnage and 85 percent of the valuable metals. It typically shows grades of about 10 percent Pb and 15 percent Zn, with 25 percent Fe occurring mainly as pyrrhotite. The hanging wall rocks are graded quartzwacke and mudstone.

Our most successful shotpoint profile was laid along the 2713 opening at level 2700, in the eastern part of the mine (Figure 6). The main band of the orebody lies about 30 m above the 2713 opening. (We detonated five shots above the total package of bedded ore, in opening 2850XCE, without obtaining recognizable events.) In total we detonated 12 charges in the 2713 opening, with 1–2 kg of explosive material in each one. Holes 1.25 m long and 70 mm in diameter were drilled for this purpose. We positioned the recording equipment and antennas at a single site on level 2700, 120 to 300 m from the various shotpoints (Figure 6).

Cores taken from above opening 2713 have aided our interpretation, and summaries of core log data are included in Figure 6. In contrast with the results from the Giant Yellowknife Mine described above, no significant low-frequency responses were recorded from any of the shots in the Sullivan Mine. All the signals appeared on the high-frequency channel (20–3 000 kHz).

Examples of the high-frequency responses appear in Figure 7. In the case shown (location B, Figure 6) strong signals were recorded with delay times starting at 2.38 ms. The strongest signals were recorded at a delay time of 4.6 ms. The next large responses occurred at 8.8 and 12.7 ms delay. Our measurements of P-wave velocities using two additional shots yielded velocities of about 5 800 m/s, which is consistent with earlier measurements by Coenraads (1982). Thus the distances to the signal sources are calculated to be, respectively, 13.8 m, 26.7 m, 51.0 m, and 73.4 m. These results are shown on Figure 6 (inset) together with geologic data from drill logs. Two other examples are plotted on the same figure together with additional geologic data.

The strongest signals coincided with the main band of the orebody. Others probably reflect the existence of pyrrhotite and other thin sulfide layers in the foot walls and hanging walls.

Figure 7b shows an expansion of two events received 4.6 and 8.8 ms after the shot from location "B." The signals are marked in Figure 6 by open arrows. Both signals have the same pulsed form, looking very similar to the high-frequency pulses recorded at the Giant Yellowknife Mine (Figure 4d). This similarity

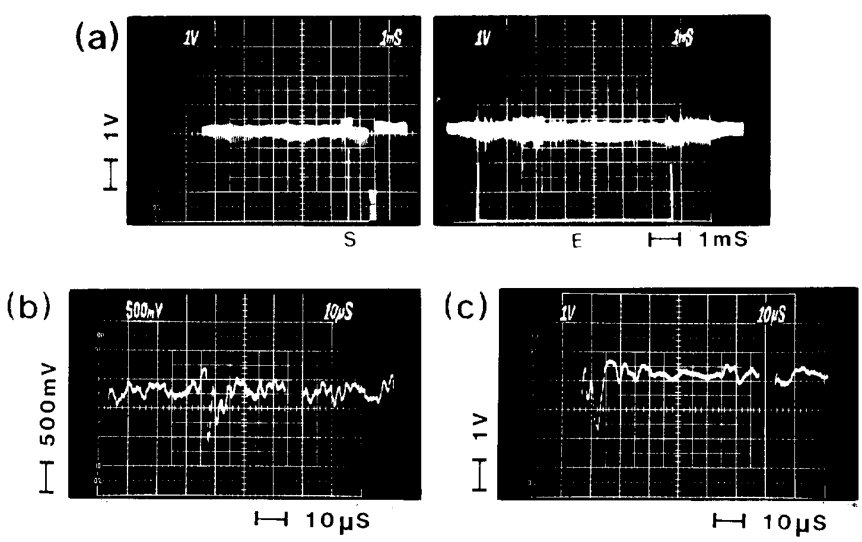


FIG. 7. Examples of high-frequency signals recorded in the Sullivan Mine. (a) Complete record. The gap in the record resulted from the recorded signal occupying two consecutive frames on the video tape. The second part of the record begins approximately 1.5 ms after the shot moment. It overlaps the first part by about 0.5 ms (half a division). (b, c) Detailed view of responses. (b) was delayed 4.6 ms after the shot and (c) was delayed 8.8 ms. The vertical scales in (a) and (c) are 1 V/division, and in (b) is 500 mV/division. The horizontal scale in (a) is 1 ms/division, and in (b) and (c) the scales are 10 μs/division. Labeling is as in Figure 4.

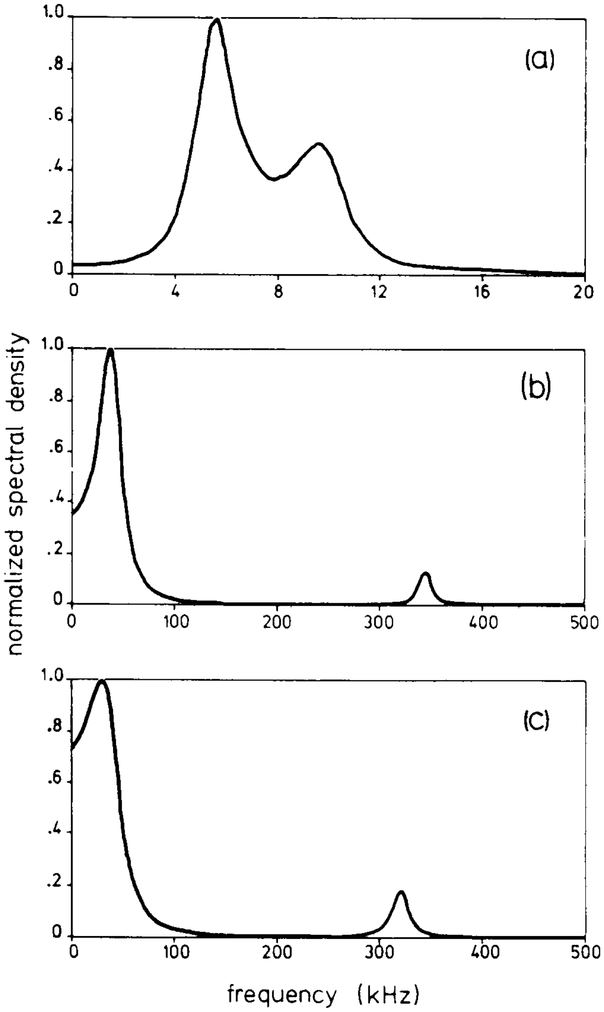


FIG. 8. Examples of maximum entropy method amplitude spectra of signals (Ulrych and Bishop, 1975). (a) Low-frequency signal from the Giant Yellowknife Mine. (b) High-frequency signal from the Giant Yellowknife Mine. (c) High-frequency signal from the Sullivan Mine.

suggests a common mechanism of origin, possibly connected with naturally occurring semiconducting minerals (Sobolev et al., 1982a, b).

SPECTRAL RESPONSE

We converted Polaroid photographs of individual events to digital data using a Talos CYBERGRAPH table digitizer. Enough points were taken to preserve the frequency content of the events. A suitable time series was produced by fitting cubic splines to the raw digitized data. The splined data preserved the essential details present in the original photographs of the events. Frequency spectral responses were estimated from the splined data using the method of maximum entropy (Ulrych and Bishop, 1975) since it is a better estimator for short records than a Fourier transform.

Amplitude spectra of the responses (Figure 8) show that low-frequency signals from the quartz lenses have a dominant frequency of about 6–10 kHz (Figure 8a), and that high-frequency pulsed signals give two main frequencies, about 40 kHz and 340 kHz (Figure 8b). The high-frequency signals from the Sullivan orebody produced frequency maxima of about 40 kHz and 320 kHz. Other signals gave spectral peaks at 90 kHz or broad, low-frequency responses. Much more work will be necessary before we can understand in detail the relations between the geologic situations and the signals they produce.

CONCLUDING REMARKS

We believe that the work reported here represents the first time that the piezoelectric and pulsed radio methods have been used successfully outside of the U.S.S.R. Our results have demonstrated the potential of these methods for geophysical surveys of ore zones conducted from within mine openings.

The traveltimes of the recorded signals absolutely preclude that we are mistaking seismic signals for EM signals such as the interaction of the seismic wave with the antennas. Also noteworthy are the surprisingly large magnitudes of the recorded responses.

Experience in the U.S.S.R. has demonstrated the economic potential of these methods. The methods examine a much larger volume of rock than do cores. The result could be a substantial reduction in the cost of exploratory core drilling. More generally, these methods are the first geophysical methods for specifically detecting quartz.

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Spectral processing was performed using the UBC Computing Centre's Amdahl 470/V8 computer.

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