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DETECTION OF BRINE LAYERS OVERLYING POTASH MINE OPERATIONS BY MEANS OF ELECTROMAGNETIC SURVEYS

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ABSTRACT

Tests of time-domain and frequency-domain electromagnetic exploration systems in a potash mine demonstrated that these systems were able to detect a localized but extensive conductive layer overlying the mine workings.

Comparison of the responses obtained in the mine, measuring the horizontal in-line component of the field, with responses obtained by means of electromagnetic scale modelling, established that the conductive layer could not be situated below the mine workings. The responses in the mine displayed a prominent edge effect which resulted only when the traverse was conducted with the receiver leading the transmitter. The vertical component of the field was unresponsive to the conductor in both time- and frequency-domain surveys, possibly as a result of the choice of coil separation.

The location of the conductive layer appeared to be within the evaporite below the Second Red Shale which normally seals the Prairie Evaporite from the Dawson Bay aquifer. This suggests that the conductive layer is brine, formed by restricted leakage through the Red Shale and lateral dispersion of the brine along the bedding of the evaporite.

INTRODUCTION

The entry of water into the normally dry and electrically resistive Prairie Evaporite of Saskatchewan produces highly conductive saturated brine which is commonly confined within solution pockets. In extreme cases these pockets are open or partially filled with rubble. However, in many cases the brine may not create a cavity but will form a localized wet zone by occupying the intergranular porosity within the salt. The strong conductivity contrast between these brine pockets and the dry evaporite suggests that they should be good targets for electromagnetic surveys conducted within the potash mines which operate in the evaporite beds (Gendzwill, 1967; Gendzwill and Pandit, 1980).

A project to test the application of time-domain electromagnetic methods (TEM) to the detection of brine within the evaporite was conducted by the Potash Corporation of Saskatchewan in association with a group of other potash producers. These surveys were conducted by Crone Geophysics of Toronto using the Crone PEM transient EM system (Crone, 1979).

The TEM surveys in the mines were followed by electromagnetic scale modelling of the response of a variety of possible geological structures formed by brine within the evaporite. This work was conducted in the electromagnetic modelling laboratory at the University of Calgary (Duckworth, 1992). The most notable result of this modelling was the recognition that the tests conducted in one mine detected an extensive horizontal brine layer overlying the workings. The present discussion concentrates on this particular result of the project. Extensive model studies of the probable electromagnetic response of localized brine pockets were also conducted but the mine tests did not provide an example of the response of a brine pocket that could be compared with the scale-model results.

The style of mining employed where these tests were conducted involves the cutting of parallel rooms which are approximately a kilometre in length and 20 metres wide separated by pillars wider than the rooms.

RESULTS OF TIME-DOMAIN ELECTROMAGNETIC TESTS

Figure 1 shows an anomaly detected in one of the mine rooms by the Crone PEM system. This particular room was chosen for tests because water had been encountered in this room during production. Ore production in the panel of the mine which contained this room was completed before this survey was conducted. All machinery associated with mining operations had been removed before the survey. The anomaly was located approximately 1 km from the location at which water was encountered but the flow was limited and it did not cause any brine to reach the part of the room in which the surveys were conducted. An almost identical anomaly was found in the adjacent parallel room but displaced along the room with respect to the anomaly depicted in Figure 1.

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I am indebted to the Potash Corporation of Saskatchewan and to the group of potash-producing companies which supported this project, for the use of data acquired in the mines and for permission to publish the model results. The assistance of mine personnel in conducting follow-up surveys was invaluable. The modelling work and the mine surveys could not have been conducted without the excellent technical work of Eric Gallant.

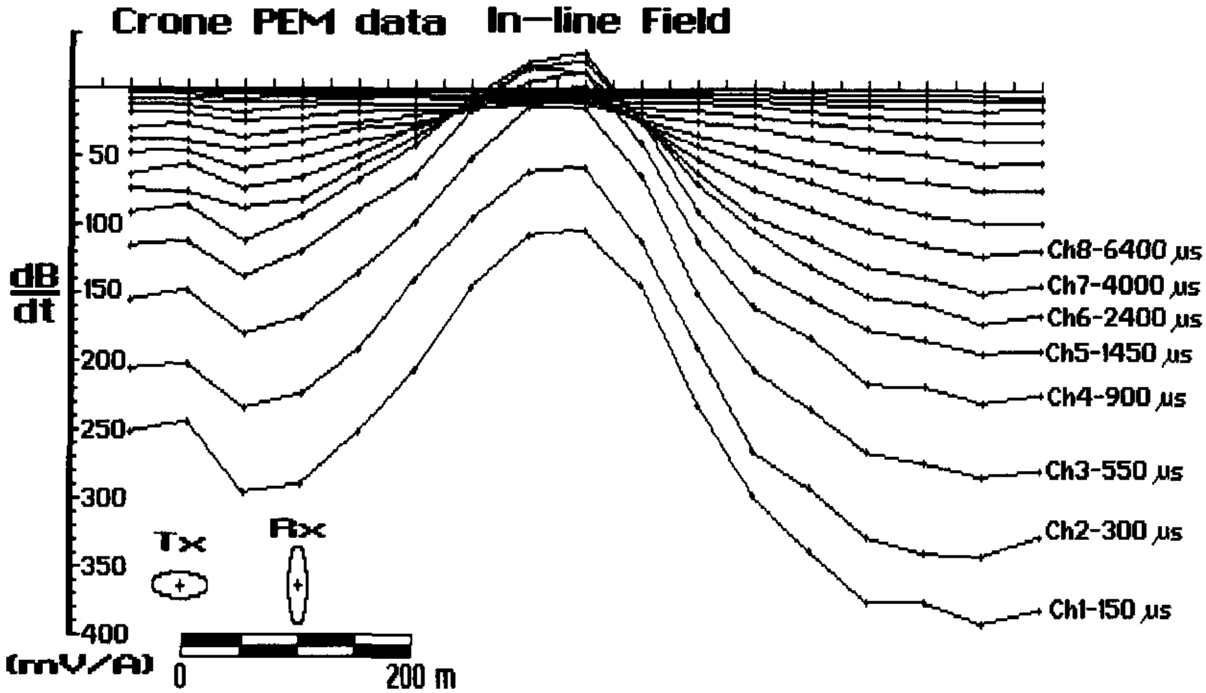


Fig. 1. Transient electromagnetic responses observed with the Crone PEM transient electromagnetic exploration system in a potash mine where water had been encountered in the mine operations.

The survey was conducted with a horizontal transmitter loop which was moved along the mine room in steps of 50 m at a fixed separation of 100 m from the receiver. Only the in-line component of the recorded electromagnetic field is shown. This is the horizontal component in the direction of the radial line from the centre of the transmitter loop to the receiver. The horizontal component of field perpendicular to this line (the cross-line field) and the vertical component of the field were also recorded but failed to show any significant anomaly at this location. A possible explanation for this unexpected result is discussed later.

The decay response shown in Figure 1 to the left of the prominent local anomaly is typical of the notably uniform response seen throughout the mine. This response is known to be caused by the conductive red shales which overlie the evaporite (Duckworth, 1977; Gendzwill and Pandit, 1980). The stratigraphic section shown in Figure 2 illustrates the relationship of the shales to the evaporite. The lower Second Red Shale is between 5 and 10 m thick and displays resistivities in downhole logs of the order of 10 ohm-m. At the interface with the evaporite the resistivity typically rises abruptly and remains high throughout the evaporite. The resistivities reached by the dry evaporite are often off scale on the resistivity logs so that it is difficult to quote resistivities but they are certainly in excess of 40,000 ohm-m. It can be inferred that the evaporite is normally dry even at the contact with the shale because any water in the evaporite would produce brines with resistivities of the order of 0.1 ohm-m or less, contained within the intergrain porosity of the salt. This would appear as a very low resistivity layer on the logs. The upper First Red Shale is considerably more conductive than

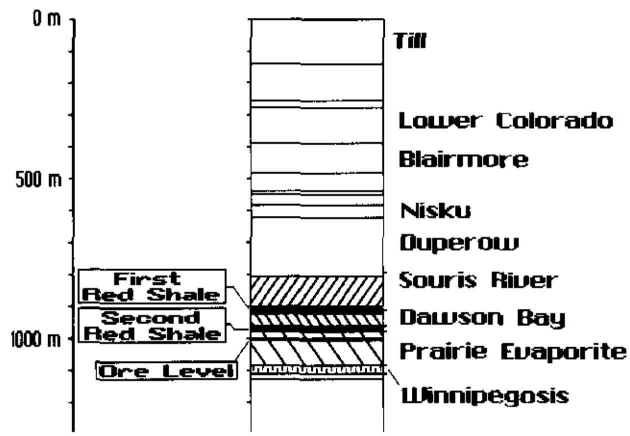


Fig. 2. The stratigraphic sequence of rock units associated with the Prairie Evaporite.

the lower, with a low resistivity of 3 ohm-m and an average of approximately 7 ohm-m over its 10-m thickness. The lower shale is located 30 to 35 m above the mine workings and the upper shale is located approximately 30 m above the lower shale.

The decay response to the right of the local anomaly in Figure 1 was notably stronger for all time channels and uniform along the 600 m of mine room that was open for surveying to the right of the localized anomaly. Water was encountered in the workings approximately 1 km to the right of the local anomaly.

This stronger, uniform response to the right of the local anomaly could be interpreted as being caused by a thickening or downthrow of either of the two overlying red shales. Alternatively, it could be caused by the presence of another uniform horizontal conductive layer, the edge of which lies in the immediate vicinity of the local anomaly. An abrupt thickening of either of the two shales is unlikely, while major faulting of the Red Shales has not been observed in the area, so that an additional conductive layer appears to be the most probable cause of this effect. This layer might be due to a change of conductivity within the Dawson Bay aquifer caused by a zone of increased porosity within that limestone. Alternatively, it might represent a layer of brine within the salt just below the lower Red Shale or a layer of brine below the mine workings. If such a layer is present then the prominent local anomaly in Figure 1 is probably an edge effect.

In order to investigate these possibilities a number of scale models of possible conductivity distributions around the mine workings were tested.

The scale-model results shown in Figure 3(a) are the in-line (horizontal radial) component of the transient secondary field due to a model in which a sheet conductor was placed between the simulated mine workings and a simulated shale conductor. As the lower Red Shale is a much less effective conductor than the thicker upper shale (Duckworth, 1977), it was decided that the shale could be simulated by a single sheet of conductor for simplicity. The shale was represented by an aluminum sheet of 0.02 mm thickness (conductance 480 S) while the truncated additional conductive layer was also represented by a sheet of aluminum foil of 0.02 mm thickness. The model coil separation was 30 cm versus 100 m in the full scale so that the linear scale factor employed in this modelling was 333:1. The separations of the coils from the two model sheet conductors in Figure 3 were 8 cm and 6 cm which represent 27 m and 20 m, respectively, in the full scale. These distances were arrived at as a result of a considerable number of tests of a variety of distances from the coils. The simulated distance of 27 m to the sheet representing the shale is comparable to the actual 35-m distance of the mine rooms below the lower shale. Thus, the modelling appears to indicate that the assumption that the lower shale was not effective was incorrect. The location of the model

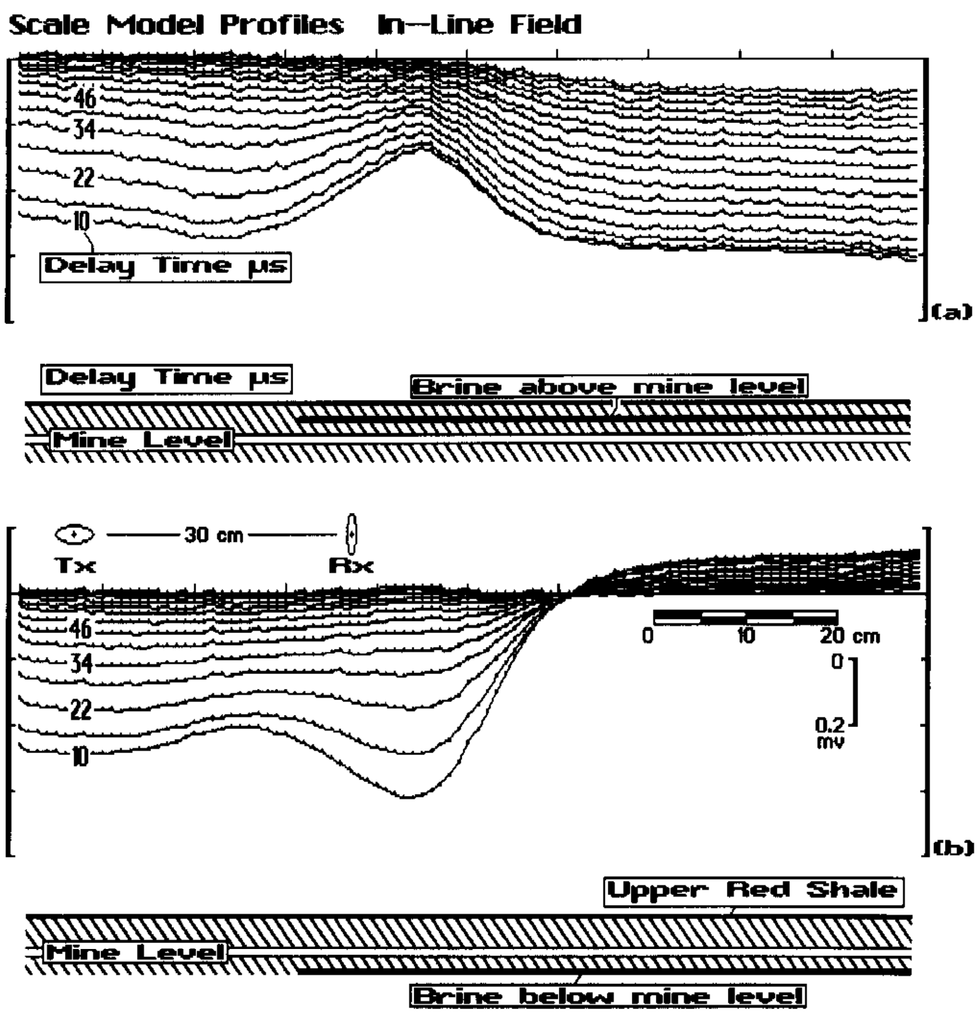


Fig. 3. (a) Scale-model transient electromagnetic profiles obtained with a model which placed a localized conductive layer above the mine room. The prominent anomaly is an edge effect due to this layer. **(b)** Profiles obtained when the localized layer was placed below the simulated mine room.

conductor which simulated the sheet responsible for the edge effect would place it within the Evaporite. The times in microseconds, at which the decay voltage was sampled by the modelling system, are shown on the profiles. The sampling times employed in the PEM system are shown in Figure 1.

The modelling system was not developed with the intent of directly modelling the PEM system, so that exact matches between the field and model data could not be achieved. The most notable difference between the model and the full-scale PEM system is in the distribution of time channels. The distribution and widths of the time channels used in the scale model is linear while the PEM system employs a distribution of time channels and widths which expands in a logarithmic manner for later times.

The vertical scales on the modelled profiles are the amplified coil output voltage. No attempt was made to normalize the output in the manner employed in the PEM system as it was not possible for a direct match to the PEM amplitudes to be achieved.

The model study was conducted with the in-line horizontal component of the field. A study of the vertical component was not conducted due to time constraints.

Time scaling was controlled by the behaviour of the transmitter coil which did not allow readings at any earlier time than 6 microseconds (as compared to 150 microseconds in the PEM system), although the data acquisition system is capable of placing the first time sample at 2.5 nanoseconds after the beginning of the decay.

The geometry of the prominent edge effect that this model generated when the local sheet of conductor was above the simulated mine level (Figure 3a) is notably similar to the geometry of the response that was measured in the mine (Figure 1). The model profiles also resemble the PEM profiles by showing stronger response and a slower decay to the right of the local anomaly. In the model, this stronger response was clearly due to the presence of the additional conductive layer. The model results indicate that the true position of the edge of the conductive layer lies to the left of the prominent anomaly peak.

Model profiles were acquired with the receiver coil first leading and then trailing the transmitter as the system passed under the simulated localized sheet conductor. If the transmitter was in the lead, the strong edge effect disappeared and the profiles (not shown) displayed a smooth transition from the weaker decays to the left of the edge of the conductor to the stronger decays to the right of the edge.

Placing the truncated conductive sheet below the simulated mine room at a depth equal to the height above the room for the previous model and again having the receiver in the lead produced the response shown in Figure 3(b). Comparison of this response with the response obtained in the mine (Figure 1) shows that the effect of the truncated sheet was reversed in polarity with respect to the response of the simulated shale conductor. This suggests very strongly that this was not the configuration of conductors that existed in the mine.

Figure 4 shows the effect of placing the lower conductor at only 3 cm above the coils to represent a conductive layer closer to the mine room. The simulated Red Shale was left in the original position. This model produced decay effects which in both geometry and decay rate came closer to the behaviour of the data acquired in the mine. However, it proved impossible to achieve the apparent negative excursion in the decay seen at the peak of the anomaly in Figure 1. The height of the model sheet above the simulated mine level in Figure 4 would indicate the conductor in the mine to be located approximately 10 m above the mine level.

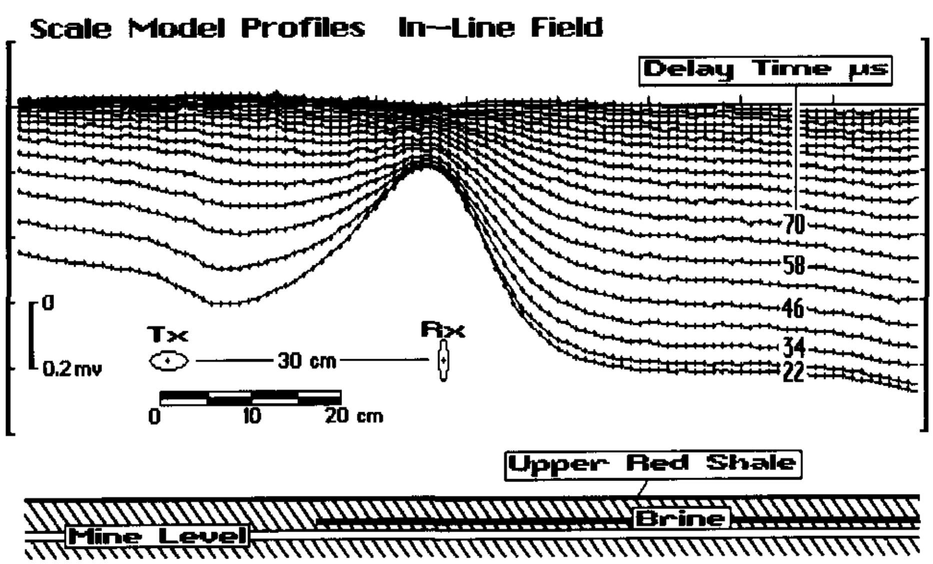


Fig. 4. Scale-model profiles obtained when the localized sheet of conductor was placed closer to the simulated mine room.

Numerous selections of the relative conductances of the two conductors and of their separation from the coil system were used in an attempt to achieve a better match between the model and field data but the inherent differences between the scale-model and field systems prevented an exact match. However, the strong similarity between the field results and the model results does suggest that the responses seen in the mine did originate from a laterally localized but wide horizontal layer of conductor and that this layer was located above the mine room.

Tests were conducted with models in which the truncated sheet was placed above the simulated shale. This might represent a zone of increased porosity in the Dawson Bay aquifer. However, this type of model did not allow an edge effect of the type observed in the mine to be generated.

Among all the various models that were tested, only the model in which the truncated sheet was placed between the mine room and the shale came reasonably close to the observed effects in the mine. This fact and the fact that water did enter the mine room, with indications that the source was above the room, suggests that the most probable cause of a localized but extensive layer of good conductor above the mine workings is a layer of brine produced by leakage of water into the top of the evaporite from the Dawson Bay aquifer. The formation of a layer rather than of a localized solution pocket suggests that the disruption of the lower Red Shale may be a linear feature such as a minor fault. If the flow through this fracture was very restricted, the brine may have dispersed laterally along the bedding of the evaporite. This mode of spreading of the brine would probably be promoted by the clay bands which are common within the evaporite.

Frequency-domain

As noted earlier, the vertical component of the secondary field observed in the PEM survey failed to detect any edge effect or even an indication of a transition from less conductive to more conductive conditions as the system passed under the edge of the sheet of brine. Surveys were also conducted by the mine operators on a routine basis using frequency-domain electromagnetic equipment which measured only the vertical component of the field. These surveys also failed to detect this layer of conductor overlying the workings. The success of the PEM system when using the in-line horizontal component of the field suggested that a frequency-domain device should also be able to detect this layer of brine if it was configured to detect the in-line horizontal component of the field. Accordingly, tests were conducted in the mine using the Max-Min frequency-domain electromagnetic system which has the ability to perform in-line field measurements as well as the more usual vertical field measurements used in this type of equipment.

The results of a Max-Min in-line field survey of the same traverse that was covered by PEM are shown in Figure 5. This illustration presents the in-phase (real) and quadrature (imaginary) components of the response. The transmitter-to-receiver separation was maintained at the same 100 m that was used in the PEM survey. A frequency range from 222 Hz to 3555 Hz was used as shown on the profiles. The vertical scale of the imaginary component in Figure 5 was enhanced to allow the features of the profile to be appreciated. In addition, the 3555 Hz imaginary profile was omitted, as it was very noisy. This may have been due to equipment deterioration in the corrosive conditions in the mine where temperatures were above 40 degrees C and the humidity was 100 percent at the time of the survey.

The profiles in Figure 5 show a prominent local edge anomaly and a clear transition from less conductive conditions to the left of the anomaly to more conductive conditions to the right. Thus, it is evident that a frequency-domain system could also have detected this conductor if configured to record the in-line field.

Figure 6 displays frequency-domain horizontal radial (in-line) field profiles obtained on the same scale-modelling system that was used to acquire the TEM modelling data. In this case the brine layer was represented by an aluminum sheet of 960 S conductance while the overlying shale was represented by a sheet of 480 S conductance. Exact scaling to the frequencies used by Max-Min was not attempted. The box within the figure approximates the view presented by the profiles in Figure 5. The edge effect is well represented in both the real and imaginary components and these model profiles display the same general character as the profiles obtained in the mine.

It is notable that the general form of the imaginary component profiles of Figures 5 and 6 provide the most direct comparison with the PEM profiles of Figure 1.

Vertical component profiles (Figure 7) were also acquired with the Max-Min equipment, again with a coil separation of 100 m. These results agree with the PEM results in that the presence of the truncated sheet of conductor can not be said to be represented in these profiles other than in a very localized feature located at the probable location of the edge of the sheet. This component of the field would normally be expected to have a stronger response to a flat-lying conductor than the in-line component except in one circumstance. If horizontal coplanar coils are placed close to a horizontal sheet of good conductor, their response shows a strong negative displacement in both the in-phase (real) component and in the quadrature (imaginary) component.

Raising the coils above the conductor while maintaining a constant coil separation, causes the response to become positive. Between these two responses a distance from the conductor exists at which the transition from negative to positive response occurs. At that distance, the secondary field from the conductor is directed horizontally so that it fails to couple with the receiver coil (Duckworth, 1970). This distance is approximately one-third of the coil separation or exactly 0.354 of the separation for a perfect conductor. Thus, a conductor located at this critical distance above the mine room could be undetectable in the vertical component of the field but it would be strongly recorded in the horizontal in-line component. For the 100-m coil separation used in both the PEM and the Max-Min surveys this appears to require the conductor to be located 35 m above the mine room which would place it just below the lower shale. The model results of Figures 2 and 3 suggest that the conductor is closer to the mine room. Possibly this issue could be resolved by additional surveys with different coil separations.

Discussion

Despite the design differences between the scale-model system and the PEM system, the strong similarity which their responses display appears to be compelling evidence that the PEM survey in the mine was responding to a localized but large horizontal sheet of conductor and that it was

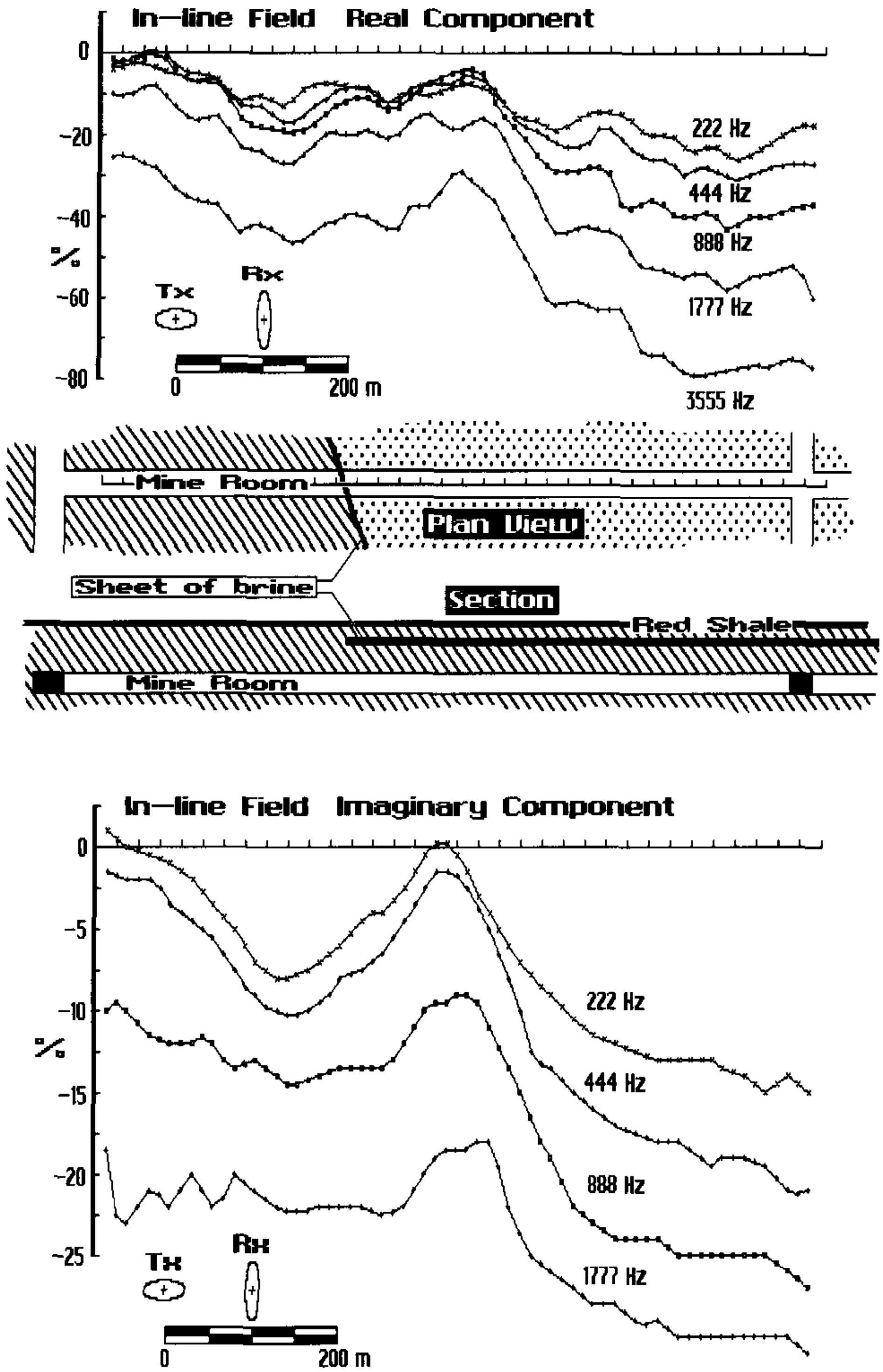


Fig. 5. Real and Imaginary component profiles of the in-line horizontal field detected by a Max-Min frequency-domain electromagnetic survey along the traverse covered by the PEM survey in Figure 1.

located above the mine room. The concept that this conductor is a layer of brine located immediately below the lower Red Shale appears to be compatible with the known immediate supply of water in the Dawson Bay aquifer located just above this shale.

The workings of the mine in which this layer of brine was detected extended approximately 1 km under this layer before water was encountered in the workings. Thus, this type of brine structure may not be an immediate hazard to mining. However, knowledge of the presence of such brine layers is evidently valuable, and electromagnetic surveys are immediately applicable to this type of problem.

The tests conducted in the mine demonstrated that for this unusual combination of horizontal sheet conductors the in-line component of the field gave the best response to the layer formed by the brine, despite the fact that the vertical component of field might normally be expected to be more sensitive to such structures. Transient (time-domain) electromagnetic systems and frequency-domain systems appear to be equally capable of detecting this type of conductor when using the in-line field and may possibly do so in the vertical component of the field for coil separations other than 100 m.

The PEM system produced notably smoother profiles than the Max-Min device. This may be due to the considerably larger transmitter used by PEM which would tend to merge the effects of local conductivity changes which the smaller Max-Min transmitter would respond to more selectively.

While the high conductivity contrast between brine and evaporite is favourable to electromagnetic surveys, the mining machines with their power systems and the belting system running the entire length of a producing room create overwhelming electromagnetic noise. This makes it improbable that electromagnetic surveys can ever operate in active mine rooms.

It should be noted that if the shale conductors were not present and known to be above the mine then it would not have been possible to state that this additional layer of conductor lies above the mine room. It is only the fact that the response of this sheet has the same polarity as that of the shale that allows its location, above the mine room, to be identified.

The scale modelling suggests that the localized sheet of conductor has a conductance very similar to that of the lower Red Shale. The conductance of that shale is of the order of 1 S. A realistic conductivity for the wet evaporite would be 1 S/m so that the layer thickness for such a conductivity would be approximately 1 m. This conductivity is directly comparable with the conductivities displayed by high-grade metallic mineral ore structures. The lateral extent of the sheet was not determined because mine production was not pursued in this area after water was encountered, but the area of the sheet is probably several square kilometres. A conductor of this size may be detectable by means of surveys conducted on surface such as were described by Duckworth and O'Neill ('989).

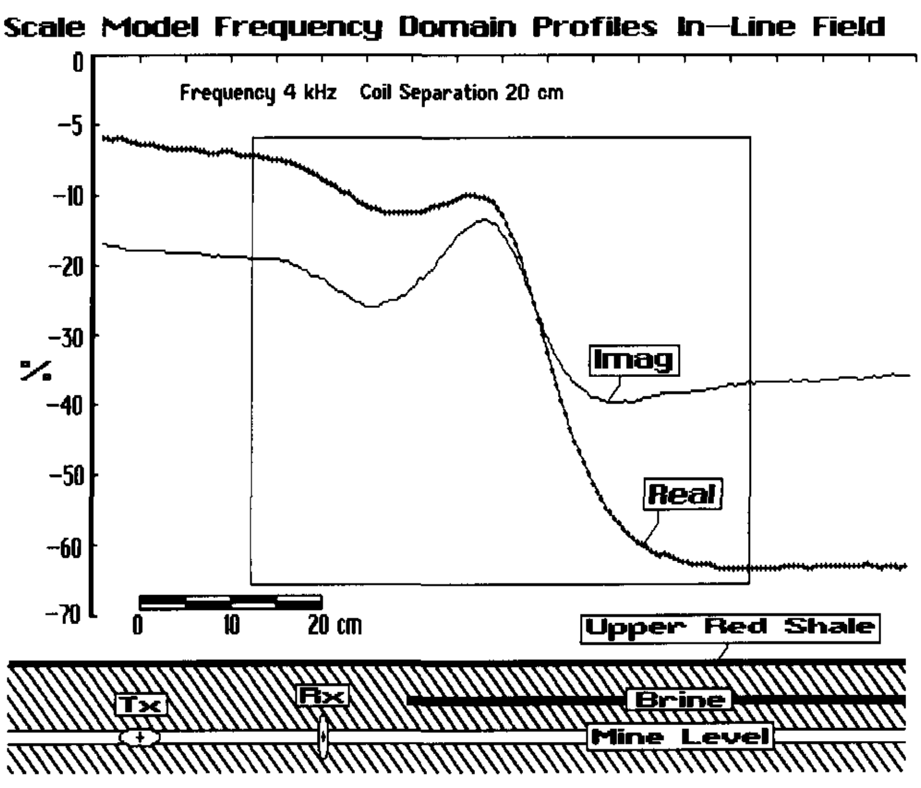
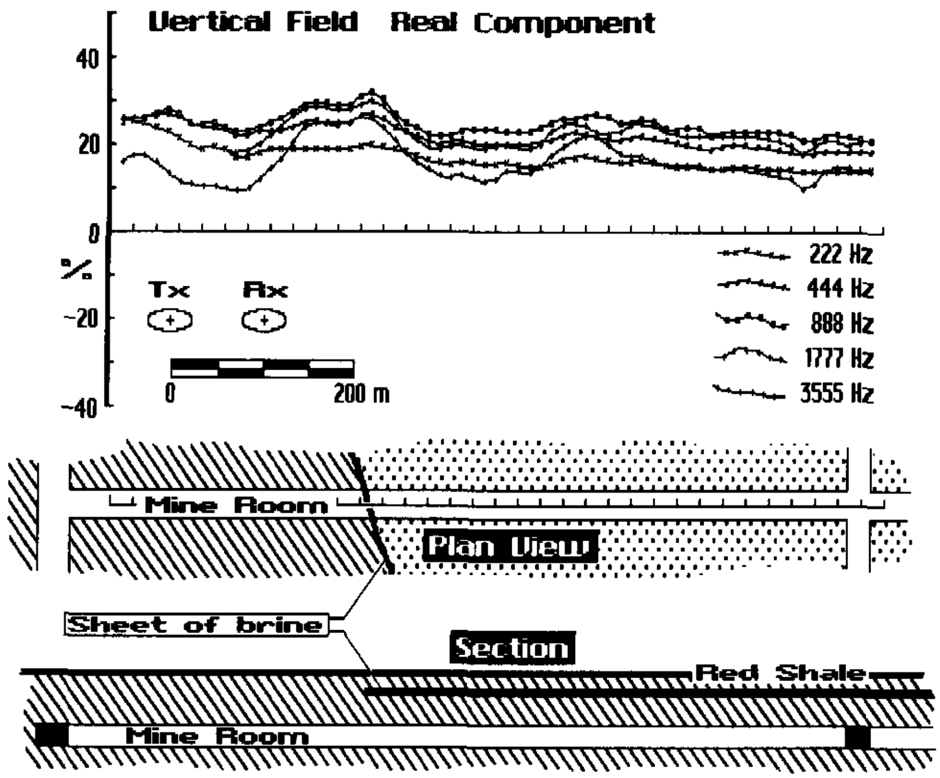


Fig. 6. Scale-model frequency-domain profiles of horizontal in-line field for a model which placed a localized sheet of conductor above the simulated mine room.



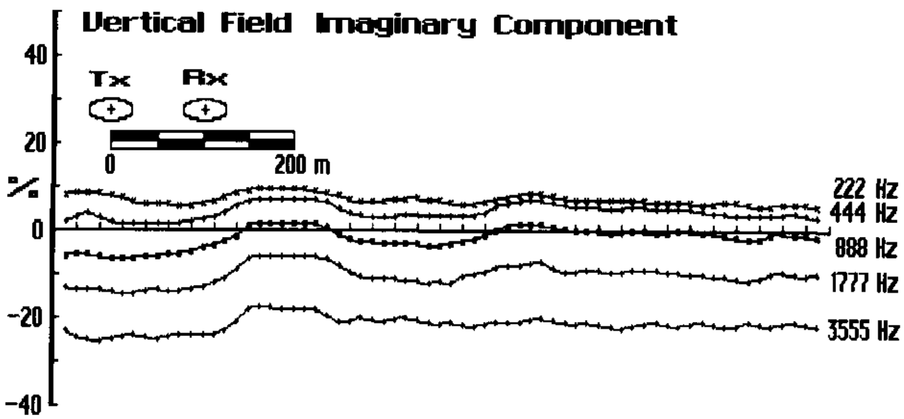


Fig. 7. Real and Imaginary component profiles of the vertical field component detected by a Max-Min frequency-domain electromagnetic survey along the traverse covered by the PEM survey in Figure 1. The lack of response to the horizontal sheet conductor is notable.

These surveys could be conducted ahead of mine development and thereby possibly reduce the risks and costs of mine development.

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