Mapping and Monitoring Softrock Mining

Chouteau, M.[1], Phillips, G.[2], and Prugger, A.[2]

1. Génie Minéral, École Polytechnique, Montréal, Québec, Canada
2. Potash Corporation of Saskatchewan Inc., Saskatoon, Sakatchewan, Canada

ABSTRACT

Geophysics is increasingly applied to potash mine development for mapping and monitoring. It is used for mapping ore-zone structure in advance of mining, and for mapping the hanging wall and footwall to gain understanding of the stratigraphy in zones of anomalous geology. It helps evaluate the thickness of the salt back and the presence of aquifers above mine openings for the design of mine layout and safety. It is used also to monitor the response of the host rock to mining activities. Environmental geophysics is also applied to map detailed stratigraphy near tailing areas. Seismic reflection and refraction, microseismics, radar, time-domain electromagnetics and radio-frequency imaging are the techniques employed to solve those problems. Their usefulness and limitations are assessed using case histories from Saskatchewan and Brazil.

INTRODUCTION

Geologically anomalous structures represent a major problem for potash mining operations. They are encountered in most of the potash mines around the world and they vary in size from metric to kilometric. They can be small barren zones and channel-like features (washouts) within the ore zone, or larger leached zones characterized by partial or complete absence of sylvite and major collapse zones of the layers above the ore zone (Mackintosh and McVittie, 1983). The need to assess potential mining hazards, including rock failure and flooding, to help mine design and planning and to avoid ore dilution have stimulated the development of methods for predicting the location of the anomalous structures. Among these, geophysics has played a major role. Phillips and Mottahed (1988) and Gendzwill and Stead (1992) give excellent reviews on the applications of a variety of geophysical methods to potash mining. A major source of information on potash mining can be found in the papers presented at the Potash ’83 conference in Saskatoon and the Kali ’91 conference in Hamburg.

In this paper, the authors do not present a complete review of the geophysical methods used worldwide by the potash industry but rather describe their experiences at PCS (Potash Corp. of Saskatchewan) in Saskatchewan and at CVRD (Companhia Vale do Rio Doce) in Brazil, concerning the usefulness and effectiveness of methods adapted to some particular problems associated with potash mining. We therefore present an approach based on the objective, the solution of geological problems, rather than on the tools, the various geophysical techniques. Conversely, a method may obviously find applications in several mining problems.

GEOLOGICAL ENVIRONMENT AND MINING PROBLEMS

Geology

Geological description of the potash mines in Saskatchewan can be found in Mackintosh and McVittie (1983), Annan *et al.* (1988) and Gendzwill and Stead (1992).

Much of southern Saskatchewan is underlain by the “Prairie Evaporite”, a layered sequence of salts and anhydrite which contains the western world’s largest reserve of potash. The potassium extracted from the sylvite ore is mainly used as a fertilizer. The areal distribution of potash-bearing rocks in west-central North America is shown in Figure 1a. The 100–200 m thick Prairie Evaporite is overlain by approximately 500 m of Devonian carbonates, followed by 100 m of Cretaceous sandstone, followed by 400 m of Cretaceous shales and Pleistocene glacial tills to surface; it is underlain by Devonian carbonates (Fuzesy, 1982a). A generalized geological section is shown in Figure 2. Ten potash mines were brought into production in Saskatchewan in the period 1960 through 1970 (Fuzesy, 1982a). Eight of these are conventional underground mines, and there are two mines where solution methods are used. Mines operate at 900–1100 m depth within 15–50 m of the top of the Prairie Evaporite. The underground operators extract ore by continuous mining systems, mining 35–50% of the 2.5–5 m thick horizontal seam. Production rates are as high as 20 000 tonnes cut per day, with 5 million tonnes cut per year at one mine. Stress-relief mining systems are employed, to a varying degree, at all mines. Mining methods employed in the province are described in Jones and Prugger (1982).

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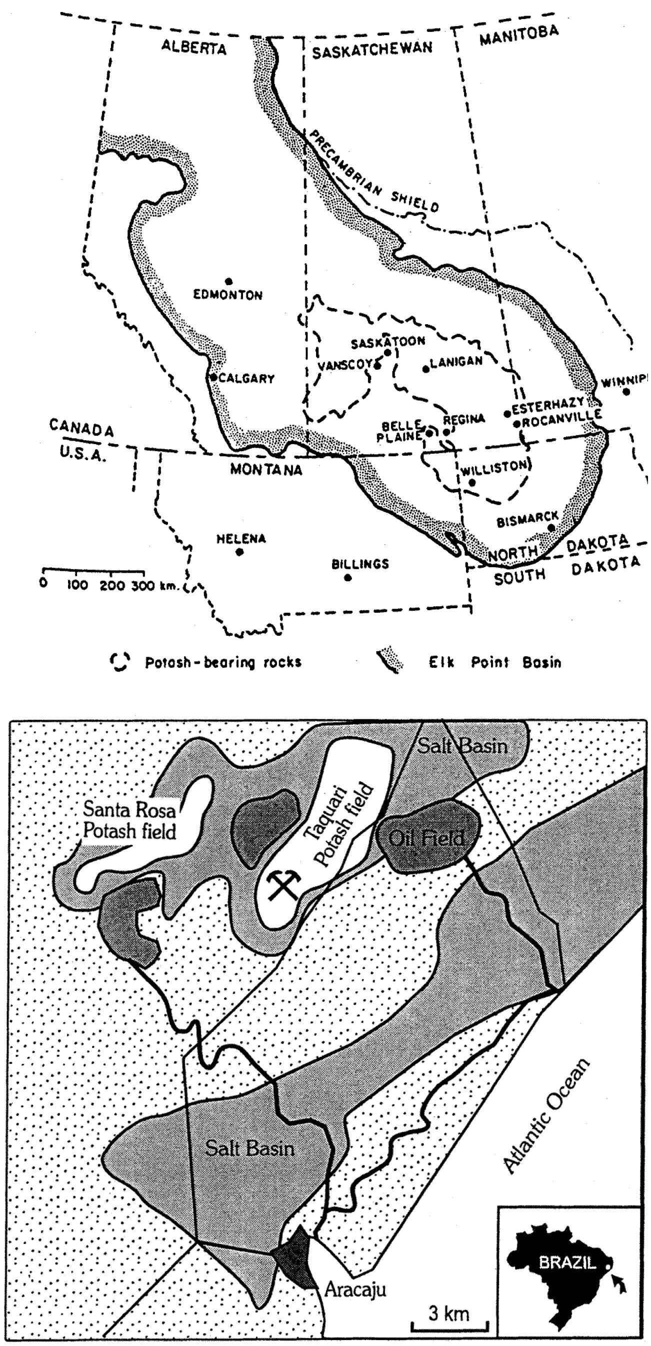

Figure 1: *Areal distribution of potash-bearing rocks (**a**) in the Elk Point Basin, west-central North America (from Fuzesy, 1982b) and (**b**) in the Sergipe Basin in northeastern Brazil.*

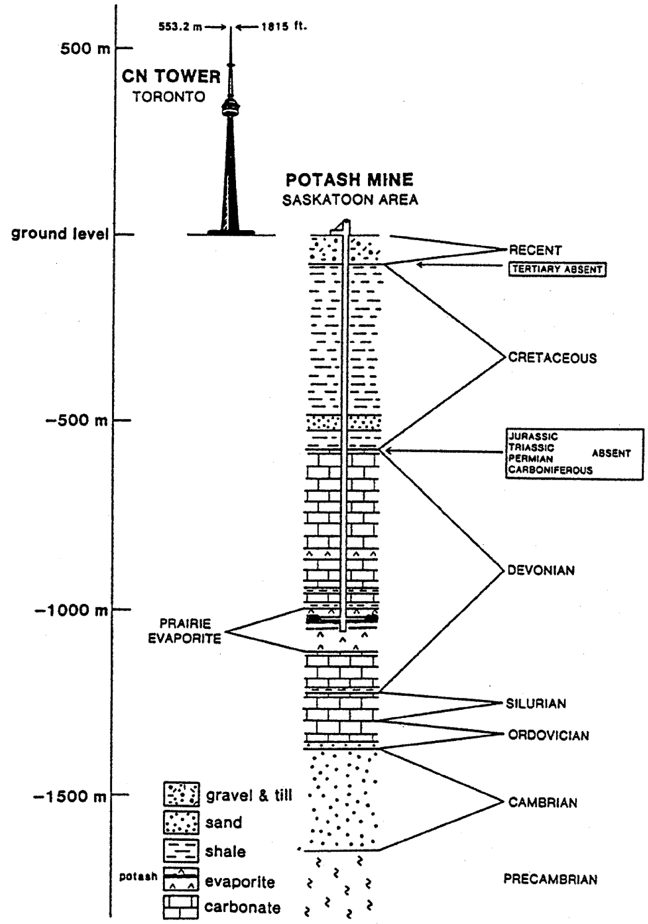

Figure 2: *Generalized geological cross-section through a potash mine shaft near Saskatoon (from Fuzesy, 1982a).*

The Taquari-Vassouras mine is located near Aracaju (Sergipe state) in north-east part of Brazil (Figure 1b). The stratigraphic column of the Taquari-Vassouras sub-basin consists, from the base up to the top, of sediments of age varying from the lower Cretaceous (Aptian) to the Terciary, that overlie discordantly the crystalline basement. The potash deposit is found at a depth of 450–500 m in the Ibura Evaporites which consist, from the bottom up, of limestones, anhydrites, halites, carnalites, tachydrites, with interspersed shales, halites with seams of silvinite, calcilutites (clayey fine-grain limestones) and shales (Figure 3). There are two main potash zones, the Upper Basal Silvinite and the Lower Basal Silvinite; however, for technical reasons, only the former is currently being mined. A thin (6–8 m), poorly-consolidated aquifer sandstone layer is commonly encountered in the mine zone above the openings at an average distance of 80 m. Intensive injections were needed to stop the inflow of large volumes of brines when the two main mine shafts were bored through the sandstone in 1981 (Soubrouillard and Lourdel, 1984). Current mine production is 0.5 Mt/year.

Mining problems

Mining problems are similar in Saskatchewan and in Brazil. In this section a brief description will be given for the Saskatchewan mines.

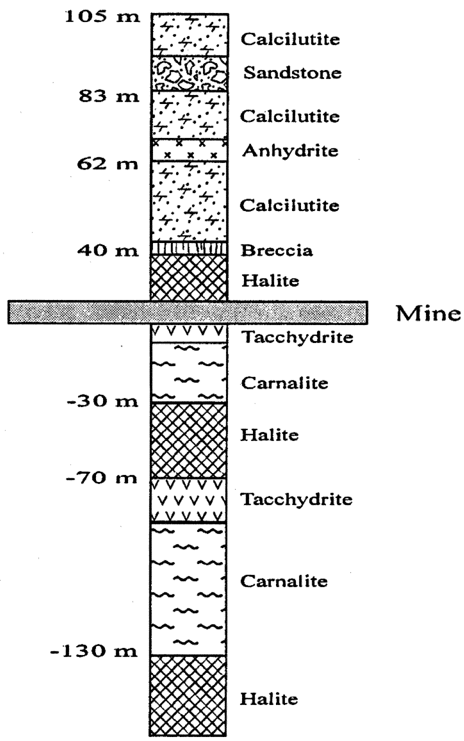

Figure 3: *Simplified geologic cross-section at the Taquari-Vassouras mining level.*

Geological units throughout the Saskatchewan potash mining region are flat-lying and relatively undisturbed over large areas. There are, however, local regions where salts at the mining level have been significantly disturbed by post-depositional water movements. To quote Mackintosh and McVittie (1983), "these geologically anomalous structures...which have been encountered at all Saskatchewan potash mines, vary from relatively small barren zones and channel-like features within the ore-zone, through to major collapses of the complete section of evaporite and limestone members above". In the worst case, these solution collapse structures extend over kilometres, with associated faulting or brecciation extending right to surface (Gendzwill and Hajnal, 1972; Gendzwill, 1978; Bediz, 1983; Gendzwill and Lundberg, 1989; Gebhardt, 1993; Gendzwill and Stead, 1992; Gendzwill and Martin, 1996). An example of such a major disturbance is shown in Figure 4. This is the image of the "Colonsay Collapse" (near Saskatoon) mapped by a 2-D seismic reflection profile. Note the complete disruption of stratigraphy in the collapse zone; the ~200 m thick Prairie Evaporite salts have been completely removed in this region, causing dramatic subsidence of all overlying formations. Foreknowledge of the existence (and location) of such disturbances is of great value to mine engineering staff. Since collapse features are an excellent conduit for groundwater, they present a significant hazard to mining operations. One mine (Patience Lake) was closed due to uncontrolled flooding in 1987, ten years after rooms were cut into a large solution collapse feature (Gendzwill and Martin, 1996); underground workings were eventually abandoned and the mine is now run as a solution operation. A water inflow into an operating potash mine is a very serious problem, leading to high rehabilitation costs at best, and closure of the mine at worst (e.g., Gimm, 1968; Prugger, 1979; Prugger and Prugger, 1991; Strathdee, 1994; Gendzwill and Martin, 1996; Gendzwill and Unrau, 1996).

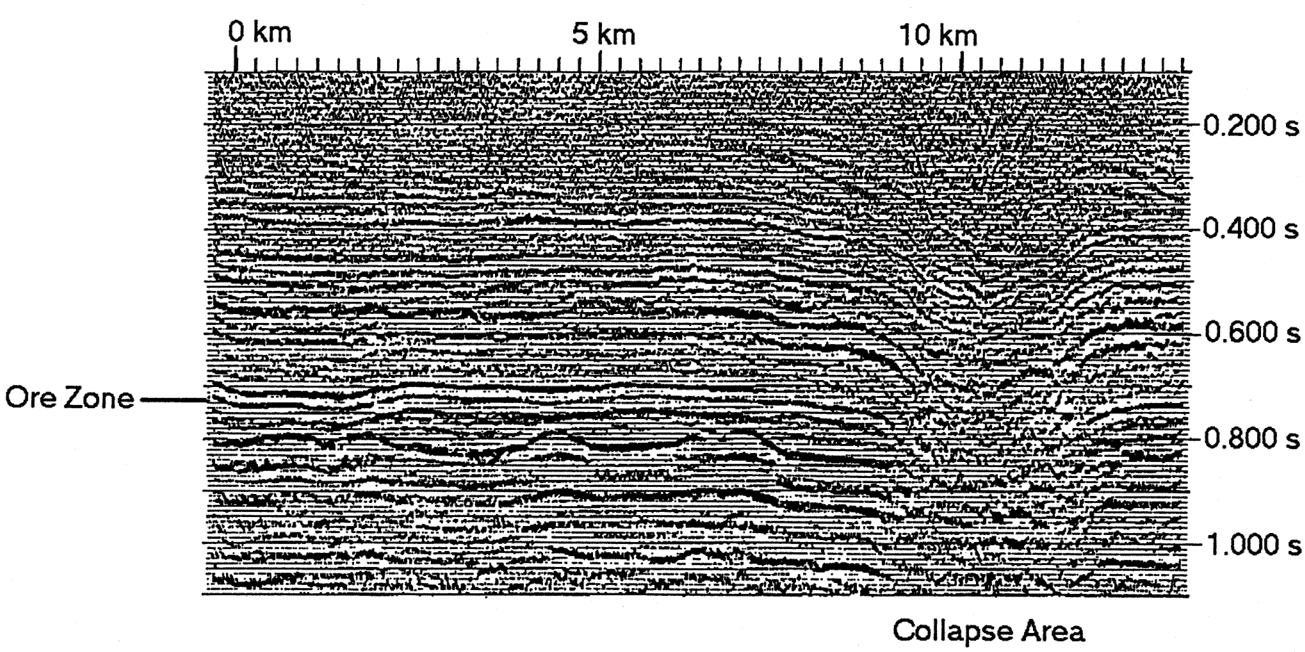

Figure 4: *Surface seismic reflection profile across the Colonsay Collapse structure near Saskatoon (after Gendzwill and Stead, 1992). The potash ore zone, near the top of the Prairie Evaporite, is at ~1000 m depth (~0.700 seconds reflection time).*

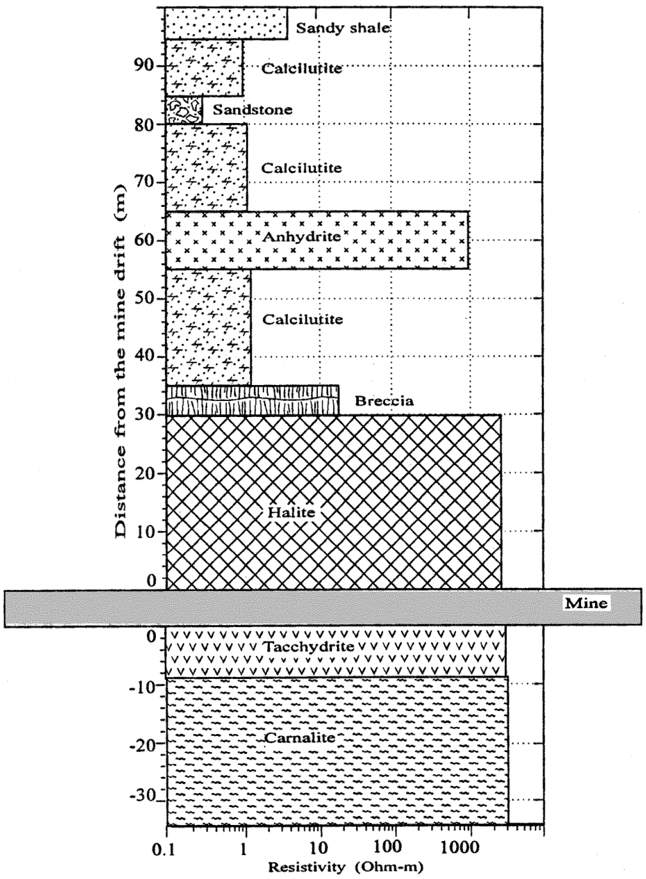

Figure 5: *Geoelectrical model of the subsurface at the mining level in the Taquari-Vassouras mine.*

PHYSICAL PROPERTIES

At the Taquari-Vassouras mine, the available geophysical well logging and core logging data were used to determine the resistivities and thicknesses of each different unit. In 1978, Schlumberger Inc. carried out induction conductivity, neutron, gamma ray and density logging in the wells drilled in the mine area. Stratigraphic information, supplied by Petromisa (previous owner of the mine), were correlated with the geophysical logs to construct geoelectrical models of the subsurface. The complete information was available only for eight wells. The recorded conductivity values have been averaged over the layer thicknesses. From the set of wells, a typical model has been constructed (Figure 5); it consists of 8 layers which are respectively, from the mine looking up:

1. a salt layer with a resistivity larger than 1 000 Ωm and a thickness of 30 m ;
2. a breccia zone with a thickness of 5 m and a resistivity varying between 20 Ωm to 1 000 Ωm ;
3. a calcilutite layer with a thickness of 20 m and a low resistivity of 1.35 Ωm ;
4. an anhydrite zone highly resistive (set to 1 000 Ωm) with a thickness of 10 m ;
5. a second layer made of calcilutite with a thickness of 15 m and a resistivity of 1.2 Ωm ;
6. the highly conductive aquifer sandstone zone (resistivity of 0.3 Ωm) with a thickness of 5 m ;
7. a third 10 m-thick zone of calcilutite with a resistivity of 1 Ωm ;
8. a medium made of arenite, shale, displaying a resistivity of 2 to 5 Ωm.

Below the mine entry, for more than 150 m down in the tachydrite and carnalite layers, conductivity logging shows no response. Conductivity logging is not sensitive to conductivity smaller than 1–2 mS/m (or resistivities higher than 500–1 000 Ωm), so bulk resistivities for salt (halite and sylvite) are not known. Only a lower bound can be obtained. Gendzwill (1983) and Duckworth (1992) give estimates of 500 Ωm (and higher) and 40 000 Ωm respectively for salt in Saskatchewan. A value of 1000 Ωm was given to salt, tachydrite, carnalite and anhydrite. Conductive layers (calcilutite and brine-saturated sandstone) display a remarkable uniform resistivity over a zone of 10 km^2 with resistivity variations less than 15%. The low resistivity of the sandstone aquifer was checked with the conductivity measurements carried out on water samples from that zone. Values of 12 to 18 S/m were obtained. Assuming a porosity ranging from 35 to 40% obtained from neutron logging, complete saturation and a cementation factor of 2, Archie's law yields a formation resistivity of 0.3 Ωm which is the average resistivity obtained from the induction logs.

From inspection of the resistivity model, the aquifer is the most conductive layer in the sequence but it is sandwiched between two conductive zones of calcilutite which might obliterate its EM response. From the composite well logs, it is noticed that the resistivity of the sandstone layer is observed to be higher when it does not contain water (>5 Ωm). The aquifer zone is located at 80 m above the top of the mine gallery. Again this is an average distance since it has been intersected at distances ranging from 48 to 104 m in the wells.

A compilation of material properties (seismic P velocity, density, resistivity, porosity) about the ore zone for the potash mines of Saskatchewan can be found in Table 1. All values are very sensitive to porosity. Comparison with the resistivities of the Taquari-Vassouras mine shows that the geologic environment at the latter is much more conductive.

Table 1: ***Compilation of material properties (seismic P velocity, density, resistivity, and porosity) in Saskatchewan potash mines.***

Name	Lithology	km/sec	kg/m^3	Ωm	ϕ(%)
Dawson Bay	carbonates	4.5–6.0	2700	20–30	5–30
2nd Redbed	shales	3.5–4.0	2500	5–10	2–10
Prairie Evap	salts	4.2–4.5	2100	100–1000	0–2
Winnipegosis	carbonates	5.5–6.5	2700	20–100	2–15

MAPPING OF ORE STRUCTURE

The ore structure is mapped on a large scale from the surface using seismic surveys or in more detail using in-seam geophysical methods such as seismic refraction and reflection, radar and time-domain electromagnetics (TDEM). Large anomalous structures can also be delineated using in-seam seismic and EM tomography.

Surface seismic reflection

A generation ago the only surface exploration tool available to the potash miner for predicting ore-zone continuity was the geological model derived from deep boreholes. Twenty to thirty holes were typically drilled in a mining region at a spacing of one per 2–5 km^2. In the last decade, surface seismic mapping methods have been used with so much success that surface exploration drilling now occurs at a rate of about 1–2 holes every 5–10 years throughout the entire industry! The reasons for this development are economic: one surface borehole costs ~$300,000; 2-D seismic profiling costs ~$5,000 per line km and 3-D imaging (at a 25 m sample grid) costs ~$50,000 per km^2.

Seismic data are collected along 2-D profiles for reconnaissance work (~100-200 m^2 resolving power), to map features like the Colonsay Collapse shown in Figure 4. 3-D surveys are conducted to map the subsurface where more detail is required (~10-20 m^2 resolving power). As mine engineers become more and more familiar with 3-D results, more and more 3-D surveys are carried out. Examples of 2-D seismic sections near potash mines can be seen in Gendzwill (1978), Bediz (1983), Gendzwill and Lundberg (1989), Gendzwill and Stead (1992), Gebhardt (1993), and Gendzwill and Martin (1996); examples of 3-D seismic results are given in Gebhardt (1993) and Strathdee (1994).

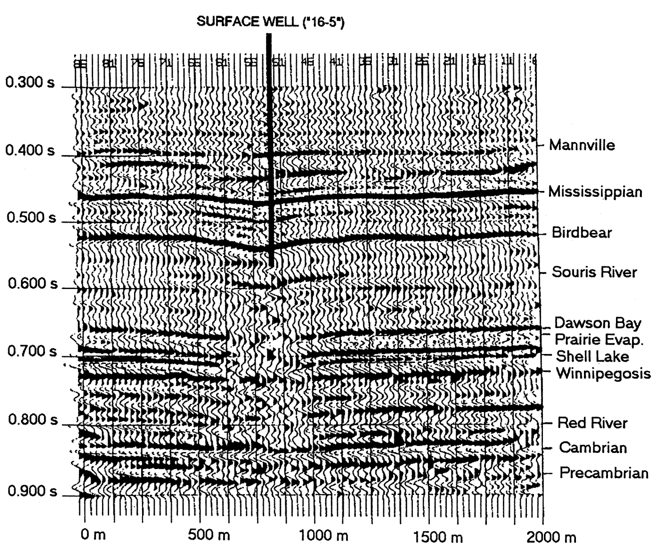

Figure 6: *Vertical 3-D seismic section across a solution collapse in the Esterhazy area. The "bin size" (distance between traces) is 25 m, and depth to the mining level (at about 0.680 seconds) is approximately 950 m.*

A vertical profile from 3-D data across a solution collapse near the PCS Rocanville mine is shown in Figure 6. Note how well the collapse zone is mapped by the complete loss of reflected energy late (deep) in the section, and subsidence of overlying, shallower units (between 600–1000 m). In this 3-D seismic data volume there is a reflection trace every 25 m in all directions: adjacent traces are 25 m apart and there is a similar data profile 25 m away on either side of the one shown here. This provides for unprecedented observational sampling of the subsurface, permitting very detailed mapping of the collapse feature (and other features as well).

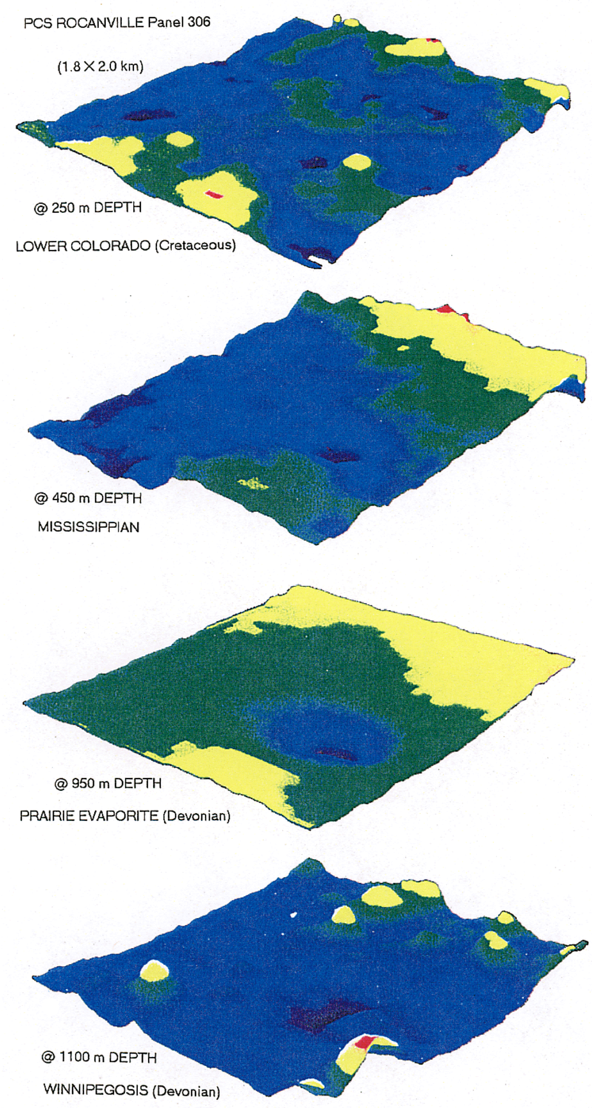

Figure 7: *3-D-seismic formation-top structure maps (derived from seismic time-picks) for four stratigraphic horizons. Light colours (red, yellow) indicate highs and dark colours (blue, black) indicate lows. The mining level is just below the "Prairie Evaporite" map (second from bottom).*

Successive sections are analysed, and formation top positions are "picked" for all sections comprising the 3-D data volume. These "time-pick" surfaces are then contoured to give formation structure (from which isopachs, flattened surfaces, etc., can be derived). A set of four of these structure sections are shown in Figure 7. Note how well the solution collapse feature shows up (below the Mississippian, at any rate). Note also how well carbonate mound structures (yellow "highs") show up in the Winnipegosis map.

Not all 3-D seismic surface surveys are successful. A survey was also carried out at the Taquari-Vassouras mine in 1989 in an attempt to image the stratigraphy, with particular emphasis on mapping ore seams, the aquifer zone and anomalous structures. Bad quality data were observed and two thirds of all seismic sections were inadequate for interpretation. Reprocessing of the data (Vieira, 1993) showed that source coupling, absorption, surface topography and noise generation resulted in poor data quality at frequencies higher than 90 Hz. The low-velocity weathered zone of variable thickness caused large static corrections problems. The use of seismic refraction tomography helped to improve the final sections; however, the results could not be used to detect geologic structures at the mine level.

In-seam geophysics

Seismic refraction — The seismic refraction method was first employed to measure potash mine salt-back thickness in the 1960s (Gendzwill, 1969); the "upside-down" survey layout is unconventional, but works well. The refraction technique uses the fact that seismic waves are bent, or refracted, in passing through changes in propagation velocity in the earth. The "bent" travel path can be calculated by Snell's law. For the geological case where a high speed layer (such as a limestone) overlies a low speed layer (such as a salt) some energy will be "critically" refracted at the interface between the two media. This is shown for potash-mine stratigraphy in Figure 8. Dynamite is used for the seismic source, and signals are recorded on commercially available lightweight, portable seismic recorders.

Source-to-receiver travel times are used to calculate salt-back thickness and propagation velocity in both the salt and the overlying limestone. Refractor velocity values are a measure of the competence of lower Dawson Bay carbonates: "high" propagation speeds (≥ 5.5 km/s) indicate a competent rock with low shale content, low porosity, and/or little fracturing; "slow" observed speeds (≤ 4.8 km/s) indicate a weak, porous, fractured rock (Gendzwill and Unrau, 1996). An example of the results of a refraction survey in a potash mine is shown in Figure 9; note the good agreement between EM47 and seismic results. Maps of layer thicknesses and material properties (velocity and conductivity) are very useful for mine planning. Areas thought to be "normal" are confirmed to be so, geological problem zones are identified early in the mining cycle, and surface seismic results are calibrated using these data.

Seismic reflection — In-seam seismic reflection surveying in potash mines is a recent development (Gendzwill and Brehm, 1993). The technique is schematically illustrated, for upward mapping of the hanging wall, in Figure 8. The method has also been used for downward mapping of the footwall, as shown in Figure 10. The advantage of this survey tool is that fine geological detail can be mapped using a mechanical source (rather than dynamite), and that measurements can be made over very short offsets. However, the technique is used sparingly because of the tremendous effort required for data acquisition (~1 m station spacing), processing (full seismic reflection analysis software is required), and interpretation (there is generally more detailed information to sort out than ever before).

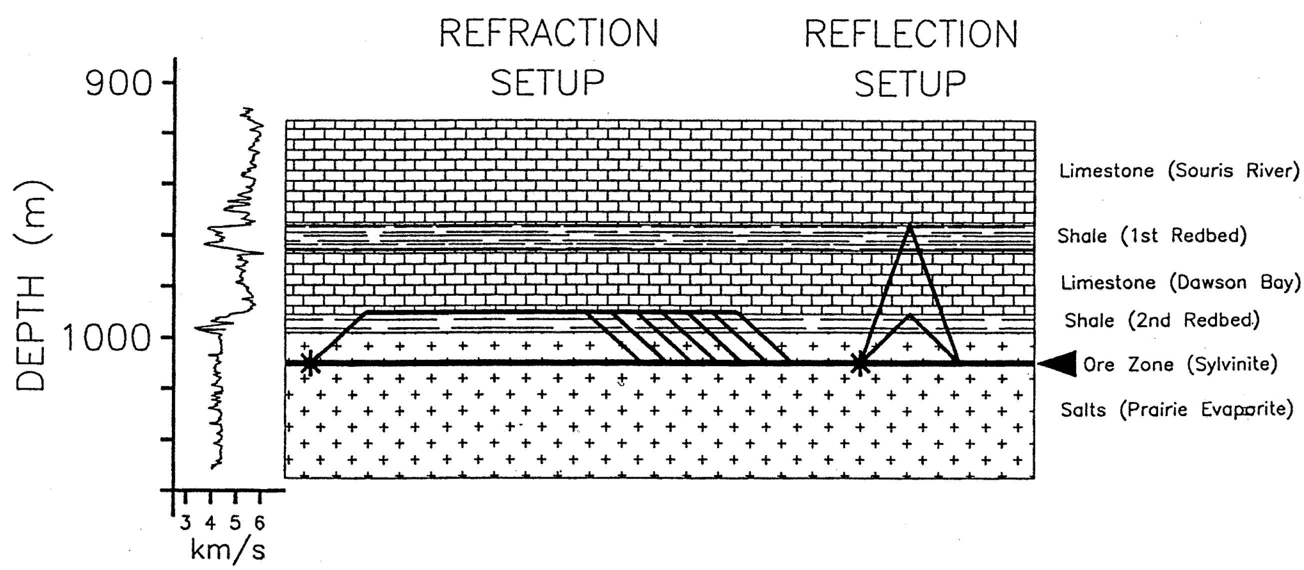

Figure 8: *In-seam seismic mapping techniques used underground in potash mines, along with a borehole sonic log and generalized stratigraphy for a Saskatoon-area mine.*

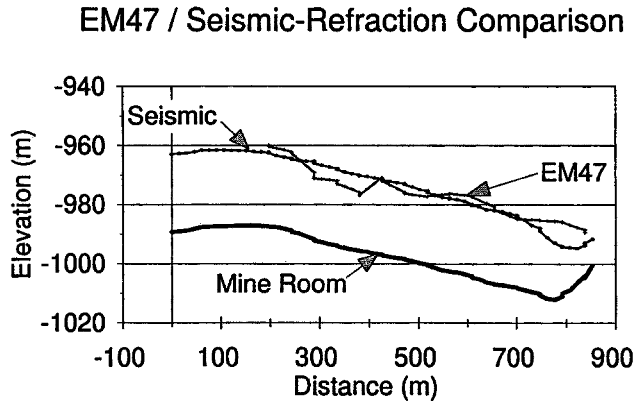

Figure 9: *Comparison of salt-back thickness (upward to the base of hanging-wall limestones) inferred from seismic refraction and EM47 profiling.*

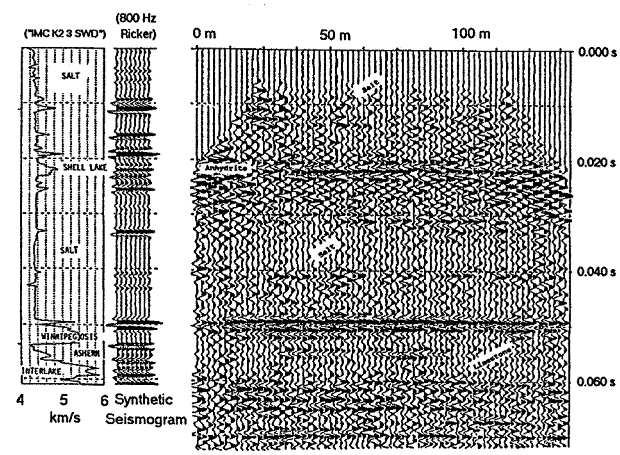

Figure 10: *Stacked section of seismic reflection data from the floor of a mine in the Esterhazy area, along with a borehole sonic log and a synthetic seismogram computed from the log. Dominant frequency in the data is 700 Hz; the Winnipegosis limestone reflector at 0.050 seconds is at about 100 m below the mine room (from Gendzwill and Brehm, 1993).*

Applications of Ground Penetrating Radar

The paper by Annan *et al.* (1988) provides an excellent reference on the utility of impulse radar for mapping stratigraphy in potash mines. Ground penetrating radar (GPR) is used in the PCS potash mines primarily for stratigraphic control, on a routine basis to map the thickness of the overlying salt, and as a problem solving tool in cases where the normal stratigraphy is disrupted by some post-depositional event. Work is typically done at 50 or 100 MHz, but higher frequencies (450 or 900 MHz) may be used where high resolution is required and the shallower penetration is not a problem, such as for mapping 'loose' roof or pillar fractures. The effectiveness of GPR varies from mine to mine, due to differences in the insoluble content of the ore zone and over- or underlying salt beds. Penetration ranges from 10 m or less in the mines near Saskatoon, to 40 m in the cleaner salt in the Esterhazy-Rocanville area (50 MHz data).

The first example (Figure 11a) shows a section of typical hanging wall stratigraphy, collected with the 50 MHz system. The antennae are mounted on a non-conductive cart and elevated to within a few centimetres of the back. The cart is then pushed along the room, and readings are taken at preset intervals (2 m in this case), controlled by an odometer wheel on the floor. The first recognizable reflector following the direct arrival is at 3 or 4 m and represents the top of the potash mineralization (Esterhazy Member). This reflection disappears in areas where potash has been selectively leached from the salt. Three or four strong peaks near 15 m correspond to the White Bear Member, a series of clay seams, each a few centimetres thick, and a 1 m thick potash bearing interval. These reflectors are consistent throughout the district and form a useful reference horizon to help determine the stratigraphic position of the mine opening in cases where the potash is missing. There are similar marker horizons in the floor which can be used for the same purpose, at depths of approximately 15 and 30 m. There are several more clay seams above the White Bear before the overlying dolomitic mudstone is reached at approximately 25 m. Attenuation within the mudstone is such that no higher reflections are normally recorded.

The second example (Figure 11b) is from the same mine, but in an area where salt dissolution from the bottom of the section has deformed the ore horizon and where potash has been selectively leached from the ore zone. This is also 50 MHz data, but collected with a 6 m step size, resulting in some possible aliasing problems in areas of steep dips. The 'Top Esterhazy' reflection disappears near 550 m, due to loss of the potash. The White Bear is identifiable throughout, but shows nearly 10 m of subsidence near the 650 m point. It recovers partially within a few tens of metres, and is back to normal by approximately the 950 m mark (Note: the data at about 990 m is distorted by a rapid drop in the room elevation which has not been compensated for in the data). With loss of the potash, mine operators continued to advance the heading 'blind', unaware that the ore zone had dropped below their elevation. It was not until drilling showed the ore zone to be in the floor that the room was brought back 'on grade' at 990 m. This room was mined before GPR was available. Current practice is to conduct GPR concurrently with mining to provide guidance to the operators and prevent the unnecessary mining of waste. Concurrent GPR could also provide a warning if the thickness of salt in the roof became inadequate or if collapse of the overlying limestone was indicated, conditions which would result in abandonment of the heading.

Seismic and RIM tomography

If 3-D surface seismic reflection survey can detect large anomalous zones such as collapse structures, in-seam investigations are necessary to delineate the structure in more detail and assess water content. Penetration of the collapse structure may result in brine inflow into the mine workings. At PCS, seismic and radiofrequency EM tomography methods have been tried with the purpose of identifying and evaluating the anomalous structures within a panel in the Prairie Evaporite. Experiments were carried out at the Rocanville mine in panel 306 to investigate a collapse structure previously detected by a 3-D surface seismic survey. An excellent summary of the trials is reported by McGaughey and Stolarczyck (1991). The seismic tomography experiment was done in

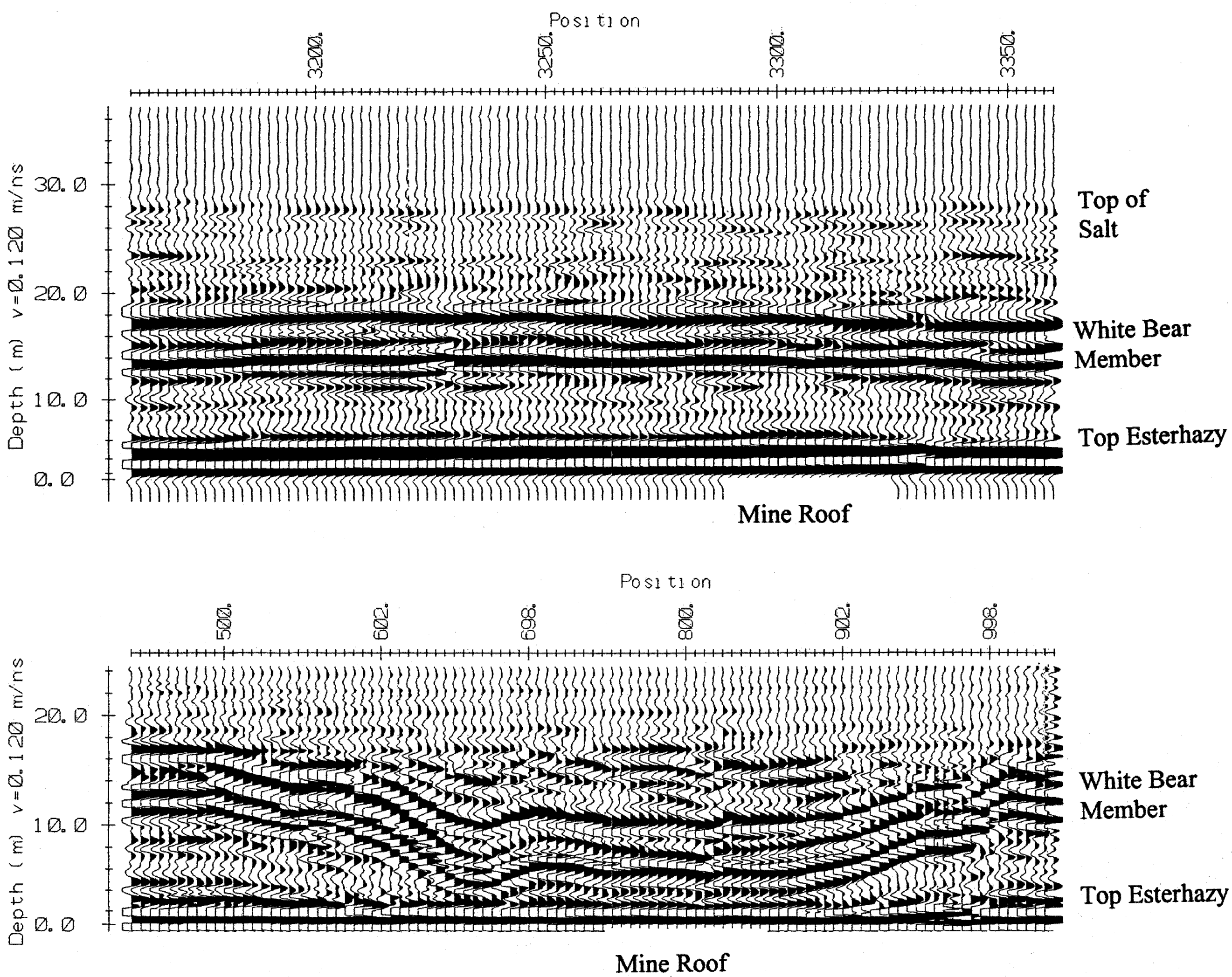

Figure 11: *50 MHz radar profiles along (**a**) a normal room and (**b**) an anomalous room. Data have been collected at 2 m and 6 m intervals respectively and corrected at room elevation. The first reflector represents the top of the potash mineralization (Esterhazy Member) that disappears where potash has been leached. The White Bear Member is a series of clay seams within the evaporite. These reflectors form a useful reference horizon to determine startigraphic position of the mine opening when the potash is missing.*

1986–1987 and the data processed by Bostock (1988). Data were reinterpreted for PCS in 1990 by Young and Falls from Queen's University. The survey consisted of a large number of pairs of seismic receivers and energy sources placed in entries delimiting the 1800 m × 1800 m square panel. The mapped slownesses indicated a low velocity anomaly at the appropriate location but in general results were ambiguous. They may be caused by poor data quality obtained from the low sampling-rate seismograph. McGaughey and Stolarczyck (1991) also suggest other difficulties, including waves travelling with a higher velocity in the carbonate formations below and above the potash seam and low contrast in wave velocity between the collapse zone and the undisturbed Prairie Evaporite. The EM tomography data were recorded in 1990 around the panel perimeter using 100 kHz signal. Received amplitude measurements were made over 3000 paths through the panel. After spreading corrections were made, data were inverted for absorption coefficient images using a SIRT (Simultaneous Iterative Reconstruction Technique) algorithm. Figure 12 shows the contour map of absorption coefficient in dB/km. A well-defined anomaly high, evidenced by values 10 dB/km (300%) or more above background, coincides with the collapse structure as mapped by 3-D surface seismics. Unlike the seismic transmission surveys which are hampered by the low velocity contrasts which prevail in these settings, high conductivity contrasts between the brine-filled collapse zone and the rock salt makes EM tomography surveys a very useful tool for mapping large disruptions in the potash seams.

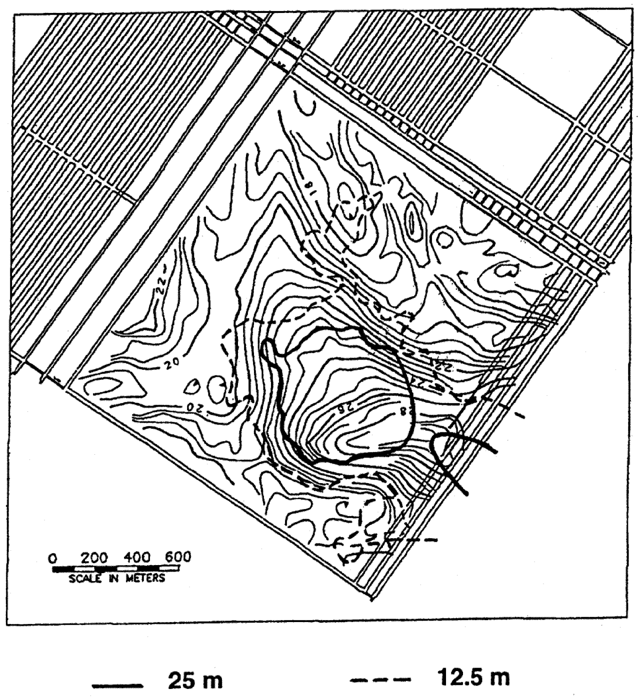

Figure 12: *Tomographic image of EM absorption coefficient (in dB/km) showing an anomalous high related to the collapse structure. It is indicated by contours of equal depth to the top of the Prairie Evaporite obtained from interpretation of 3-D surface seismic survey (modified from McGaughey and Stolarczyk, 1991).*

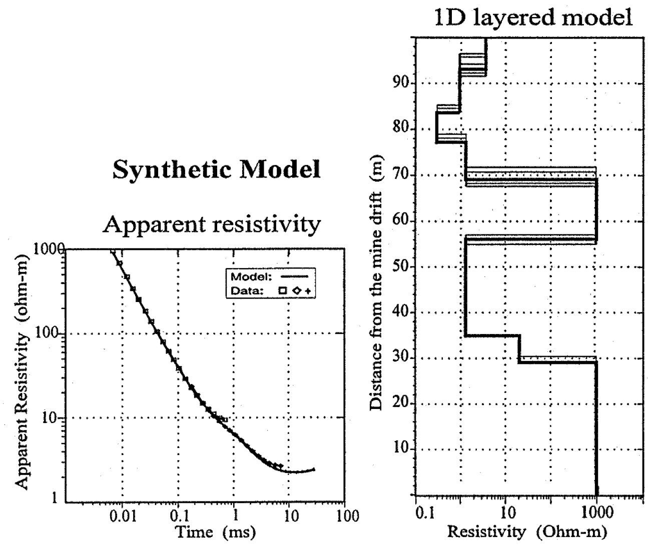

Figure 13: *1-D TDEM modelled data for the geoelectric section shown in Figure 5 and results of resistivity-constrained inversion. The aquifer zone is 5 m-thick at a distance of 80 m from the mine opening. Equivalence analysis is performed using 5% noise in the data.*

DETECTION OF BRINE LAYERS AND OTHER MINING HAZARDS

Among the methods used for detecting brine layers and other hazards, the most common are EM, seismic refraction and GPR. Applications of seismic refraction for integrity examination of the Dawson limestone and of the GPR for the thickness of salt in the roof have been introduced in the previous paragraph and they will not be further discussed here. Excellent examples of GPR contributions can be found in Annan *et al.* (1988). Here we will be mostly concerned with EM methods. A test survey performed at the Taquari-Vassouras mine will be presented.

Electromagnetic methods

The frequency-domain techniques (FEM) were the first techniques to be employed extensively to check salt-back thickness and to monitor the presence of brines in the layers overlying the mine entries. The method based on the horizontal-loop EM measures the secondary magnetic field induced in conductive features within the range of the system; the secondary field intensity is directly related to the conductivity and therefore some systems may be calibrated and used as conductivity meters (i.e., EM34 from Geonics Ltd.). Gendzwill and Bandit (1980) and Gendzwill (1983) have developed tools to interpret conductivity meter survey data from potash mines in Saskatchewan. Using scale modelling. Duckworth (1992) interprets MAXMIN data from a survey in a PCS-owned mine. In all cases the method relies on the high electrical conductivity of the Second Red Bed shale and the Dawson Bay Formation overlying the highly resistive salt. The FEM response (apparent conductivity for the conductivity meters, ratio of the secondary magnetic field to the primary magnetic field for other FEM systems) depends on the distance from the mine entry to the conductive layers and on the conductivity of the brine zone. The conductivity is controlled by brine salinity, porosity, temperature and clay content. The FEM techniques have relatively poor sounding capabilities and cannot be used to determine complex layering. More recently time-domain EM techniques (TDEM) have replaced the FEM techniques to detect brines because they offer larger depths of investigation and better sounding resolution. They measure at various time intervals the time-derivative of the magnetic field associated with diffusive currents generated in the ground after the transmitted magnetic field has been shut off. A test to detect brine within the evaporite using Crone PEM can be found in Duckworth (1992). Here we will report about trials carried out at the CVRD mine in Brazil in 1995 (Chouteau *et al.*, 1995).

TDEM trials at the Taquari-Vassouras mine

The geoelectrical model in Figure 5 shows the medium below the mine entry to be highly resistive and the medium above to consist of a few conductive layers. Previous to the TDEM trials, a feasibility study was carried out using 1-D modelling and inversion to determine whether the highly conductive aquifer within a conductive background could be detectable at distances up to 120 m. Responses were computed within the time range 6μs to 70 ms, varying the aquifer thickness from

0 to 10 m, the distance to the aquifer from 40 to 120 m, the size of the transmitting loop, the salt layer thickness and the resistivity of the breccia. Assuming a typical 5% apparent resistivity error, this study indicated that in spite of the conductive environment provided by the calcilutite, the 0.3 Ωm aquifer zone could be detectable if it is thicker than 2.5 m, at distances up to 120 m using a transmitter loop magnetic moment greater than 30 000 A.m^2. To assess the limits of the interpretation from the collected data a 1-D inversion study was carried out on data obtained from the previous modelling exercise. Inversion used a layered ridge regression technique in which the resistivities of the layers are free to vary or are fixed. The two techniques yield the resistivities and thicknesses of the eight layers and allows us to explore the range of model parameters that replicate the input data. Equivalent models and ambiguity can be evaluated. When fixed, the resistivities were set to the average resistivities of the layer and only the thicknesses were allowed to vary. The modelled data, the interpreted model from the resistivity-constrained inversion and the equivalence analysis using the ridge regression technique for a 5 m-thick water-bearing sandstone located at a distance of 80 m are presented in Figure 13.

The resistivity-constrained ridge regression inversion yields results in closer agreement to the original model than the unconstrained techniques. In general, the distance to the aquifer layer is well determined. When there is no aquifer zone, the interpreted model finds a 0.3 Ωm layer but it is very thin (<2 m). There is no significant difference between a 2 m-thick aquifer and no aquifer at all. Therefore, when interpreting the collected data, we will be able to detect the aquifer only if it is thicker than 2 m. This result confirms the previous modelling results. Also from the inversion test, the thickness of the salt back plus breccia is well resolved even in the case for which the resistivities of the halite and breccia are not fixed. The results also show that the thickness and distance of the aquifer are better resolved for smaller distances to the aquifer.

The high conductivity environment requires the recording of a wide time range, from 6 μs to 70 ms, if the eight layers are to be resolved. Therefore, a test survey was carried out in May–June 1995 at the mine using a wide-band system consisting of the digital Protem receiver, the EM-47 and EM-37 transmitters and 1-D high-frequency and 3-D low-frequency coils, from Geonics Ltd. (Canada). Test zones were selected in panels near boreholes for which geologic and geophysical information were available and different occurrences of the aquifer (presence or absence of brines) were anticipated. The highly variable geometry of the panels forced us to use transmitter loops of different sizes and shapes, square to highly elongated rectangular loop (180 m × 20 m); the central loop and offset loop configurations were used. High quality data were acquired in spite of possible signal interference from abandoned ventilation pipes, cables, and conveyor parts. In the central loop configuration, an abrupt change was noticed in the late time response (>20–30 ms). Because the recorded responses show high signal-to-noise ratio, consistent results might be caused by strong lateral conductors at some distance away from the receiver or by induced polarization effects. Offset loop data do not show anomalous late-time behaviour. Central loop data collected above 30 ms were not used in the interpretation.

In Figure 14, we present the measured central-loop TDEM sounding data plotted as late-time apparent resistivity versus time for panel X1 with the interpreted vertical section above the mine drift. Distances are measured vertically up from the floor of the mine drift. Also shown is the geological log information from the nearest borehole GTP-32 some 100 m away. Results from the resistivity-constrained inversion shows that a 5 m-thick brine-saturated layer with a resistivity of 0.3 Ωm is detected

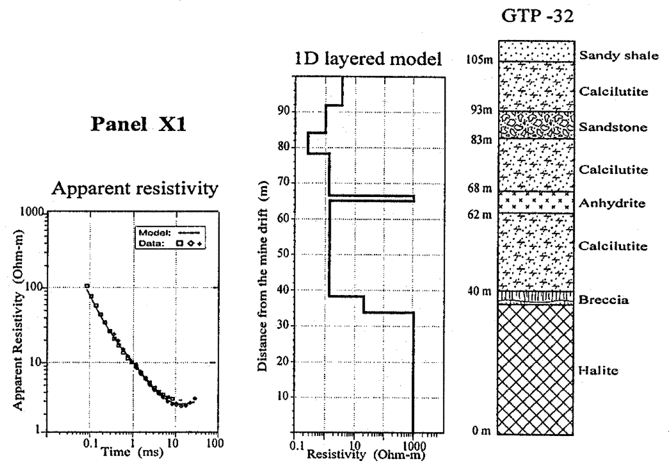

Figure 14: *1-D resistivity model obtained from resistivity-constrained inversion of data collected in panel X1. Comparison with the geologic log from nearest borehole (GTP32) show excellent correlation with stratigraphy. The aquifer zone is detected at a distance of 78 m.*

at a distance of 76 m comparable to the distance of 83 m for the 7 m-thick layer found in GTP-32. Also, the integrated thickness of 39 m for salt and breccia is almost identical to the borehole data (40 m). The slight differences in thicknesses between the resulting model and the borehole stratigraphy can partly be attributed to the large distance from the sounding site to the borehole and the moderate dip of the layers (~5°).

In Table 2, we summarize the interpretation results with regards to the detection of the aquifer layer and compare them with the available geologic/hydrogeologic information. There is a good agreement between the presence of a 0.3 Ωm conductive layer thicker than 2.5 m and the occurrence of the aquifer from available well information. For example, in panel X1, the conductive layer is well resolved and its distance is close to the distance measured in neighbouring wells for the aquifer sandstone. In panel B2, the conductive zone is found at a distance of 50 m while the aquifer zone was found at a distance of 75 m in GTP24. The discrepancy in distance could be caused by topographic changes in the sandstone layer. In panel E1, we do not detect a conductive zone related to the aquifer, a result confirmed by GTP20 but not by GTP23. Again it is possible that lateral changes in permeability of the sandstone layer render the region of panel E1 "dry". In panels G3 and H5, contrary to the information from well GTP8, it is possible that the aquifer sandstone might be present at a distance between 70 and 81 m above the mine workings.

Also not discussed here but well displayed in all cases is the good resolution of the technique for finding the thickness of the salt and the breccia layer above the mine drift. The interpreted distance is always within 5% of the thickness observed with borehole logging.

The survey sounding results shown above indicate that when the resistivities of the layers are fixed, the interpreted 1-D models are very similar to the stratigraphic sections available from the wells. In particular, the thickness of the salt and breccia layer is well resolved (≤5%).

The information related to the aquifer lie in the time range between 1 and 70 ms and it is within that range for T>20 ms that we observe abrupt changes in the central loop responses. Interference of mining artefacts and machines, 3-D brine "pods" or induced polarization effects

Table 2: ***Summary of the TDEM interpretation for the aquifer zone at the Taquari-Vassouras mine compared with the available well information.***

TDEM Survey				Well information	
PANEL #	**Depth to 0.3 Ωm layer (m)**	**Thickness of 0.3 Ωm layer (m)**	**Presence of aquifer (>2.5 m)**	**Well (GTP)**	**Depth (Thickness of aquifer) (m)**
H_1	82.3 (70.6 – 99.9)	2.5 (1.0 – 4.9)	no	8	- (–)
G_3	69.2 (68.3 – 79.8)	4.0 (2.33 – 6.0)	possible	8	- (–)
H_5	81.3 (64.3 – 99.0)	5.0 (2.1 – 7.8)	possible	8	- (–)
H_4	108 (97.6 – 132.6)	22	yes	42	?
F_4	73 – 88	22	yes	20 33	- (–) ?
B_2	49.6 (47.6 – 55.0)	3.5 (2.1 – 6.9)	yes	24	75 (5)
X_1	76.5 (74 – 96)	4.2 (1.8 – 7.4)	yes	23 28 32 30	80 (20) 90 (3) 67 (12) 83 (7)
E_1	105.3	1.4 (0.1 – 4.6)	no	20 23	– 80 (20)
B_1	62.2 (59 – 72)	0.7 (0.1 – 2.3)	no		

are possibilities. Interference of metallic, connected conductive parts is known to affect all electromagnetic system since the transmitted EM signal will induce currents in them; this might have happened in the panels under development (i.e., H4) but barely in abandoned panels like X1. Finally, induced polarization effects have been reported (El-Kaliouby *et al.*, 1995) to affect late time windows in clay-water mixture environment which exists in water aquifers. If this was demonstrated, TDEM surveys could bring additional information indicating the presence of water in clay environment.

MONITORING RESPONSE OF HOST ROCK

Permanent seismic monitoring systems are operated by mine engineering staff at a number of potash mines in Saskatchewan, and temporary monitoring studies have been conducted at virtually every mine. To date, noticeable earthquakes (local Richter magnitudes > 2.5 and < 3.9, or 10^{+8} to 10^{+10} Joules radiated energy) have been observed at five mines, occurring as infrequently as one event every few years. Small-scale microseismic activity (with measured radiated energies as low as a few Joules) is common, and has been observed at every mine where monitoring programs have been conducted. The activity rate for these microseisms ranges from a few events per week to over 50 events per day.

Mine operators pursue studies of mine-induced seismicity in an attempt to quantify (using remote measurements) the geomechanical response of the "host rock" to the cutting of rooms during mining. An understanding of these processes is thought to be useful in predicting and comprehending hazards, and in evaluating the overall "performance" of a mine design (i.e., how successfully rock stress is managed in the mine).

Prior work has established that there is no relationship between microseisms and earthquakes: small events tend to be located within mining level salts while large events occur in overlying limestones. Two different fracture mechanisms (deduced from the study of seismic waveforms) have been proposed for the large events and the microseisms (Gendzwill, 1984; Prugger and Gendzwill, 1993). However, microseismic event location patterns were found to be more chaotic than anticipated, and it has been difficult to relate them to other geological and/or mining observations. A typical example of short-term (three-month) results is shown in Figure 15. Notice that all events are weak, and that most of the activity is concentrated in stress-relief "wings"; few events occur in the travelways running down panel centres. This is considered to confirm the success of the mine layout employed at PCS Allan: no large-scale rock failure is observed, and small-scale failure occurs where it is intended to take place.

Over the long term (≥1 year) event patterns are more difficult to explain. The clearest relationship seen is one between microseismic activity and ground subsidence measured on surface: small-scale seismicity occurs most frequently in areas where surface subsidence is the greatest (and not at barrier pillars, where flexure of overlying strata is greatest). This is seen at many mines, and seems to be independent of specific mining method. An intriguing observation is that lineations of microseisms appear in some event location maps. These patterns imply faults, but this inference has yet to be corroborated by other, independent observations. Other relationships have been investigated, (between event location and extraction pattern, occurrence of geological anomalies, and in-mine rock mechanics measurements—including the mapping of rock failure), but no consistent, definitive trends or links have been worked out yet.

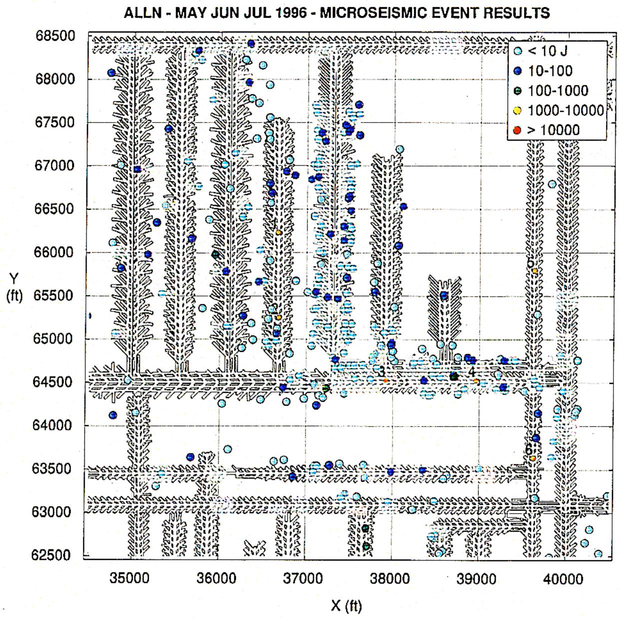

Figure 15: *Microseismic event location map, May through July 1996, for the PCS Allan potash mine (near Saskatoon). Events are colour-coded for radiated energy in Joules. Note that distances in this figure are in feet because mine-coordinates for this mine are in feet.*

ENVIRONMENTAL GEOPHYSICS

Waste salt and insolubles are stored in surface tailings areas consisting of a salt tailing pile and a brine pond contained by dykes. Brine migration beyond the dykes may contaminate soils and groundwater in the surroundings. Monitoring of the impact of waste on the groundwater regime is now part of the license to operate a potash mine in Saskatchewan. Phillips and Maathuis (1997) describe the geophysical methods used and present some case histories from PCS mines. Surface EM methods (TDEM : EM47 ; FEM : EM31/34 from Geonics Ltd.) are employed to map conductivity variations associated with brine flows around containment dykes. Borehole EM (EM39 from Geonics Ltd.) is used to resolve vertical conductivity variations and it is most useful for interpreting the surface EM data.

Knowledge of the stratigraphy of the glacial till around the tailing sites and of the bedrock topography is very useful for predicting contamination paths and concentration. Mapping is carried out using TDEM (EM47) and high-resolution seismic reflection.

DISCUSSION AND CONCLUSIONS

As mentioned by Phillips and Mottahed (1988), there are geophysical methods "which could be termed 'practical tools' to distinguish them from the host of 'potentially useful' methods which remain to be proven." It should also be added that there are practical methods that can be used routinely and others that are employed at times for particular problems only. On the scale of the mine area, reconnaissance 2-D and high-resolution 3-D surface seismic surveys are useful methods to map ore in advance of mining and to detect medium- to large-scale anomalous structures such as collapse zones. Avoiding those risk areas is beneficial to mine planning and safety and improves ore recovery. At the mine level, GPR has proven to be a very effective tool to map the ore zone structure within the salt layer and can be used to 'track' mineralization as well as to map discontinuities. Seismic refraction is used to determine salt back thickness but radar and light TDEM can be more appropriate (cost effective) for that purpose. However, it is useful to check integrity of the overlying aquifer limestone in geologically anomalous zones. EM tomography is still a tool under development for mapping the ore structure within a panel area. Promising results have been obtained at Rocanville. However, resolution is still coarse due to the poor data signal/noise ratio, the relatively low frequency used with current acquisition systems, and the simple imaging technique. Improvements needed, i.e., larger transmitter power, better receiver dynamic range and 3-D EM inversion, are within reach and the method will play a more important role in the future. Seismic tomography does not appear to be very effective at detecting detailed anomalous features, mainly because the velocity changes associated with those features are too small and the higher velocities in the layers above and below the panel prevent the recording of clear first arrivals.

The survey at the Taquari-Vassouras mine has demonstrated the potential of the TDEM method to detect water-bearing sandstone layers at a large distance from the mine openings in a conductive environment. In most surveyed panels, the results were clearly correlated with the known stratigraphy and water occurrence. However, before deciding on the appropriateness of the TDEM technique for the aquifer identification and characterization at Taquari-Vassouras, we need to resolve the origin of the data distorsion at late-time. Assuming that it is IP effects, can useful information be extracted from the late-time data? How will IP effects influence the TDEM interpretation of the aquifer? We have also to address the problem of how confident we are that the 0.3 Ωm layer detected by TDEM really is the aquifer? Unless test holes are drilled to verify the interpretation there is no way we will be 100% sure. Since 3-D seismic reflection was not able to delimit the water-bearing sandstone from the surface, the TDEM is likely to be the only geophysical technique to detect it at a large distance (80 m) in a conductive environment. The large transmitter moment needed, i.e., large loop size, restricts surveys to existing mine openings (rooms, exploration entries) and therefore TDEM is mainly useful for detecting brine-saturated layers above mine workings but not ahead (in advance) of mine development.

Some methods not currently used or tried at PCS and CVRD might see significantly increased applications if equipment and/or surveys become more affordable. For example, Kali und Salz AG in Germany (Dr. Lukas, person. comm.) is successfully using a borehole radar developed in-house to map structure and ore occurrence in advance of mining in 1 000 m-long horizontal exploration drillholes. Twenty-five to thirty km of borehole radar surveys are carried out annually. Nuclear magnetic resonance (NMR) is a method for which reliable modern equipment has recently become available and which may perhaps be used to detect free-water content in layers above the mine workings.

Gebhardt (1993) compares the benefits, the costs and the general usefulness of various available techniques used in planning a mining area from the mining engineer point of view. 2-D and 3-D surface seismics are ranked as good and excellent respectively. The acceptance and integration of geophysical methods at various stages in the development of a potash mine is a definite sign of their utility for the future.

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