Potash production in Saskatchewan

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Geoscientific methods for the investigation of orebodies and surrounding evaporite and sedimentary rock have contributed to the security of supply of potash from Saskatchewan. This article reviews geology, geochemistry and geophysics research that has enabled better characterization of the mining environment and detection of geological structures that may increase the potential for mine flooding.

The goal of this series of reports is to present developments in potash technology that have occurred since the milestone First International Conference on Potash Technology convened in Saskatoon, Saskatchewan in October 1983. Progress on mining, environmental and potash materials topics, that is not always apparent to customers of potash producers, has caused significant changes to occur in the science and technology used to produce about 22% of the world's supply of this fertilizer commodity.

These articles are based on the findings of more than 150 Research and Development (R&D) projects that have been jointly funded by industry and government. Between 1989 and 1994, this $6.7 million commitment to R&D by the five member companies of the Saskatchewan Potash Producers Association (SPPA) and the governments of both Canada and the province of Saskatchewan has been focused on three priorities:

- Development of mining technologies that improve productivity or reduce the risk and cost of conventional operations, particularly geoscience applications which allow for management of the chance and consequences of mine flooding.
- Assessment of the long term effects of potash operations on the Saskatchewan environment, and demonstration of decommissioning technologies for containment or disposal of salt tailings from potash production.
- Investigation of process and materials fundamentals that control the properties of potash products and which can be applied to ensure the delivery of superior fertilizer and industrial grade products to global markets.

This article deals with aspects of the first of these priorities.

Risk management of potash mine flooding

The Prairie Evaporite Formation contains immense reserves of flat-beded potash deposits in three principle ore horizons and is bounded above and below by water-bearing strata. Mined openings create potential for fluid inflow if flow paths develop between the mine and these aquifers. During the last decade three major brine inflows have occurred in Saskatchewan which have resulted in the loss by flooding of one conventional mine (PCA, now PCS Patience Lake Division, converted to a solution mine), the continuing need to control a chronic inflow (IMC Canada, K-2), and the successful plugging in 1985 of another inflow (PCS Rocanville Division). The total cost of control of these and other less serious fluid inflows has exceeded $550 million.

A study by Arthur D. Little Inc. in 1981 applied risk analysis principles to define possible mechanisms of potash mine flooding and to estimate the probability and consequences of inflows of different types. This report, together with the experience of mine operators, and the concern of potash industry executives about the strategic impact of mine flooding on the Saskatchewan capability to reliably supply markets with potash, provided the direction and motivation to reduce the risk to mines.

The R&D programme described below has developed a better understanding of mine geology and new exploration tools with which to reduce the probability of fluid inflows. In addition, design criteria for siting, construction and materials selection for bulkheads to be used for control of the conse-
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Of the 10.3 million tonnes of KCl produced in 1992, about 79% was mined by conventional technology, and the remainder by solution methods. Shaft mining at PCS Inc. operations, IMC Canada, Cominco Fertilizers and Central Canada Potash relies on highly efficient and productive (about 200 KCl tonnes/100 man-hours) continuous mining methods which have been customized by each production site. Solution mining at Kalium Canada and PCA (now PCS Patience Lake Division) yielded about 2.1 million KCl tonnes.

Conventional mining of ore with boring machines proceeds at depths of greater than 1,000 meters (see Fig. 1) in sylvinitite ore horizons, a combination of co-deposited KCl and NaCl and interbedded clay minerals. During the Devonian period, about 350 million years ago, the chloride minerals were crystallized from evaporating brines under locally complex depositional conditions. The geology of potash beds today presents both the variability established at the original time of deposition, as well as subsequent hydrogeochemical changes caused by dissolution and recrystallization.

Potash beds worked by miners today are generally found to contain normal sylvinitie or sylvinitie-carnallite ore with an apparently random distribution of geological anomalies such as collapse structures (Fig. 2) that were created by either contemporaneous or post-depositional fluid-inursion events. The primary objective of the geoscience research described below is to provide potash miners with new geological knowledge and geophysical and geochemical exploration techniques for early reliable identification of geological anomalies that might adversely affect mine risk, underground safety, or potash ore production.

Geology and geochemistry

Since 1985 Kyser, Renaut and associates of the Geological Sciences Department, University of Saskatchewan (U of S) have worked closely with potash producers to understand the genesis and geological evolution of the Prairie Evaporite and to develop new methods for identification and characterization of geological anomalies, a term used to classify a wide range of features encountered within the evaporite rock such as those illustrated in Fig. 3 (from Boys).

Two topics have been particularly important. First, the geology of the 30 to 40 metre thick primarily dolomite limestone Dawson Bay Formation which lies above the Prairie Evaporite halite and sylvinitie salt deposits has been investigated to determine its structure, porosity and other properties that can affect...
fluid flow. Second, the compositions of brine seepages or inflows into mines or shafts, or of microscopic inclusions trapped in halite crystals of the ore, have been used to explain the age and possible origin of the fluids. Results from geological and geochemical projects have contributed to the understanding of fluid inflow potential.

Geological analysis of archived Dawson Bay samples have shown a considerable difference between drill cores typical of the central and southeastern Saskatchewan potash mining areas. Renaut, Ahlstrom and Gu Chenggao have described the complex depositional history of the four members of the Dawson Bay Formation and related the bed thickening and apparent increase in porosity in the latter area to greater proximity to the Devonian depositional edge in southeastern Saskatchewan. Petrographic and electron microscope and microprobe methods have been used throughout this work to characterize the rocks. These studies have confirmed earlier evidence that the Dawson Bay Formation is generally "wet" in the Rocanville-Estherley area, but generally "dry" over potash mines in the Saskatchewan area, and have provided a more detailed geological explanation of the differences among cores. This new knowledge can now be applied to the selection and application of gourds that may be required to prevent or control future brine inflows into potash mines. It has also provided a more accurate geological model for interpretation of both in-mine and surface geophysical surveys. Fluids present in the orebody and in overlying strata also provide miners with information on the history of the rock and of changes that have occurred since Devonian time. After a decade of study and cooperation with mining companies, Prof. Kyser and his research team have proposed that the Prairie Evaporite Formation has been hydrologically active, and that both the rock and fluids record geochemical evidence of fluid events which have altered the original orebody geology and affected the risk of mining today.

While the basic principles of geochemical investigations work are straightforward, the development of the necessary laboratory techniques has required careful analyses by Wittrup, Chipley, Kocher and Morgan, all Kyser team members at the U. of S. The methodology described below is now accessible to potash companies to help answer specific questions about mine geology. This package of risk assessment tools is a direct result of university-industry cooperation on geochemical science and applications.

Three types of experimental measurements and empirical correlations developed at the U. of S. yield information on the age and origin of rocks and brines. First, stable isotope ratios of the water component, that is Deuterium/Hydrogen (D/H) and Oxygen-18/Oxygen-16 (O-18/O-16) ratios, determined by mass spectrometric methods have been related to the depth and the geological formation from which the fluid originated. Second, trace elements present at concentrations as low as parts-per-billion have been analyzed using a state of the art Inductively Coupled Plasma-Mass

Fig. 3: Geological Anomalies in Potash Orebodies

Three main types of anomalies encountered in Saskatchewan mines are identified and illustrated by Royle in A) Washout, B) Leach and C) Leach-Collapse structures with progressively greater risk to mining operations.
Spectrometer (ICP-MS) to detect halos or changes in impurity levels and element ratios around geological anomalies. Third, observation of the crystallization or dissolution temperatures of micron-sized daughter minerals within microcosmic brine inclusions trapped in halite crystals provides information on the probable temperature of formation of the ore body.

The initial stable isotope research of Wittrup and Kyser showed that a general correlation exists between the 8D and 8O-18 values for water and the depth or formation from which the fluids are sampled in mine shafts. This important relationship has been utilized to determine the possible origin of brines that seep or flow into mines or which are trapped within ore body halite crystals. These specialized water analyses indicate the extent to which more modern waters have mixed with ancient Devonian fluids since the potash beds were deposited, and provide an indication of the risk associated with geological structures encountered during mining.

The development of ICP-MS methods at the U of S for rapid multielement analysis of chloride brines has facilitated collection of data on formation fluids and from samples taken around known structures in the ore horizon. Fingerprinting, or interpretation of data on formation fluids is complicated by the uncertainty in the extent of geochemical interaction with other minerals. However, trends in elemental ratios such as Sc/Mn, Sr/Pb, Rb/Ba, and Co/Co appear to be useful for distinguishing among fluid types and for detection of anomalous geology.

The presence of microscopic brine inclusions (about 10 to 100 microns in size) within halite crystals of potash ore (Fig. 4) has given the Kyser group access to fluids that were trapped within the solid phase at the time of crystallization. By cooling or heating thin section samples on a microscope stage, crystal formation in the brine or dissolution of other daughter microcrystals like carnallite can be observed. Temperatures at which these events occur are another indication of the original conditions under which the halite crystal was deposited.

Chapple and Kyser have interpreted these thermometric data and combined them with other stable isotope measurements on water recovered from fluid inclusions in halite from potash ore to conclude that at least three major fluid events have modified the Prairie Evaporite potash ores since the original Devonian deposition. These analyses have also provided a new technique for classification and risk assessment of geological anomalies encountered during mining. For example, when fluid inclusions in halite contain trapped waters characteristic of more recent Cretaceous age events exclusively, then additional exploration data may be acquired to determine if there is a currently active connection to overlying aquifers.

The convincing geochronological picture of an evaporite deposit that has been repeatedly altered during the last 180 million years is supported by surprising results from two other research projects. Palaeomagnetic studies by Kyser on rock samples of known physical orientation have shown that the magnetization of this type of rock is not constant within a potash ore horizon. It varies because traces of red-coloured hematite record the direction of the Earth’s magnetic field at the different times of primary or later crystallization of the salts. As the historic pattern of migration of the Earth’s magnetic field is known, measurement of the magnetization of a sample and comparison with geochronological standards allows estimation of the time of formation or geochemical change of the rock. Palaeomagnetic analyses of clay bands samples is another potentially useful tool for investigation of anomalous underground structures.

The use of naturally occurring pollens and spores as tracers to confirm aquifer flow patterns and to date events in sediments is not new. However, the discovery by the U of S of 100 million years old palynomorphs in clay seams of Devonian potash ore (about 360 Ma) was initially a surprise to researchers as the formations are stratigraphically separated by 500 metres. Preliminary work has shown that diverse spore assemblages concentrated in a clay band can be uniformly distributed laterally. Differences among the spore sets have been observed between clay bands and within ore bed anomalies such as washouts. The presence of both Cretaceous and Devonian palynomorphs suggests that more than one fluid event has altered potash ore, a conclusion that is consistent with geochronological interpretations.

Although palaeomagnetic and palynological methods are not yet used routinely as part of geological assessment practices, initial results from these studies have supported the U of S model of Prairie Evaporite evolution. All data suggest that potash deposits have been repeatedly altered since the Devonian period.

**Geophysics science and technology**

Miners want the capability to accurately characterize and visualize the orebody in which they work over both short and long ranges. In the last decade, advances in applications of geophysical exploration methods have helped potash miners to achieve this goal, and to minimize mining costs and risk. This section summarizes a few important Saskatchewan advances.
Seismic survey technologies

Two and three dimensional seismic surveys, originally developed for oil and gas exploration, have now been used with considerable success at all conventional potash mining operations in Saskatchewan. This technology can detect discontinuities in formations above, within, and below the Prairie Evaporite, especially the presence of large anomalous structures that may affect mining. Field surveys and data reduction and interpretation are typically contracted out to specialized firms such as Boyd Exploration Consultants Ltd. or Western Geophysical of Calgary, Alberta.

Seismic data are collected with either single line (2-D) or two dimensional array of geophones (3-D) that are placed on Saskatchewan farmland over the block of ground to be explored (Fig. 5). Vibrations generated by explosives or mechanical devices are transmitted through the ground and signals reflected by different formations are detected by the transducer grid. The large sets of recorded field data are analyzed to yield computer-generated three dimensional images of the evaporite and sedimentary sequences. Depending on the design of the survey, structures as small as 10 meters have been resolved at the potash mine level, 1,000 metres below the surface.

To validate this 3-D methodology, surveys have been completed over known anomalies, such as that encountered at the PCS Rocanville Division in 1985. At this site a classical collapse structure, created by localized leaching of evaporite minerals and failure of overlying formations, is clearly revealed. Figure 6 is a plan view of the computer generated image of the elevation of the top of the Prairie Evaporite salt. The collapse depression is highlighted by false-colour mapping.

Computer simulations of two-dimensional slices through the 3-D analyses can also be selected to display stratigraphic features within different vertical planes. Geologists and associates at PCS Inc. have shown how this information can help to identify anomalies such as collapses or faults, to better interpret the associated risk to mining and to define recoverable ore. This 3-D seismic survey technology may now be used to explore areas of the potash orebody before, during, or after production mining at a cost per survey of about $0.1 million per square mile.

A decision analysis project has shown how this extra cost can be justified by the value of extra information provided by the 3-D technique.

Seismic geotomography

In-mine seismic geotomography has been attempted by Young of Queen's University to yield images of geological anomalies that are present within the plane of the orebody. This method requires physical access to the mining block through development entries that are completed around the perimeter of the target area, therefore it is more limited in utility than the 3-D method. Seismic data are collected by geophones installed so as to receive dynamically generated sound waves transmitted laterally through the rock mass. The compression and shear wave arrival times from many ray paths are used in the tomographic computer analysis to construct a map of the variation of sound velocity in rock as a function of location in the ore.

Initial underground experiments were completed around the Rocanville collapse structure. A string of 24 geophones and 96 dynamite shot points were required to collect data around the 1820-meter square mining panel. The location and definition of the anomaly was inferior to that delivered by either the 3-D survey technique or the radio imaging method described below. In addition, as
the time required to prepare for and collect data underground was found to be excessive, further development of the seismic geotomography technique by potash producers has been postponed.

**Radio Imaging Method (RIM)**

Electromagnetic (EM) geotomography has been applied to investigate several known or suspected geological anomalies and found to have potential for characterization of evaporite rock over distances of up to 1500 meters. The principle of the method is illustrated in Fig. 7.

Underground field surveys carried out by Rim Tech of Denver, Colorado collect radio wave amplitudes at several thousand mobile receiver stations around a mining area, as the transmitter is also moved around the boundary in predefined rooms. When geologic conditions permit detection of 100 or 300 KiloHertz signals, data interpretations can yield information on the average formation thickness and conductivity properties of the rock along the path between the transmitter and receiver. Initial work has been focused on validation of RIM by surveys of anomalies previously characterized by other methods[13]. Figure 8 presents the results of a mine-level RIM survey of the Rocanville collapse, for comparison with Figure 6.

A reduction in the observed signal strength below that caused simply by distance from the transmitter occurs when the radio frequency energy is absorbed by a conducting material such as brine. Processing of the data to relate absorption rate to the transmitter-receiver ray position can provide a quick indication of a conductivity anomaly. Further analyses by McGaughey and others of the six RIM data sets by the Simultaneous Iterative Reconstruction Technique (SIRT) has produced tomographic maps of energy absorption coefficients for sections of the potash orebody[14]. These results have helped to define and confirm geological anomalies at each mine.

To provide confidence in RIM and EM tomographic interpretations, additional computer simulations of the electromagnetic phenomena have been completed using a variety of computer modeling programs. Important technical questions about the location of the transmitter and receiver with respect to the location of the anomaly, and the effect of the anomaly thickness and resistivity on the observed results have been investigated theoretically. This work has provided the capability to estimate some properties of such structures within the Prairie Evaporite, using RIM surveys data.

**Electromagnetic surveys**

Both frequency- and time-domain methods are useful for rapid underground mapping of the salt back thickness above-mine openings and for determination of the conductivity of overlying formations. Data collected using Geonics EM34 double coil continuous wave instrumentation operated at frequencies (coil spacings) of 400 Hz (40 m), 1600 Hz (20 m), and 6400 Hz (10 m) are now interpreted by comparison to new EM model response graphs. The principle of this EM survey is shown in Fig. 9.

The 3-D computer code EM3D (University of Utah) has been utilized by Pandit to improve older field measurement simulations. A more detailed 8-layer earth model representing the geological section between the Winnipegosis and the Souris River formations has been used. More than 1,900 separate cases have been calculated and are tabulated to facilitate the routine interpretation of surveys for transmitter-receiver coils oriented in either the horizontal or vertical coplanar configurations[14].

Pulse or Time-domain EM surveys using the Chrome PEM or Geonics EM-47 have also yielded information on variation of the conductivity of rock around mine openings and the possible presence of brine[15]. With the EM-47 a 1.5 to 2.0 amp pulsed current is applied to an 8-cm 5 m x 5 m transmitter coil and changing vertical magnetic fields induced in the rock are measured with a receiver loop 10 metres away. Signals are sampled at 20 time intervals between about 7 and
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707 microseconds after the current to the induction coil is shut off. Changes in the magnitude and direction of the transient magnetic field at the receiver, particularly of the z-axis component, are used to detect anomalous high-conductivity zones above or below the mining horizon.

Converting R&D into technology

While each of the geoscientific tools reviewed above have been used independently to address specific potash mining questions, one industry project has demonstrated how the separate methods can be combined into a practical technology for production-support exploration and risk assessment. Dainipik of PCS Inc. coordinated the efforts of a university and industry team that completed an extensive geological, geochemical and geophysical study of two anomalies that were exchanges in the PCS Inc. Allan Division mine.

The three goals of this Integrated Geology Study were to conduct a multi-disciplinary investigation of two anomalies in a potash mine, to compare the results of different methods, and to demonstrate the value of improved information and geological interpretation as input to mining decisions. The project accomplished its objectives with these notable highlights:

- Detailed geological mapping of small scale, lower risk disturbances within the ore body, such as washouts, leach zones and minor collapse structures (see Fig. 1), can help to explain their likely mechanisms of formation, and can provide additional experience in recognition of these classes of anomalies.
- Fluid inclusion and stable isotope analyses can determine when ore body alteration and anomaly development occurred, and which fluids affected the observed features.
- Palynological identification of the type and distribution of spores in evaporite samples can support geochemical evidence for hydro-geological changes.

- In-mine RIM, refraction seismic, electromagnetic and Radar geophysical surveys can provide evidence for geological disturbances that are not visually evident within the mining horizon or resolved by surface seismic data.

The integration and mapping of all geological data using Geographic Information System (GIS) software has started. Borehole logs from exploration wells, 2-D and 3-D seismic survey data, mine layout, ore grade with position, surface lineament analysis and other primary or interpreted information can be selected, filtered, analysed, displayed and mapped for use in decision-making. No single commercial software product has been adopted as a standard, but most companies use Computer Aided Design (CAD) packages to maintain geological and mine files that can be imported for GIS mapping projects. This has greatly improved the capability to display complex sets of data and to visualize the mine environment in three dimensions.

Mining risk analysis - application to decision-making

The critical application for these Earth Science tools is to reduce the risk of mine flooding that is associated with potash mining. When Brecher and Hadlock of A.D. Little assessed the risk of mine flooding for PCS in 1981, the Saskatchewan industry history up to that point indicated that the chance of experiencing a major inflow of water was about 1%/year. During the remainder of the decade one Saskatchewan mine was abandoned, another continues to manage a chronic inflow, and a third recovered from a flooding event. Each incident of this type has the potential to impact available potash supplies to global markets.

In real terms, the geoscience R&D reviewed in this article and the package of dependent "risk avoidance" exploration technologies has conservatively achieved a reduction of mine flood risk by at least an order of magnitude. The chance of penetration of a major geological anomaly or of connecting a mine to a bounding aquifer has dropped greatly as the capability to explore the potash orebody has improved. Although techniques are now available to mine operators to avoid high risk areas, the decision to utilize these methods, all of which add to direct exploration or production-interruption costs, still depends on human experience and judgement.

Use of probabilistic risk analysis methods to help quantify potash mining geological risk is still in its infancy. The challenge that remains for geoscientists and potash mining engineers is to further refine exploration technologies and to improve methods for objective assessment of risk so as to eliminate the loss of potash mines by flooding.

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