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An Overview of the Geology of Solution Mining Of Potash in Saskatchewan

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AN OVERVIEW OF THE GEOLOGY OF SOLUTION MINING OF POTASH IN SASKATCHEWAN

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Abstract

Presently, there is great interest in exploring for, and developing, potash deposits around the world. This interest has created record levels of interest in potash deposits within the Elk Point Basin sequence of Saskatchewan. Potash has been mined in the province since 1959 and, presently, there are 10 operating mines, 8 of which are underground extraction mines, 1 which is a flooded underground mine (PCS Patience Lake), but presently operating as a solution mine, and 1 solution mine located at Belle Plaine Saskatchewan. It is estimated that there are some 8 billion short tons of recoverable KCl reserves (5 billion short tons K_2O equivalent) using conventional (underground techniques, but some 110 billion short tons of recoverable KCl reserves (65 billion short tons) solution mining techniques. Numerous permits for ground that industry considers as prospective for further potash extraction have been taken since 2005; however, the majority of these lands are along the "Conventional Mining Belt," the trend where the beds are extractable using underground mining techniques.

The trend of lands amenable to solution mining are located to the south of the "Conventional Mining Belt" further into what is termed the "Williston Basin" of Saskatchewan and the northern plains states of the United States.

The potash deposit itself consists of generally flat-lying sedimentary deposits of interbedded halite, sylvite, carnallite, clay, and minor anhydrite and dolomite beds that can be mapped from central Alberta through to Manitoba, North Dakota, and Montana.

In the 1960s, most of the ground in central Saskatchewan considered prospective for potash mineralization was held by a wide variety of companies experienced in the methods of conventional underground mining, such as International Minerals and Chemicals Corporation and Potash Company of America. Along the trend considered too deep for conventional mining, while a number of resource companies held permits, and several pilot solution mining projects were undertaken, such as the work of Imperial at Findlater Saskatchewan, Lumsden Potash at Bethune, and Lynbar Mining at Duval, the only company to proceed with a commercial solution mining operation was Pittsburgh Plate Glass (PPG) at Belle Plaine.

This paper presents a summary resource characterization for two such abandoned pilot test sites. The mineral resource for these sites (net of areas where geophysical surveys suggest dissolution and collapse structures) is estimated at 5 to 6 million tonnes of K_2O equivalent per section. This is equivalent to 2.04 tonnes of K_2O per square meter or 2,040,000 tonnes per square kilometre.

Key words: Bedded Salt Deposits, Canada, Elk Point Basin, Evaporites, Geology, Potash, Potassium Minerals (Carnalite, Potassium Chloride), Prairie Evaporite Formation, Saskatchewan, Solution Mining and Potash

Introduction

Presently, there is great interest in exploring for, and developing, potash deposits around the world. This interest has created record levels of interest in potash deposits within the Elk Point Basin sequence of Saskatchewan. Potash has been mined in the province since 1959 and, presently, there are 10 operating mines, 8 of which are underground extraction mines, 1 which is a flooded underground mine (PCS Patience Lake) but presently operating as a solution mine, and 1 solution mine located at Belle Plaine Saskatchewan. It is estimated that there are some 8 billion short tons of recoverable KCl reserves (5 billion short tons K_2O equivalent) using conventional (underground techniques, but some 11 billion short tons of recoverable KCl reserves (65 billion short tons) solution mining techniques (Holter, 1969 p. 57). Numerous permits for ground that industry considers as prospective for further potash extraction have been taken since 2005; however, the majority of these lands are along the "Conventional Mining Belt," the trend where the beds are extractable using underground mining techniques.

This report is based upon a technical report prepared at the request of ISX Resources, Inc. (ISX), in support of an exploration program being organized and financed by ISX. Their kind permission to allow publication of this paper is hereby gratefully acknowledged.

The information upon which this paper is based was obtained from public record sources, specifically, well files consisting of drilling reports, geological reports, potash assay analyses, assessment files, and published reports and papers as listed in the Reference section.

Geographical Setting

Generally, lands prospective for potash in Saskatchewan consist of flat to gently rolling cleared farmland with local mixed poplar/aspen bluffs. Some of the lands are unbroken grassland and are used as pasture. The cleared lands are utilized primarily for farming purposes, although there is scattered pasture and grazing lands. The entire region is generally accessible by a network of 'grid" section gravel and paved roads, including a major paved highway, rail access, and natural gas distribution pipelines.

The trend of lands amenable to solution mining are located to the south of the "Conventional Mining Belt" further into what is termed the "Williston Basin" of Saskatchewan and the northern plains states of the United States (see Figure 1). Various parameters are used to define the contact of the "Solution Mining Belt" and the "Conventional Mining Belt," the most common being the depth of burial of the potash-bearing beds from surface. Presently, the southern edge of the "Conventional Mining Belt" is the subsurface depth of approximately 1,100 m, which is considered to be the maximum depth at which underground extraction can safely be accomplished. Depending upon the expert, the solution mining trend begins immediately to the south of this edge, or it is offset further to the south, beginning along the line where the potash beds are buried deeper than 1,450 m below surface.

History of Solution Mining of Potash in Saskatchewan

In the 1960s, most of the ground in central Saskatchewan considered prospective for potash mineralization was held by a wide variety of companies experienced in the methods of conventional underground mining, such as International Minerals and Chemicals Corporation and Potash Company of America. Along the trend considered too deep for conventional mining, while a number of resource companies held permits and several pilot solution mining projects were undertaken, such as the work of Imperial at Findlater Saskatchewan, Lumsden Potash at Bethune, and Lynbar Mining at Duval, the only company to proceed with a commercial solution mining operation was Pittsburgh Plate Glass (PPG) at Belle Plaine, presently operating as a potash solution mine by Mosaic, Inc. Figure 2 shows the location of Findlater and Lumsden solution pilot test and the Mosaic lease areas.

One of the more notable solution mining pilot projects was undertaken by Imperial Oil, Ltd. in the early 1960s at Findlater, Saskatchewan, some 25 kilometers (km) north of the Belle Plaine commercial solution mining operation. Work on the project commenced in 1960 with pilot operations continued with fluids being circulated through a cavity system consisting of two cavern wells at variable rates and temperatures and with variable concentrations with circulation between caverns attempted by means of hydraulic fracturing.

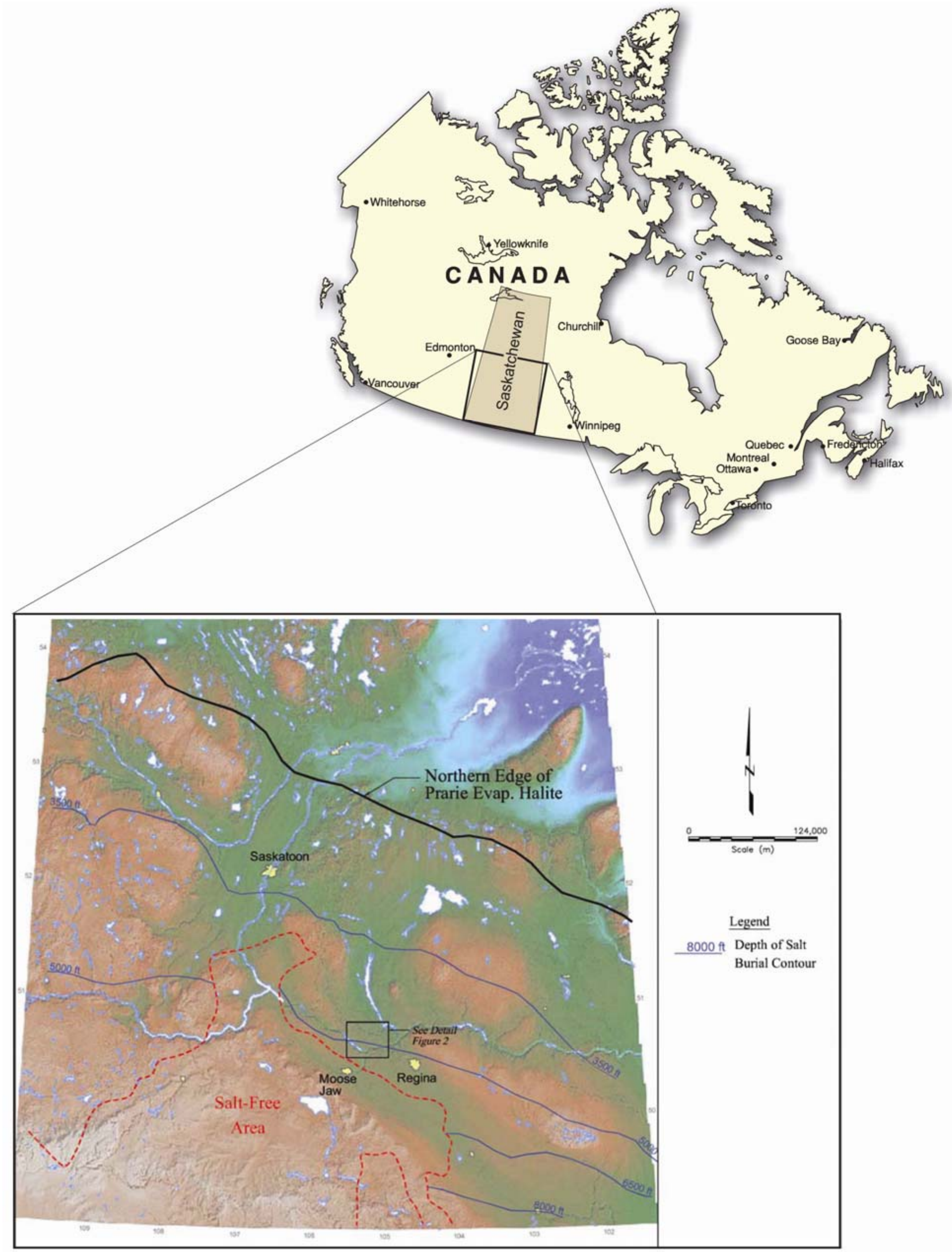

Figure 1: Location map of Saskatchewan potash deposits and distribution of potash beds mineable using solution technology (modified from Holter 1969)

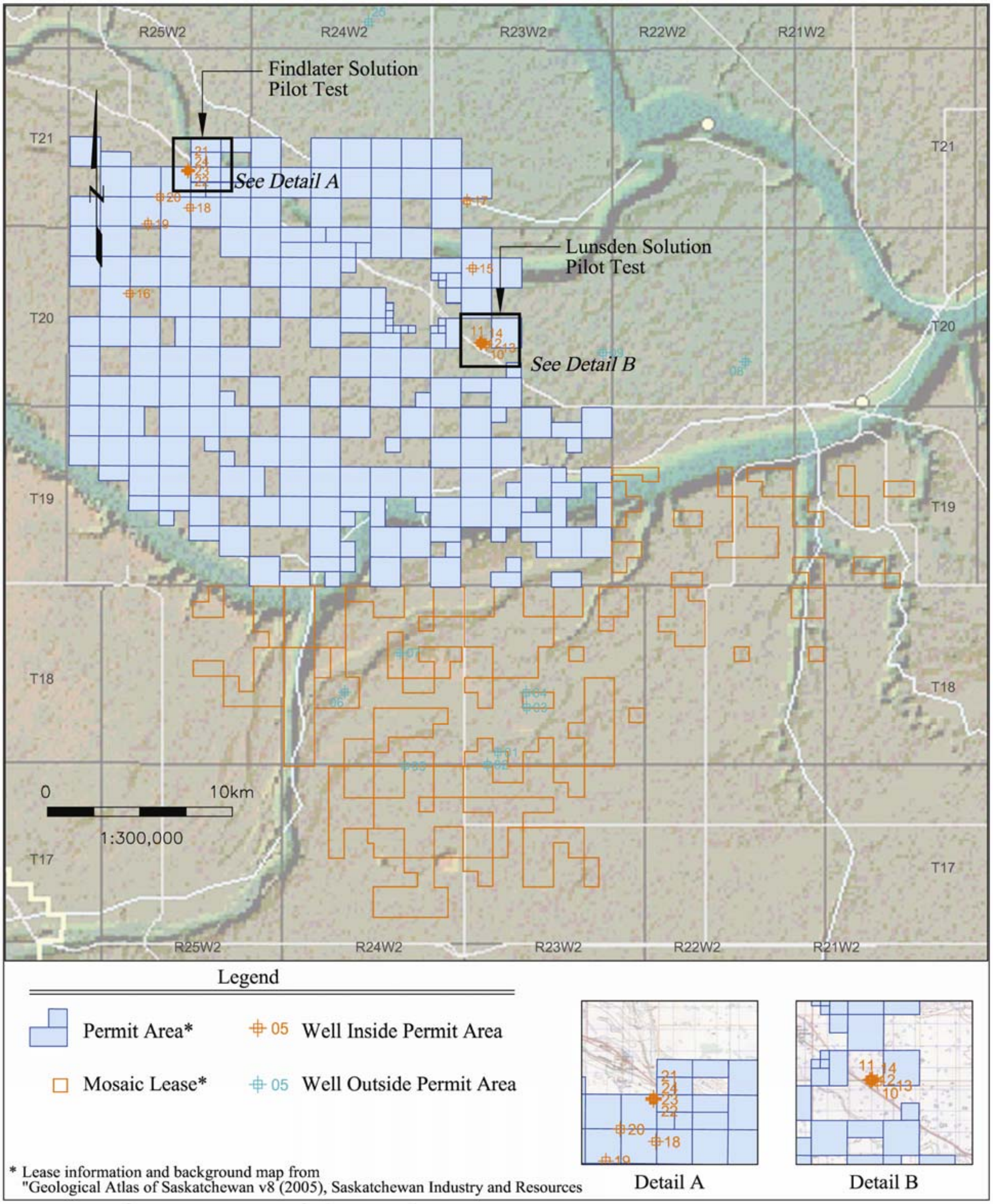

Figure 2: Location of Findlater and Lumsden solution pilot tests, ISX permit areas, and the Mosaic lease areas

A second solution mining pilot project was undertaken by the Lumsden Potash Development Company, Ltd., during 1967. This project consisted of drilling three drill holes, two into the Prairie Evaporite Formation and one into the overlying Mannville Formation as a water source well. The report describes the results of the pilot test, which included the installation of a pilot plant and primary cavern formation by means of fluid circulation between two caverns, the Lumsden Bethune #1 and #3 wells, and also involved establishing communication between caverns by means of hydraulic fracturing, the results of which were claimed as being "proprietary." The report states that the results of the tests are "proprietary," but "they did obtain an anticipated result and provided no difficulties or unexpected events" (Manker, "Exploration Work on C. M. Taylor Potash Permit #1" dated June 25, 1968, p. 3).

Other solution mining attempts include the Lynbar Duval project, the General Petroleums Kutawagan project, the Western Potash Unity project, and the W.P. James project southwest of Saskatoon, Saskatchewan. Of these, the only project which claimed success on a pilot scale was the Lynbar Mining attempt at Duval, which again used proprietary technology.

The Mosaic Company operates the Mosaic Belle Plaine potash solution mine. The plant site of the Belle Plaine Mine is approximately some 16 miles (26 km) south of the estimated centre point of KP 289. This mine has been in operation since the early 1960s, and it is estimated that the mine has produced in excess of 60 million tonnes of KCl (Ron Brown pers. comm.)

Regional Geological Setting

The regional subsurface stratigraphic column of central Saskatchewan is presented in Figure 3. The geological column may be subdivided into three broad intervals with approximate depths taken from examination of wells within the Permit Area:

- An uppermost sequence extending from surface to an approximate depth of some 175 to 200 m of glacial tills, gravels, and clays and containing fresh water aquifers.
- A medial sequence extending from the base of the glacial sediments to an approximate depth of of some 800 m consisting of Jurassic to Cretaceous shales, siltstones, and sandstones with limited aquifers of brackish water.
- A lowermost sequence extending from the Palaeozoic/Mesozoic Unconformity to below 1,900 m consisting of Cambrian to Upper Devonian carbonates, evaporates, and basal shales and sandstones.

The above strata comprise the Phanerozoic sequence, which is itself underlain by gneisses and granites of the Precambrian.

Bedded and laterally extensive evaporite beds containing deposits of halite, sylvite, and carnallite are found within the medial sequence, specifically within Middle Devonian strata commonly called the "Elk Point Group" and ranging from some 2,500 m in the south of the Province to surface outcrop in northwestern Manitoba. This geological sequence is bound at its base by an unconformity spanning the upper Silurian to lower Middle Devonian (Givetian) and at its top by locally disconformable carbonate deposits of the Middle Devonian Dawson Bay formation. The evaporite beds are specifically correlated to the "Prairie Evaporite Formation," which is in depositional contact with the earlier to possibly locally contemporaneous Middle Devonian Winnipegosis Formation. The basal contact of the Prairie Evaporite and Winnipegosis is marked by the sharp transition from halite of the Prairie Evaporite to mixed limestone, dolomite, and anhydrite of the Winnipegosis. The uppermost contact between the Prairie Evaporite and the Dawson Bay consists of shale to locally silty regolith deposit named the "Second Red Beds." Regionally, the Winnipegosis forms a broad flat basin to platform deposit with local development of limestone/dolomite "reefs."

The Elk Point Group was deposited within what is termed the Middle Devonian "Elk Point Seaway," a broad intracratonic basin extending from North Dakota and northeastern Montana at its southern extent north through southwestern Manitoba, southern and central Saskatchewan, and eastern to northern Alberta. Northward from this point, the seaway was divided into a series of smaller basins by tectonic features.

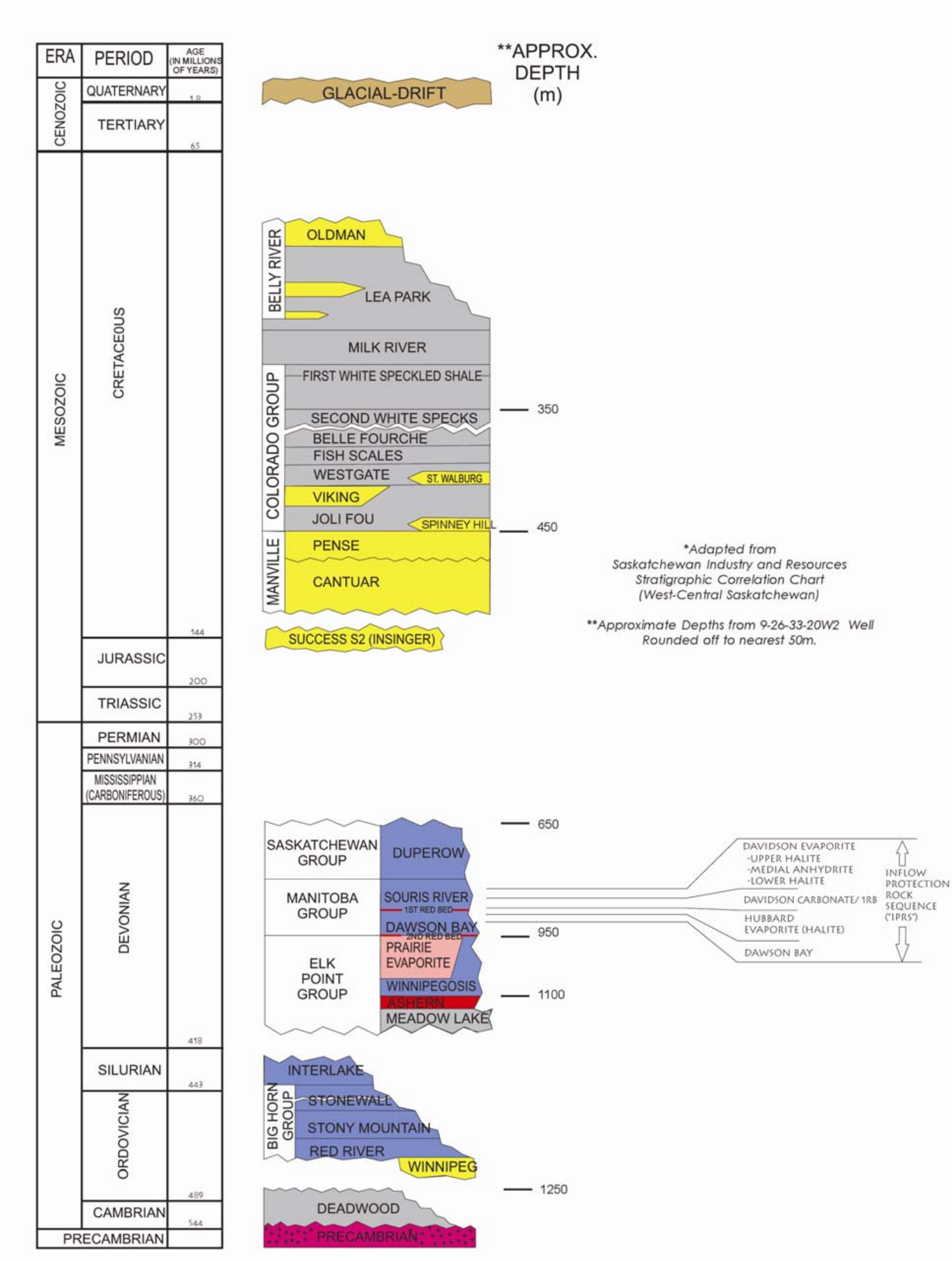

Figure 3: Stratigraphy of the Phanerozoic Sequence, Central Saskatchewan (Note: Included in the Findlater Area are the Upper Devonian Birdbear and Torquay formations and the Mississippian Bakken and Lodgepole formations)

Overlying the Elk Point is a sequence of rocks commonly referred to as the "Manitoba Group" and consisting of the Dawson Bay Formation and overlying Souris River Formations. Present within this sequence are two halite beds: (1) the "Hubbard Salt," which is the uppermost bed of the Dawson Bay, and (2) the "Davidson Evaporite" composed of two halite beds separated by an anhydrite bed. These are important from a mining viewpoint as they form a flood protection zone separating the Prairie mining horizon from the water and brine aquifers present within the Mesozoic sands. The absence due to dissolution and removal of the Hubbard and Davidson halites is an indicator of potential mining difficulties for conventional underground mines in that at some point brine and water capable of dissolving halite made contact with the halite beds and, thus, may also have penetrated to the mining level; the authors do not consider these relevant for solution mining other than to determine possible dissolution zones of the underlying Prairie Evaporite strata. Dissolution of any salt in the geological column points to the risk of mine flooding for conventional underground mining so such areas are typically avoided by Saskatchewan potash mine operators.

Deposit Type

The term "potash" is a colloquial term that is a contraction of "muriate of potash," which is expressed by the chemical formula "K_2O" or "potassium oxide." The terms "muriate of potash" and the contraction "K_2O" are commonly used in the Saskatchewan potash industry to refer to the sales product (i.e., potassium oxide resulting from the mining and milling of sylvite-bearing rock or "sylvinite"). "Sylvite" refers to the potassium mineral "sylvite" or potassium chloride ("KCl"). The product mined and sold is KCl. A ton of KCl contains an equivalent of 0.63 tons of K_2O.

In this paper, the term "sylvinite" is used to describe the mixture of sylvite (KCl) and halite (NaCl) that is the source of the "potash" sylvinite may also contain clay and anhydrite and dolomite crystals that are collectively identified in the assay reports as "water insolubles." Other impurities include carnallite ($KCl.MgCl_3.6H_2O$) and kieserite ($MgSO_4.H_2O$). The presence of magnesium is unfavourable and concentrations over 0.25% magnesium can impact plant performance and require special non-standard processing. In the historical record, assays for magnesium (Mg) and/or carnallite are listed; however, the "carnallite" assay value is a calculated value based on the equivalent magnesium chloride ($MgCl_2$) content. The equivalent $MgCl_2$ content is 3.91 times the Mg content. The equivalent mineral carnallite content is 11.42 times the magnesium content or 2.92 times the $MgCl_2$ content. Throughout this paper carnallite content is reported as equivalent magnesium chloride ($MgCl_2$).

The geology of the potash-bearing beds of the Middle Devonian Prairie Evaporite Formation has been well documented.[1] The following commentary is derived in large part from Holter and from the second author's personal experience. Overall, the potash-bearing beds may be described as being a bedded sedimentary rock, deposited across the Middle Devonian Elk Point Seaway. These beds are remarkably consistent over all of Saskatchewan and portions of Manitoba, North Dakota, and northeast Montana with individual clay seams and sylvinite-bearing intervals correlatable over great distances.[2]

The widespread consistency of the potash-bearing sub-members and the even, bedded nature of the sylvinite intervals result in highly mechanized conventional underground mining operations. In areas suitable for solution mining, this property suggests that a borehole drilled to establish a mining cavern can be moved laterally, should the grade or thickness encountered within the borehole be deemed insufficient for mining purposes.

Figure 4, from Fuzesy (1982), presents the regional stratigraphy of the Upper Prairie Evaporite in Saskatchewan, and is based for the most part on the stratigraphic nomenclature is presented in Holter (1969) and specifically highlights the correlation of the gamma ray and neutron log with the mineralogy and lithology of the Patience Lake Member and the Belle Plaine Member. The Prairie Evaporite Formation is divided into a lowermost "Lower Salt" and an overlying unnamed unit containing three potash-bearing units and one "marker beds," in ascending order the Esterhazy Member, White Bear Marker Beds, Belle Plaine Member, and Patience Lake Member. Figure 4 shows the uppermost Members and also the presence of carnallite in the Belle Plaine Member. Carnallite has not been found

[1] For a comprehensive discussion of Prairie Evaporite economic geology, please refer to Holter 1969.

[2] For example, see Phillips 1982, "Nomenclature for Use in Saskatchewan Potash," 7th Annual CIM District Four Meeting, wherein clay seam and ore bed stratigraphy is established throughout the Saskatchewan Commercial Potash Belt.

in significant concentrations in the core hole assay results from the Permit Area; however, indications of carnallite were noted in visual examination of the Bethune #1 core (see following section on "Carnallite Distribution").

Figure 5 shows a regional cross section from Saskatoon to some 100 miles southeast of the permit area. This cross section illustrates the regional consistency of the Prairie Evaporite.

Geology of the Potash-Bearing Beds

In the Elk Point Basin of Saskatchewan, the Esterhazy, Belle Plaine, and Patience Lake members are generally present; however, their local distribution varies. For instance, the Esterhazy is prominent in the eastern and southern portions of Saskatchewan and absent in central Saskatchewan, while the overlying Patience Lake and Belle Plaine members may be eroded to the east by the unconformity forming the Second Red Beds. Also present are the "White Bear Marker Beds," which is a distinctive unit of thin interbedded clay, halite, and sylvinite beds present between the Belle Plaine and Esterhazy members. The following is a summary of the key stratigraphic boundaries determined for the region deemed amenable to solution mining:

- Patience Lake Member: The uppermost member of the Prairie Evaporite member with potash potential. The top 7 to 14 m (25 to 45 ft) of the Patience Lake Member is halite with clay bands. The sylvite-rich beds within this unit are mined using conventional underground mining techniques in the Saskatoon and Lanigan areas of Saskatchewan and by solution mining techniques at the Mosaic Belle Plaine potash mine.

- Belle Plaine Member: The Belle Plaine Member underlies the Patience Lake and is separated from it by barren halite beds. The Belle Plaine is mined using solution mining techniques at the Mosaic Belle Plaine potash mine.

- Esterhazy Member: The Esterhazy Member is separated from the Belle Plaine Member by the White Bear Marker Beds, a sequence of clay seams, low-grade sylvinite beds, and halite. The Esterhazy Member is mined using conventional underground techniques at the Esterhazy and Rocanville potash mines and by solution mining techniques at the Mosaic Belle Plaine potash mine. The Esterhazy potash beds are thin and of low grade in the areas where cored within the Permit Area so may not be as desirable as the upper two members for solution mining. The potash beds are underlain by halite and could be partially recovered during sump development during cavern development.

The typical sylvinite interval within the Prairie Evaporite Formation consists of a mass of interlocked subhedral to euhedral sylvite crystals that range from pink to translucent and which may be rimmed by greenish-grey clay or bright red iron insolubles, with minor intercrystalline halite randomly disseminated throughout the interval. Local large (greater than 2.0–2.5 cm) cubic translucent to cloudy halite crystals may be present within the sylvite groundmass and overall, the sylvinite ranges from a dusky brownish red color (lower grade, 23%–27% K2O grade with an increase in amount of insolubles) to a bright, almost translucent pinkish-orange color (high grade, 30%+ K2O grade). The intervening barren beds typically consist of brownish red, vitreous to translucent halite with minor sylvite and increased insolubles content.

In determining mineralized and non-mineralized intervals for purposes of mineral resource estimation, an examination of core assays and comparison of assay intervals and distribution of mineralized and non-mineralized intervals to the borehole gamma ray–neutron geophysical logs was undertaken. This is required to determine the correlation between the assay interval measurements and the measurements of bed elevations as determined from borehole geophysical logs. The thickness from the gamma logs maybe taken from the highest gamma count greater than 250 units to the lowest point where the count exceeds 250 units. Judgment is required to decide where to locate the cut-offs because in each potash zone there is often an isolated thin interval of potash above or below the main high-grade bed, and this thin potash bed may be included if the thickness of the intra-burden material, the material between the high-grade beds, is also thin.

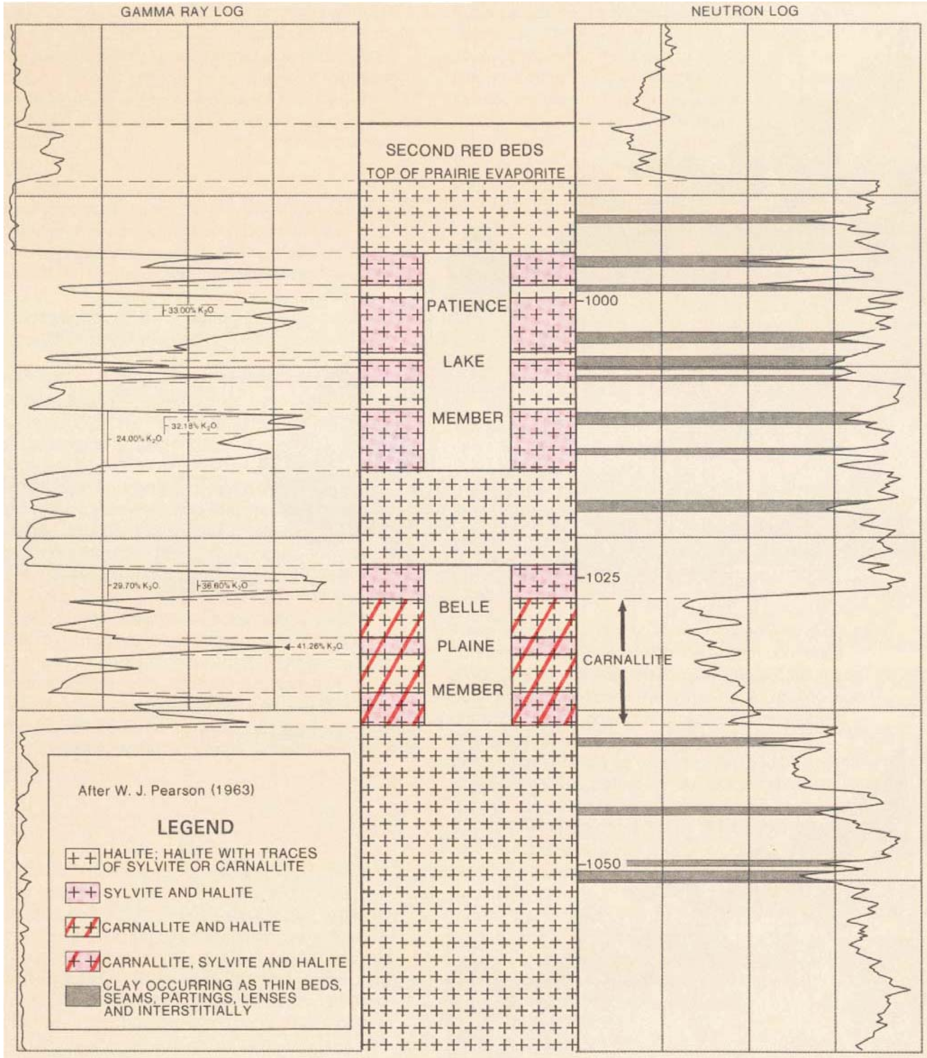

Figure 4: Stratigraphy of the Upper Prairie Evaporite Formation and Correlation of Gamma and Neutron Logs with Mineralogy (from Fuzesy 1982)

Disturbances Affecting Geology of Potash-Bearing Members

The potash-bearing beds may be affected by three general types of anomalies. In general, a disturbance that affects the normal character of the sylvinite-bearing beds is considered an "anomaly" and, thus, represents an area which is not suitable for mining. Figure 6 illustrates the types of disturbances that created anomalous altered zones within the main sylvinite-bearing beds as is typical for Saskatchewan potash mining properties. These anomalies range from localized features less than a square kilometer in extent to disturbances that are regional (i.e., several square kilometers in extent).

These types of disturbances are commonly encountered in Saskatchewan underground potash mines. The impact of such anomalies upon mining operations is that the grade of the potash ore being sent to the mill drops as mining cuts through anomalous ground, or that a portion of the potash ore reserve is left in the ground as mining operations abandon the anomalous ground as a safety pillar surrounding it. Generally, a combination of surface reflection seismic (2D and 3D), careful examination of surface drill holes, underground ("in-seam") geophysics, and geological observations of mining rooms is sufficient to identify potentially anomalous ground.

An important aspect of estimating the potash potential of the permit is to identify portions of the ground that may contain disturbances that affected the Prairie Evaporite. While drill holes may offer a vertical profile through an anomaly, if such a hole fortuitously penetrated a disturbance, drill holes do not provide

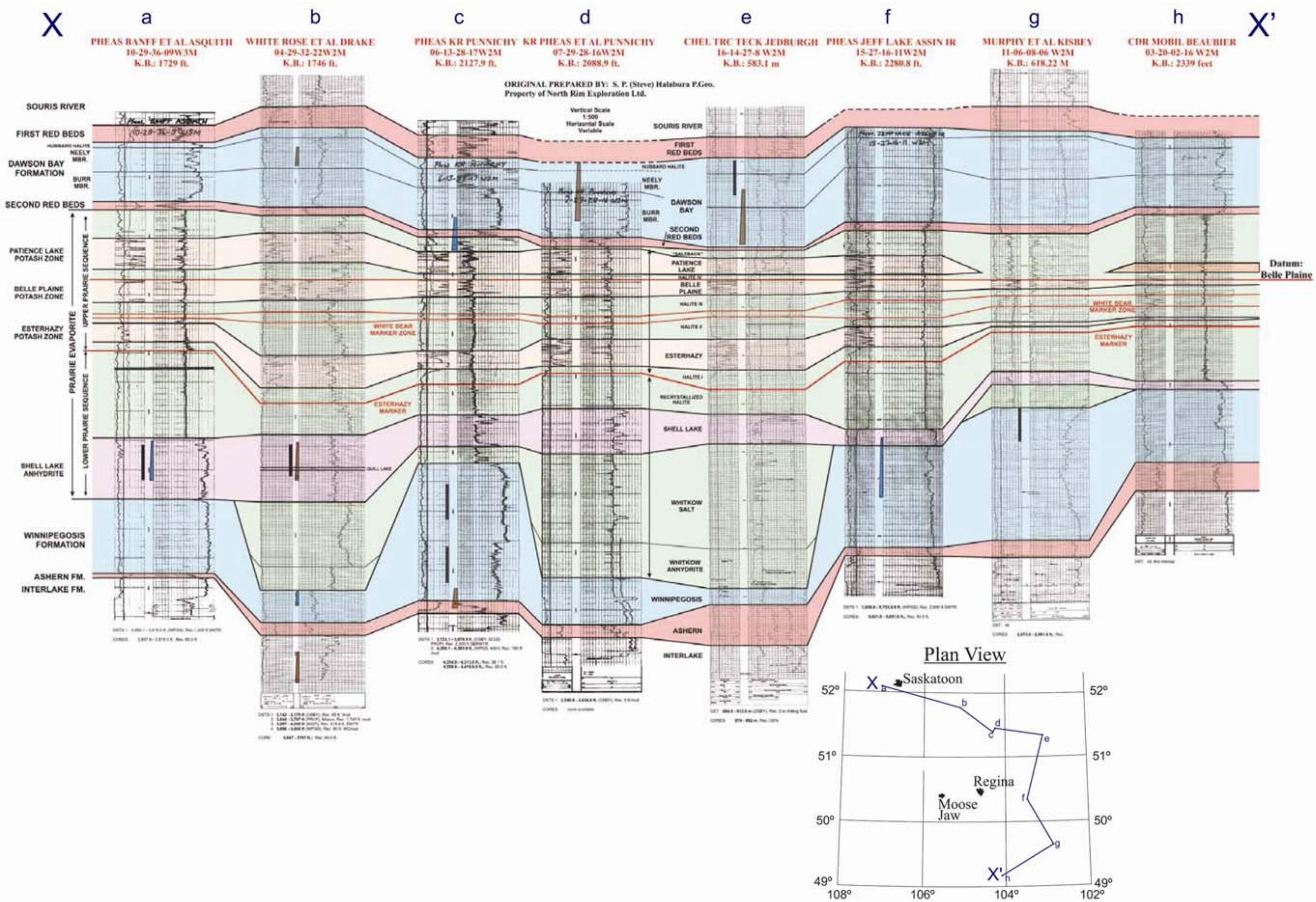

Figure 5: Regional cross section across the Elk Point Basin of Saskatchewan

any information as to the lateral extent of the anomaly. Reflection seismic surveys offer the possibility to map the lateral extent of anomalies related to large-scale alteration of the Prairie Evaporite Formation; for instance, the dissolution of the main mass of Prairie Evaporite with subsequent collapse of the overlying beds into the dissolution cavern; however, they may not necessarily define the lateral extent of more subtle anomalies such as washout or leach anomalies.

Exploration Considerations and Estimation of Solution Mining Potential

Generally, there is a reasonable distribution of drill holes across the potential potash mining belt to allow for the estimation of exploration potential. The drill holes are divided into two groups: (1) those drilled for the purpose of potash exploration with core and assay data and (2) those drilled for the purpose of oil and natural gas exploration with gamma-ray logs to identify the presence of potash.

Operators are required to submit all exploration data to the Government of Saskatchewan and the availability of this historical data is one of the advantages of exploring for potash (or any other commodity, for that matter) in Saskatchewan. This data is held at the Geodata Branch of Saskatchewan Industry and Resources in Regina. Each well record consists of the following data item, where it was available in the original files:

- Spreadsheet showing stratigraphic tops and chemical analysis for core intervals as undertaken by the operator.

- Variable area plot showing depth of assay interval and respective chemical composition for the interval expressed as percentages of K_2O, carnallite, and insolubles.

- Gamma ray-neutron log scanned from original well borehole with stratigraphic tops marked on log.

- Table showing drill hole technical information in metric and Imperial units.

- Copy of potash assay results as found in individual drill hole file.

The key parameters for solution mining evaluation are the following:

- Thickness of Mineralization—As the solution mining method would allow for the selective removal of each of the mineralized members.

- Grade of the Potash Bed—This can control the concentration of the product liquor, the rate of solution mining, and the effectiveness of secondary mining.

- Depth of Burial—As temperature increases with depth, thus, making the solution process more efficient.

- Carnallite Content—As increased amounts of carnallite decrease the efficiency of cavern dissolution and potash recovery.

- Presence of depositional anomalies that reduce the thickness or grade of the potash zones.

- Presence of faults or similar geologic features that displace the potash beds.

- The Dip of the Potash Beds—Excessive dip can limit the size of the caverns and the resource recovery.

The presence of clay layers in the immediate roof as they can lead to premature roof fallout and limit the size of the cavern.

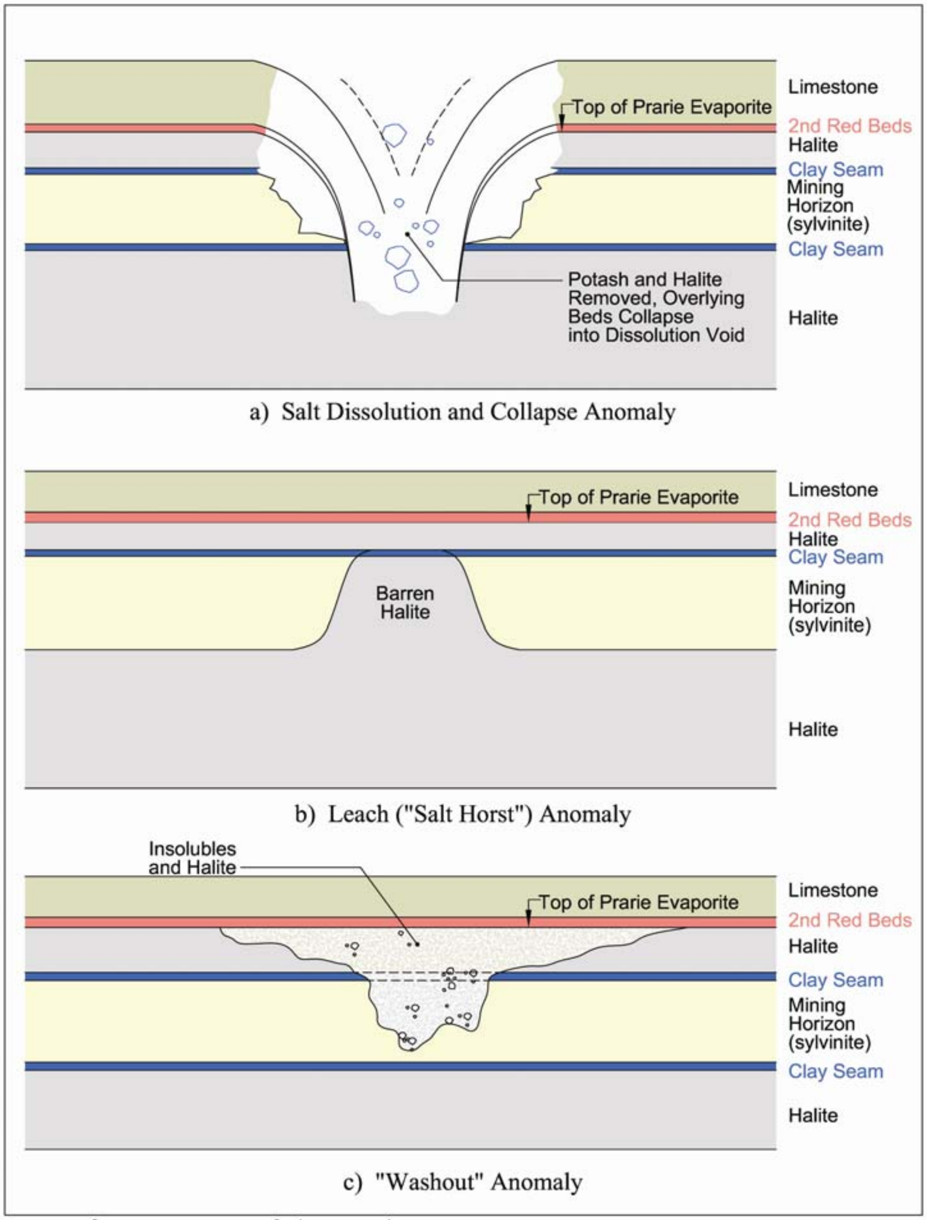

Figure 6: Disturbances Affecting Geology of Potash-bearing Members

In undertaking an exploration project, the first task of the geologist is to estimate the quality and amount of potash contained within the exploration lease or permit. In undertaking such an estimation, the geologist must clearly define the top and base of the potential mining bed. The most practical method of establishing mineral resource boundaries is to place the top of a potential mining bed at the top of the uppermost sylvinite bed of a particular potash member (i.e. Patience Lake, Belle Plaine) and the lower boundary at the base of the lowermost sylvinite bed. For purposes of calculating mineral resource grade and tonnage, the top of the interval is, thus, taken as the top of the uppermost sylvinite bed, while the base is placed at the bottom of the lowermost sylvinite bed with no consideration made for removal of any clay seams in the “roof” or “floor.”

While it is not the intent of the authors to present thickness, grade, and contaminant information for the entire region prospective for solution mining of potash in Saskatchewan, the following table presents a summary of potash mineral resource parameters for the Imperial Findlater and Lumsden Bethune abandoned pilot test projects. Table 1 presents the aggregated average thickness, weighted average of potash grade (expressed as potassium oxide or “% K_2O”) carnallite (as $MgCl_2$ equivalent), and insolubles for each of the two potash-bearing members (Patience Lake and Belle Plaine) using the available assay data for all five holes.

Table 1. Grade and Thickness Parameters for Imperial Findlater and Lumsden Potash Bethune Pilot Project Test Holes

Parameter	Patience Lake	Belle Plaine	Patience Lake to Belle Plaine
Thickness (m)	11.56	6.86	25.83
Grade (% K2O)	21.13	20.06	18.86
% Carnallite (MgCl2)	0.35	0.28	0.30
% Insolubles	10.80	3.64	8.15

Thickness values are arithmetic average; K_2O grade, carnallite, and insolubles are length-weighted averages.

Tables 2 and 3 present the total thickness and the weighted average potash grade, carnallite (as $MgCl_2$ equivalent), and insolubles from the Patience Lake to the Belle Plaine mineralized as calculated from chemical assays of cores at the Imperial Oil Findlater and Lumsden Potash Bethune potash pilot plant sites, respectively. Even though these sites are separated by 8 miles, the characteristics of each bed are similar.

Table 2. Thickness and Weighted Average Grade for Lumsden Potash Bethune Pilot Project Test Holes

Parameter	Patience Lake	Belle Plaine	Patience Lake to Belle Plaine
Lumsden Potash Bethune Pilot Project (2 drill holes)			
Thickness (m)	11.05	5.96	24.25
Grade (% K_2O)	22.16	21.43	17.30
% Carnallite ($MgCl_2$)	0.36	0.25	0.36
% Insolubles	10.20	3.83	7.37

Table 3. Thickness and Weighted Average Grade for Imperial Findlater Pilot Project Test Holes

Imperial Findlater Pilot Project (3 drill holes)			
Thickness (m)	11.91	7.46	26.88
Grade (% K_2O)	20.48	19.33	16.28
% Carnallite ($MgCl_2$)	0.34	0.31	0.26
% Insolubles	11.17	3.53	6.75

Thickness values are arithmetic average; K_2O grade, carnallite, and insolubles are length-weighted averages.

A review of water insolubles as determined from chemical assays of available drill cores for the Imperial and Lumsden Potash sites shows average concentrations that range from a low value of some 2.2% in the Esterhazy Member to 10.2% in the Patience Lake Member. This is consistent to what was determined by Holter (1969) who quoted a range of "less than 4 percent to over 10 percent and increase away from the northern edge toward the southeast…Locally, high amounts are found near the local carnallitic area southwest of the Quill Lakes. Insolubles are more abundant in the Patience Lake Member than in the lower members."

Examination of assays of drill holes from the two sites show that in most cases the concentration of carnallite ($KClMgCl_2.6H_2O$) expressed as $MgCl_2$ is less than 1%. Carnallite can occur in thin veins or seams that appear sporadically within the assays of the members and are responsible for the magnesium occurrences in the chemical assays.

In any exploration program, it is critical to assess the magnesium content in the form of carnallite mineralization. During solution mining, the plant feed liquid will be supplied from multiple wells with each well at a different stage of development; this results in mixing of the feed liquid from individual wells. The plant feed liquor will be dependent on the average grade of potassium, halite and carnallite. For the Imperial and Lumsden Potash sites, the available assay data suggests that a plant feed magnesium content will be less than $1/30^{th}$ of the KCl content. This is lower than the magnesium in the plant feed to the conventionally mined potash operations in Saskatchewan; however, additional core assaying is recommended when dealing with historical data so as to confirm the magnesium assay and to assay portions of the core that has not been previously assayed, particularly the core in the floor of the beds and the core from between potential mining horizons.

Examination of the outer surfaces of drill hole cores from historical exploration programs is important in identifying evidence of dissolution of core that can be attributed the drilling process. Intervals of drill core where the surface of the core is etched and portions of core where the rock is disaggregated may be evidence for dissolution during drilling of the highly soluble mineral carnallite.

Sylvinite-bearing intervals are determined for exploration drill holes by identifying all intervals in which KCl and/or K_2O content exceeds a pre-determined “cut-off” grade. The cut-off grade as proposed by Holter (1969) is 12% K_2O; however, to be conservative, the authors have used a cut-off grade of 15% K_2O. Typically the occurrence of thin “barren” or poorly mineralized sylvinite beds within the larger mineralized interval is common and is to be expected, as will lenses or stringers of high-grade potash separated from higher grade and thicker intervals by barren or low-grade potash. In such cases, a decision must be made to include the low-grade stringer or to exclude it. Review of nearby holes might reveal a trend in the thickness and grade of the low-grade stringer and this might influence the decision to include or exclude it. Including the stringer might reduce the average grade below the target of 20% and, in some instances, this may be acceptable if the stringer increases the overall potash recovery and other holes support the inclusion of the stringer.

Mineral Resource Estimation: Assumptions and Methodology

In determining the potential extent, quality, and volume of potash mineral resource, explorers can be guided by the following principles of exploration techniques and sampling methods commonly employed by other Saskatchewan potash mine operators.

The primary tool employed by Saskatchewan potash operators is drill core as obtained by oil well drilling technology. The extent of potash mineralization and continuity between drill holes (i.e., areal extent of potash beds) is presently determined by subsurface mapping and maps compiled from dated and limited “2D” seismic lines, the limiting factor being either property boundaries or structural disturbances related to dissolution of the Prairie Evaporite and subsequent collapse of overlying beds.

While in the past, information obtained from drill holes and limited “2D” seismic line coverage was deemed sufficient to proceed with mine development, current practice would require that at least the initial development area be evaluated as to mining suitability and development workings location through “3D” seismic investigation.

In Canada, it is recommended that mineral resource estimations follow the principles set forth in National Instrument (NI) 43-101, a document adopted by securities regulators across the country. For exploration purposes, this standard classifies the economic mineralization in terms of Inferred, Indicated, and Measured Mineral Resource. In the vicinity of the cored drill holes, the evidence is sufficient to classify areas as Inferred and Indicated Mineral Resource. No Measured Mineral Resource is identified because no engineering studies have been completed. As an example, the classification of resources as Inferred and Indicated Mineral Resource is as follows:

- Indicated Mineral Resource: Within 1 mile (1.60 km) of a cored and assayed drill hole.
- Inferred Mineral Resource: Within 1 mile (1.60 km) minimum and 5 miles (8.05 km) maximum radius of cored and assayed drill hole.

For estimation of mineral resource at higher levels of confidence, such as the “Indicated” or “Measured” level, the areal extent surrounding a drill hole for which it is reasonable to infer geological conditions (i.e., “area of influence”) is generally 1 to 2 miles (1.6 km to 3.2 km).

For purposes of estimation of mineral resource, it is recommended that the “economic cut-off” for the roof and floor picks be assumed to be where the local potassium oxide content greater than 15% K_2O and where the average grade in the potash mining zone is greater than 20%. Selected potash mining zones should also have insolubles less than 15% and $MgCl_2$ content less than 0.5% average in the potash mine zone. The proposed mining interval will contain interbeds that are less than 15% K_2O, but given the mining method of using successive cavern dissolution “cuts,” it may not be possible to selectively mine only beds that are of economic quality.

In calculating the mineral resource tonnages, the following procedures are recommended:

1. The total interval volume (mineral interval) for each area is calculated by multiplying the net area by the thickness of the potential solution mine interval for each of the mining cuts.

2. The volume thus calculated is then multiplied by a sylvinite tonnage factor of 1,980 kilograms per cubic meter to determine “gross sylvinite tonnage.”

3. A deduction of the area is then made to account for the presence of mining anomalies not detected by existing drill holes and seismic lines, this amount ranging from 25% to 35% depending upon the area and whether anomalies can be identified from existing historical data.

4. A deduction of “extraction ratio” is then made to account for the mineral resource that is left in the ground to provide support and reduce surface subsidence, this being in the form of pillars left around exploration drill holes and potash production caverns, in this paper proposed as being an extraction ratio of 40% for solution mining operations (i.e., 40% of the sylvinite is removed and 60% is left in place to support the mine).

5. An additional deduction of 10% is then applied to account for possible plant and cavern losses, including losses to purge and dust. The cavern losses are the potash remaining in the brine in the cavern.

After the above deductions an estimate of potash tonnage per “section” (square mile) may be made.

As an example, the following is a simple calculation of resource per square mile. Using a simple calculation of area (1 ‘section” is 640 acres or 1 square mile = 2.59 square kilometers) times average thickness (in this example an estimated 26 m) for the Patience Lake and Belle Plaine members times sylvinite density (1.98 tons per cubic meter) times the K_2O grade (in this example an estimated 19%) less the 25% allowance for unidentified anomalies gives an estimated tonnage contained within the bounds of one section as being some 19 million tonnes of sylvinite. Using a weighted average grade for the two members of 17% K_2O, a potential yield of potash expressed in terms of K_2O is some 6.75 million tonnes per section (i.e., per 640 acre tract). This is equivalent to some 2.5 million tonnes per square kilometer. This number, which is based on estimated averages, will vary locally and from area to another.

Possible Solution Mining Scenarios for Prairie Evaporite Formation

In estimating the Mineral Resource for the potash-bearing members, no mining case was considered other than the removal, by dissolution, of the “potential solution mine interval” of each of the Patience Lake and Belle Plaine members. An attempt has been made to determine the specific solution mining intervals (i.e., the “top” and “base” of possible mining cuts). Further, geological characterization and engineering design is required to confirm these parameters, and until such work is undertaken, it will not be possible to determine measured resource and reserves.

At this point, for the estimation of Mineral Resource for the potash-bearing members, it is assumed that a solution mining method that would be able to substantially remove the entire mineral resource interval and any clay seams as required by rock mechanical considerations is reasonable and within the scope of current technology. Application of a specific solution mining method would depend upon the size and the stability of the cavern thus formed.

Generally there are two types of solution mining. In “live” or primary mining, water is circulated so as to dissolve all the evaporite including halite and sylvite, while secondary of “selective” mining, halite rich brine is injected and is retained within the cavern and allowed to selectively dissolve the sylvite, leaving the halite behind within the cavern. Because solution mining starts at the base of selected potash intervals, it is more correct to describe a potential mining interval as extending “from the base of the mineralized zone to the top.” The Indicated or Inferred resource estimate can be based on either solution mining only the two individual “potential” solution mine intervals associated with the Patience Lake Member and the Belle Plaine Member, or mining from the bottom of the Belle Plaine “potential” solution mine interval to the top of the “potential” solution mine interval for the Patience Lake Member.

Regionally the potential mining zone in the Patience Lake Member is the thickest and of highest grade followed by the potential mining zone in the Belle Plaine Member. The potential mining zone in the Esterhazy Member is generally thin, of lower potash grade, and separated from the bottom of the Belle Plaine Member by some 17 to 21 m of halite and clays.

Project Risk

Exploration programs seeking solution mining opportunities in Saskatchewan face three risks to successful execution of a mine development plan. These are continuity, quality, and processing risk.

- Continuity Risk: This risk is uncertain concerning the continuity of potash mineralization over a selected permit area. It can be mitigated by means of reinterpretation of existing “2D” seismic trade lines and the acquisition of new 2D reconnaissance seismic lines so as to confirm the general continuity of potash mineralization.

- Quality Risk: This risk is uncertainty concerning the quality of potash mineralization in a selected permit area. This risk can be mitigated with the drilling of additional confirmatory surface drill holes.

- Processing Risk: There may be uncertainty concerning the energy required to economically recover potash from a solution mining operation. This risk can be mitigated by the preparation of a conceptual mining study aimed at identifying a basic mining process and flow process and which incorporates various scenarios as to energy input and management.

Conclusions

Potash mineralization, in the form of sylvite-bearing sylvinite rock, is present underlying substantially all of southern Saskatchewan, except in regions where drilling and seismic anomalies suggest the dissolution and removal of the Prairie Evaporite sequence. The potash-bearing sylvinite rock is mineralogically simple and consists of a mechanical mixture of sylvite (KCl), halite (NaCl), with minor amounts of carnallite ($MgCl_2 \times 6H_2O$) and insolubles such as clay, dolomite, and anhydrite.

The beds of the Middle Devonian Prairie Evaporite Formation considered to have economic potential for the solution mining of potash are, in descending order, the Patience Lake Member and the Belle Plaine Member. The Esterhazy Member has potential for solution mining pending further resource definition and conceptual mine planning. It is the authors’ opinion, based upon their limited review of the geology of these potash members, that the potential for potash solution mining exploration projects in Saskatchewan is very good.

Presently, potash mining and development companies are making great efforts in identifying potential conventional mining properties along the northern edge of the Prairie Evaporite formation; however, there is little exploration at present along the southern margin (i.e., that portion of the Prairie Evaporite favorable to solution mining. Possible reasons for this include:

- Uncertainty as to geological composition (i.e., carnallite content and distribution).

- Concerns over processing and operating costs, specifically those requiring the input of energy in the form of natural gas.

- Design uncertainty as to possible solution technology, including process plant manufacture and design.

- The classic question, “If it works so great, why is Belle Plaine the only operating solution mine in Canada?”

In response to the above, it is difficult to use the experiences of the previous round of solution mining exploration and pilot tests as these efforts used the technology and economics of the 1960s; for instance, a failed pilot test that attempted to connect caverns using hydrofracing technology will be a failure today; however, would the test work if a new cavern construction and design methodology was used, or if horizontal wells as opposed to vertical wells were used?

In conclusion, it is the authors’ opinion that re-evaluation of the solution mining potential of southern Saskatchewan is worthwhile especially in light of the development of new technology, high global prices, and the availability of investment capital.

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References

Danyluk, T.K., G.D. Phillips, A.F. Prugger, and M.S. Pesowski (1999), “Geophysical Analysis of an Unusual Collapse Structure at PCS Potash, Lanigan Division” *Mining: Catalyst for Social and Economic Growth*, 101st Annual General Meeting of CIM, May 2–5.

Fuzesy, A. (1982), “Potash in Saskatchewan,” Saskatchewewan Industry and Resources Report 181, 44 p.

Hardy, M.P. and S.P. Halabura (2007), “Technical Report Concerning Subsurface Mineral Permit KP 289, Findlater Area, Saskatchewan,” unpublished report prepared for ISX Resources, Ltd., 107 p.

Holter, M.E. (1969), *The Middle Devonian Prairie Evaporite of Saskatchewan*, Saskatchewan Department of Mineral Resources, Report No. 123, Figure 4 “Middle Devonian Evaporite Cycles and Prairie Evaporite Formation Nomenclature.”

Mackintosh, A.D. and G.A. McVittie (1983), “Geological anomalies observed at the Cominco Ltd. Saskatchewan potash mine” in “Potash 83: Potash Technology – Mining, Processing, Maintenance, Transportation, Occupational Health and Safety, Environment” edited by R.M. McKercher, Pergamon Press, Toronto, pp. 59–64.