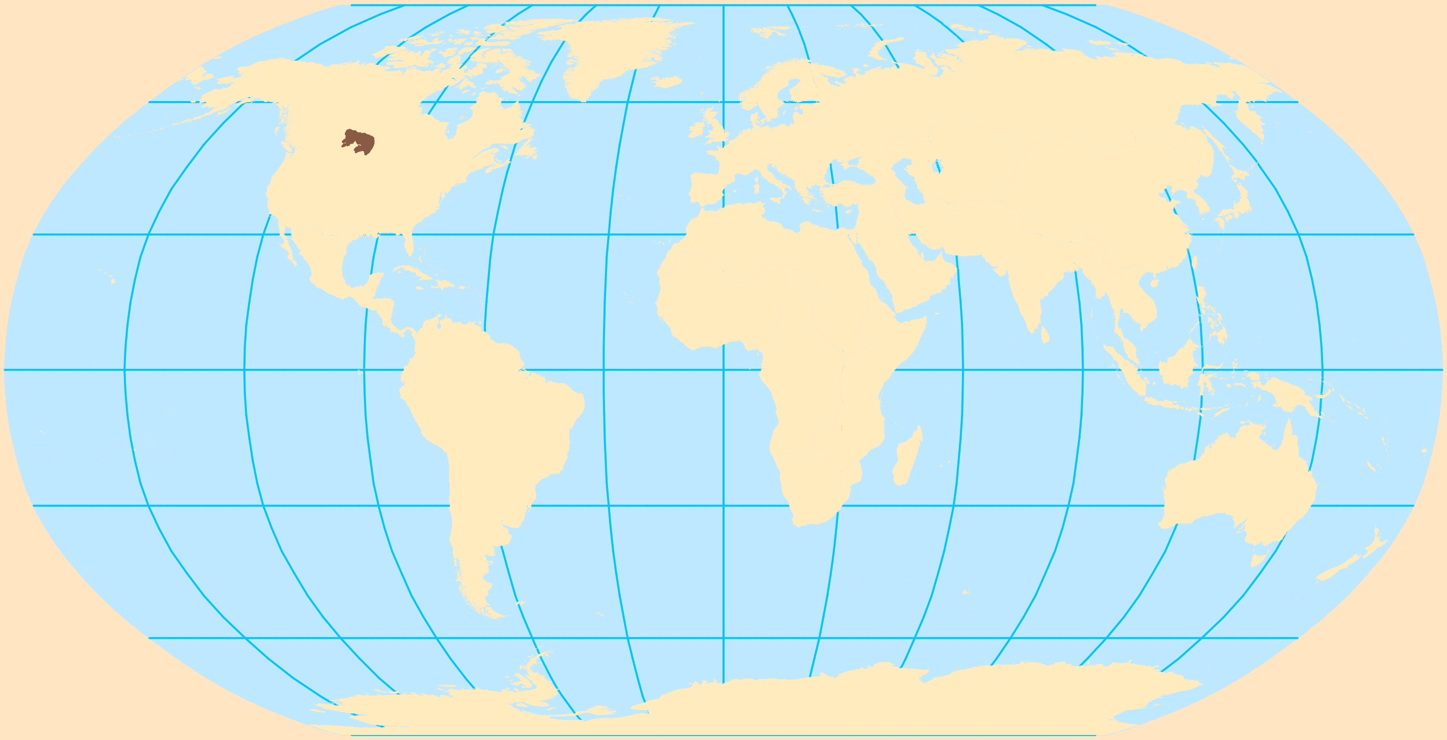
Global Mineral Resource Assessment

# Geology and Undiscovered Resource Assessment of the Potash-Bearing, Middle Devonian (Givetian), Prairie Evaporite, Elk Point Basin, Canada and United States



Scientific Investigations Report 2010–5090–CC

**U.S. Department of the Interior**
**U.S. Geological Survey**

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Michael L. Zientek, Jane M. Hammarstrom, and Kathleen M. Johnson, editors

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By Mark D. Cocker, Greta J. Orris, Pamela Dunlap, Chao Yang, and James D. Bliss

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# Acronyms and Abbreviations

| | |
|---|---|
| 3D | three-dimensional |
| AGE | adaptive geometric estimation |
| APD | Area of Potash Dispositions |
| Bt | billion metric tons |
| CAD | Canadian dollar |
| FGDB | file geodatabase |
| GIS | geographic information system |
| KL | surface leases |
| KP | potash permits |
| Ma | mega-annum |
| MAIM | metal and industrial mineral |
| MOP | muriate of potash |
| Mt | million metric tons |
| NI | Canadian Securities Administrators National Instrument |
| PGE | platinum group elements |
| ppm | parts per million |
| SGS | Saskatchewan Geological Survey |
| SOP | sulfate of potash |
| SRC | Saskatchewan Research Council |
| t | metric ton (ton) |
| Tt | trillion metric tons |
| USD | U.S. dollar |
| USGS | U.S. Geological Survey |

# Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| yard (yd) | 0.9144 | meter (m) |
| | **Area** | |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | **Volume** | |
| cubic mile ($mi^3$) | 4.168 | cubic kilometer ($km^3$) |
| | **Mass** | |
| ton, short (2,000 lb) | 0.9072 | metric ton (t) |
| ton, long (2,240 lb) | 1.016 | metric ton (t) |
| | **Density** | |
| pound per cubic foot ($lb/ft^3$) | 0.01602 | gram per cubic centimeter ($g/cm^3$) |

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| centimeter (cm) | 0.3937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| meter (m) | 1.094 | yard (yd) |
| | **Area** | |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |
| | **Volume** | |
| cubic kilometer ($km^3$) | 0.2399 | cubic mile ($mi^3$) |
| | **Mass** | |
| metric ton (t) | 1.102 | ton, short [2,000 lb] |
| metric ton (t) | 0.9842 | ton, long [2,240 lb] |
| | **Density** | |
| gram per cubic centimeter ($g/cm^3$) | 62.4220 | pound per cubic foot ($lb/ft^3$) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

# Geology and Undiscovered Resource Assessment of the Potash-bearing, Middle Devonian (Givetian), Prairie Evaporite, Elk Point Basin, Canada and United States

By Mark D. Cocker,[1] Greta J. Orris,[1] Pamela Dunlap,[2] Chao Yang,[3] and James D. Bliss[2]

## Abstract

The U.S. Geological Survey (USGS) assessed undiscovered potash resources in the Elk Point Basin in Canada and the United States as part of a global mineral resource assessment. The Elk Point Basin is a large, Middle Devonian (Givetian) intracratonic evaporite basin covering approximately 1,200,000 square kilometers (km$^2$) and filled mainly with marine evaporite and minor clastic sedimentary rocks that contain stratabound potash-bearing salt. The potash-bearing salt is concentrated in four stratigraphic members (Patience Lake, Belle Plaine, White Bear, and Esterhazy) in the upper 100 meters (m) of the Prairie Evaporite and are separated by beds of halite (NaCl) that contain lesser—presently non-economic—amounts of sylvite (KCl) and carnallite ($KMgCl_3 \cdot 6H_2O$). The principal ore-bearing salt contains mainly sylvite. Four permissive tracts were defined that permit the presence of undiscovered stratabound potash (both sylvite- and carnallite-bearing salt) using geological criteria.

Permissive tracts are defined by the spatial extent of each stratigraphic member that is at least 1 m thick, are less than 3 kilometers (km) from the surface, contain at least 4 percent equivalent potassium oxide ($K_2O$), and contain the currently known resources. The permissive tracts include known potash deposits and potash occurrences as wells or mines not in production and show where undiscovered potash resources may be present. Well data are used to define the extent, thickness, average $K_2O$ equivalent grades, and volumes of each member. Data were supplied by the Saskatchewan Geological Survey or were obtained from published National Instrument (NI) 43-101 technical reports and other published reports, such as annual 10-K reports or news releases.

The Elk Point Basin is the world's largest source of potash, producing 23.0 million metric tons (Mt) of potassium chloride (KCl) (the equivalent of about 14.4 Mt of $K_2O$) in 2018. In terms of global importance, the Elk Point Basin may contain 40 to greater than 50 percent of the world's potash resources. Since 1962, potash companies have mined more than 1.5 trillion metric tons of ore containing 605 Mt of KCl (the equivalent of about 380 Mt of $K_2O$). The total value of the ore produced through 2018 is on the order of $70 trillion (CAD). Potash is currently produced from eight conventional and three underground solution mines at depths ranging from 900 m to nearly 1,800 m. Estimates of the amount of potash in the Elk Point Basin vary considerably and the data and methods used in those estimations are not well documented. Known potash resources are approximately 99 billion metric tons (Bt) of ore containing 22 Bt of $K_2O$ equivalent.

As a result of new mine openings and increased production capacity at existing mines, the total production capacity of mines in the Elk Point Basin has increased significantly (to about 32.8 Mt of KCl or 22.8 Mt of $K_2O$ equivalent per year). Additional production capacity of about 31 Mt of KCl (or 17 Mt of $K_2O$ equivalent) per year could be realized over the next decade if several current (as of 2019) exploration and development projects reach production status.

Stratabound potash-bearing salt of the Prairie Evaporite presently underlies a total area of about 188,000 km$^2$ and has a total volume of about 2,690 cubic kilometers (km$^3$). Post-depositional solution processes considerably modified the mineralogy and presence of the potash-bearing salt. These changes had a profound effect on the volume and grade of potash resources that remained in the Prairie Evaporite and are a major consideration of exploration and mining operations as well as in this assessment of undiscovered potash resources.

This USGS assessment includes the locations and possible amounts of undiscovered potash resources in the Prairie Evaporite. Volumes for each stratigraphic member were computed using member thicknesses and areal extent modified by actual, estimated geologic loss owing to salt dissolution and extraction ratios, as well as estimated distribution of carnallite and sylvite. Both sylvite- and carnallite-bearing salts were assessed for potash in this study. The assessment uses modern published grade and tonnage data. The amount of undiscovered potash is estimated by using Monte Carlo simulations to combine volume estimates of the potash-bearing members with probability distributions for average grade and bulk density.

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[2] U.S. Geological Survey, retired.

[3] Saskatchewan Geological Survey, Canada.

Mean potash grades (expressed as percentage of $K_2O$ equivalent) calculated using drill core analyses are 17.76 for the Patience Lake Member, 15.98 for the Belle Plaine Member, 10.66 for the White Bear Member, and 15.30 for the Esterhazy Member. Geologic losses reported as extraction ratios during mining may range from 27.5 to 41.6 percent and are dependent on mining method and local geologic conditions. The assessment determined that mean estimated undiscovered $K_2O$ equivalent resources for the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members are 340, 220, 34, and 190 Bt, respectively, and estimated a total mean of 790 Bt for the entire Prairie Evaporite above a depth of 3 km. The total mineralized rock tonnage is estimated to be about 5,000 Bt. Most of the assessed potash is located within Saskatchewan with lesser amounts in Alberta and Manitoba as well as Montana and North Dakota within the United States.

Although carnallite is mined for potash in Europe, it has historically been avoided in mining plans for potash-producing companies in Saskatchewan because of mining, processing, and grade considerations. Carnallite-rich salt is locally present in concentrations and volumes that could be a significant resource of magnesium chloride ($MgCl_2$) obtained as a byproduct of processing the carnallite for potash. Previously estimated reserves (not NI 43-101 compliant) of mineralized material from 1955 to 2019 are 695 Mt at 22.1 percent $MgCl_2$. The total amount of $K_2O$ equivalent as carnallite was estimated during this USGS assessment to be about 120 Bt (or 180 Bt KCl). With uncertainties in defining the areal extent of carnallite in each of the potash-bearing members, the amount of $MgCl_2$ as carnallite in the Elk Point Basin could be approximately 180 Bt.

# Introduction

The following sections explain what potash is, how it occurs, and its growing global importance. Included is a brief introduction to the potash deposits that occur within the Elk Point Basin, when and how they were developed, and previous estimates of the amount of potash contained in the basin. This assessment is part of the U.S. Geological Survey (USGS) assessment of undiscovered global copper, platinum group minerals, and potash resources (Schulz and Briskey, 2003; Orris and others, 2014).

## Potash

The term potash refers to a variety of mined and manufactured salts (see table A1 of appendix A), all of which contain the element potassium in water-soluble form (Jasinski, 2020). Potassium is an essential nutrient (with no known substitutes) for plants, animals, and humans; 90–95 percent of potash is used for fertilizer (Prud’homme and Krukowski, 2006). Potash is a non-renewable resource, and the primary sources of potash are evaporites, which occur mainly in marine salt basins and a few brine-bearing continental basins (Orris and others, 2014; Yager, 2016). Industry uses the term potash to refer to potassium chloride as well as to potassium sulfate, nitrate, and oxide (Neuendorf and others, 2005). The principal products of potash mining are potassium chloride (KCl), which is referred to as muriate of potash (MOP), and potassium sulfate ($K_2SO_4$), which is referred to as sulfate of potash (SOP). Various MOP and SOP fertilizer specific products are classified by particle size and percent of potassium oxide ($K_2O$; Prud’homme and Krukowski, 2006). A byproduct of potash solution mining is a clean salt brine used to produce salt (Prud’homme and Krukowski, 2006).

## Types of Potash Deposits

Potash-bearing salt deposits are accumulations of potassium chloride and potassium sulfate evaporite minerals intimately associated with halite (NaCl) and related basin-wide evaporites (appendix A). Most potash-bearing salt deposits form by evaporation of large volumes of seawater in hydrographically restricted or isolated basins under hyperarid conditions (Kendall, 2010; Orris and others, 2014; Warren, 2016). Hyperarid climatic conditions promote high evaporation and salt precipitation rates, resulting in hypersaline conditions and eventual deposition of water-soluble potassium (K) and magnesium (Mg) minerals. Stratabound potash-bearing salt deposits are characterized by relatively flat-lying, undeformed, potash-enriched beds that range from 1 centimeter (cm) to approximately 10 meters (m) thick and that can extend for tens to hundreds of kilometers within a basin (Orris and others, 2014; Cocker and others, 2017).

## Global Demand for Potash, Global Resources, and Production

During the past several decades, the global requirement for fertilizers has grown considerably because of the necessity to increase the quantity and quality of food production grown on decreasing amounts of available arable land (Brown, 2011; Cocker and others, 2016). As there is no known substitute for potash in fertilizer, price increases in fertilizer are passed on via increased food prices (Kowalewski and Śpiewanowski, 2017). Global changes in fertilizer prices and potash companies’ long-term planning have influenced exploration and development in potash. As late as May 2004, potash prices were as low as $122 per metric ton, but increased dramatically to a high of $822 per metric ton in February of 2008 (Index Mundi, 2020). Although prices have decreased to approximately $250 per metric ton (Stedman and Green, 2017), some see the potash industry, particularly in Saskatchewan, as robust.

## Potash Deposits in Elk Point Basin

The Middle Devonian (Givetian) Elk Point Basin in Canada and the United States (figs. 1, 2, 3) contains one of the world’s largest stratabound potash deposits and supplies a major part of the world’s potash. The stratabound potash

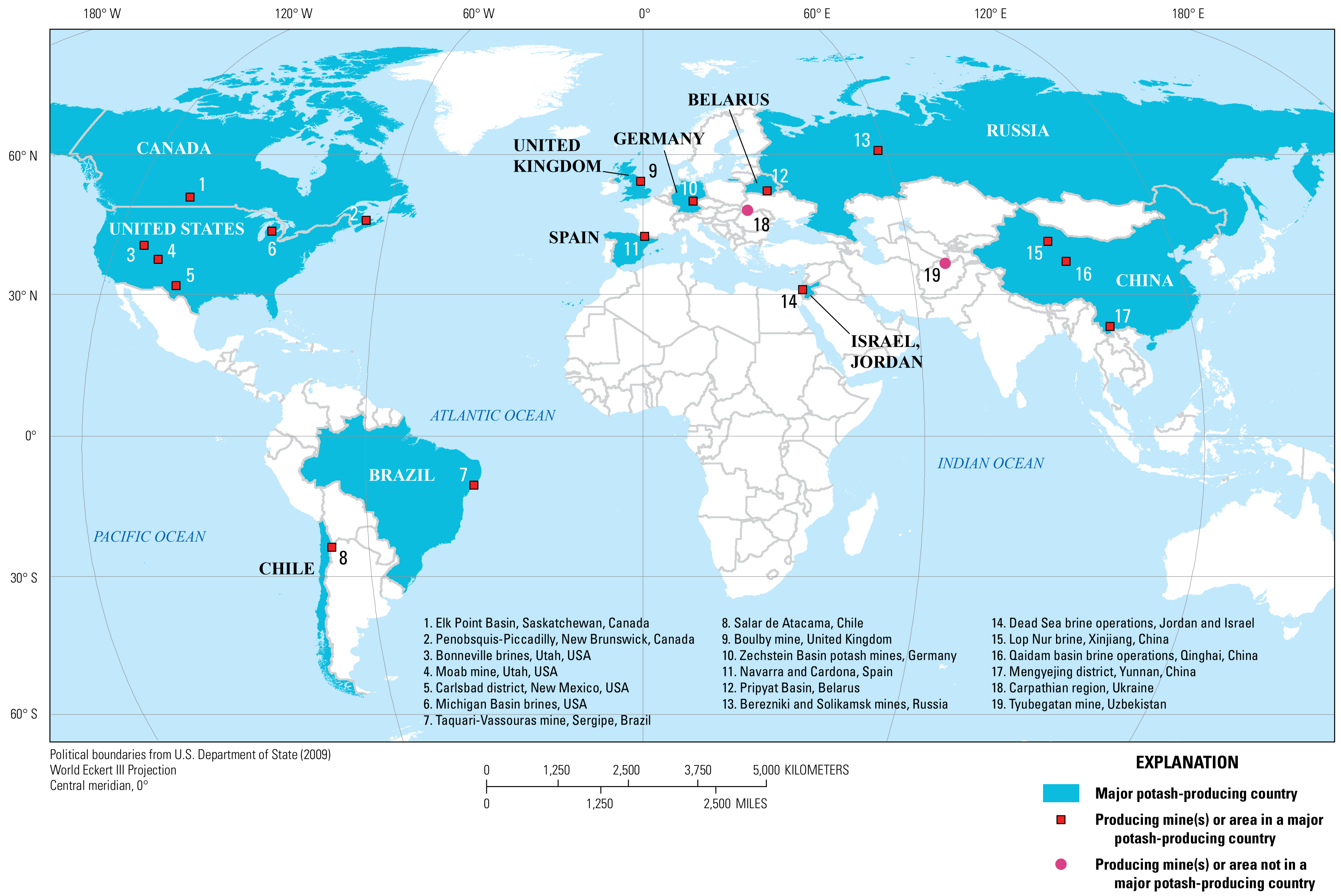
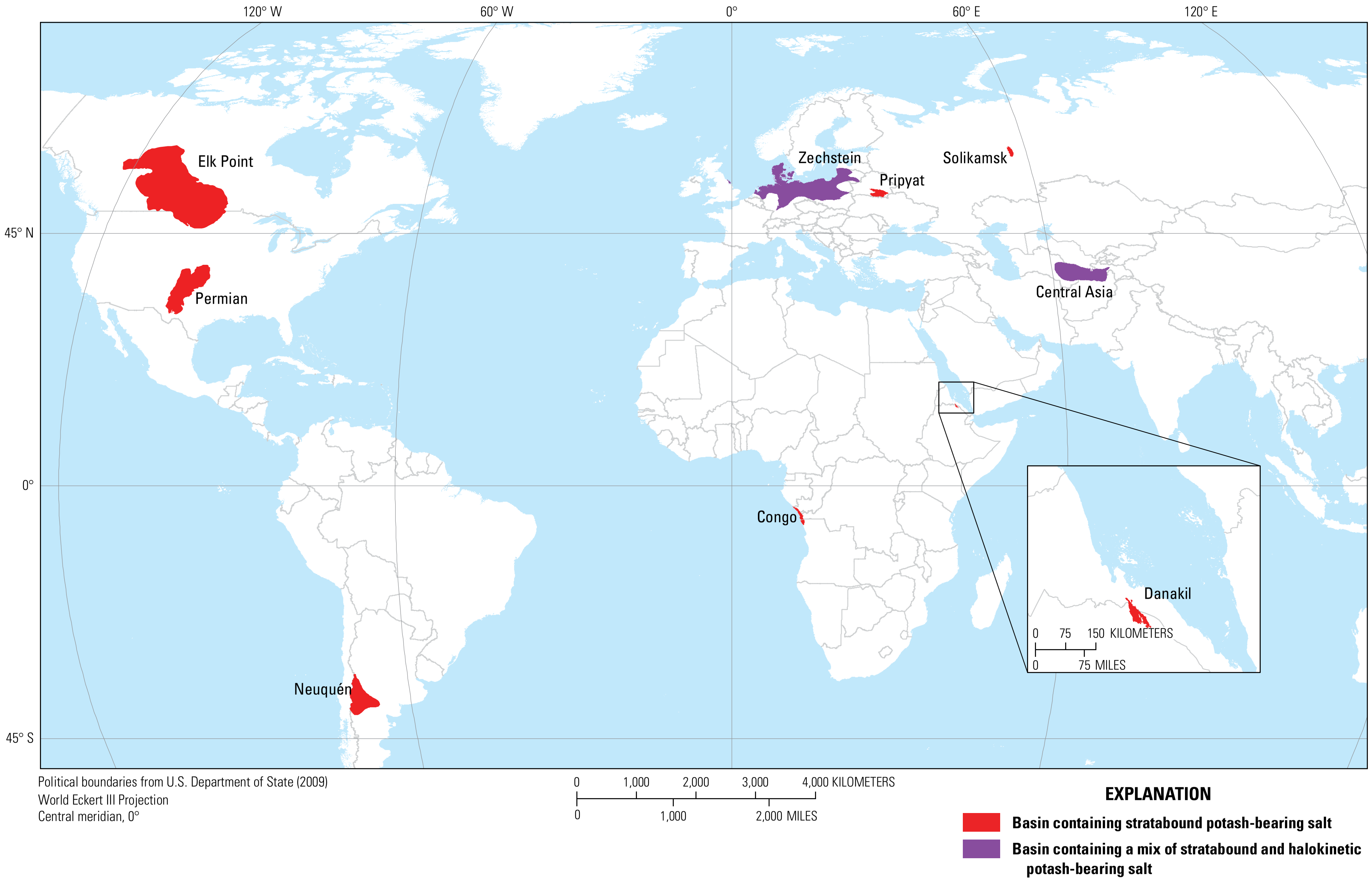


**Figure 1.** Map showing the important potash-producing countries and mines. Modified from Orris and others (2014).



Political boundaries from U.S. Department of State (2009)
World Eckert III Projection
Central meridian, 0°

**Figure 2.** Map showing the location of Elk Point Basin and additional stratabound potash-bearing salt basins. Modified from Orris and others (2014).

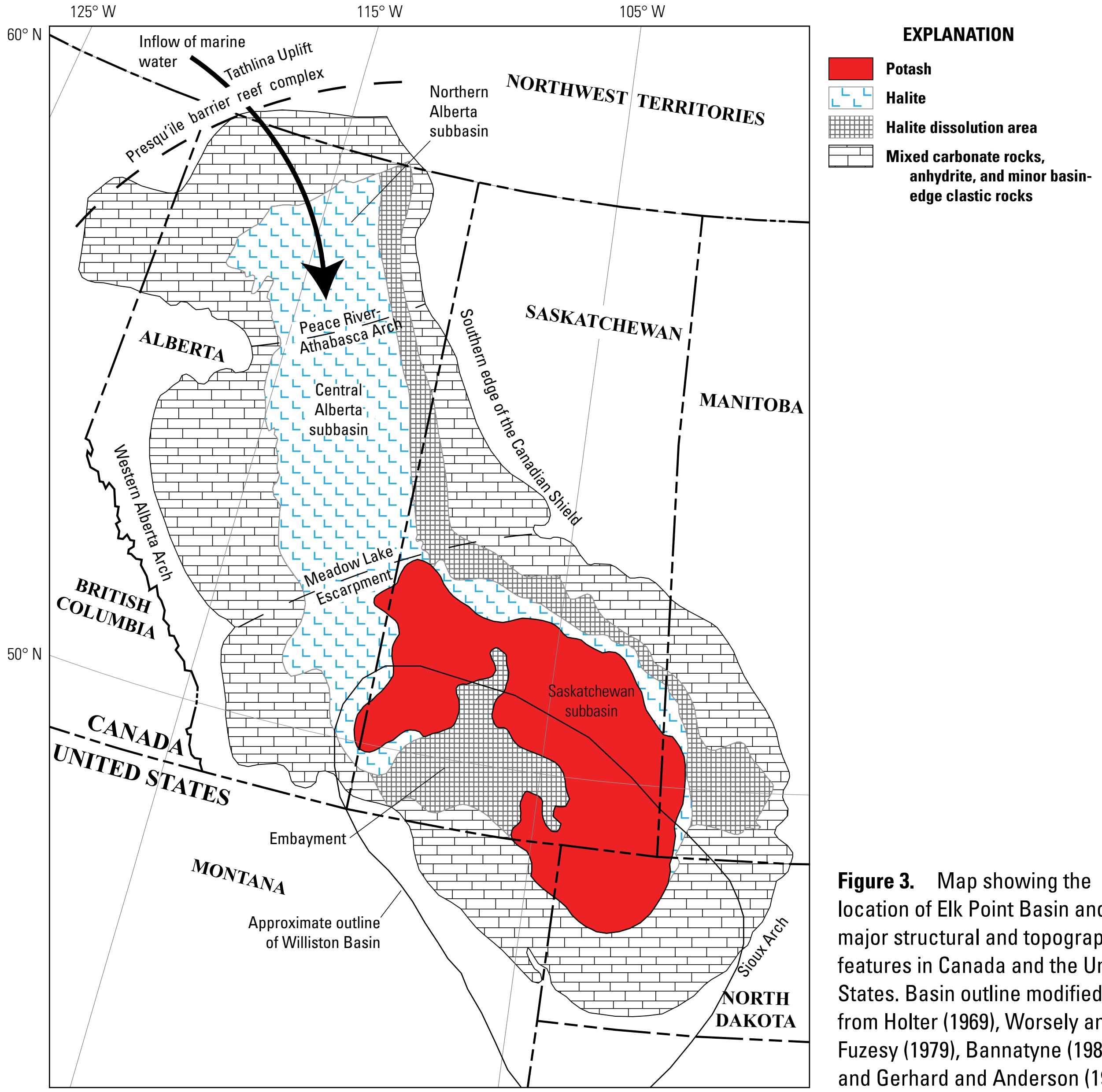


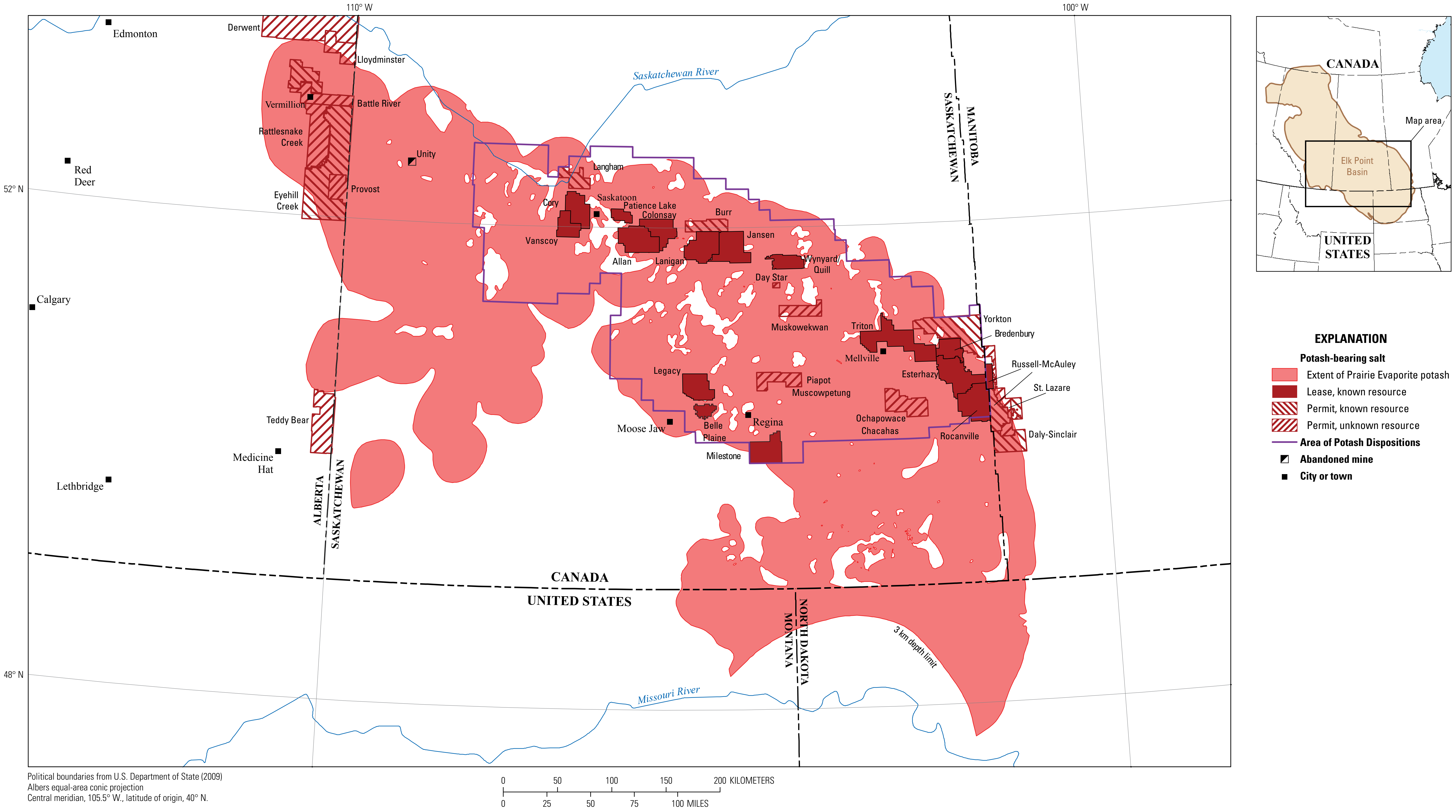
**Figure 3.** Map showing the location of Elk Point Basin and major structural and topographic features in Canada and the United States. Basin outline modified from Holter (1969), Worsely and Fuzesy (1979), Bannatyne (1983), and Gerhard and Anderson (1988).

deposits in Elk Point Basin are composed dominantly of sylvite (KCl) and localized concentrations of carnallite ($KMgCl_3 \cdot 6H_2O$) in the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members of the Prairie Evaporite (Holter, 1969; Boys, 1990; Yang and others, 2009b).

## Historical and Evolving Importance of Potash Mining in the Elk Point Basin

Potash was discovered in the Elk Point Basin in 1942 (Fuzesy, 1982). Since then, the potash industry has experienced periods of rapid growth and development alternating with periods of relative inactivity. The initial exploration activity was followed by the development of 10 underground mines between 1962 and 1970 (fig. 4). Recently, global and regional factors—as well as technological advancements in solution mining—reinvigorated potash exploration and mining activity. At least 130 companies have been involved in potash development from 1942 to 2020 (table 1). The list of companies in table 1 was compiled from a variety of sources, including drill hole records, periodically published potash disposition maps, and disposition databases maintained by the Saskatchewan Ministry of Energy and Resources.

The Elk Point Basin has been estimated to contain 46–75 percent of the world's known potash reserves (Barry, 1989; Natural Resources Canada, 2015; Vining and Moore, 2017). World potash resources were estimated to total about 250 billion metric tons (Bt) of $K_2O$ equivalent (Jasinski, 2020).



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 4.** Map showing the area underlain by stratabound, potash-bearing salt of the Middle Devonian Prairie Evaporite in Canada and the United States with active potash lease and permit areas as of 2017 (note that many of the permit areas are not shown in this figure for clarity). Underground potash permits and leases plus Freeholds, First American lands, and restricted Crown lands cover the entire Area of Potash Dispositions in Saskatchewan (Slimmon, 2009). km, kilometer.

**Table 1.** List of companies (including individuals) that have engaged in potash-related exploration or production since or during the period from 1942 to 2018.

[This list may include companies' exploration for oil and gas with reported potash results and may not be inclusive. Names may not be the complete, formal company name, but are as shown in the references cited herein. Company names may have changed over time. Co, Company; Corp., Corporation; Inc., Incorporated; Ltd., Limited]

| Count | Company |
|---|---|
| | Companies with potash land rights in Saskatchewan, as of 1966 (British Sulphur Corp., Ltd., 1966, 1984; Rauche and others, 2016) |
| 1 | Alwinsal Potash of Canada, Ltd. |
| 2 | Atlantic Refining Co. |
| 3 | Apollo Minerals |
| 4 | Banff Oil, Ltd., and Aquitaine Company of Canada, Ltd. |
| 5 | Bison Petroleum & Minerals, Ltd. |
| 6 | Brinco Holdings, Ltd. |
| 7 | British American Oil Company, Ltd. |
| 8 | Canberra Oil Company, Ltd. |
| 9 | Central-Del Rio Oils, Ltd. |
| 10 | Central Farmers Fertilizer Co. of Chicago |
| 11 | Columbian Oil, Ltd. |
| 12 | Cominco, Ltd. |
| 13 | Consolidated Morrison |
| 14 | Continental Minerals, Inc. |
| 15 | Continental Potash Corp., Ltd, |
| 16 | Dafoe Minerals, Ltd. |
| 17 | Domtar Chemicals, Ltd., Sifto Salt Division |
| 18 | Duval Corp. |
| 19 | John B. Goetz |
| 20 | Great Canadian Potash Corp., Ltd. |
| 21 | John D. Ground |
| 22 | Houston Oils, Ltd. |
| 23 | Imperial Oil, Ltd. |
| 24 | International Minerals & Chemical Corp. (Canada), Ltd. |
| 25 | William James |
| 26 | William C. Lagos |
| 27 | Kerr-McGee Oil Industries, Inc. |
| 28 | Kalium Chemical, Ltd. |
| 29 | King Resources Co. |
| 30 | Marlea Exploration Co., Ltd. |
| 31 | Mill City Petroleums, Ltd. |
| 32 | Mule Creek Oil Co., Inc. |
| 33 | National Potash Co. |
| 34 | Noranda Mines, Ltd. |
| 35 | Murray Pezim |
| 36 | Placid Oil Co. |
| 37 | Potash Company of America |
| 38 | Prairie Potash Mines, Ltd. |
| 39 | Scurry Rainbow Oi1, Ltd. |
| 40 | Shell Canada, Ltd. |
| | Companies with potash land rights in Saskatchewan, as of 1966 (British Sulphur Corp., Ltd., 1966, 1984; Rauche and others, 2016)—Continued |
| 41 | Socony Mobil Oil of Canada, Ltd. |
| 42 | Sohio Petroleum Co. |
| 43 | Southwest Potash Corp. |
| 44 | Sylvite of Canada, Ltd. |
| 45 | Tidewater Oil Co. |
| 46 | Tombill Mines, Ltd. |
| 47 | United States Borax & Chemical Corp. |
| 48 | Winnipeg Western Land Corp., Ltd. |
| | Companies drilling in Saskatchewan and Manitoba prior to or during 1965 (may not be inclusive) |
| 1 | Borax Consolidated |
| 2 | Campana |
| 3 | Canadian Exploration, Ltd. (Canex) |
| 4 | Canberra |
| 5 | Dominion Potash/Dominion Energy |
| 6 | Freeport Sulphur (National Potash Co.) |
| 7 | General Petroleum Saskatoon |
| 8 | Great Canadian |
| 9 | Honolulu |
| 10 | Imperial Oil, Ltd. |
| 11 | Kenneco |
| 12 | Madsen |
| 13 | Manitoba Western Potash |
| 14 | Mobil |
| 15 | Placid |
| 16 | Porcupine Prime |
| 17 | Scurry |
| 18 | Shell |
| 19 | St. Mary |
| 20 | Superior |
| 21 | Texas Gulf |
| 22 | Tide Water Flint |
| 23 | United Comstock |
| 24 | United States Potash |
| | Companies noted to be mining in Saskatchewan presently or recently, as of 1982 (Fuzesy, 1982) |
| 1 | Amax Potash, Ltd. |
| 2 | Central Canada Potash |
| 3 | Cominco, Ltd. |
| 4 | Duval Corp. |

**Table 1.** List of companies (including individuals) that have engaged in potash-related exploration or production since or during the period from 1942 to 2018.—Continued

| Count | Company |
|---|---|
| | Companies noted to be mining in Saskatchewan presently or recently, as of 1982 (Fuzesy, 1982)—Continued |
| 5 | Hudson Bay Mining and Smelting Co., Ltd., Sylvite of Canada Division |
| 6 | International Minerals & Chemical Corp. (Canada), Ltd. |
| 7 | Kalium Chemicals, Ltd., Division of PPG Industries Canada |
| 8 | Noranda Metal Industries, Ltd., Central Canada Potash Division |
| 9 | Potash Company of America |
| 10 | Potash Corporation of Saskatchewan Mining, Ltd. |
| 11 | Texasgulf Potash |
| | Companies with potash land rights in Alberta, Manitoba, North Dakota, and Saskatchewan from 2008 to 2018 (Mackintosh, 2006; Berenyi and others, 2008; Bout and Chiang, 2008; Saskatchewan Ministry of Energy and Resources, 2011b) |
| 1 | Agrium (now Nutrien) |
| 2 | Anglo Minerals, Ltd. |
| 3 | Athabasca Potash, Inc. |
| 4 | BHP Billiton Canada, Inc. |
| 5 | Canada Golden Fortune Potash Corp. |
| 6 | Canada Potash Corp. |
| 7 | Canada United Potash, Ltd. |
| 8 | Canada Wanbei Hengjia Potash Co., Ltd. |
| 9 | Canasia Industries Corp. |
| 10 | CanPacific Potash, Inc. |
| 11 | Compass Minerals Canada Corp. |
| 12 | Dahrouge Geological Consulting, Ltd. |
| 13 | Encanto Potash Corp. (Encanto Resources) |
| 14 | Gensource Potash Corp. |
| 15 | Grizzly Discoveries, Inc. |
| 16 | ISX Resources, Inc. |
| 17 | JSC Acron |
| | Companies with potash land rights in Alberta, Manitoba, North Dakota, and Saskatchewan from 2008 to 2018 (Mackintosh, 2006; Berenyi and others, 2008; Bout and Chiang, 2008; Saskatchewan Ministry of Energy and Resources, 2011b)—Continued |
| 18 | KCL |
| 19 | Karnalyte Resources, Inc. |
| 20 | Kennecott Canada Exploration |
| 21 | K+S Potash Canada GP |
| 22 | Manitoba Potash Corp. |
| 23 | Mosaic Potash |
| 24 | Mountain Capital, Inc. |
| 25 | M&J Potash Corp. |
| 26 | North Atlantic Potash, Inc. |
| 27 | Potash One, Inc. |
| 28 | Potash Corporation of Saskatchewan (now Nutrien) |
| 29 | Potash North Resource Corp. |
| 30 | RAY |
| 31 | Rio Tinto Potash Management, Inc. |
| 32 | Sherritt International Corp. |
| 33 | Sirius Minerals Public Ltd. Co. (Dakota Salts) |
| 34 | Taiji Resources, Ltd. |
| 35 | Takara Resources, Inc. |
| 36 | Vale Potash Canada Ltd. |
| 37 | Western Potash (Western Resources) |
| 38 | W.S. Ferreira, Ltd. |
| 39 | Yancoal Canada Resources Corp., Ltd. |
| 40 | Saskatchewan, Ltd. |
| 41 | Manitoba, Ltd. |
| 42 | Potamine Potash Mining Co. of Canada, Inc. |
| 43 | Canamax Resources, Inc. |
| 44 | Amax Minerals, Ltd. |
| 45 | Enterprise Miniére et Chimique (EMC) |

In 2019, Canada was the largest producer of potash, with 13 million metric tons (Mt) of $K_2O$ equivalent. Most of the potash came from Elk Point Basin (Jasinski, 2020). Canada is followed in productivity by Belarus, Russia, China, Germany, Israel, Jordan, and Chile, with a total world production of about 43 Mt of $K_2O$ equivalent (Cocker and others, 2016; Jasinski, 2020). Most of the Canadian potash is exported to the United States, China, Brazil, and India (Natural Resources Canada, 2015). With potash production in the United States (presently from the Carlsbad and Paradox Basins) consistently below domestic demand, potash imports have exceeded domestic production since about 1971–72 (Garrett, 1996), and Canada has become the principal source of potash for the United States (Prud'homme and Krukowski, 2006).

All of the potash mines in Saskatchewan, along with subsurface potash permits and leases, lie within the Area of Potash Dispositions (APD; fig. 4), also referred to as the Potash Exploration Area (Berenyi and others, 2008; Yang and others, 2009a). This area includes land potentially available for surface-related potash exploration work, and the potash permits (referred to as a KP along with the permit number) are issued by the Land Tenure and Mineral Rights Office of the Ministry of the Economy (Hatch, 2012; Bram Nelissen, Saskatchewan Ministry of the Economy, written commun., December 2017). Subsurface potash leases (referred to as a KL along with the lease number) are required for mine development and production. Included in permit applications are plans for (1) mine construction, (2) disposal of mining byproducts (including salt and insoluble minerals and brines), and (3) mine reclamation, including monitoring. Figure 4 shows the locations of potash permits and leases with current reported activity (as of 2018) for the Patience Lake, Belle Plaine, and Esterhazy Members tracts. The White Bear Member was additionally assessed as part of this study because it is viewed as an undiscovered resource. Although no permits or leases specifically involve the White Bear Member, it may be included in some underground solution mining permits and leases. More detailed information is available in the subsurface disposition searchbook of the Saskatchewan Ministry of Energy and Resources (2011b). Potash-mining companies lease mineral rights from the Saskatchewan Government (Crown resources) for renewable periods of 21 years and other (Freehold) owners under long-term agreements (Mosaic Company, 2016; Funk and others, 2018a,b,c).

Exploration and development in Saskatchewan has been episodic in nature, and this is reflected by the number of potash permits or leases and in the number of publications containing geological data on potash resources (fig. 5). The number of owned or leased potash mineral rights in Saskatchewan ranged from as few as 11 in 1965 to as many as 176 permits and 11 leases in 2008 (table 1). In Manitoba, five companies owned potash land rights in 1966 (Nicolas, 2016). The recent increases in global potash demand and prices provide the impetus for renewed exploration, as well as for planned new mines and increased mine productivity in established mines. By 2009, nearly all of the APD in Saskatchewan was permitted or leased for potash exploration or mine development (Berenyi and others, 2008). As of late 2019, at least 45 companies had potash mineral rights in Alberta, Manitoba, North Dakota, and Saskatchewan.

Additional recent potash exploration was conducted in adjacent parts of Manitoba and Alberta (fig. 4) and South Dakota. Several companies (Grizzly Diamonds [later Grizzly Resources], Canasia Industries, and Silver Lake Resources) have recently acquired metal and industrial mineral (MAIM) exploration permits in parts of Alberta (fig. 4) adjacent to Saskatchewan (Klarenbach, 2009; Shearer, 2011; Dufresne and McMillan, 2012). The Alberta Department of Energy's Coal and Mineral Development Unit issues MAIM permits (Shearer, 2011). Except for some limited potash exploration activity noted by Klarenbach (2008), Grizzly Diamonds, Ltd. (2008), Klarenbach and Gray (2009), and Pacific Potash Corp. (Shearer, 2011), there has been no further reported exploration activity. In the 1980s and 1990s, there was exploration activity in adjacent but undeveloped parts of Manitoba by six companies (Nicolas, 2016). From the early 1980s to about 2008 (Bannatyne, 1983; Western Potash Corp., 2008; Nicolas, 2016), exploration focused on the Esterhazy Member, which is being mined in the Rocanville and Esterhazy Mines in adjacent parts of Saskatchewan.

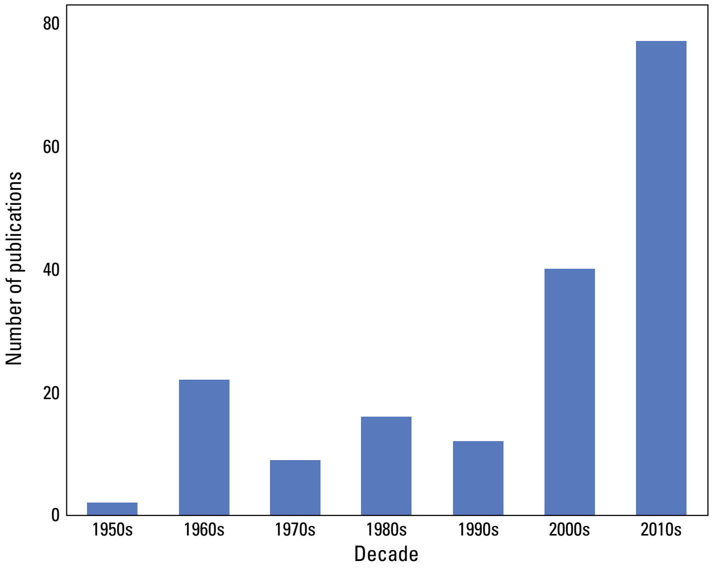


**Figure 5.** Plot showing the number of publicly available reports on the Elk Point Basin published per decade.

In the United States, the depth of the Prairie Evaporite has proven to be a prohibitive factor to potash exploration. After Sirius Minerals, Plc., drilled a deep hole in North Dakota, the excessive depth (about 2,800 m) and low potash grades (11.8 percent $K_2O$ equivalent over 8.5 m in the Esterhazy Member), the company decided to focus their exploration efforts on another potash deposit (Woodsmith Mine) in the United Kingdom (Sirius Minerals, Plc., 2011, 2018; Wetzel, 2012).

Since 2009, two new mines were put into production in Saskatchewan, two others are in various stages of predevelopment, two mines were extended with construction of new shafts, and most of the older mines had increased their production capacity (Hatch, 2012; Hogan and others, 2013; Fracchia and others, 2017a,b,c). Presently, 13 mines (including the two mine extensions) are in production. Saskatchewan remains at or near the top of mining companies' best jurisdictions for investment over the past 2 years (Stedman and Green, 2017). Based on reserve estimates and production rates, currently operating mines in Saskatchewan have life expectancies of an additional 55–83 years (table 2).

Ownership of potash properties has been in a state of flux since the early development of potash mining. Fuzesy (1982) provides a summary of the early stages of potash mining in Saskatchewan through 1982 and table 1 lists companies that have been active in potash exploration in the Elk Point Basin. With essentially all of the APD under permit or lease, some companies and foreign countries have sought to acquire essential potash resources in Saskatchewan through acquisitions or preproduction contracts with new projects. Company mergers such as Agrium and Potash Corp. in 2018 to form Nutrien increased the market share of the combined companies, and acquisitions such as BHP Billiton's purchase of Athabasca Potash (Davis, 2010) and K+S Potash Canada's purchase of the Findlater/Bethune property (now Legacy mine; Shah, 2013) has changed the potash mining landscape both in Canada and worldwide. Several foreign countries have secured potash resources in Saskatchewan either by acquisition of potash properties or through preproduction agreements with junior mining companies in Saskatchewan that were seeking funding to advance their projects. These

**Table 2.** Mine life and production capacity of active and potential potash mines in Saskatchewan.

| Company | Mine | Production capacity in 2012 (Mt KCl/yr) | Present capacity in 2018 (Mt KCl/yr) | Present production capacity (Mt $K_2O$/yr) | Anticipated production capacity (Mt KCl/yr) | Anticipated production capacity (Mt $K_2O$/yr) | Production years | Expected lifetime, in years (based on various reserve estimates) | Total expected lifetime, in years | Expansion cost (billions CAD) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Potash Corporation of Saskatchewan[a] | Allan | 1.6 | 3.6 | 2.23 | 3.6 | 2.23 | 44 | 83 | 127 | 0.77 | Moore (2010); Hatch (2012); Hogan and others (2013); Rauche and others (2016) |
| Potash Corporation of Saskatchewan[a] | Cory | 2 | 3 | 1.86 | 3 | 1.86 | 48 | 55 | 103 | 1.65 | Moore (2010); Hatch (2012); Rauche and others (2016); Fracchia and ohers (2017b) |
| Potash Corporation of Saskatchewan[a] | Lanigan | 3.3 | 3.8 | 2.36 | 3.8 | 2.36 | 46 | 82 | 128 | 0.41 | Moore (2010); Hatch (2012); Fracchia and others (2015); Rauche and others (2016) |
| Potash Corporation of Saskatchewan[a] | Patience Lake | 0.4 | 0.4 | 0.25 | 0.4 | 0.25 | 60 | nd | nd | 0.11 | Fuzesey (1982); Moore (2010); Hatch (2012) |
| Potash Corporation of Saskatchewan[a] | Rocanville | 2.7 | 6 | 3.72 | 6 | 3.72 | 46 | 69 | 115 | 2.8 | Moore (2010); Hatch (2012); Fracchia and others (2017a) |
| Agrium[a] | Vanscoy | 1.8 | 2.8 | 1.74 | 2.8 | 1.74 | 45 | 61 | 106 | 2.33 | Moore (2010); Hatch (2012); Bartsch and others (2014) |
| Mosaic Company | Esterhazy K1 and K2 | 5.3 | 5.3 | 3.29 | 5.3 | 3.29 | 56 | nd | nd | nd | Hatch (2012) |
| Mosaic Company | Colonsay | 1.8 | 2.5 | 1.55 | 2.5 | 1.55 | 48 | nd | nd | nd | Hatch (2012); Rauche and others (2016) |
| Mosaic Company | Belle Plaine | 2.8 | 2.8 | 1.74 | 2.8 | 1.74 | 56 | nd | nd | nd | Hatch (2012) |
| Potash Corporation of Saskatchewan[a] | Rocanville West (also known as Scissors Creek | nd | 2.9 | 1.80 | 2.9 | 1.80 | nd | nd | nd | nd | Hatch (2012); Rauche and others (2016) |
| Mosaic Company | Esterhazy K3 | nd | 2.7 | 1.67 | 2.7 | 1.67 | nd | nd | nd | 2.0 | Hatch (2012, 2021); Rauche and others (2016) |

**Table 2.** Mine life and production capacity of active and potential potash mines in Saskatchewan.—Continued

| Company | Mine | Production capacity in 2012 (Mt KCl/yr) | Present capacity in 2018 (Mt KCl/yr) | Present production capacity (Mt $K_2O$/yr) | Anticipated production capacity (Mt KCl/yr) | Anticipated production capacity (Mt $K_2O$/yr) | Production years | Expected lifetime, in years (based on various reserve estimates) | Total expected lifetime, in years | Expansion cost (billions CAD) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| K+S Canda Potash | Legacy (also known as Bethune or Findlater) | nd | 1 | 0.62 | 4 | 2.48 | nd | nd | nd | nd | Hardy and others (2009a); Hatch (2012); Spachtholz (2013) |
| BHP Billiton | Jansen | nd | nd | nd | 8 | 4.96 | nd | 50 | nd | nd | Halabura and Gebhardt (2006); Tarikh (2010); Hatch (2012) |
| Karnalyte Resources, Inc. | Wynyard | nd | nd | nd | 2.1 | 1.30 | nd | 60 | nd | nd | Rauche and others (2016); Karnalyte Resources, Inc. (2020) |
| Western Resources Corp. | Milestone | nd | nd | nd | 2.8 | 1.74 | nd | 40 | nd | nd | Hardy and others (2013) |
| Encanto Potash Corp. | Muskowe-kwam | nd | nd | nd | 3.4 | 2.11 | nd | 50 | nd | nd | Myers and others (2017) |
| Gensource Potash Corp. | Vanguard | nd | nd | nd | 0.25 | 0.16 | nd | 40 | 100 | 0.21[b] | Fourie and others (2018) |
| Encanto Potash Corp. | Langham | nd | nd | nd | 1 | 0.62 | nd | nd | nd | nd | Hardy and others (2009b) |
| Gensource Potash Corp. | Lazlo | nd | nd | nd | 1 | 0.62 | nd | nd | nd | nd | Hambley and Halabura (2014) |
| Potash North Resource Corp. | Yorkton | nd | nd | nd | 1 | 0.62 | nd | nd | nd | nd | Hardy and Halabura (2008); Spachtholz (2013) |
| Yancoal | Southey | nd | nd | nd | 2.8 | 1.74 | nd | nd | nd | nd | Rauche and others (2016) |
| Athabasca Potash | Burr | nd | nd | nd | 1 | 0.62 | nd | nd | nd | nd | Lomas (2008) |
| Agrium[a] | Leech Lake | nd | nd | nd | nd | nd | nd | nd | nd | nd | Bout and Chiang (2008) |
| Total | | 21.7 | 32.8 | 22.82 | 63.15 | 39.15 | | | | | |

[a] Now Nutrien, as of 2018 (Skerritt and Casey, 2016).

[b] Construction costs.

countries' interests are represented by Vale (Brazil), JSC Acron (Russia), National Federation of Farmers' Procurement, Processing, and Retailing Cooperatives (NACOF; India), and Anhui Huilong Agricultural Group (China) (Davis, 2010; Holter, 2010a,b,c,d,e,f; Encanto Potash Corp., 2017; Canada Golden Fortune Corp., 2019).

The early exploration activity contributed to a limited patchwork understanding of the geology of Elk Point Basin potash and is reflected in the number of publications (fig. 5) that focus on the Elk Point Basin (2 in the 1950s, 22 in the 1960s, 9 in the 1970s, 16 in the 1980s, 12 in the 1990s, and at least 117 since 2000; see "References Cited" section). Holter (1969) established the stratigraphy of the Prairie Evaporite, and that study has since served as the industry's standard for further exploration and mine development. Studies by Fuzesy (1982) and Boys (1990) expanded the basic understanding of Elk Point Basin potash geology. Despite some limited geological and engineering studies in the mines, little knowledge of the potash geology or of the basin's potential potash resources was publicly available for the next 40 years. During the decades after the first mines were established, there were relatively few incentives to expanding industry production in Saskatchewan, and no significant exploration was reported outside of the established potash lease (mine) areas.

Beginning in the early part of the 21st century, global potash prices began to increase dramatically, causing an increasing worldwide interest in exploration and development of potash deposits. With large but relatively unknown areas of the Elk Point Basin being favorably prospective for new deposits, exploration activity in the rest of the APD began in earnest. The numerous Canadian Securities Administrators National Instrument (NI) 43-101 technical reports released during the early years of this century included detailed exploration and estimated resource data for potash permit and lease areas. These studies were enhanced by drill hole data and geologic interpretations in several Saskatchewan Geological Survey (SGS) publications (Yang and others, 2009a; Yang and Schuurmans, 2018). Partially as a result of the expanded knowledge of Elk Point Basin's potash geology, more new mines have been developed in the Elk Point Basin during the past 10 years than in any other basin worldwide (Cocker and others, 2016, 2017). The potential for undiscovered potash resources is dependent on the geologic data as documented in those publications and as estimated in this report. High potash resource estimates could extend potash production in this basin for an indefinite period beyond the 21st century. Changes in global supplies and demand, as well as the amount of undiscovered potash resources, may favor continued new mine development in the basin.

When the global demand for potash collapsed in 2009–2010, potash production in Saskatchewan (fig. 6) decreased by 59 percent (Stone, 2010). However, the industry was able to withstand the downturn, and potash companies began to adopt a long-term, global view of the potash market and to develop plans that extended beyond shorter term price fluctuations. Continued optimism about future potash demand fostered exploration and acquisition activity through 2019. During periods of reduced global demand and lower prices, potash companies reduce or suspend their production and may even close higher cost mines (Friedman, 2018) but maintain their mineral inventories in large storage warehouses either onsite or at port facilities to meet export obligations. Many of the potash operations in Saskatchewan take these opportunities of a mine's reduced production to expand their production capacity and efficiency (Cocker and Orris, 2014).

A primary consideration of present and future potash exploration in the Elk Point Basin is how much potash remains to be developed. One of the earliest estimates of the amount of potash from the provincial Department of Mineral Resources evaluated it as being "almost unbelievably large" and was interpreted to represent reserves of 5–100 Bt (Daly, 1955). Estimates of resources since that time have varied considerably and have no documented parameters establishing how those estimates were attained (table 3). What is known of the amount of potash in the Elk Point Basin is the actual mine production, published reserves or identified resources, and the presence and grades of the potash from various exploration wells. The "References Cited" section includes many of the published references for resource and reserve data and table 4 shows a summary of the principal references that contain

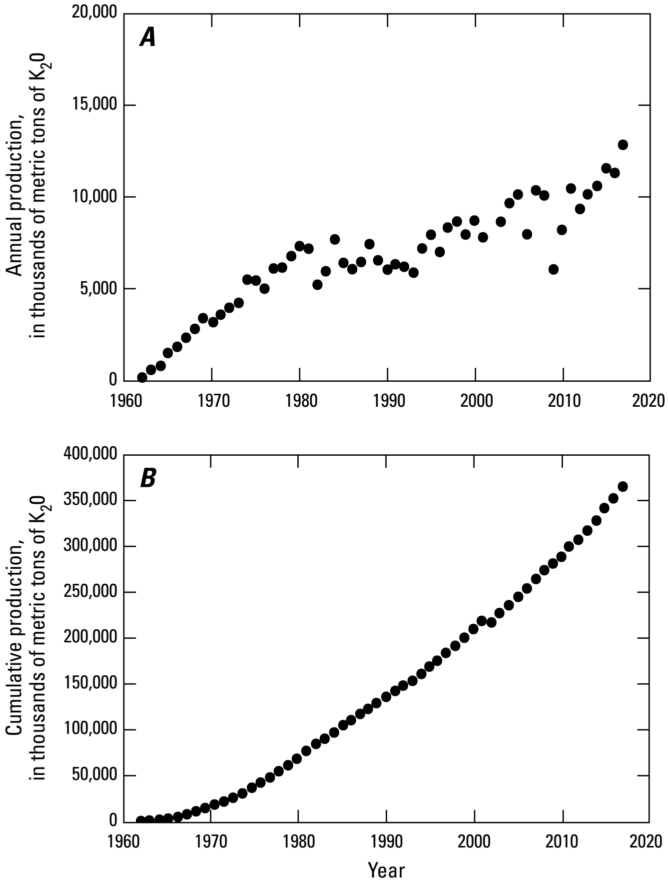


**Figure 6.** Graphs showing potash production (*A*) and potash volume sold (*B*) in Saskatchewan from 1962 to 2017. Data are from the Saskatchewan Ministry of Energy and Resources (2009) and the Saskatchewan Ministry of the Economy (2014b, 2018). $K_2O$, potassium oxide.

**Table 3.** Summary of previous resource estimates of potash in the Prairie Evaporite, Elk Point Basin, Canada and the United States.

[Bt, billion metric tons; $K_2O$, potassium oxide; nd, no data or information provided]

| Geographic area | Geologic unit | Total calculated tonnage (Bt) | Total known $K_2O$ resources (Bt)$^{a}$ | Total calculated (or reported) $K_2O$ resources (Bt) | Recoverable or calculated $K_2O$ reserves (Bt) | Estimated $K_2O$ reserves and resources (Bt) | Solution mining $K_2O$ reserves (Bt)$^{b}$ | Undefined $K_2O$ (Bt)$^{b}$ | Proven carnallite $K_2O$ resources (Bt)$^{b}$ | Year | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Saskatchewan | Prairie Evaporite | nd | nd | nd | nd | 5 to 100$^{c}$ | nd | nd | nd | 1955 | Daly (1955) |
| Saskatchewan | Prairie Evaporite | nd | nd | 5.8$^{b}$ | nd | nd | nd | nd | nd | 1957 | Goudie (1957) |
| Saskatchewan | Prairie Evaporite | nd | nd | nd | 6.4$^{b}$ | nd | nd | nd | nd | 1960 | Pearson (1960) |
| Saskatchewan | Prairie Evaporite | nd | nd | 5$^{b}$ | nd | nd | nd | nd | nd | 1960 | Bates (1960) |
| Saskatchewan | Patience Lake and Esterhazy Members | nd | nd | nd | 4.5$^{b}$ | nd | 62.5 | nd | nd | 1969 | Holter (1969) |
| North Dakota | Prairie Evaporite | nd | nd | nd | nd | 50.0 | nd | nd | nd | 1979 | Anderson and Swinehart (1979) |
| Manitoba | Esterhazy Member | nd | nd | 0.1$^{b}$ | nd | nd | nd | nd | nd | 1983 | Bannatyne (1983) |
| Saskatchewan | Patience Lake and Esterhazy Members | nd | nd | nd | 67$^{b}$ | nd | nd | nd | nd | 1969, 1985 | British Sulphur Corp., Ltd. (1984) |
| Saskatchewan and Manitoba | Prairie Evaporite | nd | nd | nd | nd | 15.0 | 30.0 | nd | nd | 1989 | Barry (1989) |
| Canada (mainly Saskatchewan) | Not noted | nd | nd | nd | nd | nd | nd | 9.7 | nd | 1989 | Roskill Information Services, Ltd. (1989) |
| Saskatchewan | Prairie Evaporite | nd | nd | nd | nd | 5.0 | 69.0 | nd | nd | 1996 | Harben and Kužvart (1996) |
| Canada | Not noted | nd | nd | nd | nd | 15.4 | nd | nd | nd | 2008 | Bout and Chang (2008) |
| Saskatchewan | Patience Lake A and B zones? | nd | nd | nd | 10.5 and 14.0$^{b}$ | nd | 42.0 | nd | nd | 1981 | Kelley (2001) |
| Saskatoon mining district, Saskatchewan | Patience Lake and Belle Plaine Members | nd | nd | nd | nd | nd | nd | nd | 20 | 1985 | Fuzesy (1985) |
| Canada | Not noted | nd | nd | nd | nd | 107.0 | nd | nd | nd | 1973 | Stone (2009) |

**Table 3.** Summary of previous resource estimates of potash in the Prairie Evaporite, Elk Point Basin, Canada and the United States.—Continued

| Geographic area | Geologic unit | Total calculated tonnage (Bt) | Total known $K_2O$ resources (Bt)[a] | Total calculated (or reported) $K_2O$ resources (Bt) | Recoverable or calculated $K_2O$ reserves (Bt) | Estimated $K_2O$ reserves and resources (Bt) | Solution mining $K_2O$ reserves (Bt)[b] | Undefined $K_2O$ (Bt)[b] | Proven carnallite $K_2O$ resources (Bt)[b] | Year | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Saskatchewan | Prairie Evaporite | nd | nd | nd | nd | 67.0 | nd | nd | nd | 2006 | Mackintosh (2006) |
| Canada | Not noted | nd | nd | nd | nd | 1.0 | nd | nd | nd | 2014 | Jasinski (2015) |
| North Dakota and Montana | Williston Basin (probably Prairie Evaporite) | nd | nd | 7[b] | nd | nd | nd | nd | nd | 2015 | Jasinski (2017) |
| North Dakota | Prairie Evaporite | nd | nd | nd | nd | 32 | nd | nd | nd | 2010 | Dakota Salts (2010) |
| Saskatchewan Potash Permit Area (solution mining area) | Belle Plaine and Esterhazy Members | 2.144[d] | nd | 0.359[d] | 0.113[d] | nd | nd | nd | nd | 2010 | Halabura and others (2010) |
| Saskatchewan Potash Permit Area (areas with no planned conventional or solution mining)[a] | Belle Plaine and Esterhazy Members | 14.65[d] | nd | 2.344[d] | nd | nd | nd | nd | nd | 2010 | Halabura and others (2010) |

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[a] Known tonnages calculated from various National Instrument 43-101 and 10-K reports listed in the "References Cited" section.

[b] No documentation of how these numbers were arrived at was found in the literature. Some estimates (for Canada) include potash in New Brunswick but reflect only a minor contribution from that location.

[c] Noted as almost unbelievably large reserves; total tonnage or tons of $K_2O$ are not defined.

[d] Tonnages recalculated based on data for the solution mining area results provided by Halabura and others (2010).

**Table 4.** Principal sources of information for the Elk Point Basin used by the assessment team.

[NA, not applicable; U.S., United States; $K_2O$, potassium oxide]

| Theme | Name or title | Scale | Reference |
|---|---|---|---|
| Geology | Geological map of Canada | 1:5,000,000 | Wheeler and others (1996) |
| Geology | Sedimentary basins of Canada | 1:5,000,000 | Mossop and others (2004) |
| Geology | Distribution of lower Givetian strata | 1:5,000,000 | Mossop and Shetsen (1994) |
| Geology | Isopach map of the Belle Plaine Member | 1:1,000,000 | Holter (1969) |
| Geology | Structure contour and isopach map of the Devonian Prairie Evaporite | 1:1,000,000 | Martiniuk and Bezys (1998) |
| Geology | Geological atlas of Saskatchewan | 1:1,000,000 | Slimmon (2009) |
| Geology | Distribution and thickness of the Prairie Evaporite in the Elk Point Basin | 1:9,500,000 | Bannatyne (1983) |
| Geology | Distribution of potash in Manitoba | 1:1,000,000 | Bannatyne (1983) |
| Geology | Gross thickness of the Belle Plaine Member of the Prairie Formation in northwestern North Dakota and northeastern Montana | 1:2,000,000 | Anderson and Swinehart (1979) |
| Geology | Isopach map of the Belle Plaine Member of the Prairie Evaporite | 1:3,000,000 | Worsley and Fuzesy (1979) |
| Geology | Structure contour and isopach map of the Devonian Prairie Evaporite | 1:1,000,000 | Martiniuk and Bezys (1998) |
| Geology | Index map showing the location of the Williston Basin and the Superior-Churchill boundary of the Canadian Shield | NA | Gerhard and Anderson (1988) |
| Mineral occurrences and geology | ElkPt_well (feature within the geodatabase that accompanies this report) | NA | Bannatyne (1983); Yang and others (2009a); Roy Eccles (Alberta Geological Society, written commun., 2010) |
| Subsurface geology | Cross sections | NA | Holter (1969) |
| Subsurface geology | Cross sections | NA | Meijer Drees (1986) |
| Land (potash permit and lease) status | Geological atlas of Saskatchewan, ver. 12 | 1:1,000,000 | Slimmon (2009) |
| Carnallite and sylvite extent | Potash in Saskatchewan | Approximately 1:5,000,000 | Holter (1969); Fuzesy (1982) |
| Areas of no salt in Prairie Evaporite | Potash in Saskatchewan | Approximately 1:5,000,000 | Fuzesy (1982) |
| Potash dispositions | Potash in Saskatchewan—An overview of exploration and developments | Various | Berenyi and others (2008); Saskatchewan Ministry of Energy and Resources (2011b), Saskatchewan Ministry of the Economy (2016a) |
| Geology | Depths to potash bearing formation, Williston Basin—U.S. portion | 1:760,320 | Great Northern Railway Company (1965) |
| Drill hole analyses | Preliminary investigation of potash potential in Alberta | NA | Eccles and others (2009) |
| Drill hole analyses | National Instrument 43-101 technical reports (Alberta) | NA | Klarenbach (2008, 2009); Dufresne (2012) |
| Drill hole analyses | National Instrument 43-101 technical reports (Manitoba) | NA | Western Potash Corp. (2008, 2010); Duke (2008) |
| Drill hole depths and intercepts | The potash members of the Prairie Formation in North Dakota | NA | Kruger (2014) |
| Drill hole analyses | North Dakota assay results | NA | Sirius Minerals, Plc. (2011) |

**Table 4.** Principal sources of information for the Elk Point Basin used by the assessment team.—Continued

| Theme | Name or title | Scale | Reference |
|---|---|---|---|
| Drill hole depths and intercepts | Isopach and salt-back thickness map of the Patience Lake, Esterhazy, and Belle Plaine Members of the Prairie Evaporite Formation (isopach and formation tops data included) | NA | Yang and others (2009a); Yang and Schuurmans (2018) |
| Drill hole analyses | Potash-rich members of the Devonian Prairie Evaporite in Saskatchewan: Isopachs, carnallite contours, and $K_2O$ grades | NA | Yang and Love (2015); Yang and others (2018) |
| Drill hole depths and intercepts | Thickness of potash-rich members of the Devonian Prairie Evaporite in Saskatchewan (Townships 1 to 50, Range 30W1M to Range 30W3M) | NA | Yang (2016a) |
| Drill hole analyses | National Instrument 43-101 technical reports (Saskatchewan) | NA | Halabura and others (2005); Halabura and Gebhardt (2006); Mackintosh (2006); Hardy and Halabura (2007, 2008); Lomas (2007, 2008); Abbott and Kuchling (2009); Hardy and others (2009a,b, 2010a); Stone and others (2009); Holter (2010a,b,c,d,e,f); Molavi and others (2010); Moore and others (2010a,b,c,d, 2011); Hambley and others (2011, 2015); Stirrett and Gebhard (2011); Stoner and Mackintosh (2012); Bartsch and others (2014); Hambley and Halabura (2014); Fracchia and others (2015, 2017a,b); Western Potash Corp. (2015); Debusschere and others (2016); Rauche and others (2016); Fourie (2017); Myers and others (2017) |
| Drill hole depths and intercepts | Depths to potash-bearing formation, Williston Basin-U.S. portion | NA | Great Northern Railway Company (1965) |
| Drill hole analyses | Western Potash Corp. reports results from fifth exploration well on the Russell-Miniota property and start of drilling on QP-168/172: Vancouver, British Columbia | NA | Western Potash Corp. (2008) |
| Drill hole analyses | Report to Western Potash Corp.—Manitoba potash project: Winnipeg, Manitoba | NA | Duke (2008) |
| Drill hole analyses | Western Potash Corp. announces assay results from first four potash exploration wells from its Russell Miniota Project | NA | Varas (2008) |
| Drill hole analyses | Unpaginated drill hole logs | NA | Saskatchewan Ministry of Energy and Resources (2009) |
| Exploration | National Instrument 43-101 technical reports | Various | Halabura and others (2005); Halabura and Gebhardt (2006); Mackintosh (2006); Hardy and Halabura (2007, 2008); Lomas (2007, 2008); Abbott and Kuchling (2009); Hardy and others (2009a,b, 2010a); Stone and others (2009); Holter (2010a,b,c,d,e,f); Molavi and others (2010); Moore and others (2010a,b,c,d, 2011); Hambley and others (2011, 2015); Stirrett and Gebhardt (2011); Stoner and Mackintosh (2012); Bartsch and others (2014); Hambley and Halabura (2014); Fracchia and others (2015, 2017a,b); Western Potash Corp. (2015); Debusschere and others (2016); Rauche and others (2016); Fourie (2017); Myers and others (2017) |
| Exploration | Potash in Canadian Minerals Yearbook | NA | Stone (2010) |
| Salt dissolution areas | Salt dissolution areas | Various | This report (table 7) |
| Potash mine production | Saskatchewan annual potash mine production | NA | Saskatchewan Ministry of the Economy (2018) |

the geological descriptions, drill hole and analytical results, and resource and reserve estimates used in this assessment. There are large expanses of the potash mineralization in the Elk Point Basin that have little detailed data regarding grades, thicknesses, and mineralogy; the scarcity of data limits more accurate estimates of the total amount of potash.

## Estimates of Potash Reserves and Resources

From 1962 to 2018, underground mines in Saskatchewan produced a total of 600 Mt of KCl (the equivalent of about 378 Mt of $K_2O$). In 2018, the mines produced 23 Mt of KCl (the equivalent of about 14.4 Mt of $K_2O$). Despite price fluctuations and various periods of mine operation suspensions (fig. 6*A*), total production has increased at a reasonably steady rate (fig. 6*B*). Based on an estimated total known potash resource in Saskatchewan of approximately 103 Bt of potash-bearing salt containing approximately 20.7 Bt of $K_2O$ (table 5), this resource could last much longer than 100 years at the current production rate.

Numerous estimates of the potash reserves and resources for the Elk Point Basin were published over the >50 years of exploration and mining (table 3). Except for the individual mines or recent exploration projects described in NI 43-101 technical reports, it is unclear how those estimates were attained or what area or part of the stratigraphic section they were estimated for. An approach to estimating the amount of potash that remains to be developed is to estimate the total amount of potash that could be contained in the basin and subtract the amount of potash that has been mined and what is known to exist (or estimated) from drill hole data. The amount of a mineral resource that is not known is referred to as "undiscovered" by the USGS. "Undiscovered" is a term that has specific usage in USGS mineral resource assessments. The term "undiscovered mineral resources" refers to a variety of situations in which location, grade, quality, and quantity of mineralized material are not known or have not been estimated from specific geologic evidence (U.S. Bureau of Mines and U.S. Geological Survey, 1976).

The USGS has recently assessed undiscovered resources of copper, platinum-group elements (PGE), and potash in selected mineral deposit types around the world (Hammarstrom and others, 2010; Wynn and others, 2016; Cocker and others, 2017). A potash assessment workshop held in Tucson, Arizona, in May 2009 included an overview of the geology of the study area, discussions on potash-bearing salts within the Elk Point Basin, selection of an appropriate mineral deposit model and an assessment method, and delineation of permissive tracts. Follow-up meetings, including several onsite mine tours, were held in Saskatoon and Regina, Saskatchewan, in 2010 and 2011, and included a preliminary review of the assessment presented at the Saskatchewan Open House in December 2010 (Cocker and others, 2010). Using the recent previously unpublished data made available in 2018 (Yang and Schuurmans, 2018), estimated potash resources were recalculated for the Elk Point Basin in Canada and the United States (table 5). This estimate represents a synthesis of current, readily available information as of 2019.

For most USGS assessment studies, the method for estimating undiscovered resources relies upon estimating the number of undiscovered deposits of a given type (Singer and Menzie, 2010). However, for stratabound or stratiform mineral occurrences like potash-bearing salt or reef-type PGEs (Zientek and others, 2014), different approaches were

**Table 5.** Summary of 2019 assessment results of undiscovered potash resources in the Prairie Evaporite, Elk Point Basin, Canada and the United States.

[Bt, billion metric tons; km², square kilometers; km³, cubic kilometers; $K_2O$, posassium oxide. Undiscovered resources assessed to depth of 3 kilometers. Assessment date is November 14, 2019]

| Member of Prairie Evaporite | Tract number[a] | Tract area (km²) | Volume (km³) | Known potash resources (Bt $K_2O$ equivalent) | Past production (Bt $K_2O$ equivalent) | Mineral reserves and past production (Bt $K_2O$ equivalent) | Median estimate of undiscovered potash resources (Bt $K_2O$ equivalent) | Mean estimate of undiscovered potash resources (Bt $K_2O$ equivalent) | Total potash resources (mean undiscovered plus known) (Bt $K_2O$ equivalent) |
|---|---|---|---|---|---|---|---|---|---|
| Patience Lake | 003sbK0001a | 138,884 | 1,070 | 11.98 | 0.18 | 48.11 | 340 | 340 | 350 |
| Belle Plaine | 003sbK0001b | 125,722 | 740 | 3.40 | 0.02 | 9.71 | 210 | 220 | 220 |
| White Bear | 003sbK0001c | 54,060 | 170 | 0.00 | 0.00 | 0.00 | 34 | 34 | 34 |
| Esterhazy | 003sbK0001d | 100,193 | 710 | 4.67 | 0.12 | 15.32 | 200 | 190 | 200 |
| Total | | | 2,700 | 20.05 | 0.31[b] | 73.84 | 810 | 780 | 800 |

[a] Tracts represent permissible areas for undiscovered potash resources; how they are defined is discussed in detail in this report.

[b] Actual total is about 0.337 Bt of $K_2O$.

devised to probabilistically estimate the amount of mineralized material in a geologically constrained volume. For these deposit types, some part of the mineralized rock unit may be explored well enough that companies or government agencies can formally report mineral resources or mineral reserves and begin mining. Outside areas where a formal mineral resource has been defined by drilling, the mineralized material in the layer is insufficiently characterized and considered undiscovered. In other words, for the potash-bearing salt members in Saskatchewan, "undiscovered resource" refers to mineralized material that does not meet the criteria for reserves or measured, indicated, or inferred resources as defined by Canadian Securities Administrators NI 43-101 Standards of Disclosure for Mineral Projects (Canadian Securities Administrators, 2011) and recently updated by the International Council on Mining and Metals (2013). Or in the case of reserve and resource data reported prior to 2005, materials termed undiscovered resources are not considered to be reliable. The use of the term "reserves" may vary considerably where used to refer to publicly owned potash properties in Canada and the United States and to state-owned properties in other countries such as in Belarus and Russia (Cocker and others, 2017; Jasinski, 2017).

This assessment considers only the undiscovered and potentially recoverable potash resources that may be present in the Prairie Evaporite to a depth of 3 kilometers (km) with a minimum thickness of 1 m and a $K_2O$ equivalent grade of 4 percent or greater. It does not attempt to estimate the amount of economically recoverable potash resources over the entire Prairie Evaporite or within select geographic or political boundaries, such as the APD in Saskatchewan, or within different provinces or states. The USGS requires the estimates of resources to be reproducible given the data used, how the assessment was done, and consideration of uncertainties in data and parameters used in the assessment. In order to meet the requirements of that task, this report documents the geological reasons for what was assessed and how it was assessed. Included in the text, tables, and figures are descriptions of the known resources. The criteria that were used to select data for the assessment are discussed, including uncertainties in those data. Finally, the assessment results (summarized in table 5) are compared to previous estimates and the importance of the assessment results are discussed.

### Structure of this Report

This report describes the geological development of the Elk Point Basin, the stratigraphy of the potash-bearing Prairie Evaporite, the known extent of potash in the Prairie Evaporite, and geologic factors affecting the areal extent, thickness, and mineralogy of those members. Each member description includes a discussion of the stratigraphic position (levels), genesis, and modification of the potash-bearing salt that affects the grade and tonnage calculations, followed by an assessment of undiscovered potash resources. Appendixes include: (1) a short descriptive model of stratabound potash-bearing salt deposits (appendix A), (2) a glossary of potash- and salt-related terms (appendix B), (3) a summary of the adaptive geometric estimation (AGE) method used to evaluate the undiscovered resources in the Prairie Evaporite (appendix C), (4) a description of an @RISK script with equations and parameters used in the assessment (appendix D), and (5) biographical information for the members of the assessment team (appendix E). The accompanying digital map files provide permissive tract outlines, outlines of areas dominated by carnallite, thickness data for wells, and isopach data in a geographic information system (GIS) geodatabase format. Locations of wells from which data were used were published by Yang (2016a) and Yang and Schuurmans (2018).

## Geologic Development of the Devonian Elk Point Basin and Stratigraphy

The location and subsequent development of the Elk Point Basin strongly influenced the extent and volume of the contained evaporite deposits. Concentration, enrichment, and preservation of the contained potash is dependent on the regional development of the evaporite sequence.

### Basin Tectonics, Structure, and Architecture

The Elk Point Basin (fig. 3) is a southeast-trending large epicratonic embayment that extended into the Laurussia supercontinent (that existed around 335 to 175 million years ago) from the Panthalassa Ocean (Miall, 2008) and extends from British Columbia and Northwest Territories through Alberta and Saskatchewan into Manitoba, Montana, and North Dakota (Holter, 1969; Yang and others, 2009b). The present extent of Elk Point Basin is approximately 1,950 km long by 650–800 km wide and covers approximately 1,200,000 square kilometers ($km^2$). Strata of the Devonian (Givetian) Elk Point Group unconformably overlie Precambrian or lower Paleozoic rocks of that cratonic platform. Koehler (1997) suggests that Ordovician and Silurian platform rocks were eroded to form the northwest-southeast depression that became the Elk Point Basin. The erosional unconformity at the base of the Elk Point Group has as much as 1,400 m of relief (Meijer Drees, 2008). Lower to Middle Devonian clastic sedimentary rocks, red beds, evaporite rocks, and carbonate rocks of the Elk Point Group were deposited in that basin (fig. 7) when that embayment was repeatedly inundated by seawater (Holter, 1969; Kent, 1984). Kaminski and Jaupart (2000) suggest cratonic basin subsidence may be related to a thermal anomaly in the underlying lithosphere.

The Elk Point Basin was confined on the northeast, southeast, and southwestern sides by low-lying landmasses (Holter, 1969) underlain by tectonic ridges and arches that include the Western Alberta Arch (or Ridge), Sioux Arch, and Tathlina Uplift (or High) (Chipley and Kyser, 1989; Koehler,

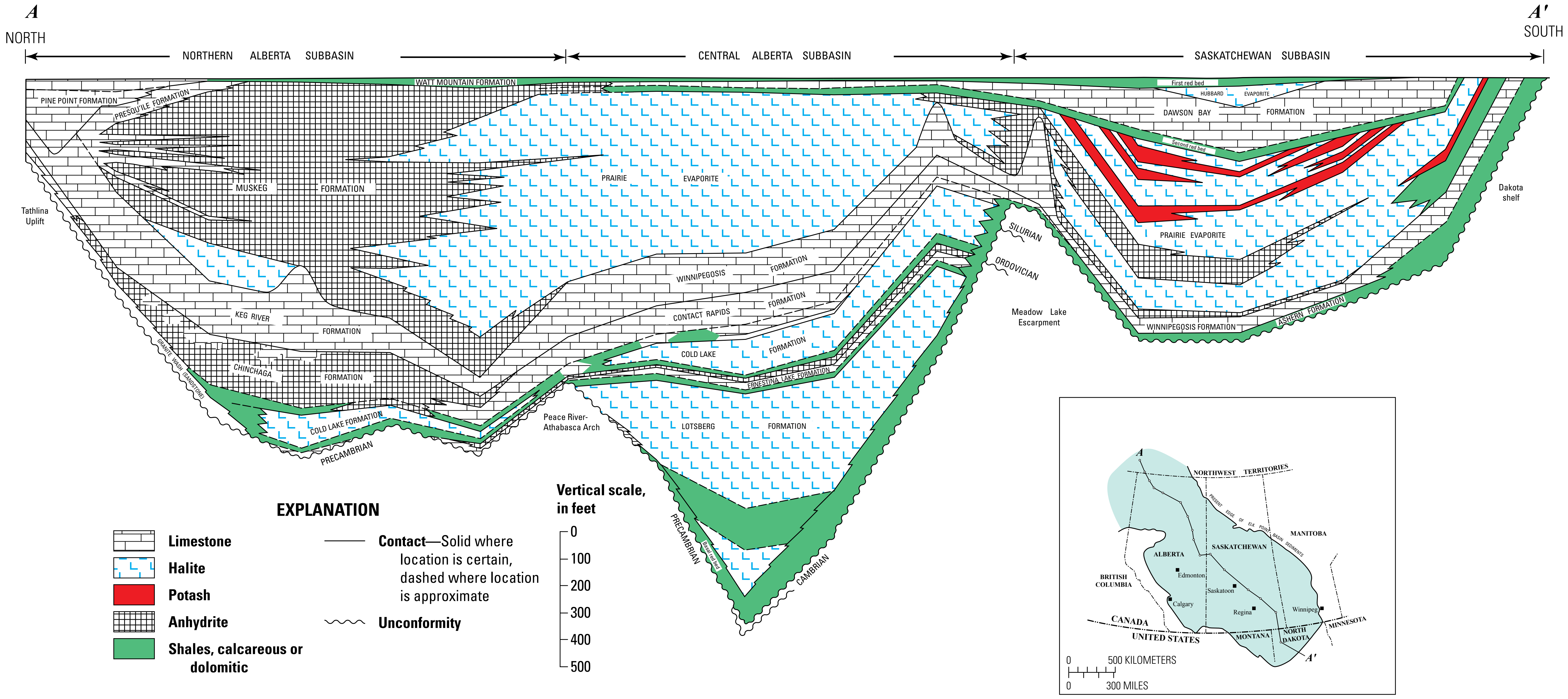


**Figure 7.** Longitudinal cross section through the Elk Point Basin in Canada and the United States. Modified from Holter (1969).

1997; Meijer Drees, 2008). These ridges became emergent during the late Silurian to Early Devonian and remained emergent during the Middle Devonian. Precambrian rocks of the Canadian Shield border the Elk Point Basin to the northeast (fig. 3).

Variations in thickness of the Elk Point Group are generally related to the pre-Devonian paleotopography (Meijer Drees, 2008) and to post-depositional dissolution (Holter, 1969). Paleotopographic highs such as the Peace River-Athabasca Arch and the Meadow Lake Escarpment divide the Elk Point Basin into the northern Alberta, central Alberta, and Saskatchewan subbasins (figs. 3, 7). The softer clastic rocks were eroded to the edge of the more resistant carbonate rocks along the Meadow Lake Escarpment (Koehler, 1997). The Meadow Lake Escarpment is generally viewed as a purely topographic feature and provides the relief for the southern edge of the lower Elk Point Group (Wright and others, 1994; Koehler, 1997; Meijer Drees, 2008). Upper Elk Point Group strata cover this escarpment and extend the length of the Elk Point Basin. These strata are found in the northern Alberta, central Alberta, and Saskatchewan subbasins (figs. 3, 7).

The Meadow Lake Escarpment has also been interpreted as a tectonic hingeline (the Meadow Lake Hingeline as described by Aitken [1993a,b]). Aitken's interpretation is that, in the Middle Ordovician through Silurian, subsidence that formed the Williston Basin was down to the southeast along this hingeline where the hingeline marked the northern flank of that basin. This was followed by a reversal of movement on this hingeline that caused the central Alberta and northern Alberta subbasins to subside and allowed a marine incursion during the Early Devonian. This proposed Meadow Lake Hingeline is substantially more than 400 km from the Williston Basin (fig. 3), and it seems unrelated to the formation of the Williston Basin. Aitken's emphasis is on the Elk Point Basin as a tectonic rather than an erosional topographic basin, as Meijer Drees and others (2002), Meijer Drees (2008), and Wright and others (1994) have documented.

The ancient shelf edge as defined by shale-rich, marine deposits is located in northeastern British Columbia (Meijer Drees, 2008). Carbonate rocks that make up the Presqu'ile barrier reef complex mark the shelf edge and separate the shaly marine deposits to the northwest from the evaporite deposits in the Elk Point Basin (figs. 3, 7).

The extensive lateral continuity of the potash-bearing salts in the Prairie Evaporite (described in the "Prairie Evaporite Stratigraphy and Potash Deposition" section) is related to the crustal stability of the Elk Point Basin during evaporite deposition. The general dip to the southwest and south-southwest may be due to post-Devonian epeirogenic events along the western margin of the Paleozoic craton (Meijer Drees and others, 2002) or to crustal downwarping associated with development of the Williston Basin and its overlap of the Elk Point Basin (figs. 3, 7) in the southeast (Gerhard and others, 1982). Fowler and Nisbet (1984) described the subsidence of the Williston Basin as continuous for most of the Phanerozoic. Their subsidence curves indicate that much of the subsidence of the Williston Basin occurred in the Late Devonian (after the deposition of the Middle Devonian Elk Point Group) through the Mississippian and slowed considerably by the Pennsylvanian.

The geographic and geologic location of the Middle Devonian evaporite units lies exclusively within the Elk Point Basin (figs. 3, 7). Other authors assign evaporite units of the Prairie Evaporite to other basins, such as the Western Canadian Sedimentary Basin (Wright and others, 1994; Grobe, 2000; Meijer Drees, 2008) or the Williston Basin (Baillie, 1953; Gerhard and Anderson, 1988; Kruger, 2014), but neither of these other basin's architectures or proposed development account for the overall distribution of the evaporites in the Elk Point Basin as described in the literature and discussed below. Adding to the name confusion, the Elk Point Basin has also been referred to as the Alberta Potash Basin, the Prairie Evaporite Basin, the Elk Point Basin, and the Western Canadian Sedimentary Basin in the same publication (Warren, 2016).

Salt deformation, or halokinesis, is absent in the Prairie Evaporite either within the salt beds or as halokinetic structures. Localized warping was noted as two large, gently folded synclines to the east and west of the Quill Lake region (fig. 4; Holter, 1969). The general lack of salt deformation is attributed to the underlying relatively stable continental platform during and subsequent to the formation of the evaporite sequences.

## Basin Stratigraphy

The overall Paleozoic stratigraphy of this basin consists of three major unconformity-bounded sequences of continental platform rocks that overlie the Precambrian crystalline rocks (figs. 7, 8) in the study area (Wright and others, 1994; Saskatchewan Ministry of the Economy, 2014a). These sequences correspond to the Sauk, Tippecanoe, and Kaskaskia sequences as described by Sloss (1963, 1988). The Sauk sequence consists of interbedded red beds and shale of the Cambrian Deadwood Formation, which unconformably overlies Precambrian rocks. The lowermost unit of the Tippecanoe sequence is a sandstone of the Upper Ordovician Winnipeg Formation that unconformably overlies the Deadwood Formation. The Tippecanoe sequence continues upward with platform carbonate rocks of the Upper Ordovician Bighorn Group and the Lower Silurian Interlake Group. These carbonate rocks were deposited on the Williston platform and are preserved only within the Williston Basin and parts of the Ordovician and Silurian continental shelf (Cecile and Norford, 1993).

Unconformities mark the lower and upper boundaries of the Kaskaskia sequence. The Lower and Middle Devonian Elk Point Group overlie the lower unconformity, which is an erosional feature with considerable relief. The upper unconformity truncates the Devonian Saskatchewan and Three Forks Groups and the Mississippian Madison and Big Snowy

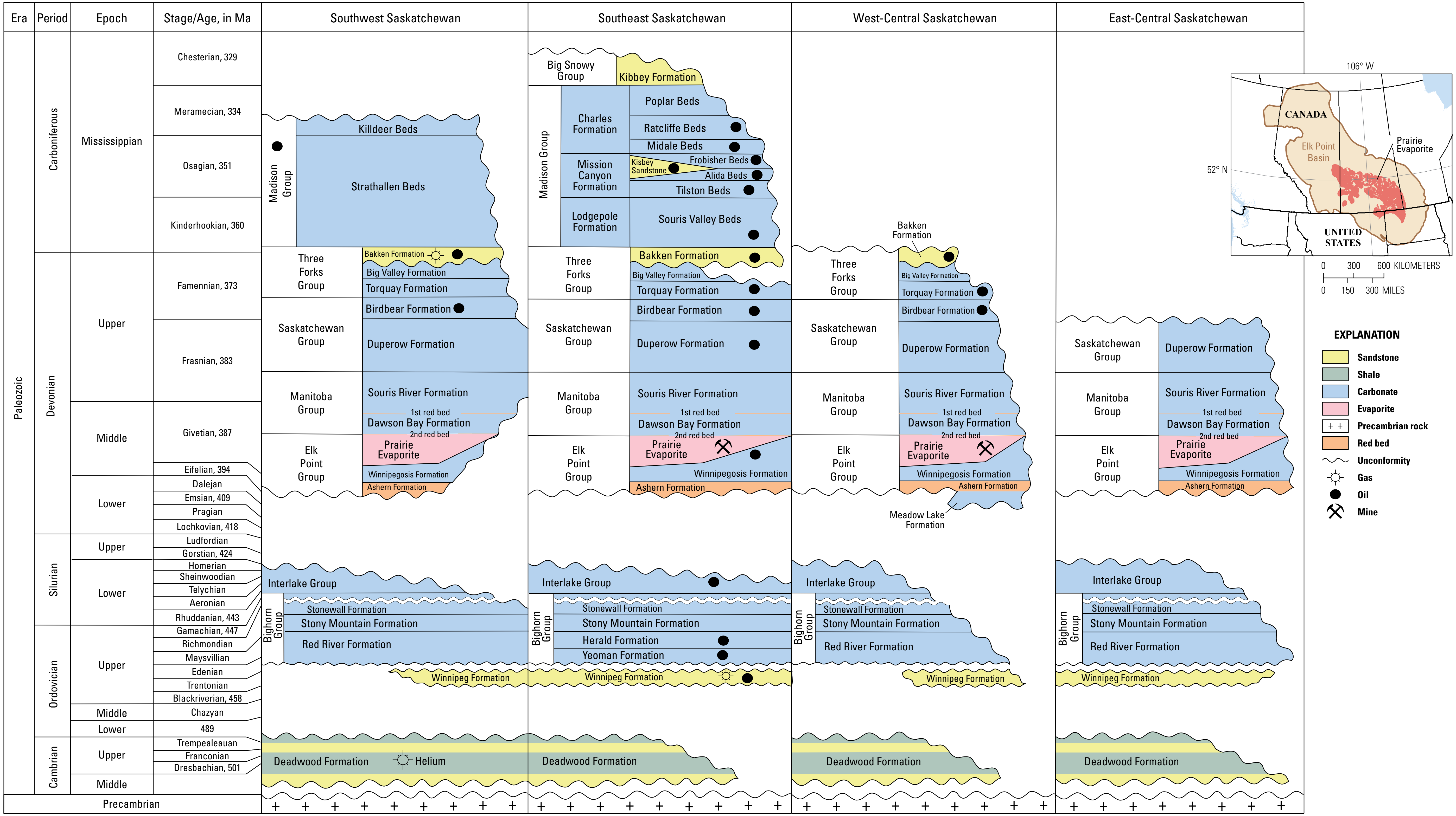


**Figure 8.** Paleozoic stratigraphy of the Elk Point Basin, Saskatchewan, Canada. Modified from Sakatchewan Ministry of Energy and Resources (2011a). The locations of these sections are relative to latitude 52° N. and longitude 106° W. as shown on the inset map. Ma, mega-annum.

Groups and is overlain by a thin green or reddish-brown shale unit (figs. 7, 8; Holter, 1969; Meijer Drees, 2008).

The Elk Point Group lies approximately 900–1,000 m below the present surface in Saskatchewan and extends below a depth of 3,000 m in northern parts of North Dakota and Montana. The Elk Point Group is divided into two subgroups (Grayson and others, 1964; Meijer Drees, 1986). The lower unit is referred to as the lower Elk Point subgroup and it contains the sediments accumulated in three paleo-topographic subbasins situated in northern Alberta, central Alberta, and Saskatchewan (figs. 3, 7). These subbasins are separated from each other by paleotopographic high areas such as the Keele Arch, Peace River Arch, Prairie Plateau, Tathlina Uplift, and Western Alberta Arch. The lower Elk Point subgroup consists of a succession of red beds that include several halite and anhydrite units that are overlain by a facies transition from red beds to interbedded anhydrite and shale. The spatial distribution of red beds and evaporites in the lower Elk Point subgroup indicate deposition in two nonmarine continental basins separated by the Peace River Arch (Meijer Drees, 1986). A fossiliferous carbonate unit forms the base of the upper Elk Point subgroup and is overlain by thick and extensive deposits of halite, potash-bearing salt, and anhydrite.

Stratigraphic units of the lower Elk Point subgroup in the northern and central Alberta subbasins include a basal red bed unit and the Lotsberg, Ernestina Lake, Cold Lake, Contact Rapids, and Chinchaga Formations (figs. 3, 7). Evaporites include the salt-bearing Lotsberg and Ernestina Lake Formations and the Cold Lake Formation evaporites (Holter, 1969; Meijer Drees, 1986, 2008; Grobe, 2000). In the Saskatchewan subbasin, the lower Elk Point subgroup is represented by the Ashern Formation.

The basal red beds unit, shown as shales in figure 7, is interpreted as a shoreline deposit of a saltwater lake with the overlying evaporites deposited in a partly or completely desiccated lake (Meijer Drees, 2008). The Lotsberg Formation consists of a lower salt unit, as thick as 60.9 m, and an upper salt unit, as thick as 152.4 m, separated by a shale unit as thick as 60.9 m (Meijer Drees, 1986). The Ernestina Lake Formation consists of a basal red dolomitic shale unit (3.6 m thick), a middle anhydritic limestone unit (10.3 m thick), and an upper anhydrite bed (5.8 m thick). The Cold Lake Formation consists of a lower member of red calcareous shale (6 m thick) and an upper member of salt (49.7 m thick). The Contact Rapids Formation consists of a lower member of greenish gray and red argillaceous dolostone (9.7 m thick) and red dolomitic shale and an upper member of brownish gray argillaceous dolostone and dolomitic shale (34.7 m thick). The Chinchaga Formation is as thick as 97.5 m, consists of anhydrite and dolostone, and grades southward into the Contact Rapids Formation (Meijer Drees, 1986).

Along the southwestern edge of the Elk Point Basin (fig. 3), a nearshore, argillaceous facies onlaps the Western Alberta Arch and part of the Peace River Arch (Meijer Drees, 1986). Nearshore facies of the Prairie Evaporite contain greenish gray, argillaceous anhydrite or anhydritic shale as thin beds within the salt. Light brown laminated mudstone or wackestone interbedded with laminated anhydritic dolostone are also indicative of a nearshore facies. Salt beds are generally absent in the nearshore facies. Nearshore facies along the northeastern edge of the Elk Point Basin are not preserved owing to subrosion in the updip parts of the Prairie Evaporite (Meijer Dress, 1986). South of the Meadow Lake Escarpment, the Contact Rapids Formation grades into the Ashern Formation. The Ashern Formation consists of reddish brown, sandy shale, overlain by dolomitic shale and dolostone, that ranges from 3 to 15.2 m thick. These red beds unconformably overlie Silurian or Ordovician carbonate rocks (Meijer Drees, 1986). The upper part of the upper Elk Point subgroup consists of the Keg River, Pine Point, Presqu'ile, Muskeg, and Bistcho Formations in the northern Alberta subbasin and the Winnipegosis Formation and Prairie Evaporite in the Saskatchewan subbasin (figs. 3, 7). The Keg River and Winnipegosis Formations are laterally equivalent and consist of marine carbonate rocks.

The dolomitized carbonate deposits of the Winnipegosis Formation consist of platform, reefal mound, and intermound facies. The platform facies is fossiliferous, algae-rich lime mudstone to wackestone (Kent, 1984). The reefal mound facies is characterized by pinnacle reefs (Gendzwill, 1978; Meijer Drees and others, 2002) that extend upward from the base of the Prairie Evaporite. They are flat topped, broadly circular, and range from 70 to 110 m high and as large as 8 km across (Baar, 1972, 1973; Boys, 1990). Between the reefs, the intermound facies consists of bituminous carbonate and anhydrite laminates that are 0.6–16 m thick (Wilson, 1985; Boys, 1990; Fu and others, 2006). These strata were referred to as the Ratner laminate as a member of the Winnipegosis Formation.

The pinnacle reefs occur on paleotopographic highs between the subbasins (fig. 7), on an east-west trending carbonate bank (the Quill Lake Bank), and on local paleotopographic highs throughout the Saskatchewan subbasin as mapped with seismic surveys (Gendzwill, 1978; Zhang and others, 2001; Fu and others 2006). Three-dimensional (3D) seismic sections display detailed views of these reefs relative to the Prairie Evaporite stratigraphy (Moore and others, 2010a,b,c,d, 2011). The distribution of the pinnacle reefs shows an apparent spatial and genetic relation to salt and potash dissolution areas (Gendzwill, 1978).

The Pine Point and Presqu'ile Formations consist of forereef and reef limestone and dolostone and compose the marine Presqu'ile barrier reef complex (figs. 3, 7). The Presqu'ile barrier reef complex developed across the narrow entrance between the open ocean and the Elk Point Basin (Holter, 1969; Maiklem, 1971). Basinward, the Presqu'ile Formation interfingers with the anhydrite of the Muskeg Formation. The Muskeg Formation consists of a 158-m-thick basal unit of interbedded anhydrite and dolostone, a 39.3-m-thick middle dolostone unit, and a 14.3-m-thick upper unit of interbedded limestone and dolostone (Meijer Drees, 1986). This unit grades southeastward into the Prairie Evaporite. The Prairie Evaporite extends from the northern Alberta subbasin through the central Alberta subbasin and into the Saskatchewan subbasin located about 880 km from the Presqu'ile barrier reef complex (figs. 3, 7). The only known potash-bearing salt is confined to the Saskatchewan subbasin.

Above the Elk Point Group, the Devonian section is approximately 500 m thick. Most of the rocks contained in the Devonian section are carbonates (Choteau and others, 1997). The Middle to Upper Devonian Manitoba Group (fig. 8) overlies the Elk Point Group and is mainly developed in the Saskatchewan subbasin. It consists of the Dawson Bay and Souris River Formations. These units comprise red beds, dolomite, anhydrite, and halite. Within the Dawson Bay Formation, the Hubbard Evaporite is mainly composed of halite as thick as 18.9 m. The Souris River Formations contains the Davidson Evaporite, which contains halite as thick as 63.7 m (Meijer Drees, 1986). Salts of the Hubbard and Davidson Evaporites act as barriers protecting the underlying potash-bearing salt of the Elk Point Group from dissolution by water and brine in overlying aquifers (Hardy and others, 2010a,b).

The lower part of the Kaskaskia sequence consists of three complete cyclic depositional sequences, or evaporite cycles, which are defined by Holter (1969) and Fuzesy (1982) as comprising an ascending depositional sequence of red beds, carbonates, sulfates (mainly as anhydrite), salts, and potash salts. These evaporite cycles may also include clastic rocks along the basin margins. In some of these sequences, evaporites may be more extensive than in other sequences. The evaporite cycles (figs. 7, 8) include: (1) the Ashern Formation, Winnipegosis Formation, and Prairie Evaporite, (2) the Dawson Bay Formation, and (3) the Souris River Formation (Holter, 1969; Boys, 1990).

Upper Devonian (fig. 8) units of the Kaskaskia sequence include the Saskatchewan and Three Forks Groups. The Duperow, Birdbear, Torquay, and Big Valley Formations consist of limestones, dolostones, and anhydrite (Meijer Drees, 1986). The rocks of the Duperow, Birdbear, and Torquay Formations are regarded as marginal marine or lagoonal evaporites (Meijer Drees, 1986). Sandstone of the Bakken Formation is in unconformable contact with the Big Valley Formation (fig. 8). About 100 m of Cretaceous sandstone are above the Devonian section. The remainder of the section up to the surface is composed of Cretaceous shales and Pleistocene glacial till (Choteau and others, 1997). The Duperow, upper Souris River, and Blairmore Formations and glacial till are important aquifers that may cause flooding during mine-shaft construction and must be frozen and sealed (Roessner, 1980). Wittrup and Kyser (1990) determined that three types of mine-level fluid may be involved in floodings: (1) halite- and sylvite-saturated basinal brines, mainly connate water, from overlying Devonian formations; (2) undersaturated, mainly meteoric, waters from stratigraphically higher aquifers such as the Cretaceous Mannville Group; and (3) calcium-rich brines that may represent Devonian fluids associated with recrystallization of the evaporites. These may enter the potash-bearing strata through collapse structures or related fractures, which may be reactivated through mining.

## Prairie Evaporite Stratigraphy and Potash Deposition

The term Prairie Evaporite was first used by Baillie (1953) to describe a thick unit of salt and minor anhydrite in the subsurface of southern Saskatchewan (Meijer Drees, 1986). This formation includes all strata above the underlying Winnipegosis Formation and below the second red bed that occurs at the base of the overlying Dawson Bay Formation (Yang and others, 2009b). The type section designated by Baillie (1953) was in the Imperial Davidson no. 1 well, located in Dominion Land Survey 16, section 8, township 27, range 1, west of the third meridian. Because of missing data and material, Holter (1969) established a new reference section in the White Rose et al. Drake well (4-29-32-22), located in Dominion Land Survey 4, section 29, township 32, range 22, west of the second meridian. This stratigraphic unit has been referred to as the Prairie Formation, the Prairie Evaporite, and the Prairie Evaporite Formation. This report will refer to this unit as the Prairie Evaporite (Nancy Stamm, USGS, written commun., 2012).

In Saskatchewan, drill hole data show the Prairie Evaporite ranges in thickness from less than 1 m along the northern and southern borders of the basin to a maximum of 215–218 m (Holter, 1969; Stone and others, 2009). The average thickness of the Prairie Evaporite is 106 m. In many of the early studies and drill-hole logs, potash-bearing strata in the upper part of the Prairie Evaporite were commonly referred to as zones, such as zones 1, 2, and 3 (Goudie, 1957; Holter, 1972), potash beds $A_1$, $A_2$, $B_1$, and $B_2$ (Great Northern Railway Company, 1965), zones A, B, C, D, and E (Harding and Gorrell, 1967), third, second, and first potash beds (Gorrell and Alderman, 1968), or as zones K1, K2, and K3 (Klingspor, 1966). Holter (1969) established the presently accepted stratigraphic nomenclature currently used by industry, the SGS, and by the USGS in this assessment. Additional contributions to the Prairie Evaporite stratigraphy include those of Reinson and Wardlaw (1972), Worsley and Fuzesy (1979), Meijer Drees (1986), Jin and Bergman (2001), Zhang and others (2001), Yang and others (2009b), and Kruger (2014). More detailed drill logs contained in the recent NI 43-101 technical reports included in the "References Cited" section, table 4, and throughout the text of this report provide details peculiar to the Prairie Evaporite stratigraphy within each permit or lease area and reflect both the heterogeneity and homogeneity of the Prairie Evaporite. In some permit and lease areas, the potash stratigraphy is further subdivided.

## Primary Divisions of the Prairie Evaporite

The Prairie Evaporite is roughly divided into two main units separated by strata composed of anhydrite and laminated dolomite, variously referred to as the middle anhydrite (Holter, 1969), the Shell Lake Member, or the Shell Lake marker bed (Reinson and Wardlaw, 1972; Marsh and others, 2001; Zhang and others, 2001), and produces a good seismic reflector. Repeating upward successions of anhydrite, interbedded anhydrite and dolomite, and halite are described in this member. Previous studies suggested that the Shell Lake Member was a continuous unit overlying Winnipegosis Formation reef mounds, but subsequent work shows that this unit terminates against fully developed reef mounds.

Reinson and Wardlaw (1972) and Meijer Drees (1986) refer to the Prairie Evaporite rocks below the Shell Lake Member as the Whitlow Member. The Prairie Evaporite strata below the Shell Lake Member include a lower anhydrite unit and an upper salt unit. The lower anhydrite unit consists of nodular mosaic and massive anhydrite. The anhydritic beds consist of nodular-bedded, dolomitic anhydrite; distorted, nodular-mosaic anhydrite; and streaky, laminated anhydrite. The anhydritic beds contain remains of dolostone and dolomitic fossil fragments or pisoliths (Klingspor, 1966; Bebout and Maiklem, 1973; Corrigan, 1975). The upper salt unit of the lower Prairie Evaporite consists of halite with minor interbedded anhydrite laminae, generally less than 1 cm thick (Reinson and Wardlaw, 1972). The salt beds are composed of recrystallized semi-translucent halite with light gray, anhydritic laminae (Meijer Drees, 1986). The alternating halite and anhydrite laminae (or couplets) in the lower part of the Prairie Evaporite are believed to represent a primary deposition of halite and gypsum related to a cyclic influx of seawater or brine (Wardlaw and Schwerdtner, 1966). Similar varvelike couplets of calcite-anhydrite are believed to represent annual deposition in the Castile and Salado Formations in the Permian Basin located in west Texas and New Mexico (Dean and Anderson, 1978). The lower Prairie Evaporite couplets may also indicate yearly cyclic deposition.

The Prairie Evaporite strata above the Shell Lake Member consists mainly of halite and potash-bearing salt. The basin-wide distribution of halite and potash-bearing salt is generally shown in figures 3 and 7 (Holter, 1969). The Prairie Evaporite dips about 3.9 meters per kilometer (m/km) to the southwest and increases to about 7.8 m/km (Holter, 1969, Meijer Dress, 1986) in places, whereas individual members dip 2–4 m/km to the south and 1–2 m/km to the west (Yang and others, 2009b). The dips increase toward the southwest and west from about 3.9 to 7.8 m/km (Meijer Drees, 2008) or from 2 to 6 m/km (Yang and others, 2009b). Strike of the formation is generally to the northwest. Recent potash exploration drilling in North Dakota intersected the Esterhazy Member at a depth of 2,702 m (Sirius Minerals, Plc., 2011).

The upper part of the Prairie Evaporite is composed of halite and potash beds; the potash-rich strata are referred to as members, and the halite-rich intervals have recently been referred to as interbeds. Four potash members have been recognized in this sequence in Saskatchewan: in ascending order, they are the Esterhazy, White Bear, Belle Plaine, and Patience Lake Members (fig. 9; Holter, 1969; Fuzesy, 1982; Yang and others, 2009a). Two additional potash members overlying the Patience Lake Member, the Mountrail and White Lake members, were recently recognized in North Dakota (Kruger, 2014) but have not been recognized in Canada nor been formally described. The potash-bearing members are stratabound and consist mainly of sylvite or carnallite intermixed with halite (figs. 10, 11). These members within the Prairie Evaporate are commonly thought to be composed of a continuous thickness of potash-bearing salt. In some locations, this scenario is probably true, but in other locations, the content of potash (or the ratio of sylvite or carnallite to halite) may vary significantly throughout the member (fig. 11). In some locations, the members may be informally divided into two or more submembers (reflecting differences in potash contents between the submembers) or into relatively thick intervals of dominantly halite that separate relatively richer potash intervals. These variations may be related to local variations in physical and chemical conditions during precipitation of the evaporite minerals. Identification of these submembers may strongly influence resource calculations and mine plans.

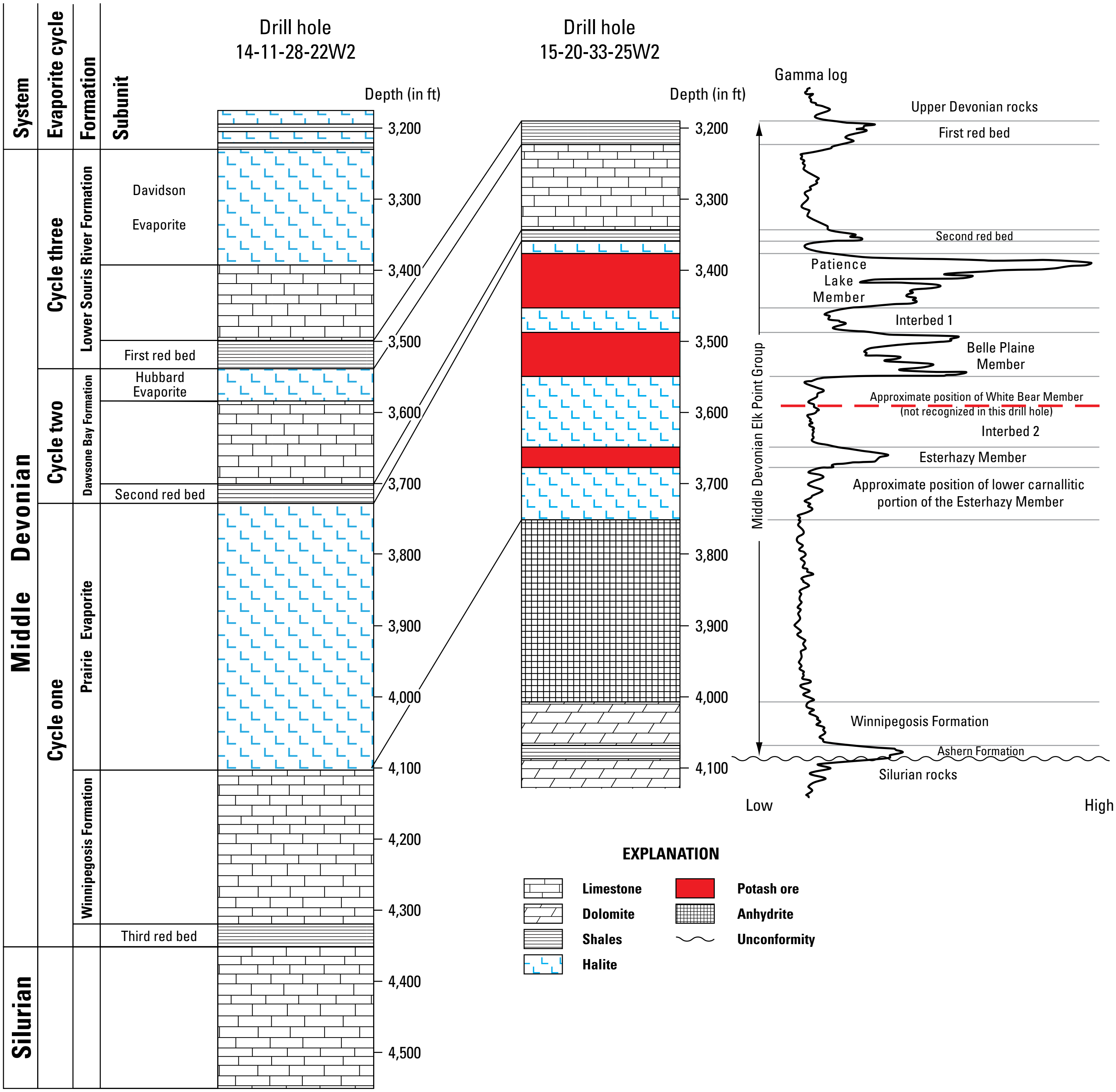


**Figure 9.** Stratigraphic column of the Middle Devonian section in the Saskatchewan subbasin, including the Prairie Evaporite. Modified from Klingspor (1966) and Van Der Plank (1963). The approximate position of the White Bear Member is shown by a dashed red line. Locations of interbeds 1 and 2 and the lower carnallitic part of the Esterhazy Member are also shown. ft, feet.

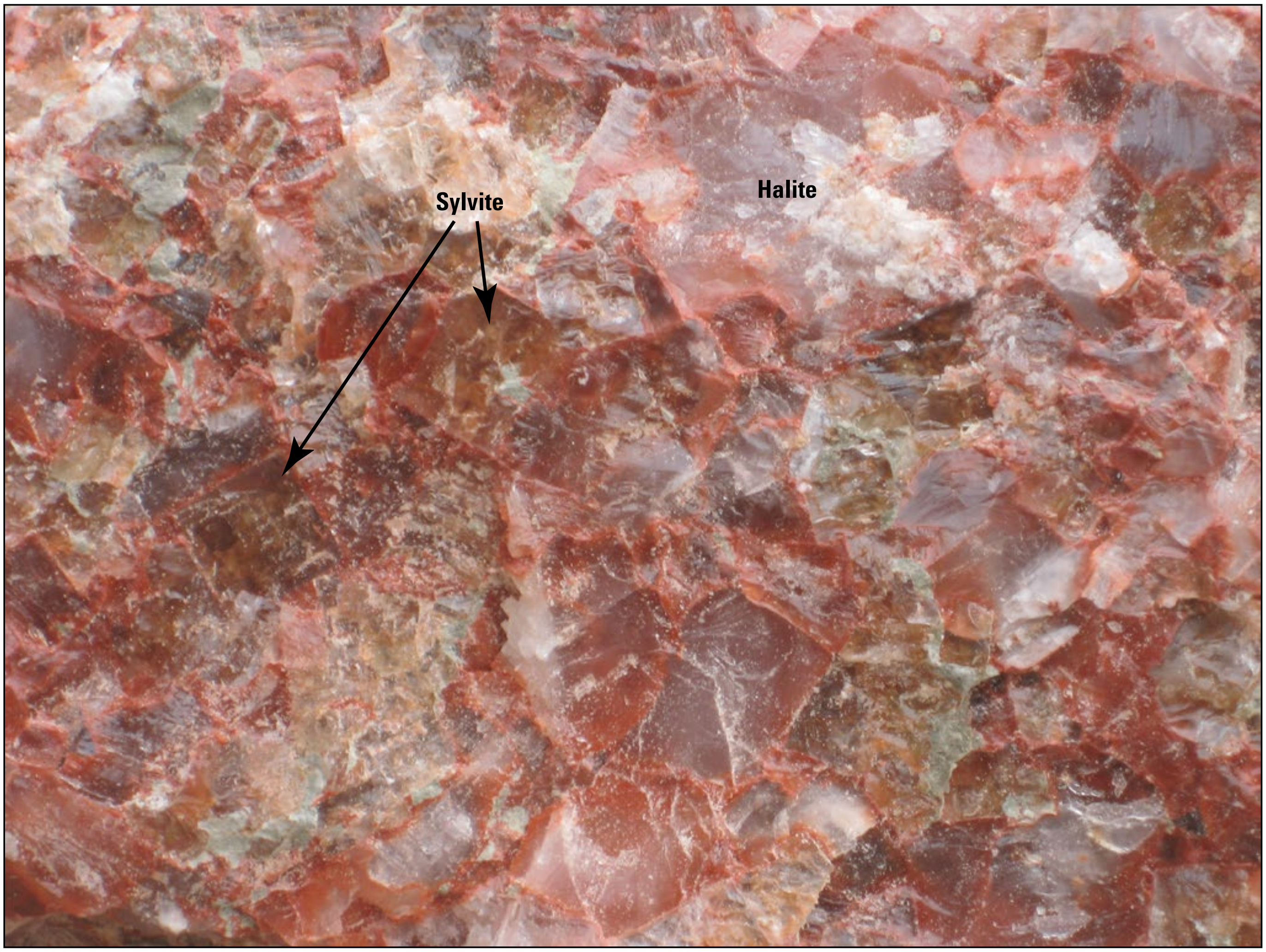


**Figure 10.** Photograph of sylvinite ore, a mixture of sylvite (generally red from included hematite) and halite (generally white to colorless) from Mosaic Company's Colonsay Mine, Saskatchewan, Canada. Field of view is approximately 6 centimeters. U.S. Geological Survey photograph by M. Cocker. Location of mine is shown in figure 4.

## Definition of the Upper and Lower Boundaries of the Prairie Evaporite Members

The upper and lower boundaries of each member are not clearly defined in the literature, in NI 43-101 technical reports, or in historical exploration well records. Defining the members is by no means a philosophical exercise, as estimates of resource and reserve tonnages and grades depend on volume calculations and mineralogical compositions that affect rock density.

This USGS assessment relies on drill hole (well) data. The results are subject to the vagaries and historical development of drilling and sampling practices and procedures, analytical methods, geophysical techniques, knowledge of the potash stratigraphy, economic factors (for example, cutoff grade and mining method), as well as data acquisition and interpretation. Drill hole data and chemical analyses of the drill core of varying quality are available from the 1950s through 2019, nearly 70 years in which drilling techniques, drilling strategies, geophysical equipment, sampling techniques, and knowledge of the Prairie Evaporite stratigraphy have evolved. Definition of the upper and lower boundaries may differ between drill holes on the same project area or between project areas, and there may be real changes in the geology between drill holes and not just how the upper and lower boundaries are defined. Some of these potential differences in unpublished definitions of the upper and lower boundaries can be gathered from studies such as by Boys (1990), NI 43-101 technical reports such as by Hambley and Halabura (2014), Hardy and Halabura (2008), and Hardy and others (2009a), as well as other types of published articles such as those by Holter (1969), Woodhouse (1994), and Nelson (2007), among others. This assessment uses the published thicknesses and grades of the member intercepts to estimate the undiscovered resources as reported by the SGS (Yang and others, 2009a; Yang and Schuurmans, 2018).

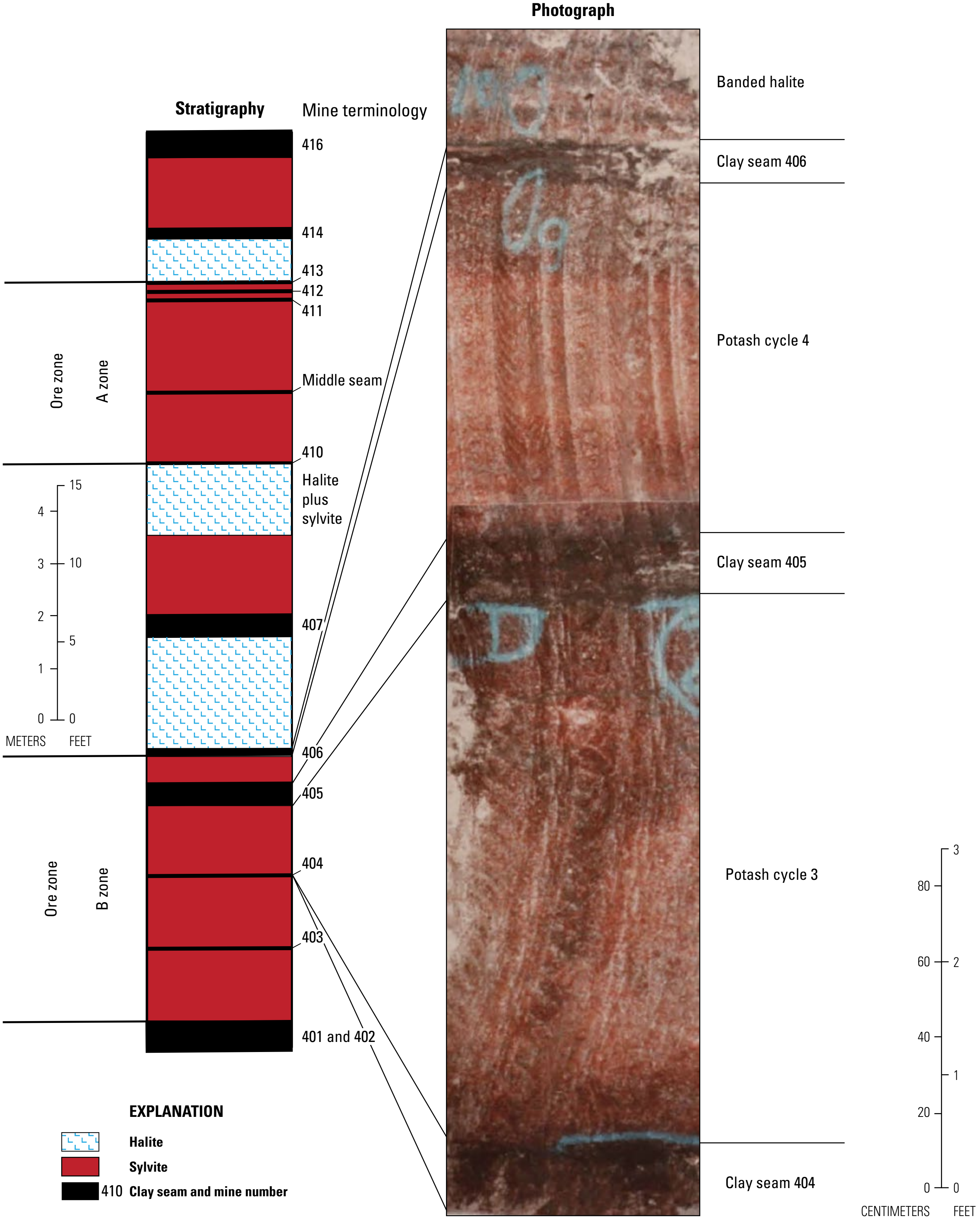


**Figure 11.** Detailed stratigraphy of the Patience Lake Member of the Prairie Evaporite. Modified from Boys (1990) and Moore and others (2010a). The A zone production horizon is the primary source of potash production in mines working this member. The B zone production horizon is being worked in the Lanigan Mine only. Photograph of potash cycles 3 and 4 in the B zone production horizon within the upper portion of the Patience Lake Member at Potash Corporation of Saskatchewan's Cory Mine, Saskatchewan, Canada. Potash cycles are described in the text. Locations of mines are shown in figure 4. Photographs from Boys (1990) with permission from the Department of Geological Sciences at the University of Saskatchewan.

In drill intercepts and mine workings, contacts may be defined by the exploration or mining company using geology, geochemistry (for example, potash grade), or geophysical responses. There appear to be no formal descriptions of these members in the published literature noted above. The upper and lower contacts are not precisely defined in the drill intercepts or mine workings, and lateral differences in a member's contacts are not noted. The absence of descriptions can lead to discrepancies in member thicknesses and assayed intervals, affecting resource calculations within or between different permit or lease areas.

Recently, salt strata between the individual potash members have been evaluated as potential potash resources. These halite interbeds may contain thin beds of potash-bearing salt as well as disseminated potash minerals. Drilling on the Milestone, Legacy, and Muskowekwan project areas investigated the composition of the strata between the Patience Lake and Belle Plaine Members. These strata are referred to as interbed 1 (Stirrett and Gebhardt, 2011; Hardy and others, 2013; Hambley and others, 2015). Interbed 2 refers to the strata between the Belle Plaine and Esterhazy Members (Hardy and others, 2013). In some areas, this interbed may contain the potash-bearing strata referred to as the White Bear Member, but those strata are not commonly identified in recent drilling results given in the NI 43-101 reports.

The salt beds above each potash member are also referred to in the Saskatchewan potash industry as the salt-back of each member. This salt serves as an impermeable barrier to protect the potash-bearing salt and potash mining operations from groundwater intrusion from overlying aquifers. Within each mine, the salt-back may include the overlying parts of each member that are not included in the current mining zone. A minimum salt-back thickness of 9 m is a commonly accepted requirement for conventional underground mining in Saskatchewan (Yang and others, 2009a). Table 6 indicates that the salt-back thicknesses in the operating mines may differ substantially from that 9-m requirement (fig. 12). The general mean thickness of the salt-back above each potash-bearing section has a relatively narrow mean range of 5.5–7.6 m.

Figure 12*A* shows all the salt-back thicknesses measured above the Patience Lake Member as perhaps representing two populations. If these two populations are plotted separately, their mean thicknesses are 27.4 m (fig. 12*B*) and 6.4 m (fig. 12*C*). The mean salt-back thickness shown in figure 12*C* is similar to that of the other members at 6.0, 7.6, and 5.5 m (fig. 12*D*–*F*). The larger mean salt-back thickness shown in figure 12*B* may represent several evaporite cycles where no or little potash was precipitated in the parts of the basin sampled by drill holes.

**Table 6*A*.** Thicknesses of potash members and overlying salt-back of the Prairie Evaporite.

[m, meter; ft, foot]

| Member | Mean thickness (m) | Minimum thickness (m) | Maximum thickness (m) | Local maximum thickness (m) | Mean salt-back thickness (m) | Minimum salt-back thickness (m) | Maximum salt-back thickness (m) | Conventional mining heights (m) |
|---|---|---|---|---|---|---|---|---|
| Patience Lake | 11 | 3 | 18 | 31 | 13.0 | 0.1 | 45 | 3.35–3.7[b] and 4.9[c] |
| Belle Plaine | 7 | 3 | 12 | 23 | 5.5 | 0.1 | 54 | No conventional mines |
| White Bear | 4 | 1 | 10 | 10 | 7.6 | 0.7 | 54 | No conventional mines |
| Esterhazy | 9 | 1 | 15 | 26 | 6.0 | 3.0 | 60 | 2.44[d] and 2.59[e] |

[a] Mining heights based primarily on the mining machines employed and the thickness of high-grade potash. The A zone in Lanigan Mine is cut to a height of 3.7 m (12 ft); B zone borers in Lanigan Mine are 2.7 m high and cut two lifts for a total of 4.9 m (16 ft) (Fracchia and others, 2015).

[b] A zone.

[c] B zone, Lanigan Mine.

[d] Based on older Rocanville machines.

[e] Based on newer Rocanville machines.

**Table 6*B*.** Salt-back thickness (in meters) of operating mines in Saskatchewan.

[Some apparent differences in salt-back thicknesses from different sources in Stone and others (2009). NA, not applicable]

| Member of the Prairie Evaporite | Allan Mine | Belle Plaine Mine | Colonsay Mine | Cory Mine | Esterhazy (K1 and K2) Mine | Lanigan Mine | Patience Lake Mine | Rocanville Mine | Vanscoy Mine |
|---|---|---|---|---|---|---|---|---|---|
| Patience Lake | 18–21 | 1–3 | 12–15 | 15–18 | NA | 3–6 | 1–3 | NA | 9–12 |
| Belle Plaine | 12–15 | 9–12 | 9–12 | 6–9 | 3–6 | 3–6 | NA | NA | NA |
| Esterhazy | NA | 9–12 | NA | NA | 9–12 | NA | NA | 6–9 | NA |

In the Esterhazy and Rocanville Mine areas, the salt-back thickness for the Esterhazy Member is measured from the top of the member to the base of the next overlying potash member or to the top of the Prairie Evaporite. The thickness of the salt-back is quite variable owing to removal of the overlying potash-bearing salt members by subrosion in the updip parts of the basin and overlying the top of the Esterhazy Member, and may reach as much as 60 m (Yang and others, 2009b).

Each member consists of bedded evaporite sequences or cycles (Holter, 1969). Each of these cycles consists of mixtures of halite plus sylvite (or carnallite dominated by halite) at the base that grade upward into dominantly sylvite or carnallite. The amount of insoluble minerals increases upward in each cycle, and the cycles are eventually capped by a thicker bed of insoluble minerals or a clay seam, which become more abundant in the younger members and particularly in the Patience Lake Member (Boys, 1990; Yang and others, 2009b). Insoluble materials within the halite and potash salts are primarily clay, quartz, anhydrite, and dolomite.

Clay seams are numbered according to the member in which they are located and their stratigraphic position within each member (Phillips, 1982). In the Esterhazy Member, clay seams are numbered from 101 to 104 from the lower to upper part of this unit. The White Bear Member contains seams 201 to 203. The Belle Plaine Member contains seams numbered from 301 at the base to 307 at the top. In the Patience Lake Member in the Cory Mine, the clay seams (fig. 11) are numbered from 401 at the base to 416 at the top of the member and include a middle seam between seams 410 and 411 (Boys, 1990). Bedding is remarkably continuous with evaporite cycles and clay seams traceable from mine to mine

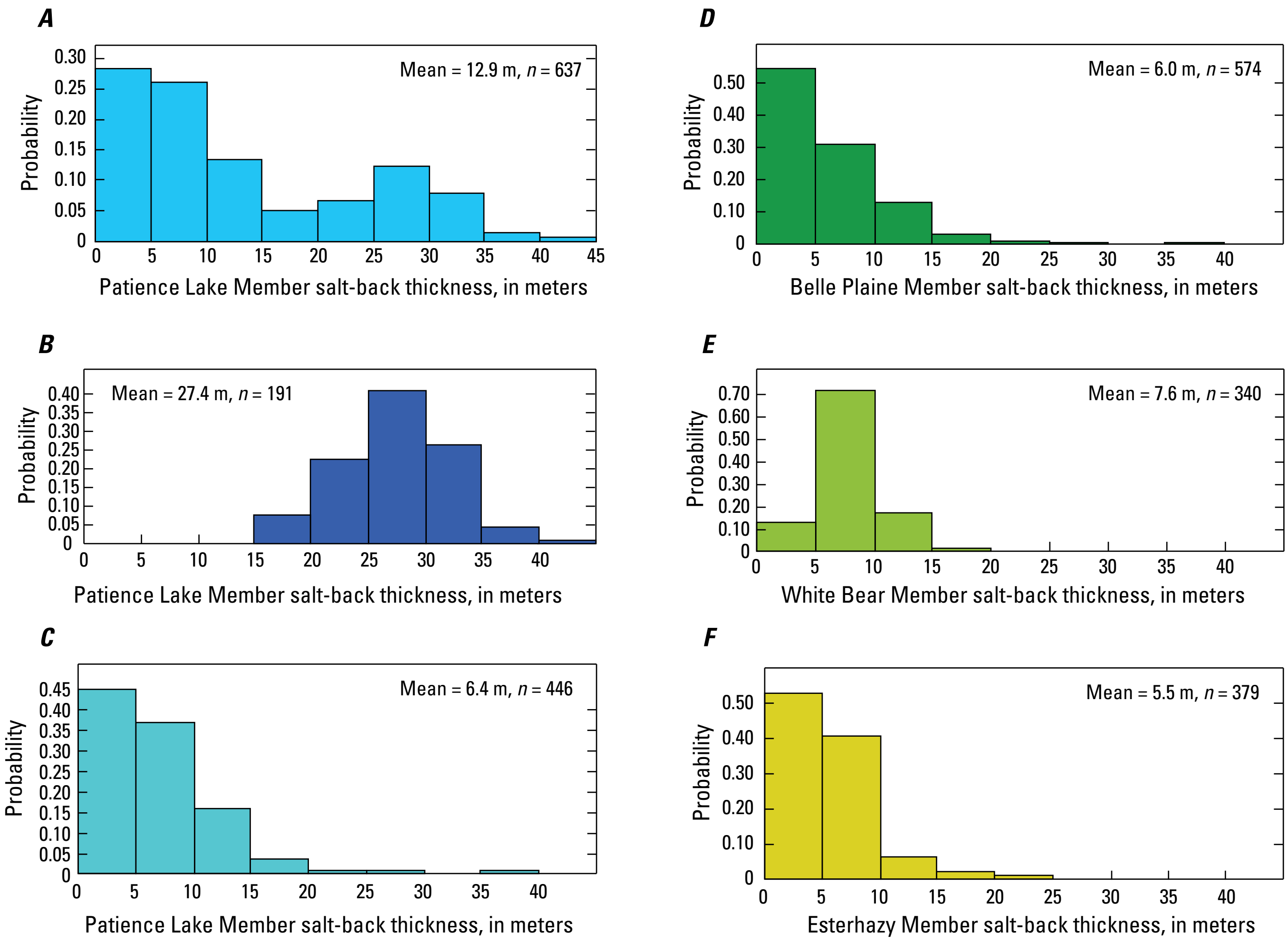


**Figure 12.** Graphs showing salt-back thicknesses of the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members of the Prairie Evaporite as per drill hole (well) data from Yang and others (2009a). Mean values (in meters [m]) and the number of samples (*n*) measured are given. The distribution of salt-back thicknesses for the Patience Lake Member (*A*) suggests two thickness populations. One of these potential populations (*C*) has a mean (6.4 m) and distribution similar to those of the other potash members (*D*, *E*, *F*) and the other (*B*) may represent several evaporite cycles with the potash mineralization absent.

over tens of kilometers or more. The number of clay seams may indicate as many as 16 evaporite cycles occurred during deposition of the Patience Lake Member (fig. 11). Clay seams are commonly used as guides during mining, and overhead seams may be included in the mined ore for safety purposes. Conventional underground mines in the Patience Lake Member include four of these cycles in zones A and B (fig. 11) and will include at least three of the clay seams in the mined ore. Inclusion of the clay seams dilutes the potash grade and adversely affects ore processing.

Primary bedding details and secondary dissolution features are best observed in the conventional underground mine workings in the Patience Lake Member and are described by Holter (1969) and Boys (1990). These features are described in this report in the “Patience Lake Member” and “Alteration and Solution Effects on the Prairie Evaporite” sections and are probably present in the other potash members of the Elk Point Basin. In some areas of the Elk Point Basin, the thicknesses of the potash beds may narrow to zero and reflect primary non-deposition or secondary dissolution. Thicknesses of less than 1 m may not be recognized during downhole geophysical or geological logging.

The potash-bearing members represent the culmination of moderate-scale, cyclic, evaporite deposition on the order of tens of meters. The lowermost and relatively complete evaporite cycle consists of the Winnipegosis Formation carbonate rocks, anhydrite, and halite in the lower part of the Prairie Evaporite, which culminates in potash-bearing salt of the Esterhazy Member. The halite to potash-bearing salt sequences of the White Bear, Belle Plaine, and Patience Lake Members represent three additional potash-evaporite cycles (Yang and others, 2009b) that may be equivalent to the fifth-order sequences of Moore (1993). The Mountrail and White Lake members in North Dakota (Kruger, 2014) may represent two additional potash-evaporite cycles.

Based on a GIS analysis of the areas presently underlain by salt and the salt dissolution areas shown in figure 3, salt once covered at least 628,000 km$^2$ (approximately 52 percent) of the basin area. Presently, only 40 percent of the basin is underlain by salt; the rest is underlain by limestone. Zharkov (1984) estimated a minimal salt volume of the basin to be 40,000 cubic kilometers (km$^3$) based on a salt extent of 350,000 km$^2$. Using that estimate and the presently known extent of the salt, the present volume of salt may be on the order of 55,000 km$^3$. An approximate estimate of the volume of present-day seawater that would be required to produce that volume of salt is on the order of 3,000,000 km$^3$ (based on data from Braitsch, 1971, and Pohl, 2011).

Potash-bearing salt of the Prairie Evaporite underlies a total area of about 188,000 km$^2$, which represents approximately 39 percent of the present salt area or 30 percent of the former postulated extent of the salt (fig. 3). The average volume of potash-bearing salt for all of the members combined is approximately 2,700 km$^3$. With an average KCl content of about 29 percent, the volume of KCl would be approximately 780 km$^3$. The ratio of halite to sylvite is estimated to be 70:1 in the Elk Point Basin. The solution embayments show that a substantial part of the potash-bearing salt has also been removed by solution. The northern and southern edges of the Prairie Evaporite are marked by a solution collapse breccia consisting of younger, overlying insoluble strata (Holter, 1969; Meijer Drees, 2008). The present total volume of the potash-bearing salt is about 2,690 km$^3$. Based on the previous estimate of total salt volume, the potash-bearing salt occupies approximately 5 percent by volume of the Prairie Evaporite salt.

## Esterhazy Member

The Esterhazy Member is the lowest potash-bearing member of the Prairie Evaporite and is the second-leading potash producer, mainly in the eastern part of the Saskatchewan subbasin where depth, grade, salt-back, and sylvinite thickness are favorable for conventional underground mining. The Rocanville; Rocanville West; and K1, K2, and K3 (Esterhazy) mines (fig. 4) recover potash from the Esterhazy Member. The St. Lazare and Triton (or Leech Lake) potash projects (fig. 4) are projected to eventually become conventional underground mines in the Esterhazy Member. Updated information on the status of these projects appears not to have been posted since reports by Bout and Chiang (2008) or Nicolas (2016).

The Esterhazy Member slopes southwestward at 3–7 m/km. Depths to the top of the Esterhazy Member range from about 840 m along the northeastern edge of the tract to 2,756 m in southeastern Saskatchewan (Yang and others, 2009b) and to more than 3 km in North Dakota and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979; Kruger, 2014). The increasing depth to the south technically rules out conventional and solution mining much beyond the current mines noted above. The Milestone Mine in the southwestern part of the Elk Point Basin is presently the deepest using solution-mining techniques at a depth of approximately 1,770 m (Hambley and others, 2015). The depth of 3 km (fig. 4) marks the limit of technically feasible mining.

Detailed lithologic information regarding the Esterhazy Member is difficult to find or is absent from publicly available literature. The available information indicates that this member is composed of several beds of sylvinite or local carnallitite separated by halite interbeds and clay seams (Holter, 1969; Moore and others, 2010d; Rauche and others, 2016). In the Wynyard permit area, three distinct high-grade sylvite-bearing salt horizons are separated by lower grade sylvite-bearing salt and are grouped into two mineralized zones: Esterhazy zone 1 and Esterhazy zone 2 (Rauche and others, 2016). Division of the Esterhazy Member into various mineralized zones is governed, in part, by the mining method proposed to be used to recover the potash and magnesium chloride ($MgCl_2$).

A description of the Esterhazy Member in the Esterhazy K1 mine indicates a series of low to medium grade sylvite-bearing halite beds (nos. 1–35) overlying the medium to high grade mining zone beds (nos. 40–50; fig. 13). Thickness of the upper beds in Esterhazy K1 mine is about 6.4 m, and thickness of the lower beds is 2.6 m (Keys and Wright, 1966). The Esterhazy Member thickness is commonly expressed in terms of the best $K_2O$ equivalent grade for 2.44 m, 2.59 m, or mining height (Bannatyne, 1983; Fracchia and others, 2017a), which would be similar to the mined interval described by Keys and Wright (1966). Potash grades for conventional underground mines range from 22 to 24.5 percent $K_2O$ equivalent (tables 7, 8, 9). Potash grades for solution mines may range from 10.4 to 22 percent $K_2O$ equivalent. Lower grades for solution mines result from inclusion of lower grade and possibly carnallitic material in the solution mining. In the area of the Legacy Mine, this member is also characterized by being typically coarser grained (mineral diameters greater than 2–3 cm) than the other members (Hardy and others, 2009a).

Support pillars are still required to limit ground subsidence above solution mine workings (Halabura and Hardy, 2007). Mine plans for the Patience Lake, Legacy, Belle Plaine, and Milestone Mines (Halabura and Hardy, 2007; Hardy and Halabura, 2007; Hardy and others, 2013) and for several new potash projects (Muskowekwam and Wynyard) call for pillars around exploration drill holes and potash production caverns (Stirrett and others, 2013; Rauch and others, 2016). Pillars account for approximately 35–40 percent of the potash contained within the mined member(s), and the salt interbeds between the members are regarded as a resource (Hardy and Halabura, 2007; Hardy and others, 2013; Rauche and others, 2016). Resources are reduced to account for cavern loss which is related to the amount of concentrated brine remaining in the cavern at closure.

The Esterhazy Member contains the least amount of insoluble minerals (with a mean of 1.87 percent disseminated insoluble minerals based on drill hole data in the Milestone and Wynyard NI 43-101 project reports [Piché and others, 2011; Rauche and others, 2012, 2016; Hardy and others, 2013; Hambley and others, 2015]) or as clay seams (nos. 101–104; Phillips, 1982). The location of these clay seams relative to the bedding of the Esterhazy Member shown in figure 13 is not documented in the available literature (Keys and Wright, 1966; Hambley and others, 2011).

Carnallite is present in varying amounts (Stoner and Mackintosh, 2012) as interstitial, reddish-orange amorphous crystal masses commonly rimming sylvite (Myers and others, 2017) or as carnallitite in the Esterhazy K1 mine (Keys and Wright, 1966). Holter (1969) notes that the Esterhazy Member contains the lowest percentage of carnallite in the Prairie Evaporite. Most reported carnallite grades are less than 6 percent with the higher carnallite grades (as high as nearly 14 percent) reported in wells within the Muskowekwam, Yorkton, and Wynyard project areas (Hardy and Halabura, 2008; Rauche and others, 2016; Myers and others, 2017). The carnallite-bearing salt in the Milestone Mine and Wynyard project area and the Esterhazy K1 mine is thought to be primary carnallite that has not been altered to secondary sylvite (Keys and Wright, 1966; Hambley and others, 2011). Alteration of the top of the carnallite has left a carnallite-sylvite contact (fig. 13) along the top of the ore zone.

An isopach map of this member was produced from drill hole data (Great Northern Railway Company, 1965; Bannatyne, 1983; Western Potash Corp., 2008; Yang and others, 2009a), which are shown in figure 14. The mean thickness of the Esterhazy Member is 9 m (Yang and others, 2009b). In the area between Regina and Moose Jaw, unit thickness may exceed 15 m, and in the area between Melville and Quill Lake, this member may be as thick as 26 m (fig. 15). In Manitoba, thicknesses of this member range from 1.52 to 4.2 m (Bannatyne, 1983; Western Potash Corp., 2008). Based on drill hole data (Yang and Love, 2015), there is a strong correlation of carnallitite thickness (fig. 16) with member thickness ($r^2$=0.9977). In other words, as the ratio of amount of contained carnallitite to member thickness increases, so does the thickness of the member.

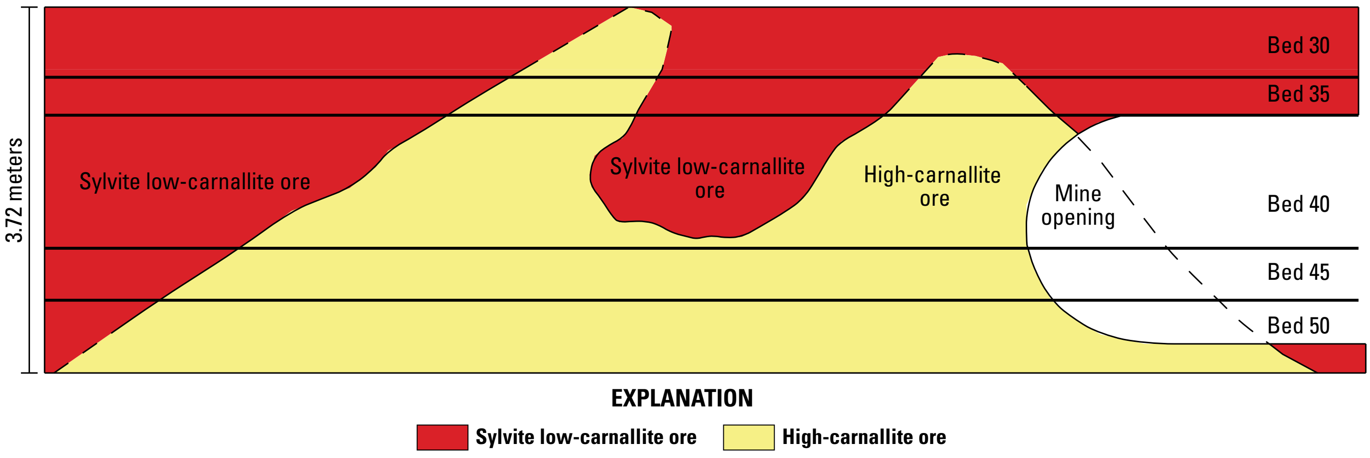


**Figure 13.** Cross section of the Esterhazy Member potash-bearing beds 40–50 and the sylvite-carnallite contact in the Esterhazy Mine, Saskatchewan, Canada. Modified from Keys and Wright (1966).

**Table 7.** Known and estimated resources of potash within the Patience Lake Member, tract 003sbK0001a, Canada and the United States.

[Grades and tonnages dependent on mine type. Zones included in solution mines are presumed to be both zones A and B. Please see operational definitions of discovered and undiscovered resources in this report. Production data as of date of cited references. For these determinations, the mean grade (percentage of $K_2O$ equiv.) is 21.67 (SD = 4.3), mean tonnage is 3.76 Bt (SD = 3.36 Bt), and mean contained $K_2O$ eqiv. is 0.856 Bt (SD = 0.760 Bt). Bt, billion metric tons; conv., conventional underground mine; equiv., equivalent; $K_2O$, potassium oxide; MOP, muriate of potash (KCl); nd, no data; prod., production; res., reserves; SD, standard deviation; sol., underground solution mine; yr, year; %, percent]

| Mine or project name | Patience Lake Member zone | Latitude | Longitude | Calculated tonnage (Bt, in place) | Reported tonnage (Bt, in place) | Ore grade (% $K_2O$ equiv.) | Contained $K_2O$ equiv. (Bt, in place) | Mine type | Prod. | Prod. finished product MOP (Bt) | Prod. finished product $K_2O$ (Bt) | Prod. time (yr) | Prod. plus contained total tonnage (Bt) | Prod. plus conatained total $K_2O$ tonnage (Bt) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Allan | A | 51.9318 | −106.0744 | nd | 4.076 | 24.800 | 1.011 | Conv. | Yes | nd | nd | nd | nd | nd | Moore and others (2010c); Fracchia and others (2017a); Funk and others (2018a) |
| Allan | B | 51.9318 | −106.0744 | nd | 4.611 | 20.400 | 0.941 | Conv. | Yes | nd | nd | nd | nd | nd | Fracchia and others (2017a); Funk and others (2018a) |
| Allan | Res. | 51.9318 | −106.0744 | nd | 0.335 | 24.800 | 0.083 | Conv. | Yes | nd | nd | nd | nd | nd | Fracchia and others (2017a); Funk and others (2018a) |
| Allan (total) | A, B, res. | 51.9318 | −106.0744 | nd | 9.022 | 22.770 | 2.035 | Conv. | Yes | 0.053 | 0.032 | 49 | 9.461 | 2.067 | Fracchia and others (2017a); Funk and others (2018a) |
| Belle Plaine | A, B | 50.4295 | −105.1976 | 4.275 | 4.095 | 18.000 | 0.770 | Sol. | Yes | nd | 0.737 | nd | nd | 1.507 | Mosaic Company (2016); IMC Global (2004) |
| Legacy (Bethune, Findlater) | A, B | 50.6460 | −105.3785 | 15.429 | 15.429 | 20.000 | 3.083 | Sol. | Yes | 0.01 | nd | nd | nd | 3.083 | Hardy and others (2009a); K+S Potash Canada, Ltd. (2017) |
| Burr | A, B | 52.0121 | −105.1949 | 1.325 | 1.325 | 22.400 | 0.297 | Conv. | No | nd | nd | nd | nd | nd | Lomas (2008) |
| Colonsay | A, B | 51.9331 | −105.7664 | 1.774 | 1.825 | 25.700 | 0.469 | Conv. | Yes | 0.060 | 0.040 | nd | 1.889 | 0.506 | British Sulphur Corp., Ltd. (1984); IMC Global (2004); Mackintosh (2006); Mosaic Company (2016) |
| Cory | A | 52.0930 | −106.8534 | nd | 2.060 | 22.500 | 0.464 | Conv. | Yes | nd | nd | nd | nd | nd | Moore and others (2010b) |
| Cory | B | 52.0930 | −106.8534 | nd | 3.142 | 20.400 | 0.641 | Conv. | Yes | nd | nd | nd | nd | nd | Fracchia and others (2017a); Funk and others (2018a) |
| Cory | Res. | 52.0930 | −106.8534 | nd | 0.249 | 22.800 | 0.057 | Conv. | Yes | nd | nd | nd | nd | nd | Fracchia and others (2017a); Funk and others (2018a) |
| Cory (total) | A, B, res. | 52.0930 | −106.8534 | nd | 5.451 | 21.303 | 1.161 | Conv. | Yes | 0.0363 | 0.0214 | 48 | 5.949 | 1.184 | Fracchia and others (2017a); Funk and others (2018a) |
| Jansen | A, B | 51.8996 | −104.7140 | 3.370 | 3.705 | 25.400 | 0.941 | Conv. | No | nd | nd | nd | nd | nd | Halabura and others (2005); BHP Billiton (2010) |
| Langham | B | 52.3810 | −106.9110 | 0.046 | 0.048 | 31.000 | 0.015 | Conv. | No | nd | nd | nd | nd | nd | Hardy and others (2009b) |
| Lanigan | A | 51.8529 | −105.2083 | nd | 4.084 | 23.500 | 0.960 | Conv. | Yes | nd | nd | nd | nd | nd | Moore and others (2010a) |

**Table 7.** Known and estimated resources of potash within the Patience Lake Member, tract 003sbK0001a, Canada and the United States.—Continued

| Mine or project name | Patience Lake Member zone | Latitude | Longitude | Calculated tonnage (Bt, in place) | Reported tonnage (Bt, in place) | Ore grade (% $K_2O$ equiv.) | Contained $K_2O$ equiv. (Bt, in place) | Mine type | Prod. | Prod. finished product MOP (Bt) | Prod. finished product $K_2O$ (Bt) | Prod. time (yr) | Prod. plus contained total tonnage (Bt) | Prod. plus conatained total $K_2O$ tonnage (Bt) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lanigan | B | 51.8529 | −105.2083 | nd | 5.329 | 20.300 | 1.082 | Conv. | Yes | nd | nd | nd | nd | nd | Funk and others (2018b) |
| Lanigan | A, res. | 51.8529 | −105.2083 | nd | 0.468 | 23.500 | 0.110 | Conv. | Yes | nd | nd | nd | nd | nd | Funk and others (2018b) |
| Lanigan | B, res. | 51.8529 | −105.2083 | nd | 0.303 | 20.300 | 0.062 | Conv. | Yes | nd | nd | nd | nd | nd | Funk and others (2018b) |
| Lanigan (total) | A, B, res. | 51.8529 | −105.2083 | nd | 10.184 | 21.730 | 2.213 | Conv. | Yes | 0.058 | 0.0365 | 49 | 9.378 | 2.249 | Funk and others (2018b) |
| Lazlo[a] | A, B | 51.0492 | −105.8333 | 0.346 to 0.662 | 0.660 | 22.350 | 0.0518 to 0.148 | Sol. | No | nd | nd | nd | nd | nd | Hambley and Halabura (2014) |
| Milestone | A, B | 50.2394 | −104.2639 | 4.477 | 4.477 | 17.600 | 0.787 | Sol. | No | nd | nd | nd | nd | nd | Western Potash Corp. (2010) |
| Muskowekwam | A, B | 51.3280 | −104.0831 | 1.067 | 1.067 | 19.000 | 0.203 | Sol. | No | nd | nd | nd | nd | nd | Stirrett and Gebhardt (2011); Stirrett and others (2013); Myers and others (2017) |
| Patience Lake | A, B | 52.0895 | −106.3765 | 0.362 | 0.362 | 18.000 | 0.065 | Sol. | Yes | 0.06 | 0.04 | nd | nd | 0.102 | Mackintosh (2006) |
| Vanscoy | A, B | 52.0088 | −107.0916 | 1.943 | 1.943 | 24.500 | 0.476 | Conv. | Yes | nd | nd | nd | nd | nd | Mackintosh (2006, 2009); Bartsch and others (2014) |
| Vanscoy | A, B | 52.0088 | −107.0916 | 0.232 | 0.232 | 25.300 | 0.059 | Conv. | Yes | nd | nd | nd | nd | nd | Mackintosh (2006, 2009); Bartsch and others (2014) |
| Vanscoy | A, B | 52.0088 | −107.0916 | 2.175 | 2.175 | 24.594 | 0.535 | Conv. | Yes | 0.061 | 0.04 | nd | nd | 0.573 | Mackintosh (2006, 2009); Bartsch and others (2014); Funk and others (2019) |
| Vanguard[b] | A, B | 50.8410 | −106.2208 | 2.427 | 2.427 | 22.400 | 0.544 | Sol. | No | nd | nd | nd | nd | nd | Fourie (2017); Fourie and others (2018) |
| Wynyard | A, B | 51.7062 | −104.1063 | 2.662 | 2.662 | 10.900 | 0.289 | Sol. | No | nd | nd | nd | nd | nd | Piché and others (2011); Rauche and others (2016) |
| Total known resource | | | | nd | 54.098 | 24.782 | 13.406 | All | All | nd | nd | nd | nd | nd | |
| Total resource for producing mines | | | | nd | 48.078 | 23.342 | 10.742 | All | Yes | nd | nd | nd | nd | nd | |

[a] Values listed are potential mineralization estimates (which are not National Instrument 43-101 compliant) and are not included in totals.

[b] Updated grade and tonnage data for Vanguard lease area from Fourie and others (2018) are not included in this assessment.

**Table 8.** Known and estimated resources of potash within the Belle Plaine Member, tract 003sbK0001b, Canada and the United States.

[Grades and tonnages dependent on mine type. Please see operational definitions of discovered and undiscovered resources in this report. Production data as of 2019. For these determinations, the mean grade (percentage of $K_2O$ equiv.) is 17.86 (SD = 3.82), mean tonnage is 2.79 Bt (SD = 2.99 Bt), and mean contained $K_2O$ eqiv. is 0.453 Bt (SD = 0.425 Bt). Avg., average; Bt, billion metric tons; equiv., equivalent; $K_2O$, potassium oxide; SD, standard deviation; %, percent]

| Mine or project name | Latitude | Longitude | Tonnage (Bt, in place) | Ore grade (% $K_2O$ equiv.) | Contained $K_2O$ equiv. (Bt) | Mine type | Production | References |
|---|---|---|---|---|---|---|---|---|
| Belle Plaine | 50.4295 | −105.1976 | 2.138 | 18.000 | 0.385 | Solution | Yes | IMC Global (2004); Mosaic Company (2016) |
| Legacy (Bethune, Findlater) | 50.6460 | −105.3785 | 7.476 | 18.400 | 1.373 | Solution | Yes | Hardy and others (2009a) |
| Jansen | 51.7830 | −104.7170 | 1.857 | 21.700 | 0.402 | Conventional | No | Halabura and others (2005); BHP Billiton (2010) |
| Langham | 52.3810 | −106.9110 | 0.246 | 20.800 | 0.051 | Conventional | No | Hardy and others (2009b) |
| Milestone | 50.2394 | −104.2639 | 2.079 | 17.600 | 0.367 | Solution | No | Western Potash Corp. (2010) |
| Muskowekwam | 51.3280 | −104.0831 | 1.131 | 18.600 | 0.211 | Solution | No | Stirrett and Gebhardt (2011); Stirrett and others (2013); Myers and others (2017) |
| Wynyard | 51.7062 | −104.1063 | 3.870 | 9.900 | 0.384 | Solution | No | Piché and others (2011); Rauch and others (2016) |
| Lazlo[a] | 51.0492 | −105.8333 | 0.324 to 0.368 | 19.930 | 0.0486 to 0.0734 | Solution | No | Hambley and Halabura (2014) |
| Vanguard[b] | 50.8410 | −106.2208 | 1.015 | 20.370 | 0.207 | Solution | No | Fourie (2017); Fourie and others (2018) |
| Total known resource | | | 19.812 | 17.86 (avg.) | 3.380 | All | | |
| Total reource for producing mines | | | 9.614 | 18.275 | 1.758 | All | Yes | |

[a] Values listed are potential mineralization estimates (which are not National Instrument 43-101 compliant) and are not included in totals.

[b] Updated grade and tonnage data for Vanguard lease area from Fourie and others (2018) are not included in this assessment.

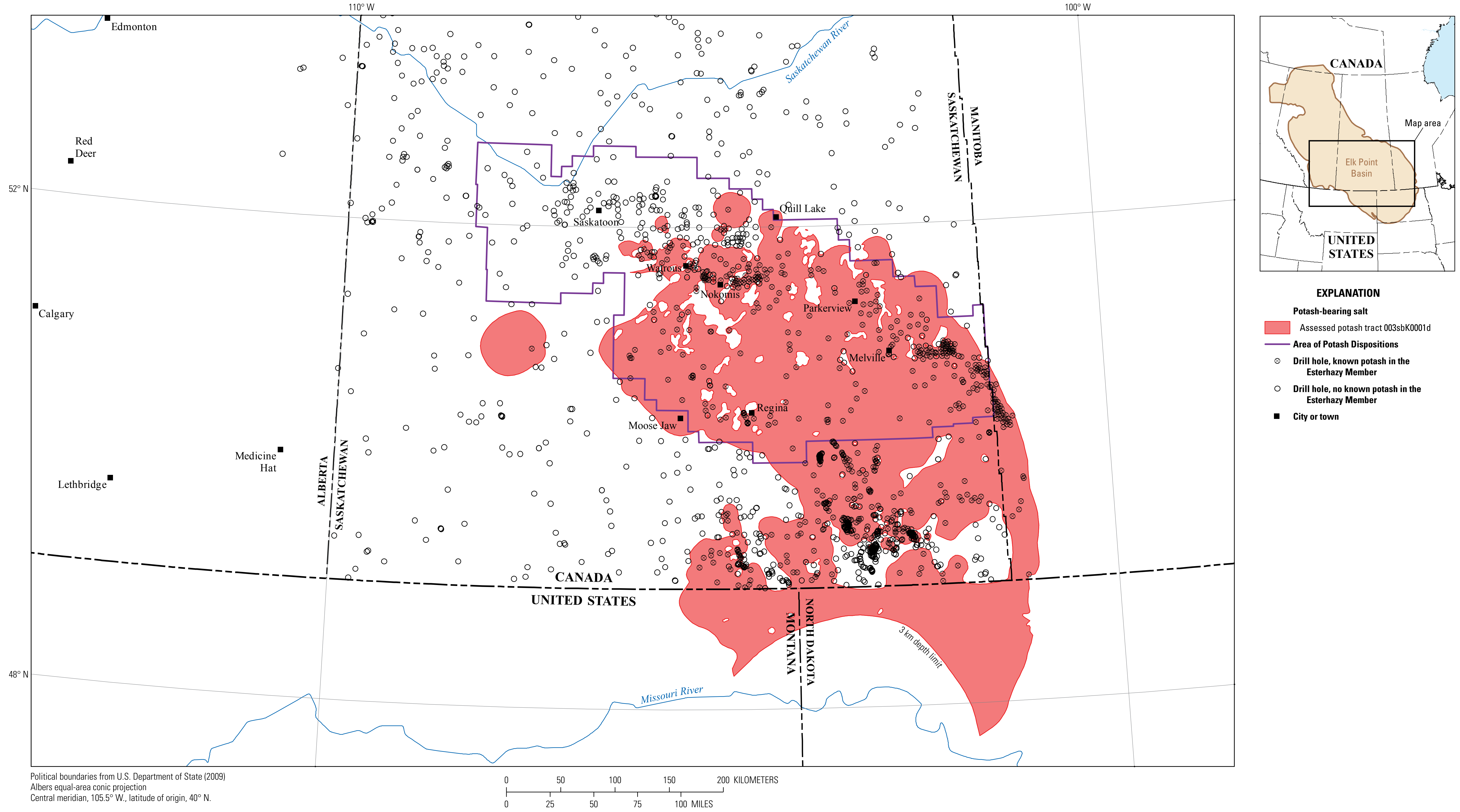
**Table 9.** Known and estimated resources of potash within the Esterhazy Member, tract 003sbK0001d, Canada and the United States.

[Grades and tonnages dependent on mine type. Please see operational definitions of discovered and undiscovered resources in this report. Production data as of 2019. For these determinations, the mean grade (percentage of $K_2O$ equiv.) is 21.07 (SD = 4.35), mean tonnage is 6.41 Bt (SD = 7.73 Bt), and mean contained $K_2O$ eqiv. is 1.51 Bt (SD = 1.93 Bt). Bt, billion metric tons; equiv., equivalent; $K_2O$, potassium oxide; nd, no data; SD, standard deviation; %, percent]

| Mine or project name | Latitude | Longitude | Tonnage (Bt, in place) | Grade (% $K_2O$ equiv.) | Contained $K_2O$ equiv. (Bt) | Mine type | Production | Reference |
|---|---|---|---|---|---|---|---|---|
| Belle Plaine | 50.4295 | −105.1976 | 2.138 | 18.000 | 0.385 | Solution | Yes | IMC Global (2004); Mosaic Company (2006, 2009) |
| Legacy (Bethune, Findlater) | 50.6853 | −105.3530 | 7.211 | 16.800 | 1.211 | Solution | Yes | Hardy and others (2009a) |
| Esterhazy (K1) | 50.7277 | −101.9316 | 3.337[2] | 24.4[b] | 0.814[b] | Conventional | Yes | IMC Global (2004); Mackintosh (2006); Mosaic Company (2016) |
| Esterhazy (K2) | 50.6629 | −101.8610 | [b] | [b] | [b] | Conventional | Yes | IMC Global (2004); Mackintosh (2006), Mosaic Company (2016) |
| Esterhazy (K3) | 50.6445 | −101.9949 | nd | nd | nd | Conventional | Yes | Berube (2012) |
| Lazlo[a] | 51.0492 | −105.8333 | 0.167 to 0.378 | 15.720 | 0.0250 to 0.0595 | Solution | No | Hambley and Halabura (2014) |
| Milestone | 50.2394 | −104.2639 | 2.269 | 22.000 | 0.498 | Solution | No | Western Potash Corp. (2010) |
| Rocanville | 50.4726 | −101.5450 | 4.489 | 23.400 | 1.050 | Conventional | Yes | Funk and others (2018b) |
| Rocanville reserves | 50.4726 | −101.5450 | 0.550 | 23.400 | 0.129 | Conventional | Yes | Funk and others (2018b) |
| Rocanville reserves and resources | 50.4726 | −101.5450 | 5.039 | 23.400 | 1.179 | Conventional | Yes | Funk and others (2018b) |
| Rocanville West (Scissors Creek) | 50.4527 | −101.7701 | nd | nd | nd | Conventional | Yes | Funk and others (2018c) |
| Russell[a] | 50.6600 | −101.3700 | 0.392 | 22.500 | 0.089 | Conventional | No | Banatyne (1983); Bamburak (2007); Bout and Chiang (2008); Nicolas (2015, 2016) |
| St. Lazare[a] | 50.3170 | −101.3144 | 6.372 | 22.000 | 1.402 | Conventional | No | Bannatyne (1983); Bamburak (2007); Bout and Chiang (2008); Nicolas (2015, 2016) |
| Triton | 51.0723 | −102.5524 | 3.502 | 24.500 | 0.858 | Conventional | No | Bout and Chiang (2008) |
| Wynyard | 51.7062 | −104.1063 | 2.499 | 10.400 | 0.261 | Solution | No | Piché and others (2011) |
| Total known resource | | | 32.759 | 20.444 | 6.697 | All | | |
| Total resources for producing mines | | | 9.964 | 22.578 | 2.250 | All | Yes | |

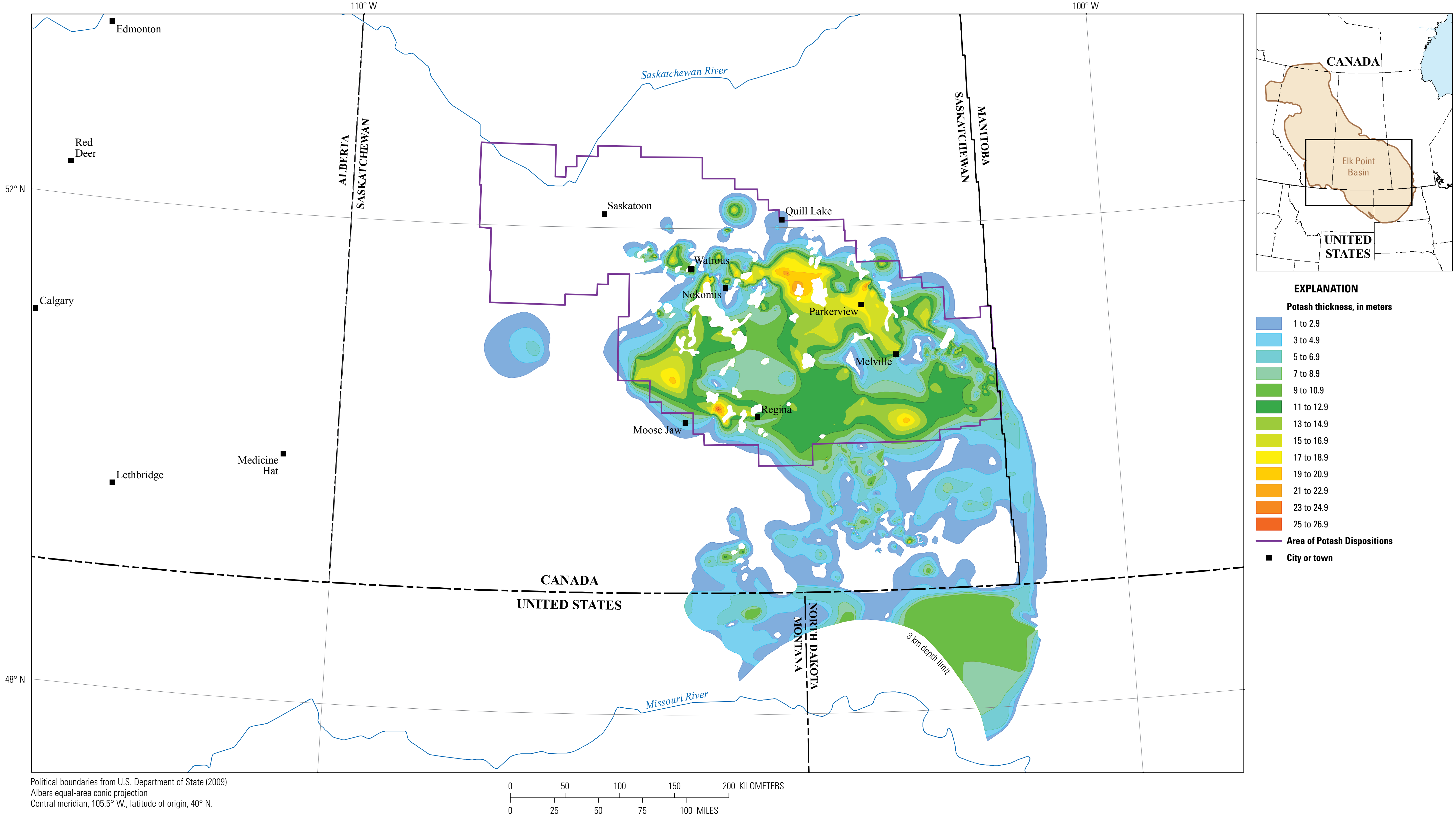
[a] Values listed are potential mineralization estimates (which are not National Instrument 43-101 compliant) and are not included in totals.

[b] Data for mines K1 and K2 are combined in the cited references.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 14.** Map of the location and extent of permissive tract 003sbK0001d that includes the Esterhazy Member of the Prairie Evaporite in Canada and the United States. The drill holes in Canada that were used to define the permissive tract and construct the isopach map (fig. 15) are shown (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979; Bannatyne, 1983; Western Potash Corp., 2008; Yang and others, 2009a). km, kilometer.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 15.** Isopach map showing the thickness of potash in permissive tract 003sbK0001d that includes the Esterhazy Member of the Prairie Evaporite in Canada and the United States. Contours are derived mainly from the dirll holes in figure 14. km, kilometer.

With few published descriptions of the Esterhazy Member, the delineation of the vertical extent of this member may differ between wells and potash mines. Resource and reserve grades reported in NI 43-101 reports are estimated by using different portions of the stratigraphic section for deep solution mines such as Legacy, Belle Plaine, and Milestone Mines as compared to those of the Rocanville and Esterhazy conventional mines. In the Milestone Mine and Wynyard project areas, for example, the top of the Esterhazy Member is placed at the top of the first sylvinite bed below the salt of interbed 2, and the lower boundary is placed at the base of the sylvinite bed at the contact with the underlying barren halite (Hardy and others, 2013; Rauche and others, 2016). At first glance, this definition of the lower boundary may be appropriate.

However, many of the potash exploration projects do not drill to the depths of the Esterhazy Member and, of those that do, most do not drill or assay below the base of the Esterhazy Member as defined by down-hole geophysics. In the Milestone Mine, the well data indicate the presence of potash minerals above and below the defined top and base of the Esterhazy Member (fig. 9) in six drill holes. In the WPX Western Riceton 4-35-14-17 W2M well, the potash-bearing salt containing carnallite is separated from the defined base of the Esterhazy Member by approximately 10 m. In the WPX Western Riceton 13-14-14-17 W2M well, the carnallite may extend 15 m below the base of the Esterhazy Member. In the Wynyard project area, the top and bottom of the potash—indicated by the presence of $K_2O$ and carnallite—extend beyond the defined top and base of the Esterhazy Member (Rauche and others, 2016). In the Muskowekwam project area, carnallite is present for about 10 m below the identified base of the Esterhazy Member (Stirrett and others, 2013; Myers and others, 2017).

The lowermost drilled carnallite may be considered part of the Esterhazy Member or may be part of a separate potash-bearing salt unit. The extent of the thicker parts of the Esterhazy Member is unknown and affects calculations of tract volume and hence estimated tonnages of undiscovered potash, as described in the "Potash Exploration and Mine Development within the Elk Point Basin" section. It would appear from these occurrences that carnallite began to precipitate prior to sylvinite as the presently defined base of the Esterhazy Member in the Elk Point Basin or that sylvinite was altered from the underlying carnallite.

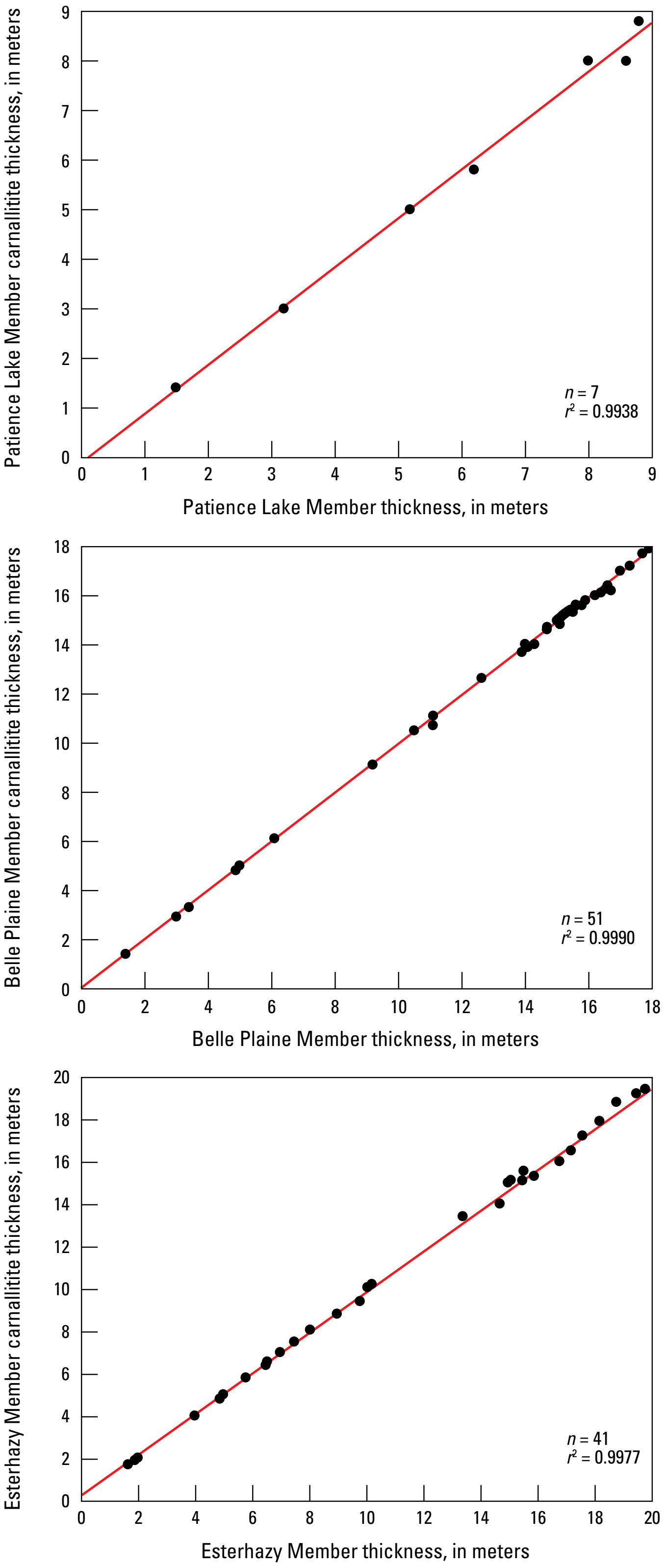


**Figure 16.** Plots of carnallitite thickness versus member thickness for the Patience Lake Member (*A*), Belle Plaine Member (*B*), and Esterhazy Member (*C*). The carnallitite thickness to member thickness ratio for the Esterhazy Member ranges from 0.8 to 1.00 (*n*=41). Sample counts (*n*) and correlation coefficients ($r^2$) are given for each plot.

## Interbed 2

Interbed 2 is an informal section of potash-bearing salt between the top of the Esterhazy Member and the base of the Belle Plaine Member and includes the White Bear Member (fig. 9). Interbed 2 consists dominantly of halite with disseminated sylvite and carnallite, plus generally thin, sylvite- and carnallite-bearing halite beds and halite (Holter, 1969; Hardy and others, 2009a, 2010a, 2013). Because of recent interest in solution mining parts—specifically, interest in all of the sections including the Belle Plaine Member to the Esterhazy Member—some potash projects have included interbed 2 in their assessments (Hardy and others, 2009a, 2013) but not in their resource calculations. Reported thicknesses range from 11.10 to 43 m in the northern edge of the Saskatchewan subbasin (Holter, 1969). Available potash grades range from 1.60 to 5.10 percent $K_2O$ equivalent. Carnallite content is generally low and ranges from 0.36 to 0.57 percent. The insoluble mineral content is low: only about 1.23–4.65 percent $K_2O$ equivalent based on drill hole data in the NI 43-101 reports (Hardy and others, 2009a, 2013). This USGS assessment did not attempt to contour the available drill hole data, and the potash resources contained in this stratigraphic interval were not estimated except for that portion identified as the White Bear Member.

## White Bear Member

Historically, the White Bear Member has been regarded as a marker bed (Holter, 1969) and not as an economic source of potash because of its thickness, generally lower potash grade, distribution, and greater depths than the Patience Lake and Belle Plaine Members. Because this member has commonly been referred to as a marker bed, its presence in any particular well may not be reported, or the interval may not be analyzed because of a weak geophysical signature. In other cases, it actually may not be present (fig. 9). In some wells, the White Bear Member is recognized as a single interval of potash-bearing salt. It may be included in the interbed 2 interval in recently drilled wells reported in some NI 43-101 reports. In other wells, intervals with several potash-rich strata are collectively called the White Bear Member (Hardy and others, 2009a). In Manitoba, Bamburak and Nicolas (2009) refer to an upper potash intercept as the Pink Panther potash bed and the lower intercept as the White Bear potash member. This is an informal division of the White Bear Member into submembers of potash-rich intervals separated by intervals containing lesser amounts of potash. The actual extent, thickness, and potash grade of this member appear not to be as consistent as those of the other members (figs. 17, 18). Careful examination of those drill holes where potash-bearing strata have not been identified as belonging to the White Bear Member may extend the range of this member beyond what is shown in figure 18.

Based on thickness data from wells shown in figure 17, an isopach map of the White Bear Member shows its extent and variations in thickness (fig. 18). In Saskatchewan, the thickness of the White Bear Member ranges from 1 to 10 m with a mean of 4 m (table 6*A*). This unit is thickest in southeastern Saskatchewan (Worsley and Fuzesy, 1979; Yang and others, 2009b). In Manitoba, thicknesses of the White Bear Member range from 1.52 to 2.5 m (Bannatyne, 1983).

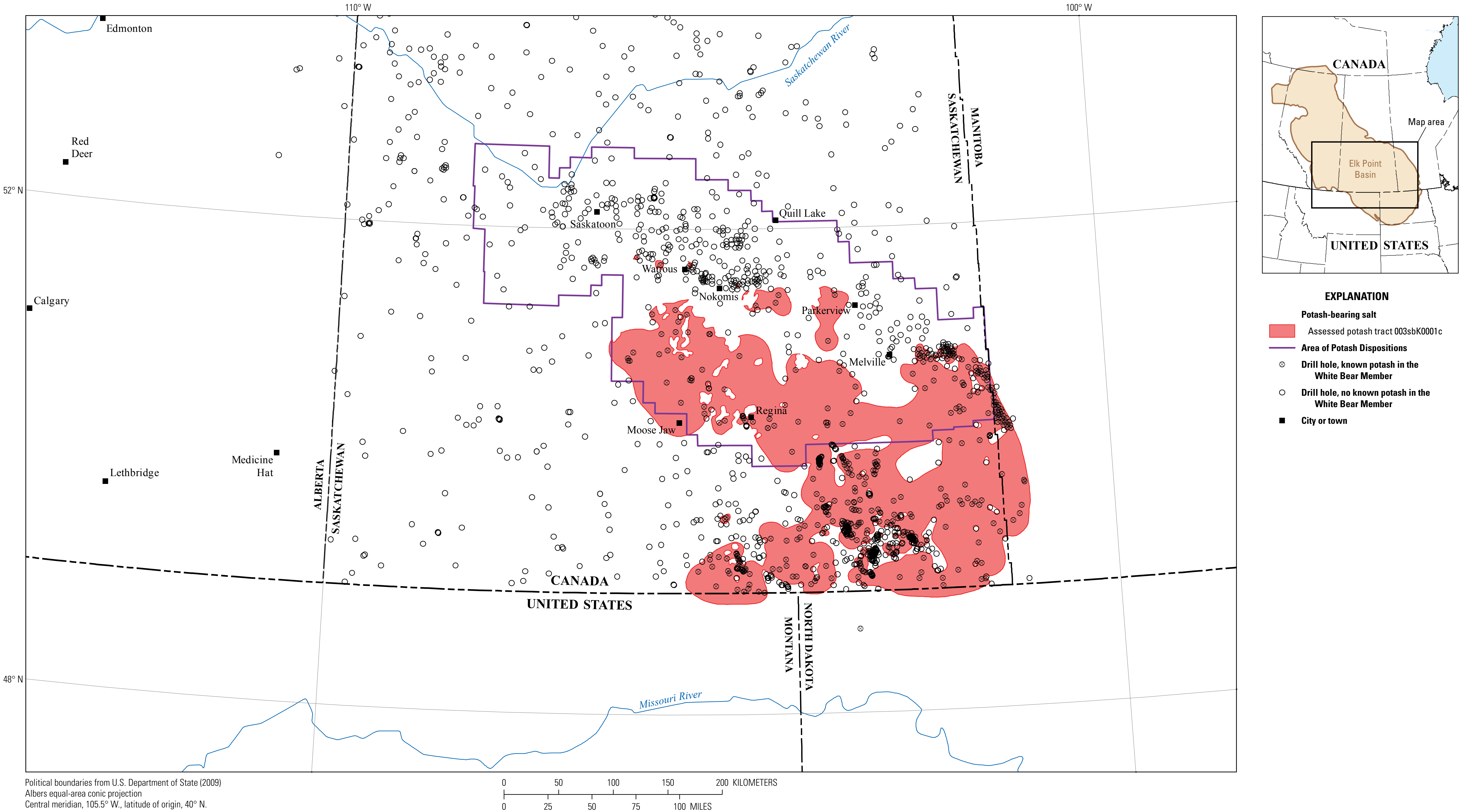
Previous studies by LeFever and LeFever (2005) did not recognize the White Bear Member in North Dakota. More recent maps and data by Kruger (2014, 2016) indicate the White Bear Member extends further into North Dakota than shown in figure 18 and is as thick as 10 m in northern North Dakota. The greater thicknesses in southeastern Saskatchewan and North Dakota may reflect the presence of the two submembers rather than just one interval of potash-bearing salt.

Yang and others (2009a) describe this member as interbedded low-grade sylvite beds, halite beds, and clay seams. Kruger (2014, 2016) does not describe the mineralogy of this unit but includes carnallite in his estimates of its composition.

In Saskatchewan, well assays range from 3.31 to 16.13 percent $K_2O$ equivalent over intervals of 1–15 m. An exploration drill hole in North Dakota intersected 1.57 m of the White Bear Member with a $K_2O$ equivalent grade of 3.31 percent at a depth of 2,685 m (Sirius Minerals, Plc., 2011). Sylvite and carnallite concentrations were estimated from well log data and plotted on a map for North Dakota, but $K_2O$ equivalent grades were not reported (Kruger, 2016).

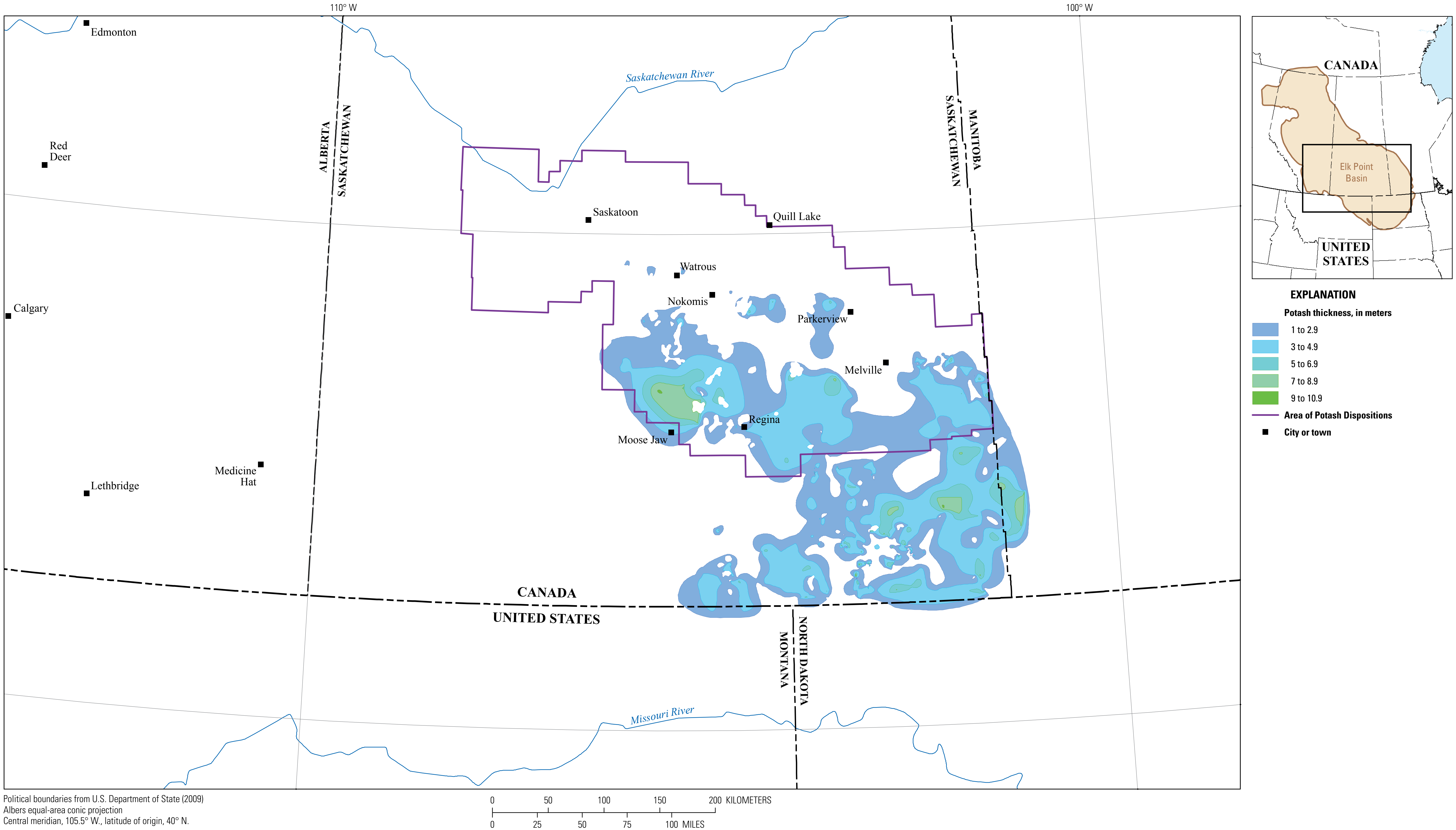
Depths to the White Bear Member range from about 830 m along the northeasternmost edge of the Saskatchewan subbasin to 2,750 m in southern Saskatchewan (Yang and others, 2009b). A northwest-southeast structure section extending into southeastern Saskatchewan (Meijer Drees, 1986) indicates a significant increase in depth toward North Dakota to depths consistent with those shown by Yang and others (2009b). Kruger (2014) reported depths to the White Bear Member range from 1,718 to 3,834 m. Recent drilling intersected the White Bear Member just south of the Saskatchewan-North Dakota border at a depth of 2,685 m (Sirius Minerals, Plc., 2011). At that depth, the potash was considered to be of too low grade and too thin (3.31 percent $K_2O$ equivalent over 1.57 m) to be economic.

The thickness of the salt-back for this member is measured to the base of the overlying Belle Plaine Member (fig. 12) or Patience Lake Member, if these members are present. If the overlying Belle Plaine or Patience Lake Members are not present, the salt-back may be measured to the top of the Prairie Evaporite and may be as thick as 54 m (Yang and others, 2009b).



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 17.** Map of the location and extent of permissive tract 003sbK0001c that includes the White Bear Member of the Prairie Evaporite in Canada and the United States. The drill holes in Canada that were used to define the permissive tract and construct the isopach map (fig. 18) are shown (Yang and others, 2009a). Data for drill holes in North Dakota were not available at the time this map was created.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 18.** Isopach map showing the thickness of potash in permissive tract 003sbK0001c that includes the White Bear Member of the Prairie Evaporite in Canada and the United States. Contours are derived mainly from the drill holes in figure 17. Data for drill holes in North Dakota were not available at the time this map was created.

## Belle Plaine Member

The Belle Plaine Member is the third most productive unit of the Prairie Evaporite and is being mined only in the southern part of the basin at the Belle Plaine, Legacy, and Milestone Mines (fig. 4). The Belle Plaine Member in the Wynyard project near Quill Lake (fig. 4) was being evaluated as a possible solution source of potash (Rauche and others, 2016). Other projects exploring the potash potential of the Belle Plaine Member include the following permit and lease areas: Burr, Jansen, Lazlo, Langham, Muskowekwam, and Vanguard (Halabura and Gebhardt, 2006; Lomas, 2008; Hambley and Halabura, 2014; Fourie, 2017; Fourie and others, 2018; Myers and others, 2017).

The mineralogy, grade, depth, and underground temperatures in the southern and southwestern parts of the Elk Point Basin are favorable for solution mining of the Belle Plaine Member. As there are no underground exposures of this member, descriptions of this unit are based solely on drill hole logs and core descriptions. The mineralogy (mainly sylvite, halite, and insoluble minerals) appears to be similar to the other potash members of the Prairie Evaporite with locally higher concentrations of carnallite (Holter, 1969). Based on data from NI 43-101 reports, the mean insoluble mineral content is greater (4.67 percent) than in the Esterhazy Member.

Figures 19 and 20 show the extent and thickness variations in the Belle Plaine Member. The overall mean thickness of the Belle Plaine Member is 7 m, but the unit may be as thick as 23 m northeast of Saskatoon (Yang and others, 2009b). For those drill holes with intercepts in the Belle Plaine Member, there is an excellent correlation of carnallitite thickness to member thickness ($r^2$=0.9990), and this relation is illustrated in figure 16. The variation in thickness of the Belle Plaine Member may be related to differences in carnallite content or the variations in thickness of submembers.

The Belle Plaine Member is depicted either as an interval of continuous though variable potash mineralization, such as in the Legacy Mine area (Hardy and others, 2009a), or as being locally divided into two submembers separated by halite or lower grade potash-bearing salt in the Jansen and Wynyard lease areas and Burr permit area (Halabura and Gebhardt, 2006; Lomas, 2007, Rauche and others, 2012). In the Vanguard permit area, seven submembers were recognized based on drillhole potash grades (Debusschere and others, 2016; Fourie, 2017; Fourie and others, 2018). In some areas, subdivision of this member based on lithology is not readily apparent (Piché and others, 2011) and is consequently dependent on differences in potash grades. In the Wynyard lease area, the upper submember is 10 m thick and the lower submember is 5 m thick on average (Rauche and others, 2012).

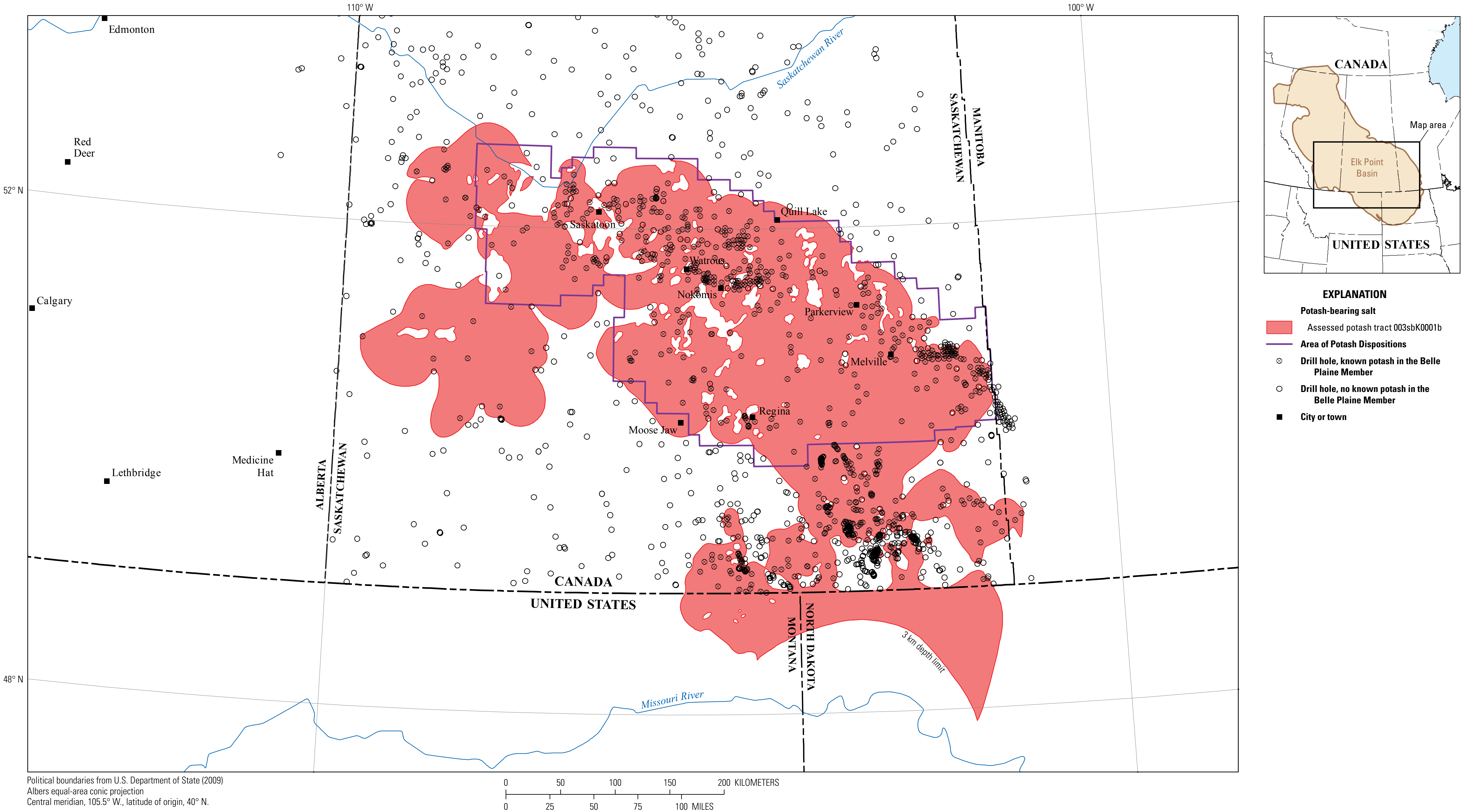
The solution process increases in efficiency with increasing temperature. Sylvite solubility increases with rising temperature, which increases with depth. Depths to the Belle Plaine Member range from about 815 m (Yang and others, 2009b) along the northeastern edge of the Saskatchewan subbasin to greater than 3 km in North Dakota and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979). This member dips southwestward at 2–7 m/km (Yang and others, 2009b). Parts of the Belle Plaine Member deeper than 3 km are not included in this assessment. In the Legacy Mine area, underground temperatures range from 40 to 46.7 degrees Celsius (°C) (Hardy and others, 2010b). In the Milestone Mine area, bottom-hole temperatures range from 58 to 65.5 °C (Hardy and others, 2013). Temperatures in the Belle Plaine Mine area are probably similar to those in the Legacy and Milestone Mine areas.

The thickness of the Belle Plaine Member salt-back is generally measured to the base of the Patience Lake Member. Where the Patience Lake Member is absent, the Belle Plaine Member salt-back extends to the top of the Prairie Evaporite salt-back and may be as thick as 54 m. The Belle Plaine Member salt-back is also referred to as interbed 1 in several NI 43-101 project reports (Hambley and others, 2011; Rauche and others, 2016; Myers and others, 2017).

## Interbed 1

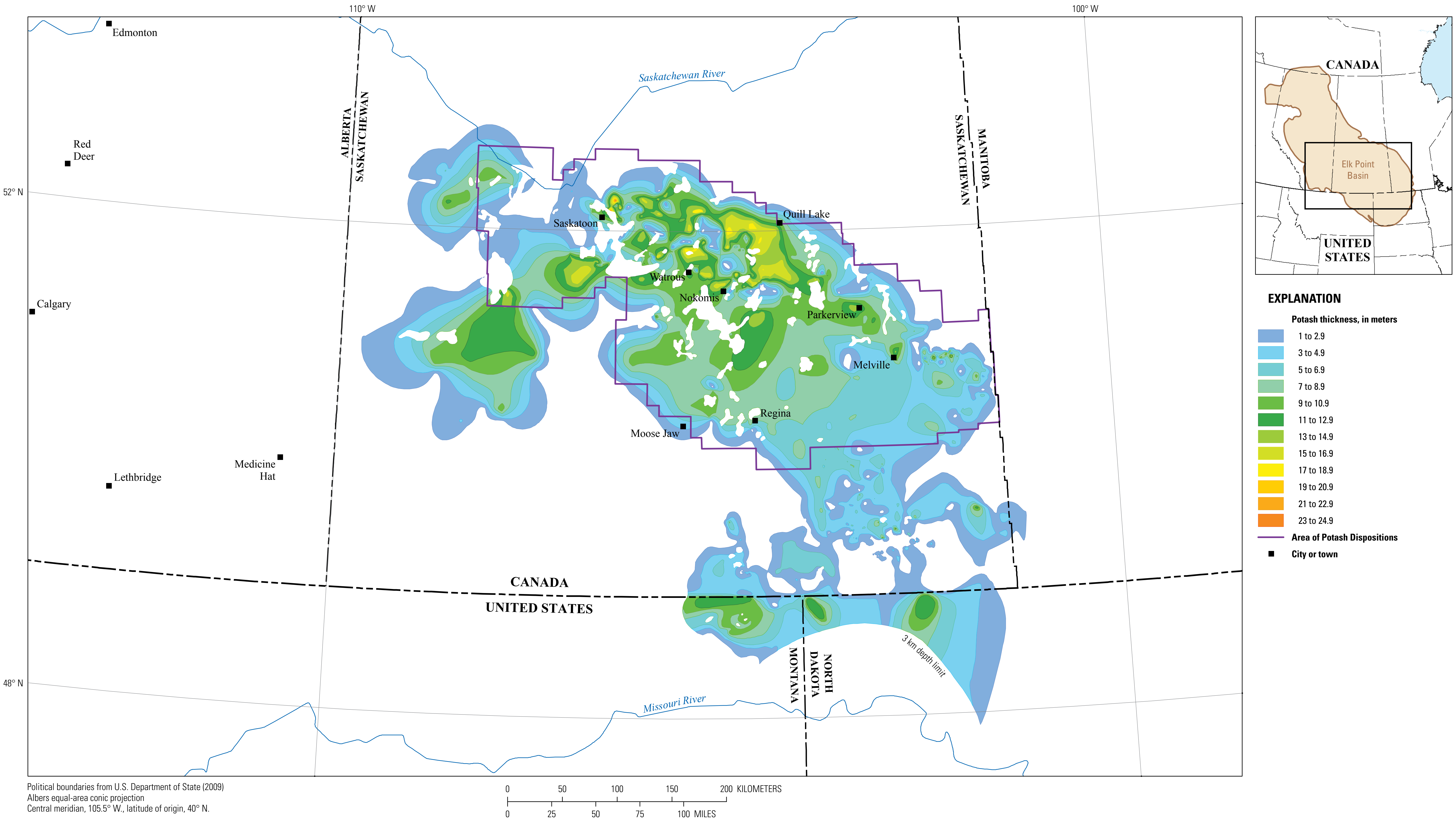
Interbed 1 is an informal section of potash-bearing salt lying stratigraphically between the top of the Belle Plaine Member and the base of the Patience Lake Member (fig. 9). It consists dominantly of halite with generally thin sylvite- and carnallite-bearing halite beds and disseminated sylvite and carnallite in halite (Holter, 1969; Hambley and others, 2011; Rauche and others, 2016). Some potash projects have included in their assessments the Patience Lake Member to the Belle Plaine Member within an interval that includes interbed 1. Myers and others (2017) reported that this interbed had an average thickness of 6.10 m with an average $K_2O$ equivalent grade of 3.84 percent in the Muskowekwan permit area. Average carnallite content was 0.62 percent and the insoluble mineral content was 5.01 percent.

In the Legacy Mine area, this interbed had an average thickness of 5.67 m with an average $K_2O$ equivalent grade of 5.67 percent. The amount of carnallite ranged from 4.50 to 10.99 percent, and the insoluble mineral content ranged from 4.28 to 9.24 percent (Hardy and others, 2009a,b, 2010a, 2013). In the Milestone Mine area, the average potash grade was 2.98 percent equivalent $K_2O$ across an average thickness of 4.27 m (Hambley and others, 2011; Hardy and others, 2013). In analyses reported in NI 43-101 technical reports (Hambley and others, 2011; Rauche and others, 2016; Myers and others, 2017), carnallite content ranged from 0.24 to 0.79 percent and the insoluble mineral content ranged from 3.40 to 12.50 percent. Holter (1969) includes an approximately contoured thickness map of interbed 1, but this USGS assessment did not attempt to estimate the potash resources contained in this interval.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 19.** Map of the location and extent of permissive tract 003sbK0001b that includes the Belle Plaine Member of the Prairie Evaporite in Canada and the United States. The drill holes in Canada that were used to define the permissive tract and construct the isopach map (fig. 20) are shown (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979; Yang and others, 2009a). km, kilometer.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 20.** Isopach map showing the thickness of potash in permissive tract 003sbK0001b that includes the Belle Plaine Member of the Prairie Evaporite in Canada and the United States. Contours are derived mainly from the drill holes in figure 19. km, kilometer.

## Patience Lake Member

The Patience Lake Member is the major source of potash mined in the Elk Point Basin in the area around Saskatoon (fig. 4). The Patience Lake, Allan, Colonsay, Cory, Lanigan, and Vanscoy Mines recover potash from this member. The Milestone Mine will eventually recover potash from this member as solution mining moves upsection. The extent and thickness variations for the Patience Lake Member are depicted in figures 21 and 22. Qualities that make this member ideal for conventional underground mining in this area include potash grade, continuity of bedding (both marker clay seams and potash beds), salt-back thickness, mineralogy (mainly as sylvite), and depth to the potash-bearing salt. Because of the extensive underground mining of the Patience Lake Member and the resulting underground exposures, it has been described in more detail than the other members. Physical characteristics of this member are generally similar to that of the underlying members. One of the main differences between this member and the others is that the Patience Lake Member contains a greater amount of insoluble material as disseminations and in the form of thin clay seams (figs. 11, 23), which serve as important markers for visually defining the stratigraphy of this unit. The overall mean amount of insoluble material in this unit is 6.8 percent but locally can be as high as 11.0 percent (Hardy and others, 2009a,b).

The Patience Lake Member of the Prairie Evaporite generally ranges from 3 to 18 m thick (fig. 22), with a mean thickness of 11 m (table 6*A*). For those drill holes with intercepts in the Patience Lake Member, there is an excellent correlation of carnallitite thickness to member thickness ($r^2$=0.9938). As noted in the other members, the thickness of the member increases with the increase in the ratio of carnallitite to member thickness (fig. 16). With only seven drill hole intercepts, this relation is not as robust as that in the Belle Plaine Member. In areas west of Saskatoon (fig. 22), this member is as much as 31 m thick (Yang and others, 2009b).

The Patience Lake Member is depicted either as an interval of continuous though variable potash content, such as in the Legacy Mine area (Hardy and others, 2009a; Cocker and Orris, 2019), or as two intervals in the Allan, Cory, Lanigan, and Wynyard lease areas (Moore and others, 2010a; Rauche and others, 2012). In the Vanguard permit area, four submembers are recognized (Debusschere and others, 2016; Fourie, 2017; Fourie and others, 2018). In the area stretching from the Vanscoy Mine in the west to at least the Jansen Mine to the east, the Patience Lake Member is generally considered to be two minable potash-bearing zones referred to as either the upper and lower Patience Lake submembers or the lower layer III (or B zone) and the upper layer IV (or A zone; fig. 11; Boys, 1990; Moore and others, 2010a). Banded halite with variable amounts of sylvite (fig. 24) separates the upper and lower parts of the Patience Lake Member. The upper submember contains four potash-bearing salt beds, referred to as cycles, and the lower submember contains six or seven cycles (Boys, 1990). The section illustrated in figure 11 depicts some but not all of these cycles. The enrichment of potash in each of the four cycles within the A and B zones contributes to the mined ore grades (Cocker and Orris, 2019). In the Vanguard permit area, the Patience Lake Member is divided into the PLM1, PLM2, PLM3, and PLM4 submembers that range in thickness from 1.33 to 5.13 m (Fourie, 2017).

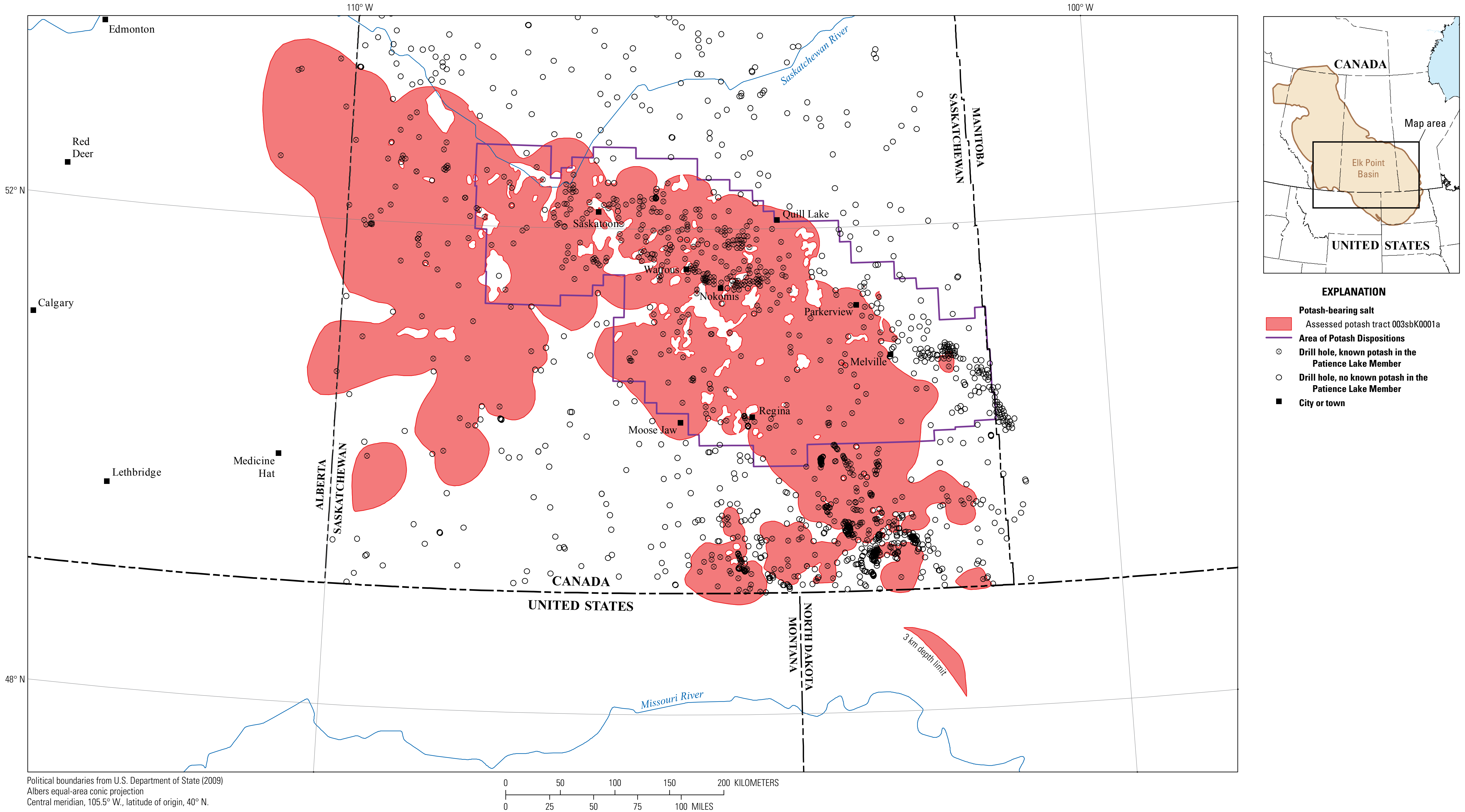
In the Patience Lake Member, clay seams are traceable from mine to mine across tens to hundreds of kilometers (Boys, 1990; Yang and others, 2009b; Moore and others, 2010c). For example, in the Cory Mine, potash cycles 3 and 4 of the upper part of the Patience Lake Member are capped by clay seams 405 and 406, respectively (fig. 11). Correlation of these numbered clay seams to other parts of the Patience Lake Member in the Elk Point Basin are more challenging.

Polygonal patterned fractures in the clay seams are believed to be desiccation cracks formed as a result of subaerial exposure and drying up of the brine that formed the underlying potash-bearing layer. Other evidence of subaerial exposure and desiccation include washout channels, microkarst pits, and chevron halite textures (Boys, 1990). Chevron halite textures are also interpreted as evidence of deep water deposition (Meijer Drees, 1986).

The thickness of the uppermost salt of the Prairie Evaporite—the salt or salt-back above the Patience Lake Member—is highly variable, ranging from 0.1 to 45 m with a mean thickness of 13 m (Yang and others, 2009b). The bimodal distribution (fig. 12) of salt thickness above the Patience Lake Member to the top of the Prairie Evaporite is distinct with means of 27 m for the thicker salt and a mean of 6 m for the thinner salt. The mean thickness of the thinner salt above the Patience Lake Member is essentially the same as that of the salt above the Esterhazy and Belle Plaine Members (table 6*B*). An isopach map of the salt-back overlying the Patience Lake Member in Yang and others (2009b) illustrates a distinct thickening of the salt-back in the southern part of Saskatchewan mainly below 50° latitude.

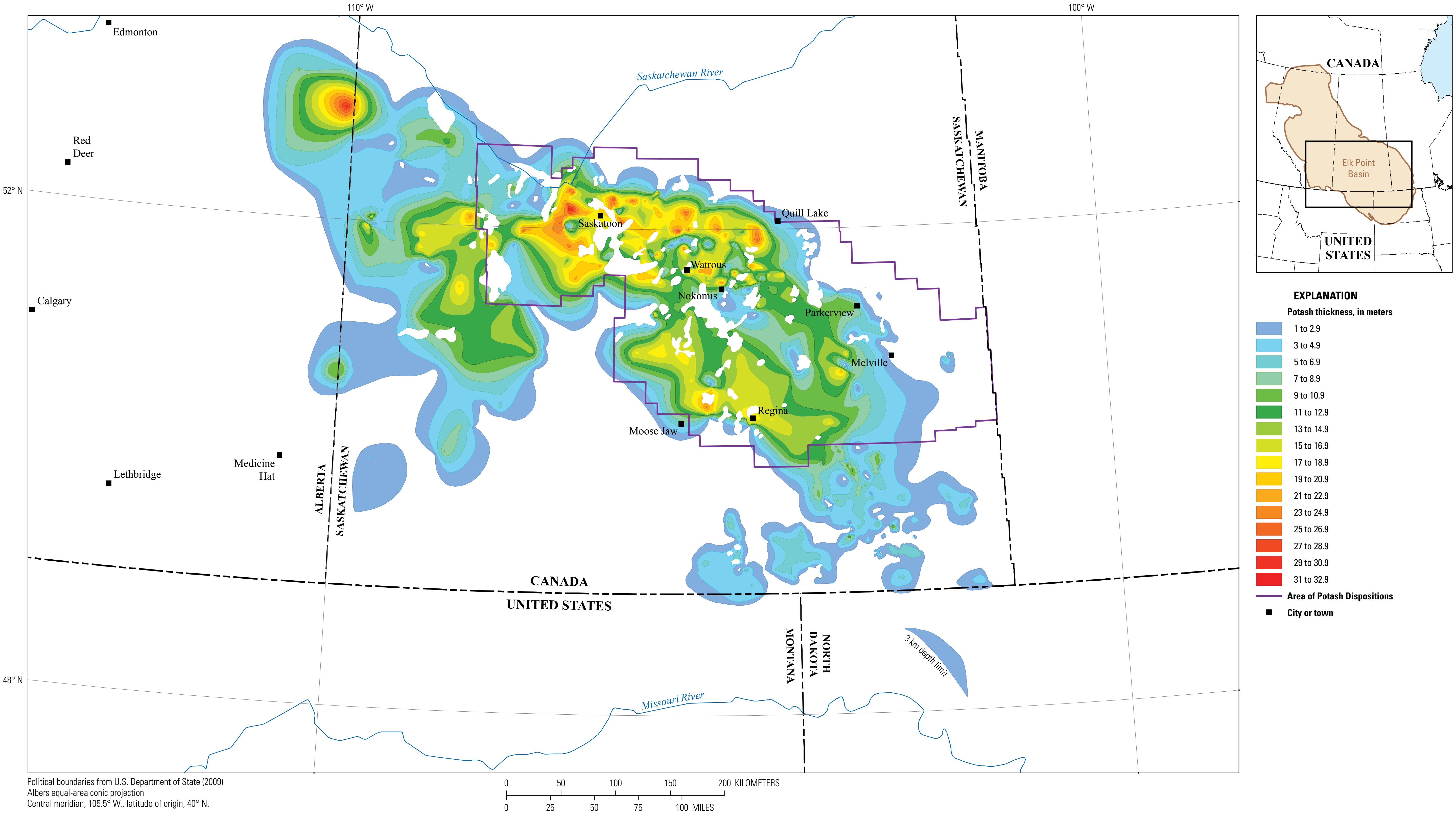
One interpretation of these two salt-back populations above the Patience Lake Member is that they may represent parts of two additional evaporite cycles in which the potash-bearing salt is no longer present but would have been if those evaporation cycles had continued from halite to potash salts. The Mountrail and White Lake members described below may represent the two missing potash-bearing salt strata. Another interpretation is that the thinner salt represents the remaining part of the thicker overlying salt that has been entirely removed by subrosion.

Depths to the Patience Lake Member range from about 800 m along the northeastern edge of the Saskatchewan subbasin to 2,713 m in southern Saskatchewan (Yang and others, 2009b), and to greater than 3,700 m in North Dakota and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979). The shallow depths to the Patience Lake Member allowed the early development of conventional underground mines (fig. 4). This member dips southwestward at 2–6 m/km (Yang and others, 2009b).



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 21.** Map of the location and extent of permissive tract 003sbK0001a that includes the Patience Lake Member of the Prairie Evaporite in Canada and the United States. The drill holes in Canada that were used to define the permissive tract and construct the isopach map (fig. 22) are shown (Anderson and Swinehart, 1979; Klarenbach, 2008, 2009; Eccles and others, 2009; Klarenbach and Gray, 2009; Yang and others, 2009a,b, 2018; Pacific Potash Corp., 2012; Yang, 2016a). km, kilometer.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 22.** Isopach map showing the thickness of potash in permissive tract 003sbK0001a that includes the Patience Lake Member of the Prairie Evaporite in Canada and the United States. Contours are derived mainly from the drill holes in figure 21. km, kilometer.

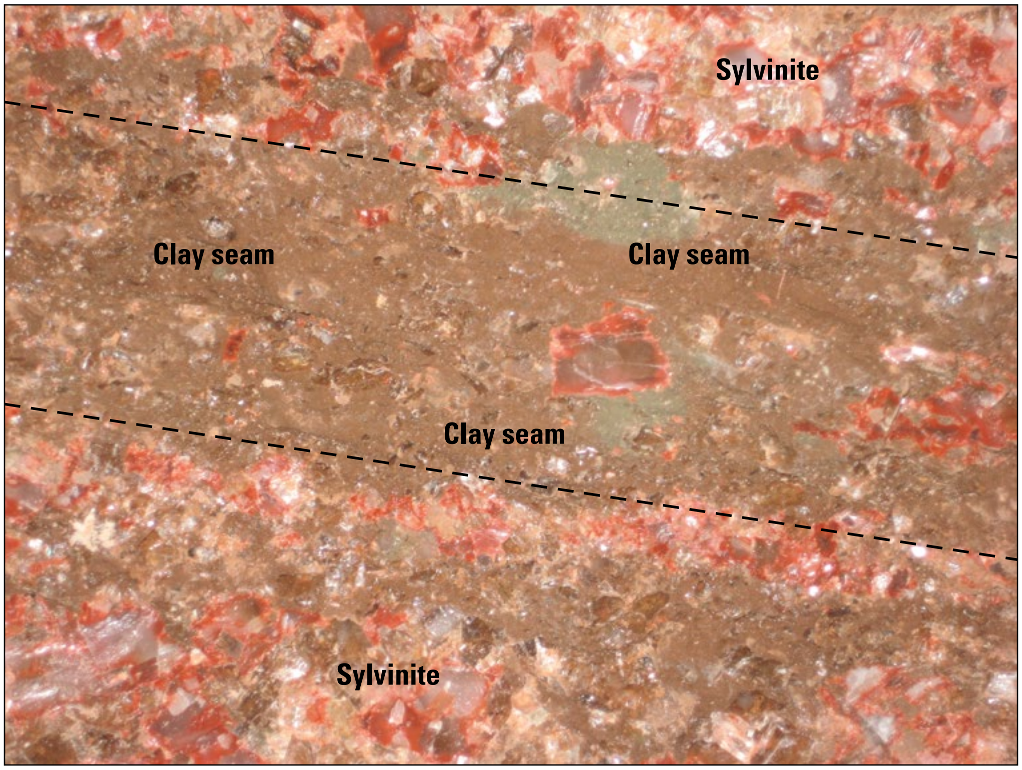


**Figure 23.** Photograph showing a clay seam in an ore zone (Colonsay Mine) of the Patience Lake Member of the Prairie Evaporite. Clay seam is approximately 5–6 centimeters thick. U.S. Geological Survey photograph by M. Cocker.

**Figure 24.** Photograph showing sylvite-bearing banded halite in Patience Lake Member of the Prairie Evaporite in ore zone A of the Cory Mine. Modified from Boys (1990); used with permission from the Department of Geological Sciences at the University of Saskatchewan.

## Mountrail and White Lake Members

LaFever and LaFever (2005) did not recognize the Patience Lake Member in North Dakota. However, Kruger (2014) identified the Patience Lake Member in numerous wells in addition to potash-bearing strata above the Patience Lake Member. Those strata were recently recognized as the Mountrail and White Lake members in North Dakota (Kruger, 2014) based on gamma ray logs from 169 wells. These members have not been recognized in adjacent parts of Canada (Holter, 1969; Yang and others, 2009b; Nicolas, 2016) or Montana (Great Northern Railroad, 1965). In North Dakota, Mountrail strata lie between 21 and 44 m above the top of the Patience Lake Member and between 1.8 and 32 m below the upper contact of the Prairie Evaporite (Kruger, 2014). Maximum recorded thickness is 3.7 m. White Lake strata lie between 9 and 27 m above the top of the Mountrail member with a maximum thickness of 1.8 m (Kruger, 2014).

Mineralogical descriptions and potash analyses are not available and, owing to their limited extent, they were not assessed. These strata may be part of the projected missing potash cycles lying above the Patience Lake Member as suggested by the occurrence of locally anomalous thick sections of salt-back described above. Because the Mountrail and White Lake members lie 30 m or more above the Patience Lake Member, they may have been deposited in Canada and Montana but were removed by surface or subsurface dissolution or may have never been deposited there.

## Mineralogy

The evaporite mineralogy of the Prairie Evaporite is relatively simple compared to other stratabound potash-bearing salt deposits (appendix A, table A1). Mineralogy and petrography of the salt is important for calculating densities used for grade and tonnage estimations. Also, grain size and grain interconnectivity are critical for planning solution-cavern development and mineral-resource estimations. Besides sylvite, carnallite and halite, and the potassium-bearing minerals polyhalite and leonite, the insoluble minerals and materials such as anhydrite, calcite, chlorite, dolomite, hematite, feldspars, goethite, gypsum, illite, magnesite, micas, pyrite, quartz, smectites, and hydrocarbons have been identified in the upper part of the Prairie Evaporite (Gorrell and Alderman, 1968; Boys, 1990). Polyhalite and leonite appear to be uncommon or have gone unnoticed during mining or drilling (Pearson, 1962). The following is a summary of mineral descriptions mainly by Holter (1969), Boys (1990), and Yang and others (2009b).

### Halite

Halite (NaCl) occurs as anhedral to euhedral crystals in essentially monomineralic salt or in mixed intergrowths with sylvite or carnallite. Crystals range in size from less than 0.63 cm to greater than 10 cm (Holter, 1969; Yang and others, 2009b). Crystal sizes are observed to decrease upward in the potash members and the halite interbeds (Klingspor, 1966; Holter, 1969). Chevron-type halite crystals (which Yang and others [2009b] attributed to syndepositional growth) with long axes oriented perpendicularly to bedding are locally observed (Wardlaw, 1964; Holter, 1969). Halite color varies from clear to brown or gray where it occurs in dominantly halitic rock. In association with sylvite or carnallite, halite is clear or cloudy and commonly coated with insoluble minerals (Holter, 1969) but never coated by red iron insoluble minerals (Yang and others, 2009b). Blue halite is locally observed (McIntosh, 1967; Holter, 1969).

### Sylvite

Sylvite (KCl) occurs as anhedral to euhedral crystals that range in size from 0.63 to 3.5 cm (Holter, 1969; Yang and others, 2009b). Sylvite is intergrown with halite and disseminated insoluble minerals, and the rock or ore is referred to as sylvinite. Crystals may be clear to cloudy, and colors range from white to pink to light orange (figs. 10, 11, 23). Zoning is locally observed parallel to crystal outlines, and the zones commonly have red rims, which are attributed to goethite and hematite. Cleavages of the few documented rare sylvite chevron crystals were parallel to bedding (Holter, 1969). Based on chemical analyses by Yang and Love (2015) and Hardy and Halabura (2008), the maximum amount of sylvite in sylvinite is about 48 weight percent in 15.30 m intervals in the Patience Lake and Belle Plaine Members and as much as 66 weight percent in a 1.8 m interval in the Esterhazy Member.

### Carnallite

Carnallite ($KMgCl_3 \cdot 6H_2O$) is commonly intergrown with halite as carnallitite rock. Carnallite grain sizes are similar to those of halite (ranging from less than 0.63 cm to greater than 10 cm), and crystals are subhedral or anhedral (Fuzesy, 1983; Yang and others, 2009b; Myers and others, 2017). Carnallite colors range from clear white to red and translucent black. Color zonation patterns include clear or black carnallite cores with red rims or red cores with black rims. Carnallite commonly contains plates of hematite and goethite fibers (Wardlaw, 1968; Holter, 1969). Small carnallite-filled fractures and carnallite-rich pods occur in sylvinite ore, particularly in the lower members of the upper Prairie Evaporite (Koehler, 1997). The carnallite pods are 1–6 m across and are predominantly colorless to white and yellow (McIntosh and Wardlaw, 1968; Fuzesy, 1983; Koehler, 1997). Narrow, vertical to subvertical fractures that are filled with secondary white or red carnallite may also locally replace sylvite and halite (Fuzesy, 1982). Carnallite is sensitive to water and dissolves by extracting moisture from the air. To prevent loss of potassium during sampling of a drill core, current practice is to wrap the core in plastic and to open only one core box at a time (Rauche and others, 2016).

The amount of carnallite in a drill hole interval is normally calculated from a chemical analysis for magnesium by multiplying the percentage of magnesium by a factor of 11.4. Generally, the presence of 6 percent or greater carnallite or 0.5 percent magnesium is avoided in Saskatchewan mining operations (Hambley and others, 2011). In conventional underground mines, carnallite-rich areas have a tendency to absorb moisture from the air, causing dissolution of the carnallite and thereby weakening the supporting pillars or walls. This requires more cavern support and a different mine layout to alleviate roof fall and floor heave (Fuzesy, 1983). Grades of carnallitic strata are generally lower than equivalent sylvinite strata, and processing of carnallite-bearing salt is more difficult and expensive than processing sylvinite (Garrett, 1996). In solution mining operations, carnallite dissolves more readily than sylvite because magnesium (from carnallite) substantially reduces potassium saturation levels in aqueous solutions and thereby reduces the efficiency of cavern dissolution and potash recovery (Hambley and others, 2011).

### Insoluble Minerals

Minerals that are not readily dissolved by water or brines are classified as insolubles. In the lower part of the Prairie Evaporite below the Shell Lake Member, insoluble minerals are mainly dolomite and anhydrite. In the Shell Lake Member, anhydrite is typically finely crystalline and light to dark gray or mottled gray brown. It occurs in halite beds as disseminated lenses, thin interbeds, or massive beds about 1 m thick (Holter, 1969). In some parts of the Prairie Evaporite, layers of 1-cm-thick anhydrite alternate with layers of 2- to 10-cm-thick halite (Wardlaw and Schwerdtner, 1966). Dolomite is usually associated with anhydrite as thin laminations to thick beds or as fine disseminations in anhydrite. Dolomite ranges from fine grained to microcrystalline (Holter, 1969).

In the upper, potash-bearing part of the Prairie Evaporite, anhydrite, dolomite, and the other insoluble minerals are generally minor in abundance occurring mainly in thin clay seams (figs. 11, 23). Clay minerals include illite, chlorite, septechlorite, sepiolite, smectite, mixed layer chlorite/smectite, corrensite, and traces of vermiculite (Boys, 1990). Concentrations of these insoluble minerals increase toward the tops of individual potash cycles, and there is an overall increase upward to the upper part of the Prairie Evaporite from the Esterhazy Member to the Patience Lake Member. Clay seams mark the top of the mining intervals in the Patience Lake Member and are removed during mining, as they commonly are a source of weakness in the roof of the mine opening (Jones and Prugger, 1982; Boys, 1990). Clays in the ore may affect the use of reagents used to process the potash, but amounts are generally too low to be detrimental. In solution mining, clay seams may affect construction of solution chambers (Molavi and others, 2010; Hambley and others, 2015), but disseminated insoluble minerals are left underground and do not affect ore processing (Hambley and others, 2015; Rauche, 2015).

### Mineral Textures

Few primary textures are observed in the salt beds, and primary textures in the sulfate beds are unknown (Meijer Drees, 1986). The lack of primary textures in the sulfate beds and the rarity of primary halite textures may indicate that most of the evaporite minerals have recrystallized (Holter, 1969; Meijer Drees, 1986). Petrological and geochemical data indicate that sylvite was replaced by both sylvite and carnallite, halite was replaced by carnallite, and carnallite was replaced by sylvite (Streeton, 1967; Holter, 1969). Solution mining is improved where sylvite grains are coarser and interlock with each other.

## Formation of the Prairie Evaporite and the Potash-Bearing Salts

The location and formation of the potash-bearing salts of the Prairie Evaporite in both geographic and stratigraphic contexts are dependent on continental and global scale conditions during the Devonian. Plate-tectonic-induced movement of the North American continental plate during the Devonian placed the Elk Point Basin between the latitudes of 10° and 20° S. that have been described as being ideal for formation of large-scale marine evaporite deposits (Chipley and Kyser, 1989; Yang and others, 2009b; Warren, 2010, 2016). Because of global-scale atmospheric wind circulation patterns, the Elk Point Basin and surrounding areas were in an exceptionally arid climate (Warren, 2010). Strong, dry, easterly tradewinds blowing across the large North American continental mass contributed to hyperarid conditions that facilitated evaporation in the basin. The hyperarid conditions and little precipitation in and surrounding the basin resulted in the absence of significant clastic input. Red beds and evaporites are generally associated with this type of environment.

The temperature of brines from which the evaporite minerals initially crystallized suggests the southern part of the Elk Point Basin in Saskatchewan was close to the Equator during the Middle Devonian. Homogenization temperatures of primary fluid inclusion assemblages in halite range from 37 to 44 °C and were interpreted to reflect surface brine temperatures in the Elk Point Basin during the Middle Devonian (Chipley and Keyser, 1989; Yang, 2016b). These temperatures are consistent with those in previous studies (Lowenstein and Spencer, 1990; Chipley and Kyser, 1989; Horita and others, 1996) and the paleolatitude of the basin during evaporite deposition (Van der Voo, 1988; Yang and others, 2009b; Yang, 2016b). Higher homogenization temperatures (46–70 °C) in diagenetic halite indicate higher brine temperatures during burial of the salt strata.

During the Devonian, the Elk Point Basin was subjected to several marine transgressions and erosion events (regressions). Lower Middle Devonian sandstones, red beds, and Lotsberg Formation salt deposits accumulated in the northern and central Alberta subbasins (fig. 7) in a tectonically stable, continental environment (Meijer Drees, 2008). With the beginning of the early Middle Devonian, the initial marine invasion of the continental basin led to the deposition of the marine carbonates of the Ernestina Lake Formation. Along the margins of the basin were red beds, evaporites, and peritidal sediments. Sedimentation constricted the marine inlet channels causing circulation to be further restricted, and excessive evaporation caused salt deposition of the Cold Lake Formation (Meijer Drees, 2008).

A second marine invasion followed deposition of the Cold Lake Formation, resulting in the filling of the northern and central Alberta subbasins with red beds and peritidal evaporites. A relative fall in sea level was followed by a regression and minor erosion. A third marine invasion occurred during the early Middle Devonian, resulting in shaly, nearshore, and peritidal carbonates onlapping the unconformity and southeastward gradation into peritidal and evaporitic carbonates of the Chinchaga Formation and nearshore clastics or red beds of the Contact Rapids and Ashern Formations. The upper, regressive part of this assemblage includes the shallow-marine carbonates of the Winnipegosis Formation and other formations (Meijer Drees, 2008).

A fourth marine transgression that occurred in the late Middle Devonian was associated with an increase in the rate of subsidence or a rise in sea level. Vertical reef growth at the entrance of the Elk Point Basin formed the Presqu'ile barrier reef complex (figs. 3, 7), which is a combination of reef and inter-reef deposits (Meijer Drees, 2008). This barrier reef complex restricted the inflow of seawater into the basin (Holter, 1969; Maiklem, 1971; Zharkov, 1984). The restriction of seawater inflow through the Presqu'ile barrier reef complex and progressive evaporation increased the salinity and density of the marine brine as it flowed southeast to the Saskatchewan subbasin of the Elk Point Basin. Maiklem (1971) indicated that, given the permeability of the Presqu'ile barrier reef and the inflow of seawater through barrier seepage, the water loss through evaporation would be 200–800 times the inflow. During the late Middle Devonian, seawater continued to flow through channels across the reef to prevent the basin from drying up completely and periodic seawater overflow of the barrier reef allowed a new influx of seawater to flood the Elk Point Basin. Restricted but continuous inflow of seawater into the Elk Point Basin rather than seepage through a barrier is required to produce the volumes of evaporites occurring in this basin in the projected time interval for salt deposition (Nunn and Harris, 2007). The distance from the Presqu'ile barrier reef to the Saskatchewan subbasin is on the order of 800 km, and the widespread and simultaneous deposition of the salt layers would require a nearly constant influx of the marine waters during each marine invasion to enable the increasingly saline water to reach the furthest regions of the basin.

Continued evaporation increased the salinity of the marine brine throughout the basin and eventually resulted in evaporite precipitation. Evaporite sediments were deposited throughout the Elk Point Basin and are laterally and vertically zoned from (1) carbonate rocks to (2) gypsum (subsequently converted to anhydrite) to (3) halite to (4) halite plus potassium chloride salts plus potassium-magnesium chloride salts (figs. 3, 7). Continued evaporation and supply of more saline marine water produced a thick alternating sequence of salt and four potash-bearing salt sequences in the Saskatchewan subbasin (figs. 7). Variable effects of wind direction and water depth may have affected circulation patterns and resulting evaporite precipitation in the basin (Brongersma-Sanders and Groen, 1970).

Within the large-scale flooding episodes that produced the Prairie Evaporite, detailed examination of the potash-bearing section demonstrates several major cycles of flooding and desiccation that correspond with the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members (Klingspor, 1966). In addition, more detailed underground studies by Boys (1990) revealed numerous cycles of sea water flooding and desiccation in the Patience Lake Member. At least 16 halite to sylvite (plus halite) to clay deposition cycles are observed (fig. 11) and 7 additional incomplete cycles of halite to clay deposition may be present as evidenced in downhole geochemical plots. Potash deposition in those seven cycles was either not achieved or the potash was removed subsequent to deposition. The section shown in figure 11 represents only a part of the Patience Lake Member, and there may have been additional flooding and depositional cycles that are not documented in the rock record (perhaps removed by subsequent dissolution events). Similar thicknesses and the downhole geochemical data of the Patience Lake, Belle Plaine, and Esterhazy Members suggest that the younger members could represent a minimum of 4 to perhaps 20 or more cycles of flooding, evaporation, and desiccation. The White Bear Member may have undergone fewer of these flooding, evaporation, and desiccation cycles as its thickness and grade are less than the other members. The continuity of the potash-bearing salt layers and the clay marker beds occurring across tens to hundreds of kilometers reflects the repeated widespread flooding, evaporation, and desiccation events throughout the Saskatchewan subbasin.

The amount of time required for salt deposition in the Prairie Evaporite can be estimated from salt thickness and observed rates of salt deposition in modern salt pans. Pohl (2011) estimated that evaporation of 1,000 m of seawater would produce an evaporite section about 18 m thick with 12 m of halite and 5–6 m of halite plus potassium chloride and magnesium chloride salts. Present maximum thickness of the Prairie Evaporite is 218 m, but there has been salt loss at the top of this unit owing to erosion associated with the unconformity at the upper contact and subrosion after burial. Original salt thickness is unknown but could be approximately 250 m assuming relatively minor salt loss.

Holter (1969) and Wardlaw and Schwerdtner (1966) estimated the minimum time required for deposition of salt in the entire Prairie Evaporite at 4,000 years using a depositional rate of 5 cm of halite per year. With halite accumulation rates at 5–150 m per thousand years (Becker and Bechstädt, 2006) and an adequate supply of brine, the present thickness of salt could have been deposited over a 1,300–40,000 year period. Whether the interval of salt deposition was 1,300, 4,000, or 40,000 years, the period was relatively short in the overall history of the Elk Point Basin. A longer time interval for salt deposition would have to assume that the salt likely would have been subjected to more surface dissolution events, such as less saline water flooding, and not been preserved.

Theories regarding the environment and depth of salt and anhydrite deposition in the Prairie Evaporite suggest shallow to deep water deposition. These theories are based on interpretations of chevron halite textures believed to be primary (Klingspor, 1966; Wardlaw and Schwerdtner, 1966; Holter, 1969; Mackintosh and McVittie, 1983) or on the absence of primary textures, which may indicate subaerial exposure and dissolution. Meijer Drees (2008) suggests anhydrite of the Muskeg Formation and salts of the Prairie Evaporite were deposited in supratidal flats, coastal lagoons, and ephemeral lakes. Boys (1990) argues for deposition of the potash beds in a shallow, areally extensive salt pan. Wardlaw and Schwerdtner (1966) suggested that initial brine depth was at least that of the thickness of the Prairie Evaporite salt (218 m). The lower part of the Prairie Evaporite may have formed in deep water (Holter, 1969; Boys, 1990).

However, the shallow salt-pan model does not account for the immense size of these members. For example, the Patience Lake Member is 139,000 km$^2$, and would have been larger prior to subrosion along its edges (fig. 4). Also, the continuity of the potash-bearing salt beds across an extensive area would require relatively deep brine flooding prior to evaporation and increased hypersalinity which would have caused precipitation of the potash beds throughout the entire elongate Saskatchewan subbasin.

Subsequent to the deposition of the Prairie Evaporite, sea level fell and the entire Elk Point Basin became emergent during the mid-Givetian regression (Meijer Drees, 2008). Parts of the Peace River Arch and Tathlina Uplift highlands were eroded and the Presqu'ile barrier reef complex was exposed. During that time, the southeastern part of the Elk Point Basin was emergent, and salts of the Prairie Evaporite were partly leached and recrystallized, perhaps with the majority of carnallite undergoing dissolution and recrystallization as sylvite. The second red bed, which marks the end of Prairie Evaporite deposition, probably represents eolian deposition accompanying a new phase of aridity in the area.

# Alteration and Solution Effects on the Prairie Evaporite

Brines and groundwater have significantly altered the original mineralogy and have affected the distribution and thickness of the Prairie Evaporite members. These effects can be seen in (1) the bromine geochemistry of the Prairie Evaporite, (2) the distribution of the primary carnallite and the secondary sylvite, which affects both grade and tonnage of the potash-bearing salt, as well as (3) large and small scale dissolution features, which affect the thickness or absence of the potash-bearing salt and hence also affect its tonnage.

## Water Bromine Geochemistry of the Prairie Evaporite

Bromine (Br) substitutes for chlorine (Cl) in halite and potassium salts and generally reflects the salinity of the brine at the time these minerals crystalized. Thus, with progressive evaporation and increased salinity, the bromine content of these minerals will increase and manifest at increasing stratigraphic height within any particular evaporite cycle. In general, bromine concentrations in halite range from 60 to 200–300 parts per million (ppm) during potash precipitation (Kühn, 1955; Holser, 1966a,b; Warren, 2006). Anomalous bromine trends can indicate secondary alteration of the primary mineralogy that affected their present distribution.

Studies by Schwerdtner and Wardlaw (1963), Wardlaw and Watson (1966), Wardlaw (1968), McIntosh and Wardlaw (1968), Streeton (1967), and Holser and others (1972) found both lower and higher bromine concentrations in halite, sylvite, and carnallite than would be expected as a primary precipitate from seawater. Also, analyses of sylvite and halite document an upward decrease in bromine, whereas the bromine content of carnallite remained essentially constant. The low bromine values and the absence of consistent bromine enrichment trends in the Prairie Evaporate indicate that much of the potash is secondary. A downward increase in bromine concentrations in sylvite and carnallite may indicate that downward migrating solutions dissolved carnallite, mobilizing bromine, and that this additional bromine was incorporated into secondary sylvite (Holter, 1969).

## Changes in Mineralogy Caused by Descending Brines

Primary carnallite altered to sylvite is documented in most potash-bearing salt basins throughout the world (Kühn, 1955; Borchert and Muir, 1964; Wardlaw, 1968; Hite and Japakasetr, 1979; Hite, 1982; Korenevskiy, 1989). Abrupt lateral and vertical changes from carnallitite or carnallitic sylvinite to sylvinite were observed in underground mines (fig. 13) and in geochemical analyses from drill holes in Elk Point Basin (Keys and Wright, 1966; Holter, 1969; Fuzesy, 1982; Yang and Love, 2015).

Leaching and dissolution of carnallite by descending brines removes $MgCl_2$ and water of hydration from the carnallite and results in precipitation of the remaining potassium chloride as sylvite. The released magnesium may cause alteration of limestone elsewhere in the section to form secondary dolomite. The results of carnallite dissolution include decreases in volume (a 30–60 percent decrease) and thickness of the affected strata, an increase in equivalent $K_2O$ grade, and a more mineralogically desirable mining and processing material (Schwerdtner, 1964; Wardlaw, 1968; Holter, 1969; Baar, 1972, 1973).

Small (probably on the order of a few to tens of square meters), carnallite-rich areas encountered during mining have only a minor effect on lowering the overall grade of the mined ore. Not all carnallite is primary, as some observations show local replacement of sylvite and sylvite plus halite by carnallite or carnallite veins cutting sylvite and halite in the Esterhazy Member (Fuzesy, 1983).

Petrographic textures and anomalously young rubidium-strontium (Rb-Sr) and potassium-argon (K-Ar) radiometric ages for carnallite suggest carnallite was dissolved and potassium chloride was reprecipitated as sylvite at various times since the primary precipitation of carnallite. Secondary fluid inclusions in halite indicate three different homogenization temperatures of 30 °C, 50 °C, and 60 °C (Chipley and Kyser, 1989). Koehler (1997), Koehler and Kyser (1991), and Wardlaw (1968) postulate three different events of descending formation waters that caused carnallite alteration. Increasing temperatures are related to increasing halite depths of 1, 1.5, and 2 km. The radiometric ages suggest carnallite alteration events occurred during the late Paleozoic, Cretaceous, and early Tertiary. The late Paleozoic carnallite alteration probably occurred soon after deposition of the Prairie Evaporite.

The areal and vertical distribution patterns described, along with the radiometric ages, indicate that widespread dissolution of carnallite and replacement with sylvite occurred repeatedly on a large scale in the Elk Point Basin. Because of the preference of the established mining industry in Saskatchewan to avoid carnallite-rich areas and to selectively mine sylvite-rich areas, more detailed maps of the distributions of these minerals—such as those of Yang and Love (2015) and Yang and others (2018)—could benefit future exploration and development.

## Areal and Vertical Distribution Patterns of Carnallite and Sylvite in the Prairie Evaporite

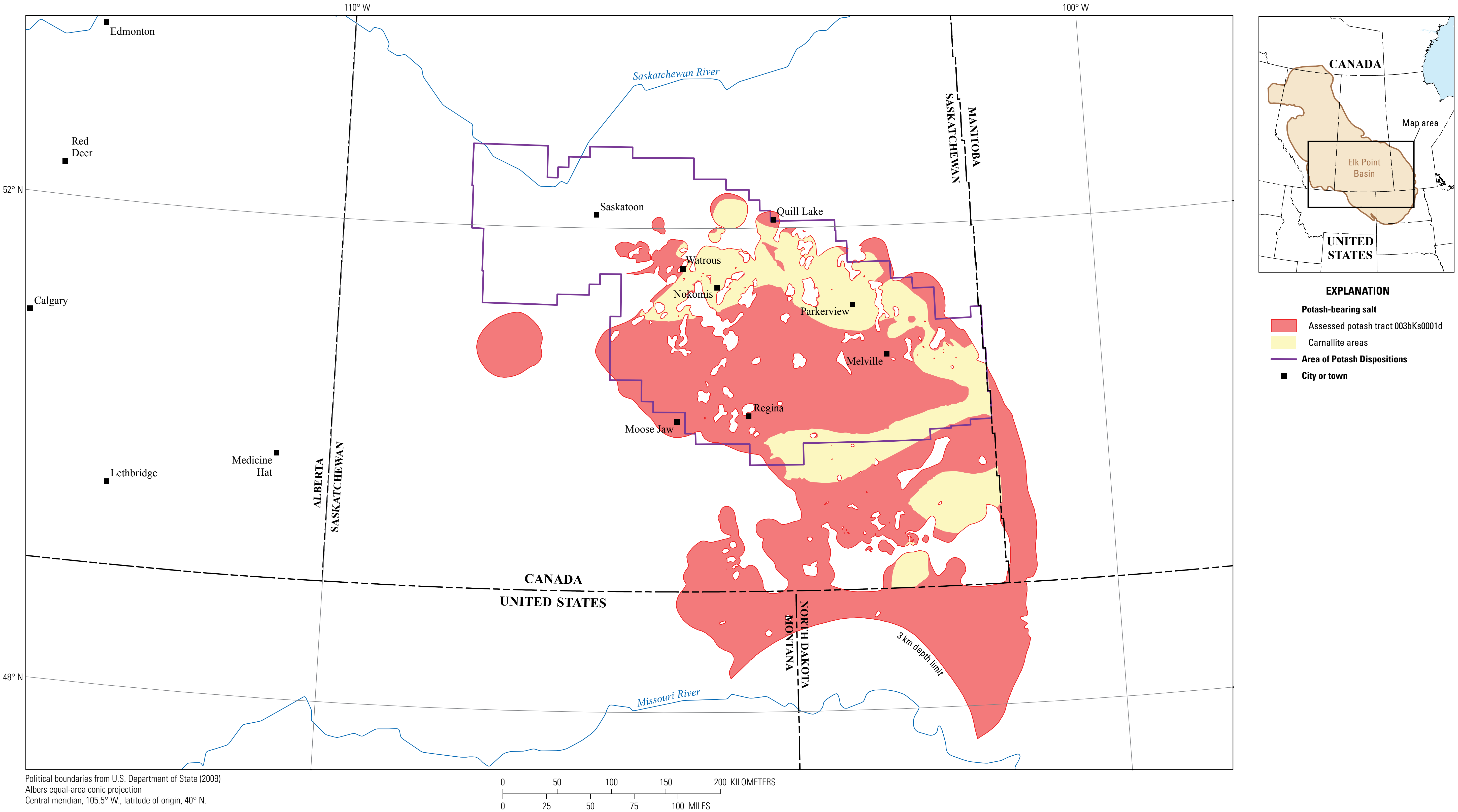
In the Prairie Evaporite, the effects of various types of water are a critical factor in the post-depositional evolution of the evaporites (Holter, 1969; Boys, 1990; Yang and others, 2009b). Variable pathways of ascending and descending brines are a major factor in determining the spatial distribution of carnallite and sylvite in the Prairie Evaporite (Schwerdtner, 1964; Wardlaw, 1968; Holter, 1969; Baadsgaard, 1987; Chipley and Kyser, 1989; Korenevskiy, 1989). The distribution of large carnallite- and sylvite-rich areas is important to the potash industry and to this assessment, as calculated volumes and densities are dependent on the dimensions of these areas. Large carnallite-rich areas generally are neither included in governmental grade and tonnage calculations (Holter, 1969; Fuzesy, 1982; Bannatyne, 1983) nor in company reports such as those by Moore and others (2010a), Molavi and others (2010), and Hardy and others (2010a).

Maps by Holter (1969), Fuzesy (1982), Yang and Love (2015), and Yang and others (2018) show the areal distribution of carnallite and sylvite for the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members in Saskatchewan (figs. 25–28), but similar maps are not available for Manitoba, Alberta, North Dakota, or Montana. The extent of the carnallite and sylvite was derived by contouring the mineralogical equivalent of the geochemical data and neutron log responses based on the drill holes available for each member at the time of publication. Uncertainties of the extents of both the carnallitic versus sylvitic regions are due to the scale of Fuzesy's 1982 maps (approximately 1:5,000,000), the indefinite boundaries of the carnallitic areas defined by Fuzesy (1982), and the limited drill hole data during the early 1980s. Newer maps of carnallite distribution (Yang and Love, 2015; Yang and others, 2018; Yang and Schuurmans, 2018) using a more extensive drill hole database limit the extent of carnallite. The newer drill hole data and maps became available after the carnallite and sylvite areas and boundaries were drawn for this USGS assessment and are probably more accurate.

Holter (1969) observed that each potash member had broad carnallitic borders, except along their southern and northern boundaries. Carnallite is in greater abundance to the north relative to sylvite, with sylvite increasing in abundance to the south. The Esterhazy Member generally contains the lowest amount of carnallite of all members in the study area, and the Belle Plaine contains the highest amount (Holter, 1969). Parts of the Esterhazy Member are dominantly carnallitic. In each of the Prairie Evaporite members, high sylvite and high carnallite areas were mutually exclusive. The updated maps of carnallite distributions (Yang and others, 2018) suggest that the actual amount of carnallite is relatively minor compared to that of sylvite, and the maps appear to confirm Holter's views that most carnallite is generally located along the northern edge of each member.

Cross sections (figs. 29–33; modified from Holter, 1969) illustrate inverted stratigraphic relations, and the bromine geochemical trends indicate dissolution of carnallite and its replacement with sylvite. Inverted stratigraphic relations are defined as carnallite-rich beds underlying sylvite-rich beds that are opposite to that of a normal evaporite depositional sequence (Schwerdtner, 1964; Wardlaw, 1968; Holter, 1969; Koehler, 1997). The carnallite-sylvite contact is stratigraphically higher in section as the edges of each member are approached from well to well (Holter, 1969).

These strata are presently inclined, but if these strata are tilted back to original horizontality (fig. 29), the probable original orientations of the secondary alteration patterns of carnallite to sylvite are apparent. The pre-tilting orientation of this carnallite to sylvite alteration pattern relative to the bedding would indicate that the alteration occurred when the bedding was still in a horizontal orientation. These figures may be a simplification of the sylvite and carnallite distribution patterns but present an overall model of the genesis of these distribution patterns. Descending brines are the generally accepted primary cause of carnallite dissolution and of its alteration to sylvite (Hite, 1982; Chipley and Kyser, 1989; Korenevskiy, 1989). These vertical distribution patterns of carnallite and sylvite would also be affected by the subsequent subrosion effects shown in figures 30–33.



**EXPLANATION**

**Potash-bearing salt**

🟥 Assessed potash tract 003bKs0001d

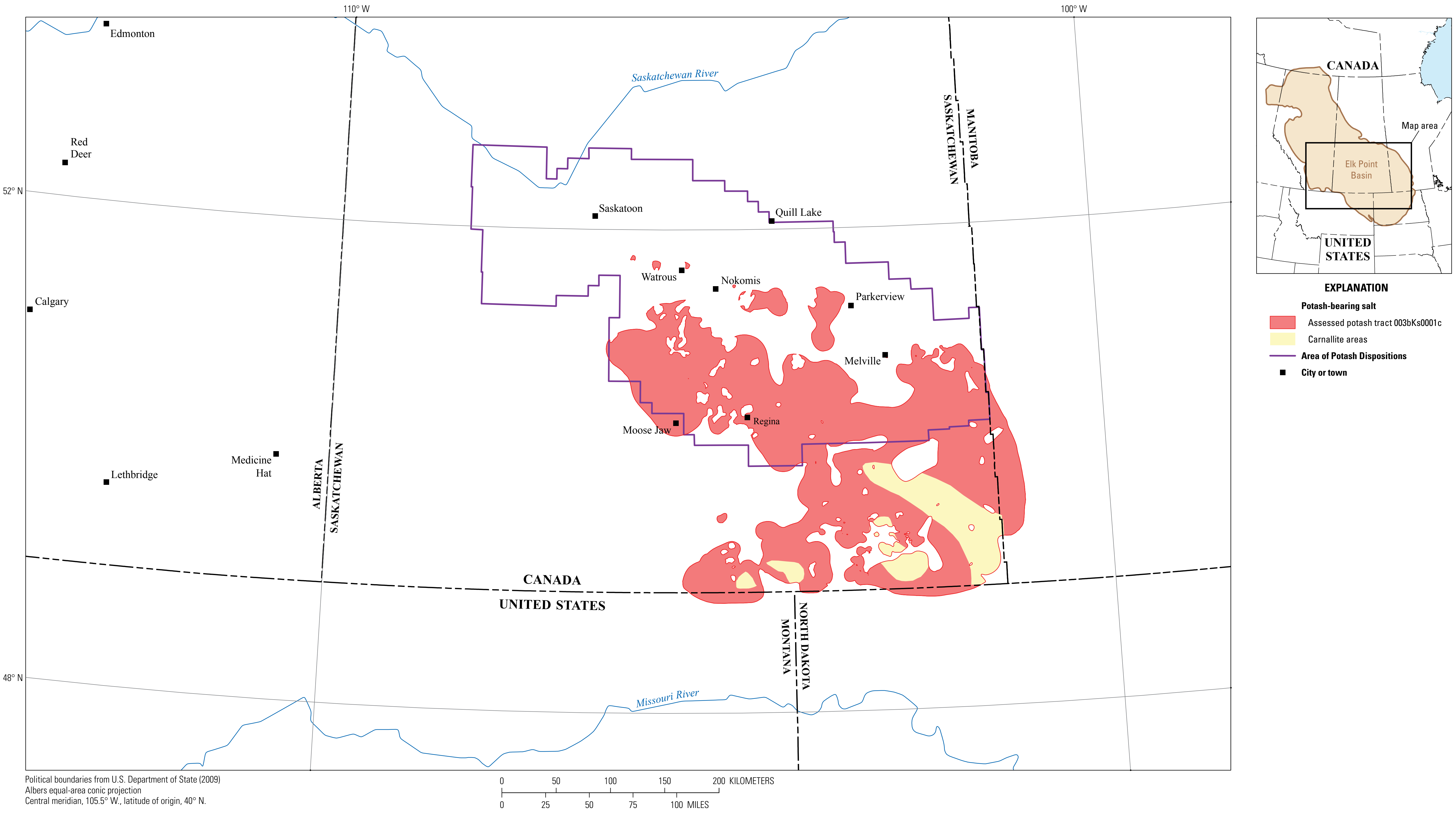
🟨 Carnallite areas

**Area of Potash Dispositions**

■ **City or town**

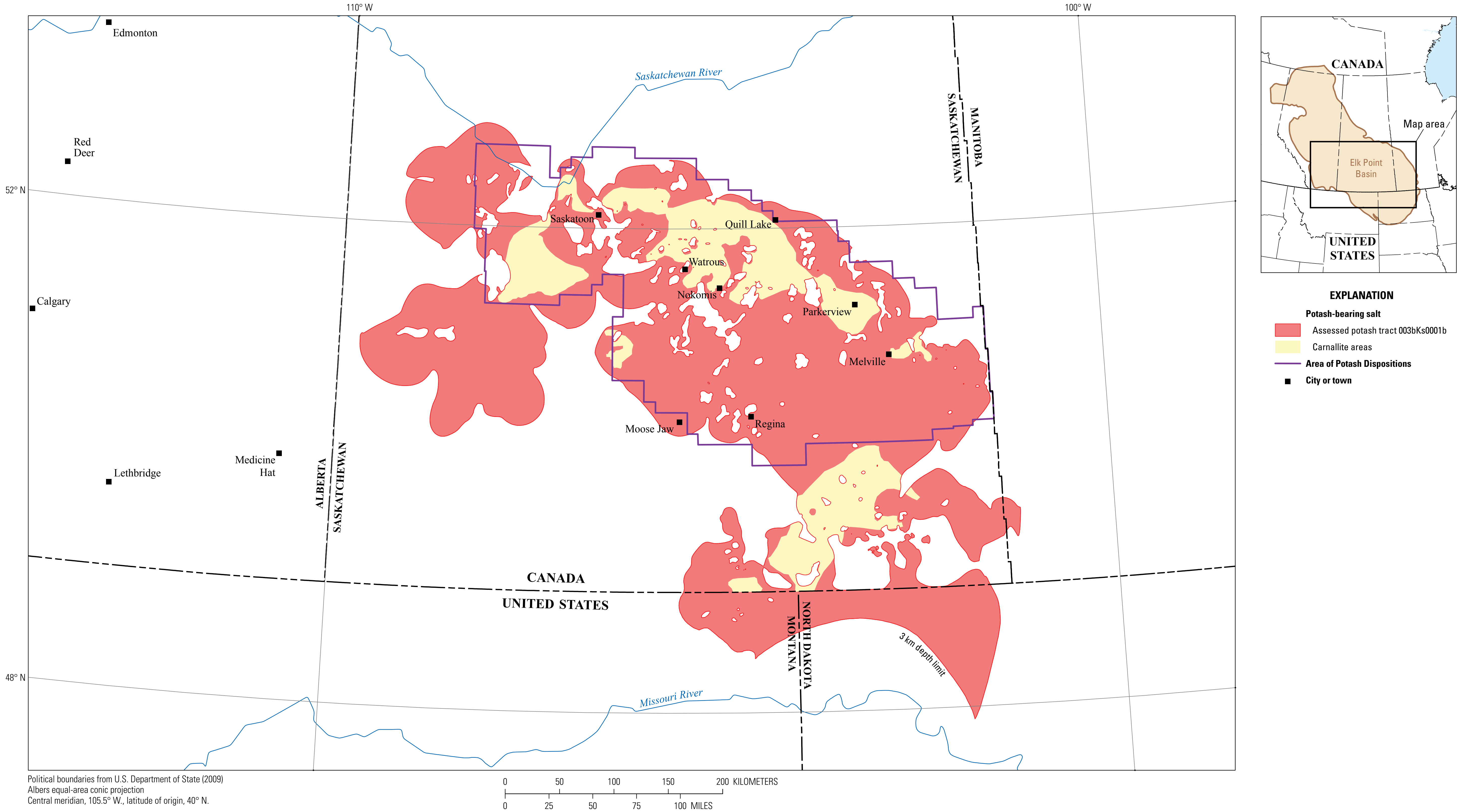
Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 25.** Map showing dominant types of mineralization in permissive tract 003bKs0001d that includes the Esterhazy Member of the Prairie Evaporite in Canada and the United States. Yellow areas are dominated by carnallite mineralization; the rest of the permissive tract is dominated by sylvite mineralization. Modifiied from Holter (1969) and Fuzesy (1982). km, kilometer.



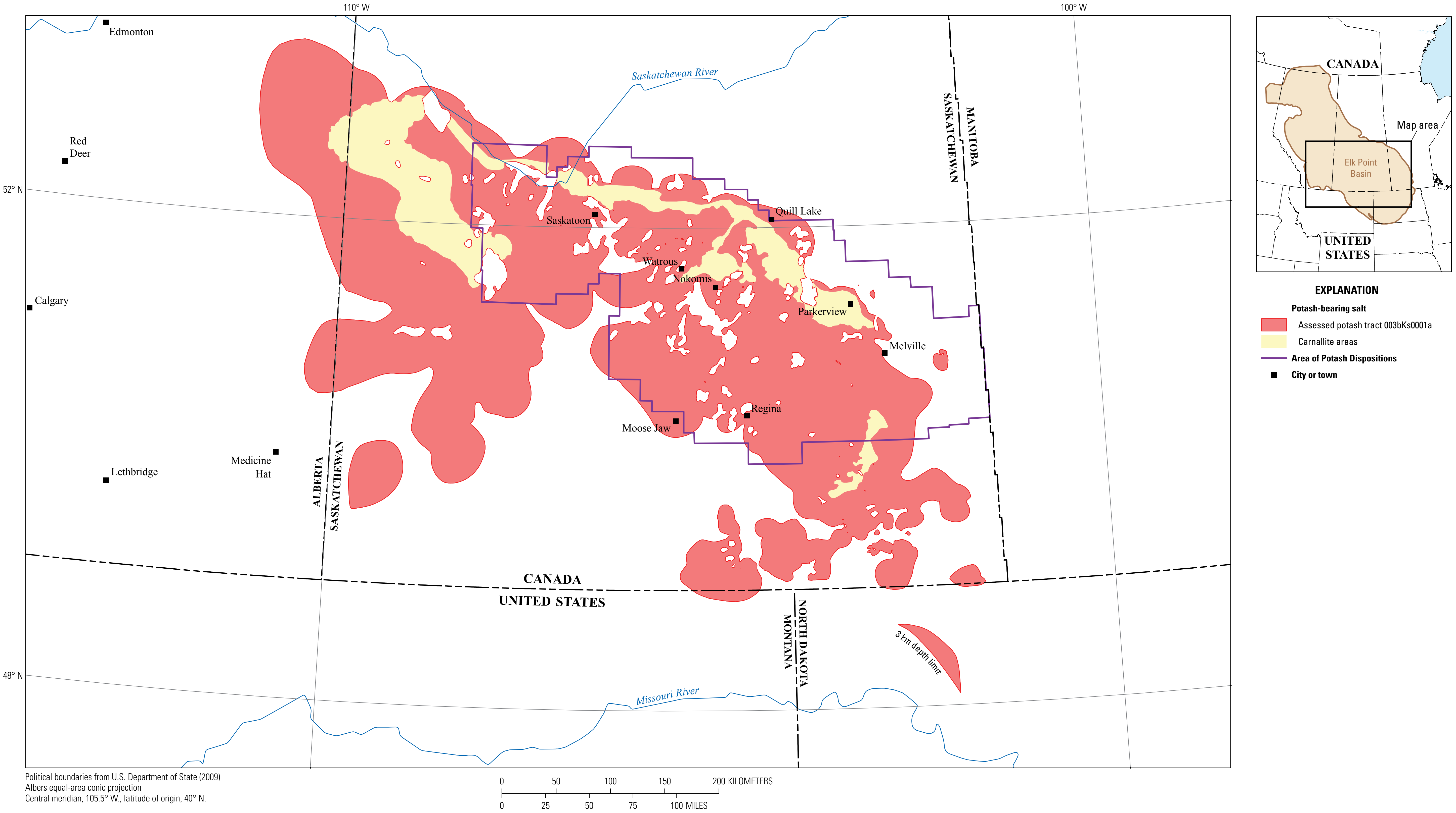
Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 26.** Map showing dominant types of mineralization in permissive tract 003bKs0001c that includes the White Bear Member of the Prairie Evaporite in Canada and the United States. Yellow areas are dominated by carnallite mineralization; the rest of the permissive tract is dominated by sylvite mineralization. Modifiied from Holter (1969) and Fuzesy (1982).



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 27.** Map showing dominant types of mineralization in permissive tract 003bKs0001b that includes the Belle Plaine Member of the Prairie Evaporite in Canada and the United States. Yellow areas are dominated by carnallite mineralization; the rest of the permissive tract is dominated by sylvite mineralization. Modifiied from Holter (1969) and Fuzesy (1982). km, kilometer.



Political boundaries from U.S. Department of State (2009)
Albers equal-area conic projection
Central meridian, 105.5° W., latitude of origin, 40° N.

**Figure 28.** Map showing dominant types of mineralization in permissive tract 003bKs0001a that includes the Patience Lake Member of the Prairie Evaporite in Canada and the United States. Yellow areas are dominated by carnallite mineralization; the rest of the permissive tract is dominated by sylvite mineralization. Modifiied from Holter (1969) and Fuzesy (1982). km, kilometer.

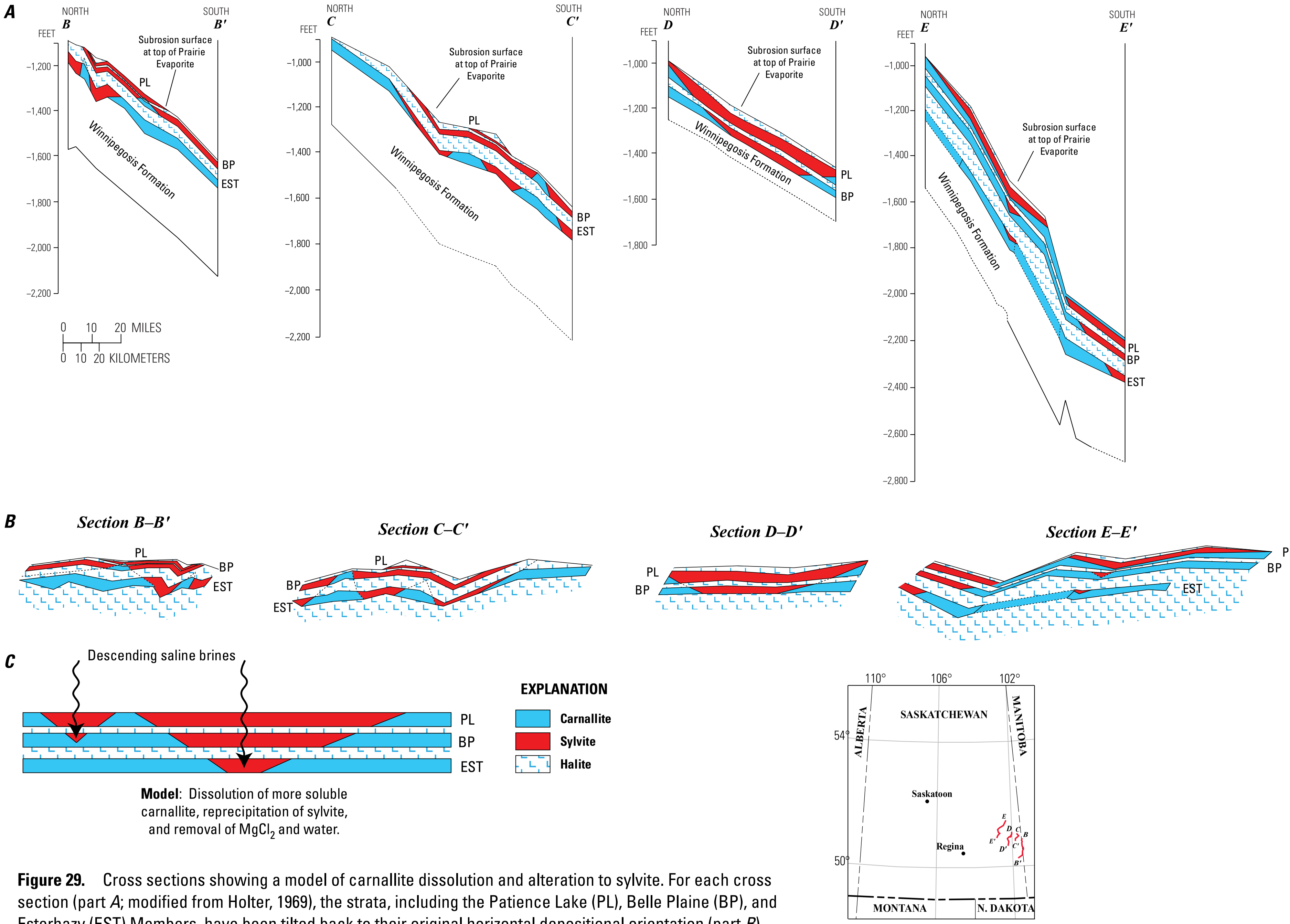


**Figure 29.** Cross sections showing a model of carnallite dissolution and alteration to sylvite. For each cross section (part *A*; modified from Holter, 1969), the strata, including the Patience Lake (PL), Belle Plaine (BP), and Esterhazy (EST) Members, have been tilted back to their original horizontal depositional orientation (part *B*). The model shows how descending saline brines may have dissolved carnallite to reprecipitate sylvite, removing magnesium chloride and water (part *C*).

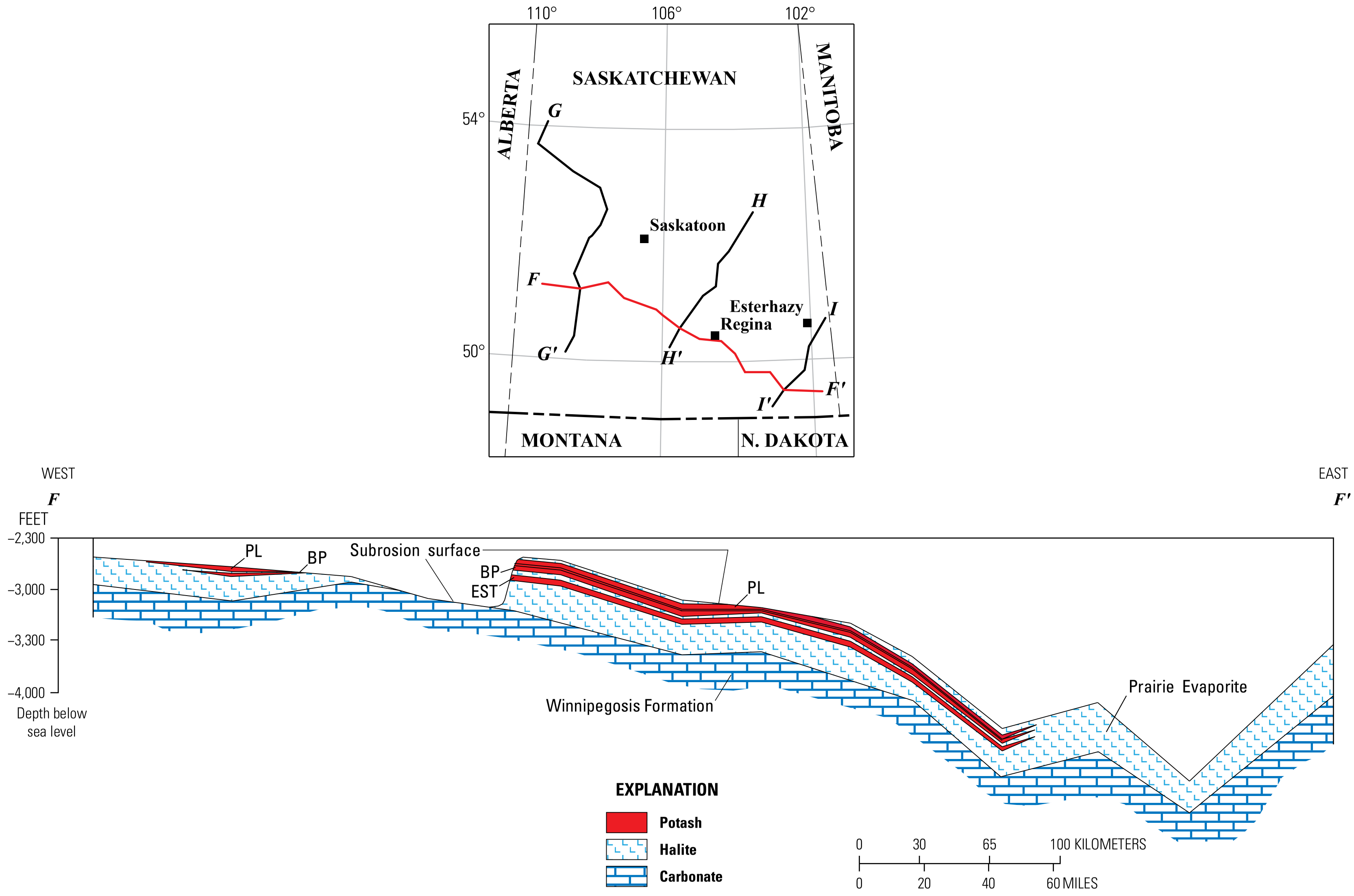


**Figure 30.** Cross section *F–F′* depicting the regional distribution of potash in the Prairie Evaporite Patience Lake (PL), Belle Plaine (BP), and Esterhazy (EST) Members in Saskatchewan, Canada. The subrosion surface is also shown. Modified from Holter (1969).

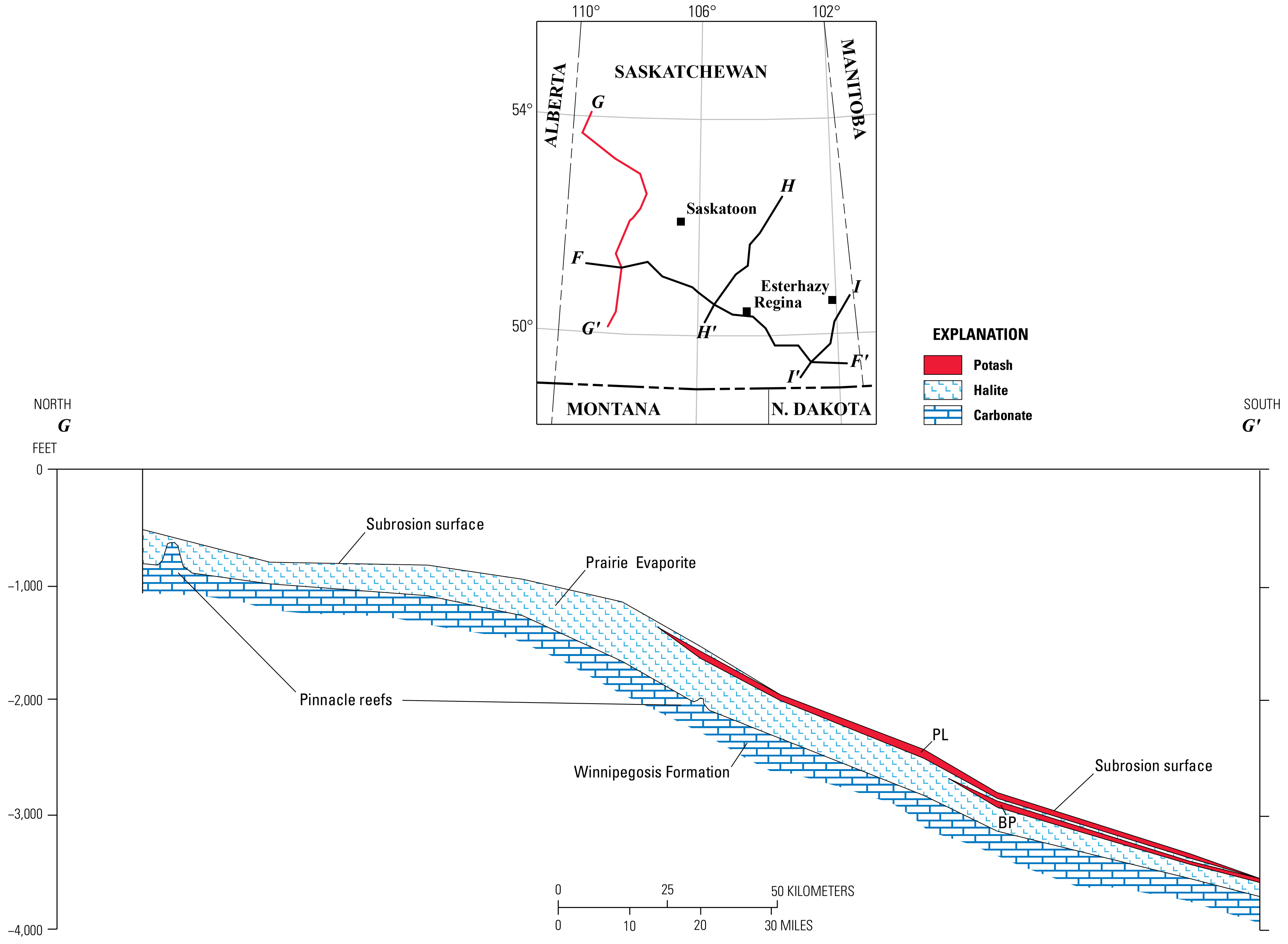


**Figure 31.** Cross section *G–G′* depicting regional distribution of potash in the Prairie Evaporite Patience Lake (PL) and Belle Plaine (BP) Members in Saskatchewan, Canada. The subrosion surface is also shown. Modified from Holter (1969).

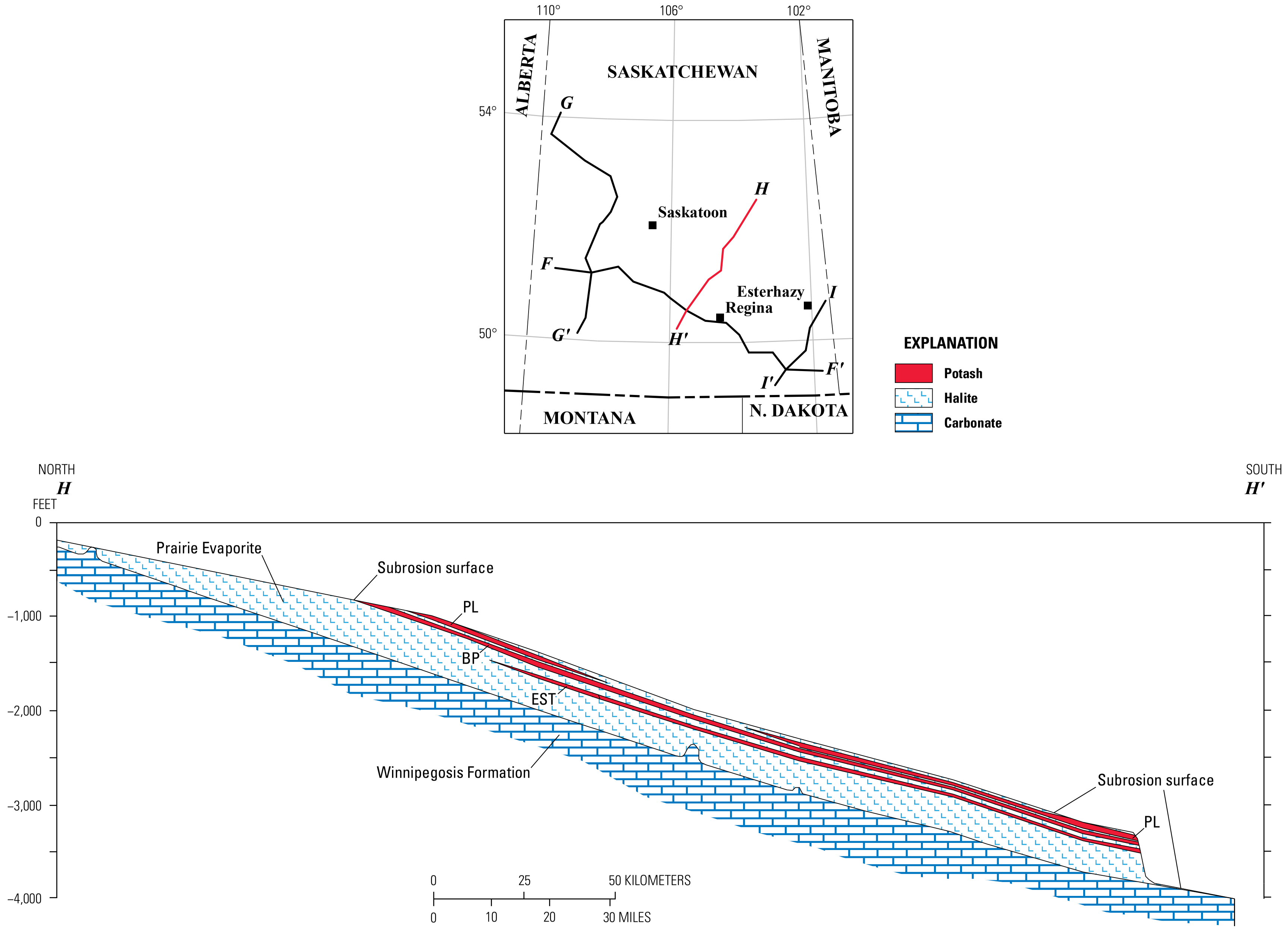


**Figure 32.** Cross section *H–H′* depicting regional distribution of potash in the Prairie Evaporite Patience Lake (PL), Belle Plaine (BP), and Esterhazy (EST) Members in Saskatchewan, Canada. The subrosion surface is also shown. Modified from Holter (1969).

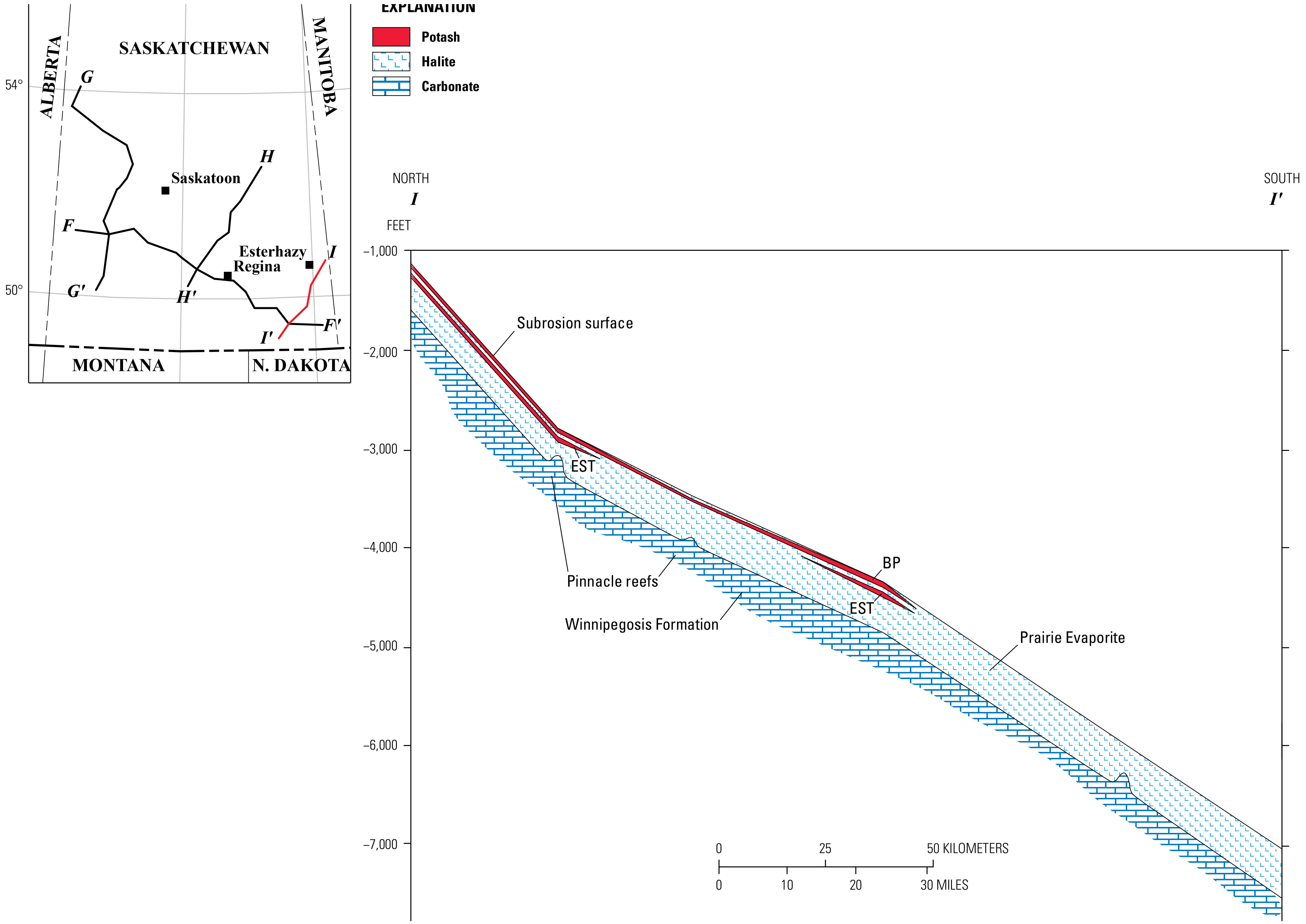


**Figure 33.** Cross section *I–I′* depicting regional distribution of potash in the Prairie Evaporite Belle Plaine (BP) and Esterhazy (EST) Members in Saskatchewan, Canada. The subrosion surface is also shown. Modified from Holter (1969).

## Mapping Carnallite Areas Using Seismic Methods

Because of the wide spacing of drill holes, seismic techniques can be used for detailed mapping of carnallite in permit and lease project areas. Carnallite is best developed where each member is thickest (fig. 16). Carnallitic potash zones are about 15–16 m (30–65 percent) thicker than equivalent sylvinitic zones (Wardlaw, 1968; Fuzesy, 1983), so the differences in thickness of carnallitic versus sylvinitic zones can be detected by two-dimensional (2D) surveys, and, more recently, by 3D seismic surveys (Molavi and others, 2010; Hambley and others, 2011; Rauche and others, 2016).

Karnalyte Resources, Inc., identified large areas of minable carnallite in the area of the Wynyard lease (fig. 4) by using a 3D seismic survey (Piché and others, 2011; Rauche and others, 2016). Western Potash Corp. also used a 3D seismic survey to define carnallite in the Milestone lease area (Hambley and others, 2011).

## Secondary Geologic Solution Effects on the Prairie Evaporite

Other solution effects on salt and other evaporite rocks have played a major role in developing the architecture of the Elk Point Basin as well as in affecting the volume and tonnage of the potash-bearing salt of the Prairie Evaporite (figs. 4, 7). Salts are highly soluble and susceptible to solution by nonsaline to saline water or brines from the time they are precipitated to when the salts are deeply buried. Removal of the Prairie Evaporite occurred at both the top and base of the formation (Gendzwill, 1978; Meijer Drees, 1986; Oglesby, 1988), along the updip edges of the Prairie Evaporite in Manitoba, across the northern edge of the Prairie Evaporite in Saskatchewan, and locally over Winnipegosis Formation reef mounds. Regional salt removal has occurred over hundreds of square kilometers in some areas and is seen in reflection seismic surveys and well data. Massive removal of salt and potash-bearing salt from southern Saskatchewan (figs. 4, 7) has taken place since the Middle Devonian and has resulted in some irregular subsequent depositional patterns and the development of solution collapse features (Holter, 1969; Worsley and Fuzesy, 1979; Boys, 1990; Gendzwill and Stauffer, 2006).

Sylvite and carnallite are also highly susceptible to solution during drilling, underground mining, or during normal movement of ground or formation waters. Carbonates are commonly important aquifers because of their high porosity and permeability, making evaporite sequences such as the Prairie Evaporite contained within platform carbonate formations more susceptible to dissolution by circulating groundwater and brines.

The effects and types of water solution are not unique to the Elk Point Basin and are documented in other potash-bearing salt basins (Linn and Adams, 1963; Borchert and Muir, 1964; Jones and Madsen, 1968; Kislik, 1970; Bachman and Johnson, 1973, Korenevskiy, 1989). Various types of water solution (fig. 34) in the Prairie Evaporite include:

1. Surface dissolution or erosion of halite or potash-bearing salt;
2. Karst structures;
3. Barren zones or salt horses in halite;
4. Dissolution of primary carnallite and reprecipitation of sylvite on a regional scale (described above); and
5. Subrosion or groundwater dissolution along the top and updip edges of a salt unit.

### Size and Importance of Solution Effects on the Prairie Evaporite

Dissolution effects that reduce the thickness (Boys, 1990) or change the distribution of salt (Holter, 1969; Fuzesy, 1982) appear as lows or holes on seismic profiles and maps. Because these lows or holes are anomalous to potash-bearing salt and salt beds and their exact nature cannot be determined except by drilling or underground mining, they have been called seismic or salt anomalies. Other terms applied to these features, some with slightly different meanings, include: anomalies, geologic anomalies, replacement zones, depletion zones, depletion and replacement zones, halite zones, salt horses, halite bodies, zones, washout zones, leached zones, and collapse zones (Linn and Adams, 1963; Kopnin, 1995). In the Prairie Evaporite and elsewhere, some salt anomalies may actually be areas of non-deposition and may not affect the potash-bearing salt in the same manner.

In addition to having major adverse effects on mining operations, salt anomalies can influence resource estimations. Because of overlying high-pressure aquifers, particularly in the Blairmore Formation with 2,700–5,500 kilopascals, dissolution features increase the aquifers' susceptibility to major flooding events and other water problems. Conventional underground mines have faced costly flooding episodes and engineering remediation (Prugger, 1979; Fuzesy, 1982; Prugger and Prugger, 1991; Garrett, 1996; Gendzwill and Martin, 1996). Some of the larger anomalies went unrecognized until they were encountered, and many small anomalies went unrecognized until additional seismic surveying became the standard pre-mining procedure. By 1996, 5 of the 17 potash mine shafts in the Elk Point Basin had major water inflows or were flooded during construction (Roessner, 1980; Garrett, 1996; Gendzwill and Martin, 1996), and 3 shafts had major water inflows before the aquifers were effectively sealed. The Patience Lake Mine encountered a major dissolution anomaly. Despite numerous attempts to stem the flooding, that effort was abandoned and it was eventually converted to a solution mine at a cost of nearly $13 million (Prugger and Prugger, 1991; Gendzwill and Martin, 1996). The Unity Mine encountered two aquifers during shaft sinking and was eventually abandoned with no recorded production. Flooding of Cominco's Vanscoy Mine forced it to shut down and undergo extensive rehabilitation for 2 years before resuming production.

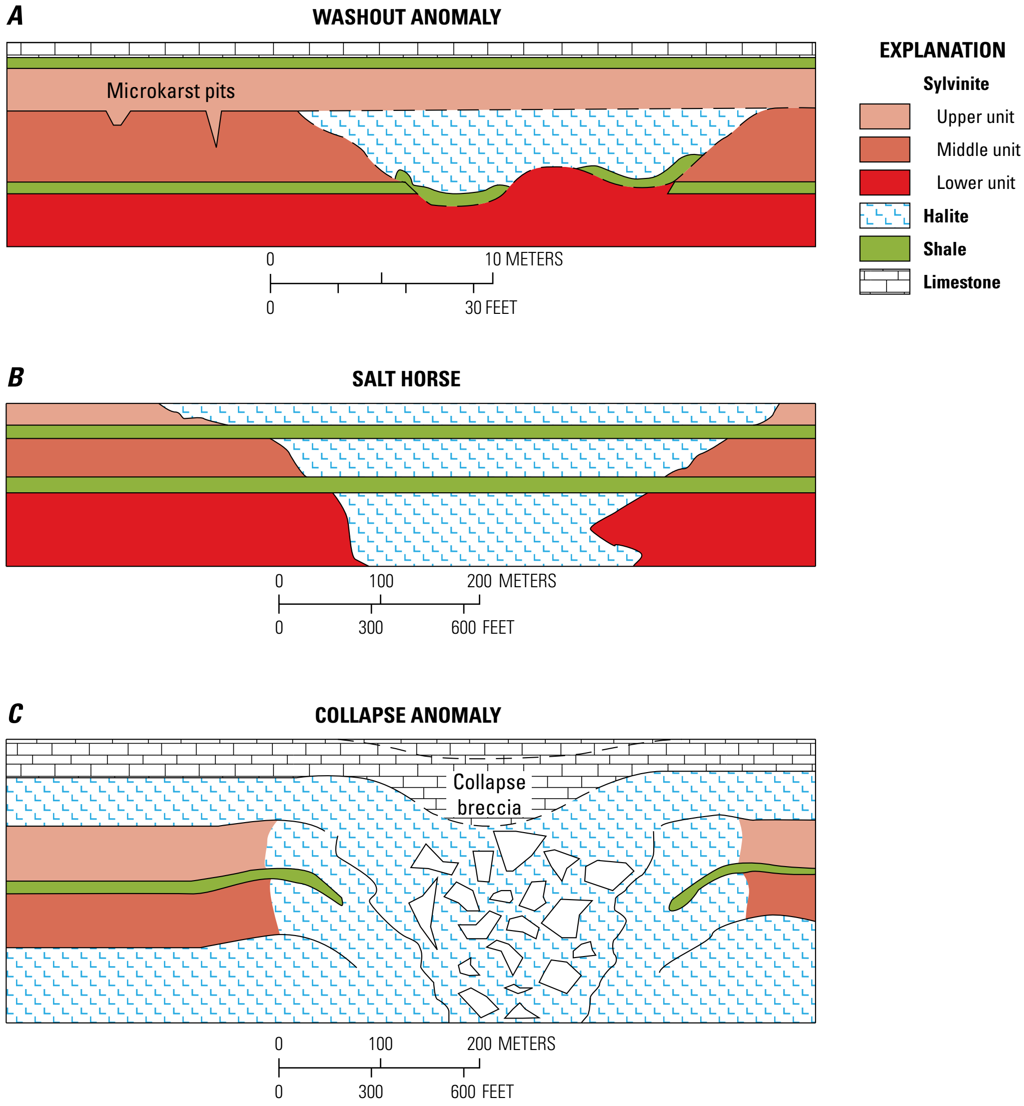


**Figure 34.** Diagrams showing the types of anomalies observed in potash-bearing salt using seismic methods. *A*, Washout anomaly, where surface dissolution or erosion removed halite or potash-bearing salt. *B*, Salt horse, where rising low-salinity fluids dissolved more soluble potash-bearing salts, leaving less soluble minerals. *C*, Collapse anomaly, where rising low-salinity fluids dissolved underlying soluble minerals, resulting in collapse of overlying strata. Modified from Boys (1990).

During mine development, buffer zones of relatively impermeable salt are created around the salt anomalies to prevent potential water leakage through these features, although six mines had major water inflows along relatively small fractures in areas not related to shafts or salt anomalies (Gendzwill and Martin, 1996). Improved shaft-sinking techniques and constant vigilance by the present potash mining companies have been largely successful in avoiding flooding disasters. Safety pillars or buffers are also established around drill holes to prevent leakage from overlying aquifers down through the drill holes.

Recently, the increased use of 3D seismic surveys provides more detail and a greater sense of confidence in defining salt anomalies than had been provided by 2D surveys (Hamid and others, 2004; Hardy and others, 2009a; Stirrett and Gebhardt, 2011). Underground geophysical studies including ground penetrating and radio frequency electromagnetic tomography radar are currently used to map the thickness of overlying strata and to identify smaller anomalous areas not detected by surface seismic surveys (Gendzwill and Martin, 1996; Choteau and others, 1997). Table 10 summarizes dimensions of these structures and buffer zones constructed around these structures in the Prairie Evaporite as noted in the literature. These phenomena and certain buffer zones are generally considered to be unminable and are subtracted from reported reserves. Some resource estimations include an estimation of unknown and undetected anomalies and added buffer zones, further reducing the potential resource estimations.

**Table 10.** Summary of seismic anomaly (salt dissolution) areas in the Prairie Evaporite, Canada, and characteristics of the potash members of the Prairie Evaporite.

[km, kilometers; m, meters; 2D, two-dimensional; 3D, three-dimensional; KP, potash permit number; KLSA, potash solution lease area number; –, no data]

| Property or area | Member or unit | Percent of area occupied by anomaly | Deduction for anomaly plus buffer | Conditions for use | Reference | Remarks |
|---|---|---|---|---|---|---|
| Elk Point Basin | Patience Lake | 7 | – | Digitized anomalies agree in area and location with those of a rectified seismic map (Holter, 1969) | Fuzesy (1982) | Digitized from Fuzesy's maps and calculated areas |
| Elk Point Basin | Belle Plaine | 7 | – | Digitized anomalies agree in area and location with those of a rectified seismic map (Holter, 1969) | Fuzesy (1982) | Digitized from Fuzesy's maps and calculated area |
| Elk Point Basin | White Bear | 4 | – | Digitized anomalies agree in area and location with those of a rectified seismic map (Holter, 1969) | Fuzesy (1982) | Digitized from Fuzesy's maps and calculated areas |
| Elk Point Basin | Esterhazy | 6 | – | Digitized anomalies agree in area and location with those of a rectified seismic map (Holter, 1969) | Fuzesy (1982) | Digitized from Fuzesy's maps and calculated areas |
| Saskatoon area mine | Patience Lake? | 8 | – |  | Baar (1973) | Measured and calculated from map of salt anomalies (fig. 19 of Baar, 1973) |
| Quill (KP 360) | Patience Lake and Belle Plaine | 10 | – | Anomalies detected in areas with 3D seismic coverage | Molavi and others (2010) | Reflects level of actual data |
| Quill (KP 360) | Patience Lake and Belle Plaine | – | 25 | Unidentified anomalies in areas with 2D seismic coverage | Molavi and others (2010) | Reflects level of actual data |
| Burr (KP 308) | Lower Patience Lake submember | 14 | – | Collapse anomalies | Lomas (2007) | Total percentage of area of mapped collapse features |
| Legacy (KP 289)[a] | Patience Lake, Belle Plaine, Esterhazy, and interbed 1 | 5 | – | Unknown geologic anomalies for measured mineral resources (within 0.8 km of drill hole) | Hardy and others (2009a, 2010a) | This adjustment is in addition to mapped anomalies |
| Legacy (KP 289)[a] | Patience Lake, Belle Plaine, Esterhazy, and interbed 1 | 9 | – | Unknown geologic anomalies for indicated mineral resources (within 1.6 km of drill hole) | Hardy and others (2009a, 2010a) | This adjustment is in addition to mapped anomalies |
| Legacy (KP 289)[a] | Patience Lake, Belle Plaine, Esterhazy, and interbed 1 | – | 25 | Unknown geologic anomalies for inferred mineral resources (within 8 km of drill hole) | Hardy and others (2009a, 2010a) | This adjustment is in addition to mapped anomalies |
| Milestone (KLSA 008) | Patience Lake, Belle Plaine, and Esterhazy | 5 | – | For measured resources (within 0.8 km of drill hole) | Hambley and others (2011) | Reflects level of actual data (3D seismic) |
| Milestone (KLSA 008) | Patience Lake, Belle Plaine, and Esterhazy | 9 | – | For indicated resourcess (within 1.6 km of drill hole) | Hambley and others (2011) | Reflects level of actual data (2D seismic) |
| Milestone (KLSA 008) | Patience Lake, Belle Plaine, and Esterhazy | – | 25 | For inferred resources (within 8 km of drill hole) | Hambley and others (2011) | Reflects level of actual data |

**Table 10.** Summary of seismic anomaly (salt dissolution) areas in the Prairie Evaporite, Canada, and characteristics of the potash members of the Prairie Evaporite.—Continued

| Property or area | Member or unit | Percent of area occupied by anomaly | Deduction for anomaly plus buffer | Conditions for use | Reference | Remarks |
|---|---|---|---|---|---|---|
| Legacy (KP 289)[a] | Patience Lake, Belle Plaine, and Esterhazy | 5 | – | Class 1 and minor collapse areas | Hardy and others (2010a) | Measured and calculated from figure 20 of Hardy and others (2010a) |
| Legacy (KP 289)[a] | Patience Lake, Belle Plaine, and Esterhazy | 10 | – | All salt solution areas | Hardy and Halabura (2007) | Estimates of 10,000 acres out of 97,240 acres affected by salt dissolution from historical maps |
| Legacy (KP 289) [a] Crown Mineral Lands | Patience Lake, Belle Plaine, and Esterhazy | 15 | – | Average anomalies for Crown Mineral Lands | Hardy and others (2009a, 2010a) | Area of Crown lands that may be affected by salt dissolution and collapse relative to total permit area |
| KP 441 | Patience Lake and Belle Plaine | 10 | – | Typical deduction for unknown, undetected anomalies | Hardy and others (2009b) | Typical deduction for unknown, undetected anomalies |
| Muskowekwan | Patience Lake, Belle Plaine | 10 | – | Typical deduction for unknown, undetected anomalies | Stirrett and Gebhardt (2011) | Typical deduction for unknown, undetected anomalies |
| Muskowekwan | Belle Plaine | 12 | – | Area affected by anomalies or buffers | Myers and others (2017) | Area affected by anomalies or buffers |
| Wynyard (KLSA 010, KP360A, Quill) | Patience Lake, Belle Plaine, and Esterhazy | 10 | – | Deduction for anomalies below detection limit of 3D seismic surveys | Piché and others (2011) | |
| Wynyard (KLSA 010, KP360A, Quill) | Patience Lake, Belle Plaine, and Esterhazy | 25 | – | Deduction for anomalies in areas with no 3D seismic surveys | Piché and others (2011) | |
| Jansen area (KP 286) | Upper Patience Lake submember | – | 25 | Unidentified mining level anomalies | Halabura and others (2005) | Unidentified mining level anomalies express the amount of resources that mining operators remove from their resource calculations as a conservative value. Unknown geologic anomalies for measured mineral resources are the same feature, expressed in different words. The numbers are not based on data, whether new or otherwise |
| Jansen | Upper Belle Plaine submember | – | 13.9 | | Halabura and Gebhardt (2006) | Anomaly plus 600 m and 350 m setbacks for different anomaly types |
| Jansen | Upper Belle Plaine submember | – | 23.9 | | Halabura and Gebhardt (2006) | Anomaly plus 1,000 m and 600 m setbacks for different anomaly types |
| Jansen | Upper Belle Plaine submember | – | 25 | Unidentified mining level anomalies | Halabura and Gebhardt (2006) | Anomaly plus 1,000 m and 600 m setbacks for different anomaly types |
| Jansen area (KP 285, 286, and 290) | Upper Belle Plain submember | – | 25 | Unidentified mining level anomalies | Halabura and Gebhardt (2006) | Anomaly plus 1,000 m and 600 m setbacks for different anomaly types |
| An overview of the geology of solution mining of potash in Saskatchewan | Patience Lake, Belle Plaine, and Esterhazy | – | 25 to 35 | Buffered areas around known anomalies to deductions for unidentified anomalies | Halabura and Hardy (2007) | Anomaly plus 1,000 m and 600 m setbacks for different anomaly types |

[a] Legacy Mine was previously known as the Bethune and Findlater project area.

## Washout Anomalies Caused by Dissolution by Surface Water or Brine

Relatively small dissolution areas at the top of salt layers are attributed to surface erosion by fresh or low-salinity water during or slightly after salt deposition (Baar, 1972, 1973; Boys, 1990) and may be referred to as washouts or washout anomalies (figs. 35, 36). Washout anomalies are associated with intraformational erosional channels in which the potash bed has been replaced or altered to halite. Figures 35 and 36 show washout anomalies (also labeled as microkarst), now filled by halite, beneath two clay seams that mark the top of a potash-bearing evaporite cycle. Unless they are uncommonly large, these anomalies are generally not considered to affect potash resource estimates or mining operations.

## Karst Development

The Paleozoic section above the Prairie Evaporite contains two major erosional unconformities (fig. 8). During those intervals, extensive karst features developed in the Upper Devonian and Mississippian carbonate section. Karst features provide channelways and groundwater transport from the overlying strata and allow the groundwater and low-salinity brines to come into contact with and to dissolve the underlying salt of the Prairie Evaporite. Dissolution and collapse anomalies form by the dissolution of the Prairie Evaporite and replacement by material caved from above (figs. 34, 36). This type of disturbance may be local (less than a square kilometer) or regional (several square kilometers or greater) and may affect the entire Prairie Evaporite section.

Similar types of structures may begin by dissolution of the underlying salt, creating a cavity and causing the collapse of the overlying rocks into the dissolution voids. Sagging of the overlying salt units into an underlying dissolution void is apparent in figure 35 and in cross sections from Meijer Drees (1986). At the Lanigan Mine, mining encountered down-dropped blocks of the overlying Dawson Bay Formation suspended within the Prairie Evaporite salt (Rauche and others, 2016). As overlying rocks collapse into the voids, fractures are propagated into the overlying strata. These fractures create additional pathways for groundwater from overlying aquifers. These structures are reported throughout the extent of the potash in Saskatchewan and North Dakota (Meijer Drees, 1986; Boys, 1990; Burke, 2001; Rauche and others, 2016).

## Salt Horses or Barren Areas Resulting from Upwelling Brines

Leach anomalies, also referred to as salt horses, are zones within a potash-bearing salt bed or group of beds where the potash minerals have been removed (fig. 35) and the less-soluble or insoluble minerals, such as halite and clays, remain (Linn and Adams, 1963; McIntosh and Wardlaw, 1968; Holter, 1969; Mackintosh and McVittie, 1983). In these barren zones, bedding is continuous from the adjacent potash-bearing areas through the salt horse (fig. 34). Clay seams are commonly the easiest traceable lithologies through these anomalies (Linn and Adams, 1963; Boys, 1990). In the Prairie Evaporite, leach anomalies are represented by post-depositional replacement of sylvite or carnallite by halite.

Thicknesses of strata within these anomalous areas are less than those of adjacent strata because of the removal of the potash salts and subsequent compaction resulting from the pressure of overlying strata. Photographs of equivalent strata just outside of a leach anomaly and within the leach anomaly in the Patience Lake Member (fig. 37) show the decrease in thickness of equivalent salt and clay seams from outside and inside a leach anomaly (Boys, 1990). Figure 37 is a photograph of the edge of a leach-collapse anomaly where the potash salts have been removed, the thickness of the equivalent salt layer has decreased, and the clay seams dip toward the center of the anomaly.

Leach anomalies are infrequently reported in the Prairie Evaporite and are generally local in extent (McIntosh and Wardlaw, 1968; Baar, 1972, 1973; Mackintosh and McVittie, 1983; Boys, 1990; Yang and others, 2009b). Few calculations of the volumes involved in leach anomalies are available in the literature. Boys (1990) calculated the thickness difference between areas containing leach anomalies (salt horses) and adjacent unaffected potash-bearing salt to be in the range of 20–25 percent. With a mean potash grade in the examined potash member in the range of 20–25 percent $K_2O$ equivalent, removal of the sylvite (or all of the potash) from this affected part of the potash member would account for that decrease in thickness. Salt anomalies make up 3–5 percent of the Krasyi II potash bed in the Verkhnehama deposit of the Cisuralian Basin in Russia (Kopnin, 1995). The volume of potash-bearing salt in those salt anomalies was reduced by 20–25 percent, which is similar to the decrease in thickness observed by Boys (1990).

These barren areas occur within potash-bearing salt beds where potash minerals are believed to have been dissolved by low-salinity brines rising from deeper levels in an evaporite basin (Linn and Adams, 1963; Jones and Madsen, 1968; McIntosh and Wardlaw, 1968). Such anomalies in the Prairie Evaporite are commonly associated with pinnacle reefs in the underlying Winnipegosis Formation (Gendzwill, 1978; Molavi and others, 2010; Hambley and others, 2011). The pinnacle reefs may have served as channelways for the ascending saline brines (fig. 7). The shape, location, and thickness of underlying pinnacle carbonate reefs can be accurately determined with 3D seismic surveys (Gendzwill, 1978; Stirrett and Gebhardt, 2011). The anomalies, however, are apparently not revealed by seismic surveys and are exclusively encountered during mining operations. As such, they are not considered in premining resource estimates.

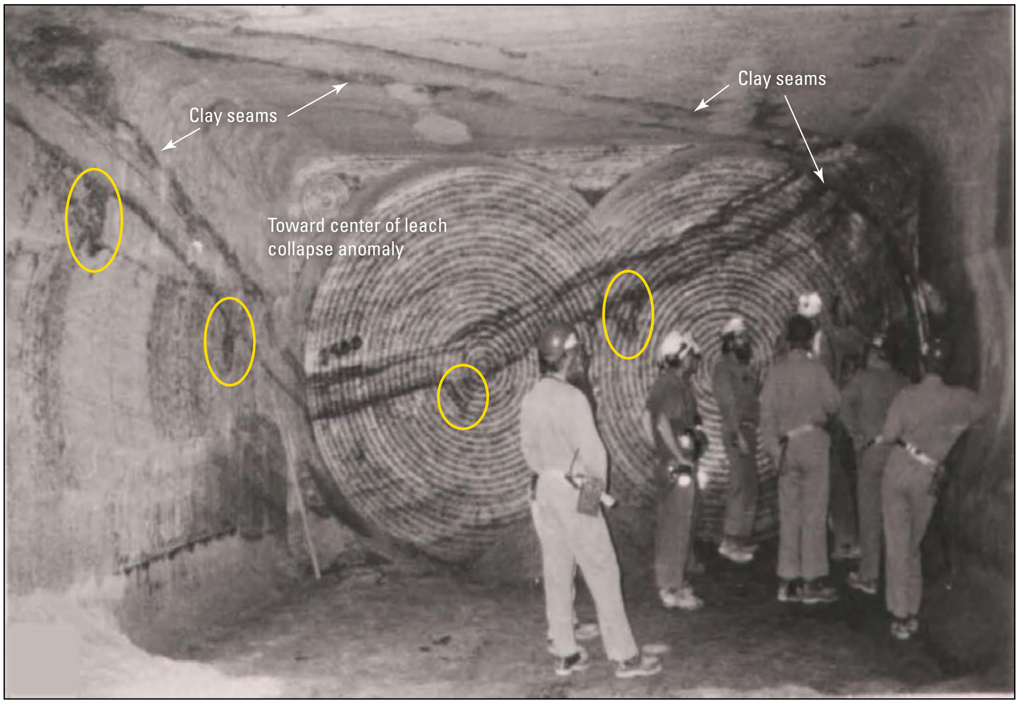


**Figure 35.** Photograph of the edge of a leach-collapse anomaly and previously formed small triangle-shaped washout channels filled by halite. These microkarst channels are circled in yellow. Photograph from Boys (1990), used with permission from the Department of Geological Sciences at the University of Saskatchewan.

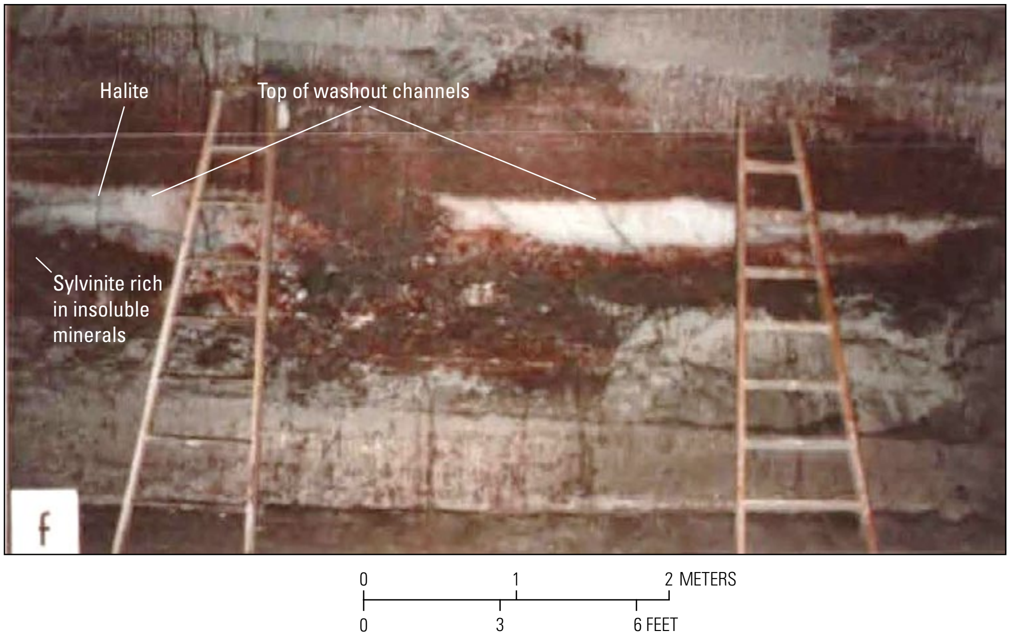
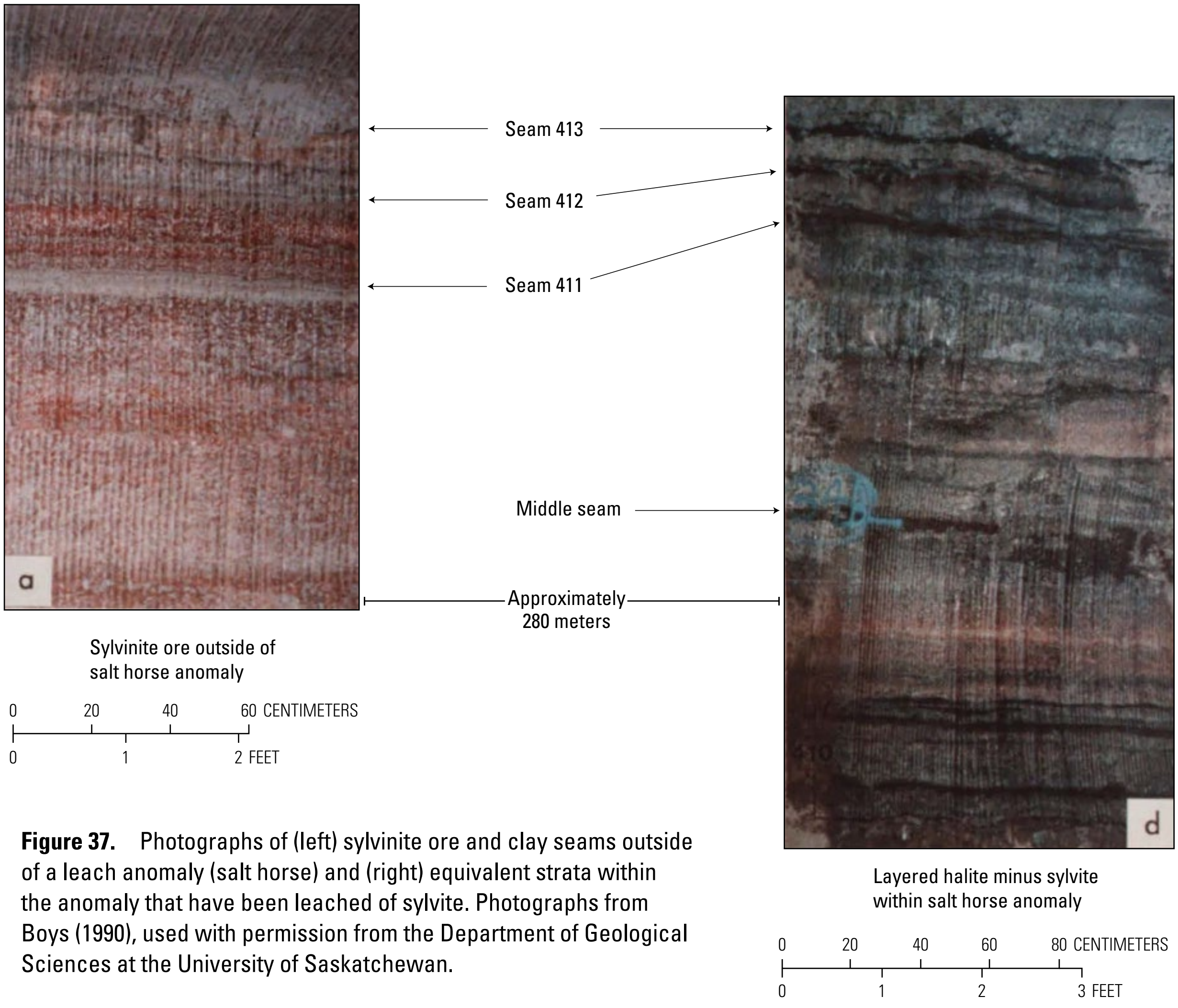


**Figure 36.** Photograph of two washout channels that have been filled with halite. They are underlain by sylvinite that is rich in insoluble minerals. Photograph from Boys (1990), used with permission from the Department of Geological Sciences at the University of Saskatchewan.



Sylvinite ore outside of salt horse anomaly

Layered halite minus sylvite within salt horse anomaly

**Figure 37.** Photographs of (left) sylvinite ore and clay seams outside of a leach anomaly (salt horse) and (right) equivalent strata within the anomaly that have been leached of sylvite. Photographs from Boys (1990), used with permission from the Department of Geological Sciences at the University of Saskatchewan.

## Removal of Salt Caused by Subrosion or Subsurface Dissolution

Soluble rocks (mainly salt, gypsum, or anhydrite) in the subsurface are dissolved where the salt is in contact with low-salinity groundwater. This process is commonly referred to as subrosion in NI 43-101 reports. Subrosion is a relatively common phenomenon, described in potash-bearing salt basins such as in the Pripyat Basin in Belarus (Korenevskiy, 1989), the Zechstein Basin in Germany (Gimm, 1968), and the Danakil Basin in Ethiopia (Rauche and van der Klauw, 2011). Salt dissolution may occur along the upper and lower boundaries of a salt-bearing unit, as well as along the updip edges of the salt unit, such as the eastern edge of the Prairie Evaporite in Manitoba and Saskatchewan (Gorrell and Alderman, 1968; Nicolas, 2016). The large embayment areas shown in figure 3 are the result of subrosion of the Prairie Evaporite salt.

Subrosion effects documented by drill hole data include: (1) layers of solution collapse breccias in the stratigraphic column where salt and other evaporites would normally be found; (2) regions with an abnormally thin salt section overlying the potash-bearing salt; (3) suprasalt rocks draping over subsalt rocks; (4) continuation of salt isopachs and potash beds across zones of salt dissolution; (5) overall thinning of all the salt units (DeMille and others, 1964; Holter, 1969; Boys, 1990); (6) development of a broadly irregular surface on the top of the section (figs. 30–33); and (7) a decrease or removal of both the salt-back and potash-bearing salt. Subrosion is most pronounced in the upper surface of the evaporite section (figs. 30–33) and along the updip edges of the Elk Point Basin. Figure 22 illustrates the overall effect on the upper surface of the Patience Lake Member through the thinning or removal of this member.

Thickness variations in the Prairie Evaporite are related, at least in part, to subrosion. The updip and upsection parts of the Prairie Evaporite have been considerably reduced or entirely removed in Manitoba and adjacent parts of Saskatchewan by subrosion (Nicolas, 2015) so that the Esterhazy Member is presently the only viable potash-bearing strata in that area. The salt-back above the Patience Lake Member in the northern part of the Saskatchewan subbasin is generally thinner above latitude 50° N. (Yang and others, 2009b). In some areas, subrosion has removed considerable parts of the potash-bearing salt beds, and, in other areas, it has cut down into underlying carbonate rocks of the Winnipegosis Formation (figs. 30–33). Meijer Drees (1986) and Nicolas (2015) show the updip edge of the Prairie Evaporite as a subrosion contact with younger, less-soluble strata draped over this contact.

Unraveling the timing of salt solution events in the Prairie Evaporite is based on studies of isopachs and structural anomalies of overlying strata (Holter, 1969; Meijer Drees, 1986; Nicolas, 2016; and Yang and others, 2009b). Localized salt solution occurred during the Middle and Late Devonian principally in the areas shown in figure 4 as embayments south of Saskatoon. During the Mississippian to Jurassic, salt solution continued in this area and along the northeastern part of the present position of the Prairie Evaporite (figs. 3, 4). Considerable salt solution occurred from the post-Jurassic through the Pleistocene all along the northeastern edge of the Prairie Evaporite and in the southern embayment (Holter, 1969; Yang and others 2009b; Nicolas, 2016).

## Potash Exploration and Mine Development in the Elk Point Basin

Potassium salts were first recognized in an oil exploration well in the Saskatchewan subbasin in 1942. Because depths to the potash beds in the early wells were 2,264 to 2,333 m, the potash beds were not considered to be of economic interest (Bartsch and others, 2014). Since the middle part of the 19th century (British Sulphur Corp., Ltd., 1966, 1984), conventional underground mines have dominated global potash production. Maximum conventional underground mining depths in salt in other parts of the world were approximately 1,000 m, and solution mining at greater depths was an untested technique. When oil exploration companies began using gamma logs on a routine basis in 1950, the widespread extent and depths of potash beds in Saskatchewan became known, and, in the ensuing flurry of exploration activity that continued into the 1960s, nine conventional underground mines and one solution mine were developed in Saskatchewan (Fuzesy, 1982). All of these mines are still in production.

In the Elk Point Basin, mining in the 1960s was concentrated in the shallowest, highest grade, minable intervals that are located in the Patience Lake and Esterhazy Members and principally situated along the northern edge of the Prairie Evaporite (fig. 4). During the early years of potash mining in Saskatchewan, the Unity, Patience Lake, and Vanscoy Mines were flooded by groundwater. The Unity Mine was abandoned prior to production, the Patience Lake Mine was converted to a solution mine, and the Vanscoy Mine was rehabilitated and eventually resumed production as a conventional underground operation.

During the past 5 years, two additional conventional underground mines—the Esterhazy K3 and Rocanville West Mines as extensions of the Esterhazy K1 and K2 and Rocanville Mines, respectively (Fracchia and others, 2017a; Mosaic Company, 2017a,b)—and two solution mines—the Legacy Mine (Shah, 2013; K+S Potash Canada, Ltd., 2015, 2017) and the Milestone Mine (Xue, 2019; Western Resources Corp., 2020)—have been developed and gone into production. The Milestone Mine has delayed completion of mine facility construction because of the global COVID-19 pandemic (Woodroof, 2020).

Despite substantial fluctuations in global potash prices, a relatively large number of companies assumed a long-term approach to potash mining and have been active during the period from 2005 to 2019 in mine expansion, potash exploration, or acquiring properties. In anticipation of an increasing demand for potash-rich fertilizers, potash companies increased their production capacity and developed new greenfield mines (Cocker and others, 2016, 2017). Table 1 presents a compilation of most of the companies involved in some aspect of potash exploration in the Elk Point Basin over the past seven decades.

The total production capacity of the Elk Point Basin (excluding the Milestone Mine) has increased substantially and now produces approximately 33.4 Mt of KCl or 22.8 Mt of $K_2O$ equivalent per year (table 2 and references therein). Production capacity increased with the extension of two conventional underground mines, the addition of two solution mines during the past decade, and with increased production shaft capacity at existing mines. K+S Potash Canada's Legacy Mine started production in 2017, Western Resources Corp. planned to begin production at its Milestone property in early 2020 (Western Resources Corp., 2020), and other companies such as Gensource Potash Corp.'s Vanguard property (Gensource Potash Corp., 2019) and Encanto Potash Corp.'s Muskowekwam property (Encanto Potash Corp., 2017) plan to begin production within a few years.

BHP Billiton has completed production, service shafts, and advanced development at its Jansen conventional underground mine (MacPherson, 2019). BHP Billiton's Jansen Mine has been under construction (mainly shaft sinking) since 2010 and, once it begins production, could have a major effect on the regional and global potash market because of its anticipated production capacity of 8 Mt KCl per year (Hatch, 2012; Shah, 2015). Previous reports stated that production started in January 2015 (Stone, 2010), but the decision to proceed to production had not yet been reached (MacPherson, 2017; Saskatchewan Ministry of the Economy, 2018). In August 2021, BHP Billiton announced that it is proceeding with completion of the Jansen Mine, with production expected to begin in 2027 (BHP Billiton, 2021).

Encanto Resources' Muskowekwan and Karnalyte Resources' Wynyard projects are in advanced stages of analysis and may be developed in the near future depending on respective corporate decisions (Rauche and others, 2016). The Wynyard project had advanced to the pre-feasibility stage for solution mining of carnallite, but the project has been suspended in part because of the COVID-19 pandemic and its effects on global potash prices and worker safety (Karnalyte Resources, Inc., 2020).

The increased potash production capacity with the addition of these mines plus several additional potential potash operations (table 2) could push the total production capacity of the Elk Point Basin to substantially more than 60 Mt of KCl or about 40 Mt of $K_2O$ equivalent per year. There is also the potential for developing mines in adjacent parts of Manitoba and Alberta. Because of the depth, lower grades, and apparent discontinuity of the potash strata in North Dakota and Montana and the abundant and more accessible potash resources in Canada, development of potash mines in adjacent parts of the United States is not anticipated in the near future.

In part because of higher initial development costs and longer development times required to develop greenfield conventional mines in Saskatchewan, a greater emphasis has been placed on development of greenfield solution mines. In 2010, costs for developing greenfield conventional underground mines in Saskatchewan were on the order of $3.5–5.0 billion (CAD) (Moore and others, 2011; Potash Corp., 2012; Karnalyte Resouces Inc., 2013; Cocker and Orris, 2014). The BHP Billiton Jansen Mine is expected to cost $14 billion (USD) with $4 billion (USD) already committed (Saskatchewan Ministry of the Economy, 2018). The length of time required for developing conventional underground mines is usually about 5–7 years (Moore and others, 2011; Berube, 2012; Hopf and others, 2012; Potash Corp., 2012; Cocker and Orris, 2014). The Jansen Mine development time is an exception; its development has already exceeded 10 years and underground and surface facilities still remain to be constructed as of October 2019 (Saskatchewan Ministry of the Economy, 2018; MacPherson, 2019).

In 2010, costs for developing greenfield solution mines in Saskatchewan were on the order of $2.0–3.5 billion (CAD), and development time was about 3–5 years (Moore, 2010; Cocker and Orris, 2014). Hatch (2012) estimates closure and reclamation costs for solution mines to be about $235 million (CAD), an amount far less than for conventional underground mines (approximately $498 million [CAD]).

Sylvite is more soluble than halite at elevated temperatures, so solution mining uses hot brines (pumped underground from the surface to enhance the temperatures of formation waters prevalent in deeper parts of the Elk Point Basin) to selectively dissolve sylvite and leave the less soluble halite and insoluble minerals below ground. The potash-rich brines are pumped to surface ponds or crystallizers, where potash (as KCl) is then extracted and undergoes further processing to various final products. Temperatures of formation waters in the deeper parts of the Elk Point Basin are in the range of 45 to 55 °C in the Legacy Mine area, 55 to 60 °C in the Belle Plaine Mine area, and 60 to 65 °C in the Milestone Mine area (Hardy and others, 2010a,b; Western Resources Corp., 2017). Measured bottom hole temperatures for a number of wells that were available at that time are also shown on a map by Holter (1969). Presently, the Belle Plaine and Legacy Mines are recovering potash from depths of about 1,600 m, and the Milestone Mine is operating at depths of about 1,770 m (Hambley and others, 2015). The planned Vanguard Mine is expected to recover potash from depths of approximately 1,500 m (Fourie and others, 2018).

Because solution mining is not as selective as conventional underground mining, more of the potash-bearing section can be mined, and larger volumes of the potash resources are considered to be part of the recoverable resources beyond the depth limits of conventional mining. Operating costs, and particularly energy costs, for solution mines are higher than for conventional underground mines ($234 million compared to $160 million annually [CAD]) (Canadian Industry Program for Energy Conservation, 2003; Cocker and Orris, 2014). As in conventional underground mines, carnallite-rich areas are avoided, as the magnesium released from the carnallite inhibits the effectiveness of the hot brines to dissolve sylvite.

## Critical Role of Water in Potash Mining

An abundant supply of water is critical to the mining and processing of potash. Potash mines require water in the extraction and processing of potash ore, as well as in waste disposal. In 2010, Potash Corporation's water usage for processing of potash from its conventional underground mines included 550 gallons per metric ton of product (gal/t) at its Lanigan Mine, 1,450 gal/t at its Rocanville Mine, 1,600 gal/t at its Allan Mine, and 6,300 gal/t at its Cory Mine (Potash Corp., 2012) for a total of approximately 10,000 gal/t (Cocker and Orris, 2014). Water usage at the other conventional mines is probaby similar to these requirements.

Water is also critical in solution mining, and water usage varies during development of the solution chambers in halite to solution of more soluble sylvinite ore. Mosaic Company's Belle Plaine solution mine in Saskatchewan uses 5,000 gallons per minute (gal/min), which is equal to 2.6 billion gallons per year (gal/yr) to produce about 2 Mt per year (Mt/yr), which is equal to 1,300 gal/t (Cocker and Orris, 2014). K+S Potash Canada's Legacy Mine will use water from Buffalo Pound Lake (Hardy and others, 2010a). Water requirements for the Legacy Mine are expected to be similar to those for the Milestone Mine. This equates approximately to 5,300 gal/t.

Where there are few available surface or shallow aquifers available, some projects are looking to obtain the use of either deep-seated brackish water from the Blairmore Formation (Karnalyte Resources, Inc., 2013) or recycled water. Anticipated production water usage is about 980–1,150 cubic meters per hour or approximately 9 million cubic meters per year to produce 625,000 metric tons per year (Rauche and others, 2012). Western Potash Corp.'s Milestone Mine will use 21.9 million cubic meters per year or the equivalent of 5.8 billion gal/yr of water from the City of Regina's treated effluent for the first 6 years (Varas, 2012) to produce 2.8 Mt/yr (Hardy and others, 2010b) or 2,066 gal/t.

The increased need for water by the potash industry (a total of approximately 300 million gallons of water in 2017) may conflict with that of other water users in Saskatchewan. Competing requirements between increasing populations, agricultural irrigation, and mining for the available water supplies may be strongly affected by the increasing number and severity of droughts related to climate change (Wheaton, 2013). Saskatchewan has recently experienced several major droughts in 1980, 1988, and 1999–2005, which adversely affected water levels in rivers and lakes.

# Mineral Resource Exploration and Estimation

Most stratabound potash-bearing salt deposits are not exposed at the Earth's surface and are commonly found at depths of several hundred meters or more beneath the surface. Exploration and evaluation of potash deposits have relied on indirect methods, such as those used in hydrocarbon exploration that include mainly seismic and deep drilling studies.

## Current Methods of Mineral Resource Exploration and Estimation

Bodies of mineralized rock are classified according to (1) their geological, mineralogical, physical, and chemical properties; (2) the level of certainty associated with the estimates of mineral potential; and (3) their profitability. For estimation and assessment studies, the words "deposit," "resource," "reserve," "discovered," and "undiscovered" are used, but with specific meanings. A "mineral deposit" is a mineral occurrence of sufficient size and grade that might, under the most favorable circumstances, be considered to have economic potential. An "ore deposit" is a mineral deposit that has been tested and is known to be of sufficient size, grade, and accessibility to be producible to yield a profit (Cox and Singer, 1986). "Mineral resources" are defined as concentrations or occurrences of material of economic interest in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, continuity, and other geological characteristics of a mineral resource are known, estimated, or interpreted from specific geological evidence, sampling, and other knowledge (Committee for Mineral Reserves Reporting Standards, 2019). The term "mineral reserve" is restricted to the economically mineable part of a mineral resource. On the basis of decreasing levels of confidence in the estimates and available information, mineral resources are divided into "measured," "indicated," and "inferred" categories, and mineral reserves are subdivided into "proven" and "probable" groupings.

Potash deposits in Saskatchewan are consistent in grade, mineralogy, and thickness over many tens of square kilometers. The potash industry has established that the resources of a deposit (permitted or leased area) can be estimated with relatively few drill holes (table 11; Holter, 2009, 2010a–f; Stirrett and others, 2013) along with 2D seismic surveys that have line spacings of 1 mile (mi) by 1 mi (1.6 km) or 1 mi by 2 mi (3.2 km) (Bartsch and others, 2014) to establish the presence and continuity of the salt. According to information in NI 43-101 reports required by the Committee for Mineral Reserves International Reporting Standards (2019), publicly traded companies use a geometric method to determine tonnage for potash resource estimates for Saskatchewan deposits. Most potash resource estimations using this method are for geographically confined areas, such as permit or lease areas. A study by Halabura and others (2010) used this method for a regional estimation of potash resources in the Saskatchewan Area of Potash Distributions (APD), which is outlined here.

1. Determine total area of potash resource within a defined area, such as a permit or lease;
2. Subtract land area not controlled by the permit or lease holder;
3. Determine which drill holes lie within the area delineated in step 2;
4. Determine the areas of radii of influence for each drill hole for the various types of mineral estimations (0.804 km for measured, 1.6 km for indicated, and 8.05 km for inferred resource; Halabura and others, 2010);

**Table 11.** Number of test or exploration drill holes per permit or lease area (Hardy and others, 2009a; Holter, 2010c; Hambley and others, 2011; Stirrett and others, 2013).

[Data were updated from Hardy and others (2009a) and Holter (2010c) to include the newer Legacy, Milestone, and Muskowekwam properties. km, kilometer; nd, no data]

| Mine site | Number of holes within a 5-km radius of the shaft or plant | Approximate average test hole separation (km) |
|---|---|---|
| Belle Plaine | 11 | 0.8 |
| Vanscoy | 12 | 2.01 |
| Cory | 3 | 4.02 |
| Patience Lake | 2 | 4.02 |
| Allan | 12 | 1.61 |
| Colonsay | 8 | 2.01 |
| Lanigan | 10 | 3.22 |
| Esterhazy K1 | 15 | 1.61 |
| Esterhazy K2 | 4 | 3.22 |
| Bredenbury | 11 | 2.41 |
| Legacy | 11[1] | nd |
| Milestone | 10[1] | nd |
| Muskowekwam | 5[1] | nd |
| Vanguard | 4[1] | nd |
| Average | 9 | 2.5[2] |

[1] Representes drill holes within the entire permit or lease area.

[2] Does not include Legacy, Milestone, Muskowekwam, or Vanguard Mines.

5. Determine the thickness of each potash-bearing zone to be used in the mineral estimation based on geophysical, geological, or geochemical logs;
6. Calculate gross mineral volumes by multiplying the area by the thickness of the mineralized interval and then by bulk density based on overall mineral composition of the potash-bearing beds;
7. Subtract volumes affected by known or anticipated solution anomalies, presence of high concentrations of carnallite, or other mining factors, such as the depth of the potash (these include various buffer zones for the anomalies and drill holes); and
8. Subtract the extraction ratio, which is a reflection of ore left underground for various practical and safety pillar supports.

In addition to estimating resources in potash permits and leases in Saskatchewan, other geologic- and mining-related factors are evaluated before an area is proven to contain economic potash. Other considerations include: continuity of the potash-bearing salt layers, thickness of the salt-back, presence of structural disturbances (that is, folds, faults, joints, or collapse structures) that affect the dip of layers and disrupt the continuity of bedding and may allow the influx of water from overlying aquifers. Assessments of infrastructure (for example, water, transportation, and energy) availability and of current and future markets are also important considerations.

For most NI 43-101 technical reports, the grades of potash-bearing salt layers are determined by chemical analysis of physical samples (drill core). All NI 43-101 technical reports note that all core samples are sent to the Saskatchewan Research Council (SRC) for chemical analysis using their Basic Potash Package as described by Hambley and others (2020). SRC operates analytical facilities in accordance with the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Standard 17025, SRC's lab management system, and selected methods of sample preparation and analysis (Hambley and others, 2020). Grab or channel samples collected within the conventional underground workings are analyzed in-house at the mill laboratories of each mine (Hogan and others, 2013; Fracchia and others, 2015; Funk and others, 2018a,b,c). In addition to analyzing the potassium content of the rock, magnesium and insoluble mineral content are also determined. Magnesium concentrations are used to estimate the amount of carnallite in the rock. Potash drilling and sampling techniques have evolved and been generally standardized over the past five decades, particularly since about 2005, with the introduction of reporting standards in NI 43-101 technical reports. During historical drilling in the 1950s and 1960s, some of the potash in the drill core or in the walls of the core holes may have been lost to improper drilling or to core sawing fluids, which caused dissolution of the potash. Core handling, sampling, and laboratory analyses are rarely documented.

Other methods to quickly obtain a quantitative estimation of potash ore grade ($K_2O$ percent) and mineralogy when potash cores are not available were developed by Nelson (2007) and Yang and Chi (2013) through geophysical log analysis. Calculated $K_2O$ grades from wire-line log results (neutron, density, and photoelectric logs) have been included along with chemical analyses in some resource estimations such as for the Burr project (Lomas, 2007, 2008). These are viewed as estimates because of uncertainties in acquisition and differences in the quality of historical versus recent geophysical logs (Nelson, 2007).

## Influence of Mining Methods on Resource Estimation

Technical reports, news releases, and various financial reports issued by potash companies over the preceding two decades provide a large and varied database of known resources and potash exploration results in the Elk Point Basin. Tables 7–9 list the potash properties and reported resources with exploration activity as of 2019 for the Prairie Evaporite members. Those reported resources are for both conventional and solution mining and are focused on the higher grade members of the Prairie Evaporite. More recent approaches to solution mining may involve incorporating more of the potash-bearing stratigraphic column, including the combined section from the Patience Lake Member through the Belle Plaine Member and the halite interbed 1. Table 12 lists the potash properties and reported resources with exploration activity as of 2019 for the combined section from the Patience Lake Member through the Belle Plaine Member.

Reported reserves for the conventional underground mines (potash lease areas) include only in-place recoverable ore, which includes the highest grade potash interval as reported for a certain mining height (table 6*A*) in a mining horizon. Mining heights are primarily dependent on the height of the continuous miners and range from 2.44 to 2.59 m in the Esterhazy Member at the Rocanville Mine, range from 2.74 to 4.9 m in the A and B zones of the Patience Lake Member at the Lanigan Mine, and are 3.35 m in the A zone of the Patience Lake Member at the Allan, Cory, and Vanscoy Mines. The greater thickness of currently minable potash ore at the Lanigan Mine generally allows a second cutting pass for the additional mining height and will affect the overall potash resource for this mine (Moore and others, 2010a). Many of the potash grades reported for the Esterhazy Member in Manitoba (Bannatyne, 1983) are for the best 8-foot (ft; 2.44 or 2.59 m) mining interval and do not report grades or thicknesses for potash-bearing strata above or below the mining horizons. The term "best 8-ft mining interval" is considered to have a combination of highest potash grade along with low concentrations of undesirable minerals, such as carnallite and insoluble minerals. In the Allan, Cory, Lanigan, Colonsay, Patience Lake, and Vanscoy Mines (Moore and others, 2010a,b,c,d; Hogan and others, 2013), as well as the undeveloped Jansen project (BHP Billiton, 2010),

**Table 12.** Known potash resources within the combined Patience Lake Member, halite interbed 1, and Belle Plaine Member interval, Canada.

[Grades and tonnages dependent on mine type. Please see operational definitions of discovered and undiscovered resources in this report. Production data as of date of cited references. Avg., average; Bt, billion metric tons; equiv., equivalent; $K_2O$, potassium oxide; nd, no data; %, percent]

| Mine or project name | Latitude | Longitude | Tonnage (Bt, in place) | Grade (% $K_2O$ equiv.) | Contained $K_2O$ equiv. (Bt) | Mine type | References |
|---|---|---|---|---|---|---|---|
| Belle Plaine | 50.4295 | −105.1976 | 4.275 | 18 | 0.77 | Solution | IMC Global (2004); Mosaic Company (2006, 2009) |
| Legacy (Bethune, Findlater) | 50.6853 | −105.353 | 15.429 | 20 | 3.083 | Solution | Hardy and others (2009a) |
| Lazlo[a] | 51.0492 | −105.8333 | 0.346 to 0.662 | 22.35 | 0.0518 to 0.148 | Solution | Hambley and Halabura (2014) |
| Milestone | 50.2394 | −104.2639 | 4.477 | 17.6 | 0.787 | Solution | Western Potash Corp. (2010) |
| Vanguard | 50.841 | −106.2208 | nd | nd | nd | Solution | Fourie and others (2018) |
| Wynyard | 51.7062 | −104.1063 | 2.662 | 10.9 | 0.289 | Solution | Piché and others (2011) |
| Total known resource | | | 26.84 | 21.2 (avg.)[b] | 5.69 | | |

[a] Values listed are potential mineralization estimates (which are not National Instrument 43-101 compliant) and are not included in totals.

[b] Grade is mean of all grades except the Lazlo property.

the mineral reserves and resources are calculated for the lower Patience Lake potash unit (or B zone). At the Lanigan Mine, both the A and B zones are being mined and the reserves and mineral resources also include the A and B zones (Fracchia and others, 2015).

Reported resources for conventional underground mines include the in-place mineralized rock (mainly pillars and buffered areas around drill holes, which may be recoverable by secondary solution mining) but apparently do not include resource reports for mineralized strata above or below the mining horizons. In contrast, resources calculated for primary solution mining may include the entire thickness of a member (or two or more members) and, in some cases, may include the interbeds between them for properties where solution mining is proposed (Hardy and others, 2009a,b, 2013; Rauche and others, 2012, 2016; Hambley and others, 2015; Debusschere and others, 2016; Fourie, 2017; Myers and others, 2017). The intervals chosen for the resource estimates are based on several factors, including potash grade, mineralogy, and proposed solution mining plan.

The confidence of the resource estimate is constrained by the amount of information that is available and by the proximity of the resource area to the samples. For those potash exploration projects that have no underground mine data, resources are estimated by calculating areas around drill holes that are assigned measured, indicated, and inferred resource values based on distances of 0.804 km, 1.6 km, and as much as 8.05 km, respectively (Halabura and others, 2010). Some project areas have no potash exploration holes within the permit area, and the potash potential is projected from nearby drill holes that may lie outside of a permit area (Holter, 2010f).

Estimated resources and reserve calculations also include tonnage reductions from mining. These reductions are expressed as extraction ratios. An extraction ratio is the relative amount of ore that is likely to be removed (known as recoverable ore) during mining compared to the amount of ore that is likely to remain in place, mainly as a result of mining method and local geological conditions (recoverable ore is equal to in-place mineralization multiplied by the extraction ratio). Extraction ratios for salt mines are considerably different than for hard rock mines because of the chemical characteristics and structural behavior of salt as opposed to most other rock types. The type of Saskatchewan conventional mining includes both (1) conventional long-room and pillar and (2) stress-relief or solution mines. Local geologic conditions include: thickness of the mined potash horizon, salt-back or depth below water-bearing carbonate rocks of the Dawson Bay Formation, and height above footwall carbonate rocks of the Winnipegosis Formation.

Ore grade or mining economics are also considerations when estimating resources. For example, the extraction ratios used when defining mineral reserves for the Allan, Burr, Cory, Lanigan, and Rocanville projects varied from 26 to 45 percent, assuming conventional underground mining and thickness of salt-back (Lomas, 2008; Moore and others, 2010a,b,c, 2011). For resource estimates for the Langham, Milestone, and Muskowekwan projects, estimated extraction ratios range from 35 to 42 percent, assuming solution mining (Hardy and others, 2009b, 2013; Stirrett and others, 2013). Reported mineral resources in NI 43-101 technical reports are exclusive of mineral reserves and include ore that may be mined by solution techniques (Moore and others, 2010a,b,c,d; Hogan and others, 2013). In this USGS assessment, extraction ratios have been used to back calculate the recoverable ore from resources presented in tables 7, 8, and 9, which are not included as recoverable by solution mining in NI 43-101 technical reports.

Conventional underground potash mining may include a variety of ore-extraction machines, ore transportation and storage systems, and various mining plans or layouts. Mining methodologies have changed over the past several decades and influence the amount and grade of ore that is recovered (Jones and Prugger, 1982; Garrett, 1996; Moore, 2006, 2010; Whyatt and Varley, 2008). Initial production in the Lanigan Mine in 1968 was by room-and-pillar methods. By 1993, panel or long-room and pillar-mining systems were in use in the Lanigan Mine in the Patience Lake Member. In the B zone (fig. 11) of the Patience Lake Member, the rooms are 1,220 m in length and the pillars are 46 m wide (Gebhardt, 1993). A stress-relief mining method was used in the A zone (Moore and others, 2010a).

Ground-support pillars are a major component of mine planning for ore and mine preservation and safety. Mines in evaporite strata are susceptible to catastrophic collapse particularly in shallow deposits where the overlying rock or mined material (such as carnallitite) is brittle and weak. Collapse of the mine may be facilitated by larger underground openings with improper spacing of ground-support pillars or the presence of shear or fault zones (Whyatt and Varley, 2008). There are numerous recent examples of potash mine collapses in the Teutschenthal, Herringen, Merkers, and Suenna Mines in Germany and in the Solikamsk-2 and third Berezniki Mines in Russia (Whyatt and Varley, 2008).

Ground-support pillars are included in resource calculations in potash deposits because they can be mined using solution methods after conventional underground mining is completed or after a mine is lost because of flooding (Moore and others, 2010b). Examples of such conversions include the Patience Lake Mine, which was lost to flooding and was converted to a solution mine, and the Intrepid Potash mine in the New Mexico Carlsbad district, which was converted from a conventional underground mine to a solution mine to recover potash from the supporting pillars (Intrepid Potash, Inc., 2012; Robinson-Avila, 2015). The measured resource at the Cory, Allan, Lanigan, and Rocanville Mines includes the potash that is left in pillars in mined-out areas (Moore and others, 2010a,b,c,d, 2011; Hogan and others, 2013; Fracchia and others, 2015). Mineral resource calculations for the other conventional underground potash mines (Mosaic Company's Colonsay and Esterhazy K1, K2, and K3 mines) in Saskatchewan (Mackintosh, 2009) are not reported, but probably include potash contained in the pillars.

# Quantitative Assessment of Undiscovered Potash and Carnallite Resources in Permissive Tracts

The USGS has developed techniques to predict the possible location and potential value of undiscovered mineral resources using methods that can be consistently replicated and compared to other assessments. Mineral potential maps made by the USGS show geographic areas where undiscovered mineral resources may be present. For an assessment, permissive tracts are defined as areas where the geology permits the existence of a particular deposit type. Data collection and analysis as well as identification or construction of appropriate deposit models are preliminary and vital steps in performing an assessment for a given mineral deposit type in a particular area. The need for data is clear, and deposit models assure a common basis of understanding for the deposit type being assessed.

For most deposit types, undiscovered mineral resources are based on a three-part form of assessment (Singer, 1993; Singer and Menzie, 2010) that relies on grade and tonnage models for the deposit type of interest and on an estimate of the number of undiscovered deposits. This approach has been widely used in USGS mineral resource assessments since the 1970s. This type of assessment is optimally applied to deposit types that can be regarded as points or areas around points such as vein or porphyry-type deposits.

However, the three-part assessment form does not work well when applied to undiscovered mineral resources that are associated with incompletely explored extensions of stratabound mineral deposits—particularly when stratabound deposits have large areal extents on the order of a hundred thousand square kilometers—such as the potash-bearing salt deposits in the Elk Point Basin (Holter, 1969; Yang and others, 2009a; Cocker and others, 2010) and the Central Asia Salt Basin (Wynn and others, 2016). In such cases, valid grade and tonnage models cannot be constructed because most stratabound mineral deposits are incompletely explored and are usually open laterally along strike or dip and may even be open stratigraphically above or below. In addition, as stratabound deposit tonnage correlates with the extent and thickness of a basin, a global tonnage model could have values that are geologically impossible for the size of a particular basin. The methodology used in this assessment is similar to that described and used by Wynn and others (2016) in their assessment of undiscovered potash resources in the Central Asia Salt Basin but with modifications related to the larger quantity of published data available for the Elk Point Basin.

Mineral resource assessments, as performed by the USGS, express amounts of undiscovered mineral resources using probabilistic estimates of the amount of in-place metal or material. Probabilistic estimates can be made for undiscovered mineral resources in incompletely explored extensions of large stratabound deposits if appropriate data are available to use for geometric analysis. For the quantitative assessment of potash in this report, the $K_2O$ equivalent tonnage is estimated minus: (1) the reserves and resources known to exist, (2) potash removed through past production, and (3) solution or non-depositional features.

The methodology used to estimate undiscovered potash resources in the Elk Point Basin is based on a descriptive model of stratabound potash-bearing salt (appendix A). The potash-bearing Prairie Evaporite is divided into four potash-bearing members (Patience Lake, Belle Plaine, White Bear, and Esterhazy Members) that are separated by lower grade potash-bearing salt (interbeds 1 and 2). Each of these members is treated as a separate tract (table 5) because of its geology, stratigraphic position, thickness, and how each member is viewed in terms of its mining potential by industry and Canadian Government organizations. These tracts are depicted in figures 14, 17, 19, and 21. Although interbeds 1 and 2 have been considered as potential solution-minable strata, they were not considered as permissive tracts during this assessment because of the paucity of drill hole assay data as well as the lack of data regarding thickness and areal extents that would be used to calculate volumes.

Permissive tracts are identified based on geology, irrespective of political boundaries. Therefore, tracts in this assessment cross country, state, and provincial boundaries. The tracts are constructed at a scale of 1:1,000,000 and are not intended for use at larger scales. Additionally, tracts were defined on the basis of a minimum thickness of 1 m for each potash member as indicated by drill hole data. The tract thicknesses include the entire thickness of each member as defined by the SGS (Yang and others, 2009a) and the additional sources noted for Alberta, Manitoba, Montana, and North Dakota in table 4. Thus, the tracts include potash-bearing strata within a member that may be present above or below the mined intervals in Saskatchewan and that may not be considered presently in resource calculations of a potash mining company. These strata include resources that may not be considered to be economically viable during the life span of potash mining in any particular mine. The tracts were not adjusted using the recently published data of Yang and Schuurmans (2018) and Yang and Love (2015). It was assumed that the extent of the tracts would not be substantially different considering uncertainties in data in other parts of the Elk Point Basin.

For the global assessment of potash (Orris and others, 2014), a minimum potash-bearing salt-bed thickness of 1 m was used to define permissive tracts for all studies so that we could compare areas and estimates of resources from different parts of the world. Although a thickness of 1 m is generally less than the minimum conventional mining thickness for potash-bearing salt in the Prairie Evaporite, a thickness of 1 to 2 m has been considered as a thickness cutoff for cavern development in the Milestone solution mine project (Hardy and others, 2013). In the United States, a minimum thickness of 1.2 m (4 ft) was used to evaluate leasable potash ore (Aguilar and others, 1976; Cheeseman, 1978; John and others, 1978). This standard was established by order of the U.S. Secretary of the Interior dated November 5, 1975 (40 FR 5186–87, Part III, D; Aguilar and others, 1976).

The maximum depth of potash assessments by the USGS has been set at 3 km (9,842 ft), based on the potential of solution mining to be technically possible to recover potash salts from depths less than 3 km. Deep salt solution mining has proven feasible at several locations, including the Hersey Mine in the Michigan Basin operating at depths of about 2,500 m (Orris and others, 2014) and a solution mine recovering salt brine from the Zechstein Basin in the northern Netherlands operating at depths of 2,900 m (Warren, 2006). An experimental solution mine that was opened in China used high-pressure, multistage pumps at depths of 3,000 m but has not been successful (Shun, 1993).

The Prairie Evaporite extends below the 3-km depth limit in North Dakota and Montana, so the extents of the affected tracts were modified to include only potash-bearing zones above that depth (fig. 4). Because the 3-km depth is not depicted on available maps when the tracts were delineated, the 10,000-ft, manually drawn, structure contour line of the top of the Prairie Evaporite (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979) was chosen to represent an approximate depth of 3 km. Detailed drill hole data for North Dakota and Montana were not available at the time of tract delineation in 2010. As the potash members are within 100 m of the top of the Prairie Evaporite, the choice of this 10,000-ft contour is probably well within the range of uncertainty in the location of that contour (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979). The isopach maps used to define the tracts are depicted in figures 15, 18, 20, and 22.

The first step in this potash-assessment process was data collection and analysis. From those data, information that was used to delineate and assess tracts includes:

1. Identification of the assessment tracts and delineation of their geographic extent based on the extent of the salt or potash-bearing salt;
2. Determination of the type or form of the potash-bearing salt, whether stratabound or halokinetic (halokinesis was not a factor in post-deposition modification of the salt in this basin);
3. Presence of potash mineralized areas, occurrences, and deposits;
4. Depth of the potash-bearing salt;
5. Potash-grade data from drill holes and mine samples;
6. Reported grades and tonnages from lease and permit areas that are considered to include discovered resources;
7. Distribution of sylvite- and carnallite-dominant areas (which affect grade and tonnage calculations), and;
8. Statistical estimates of unreported salt anomalies or dissolution areas.

Parameters required for the quantitative assessment include thicknesses, volumes, grades (as percent $K_2O$ equivalent), bulk densities, and the extent of salt dissolution in each tract (table 13). Thicknesses and volumes are calculated from drill hole data. Potash grades (expressed in percent $K_2O$ equivalent), bulk densities, and areas of salt dissolution are incomplete datasets. Parameter specification can require a large amount of subjective, professional judgment. The extent of salt dissolution requires digital removal of some dissolution areas and estimation of others based on area distributions. The percentage of $K_2O$ equivalent or potash grade requires estimations based on grade distributions. The values of the parameters used in estimating undiscovered potash for the Elk Point Basin tracts are specified in tables 13, 14, and 15, and the selection of their values are explained more completely below.

In this study, the in-place contained material in a potash-bearing salt unit is given by this relation (appendix C):

$$KT = T \times GRD \qquad (1)$$

where

$KT$ is the tonnage of contained potash as $K_2O$;

$T$ is the undiscovered in-place tonnage; and

$GRD$ is potash grade as percent $K_2O$.

Building on the previous equation, undiscovered in-place tonnage is determined by this relation:

$$T = (VOL \times DENS) - NOMIN - RR, \qquad (2)$$

where

$VOL$ is volume of the potash-bearing salt unit;

$DENS$ is the bulk density of the mineralized material;

$NOMIN$ is a correction for geologic loss (unmineralized areas); and

$RR$ is the known reserves and resources plus past production.

The methodology (appendix C) is similar to a multiplicative scheme described by Harbaugh and others (1995). That scheme calculates a volume of hydrocarbon by multiplying the thickness and area of the reservoir by other modifying factors including porosity and water saturation. Where the various multiplicative components are unknown, these components are represented by a probability distribution and multiplied through Monte Carlo simulations. The methodology used in this report uses different parameters than those used by Harbaugh and others (1995) because of the different materials involved and includes subtractions of known resources and areas with no potash including salt dissolution (salt anomalies). Wynn and others (2016) used a similar methodology in the assessment of undiscovered potash resources in the Central Asia Salt Basin. The parameters available for the Elk Point Basin are better known and more constrained than for the Central Asia Salt Basin. For this study, some of the parameters have single values (for example, volume), whereas others are represented by probability distributions. A Monte Carlo simulation is used to combine all the parameters to probabilistically estimate the tonnage of contained potash. Model parameters (table 13) are discussed in the following sections.

The areal extent of potash-bearing salt that defines these members as tracts was determined by drill hole intercepts (the file geodatabase [FGDB] feature class ElkPt_thickness in the accompanying geodatabase) and by contouring member thicknesses using the geographic information system ArcGIS ver. 10. Isopach maps of equivalent strata in North Dakota and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979) were used to extend thickness information into the United States (figs. 15, 18, 20, 22). Although additional drill hole data have recently been published for North Dakota (Kruger, 2014), it was considered that the depths of much of the Prairie Evaporite members, their thicknesses, and limited amount of grade data in North Dakota (Sirius Minerals, Plc., 2011; Kruger, 2014) and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979) would not appreciably affect the assessments made for the much larger and better attributed updip parts of the Prairie Evaporite members in Saskatchewan, Alberta, and Manitoba.

The four potash-bearing salt units of the Middle Devonian Prairie Evaporite—the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members—were assessed separately. The following four permissive tracts are delineated in this assessment: (1) tract 003sbK0001a in the Patience Lake Member, (2) tract 003sbK0001b in the Belle Plaine Member, (3) tract 003sbK0001c in the White Bear Member, and (4) tract 003sbK0001d in the Esterhazy Member (figs. 14, 17, 19, 21). Interbeds 1 and 2 did not have sufficient drill hole data to include these strata in this assessment.

## Data Used for the Assessment

Thicknesses of the stratabound potash-bearing salt members in the Prairie Evaporite were compiled from drill hole (well) data in Alberta, Manitoba, and Saskatchewan. Member thickness is generally the difference between the first and last occurrences of potash-bearing salt that define the top and base of each member or in geophysical logs, but there are uncertainties in using these criteria. Briefly, during the early stages of potash exploration drilling, member stratigraphic parameters were undefined, and this lack of definition created possible discrepancies with more recently collected drill hole data. Also, there are apparent differences in how the first and last occurrences of potash-bearing salt of each member are defined in various recent NI 43-101 reports and previous publications, such as Holter (1969), Worsley and Fuzesy (1979), Fuzesy (1982, 1985), and in historical well reports released mostly in the 1950s and 1960s.

For consistency, Yang and others (2009a,b) retained the previous picks for potash members used by Holter (1969), Worsley and Fuzesy (1979), and Fuzesy (1982, 1985). Potash-member intervals in Saskatchewan were interpreted by Holter

**Table 13.** Resource estimation parameters for the Prairie Evaporite in Canada and the United States.

[Areas and volumes derived from gridded raster images. Dist., distribution; equiv., equivalent; $K_2O$, potassium oxide; m, meter; $km^3$, cubic kilometer; Bt, billion metric ton; SD, standard deviation; $g/cm^3$, gram per cubic centimeter; NI, National Instrument]

| Parameter | Patience Lake Member | Belle Plaine Member | White Bear Member | Esterhazy Member | Source | Description |
|---|---|---|---|---|---|---|
| Thickness | Isopachs | Isopachs | Isopachs | Isopachs | Isopachs | Thickness isopachs derived from drill hole gamma ray logs |
| Area | 1-m isopach | 1-m isopach | 1-m isopach | 1-m isopach | Drill holes | Area contained within the 1-m isopach derived from drill hole gamma ray logs |
| Volume, total ($km^3$) | Dist.: triangular<br>Minimum: 932<br>Maximum: 1,210<br>Average: 1,070 | Dist.: triangular<br>Minimum: 609<br>Maximum: 861<br>Average: 735 | Dist.: triangular<br>Minimum: 117<br>Maximum: 226<br>Average: 171 | Dist.: triangular<br>Minimum: 608<br>Maximum: 809<br>Average: 709 | Calculated in ArcGIS using thickness isopachs and tract boundaries | Distribution is triangular |
| Volume, carnallite areas ($km^3$) | Dist.: triangular<br>Minimum: 150<br>Maximum: 188<br>Mode—169 | Dist.: triangular<br>Minimum: 146<br>Maximum: 191<br>Mode: 168 | Dist.: triangular<br>Minimum: 17<br>Maximum: 30<br>Mode: 24 | Dist.: triangular<br>Minimum: 178<br>Maximum: 227<br>Mode: 203 | Calculated in ArcGIS using thickness isopachs and carnallite area boundaries | Distribution is triangular |
| Volume, sylvite areas ($km^3$) | Dist.: triangular<br>Minimum: 782<br>Maximum: 1,022<br>Mode: 901 | Dist.: triangular<br>Minimum: 463<br>Maximum: 670<br>Mode: 567 | Dist.: triangular<br>Minimum: 17<br>Maximum: 30<br>Mode: 24 | Dist.: triangular<br>Minimum: 430<br>Maximum: 582<br>Mode: 506 | Calculated | Calculated as total volume minus carnallite volume |
| Anomalies | Dist.: triangular<br>Minimum: 5<br>Maximum: 15<br>Mode: 10 | Dist.: triangular<br>Minimum: 5<br>Maximum: 15<br>Mode: 10 | Dist.: triangular<br>Minimum: 5<br>Maximum: 15<br>Mode: 10 | Dist.: triangular<br>Minimum: 5<br>Maximum: 15<br>Mode: 10 | Estimated from data in table 7 of this report | Adjustment to volume and tonnage for anomalies that are not identified by available mapping or drill holes |
| Grade distribution, carnallite areas (% $K_2O$ equiv.) | Dist.: normal<br>Mean: 15.87<br>SD: 4.98<br>Minimum: 4<br>Maximum: 22 | Dist.: normal<br>Mean: 12.22<br>SD: 4.51<br>Minimum: 4<br>Maximum: 16.9 | Dist.: normal<br>Mean: 11.7<br>SD: 3.26<br>Minimum: 4<br>Maximum: 16.1 | Dist.: normal<br>Mean: 14.246<br>SD: 6.55<br>Minimum: 4<br>Maximum: 32 | Drill holes | Grade distributions were calculated from drill hole intervals that were 1 m or greater and met assay interval to member thickness criteria and a carnallite thickness to member thickness ratio of 0.5 m or greater. For White Bear Member calculations, we used values from sylvite areas because of insufficient data |
| Grade distribution, sylvite areas (percent $K_2O$ equiv.) | Dist.: normal<br>Mean: 18.31<br>SD: 3.26<br>Minimum: 4<br>Maximum: 27 | Dist.: normal<br>Mean: 16.53<br>SD: 4.60<br>minimum: 4<br>maximum: 29 | Dist.: normal<br>Mean: 11.7<br>SD: 3.26<br>Minimum: 4<br>maximum: 16.1 | Dist.: normal<br>Mean: 15.66<br>SD: 5.49<br>Minimum: 4<br>Maximum: 34 | Drill holes | Grade distributions were calculated from drill hole intervals that were 1 m or greater and met assay interval to member thickness criteria and carnallite thickness to member thickness ratio of 0.5 m or greater. For White Bear Member calculations, we used values from sylvite areas because of insufficient data |

**Table 13.** Resource estimation parameters for the Prairie Evaporite in Canada and the United States.—Continued

| Parameter | Patience Lake Member | Belle Plaine Member | White Bear Member | Esterhazy Member | Source | Description |
|---|---|---|---|---|---|---|
| In-place tonnage of mineralized rock for well-explored mineral properties (Bt) | 47.5 | 17 | 0 | 22.6 | Published sources | Compiled from published sources; data converted to in-place estimates where necessary; includes recorded past production |
| In-place $K_2O$ equiv., for well-explored mineral properties (Bt) | 11.98 | 3.4 | 0 | 4.67 | Published sources | Compiled from published sources; data converted to in-place estimates where necessary |
| Density, includes carnallite and sylvite ore (g/cm$^3$) | Variable | Variable | Variable | Variable | Published sources | Based on regression curve from measured densities and grades in appendix C |
| Extraction ratio (% of material recovered) | 26, 27, 33% for Lanigan, Cory, and Allan Mines; 27.5% for solution mining | 34.6% solution mining of Belle Plaine and Legacy Mines | No data available | 31% for Rocanville Mine | Published sources | Ranges from 26 to 33% for conventional mines and 27.5 to 34.6% for solution mines |
| Bulk density, sylvinite ore (g/cm$^3$) | 2.08 | 2.08 | 2.08 | 2.08 | NI 43-101 reports and mineral data tables | Average density for sylvinite ore with as much as 6% carnallite |
| Density, calculated based on sylvinite grade (g/cm$^3$) | =2.177−(sylvite grade×0.003) | =2.177−(sylvite grade×0.003) | =2.177−(sylvite grade×0.003) | =2.177−(sylvite grade×0.003) | NI 43-101 reports and mineral data tables | |
| Density, calculated based on carnallitite grade (g/cm$^3$) | =2.044−(carnallite grade×0.027) | =2.044−(carnallite grade×0.027) | =2.044−(carnallite grade×0.027) | =2.044−(carnallite grade×0.027) | NI 43-101 reports and mineral data tables | |

**Table 14.** Area and volume of the Elk Point Basin tracts as well as the sylvinite- and carnallitite-dominant parts of those tracts.

[Derived from gridded raster images, results rounded to three significant figures. $km^2$, square kilometers; $km^3$, cubic kilometers; $K_2O$, potassium oxide]

| Thickness | Total tract area ($km^2$) | Total tract volume ($km^3$) | Sylvinite area ($km^2$) | Sylvinite volume ($km^3$) | Carnallitite[a] area ($km^2$) | Carnallitite[a] area volume ($km^3$) | Sylvinite: carnallitite volume ratio | Sylvinite: carnallitite area ratio |
|---|---|---|---|---|---|---|---|---|
| Patience Lake Member tract | | | | | | | | |
| Minimum | 139,000 | 932 | 120,100 | 782 | 18,900 | 150 | 5.2 | 6.4 |
| Maximum | 139,000 | 1,210 | 120,100 | 1,022 | 18,900 | 188 | 5.4 | 6.4 |
| Average | 139,000 | 1,070 | 120,100 | 901 | 18,900 | 169 | 5.3 | 6.4 |
| Belle Plaine Member tract | | | | | | | | |
| Minimum | 126,000 | 609 | 103,700 | 463 | 22,300 | 146 | 3.2 | 4.7 |
| Maximum | 126,000 | 861 | 103,700 | 670 | 22,300 | 191 | 3.5 | 4.7 |
| Average | 126,000 | 735 | 103,700 | 567 | 22,300 | 168 | 3.4 | 4.7 |
| White Bear Member tract[b] | | | | | | | | |
| Minimum | 54,200 | 117 | 47,660 | 100 | 6,540 | 17 | 5.9 | 7.3 |
| Maximum | 54,200 | 226 | 47,660 | 196 | 6,540 | 30 | 6.5 | 7.3 |
| Average | 54,200 | 171 | 47,660 | 147 | 6,540 | 24 | 6.1 | 7.3 |
| Esterhazy Member tract | | | | | | | | |
| Minimum | 100,000 | 608 | 75,440 | 430 | 24,560 | 178 | 2.4 | 3.1 |
| Maximum | 100,000 | 809 | 75,440 | 582 | 24,560 | 227 | 2.6 | 3.1 |
| Average | 100,000 | 709 | 75,440 | 506 | 24,560 | 203 | 2.5 | 3.1 |
| Total average volume | | 2,685 | | | | | | |

[a] Carnallitite includes drill hole intercepts where carnallite is ≥6 percent and also includes drill holes within carnallitite areas or close to carnallitite areas that have low $K_2O$ values and unknown amounts of carnallite.

[b] White Bear Member mineralogy is uncertain; grades suggest these intercepts could be carnallite-bearing. All carnallite data for the White Bear Member do not form a normal distribution.

(1969), Worsley and Fuzesy (1979), Fuzesy (1982, 1985), and Yang and others (2009a,b) from gamma-ray logs and, where available, from other geophysical logs (for example, density, neutron, sonic, photoelectrical, or electrical) and verified using assay logs. A gamma-ray log depicts the response to radiogenic potassium-40 ($^{40}K$) and hence the relative concentration of potassium-bearing minerals. Anomalously high responses in the gamma-ray log indicate the depth and relative concentration of potash. Potash-member intervals for areas within Manitoba (Bannatyne, 1983; Western Potash, Corp., 2008) and Alberta (Grizzly Diamonds, Ltd., 2008; Klarenbach, 2008, 2009; Eccles and others, 2009; Klarenbach and Gray, 2009; Dufresne and McMillan, 2012; Massicotte, 2012) were obtained from reported assay logs. Potash-member intervals for areas within Montana were reported by Great Northern Railway Company (1965). Potash-member intervals for areas within North Dakota were reported by Anderson and Swinehart (1979) and Kruger (2014). Potash grade data from areas outside of Saskatchewan are available, but they are commonly incomplete as they do not include both member thicknesses and assayed intervals.

## Isopach Maps and Permissive Tracts

Drill hole data were processed to generate a single, standardized spatial database of points attributed with the thickness of each member (the FGDB feature class ElkPt_thickness in the accompanying geodatabase). Values for drill hole identifier, latitude, longitude, and thickness were compiled into a spreadsheet. The data were imported into the GIS as point data in (id, x, y, z1, z2, z3, z4) format, where id is the drill hole identifier; x and y are longitude and latitude, respectively; and z1, z2, z3, and z4 are thickness values recorded for the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members, respectively, at the specified location. The point dataset was then projected from a geographic coordinate system to an equal area map projection in order to produce derivative files from which the areas of the tracts and volumes of the rock unit within the tracts were calculated (table 14). The resultant point shapefile, the FGDB feature class ElkPt_thickness, contains thickness values for each of the units in more than 1,500 geophysical drill holes. Locations of these wells are shown in figures 14, 17, 19, and 21. Additional

**Table 15.** Summary of potassium oxide ($K_2O$) grade distributions of sylvite- and carnallite-rich intervals within each potash member of the Prairie Evaporite from drill hole data.

[equiv., equivalent]

| Member | Class | Mean (percent $K_2O$ equiv.) | Standard deviation | Median (percent $K_2O$ equiv.) | Number of sampled intervals |
|---|---|---|---|---|---|
| Patience Lake | All[a] | 18.54 | 4.98 | 19.11 | 213 |
| Patience Lake | Sylvite | 18.31 | 3.26 | 18.67 | 101 |
| Patience Lake | Carnallite[b] | 13.78 | 3.65 | 13.26 | 14 |
| Belle Plaine | All[a] | 16.04 | 5.17 | 16.55 | 206 |
| Belle Plaine | Sylvite | 16.58 | 4.60 | 17.38 | 100 |
| Belle Plaine | Carnallite[b] | 12.22 | 2.55 | 12.05 | 18 |
| White Bear[c] | All[a] | 11.7 | 3.26 | 11.8 | 7 |
| White Bear[c] | Sylvite | 11.7 | 3.26 | 11.8 | 7 |
| White Bear[c] | Carnallite[b] | Insufficient data | Insufficient data | Insufficient data | Insufficient data |
| Esterhazy | All[a] | 16.22 | 6.00 | 16.27 | 164 |
| Esterhazy | Sylvite | 15.66 | 5.49 | 15.62 | 44 |
| Esterhazy | Carnallite[b] | 15.31 | 5.74 | 15.62 | 59 |
| Total of all members[d] | All[a] | 17.00 | 5.47 | 17.45 | 583 |

[a] All includes all member intervals (no exclusions from thickness ratio or grade criteria).

[b] Carnallite includes drill hole intercepts where carnallite ≥6 percent $K_2O$ equivalent.

[c] White Bear Member mineralogy of three drill holes that have assayed intercepts is uncertain as two have <1 percent carnallite and one has 10.13 percent carnallite.

[d] Total does not include White Bear Member data.

drill hole data that were published during this assessment are available from the SGS (Yang and others, 2018) and were used to calculate potash grades.

The continuous raster surfaces of thickness were modified in order to: (1) incorporate linear isopach data from paper maps of Alberta, Manitoba, Montana, and North Dakota; (2) remove areas of known salt anomalies; and (3) exclude areas where potash-bearing units were greater than 3 km below the Earth's surface. Each continuous raster surface was contoured (using the contour tool in the surface analysis package of ArcGIS) with input parameters for a contour interval set to 1 m and the base contour set to 0 m to generate an initial set of isopach maps. These vector contour lines were manually revised to: (1) close contours of equal thickness, (2) incorporate additional data for Montana and North Dakota (Great Northern Railway Company, 1965), and (3) reduce the contour interval to one contour for every 2 m of thickness. The last step was taken because input data for the United States were not available in 1-m intervals. The revised isopach contour datasets were converted from line features to polygon features using the "Feature To Polygon" tool in ArcMap. Point feature attributes from the shapefile ElkPt_thickness were transferred to the output polygons.

## Delineation of the Permissive Tracts

Tract outlines are based on the shapefiles described above. The GIS generated continuous raster surfaces of thickness by extending or interpolating the area of influence around each drill hole. Four continuous surfaces were produced for thickness (z) of each unit using the natural neighbors interpolation algorithm provided in the 3D Analyst extension, with input parameters for "input points" set to ElkPt_thickness; "height source" set variously to THK_PL_M, THK_BP_M, THK_WB_M, and THK_ES_M (thicknesses of the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members, respectively); and "cell size" set to 50 m. Summary volume calculations of the sylvite- and carnallite-dominant areas of each tract are listed in table 14. Volumes for the carnallite-dominant areas that are based on the maps of Fuzesy (1982) are probably greater than volumes that could be calculated based on the more up-to-date maps of Yang and Love (2015) and Yang and others (2018). Because of the relatively small scale (approximately 0.8 inch=100 km) used for the maps shown in Fuzesy (1982), and because the outlines of the carnallite areas are not well defined, these calculated areas should be viewed as approximate.

Using the selection and field calculation tools, each polygon feature dataset was attributed for minimum thickness (the lower value of the contour interval), average thickness (the midpoint of the contour interval), maximum thickness (the upper value of the contour interval), and range in thickness (a text field describing the contour interval). Polygons with thickness less than 1 m were subsequently removed from the dataset.

Areas of known salt anomalies (salt dissolution areas) were removed from the polygon isopach files. The salt anomalies identified by Fuzesy (1982) were digitized, and the extent of these areas was removed from the polygon feature dataset derived from contour information (figs. 15, 18, 20, 22). Boundaries were edited to conform to information in the digital data file (ElkPt_thickness in the accompanying geodatabase). Because of the scale (approximately 1:5,000,000) of the maps by Fuzesy (1982), the outlines are not well defined and these calculated areas should be viewed as approximate.

The contouring program in the 3D Analyst extension generated areas that are shown as less than 1 m thick potash around drill holes that were thought to contain no potash or potash-bearing salt less than 1 m thick. These areas may be salt dissolution areas (anomalies) or areas of non-potash deposition and are not included in the potash tracts. The size and shape of these areas are defined only by the contouring program and not by seismic surveys or any other subsurface data (that is, drill holes).

The resultant files—PL_isopach, BP_isopach, WB_isopach, and ES_isopach in the accompanying geodatabase—are spatial databases of polygons for 2-m intervals of thickness of the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members in tracts 003sbK0001a, 003sbK0001b, 003sbK0001c, and 003sbK0001d, respectively. The isopach shapefiles were aggregated using the dissolve tool to form the permissive tract shapefiles (figs. 14, 17, 19, 21). The vector isopach maps represent this assessment's best estimate of the thickness variability within each tract. However, because of the low density of drill hole data available for large areas of these tracts, the resultant isopach maps are only an estimation. Although more recent subsurface data (wells) in NI 43-101 technical reports may provide more local resolution, the overall thickness trends and volume calculations are believed to be valid by the assessment team.

Visual inspection of the digital tract thickness maps generated in this study were overlain with digital maps of the corresponding members generated by Yang and others (2009b) and agree reasonably well with each other within Saskatchewan. Although the data used for the Saskatchewan area were essentially the same as that used by Yang and others (2009b) for their thickness plots, some of the contoured thickness maps generated in this study were affected by data in adjoining areas, the use of different contouring software, and the thicknesses selected for the contour intervals.

For each of these tracts, drill hole data and contour maps for North Dakota (Kruger, 2014) were unavailable at the time the tracts' were created and were not used to subsequently modify the tract maps. The contoured intervals in Saskatchewan were either joined with those mapped by the Great Northern Railway Company (1965) or by Anderson and Swinehart (1979) or they were extended approximately 10 km into the United States as a probable minimum continuation based on nearby drill holes in Saskatchewan. The assessment team determined that the existing data suggested that the Prairie Evaporite members were of insufficient grade and thickness, as well as areal extent and depth (greater than 3 km), to substantially change the overall volumes of the tracts and the estimated tonnages of $K_2O$.

The confidence with which areas underlain by potash in the Prairie Evaporite are delineated is variable and depends primarily on the density of drill holes with geophysical, geochemical, or mineralogical data to indicate the presence of potash. In Alberta, the extent of potash-bearing salt is not well defined, as only a few exploration wells were tested for the presence of potash (Eccles and others, 2009), and the drill hole stratigraphy was of insufficient detail in the published NI 43-101 reports (Klarenbach, 2008, 2009; Eccles and others, 2009; Klarenbach and Gray, 2009; Pacific Potash Corp., 2012). In Saskatchewan, data from approximately 1,500 drill holes allow better definition of the extent (fig. 4) and thickness of the potash-bearing salt. Drill hole data are more concentrated in the updip northern and eastern parts of the Prairie Evaporite (figs. 14, 17, 19, 21), so thickness contours are better defined in those areas.

### Tract 003sbK0001a: Patience Lake Member

The boundaries of the Patience Lake Member are well defined throughout southern Saskatchewan (figs. 21, 22) by drill hole data (Yang and others, 2009a,b, 2018; Yang, 2016a). In western Saskatchewan and adjacent parts of Alberta, the wide spacing of drill holes (fig. 21) increases the uncertainty of where the Patience Lake Member is present. Drill hole data for Alberta came from Eccles and others (2009), Klarenbach (2008, 2009), Klarenbach and Gray (2009), and Pacific Potash Corp. (2012). Although the intervals of potash-bearing strata are not identified, they are presumed to belong to the Patience Lake Member, as that is the only member identified in the subsurface near the Saskatchewan-Alberta border. Where the isopach maps of the Patience Lake Member in Saskatchewan reach the southern border of Saskatchewan, drill hole data and contour maps are few.

At the time this tract was defined in 2010, it was uncertain how far to extend the Patience Lake Member into the United States, because it was not recognized in the subsurface of North Dakota (Anderson and Swinehart, 1979; Murray, 2011). As there were no descriptions of the Prairie Evaporite stratigraphy in North Dakota in 2010, this study assumed the Mountrail member of Anderson and Swinehart (1979) was the equivalent of the Patience Lake Member and that the tract of the Patience Lake Member included the Mountrail member. The Patience Lake Member was recently broken out of the Belle Plaine Member and mapped in North Dakota (Kruger, 2014).

### Tract 003sbK0001b: Belle Plaine Member

The boundaries of the Belle Plaine Member are well defined by the 1-m-thickness contour from the drill hole data throughout most of southeastern Saskatchewan (figs. 19, 20). Where the isopach maps of the Belle Plaine Member in Saskatchewan show the member reaching the southern boundary of Saskatchewan, the outline of the Belle Plaine Member and contours were matched with the contours of the Belle Plaine Member in the subsurface of North Dakota and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979). The depth of the Prairie Evaporite extends below 3 km in North Dakota, and therefore the extent of the Belle Plaine Member was modified to include only the part that is less than 3 km deep.

### Tract 003sbK0001c: White Bear Member

The boundaries of the White Bear Member are well defined by the 1-m-thickness contour from the drill hole data throughout most of southeastern Saskatchewan (figs. 17, 18). In previous studies, the White Bear Member was not recognized in Montana and North Dakota (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979), but has been recognized recently in North Dakota (Sirius Minerals, Plc., 2011; Kruger, 2014). The tract outline included in this report extends the White Bear Member from just north of the Saskatchewan-United States border into the United States approximately 10 km. This extension was a conservative estimate of how far this member extends into the United States. The exploration hole drilled by Sirius Minerals intersected low-grade potash in this member in North Dakota.

### Tract 003sbK0001d: Esterhazy Member

The boundaries of the Esterhazy Member are well defined by the 1-m-thickness contour from the drill holes throughout southeastern Saskatchewan (figs. 14, 15). Where the isopach maps of the Esterhazy Member in Saskatchewan reach the southern border of Saskatchewan, the outline of the Esterhazy Member and contours were matched with the contours of the Esterhazy Member in the subsurface of North Dakota and Montana (Great Northern Railway Company, 1965; Anderson and Swinehart, 1979). The isopach map of the Esterhazy Member in Saskatchewan was matched with the contoured map of the Esterhazy Member in Manitoba (Bannatyne, 1983). The depth of the Prairie Evaporite extends below 3 km in North Dakota, and therefore the extent of the Esterhazy Member was modified to include only that part that is less than 3 km deep. Except for the exploration hole drilled by Sirius Minerals, which intersected low-grade potash in this member in North Dakota, there are no potash grade data for North Dakota at this time. Only estimated sylvite and carnallite percentages for North Dakota wells are available (Kruger, 2016).

## Volume Estimation

The volume of rock within each tract was computed in the GIS using the polygon isopach maps. The isopach maps were converted from vector format (polygons) to gridded raster images with cell size equal to 50 m, from which area and volume were calculated for minimum, maximum, and average values of thickness using the 3D Analyst extension to ArcGIS ver. 10 and the surface volume tool. The results are presented in table 14 and are a range of estimates of potash-mineralized rock.

The volume of rock containing carnallite within each tract was similarly estimated (table 14) using the areal extents reported by Fuzesy (1982). These areas required minor adjustments (mainly on the order of a few square kilometers) to incorporate recent drill hole data that indicated the presence or absence of abundant carnallite. The outline of the carnallite-rich area was used to cut out the isopach map for each tract. The volume cut out in this manner represents the volume of the carnallite-rich area as defined by Fuzesy (1982). There are some significant uncertainties in the extent of carnallite based on Fuzesy (1982) for the potash members as compared to the extent of carnallite based on Yang and Love (2015) and Yang and others (2018). The carnallite areas approximately define where carnallite is present in amounts of 6 weight percent or greater. The volume of rock containing sylvite was calculated as the total volume of a tract minus the volume of carnallite in the tract. Because of these uncertainties in the extent of carnallite, this assessment includes the combined sylvite and carnallite resource for the contained potash of each tract.

## Potash Grades

Potash grades are an important component of both this assessment and internal industry reports on the estimated reserves and resources in their mines or prospects. What grades actually represent is critical to what purpose the grade data are being used for. In this report, $K_2O$ equivalent grades may be classified in six categories, all of which have some caveats regarding their potential usage in this assessment.

1. Average grade reported for a particular mine, lease, or permit area;
2. Average grade for a particular mine as derived by calculating the mean of “grab” samples (samples collected from inside the mine) taken over the life of the mine;
3. Average grade reported in various drill hole (well) assay logs from present mine, lease, or permit areas;
4. Potash analyses in a drill hole database for Saskatchewan maintained by the SGS (which includes most of the data in category 3);
5. Potash analyses from wells drilled in areas outside of Saskatchewan for which there is some form of published documentation; and
6. Potash grades and mineralogy derived from geophysical well logs. Geophysical well logs for 545 wells in North Dakota provide a limited picture of the location and depth of potash mineralization and a generalized picture of potash mineralogy in the Prairie Evaporite of North Dakota (Kruger, 2014). Without chemical analyses of core samples to determine potash grades, a mineral resource could not be estimated according to the definitions of Canadian Institute of Mining, Metallurgy, and Petroleum Standing Committee on Reserve Definitions (2014) and tonnage estimates could not be compared directly with data used in this assessment.

## Potash Grades from Mines (Categories 1 and 2)

Reported grades could represent the overall grade of a deposit in the ground, the part of the deposit that is actually mined, or the ore that reaches the processing stage. The distinction is not always clear in various published reports. Of the 10 mines in operation in 2019, the only documented grades are from 5 Nutrien Corporation mines (Allan, Cory, Lanigan, Rocanville, and Vanscoy Mines). Most reported grades in the NI 43-101 technical reports for the resources and reserves are for the actual intervals that are being mined, such as the A or B zones of the Patience Lake Member, and not for the entire member thickness. As of 2019, published and estimated mineral resources, reserves, and grades for potash mines and prospects in the Elk Point Basin are summarized in tables 7, 8, and 9. In Saskatchewan, the average $K_2O$ equivalent grade for conventional underground mines is about 24 percent (ranging from 21 to 31 percent); in solution mines (excluding the Patience Lake Mine), the average $K_2O$ equivalent grade is about 18 percent (ranging from 10 to 22 percent).

The operating potash companies believe that average grades derived from in-mine chip or grab samples collected in conventional underground mines (fig. 38) are more representative estimates of mine ore grade than what could be estimated from the limited number of exploration drill holes (Moore and others, 2010a,b,c,d, 2011; Hogan and others, 2013; Fracchia and others, 2015; Fracchia and others, 2017a,b). In the Allan Mine, grab samples were taken from the floor at 68–74 m intervals in production panels and at 85–128 m intervals in development panels (Fracchia and others, 2017c). In the Cory Mine, grab samples were taken at 30–60 m intervals (Fracchia and others, 2017b). In the Lanigan Mine, samples were taken at 23–50 m intervals in zone A and at intervals of 60 m in zone B (Fracchia and others, 2015). At the Rocanville Mine, channel samples were collected until 2015 and, since 2015, grab samples have been taken at 60 m intervals (Fracchia and others, 2017a; Funk and others, 2018c).

Industry confidence in these ore grades comes in part from the robust number of grab samples that have been taken, with 6,719 at the Allan Mine, 4,590 at the Cory Mine, 21,715 at the Lanigan Mine, and 39,245 at the Rocanville Mine (Fracchia and others 2017a, Funk and others, 2018a,b,c), the extent of this detailed sampling throughout the mine, and the

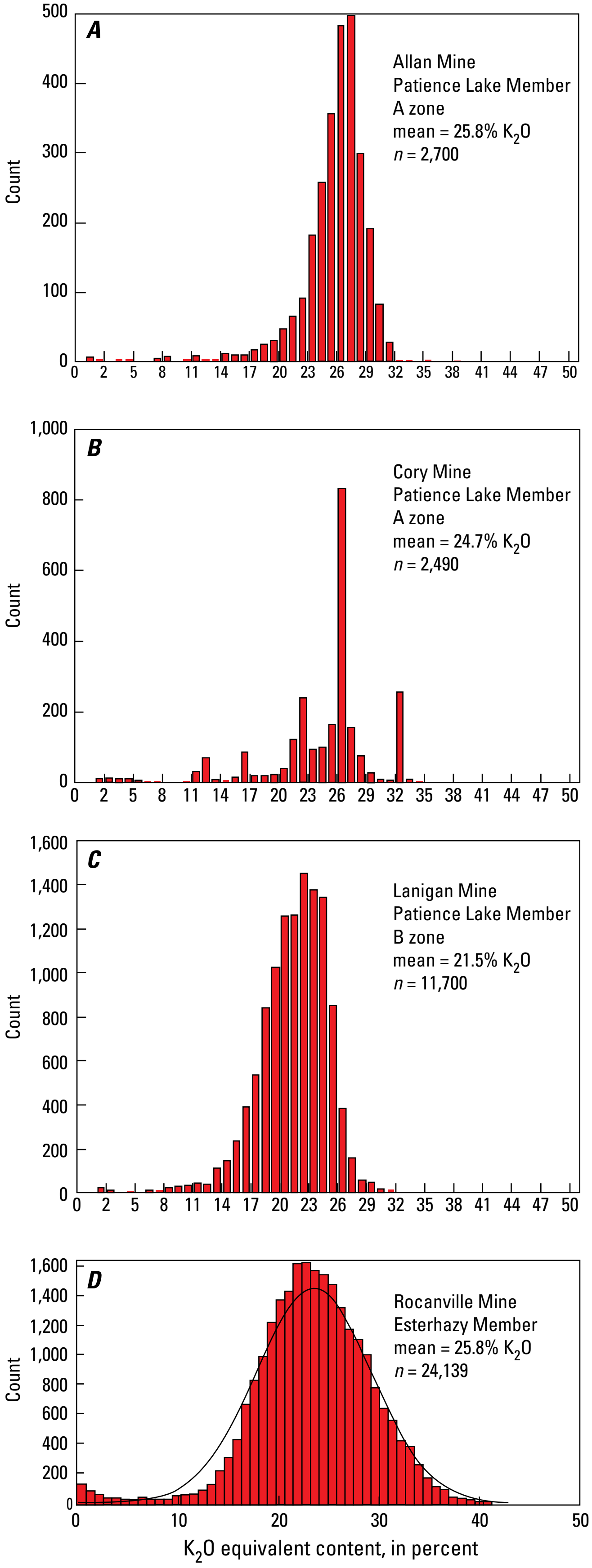


**Figure 38.** Graphs showing potassium oxide ($K_2O$) equivalent grade distributions from grab samples in the Allan (*A*), Cory (*B*), Lanigan (*C*), and Rocanville (*D*) Mines of the Potash Coporation of Saskatchewan. Mining information, mean grade (in percent [%] $K_2O$ equivalent), and number of samples (*n*) are noted on each plot. Modified from Moore and others (2010a,b,c,d, 2011). Updated versions of these grade distributions are available in more recent NI 43-101 technical reports (Funk and others, 2018a,b,c), which have more samples but indicate essentially the same mean grades. Black line in part *D* shows a fitted normal curve.

correlation with actual mine production grades. For the Allan, Cory, Lanigan, and Rocanville Mines, histograms of percent $K_2O$ equivalent grade for in-mine samples show well-defined normal distributions (fig. 38). The lack of published grade data for these grab samples prevents a more robust analysis of actual mine grades in this assessment. Maximum grades of grab samples reach about 32 or 33 percent $K_2O$ equivalent at the Corey and Lanigan Mines, 38 percent at the Allan Mine, and about 42 percent at the Rocanville Mine (Moore and others, 2010a,b,c,d, 2011). Most $K_2O$ equivalent values from in-mine grab samples are above 8 percent. Sampling at Mosaic Company's underground mines at Colonsay and Esterhazy K1, K2, and K3 are not documented by NI 43-101 reports, but sampling was probably done using similar protocols.

These grab sample grades are also consistent with those from several sets of published drill hole intercepts from the Allan, Cory, and Lanigan lease areas. Drill hole samples were restricted to the highest grade interval of 3.35 m at the Allan and Cory Mines and to the highest grade interval of 4.16–5.96 m at the Lanigan Mine (Moore and others, 2010a,b,c, 2011), and gave a combined mean $K_2O$ equivalent of 25.88 percent (number of samples [*n*] =45). This grade should be expected, because the sampling was from the mined interval. The samples in 2.59-m-thick intervals (*n*=66) from drill holes within the Rocanville lease area had a mean grade of 22.31 percent $K_2O$ equivalent. This mean mine grade of 22.31 percent $K_2O$ equivalent is about 3 percent less than the mean of the mine grab samples (fig. 38) and about 1 percent less than the average mine grade (table 7). Both the drill hole samples and the mine grab samples include both the higher and lower grade parts of several evaporite cycles and represent the actual mined intervals (Cocker and Orris, 2019).

Although these mine potash grades are consistent with each other and include a large number of samples (*n*=2,700–24,139), they only represent the particular mined zones in those mines and not the total potash resources of the potash member that may include the entire thickness of the member. Also, the sampling areas are restricted to the extent of the underground mines, which are relatively small (on the order of several tens of square kilometers) when compared to the overall extent of each potash member (for example, approximately 139,000 $km^3$ for the Patience Lake Member tract). Because of the bias in stratigraphic and areal sampling in the mine and lease areas, these data were not used for this assessment, except for comparison with drill core data discussed in the next section.

## Potash Grades from Drill Core (Categories 3, 4, 5, and 6)

Drill holes in a permit or lease area are limited in number because of the chance that they could allow water from an overlying aquifer to intrude into a future working mine. The buffer zones around the drill holes represent ore that is not considered minable. The average number of holes that were drilled per property prior to shaft sinking or to further mine development was nine (Holter, 2010c), and each drill hole was separated by 0.8–4.02 km from the adjacent drill hole (table 11). Many early drill holes from the 1950s through 1980s focused on evaluation of the shallowest parts of the Patience Lake Member and the Esterhazy Member where the members were being evaluated for conventional mining. The result is a limited and uneven distribution of drill holes with published geochemical and stratigraphic data, particularly concentrated in lease or permit areas along the northern and eastern parts of the Saskatchewan subbasin. Assays for those drill holes may be incompletely reported for a variety of reasons. Published NI 43-101 technical reports for the mined lease areas typically provide potash analyses and calculated grades from only a defined interval from a few drill holes (Moore and others, 2010a,b,c,d, 2011; Stoner and Mackintosh, 2012). A few NI 43-101 reports (such as those by Hardy and others [2009a, 2010a,b, 2013] and Rauche and others [2012] for the Legacy, Milestone, and Wynyard lease areas) may contain complete or nearly complete downhole analyses for the entire Patience Lake Member to Esterhazy Member section.

Currently, the SGS maintains a database of approximately 1,500 non-confidential geophysical well logs, several hundred assay logs from potash drill holes and oil exploration wells, and drill core of the potash intercepts in the Elk Point Basin in Saskatchewan. Additional assay results of potash exploration drill holes are also available in recently published NI 43-101 technical reports for potash projects in Saskatchewan and adjacent parts of Manitoba and Alberta. The SGS updates previously confidential data as they become publicly available. Geophysical logs of wells in the part of the Elk Point Basin within North Dakota are maintained by the North Dakota Geological Survey (Kruger, 2014). Table 4 lists the various sources of drill core assays and drill hole stratigraphy used in this assessment.

Although the stratigraphy of the primary potash members was established by Holter (1969), more of the potash-bearing section was drilled and sampled. Within any given member, only high-grade intervals (as determined from gamma-ray logs and visual core inspection) were selected for sampling and analysis. Typically in the Esterhazy Member, only the best 8-ft (2.44-m) interval—the anticipated mining height—would be reported (Bannatyne, 1983). As a result, other potash-bearing members and intervals of lower grade potash and halite interbeds are not consistently represented in the published exploration data. Incomplete sampling data could also be the result of poor core recovery or potash salt dissolution during drilling. In historical drill holes, sample intervals in the continuous core through potash-bearing salt were chosen based on natural breaks in core characteristics such as lithology, mineralogy, grain size, and grade (as estimated by gamma-ray logs) and were measured in feet and inches (Hardy and others, 2009a). Typical sampling intervals ranged from tenths of meters to meters or are fixed intervals (on the order of 30–50 cm).

During the early stages of potash exploration in the Elk Point Basin, the potash stratigraphy was poorly known and exploration was focused on those intervals that were believed to be economically minable by techniques available during the 1950s and 1960s in the United States and Europe. Sampling methods and oil-field drilling techniques, as well as what intervals were considered to be of value, have evolved to the present day. The historical drill hole sampling methods and drilling techniques were commonly not documented or standardized by early exploration companies (table 1). Many drill holes do not have geochemical analyses for parts or all potash-bearing strata of the Prairie Evaporite.

Maintaining the integrity of potash core samples throughout the processes of drilling, sawing, sampling, and storage is critical to obtaining the most representative assays and potential reproduction of the assay results, mainly owing to the soluble nature of potash salts. Potash core samples from the early (1950s to 1960s) drill holes are stored at the Subsurface Geological Laboratory of the Saskatchewan Ministry of the Economy in Regina, Saskatchewan, and have deteriorated substantially (Hogan and others, 2013; Funk and others, 2018a,b,c). Some of that deterioration is related to carnallitic core absorbing water from the atmosphere and going into solution. Reanalysis of these historical core samples is not recommended by the SGS, because potash grades would not be representative. Historical core sampling was probably similar to that at the Allan, Cory, Lanigan, and Rocanville leases, which included lengthwise dry sawing using a masonry saw to eliminate loss from solution effects (Hogan and others, 2013; Funk and others, 2018a,b,c).

Currently accepted drilling and sampling methods are documented in various NI 43-101 reports, such as those by Hardy and others (2010a) and Stirrett and others (2013). Drill core taken from exploration holes is sampled for geochemical analysis and also for geotechnical, milling, and dissolution tests. Currently, holes are drilled to the base of the Dawson Bay Formation, after which the section through all or part of the upper Prairie Evaporite is cored using drilling fluids like oil-based emulsions or diesel fluid to limit dissolution of evaporite minerals (Rauche and others, 2012). After the core is recovered, down-hole logging tools are used to acquire geophysical information such as gamma-ray, resistivity, neutron density, and sonic logs. Recovered core is wrapped in plastic at all times when not being logged or sampled to preserve core from air humidity-related dissolution. Current core sampling methodology includes lengthwise dry sawing using a band saw to eliminate loss from solution effects during the sawing process (Rauche and others, 2012).

During the early stages of this assessment, grade data for the pre-2009 drill holes were entered into a spreadsheet containing information on assay data managed by the Saskatchewan Ministry of Energy and Resources. These grade data are in the geodatabase feature class ElkPt_grades accompanying this report. The intervals corresponding to the potash-bearing members were identified and coded using the stratigraphic picks from Yang and others (2009a), Yang (2016a), and Yang and Schuurmans (2018); these reports also included older stratigraphic picks for the potash members from older well logs (Holter, 1969; Worsely and Fuzesy, 1979; Fuzesy, 1982; Fuzesy, 1983). Many of these logs are now available online from the Saskatchewan Integrated Resource Information System (http://www.saskatchewan.ca/IRIS) and can be located using geoSCOUT and Accumap. The geodatabase feature class ElkPt_grades also includes data from wells outside of Saskatchewan.

Category 5 (potash analyses from wells drilled in areas outside of Saskatchewan for which there is some form of published documentation) includes a limited number of potash drill holes that have been reported for prospects outside of Saskatchewan (table 4). These have various levels of confidence regarding what strata were drilled, preservation of the core, completeness of the investigated strata drilled, and documentation of sampling and analysis.

Category 6 includes grades estimated from downhole geophysical surveys that may be used to identify intervals containing potash minerals and provide a measure of the amounts of $K_2O$ (Nelson, 2007; Yang and Chi, 2013). However, chemical analyses of actual rock samples are required for upgrading a resource estimate from the indicated to measured category. Because of a variety of uncertainties in using historical analog versus modern digital geophysical logs, potash grades determined by geophysical methods were not used in this assessment.

## Criteria for Selection of Drill Core Analyses for Mean Grade Estimations

In this study, drill hole assay data for the present assessments of the Patience Lake, Belle Plaine, and Esterhazy Members are based on data published by the SGS and on published data of the relatively few drill holes in Alberta and Manitoba that met the following selection criteria. Updated drill hole data files can be found in Yang (2016a) and Yang and Schuurmans (2018). Drill hole assay data that met the following criteria were chosen:

1. The assayed interval was representative of the reported thickness of the drilled member. Intervals with a ratio of assayed interval to reported member thickness between 0.8 and 1.2 percent were determined to be the most representative, as discussed below.
2. The minimum assayed interval is 1 m—a minimum global mining thickness (Aguilar and othes, 1976; Cheeseman, 1978; John and others, 1978; Orris and others, 2014; Cocker and others, 2017).
3. The minimum $K_2O$ equivalent grade is 4 percent (chosen according to the USGS global potash assessment cutoff limit; Wynn and others, 2016).
4. Analyses of core samples do not represent the best mining interval in terms of mining height. Such analyses

of core samples—that is, 2.44 m or 2.59 m in the Esterhazy Member and 3.35, 3.37, and 4.9 m in the Patience Lake Member (table 6*A*)—were not considered to represent the entire thickness of those members and were therefore not included in this assessment (Bannatyne, 1983; Moore and others, 2010d, 2011; Fracchia and others, 2017a,b,c).

5. Carnallite-to-member-thickness ratios are less than 0.5–1.0. Analyses of intervals of members where the ratio was 0.5–1.0 are interpreted to contain predominantly carnallite and lesser amounts of sylvite and were therefore removed from the calculation of the percent $K_2O$ equivalent grade for the sylvinite part of each member (fig. 39). The amount of carnallite present in the drill holes was calculated by multiplying an assay for magnesium by a factor of 11.4 or a magnesium oxide (MgO) assay by a factor of 6.8943. The amount of carnallite in analyses without magnesium included is unknown. These carnallitic interval analyses were used to calculate the percent $K_2O$ equivalent grade for the carnallite-rich parts of each member (fig. 39).
6. Member thicknesses are provided. Analyses of intervals of members with no published member thickness information were removed from this assessment.

Plots of percent $K_2O$ equivalent grades for sylvite- and carnallite-rich intercepts of each member are shown in figure 39. For the sylvinitic part of the Patience Lake Member tract, the percent $K_2O$ equivalent grade was 18.31; for the carnallitic part, the grade was 13.78 percent $K_2O$ equivalent. For the sylvinitic part of the Belle Plaine Member tract, the percent $K_2O$ equivalent grade was 16.58; for the carnallitic part, the grade was 16.01 percent $K_2O$ equivalent. For the sylvinitic part of the Esterhazy Member tract, the percent $K_2O$ equivalent grade was 15.66; for the carnallitic part, the grade was 15.31 percent $K_2O$ equivalent.

To determine how well an assayed interval represents the reported thickness of the drilled member, we determined that analyses where the sampled interval was 80–120 percent of the reported member thickness from well data (Yang and others, 2009a; Yang and Love, 2015; Yang and Schuurmans, 2018) varied little from each other or were essentially identical (fig. 40). For example, if the assayed interval was 9.1 m of 18.3 percent $K_2O$ equivalent from a member with a thickness of 10 m, this was calculated to represent 91 percent of the member thickness. The 0.9 m of nonassayed material may have contained no $K_2O$ but was not assayed because it had no visible potash minerals. The sampler may have chosen the interval because it was believed to represent the total member thickness based on the criteria used to define the member. Poor core recovery may have caused differences in the interval sampled compared with the actual drilled interval. These conditions could not be evaluated in this study. For this assessment, the differences in mean $K_2O$ equivalent grade between various analyzed intervals to reported member thickness ratios between 80 and 120 percent were insignificant compared to the much larger variables such as area and volume. Figure 40 illustrates the limited change in variation between the ratio of 80 and 90 percent analyzed intervals to reported member thickness.

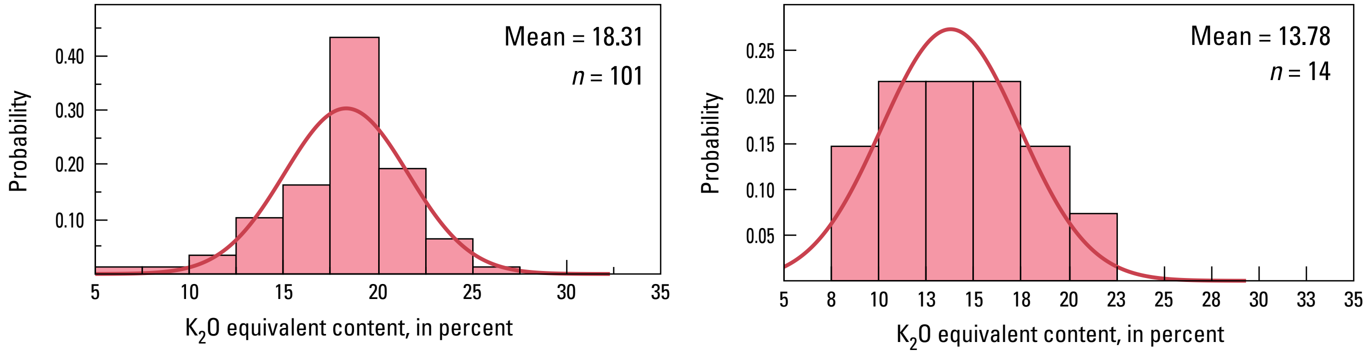
Although using these selection criteria greatly reduced the number of available drill hole analyses in the Patience Lake Member to approximately one-third of the total (115 of the 363 drill holes; table 16), this subsample was selected to characterize potassium variations that could be related to the member's assayed thickness and to total member thickness as defined by Yang and others (2009a). Similarly, subsamples of drill holes of the Belle Plaine Member (118 of 209) and Esterhazy Member (59 of 169) were deemed to meet the criteria for selection to calculate contained $K_2O$ equivalent. Because of the few available analyzed intercepts that were identified as belonging to the White Bear Member, all intercepts that met the minimum thickness were included to calculate a mean $K_2O$ equivalent grade for this member.

The percentage of each tract represented by the drill holes that had $K_2O$ equivalent analyses used in this report can be approximately estimated by using the radius of 8.05 km (or an area of 204 $km^2$) used for inferred resources calculations by the Saskatchewan potash industry (Hardy and others, 2010a). The 115 drill holes with assays for the Patience Lake Member represent a total area of about 13,400 $km^2$ or 10 percent of the total area of the Patience Lake Member tract. Similar calculations for the Belle Plaine Member (118 drill holes) and Esterhazy Member (59 drill holes) tracts indicate that the drill holes would represent 9 and 8.5 percent, respectively, of the total area of each tract. A similar calculation for the White Bear Member tract would show it to be underrepresented by the few attributed drill holes.

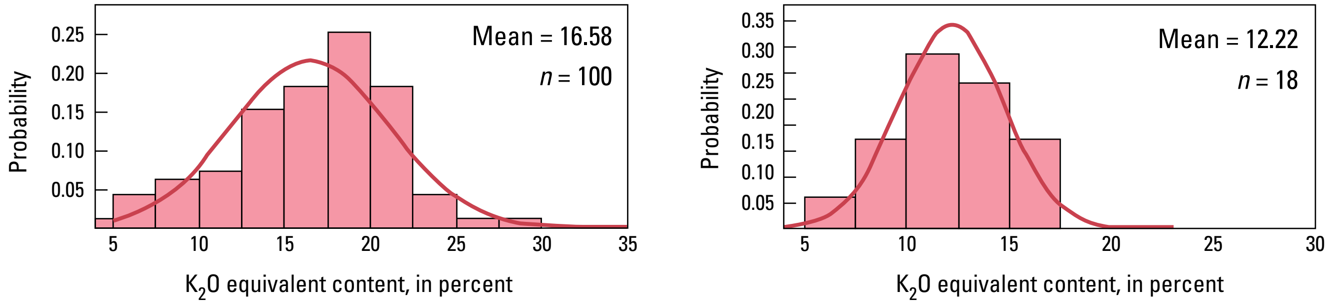
Plots of the percent $K_2O$ equivalent grades for the combined Prairie Evaporite potash intercepts and for each member and tract are shown in figure 41. The calculated mean values for the different members and tracts are summarized in table 16. Mean $K_2O$ grades (in percent $K_2O$ equivalent) for each of the members are 17.82 percent for the Patience Lake Member, 15.92 percent for the Belle Plaine Member, 11.70 percent for the White Bear Member, and 16.72 percent for the Esterhazy Member. Figure 42 shows the mean $K_2O$ equivalent grade (16.94) for the combined members of the Prairie Evaporite.

Graphs of $K_2O$ equivalent grade distributions of both sylvite- and carnallite-rich parts of each member are shown in figure 41. These drill-hole grades are lower than the mean published potash grades of the producing mines (in percent $K_2O$ equivalent) of 23.81 percent for the Patience Lake Member, 18.28 percent for the Belle Plaine Member, and 23.95 percent for the Esterhazy Member (see categories 1 and 2 in the "Potash Grades" section). The t-test in figure 41*D* suggests there are some significant differences between the distributions of $K_2O$ equivalent grades of the Patience Lake Member compared to that of the Esterhazy (*p*-value=0.0012) and Belle Plaine Members (*p*-value=0.0021) (fig. 41, table 16). Differences between the distribution of $K_2O$ equivalent grades

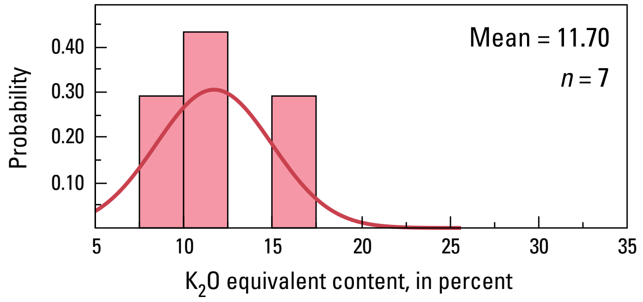
***A.* Patience Lake Member**



***B.* Belle Plaine Member**



***C.* White Bear Member**



***D.* Esterhazy Member**

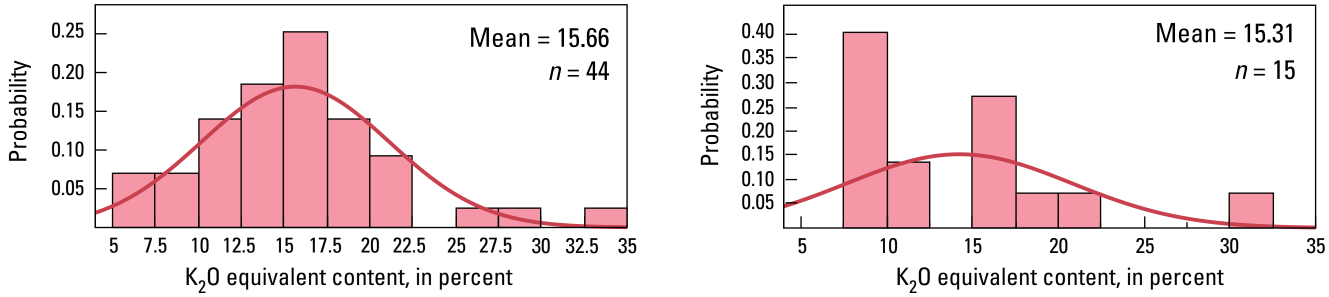


**Figure 39.** Histograms of potassium oxide ($K_2O$) equivalent grade in sylvite-rich (left column) and carnallite-rich (right column) drill holes of the Patience Lake (*A*), Belle Plaine (*B*), White Bear (*C*), and Esterhazy (*D*) Members of the Prairie Evaporite. The mean and number of samples (n) are given for each plot. Insufficient data exist for carnallite-rich parts of the White Bear Member, so they are not plotted here. One drill hole had 10.13 percent carnallite and three drill holes had less than 1 percent carnallite; others reported no carnallite. Red lines show fitted normal curves.

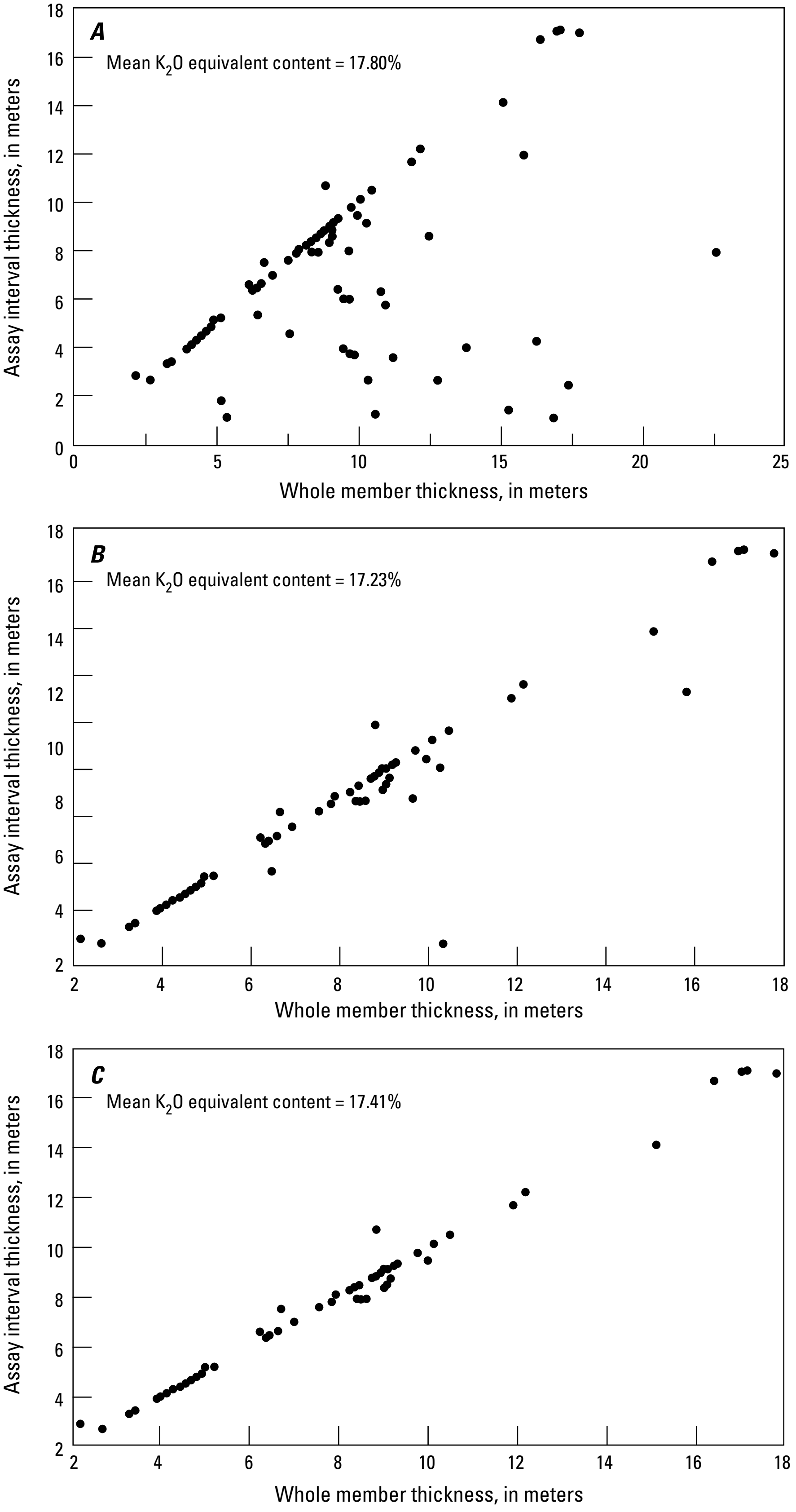


**Figure 40.** Plots showing the relation of assayed core interval thicknesses (minimum of 1 meter) to the measured total Patience Lake Member thickness. The calculated mean potassium oxide ($K_2O$) equivalent (in percent [%]) of these intervals is given for different assayed interval thickness to member thickness ratios. *A*, Ratio is 0 percent. *B*, Ratio is 80 percent. *C*, Ratio is 90 percent. Plots of these ratios from 80 to 120 percent were essentially identical with mean $K_2O$ equivalent ranging from 17.23 to 17.41 percent.

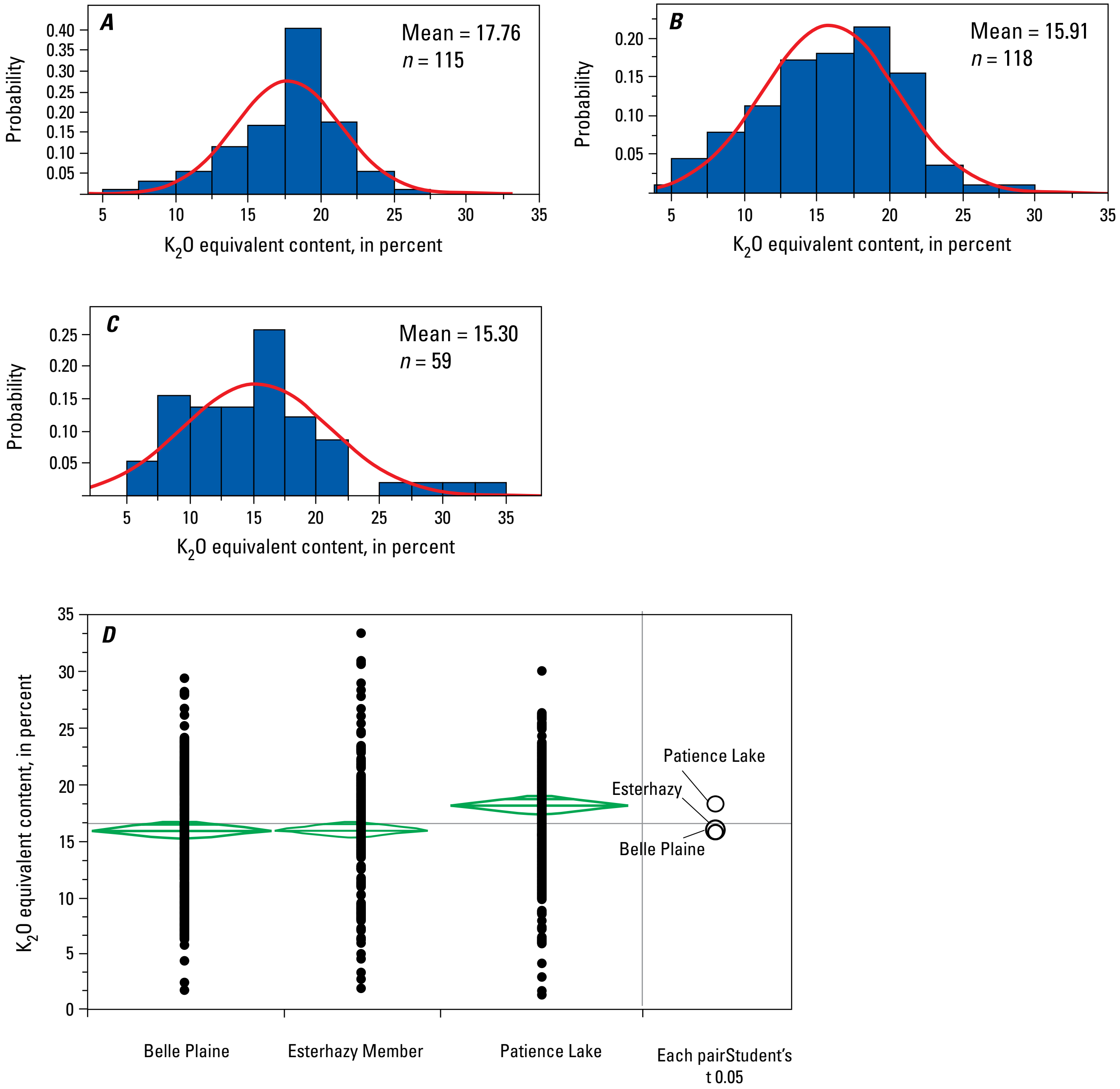


**Figure 41.** Histograms showing potassium oxide ($K_2O$) equivalent grade for combined sylvite- and carnallite-rich parts of drill holes in the Patience Lake (*A*), Belle Plaine (*B*), and Esterhazy (*C*) Members of the Prairie Evaporite. The mean and number of samples (*n*) are given for each plot. Red lines show an ideal normal distribution. Insufficient data exist for carnallite-rich parts of the White Bear Member, so they are not plotted here. Part *D* shows a comparison of the three members. Green diamonds show t-test results. A Student's t-test (right plot) was used to determine if there is a significant difference between two groups.

**Table 16.** Comparison of grade data for selected ratios of analyzed interval thickness versus measured member thickness.

[NA, not available owing to insufficient or missing data for calculation; m, meters; %, percent]

| Member | Ratio of analyzed intercept thickness to member thickness | Mean $K_2O$ (%) | Median $K_2O$ (%) | Standard deviation | Number of intercepts | Mean member thickness (m) | Mean analyzed intercept thickness (m) | Maximum member thickness (m) |
|---|---|---|---|---|---|---|---|---|
| Patience Lake (all intercepts) | 0.15–4.53 | 17.68 | 18.47 | 5.22 | 363 | 14.20 | 10.82 | 31.60 |
| Patience Lake | 0.8–1.2 | 17.82 | 18.16 | 3.60 | 115 | 13.78 | 13.08 | 31.60 |
| Patience Lake | 0.9–1.2 | 17.41 | 17.84 | 3.49 | 81 | 13.50 | 13.43 | 25.60 |
| Patience Lake | 0.99–1.01 | 16.58 | 17.56 | 3.60 | 33 | 13.72 | 13.71 | 25.60 |
| Belle Plaine (all intercepts) | 0.05–3.02 | 16.01 | 16.50 | 5.28 | 209 | 8.87 | 6.76 | 20.40 |
| Belle Plaine | 0.8–1.2 | 15.92 | 16.45 | 4.62 | 118 | 8.58 | 8.39 | 18.00 |
| Belle Plaine | 0.9–1.2 | 16.10 | 16.40 | 4.61 | 104 | 8.64 | 8.58 | 18.00 |
| Belle Plaine | 0.99–1.01 | 16.52 | 15.90 | 4.75 | 26 | 7.58 | 7.56 | 17.40 |
| White Bear (all intercepts) | NA | 11.7 | NA | 3.26 | 7 | NA | NA | NA |
| Esterhazy (all intercepts) | 0.06–1.65 | 16.12 | 16.25 | 6.07 | 169 | 10.74 | 8.82 | 22.70 |
| Esterhazy | 0.8–1.2 | 16.72 | 17.53 | 5.15 | 59 | 9.49 | 9.12 | 22.70 |
| Esterhazy | 0.9–1.2 | 15.11 | 14.70 | 6.02 | 46 | 9.18 | 9.20 | 21.70 |
| Esterhazy | 0.99–1.01 | 14.01 | 15.00 | 4.44 | 13 | 9.30 | 9.30 | 16.70 |
| Combined member intercepts | 0.8–1.2 | 16.94 | 17.45 | 5.56 | 593 | 11.32 | 8.25 | 31.60 |

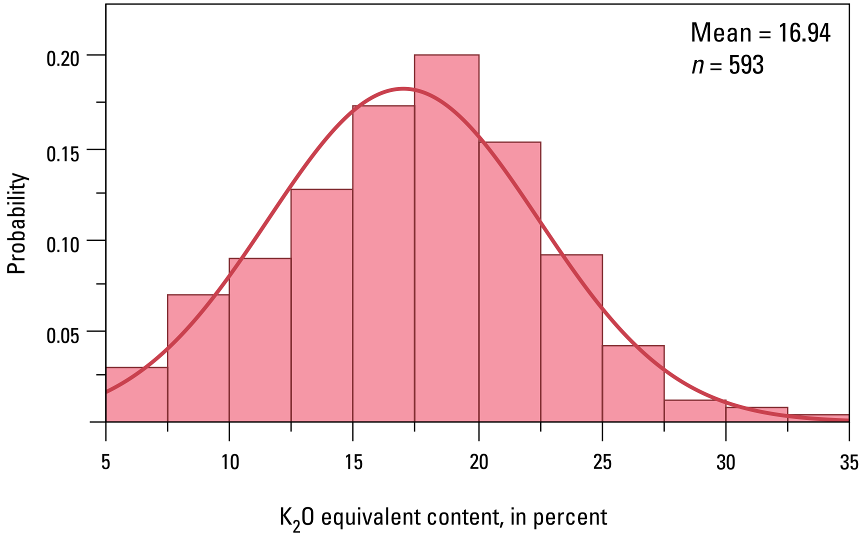


**Figure 42.** Histogram of the combined potassium oxide ($K_2O$) equivalent grades for all drill hole intercepts in the Prairie Evaporite. The mean and number of samples (*n*) is given. Red line shows an ideal normal distribution.

of the Esterhazy and Belle Plaine Members are insignificant ($p$-value=0.4694). The variances of $K_2O$ equivalent grades for each member are graphically shown in figure 41*D*. Although the $K_2O$ equivalent grades and mean value for the White Bear Member were included in this analysis, results are not shown because the number of samples ($n$=7) was small and did not yield a robust distribution.

An assessment of all drill hole intercepts combined from all members of the Prairie Evaporite ($n$=593) using the above criteria shows the $K_2O$ equivalent grades can be fitted with a normal distribution (fig. 42) and mean of 16.94 percent.

## Standardization of Values

Drill core samples from historical exploration wells were geochemically analyzed for a variety of elements and oxides by various geochemical laboratories, and the data were reported in different formats. For example, the potassium content was reported in percent K, KCl, or $K_2O$. The magnesium content, when analyzed, was reported as as Mg, $MgCl_2$, or MgO. This disparity in formats also applies to the calcium and sodium analyses. The information in the geodatabase feature class ElkPt_grades was standardized to report sample depth in meters and potassium as $K_2O$. A calculated equivalent carnallite content is estimated by multiplying percent Mg by 11.4 or percent MgO by 6.8943. If the magnesium content was not reported in the well logs, then the carnallite content was not determined. Distribution of drill holes containing intercepts with calculated equivalent carnallite greater than 6 percent correspond well with maps of carnallite-rich and sylvite-rich areas (figs. 25–28), although not all drill holes in the carnallite-rich areas in this database were carnallitic. Calculated $K_2O$ equivalent grades, well ID or name, latitude and longitude of the well location, interval thickness (in meters), name of the potash member, and sources of the drill hole data are included in the ElkPt_grades feature class in the geodatabase that accompanies this report.

Present day potash exploration and mining companies send their samples for analysis to the Saskatchewan Research Council (SRC) Geoanalytical Laboratories, which provide consistent, high-quality geochemical analyses using SRC’s Basic Potash Package that uses soluble inductively coupled plasma techniques (Hardy and others, 2013). Analyses include $K_2O$, MgO, calcium oxide (CaO), sodium oxide ($Na_2O$), percent moisture, and percent insoluble minerals. Mine samples are analyzed in-house and cross-checked with other company’s labs and with the SRC for quality control. For some of the modern reports, companies have done check assays to validate the historical geochemical data from the early potash exploration wells because of uncertainties in earlier sampling and analytical procedures, lab certification, or quality assurance and quality control procedures. In the mine lease areas, the data collected by the established potash mining companies from more than five decades of mining and thousands of documented assay results are accepted as being consistent with the historical drill hole sample results (Stoner and Mackintosh, 2012). However, in this study, a comparison of the older assays suggests that the mean grades are generally lower than those calculated from newer assays published in the NI 43-101 reports listed in the “References Cited.”

## Calculation of $K_2O$ Equivalent Grade

In this assessment, the potash grade was calculated to represent as most reasonable the entire thickness of each potash member, given the uncertainties regarding its actual defined thickness. The selection criteria described above were rigorously applied to the SGS drill hole data and drill holes outside of Saskatchewan (table 5) to calculate potash grade statistics for sylvite-rich, carnallite-rich, and sylvite plus carnallite parts of each tract (table 15).

Despite applying these criteria, the mean $K_2O$ equivalent values of the selected assayed intervals were similar to those of all assayed intervals (table 16). This relation is apparent for mean $K_2O$ equivalent values of the Patience Lake Member (17.68 percent for 363 intercepts versus 17.82 percent for 115 intercepts), Belle Plaine Member (16.01 percent for 209 intercepts versus 15.92 percent for 118 intercepts), and Esterhazy Member (16.12 percent for 164 intercepts versus 16.72 percent for 59 intercepts). Variability in the amount of carnallite versus sylvite in the Belle Plaine and Esterhazy Members may account for greater differences in the calculated means shown in table 15. For this assessment, it was decided to use the means of those intercepts that (1) had the least amount of scatter in a thickness plot, (2) were probably the most representative of a member’s thickness, and (3) had means that were most similar to each other.

## Effect of Cutoff Grades

A standard lower boundary of 4 percent $K_2O$ equivalent was used for all tracts evaluated by the USGS potash assessment team during the global assessment, although we expect that, with the possible exception of the White Bear Member tract, the Elk Point Basin tracts have an average grade that is substantially higher than this lower boundary. The lower grade cutoff is similar to the minimum USGS standards for leasable potash ore that are 4 ft (1.2 m) of 4 percent $K_2O$ equivalent as langbeinite or 4 ft (1.2 m) of 10 percent $K_2O$ equivalent as sylvite (Aguilar and others, 1976; Cheeseman, 1978; John and others, 1978). There is no upper boundary of potash grade set by the USGS standards for leasable potash ore or by any other governmental geological survey. In Saskatchewan, NI 43-101 technical reports use an economic cutoff grade of greater than 10 percent $K_2O$ equivalent, where the average grade in the mining zone is greater than 15 percent $K_2O$ equivalent (Hardy and others, 2009a, 2010b).

Based on SGS drill hole data (Yang and others, 2009a; Yang and Love, 2015; Yang and Schuurmans, 2018), only 9 out of the 581 (or 1.5 percent) sampled mineralized members with intervals of 1 m or greater contain less than 4 percent $K_2O$ equivalent. The grade of any drill hole intercept in any of the Elk Point Basin tracts would consequently be expected to be greater than 4 percent $K_2O$ equivalent, with a probability of 98.5 percent. Most analyzed drill hole intercepts contain grades that range from 4 to 30 percent $K_2O$ equivalent with a few in the Esterhazy Member tract containing as much as 35 percent $K_2O$ equivalent.

Variations in overall grade were calculated for each member (or tract) using different lower cutoff grades (4, 8, 10, or 12 percent $K_2O$ equivalent). All of the analyzed intercepts were used to determine the variation in overall grade. Best grades for defined mining heights were not used in the assessment as the other excluding criteria were used. These variations in overall member grade with different cutoff grades used in various NI 43-101 reports are summarized in table 17. In the Patience Lake Member data, the difference between the mean percent $K_2O$ equivalent varied from 18.77 to 19.72 using cutoff grades of 4 and 12 percent $K_2O$ equivalent, which represents a difference of only about 1 percent. Variations in the Belle Plaine and Esterhazy Members grades were approximately 2 or 2.5 percent, respectively, for the same cutoff grades. There are no NI 43-101 technical reports that discount the use of high grade drill hole data; however, few of those higher grade intervals (greater than 30 percent $K_2O$ equivalent) may be present.

The consistent mine grades reported in the NI 43-101 reports—and those drill hole grades in other potash permit and lease areas—suggest that the various members contain relatively high-grade potash throughout much of their extent within the Elk Point Basin. However, large parts of the tracts with no available data made it impossible for the assessment team to rule out the possibility that higher or lower mean potash grades may be prevalent.

## Potash Bulk Density and Tonnage Estimation

Tonnage calculations for the Elk Point Basin tracts require both the volume of each potash member and the bulk density of potash-bearing salt in each member. Most tonnage calculations by the potash industry in the Elk Point Basin are based on bulk densities related to average mineralogical compositions of the potash resource and thus provide a relative approximation. The bulk density used to calculate tonnages for each potash horizon in the Prairie Evaporite depends primarily on the relative concentrations of halite, sylvite, carnallite, and insoluble minerals (mainly clays), as well as their respective specific gravities (table A1 of appendix A). Clays are in relatively minor amounts (less than 10 percent) and are not considered to demonstrably affect ore density. Bulk densities of potash-bearing salt (mainly as sylvinite) that are used in Saskatchewan and reported in the literature (table 18) range from 2.0 to 2.14 metric tons per cubic meter (t/$m^3$). According to Lomas (2008), the bulk density of sylvinite with an average grade of 25 percent $K_2O$ equivalent is 2.08 t/$m^3$. Bulk densities ranging from 2.129 to 2.14 t/$m^3$ for the Patience Lake Member and a bulk density of 2.072 t/$m^3$ for the Esterhazy Member used by Moore and others (2010a,b,c,d) are estimates based on the bulk-potash raw ore (sylvinite) from Nutrien Corporation mines with grades of 21.46–25.78 percent $K_2O$ equivalent. The overall abundance of carnallite in these mines is generally considered to be less than 1 percent, and its bulk density would have little effect on the calculation of tonnage. However, carnallite may be locally more abundant in different parts of each member mainly to the exclusion of sylvite—as described in the "Prairie Evaporite Stratigraphy and Potash Deposition" section—and this inconsistent abundance may affect tonnage calculations. This assessment attempts to account for variable amounts of carnallite and sylvite in the assessment tracts.

Because the average mineralogical composition for any given member or part of a member (sylvite-rich or carnallite-rich) is not known, we used formulas that could be calculated from known potash grades where densities and grades have been both measured and documented. The formulas were derived from carnallitite and sylvinite drill hole intercepts in the Danakil and Lower Congo potash-bearing salt basins in Africa (see fig. 2 for basin locations). Density and grade data were derived from Rauche and van der Klauw (2007, 2011). Density-grade relations and predictive formulas for densities and their derivations are in appendix C. These formulas were then used to calculate potash densities based on potash grades rather than bulk densities based on the assumption of mineralogical content. In carnallite-rich areas of the Prairie Evaporite, members' densities were calculated using the formula 2.044−(carnallite grade×0.027). In sylvite-rich areas, densities were calculated using the formula 2.177−(sylvite

**Table 17.** Variation in mean overall potassium oxide ($K_2O$) grades with different cutoff grades for three members of the Prairie Evaporite.

[All analyzed member intervals are included with no separation of carnallite- or sylvite-rich areas. Also, no selection criteria regarding ratios of analyzed thickness to published member thickness are applied. White Bear Member intervals are not included because of insufficient analyzed intervals. Drill hole data from Yang and Love, 2015; Yang and others, 2009a; Yang and others, 2018. See table 4 for information sources. %, percent]

| Cutoff grade (% $K_2O$) | Patience Lake Member (% $K_2O$) | Number of analyzed intervals | Belle Plaine Member (% $K_2O$) | Number of analyzed intervals | Esterhazy Member (% $K_2O$) | Number of analyzed intervals |
|---|---|---|---|---|---|---|
| None | 18.54 | 213 | 16.04 | 206 | 16.22 | 164 |
| 4 | 18.77 | 210 | 16.18 | 204 | 16.56 | 160 |
| 8 | 19.08 | 205 | 16.82 | 191 | 17.03 | 153 |
| 10 | 19.29 | 201 | 17.41 | 177 | 18.02 | 136 |
| 12 | 19.72 | 191 | 18.04 | 161 | 18.68 | 124 |

**Table 18.** Bulk densities for potash ore, sylvinite, and carnallitite used to constrain parameters in resource calculations.

[$K_2O$, potassium oxide; t/m$^3$, metric tons per cubic meter; NA, not available]

| Basin | Property | Average grade (% $K_2O$) | Unit | Density (t/m$^3$) | Material | References | Remarks or company |
|---|---|---|---|---|---|---|---|
| Elk Point | All Saskatchewan mines | NA | Patience Lake, Belle Plaine, and Esterhazy Members | 2.0 to 2.1 | Sylvinite[1] | Fuzesy (1982) | Average ore of the three members |
| Elk Point | KLSA 008 | NA | Patience Lake, Belle Plaine, and Esterhazy Members | 2.08 | Sylvinite[1] | Hambley and others (2011) | Estimated density of the three members. Western Potash |
| Elk Point | Burr | 23.34 | Lower Patience Lake Member | 2.08 | Sylvinite[1] | Lomas (2008) | Athabasca Potash |
| Elk Point | Vanscoy | 24.44 | Patience Lake Member | 2 | Sylvinite | Mackintosh (2009) | Agrium |
| Elk Point | Jansen | 21.66 | Upper Belle Plaine Member | 2.08 | Sylvinite | Halabura and Gebhardt (2006) | BHP Billiton |
| Elk Point | Canada Potash | NA | Patience Lake Member | 2 | Sylvinite[1] | Stone and others (2009) | Canada Potash |
| Elk Point | Lanigan | 21.46 | Patience Lake Member, B zone | 2.14 | Sylvinite | Moore and others (2010a) | Potash Corporation of Saskatchewan |
| Elk Point | Allan | 25.8 | Patience Lake Member, A zone | 2.129 | Sylvinite | Moore and others (2010c) | Potash Corporation of Saskatchewan |
| Elk Point | Cory | 24.7 | Patience Lake Member, A zone | 2.129 | Sylvinite | Moore and others (2010b) | Potash Corporation of Saskatchewan |
| Elk Point | Cory | 21.5 | Patience Lake Member, B zone | 2.14 | Sylvinite | Moore and others (2010b) | Potash Corporation of Saskatchewan |
| Elk Point | Rocanville | 23.5 | Esterhazy Member | 2.072 | Sylvinite | Moore and others (2011) | Potash Corporation of Saskatchewan |
| Elk Point | KP 289 (Legacy) | NA | Patience Lake, Belle Plaine, and Esterhazy Members | 2.14 | Sylvinite | Hardy and others (2009a) | Potash One |
| Elk Point | KL 246, KL 247, KLSA 010 (Wynyard) | NA | Patience Lake, Belle Plaine, and Esterhazy Members | 1.73 | Carnallitite | Rauche and others (2016) | Karnalyte Resources |
| Elk Point | KL 246, KL 247, KLSA 010 (Wynyard) | NA | Patience Lake, Belle Plaine, and Esterhazy Members | 2.09 | Sylvinite | Rauche and others (2016) | Karnalyte Resources |
| Danakil | Allana | 18.8 | Sylvinite member | 2.14 | Sylvinite | Rauche and van der Klauw (2011) | Inferred resources |
| Danakil | Allana | 18.1 | Sylvinite member | 2.14 | Sylvinite | Rauche and van der Klauw (2011) | Indicated resources |
| Danakil | Allana | 17.4 | Sylvinite member | 2.15 | Sylvinite | Rauche and van der Klauw (2011) | Measured resources |
| Danakil | Allana | 10.2 | Upper carnallitite member | 1.83 | Carnallitite | Rauche and van der Klauw (2011) | Inferred resources |
| Danakil | Allana | 10.8 | Upper carnallitite member | 1.8 | Carnallitite | Rauche and van der Klauw (2011) | Indicated resources |
| Danakil | Allana | 9 | Upper carnallitite member | 1.79 | Carnallitite | Rauche and van der Klauw (2011) | Measured resources |
| Danakil | Allana | 7 | Lower carnallitite member | 1.93 | Carnallitite | Rauche and van der Klauw (2011) | Inferred resources |
| Danakil | Allana | 7.2 | Lower carnallitite member | 1.91 | Carnallitite | Rauche and van der Klauw (2011) | Indicated resources |
| Danakil | Allana | 7.2 | Lower carnallitite member | 1.9 | Carnallitite | Rauche and van der Klauw (2011) | Measured resources |
| Danakil | Allana | 12.2 | Kainitite member | 2.18 | Kainitite | Rauche and van der Klauw (2011) | Inferred resources |
| Danakil | Allana | 11.8 | Kainitite member | 2.09 | Kainitite | Rauche and van der Klauw (2011) | Indicated resources |
| Danakil | Allana | 11.8 | Kainitite member | 2.1 | Kainitite | Rauche and van der Klauw (2011) | Measured resources |
| Congo | Mengo | 4.2 | Horizon 1 | 1.74 | Carnallitite | Rauche and van der Klauw (2007) | Inferred resources |
| Congo | Mengo | NA | Horizon 2 | 1.86 | Carnallitite | Rauche and van der Klauw (2007) | Inferred resources |

[1] Assumed to be sylvinite as it is the currently mined ore in most Saskatchewan mines.

grade×0.003). These density values were incorporated in the undiscovered potash tonnage assessment calculations included in table 18 for the sylvite-rich and carnallite-rich areas. Volumes given in grams per cubic centimeter (g/cm$^3$) were converted to metric tons (t). Densities can be expressed as t/m$^3$ for this assessment, which is equivalent to g/cm$^3$. For sylvite, density is reported as 1.99 g/cm$^3$, which is equivalent to 1.99 kg/m$^3$ or 1.99 t/m$^3$. Tonnages for known resources were either stated in the various NI 43-101 reports listed in tables 7, 8, and 9, or were back-calculated from data in those NI 43-101 reports or annual 10-K reports listed in tables 7, 8, and 9 as well as from extraction ratios and historical production data.

Tonnages of undiscovered resources were calculated by running a Monte Carlo simulation using a script (written for the @RISK software add-on in Microsoft Excel) that was modified from a script (written for the SYSTAT software package) used for the assessment of the Central Asia Salt Basin (Wynn and others, 2016). Similar variables to those used by Wynn and others (2016), such as sampled potash grade distributions, volumes, bulk densities, and salt anomaly area distributions for each potash member, were used in the @RISK script.

## Geologic Losses Resulting from Dissolution

Determining the total extent of salt anomalies (dissolution areas) in any given potash basin or deposit is difficult because documentation is generally nonexistent to incomplete or biased. Only a part of the area underlain by potash-bearing salt in the Elk Point Basin has the necessary detailed seismic surveys to determine the number and extent of these non-mineralized areas. Many of the larger anomalies were located by early, pre-1980s, basin-scale 2D seismic surveys (Holter, 1969; Worsely and Fuzesy, 1979; Fuzesy, 1982).

Recent use of 3D seismic surveys has identified and located many of these anomalies, as well as pinnacle reefs in the Winnipegosis Formation, which may be used to predict locations of leach anomalies. 3D surveys have been limited to relatively small parts of permit or lease areas that are in more advanced stages of exploration programs. These 3D seismic surveys at various scales show sizes and vertical extents of the anomalies that greatly aid in identifying the type of dissolution feature and its potential for being a mining hazard (Holter, 1969; Gendzwill and Stauffer, 2006; Halabura and Gebhardt, 2006; Hardy and others, 2009a; Stirrett and Gebhardt, 2011). Anomalies related to karst structures and subrosion features are particularly important to identify and map.

The buffer zones constructed around dissolution areas and exploration drill holes are accounted for during resource estimations and mine development and are subtracted in the NI 43-101 technical reports for potash permits and leases. Deductions are on the order of 14, 25, and 35 percent and include the area of the seismic anomalies plus variously sized buffered areas adjacent to the seismic-anomaly areas. Depending on the type of seismic anomaly, there may be a buffer of 350 or 600 m accounting for a 14 percent reduction, or a buffer of 600 or 1,000 m for a 25 percent reduction (Halabura and Gebhardt, 2006). One type of correction is related to known anomalies and the other is for unknown anomalies that have not been detected by existing drill holes and seismic lines.

The percentage used in this assessment relies on documented anomalies from mine maps, permit or lease maps, and potash member maps. The large dissolution areas constitute 4–7 percent of the area in each of the potash members (table 10). Seismic anomalies shown on maps in the various NI 43-101 technical reports make up 5–14 percent of the permit and lease areas. On a mine scale, dissolution features constitute 8 percent of the areas mapped. With 14 documented areas, the mean and median values are 7.8 and 7.5 percent, respectively, with most of the dissolution areas occupying between 5 and 10 percent of the mapped areas. Based on subsurface mapping data, dissolution areas appear to affect the same proportion of a potash member whether the scale of observation is a mine, a permit area, or the entire member. Using that assumption, seismic anomalies could constitute 4–14 percent of the area of any one member as a whole unit (table 10). In any particular area, it could be assumed that there may be smaller or larger anomalies that occupy less than 4 percent of that area or more than 14 percent of that area.

### Subtraction of Non-Mineralized Areas Owing to Salt Dissolution

Several steps or procedures were employed in this assessment to use the available information to account for those areas that were suspected of containing no potash from the total volume. Initially, all of the known large salt-dissolution areas within and along the edges of the Elk Point Basin tracts were excluded from the tract volume estimations. These included the large dissolution embayments and subrosion along the updip boundaries of each member. These subtractions were accomplished during the initial definition of the tract boundaries using GIS software to contour drill hole data that created areas defined by the tract boundaries where potash thickness is less than 1 m and areas within the outer tract boundaries. Areas within the outer tract boundaries with less than 1 m potash-bearing salt are not considered as part of the tract boundaries and are excluded from area and volume calculations. Owing to uncertainties of drill hole data and large areas between drill holes, these areas could be larger or smaller than the results generated by the contouring program.

The next step was to remove the larger salt dissolution areas mapped by Fuzesy (1982). These areas were digitized and were digitally removed from each of the tracts prior to area and volume calculations. Fuzesy (1982) did not indicate how the dissolution areas were mapped, but it appears that Holter’s 1969 seismic map was used and augmented with newer seismic data. When a shapefile of these areas was digitally overlain on a previous seismic survey map (Holter, 1969) in the GIS, these salt dissolution areas are spatially conformable with seismic anomalies on the 1969 seismic survey map and are considered to be relatively accurate. However, the boundaries of Fuzesy's salt areas are not sharply defined, and the map scale creates uncertainty in the size and accurate location of the dissolution areas.

For the undiscovered resource assessment, an estimate was made of the unknown and unmapped but potentially present non-mineralized areas within each of the assessment tracts in Elk Point Basin. The location and size of salt dissolution areas or areas of non-deposition that are too small to be identified by either of the first two procedures or that lie in areas not covered by either the seismic surveys or drill hole data are more difficult to determine. To account for these smaller seismic anomalies and areas of non-deposition, a third procedure relies on determining what percentage or percentage range these smaller anomalies may represent and statistically sampling that range to estimate the percentage to be removed from the tracts.

A reasonable range of a correction (subtraction) for additional anomalies not defined by the drill hole data was estimated based on data in table 10. A statistically valid probability distribution curve of known anomaly areas could not be constructed because of the limited number of values. Instead, a triangular distribution curve was used to model the percentage of unmapped, non-mineralized areas using a Monte Carlo simulation (appendixes C and D). Based on the available data of known anomalies in the Prairie Evaporite (most of which were documented in the Patience Lake Member), the percentage of unmapped, non-mineralized areas were estimated as a minimum of 5 percent, a maximum of 15 percent, and a middle value of 10 percent. The minimum was rounded to 5 percent (4 and 6 percent are the lowest values in table 10), and the mode value was specified at 10 percent, given that 9–10 percent appear to be the average reported adjustments for anomalies. When combined with the areas of salt dissolution shown by Fuzesy (1982) and those defined by the contoured drill hole data in figures 15, 18, 20, and 22, the total range of unknown and unmapped non-mineralized areas owing to salt dissolution or non-deposition would be 20–25 percent for the Elk Point Basin (table 10). A similar procedure was used by Wynn and others (2016).

The resource assessments in this report do not include buffer zones for known or unknown seismic anomalies because the assessments are for the total potash resources. At the time of this assessment, no detailed subsurface data were published to locate or define potential seismic anomalies in areas outside of Saskatchewan.

## Known Potash Reserves and Estimated Resources

For the purposes of this report, there is an operational definition of known potash resources. A known resource for stratabound potash in a given location (usually a deposit or a lease or permit area) consists of known or estimated grade and tonnage of all production and all known in-place resources (tables 7, 8, 9). Resources include proven and probable reserves and recoverable, measured, indicated, and inferred resources. Some reported resource numbers have been adjusted for geologic factors, such as unmapped anomalies, or have been economically filtered (for example, through the application of an extraction ratio), and these numbers were converted to in-place reserves and resources. The total in-place tonnages in tables 7, 8, and 9 are either those reported as in-place or those that were adjusted for the economic filters and buffers attributed to known and unknown anomalies to arrive at the tonnages used for this study.

Since 2006, reserves and resources reported in NI 43-101 reports and other types of technical reports are commonly accompanied by descriptions of how the numbers were calculated. In NI 43-101 reports for the Nutrien Corporation mines (Allan, Cory, Lanigan, Rocanville, and Vanscoy Mines), the reported tonnage is in-place tonnage, as Nutrien Corporation notes that it is common practice to recover the ore located within the pillars using solution methods after conventional mining is complete or after a mine is lost to flooding (Fracchia and others, 2017a,b,c; Funk and others, 2018a,b,c). To date, none of the conventional mines have been mined out, so the remnant pillars have not been removed.

For those projects that are in the exploration or development stage, the reported tonnages are not indicated as in place. Similarly, publications reporting data for Mosaic Company's Belle Plaine, Colonsay, and Esterhazy Mines do not indicate tonnages as in place. Reported reserves and resources listed in various NI 43-101 reports and other sources listed in tables 4, 8, and 9 were converted to in-place tonnages using extraction-ratio values provided in those reports. A few reports did not state what value was used for the extraction ratio. If all other needed information was present, then these resources were converted to approximate in-place tonnages using an extraction ratio of 35 percent, which was the most commonly stated extraction ratio used in NI 43-101 technical reports.

For the four permissive tracts in the Elk Point Basin, discovered resources are located in potash leases and permit areas and include drill-indicated resources or reserves that are reported in NI 43-101 technical reports and conform to the Committee for Mineral Reserves International Reporting Standards (2019) specifications. These leases include those that are presently being mined or that have been ready for development in the past but have not yet been put into production (fig. 4). Reports published through September 2018 were considered in this assessment. Leases with reported resources include the following operating mines: Allan, Belle Plaine, Legacy, Colonsay, Cory, Esterhazy (K1 and K2), Lanigan, Milestone, Patience Lake, Rocanville, and Vanscoy Mines. The resources noted for the Triton lease area by Bout and Chiang (2008) do not have any referenced documentation but are regarded in this assessment as discovered. All listed mines have reported potash resources that can be assigned to each assessment tract (tables 7, 8, and 9; fig. 4).

With the current pace of some potash permits attaining lease status, the resources of some properties (such as

Esterhazy K3, Rocanville West, Vanguard, and Lazlo) that in 2019 could be classified as discovered were not included in this assessment. No reports contain resource information for tract 003sbK0001c that includes the White Bear Member. The permit- and lease-area boundaries and areas within the outlines shown in figure 4 are generalized in this figure for simplicity at the scale of this map and include both freehold and Crown land holdings. Lease and permit areas are based on property boundaries such as private and governmental boundaries; they do not follow the extent of the underlying potash. These permit and lease areas commonly have parts that lie outside of the tract areas (fig. 4).

Because of considerable areal overlap of the assessment tracts in the Elk Point Basin, areas in a particular potash member that are being mined (which are in or around some mines or prospects) can be regarded as known reserves. Potash members in the same areas that may be stratigraphically above or below may be considered to be undiscovered in the sense that no grade or tonnage data are published. Reserves and resources were calculated for the particular mined part of the Patience Lake Member or the Esterhazy Member (Moore and others, 2010c; Hogan and others, 2013). Reserves and resources were not calculated for the unmined strata of those members or for strata underlying the Belle Plaine, White Bear, and Esterhazy Members. This report considered the unmined strata included within the stratigraphic extents of the Patience Lake and Esterhazy Members within each lease or reported permit area as discovered. As such, the total undiscovered resources calculated in this report could be considered to be slightly underestimated. Within the total resources calculated for each member, this underestimation is probably insignificant relative to other variables such as areal extent discussed in this report.

## Known Potash Occurrences

Known occurrences of potash include drill holes with potash intercepts in the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members as well as in the abandoned Unity Mine (table 19; figs. 4, 14, 17, 19, 21). The Unity Mine shaft was flooded prior to production, and no grades or tonnages are reported in the available literature (Fuzesy, 1982). The Patience Lake Mine is shown as a deposit (fig. 4) because it has produced potash, although no reserve or resource tonnages are reported (table 19).

## Potash Estimation Summary

The undiscovered $K_2O$ equivalent content of each tract was estimated using an adaptive geometric estimation (AGE) approach developed for USGS stratabound potash assessments (appendixes C and D). Initially, the volume of potash-mineralized rock was calculated as a function of area multiplied by thickness. Because of the complexity of the area polygons, the calculation of volume is not as simple as multiplying area by thickness. A function in the GIS software was used to calculate volumes for 3D polygons of variable thicknesses. These 3D polygons were constructed by contouring the thickness from drill hole data.

Grades are randomly selected from the grade distributions and the volumes are then converted to tonnages using densities based on the selected grades discussed above (appendixes C and D, fig. C3 of appendix C). Tonnages were calculated for: (1) potash-mineralized rock and (2) contained $K_2O$ equivalent content, both in billions of metric tons. The tonnages were then modified by subtracting known resources and subtraction of a Monte-Carlo-simulation-selected estimate of total areas of salt dissolution areas.

A set of Monte Carlo simulations iteratively sampled parameter distributions 5,000 times to form an estimated distribution of undiscovered $K_2O$ equivalent values for each tract. This methodology was used and described by Wynn and others (2016). Variations in the AGE methodology that are specific to the Elk Point Basin tracts where carnallite- and sylvite-rich areas were assessed separately include:

1. The differentiation of carnallite areas from sylvite areas for the Patience Lake, Belle Plaine, White Bear, and Esterhazy Member tracts;

2. Grade (as percent $K_2O$ equivalent) distributions for both the carnallite and sylvite areas for each tract based on selected grades summarized in table 16;

**Table 19.** Known occurrences of potash (other than drill holes) within the Patience Lake Member, tract 003sbK0001a, Canada and the United States.

[m, meter; $K_2O$, potassium oxide]

| Name | Latitude | Longitude | Comments | Reference |
|---|---|---|---|---|
| Day Star | 55.517 | −104.223 | First Nations prospect area with technical report | Abbott and Kuchling (2009) |
| Ochapowace-Chacachas | 50.48 | −102.38 | First Nations prospect area with technical report | Abbott and Kuchling (2009) |
| Patience Lake | 52.0899 | −106.3776 | Solution mine with no unknown resources | Kelley (2001) |
| Piapot-Muscowpetung | 50.76 | −104.27 | First Nations prospect area with technical report | Abbott and Kuchling (2009) |
| Unity | 53.429 | −109.1132 | 3.35 m at 21.6 percent $K_2O$. Shaft flooded prior to production (1952–1960) | Fuzesy (1982); Bartsch and others (2014) |

3. Subtraction of known $K_2O$ equivalent reserves and resources in the Patience Lake, Belle Plaine, and Esterhazy Member tracts;
4. Subtraction of salt anomalies modeled using a triangular distribution;
5. No corrections for embayments because of dissolution or non-deposition along the edges of the tracts or possible salt anomalies as the the tracts were defined by the 1-m-thick potash isopachs; and
6. Density formulas were calculated from plots of grade versus density (fig. C3 of appendix C) and incorporated into the assessment calculations included in table 18. Densities are based on the grades for carnallite- and sylvite-bearing drill holes based on grade-density data of Rauche and van der Klauw (2007, 2008, 2011).

Preliminary estimations based on an adaptive geometric estimation methodology were run in SYSTAT ver. 12 statistical analysis software, which is the same software used by Wynn and others (2016). Appendix C contains a summary of the methods used by Wynn and others (2016) and preliminary estimations made in 2010 during this study. Figure C1 illustrates the methods employed in the script used by Wynn and others (2016) and the variables to be supplied by the analyst. Because the previous SYSTAT ver. 12 script is incompatible with the 2019 Windows 10 operating system, test simulations were rerun with the 2010 parameters using the @RISK statistical software, which runs in Microsoft Excel. These yielded similar results to the 2010 estimations using the SYSTAT program. Thus, the @RISK software was deemed suitable for our present estimations.

**Table 20.** Results of the @RISK adaptive geometric estimation (AGE) simulations for the Prairie Evaporite, Canada and the United States.

**Table 20*A*.** Undiscovered potash resources, in billion metric tons.

| Member | Probability | | | | | | Mean | Probability of mean or greater |
|---|---|---|---|---|---|---|---|---|
| | 0.95 | 0.9 | 0.75 | 0.5 | 0.25 | 0.1 | | |
| Patience Lake | 389 | 380 | 356 | 340 | 320 | 310 | 340 | 0.53 |
| Belle Plaine | 257 | 240 | 231 | 220 | 210 | 200 | 220 | 0.50 |
| White Bear | 44 | 41 | 37 | 34 | 30 | 28 | 34 | 0.53 |
| Easterhazy | 226 | 210 | 200 | 190 | 180 | 170 | 190 | 0.53 |
| Combined | 868 | 830 | 807 | 790 | 767 | 740 | 790 | 0.46 |

**Table 20*B*.** Total contained potash resources, in billion metric tons.

| Member | Probability | | | | | | Mean | Probability of mean or greater |
|---|---|---|---|---|---|---|---|---|
| | 0.95 | 0.9 | 0.75 | 0.5 | 0.25 | 0.1 | | |
| Patience Lake | 400 | 380 | 370 | 360 | 340 | 330 | 360 | 0.42 |
| Belle Plaine | 250 | 240 | 230 | 220 | 210 | 200 | 220 | 0.54 |
| White Bear | 44 | 40 | 37 | 34 | 30 | 28 | 34 | 0.53 |
| Esterhazy | 227 | 220 | 210 | 200 | 190 | 180 | 200 | 0.44 |
| Combined | 870 | 850 | 830 | 810 | 790 | 770 | 810 | 0.49 |

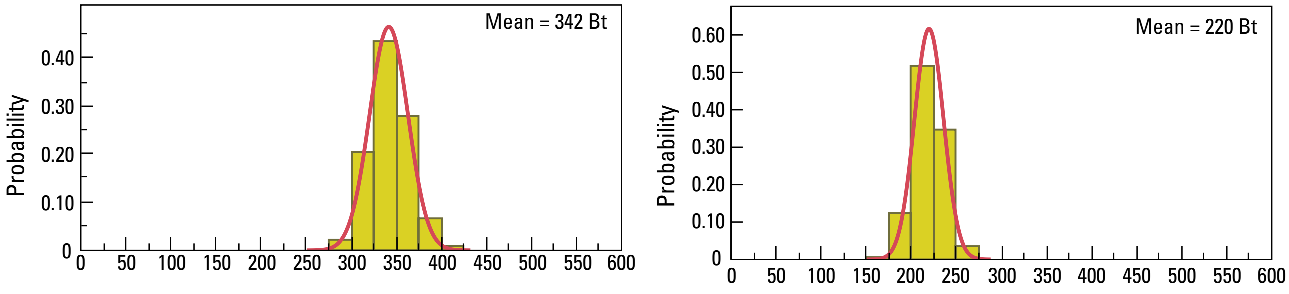
**Table 20*C*.** Total rock, in billion metric tons.

| Member | Probability | | | | | | Mean | Probability of mean or greater |
|---|---|---|---|---|---|---|---|---|
| | 0.95 | 0.9 | 0.75 | 0.5 | 0.25 | 0.1 | | |
| Patience Lake | 2,289 | 2,156 | 2,082 | 2,003 | 1,928 | 1,857 | 2,006 | 0.49 |
| Belle Plaine | 1,585 | 1,472 | 1,414 | 1,348 | 1,284 | 1,227 | 1,349 | 0.49 |
| White Bear | 424 | 383 | 356 | 328 | 301 | 276 | 329 | 0.49 |
| Esterhazy | 1,480 | 1,391 | 1,343 | 1,284 | 1,244 | 1,182 | 1,292 | 0.49 |
| Combined | 5,396 | 5,193 | 5,088 | 4,974 | 4,858 | 4,756 | 4,975 | 0.50 |

# Assessment Results

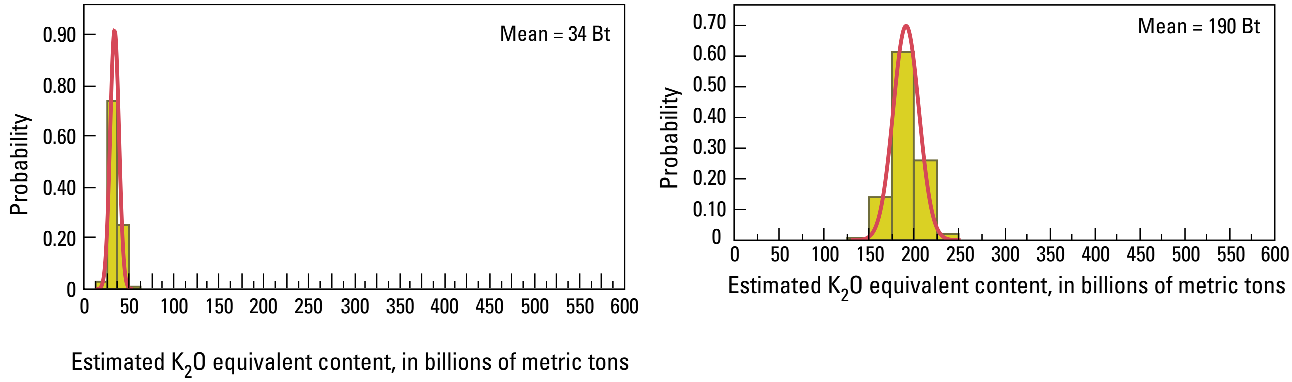
Mean estimated undiscovered $K_2O$ equivalent resources from the @RISK simulation are 340, 220, 34, and 190 billion metric tons (Bt) for the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members, respectively (tables 5, 20). Total mean undiscovered tonnages of $K_2O$ equivalent potash resources are 780 Bt. Table 5 also contains areas, volumes, total known potash resources, total production, tonnage of mineral reserves plus past production, and undiscovered tonnages of $K_2O$ equivalent for the Patience Lake, Belle Plaine, White Bear, and Esterhazy Member tracts. Estimated undiscovered tonnages for each member are plotted in figure 43 and are plotted for the entire Prairie Evaporite in figures 44 and 45. Known potash resources plus past production that lie within the Saskatchewan APD and adjacent areas of Manitoba are estimated to be about 73.8 Bt, mainly as sylvite. Total potash resources (undiscovered plus known) are on the order of 800 Bt of $K_2O$ equivalent.

The parameter that has the largest effect on volume, and hence on tonnage, is the areal extent of the tracts that are measured in square kilometers. This parameter is 5–6 orders of magnitude larger than thickness as measured in meters and potash grade as measured in percent $K_2O$ equivalent content. Figure 46 illustrates the general relation between undiscovered tonnages of $K_2O$ equivalent content and tract areas and volumes.



***A.*** **Patience Lake Member; tract 003sbK0001a**

***B.*** **Belle Plaine Member; tract 003sbK0001b**



***C.*** **White Bear Member; tract 003sbK0001c**

***D.*** **Esterhazy Member; tract 003sbK0001d**

**Figure 43.** Histograms showing estimated in-place potassium oxide ($K_2O$) equivalent content of undiscovered stratabound potash in the Patience Lake (*A*), Belle Plaine (*B*), White Bear (*C*), and Esterhazy (*D*) Members (tracts 003sbK0001a, b, c, and d, respectively) in Canada and the United States. The mean, in billions of metric tons (Bt), is given for each plot. Red lines show fitted normal curves.

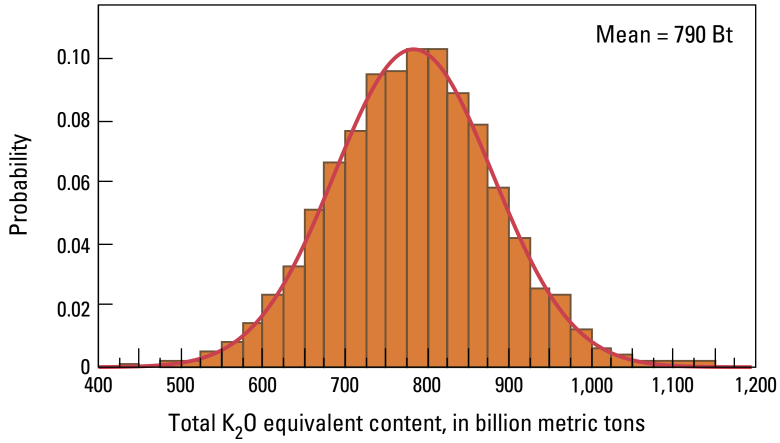


**Figure 44.** Histogram showing total estimated in-place potassium oxide ($K_2O$) equivalent content of undiscovered stratabound potash in the Prairie Evaporite in Canada and the United States. The mean, in billions of metric tons (Bt), is given.

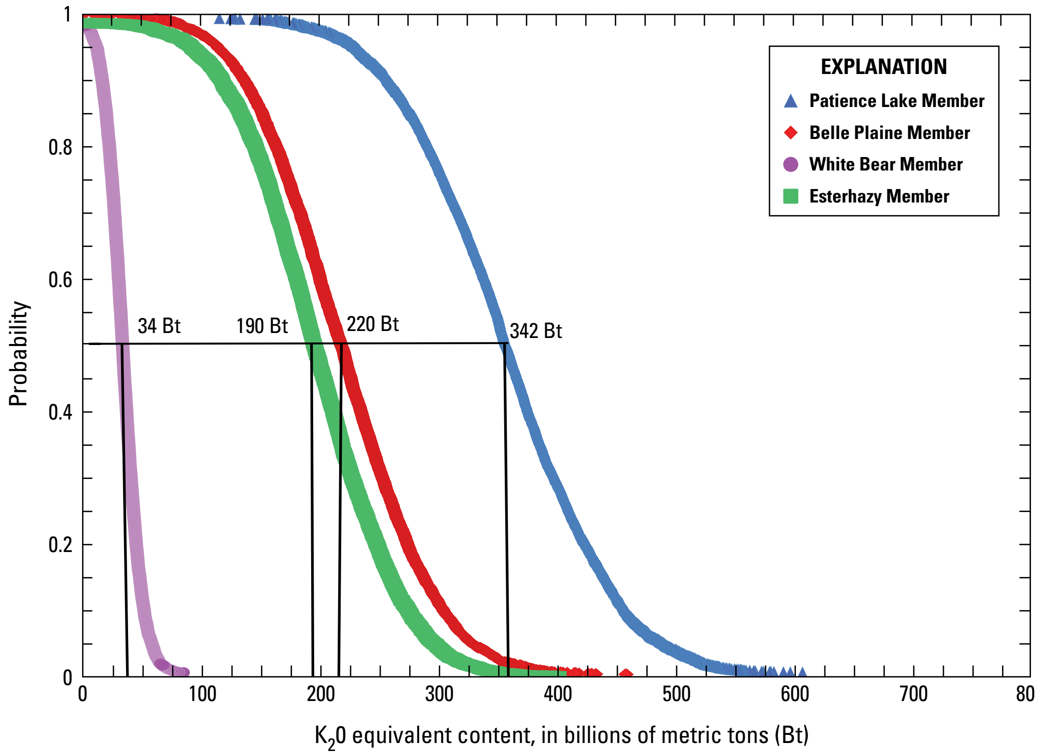


**Figure 45.** Cumulative frequency distribution plot showing the results of a Monte Carlo simulation of undiscovered resources of potassium oxide ($K_2O$) equivalent content in the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members of the Prairie Evaporite. Black lines show mean tonnage of $K_2O$ equivalent within each tract at 50 percent probability.

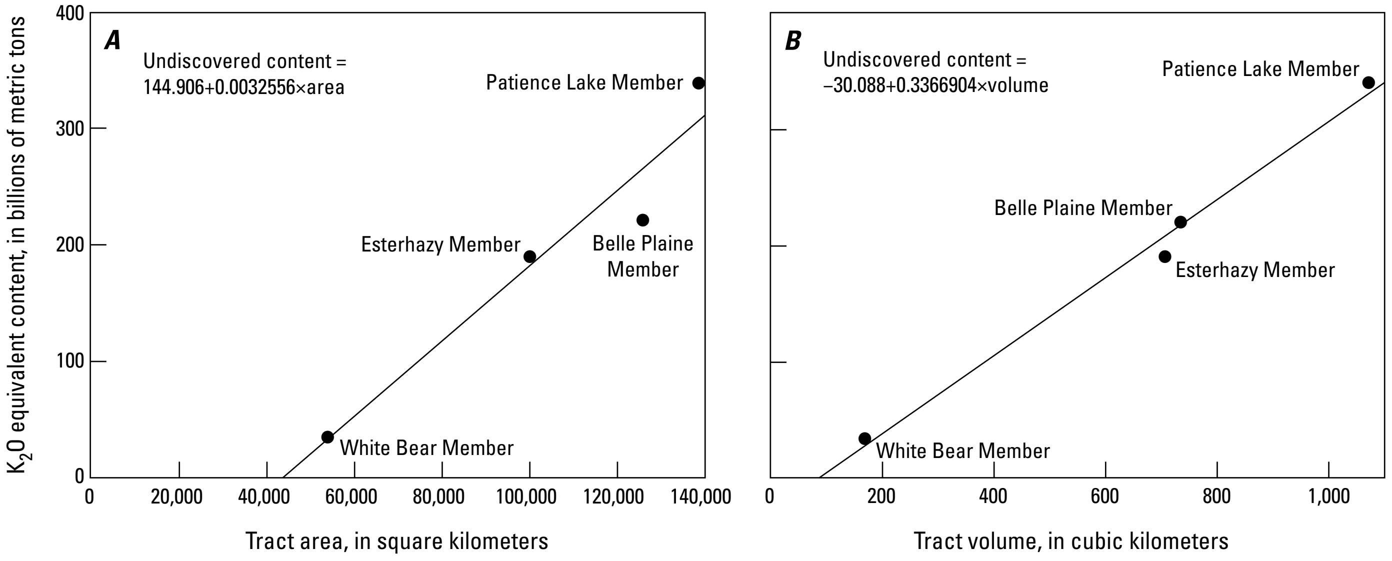


**Figure 46.** Plots of undiscovered potassium oxide ($K_2O$) equivalent content as a function of tract area (*A*) and tract volume (*B*). The equations for the fitted lines are provided.

Grades and thicknesses of the Patience Lake and Belle Plaine Members are relatively similar. The Patience Lake Member contains the largest undiscovered resources estimate (mean of 343 Bt of $K_2O$ equivalent material), principally because this member has the largest spatial extent (139,000 $km^2$) of any of the tracts. The mean undiscovered resources of the Belle Plaine Member—216 Bt $K_2O$ equivalent material—exceed those of the Esterhazy Member—194 Bt $K_2O$ equivalent material—mainly because of the difference in tract areas (the Belle Plaine Member is 126,000 $km^2$ and the Esterhazy Member is 100,000 $km^2$). The White Bear Member, which occupies the smallest area (54,200 $km^2$), has the lowest mean undiscovered resource estimate (34 Bt $K_2O$ equivalent material).

## Assessment of Carnallite-Rich Salt Resources

In the Elk Point Basin, potash reserves and resource estimations are based mainly on sylvinite ores, which are generally defined as ores that have less than 6 percent carnallite. Carnallitic salt is typically not included in published calculations of reserves and resources. Previously estimated tonnages of potash listed in table 3 that might be for the Elk Point Basin probably do not include carnallitic salt because of that exclusion. This assessment includes carnallite-rich areas, so a brief discussion of previous estimations of carnallite is included. Some potash projects have investigated carnallite-rich areas for the possibility of recovering $MgCl_2$ as a byproduct of processing the carnallite for potash. The carnallite in the Elk Point Basin was investigated as a source of $MgCl_2$ in 1955–1958, 1964–1966, 1975, 1983, and 1985 (Molavi and others, 2010), and recently in the Wynyard project area by Karnalyte Resources, Inc. (Molavi and others, 2010; Piché and others, 2011; Rauche and others, 2016).

Worsley (1975) made approximate estimates of carnallite reserves in the Patience Lake and Belle Plaine Members based on high concentrations of carnallite in drill holes. There are no published maps that show the extent of the resources and there are no drill hole data with which to confirm the resources for the purposes of the present assessment. The method used to arrive at these estimates and reserve tonnages were not documented, and the carnallite resource estimates are not NI 43-101 compliant. Worsley (1975) estimated tonnages of carnallite in the Patience Lake and Belle Plaine Members in the vicinity of Quill Lake, Parkerview, and Nokomis, Saskatchewan (figs. 4, 25–28). In the Quill Lake area, Worsley estimated 12.156 Bt of carnallite in the Patience Lake Member and 18.96 Bt of carnallite in the Belle Plaine Member. In the Nokomis area, Worsley estimated 0.907 Bt of carnallite in the Patience Lake Member and 0.59 Bt carnallite in the Belle Plaine Member. Worsley did not estimate carnallite in the Parkerview area for the Patience Lake Member because of uncertainty about its areal extent, but his estimate of carnallite in the Belle Plaine Member in this area was 0.033 Bt. In the Watrous, Saskatchewan, area, the areal extent of carnallite is unknown but Worsley presumed it was small, with concentrations similar to those in the Nokomis area. Worsely (1975) and Fuzesy (1985) delineated 20 Bt of allegedly proven carnallite reserves in the Patience Lake and Belle Plaine Members.

The Wynyard lease area is approximately in the same area of the Elk Point Basin as the areas estimated by Worsley (1975). In the most recent technical reports, estimated reserves of mineralized material (table 21) in the Wynyard lease area are 694.6 Mt at 22.1 percent $MgCl_2$ (Molavi and others, 2010; Piché and others, 2011; Rauche and others, 2012, 2016). Estimates of $MgCl_2$ reserves or carnallite resources are summarized in table 21.

Because no potassium analyses or potash grades for those areas are provided by Fuzesy (1982, 1985) or by Worsely (1975) and the areas are not defined, a comparison with the carnallite resource estimates in this USGS assessment would only be an approximation. As part of the overall estimation of the $K_2O$ equivalent tonnages in this assessment for the Prairie Evaporite, the $K_2O$ equivalent tonnages for carnallite (based on the areas defined by Fuzesy, 1982) were also calculated. These tonnages were 35 Bt for the Patience Lake Member, 35 Bt for the Belle Plaine Member, 3 Bt for the White Bear Member, and 42 Bt for the Esterhazy Member. We calculated a total of 115 Bt for the entire Prairie Evaporite.

## Comparison of Assessment Results with Previous Estimations of Potash Resources

Potash in the Prairie Evaporite has been a major interest of exploration and development activity during the past seven decades, and estimates of reserves and resources vary considerably in this basin. Most of those estimates cannot be verified as the reports included in table 3 do not define criteria for the estimations, such as: (1) what geographic or geologic entity was being estimated; (2) how reserves or resources were defined; (3) the sources, reliability, and distribution of geologic data used; and (4) how the reported tonnages were estimated. As noted elsewhere in this report, essentially all aspects of geology, mining techniques, and economics have evolved to the extent that more potash-bearing salt in the Prairie Evaporite may now be considered as resources than was historically estimated. Results obtained in this report for the estimated mean tonnages of $K_2O$ equivalent content for each of the members are substantially larger than any of the other estimates of calculated reserves and resources. Similarly, the total of undiscovered in-place potash resources (tables 5, 7–9) is substantially larger than previous estimates or calculations of reserves or resources. This section summarizes some of the reasons for the different results that can be explained with known information.

In previous basin- or province-scale estimates, the areal extents of the potash-bearing salt included in the mineral resource calculations were not documented. Some estimates are restricted to Saskatchewan (Kelley, 2001), Manitoba (Bannatyne, 1983), or North Dakota (Anderson

**Table 21.** Estimated magnesium chloride ($MgCl_2$) reserves and carnallite resources.

[Mt, million metric tons; nd, no data reported; NI, National Instrument]

| Probable mineral reserves | Mineralized material (Mt) | Average $MgCl_2$ grade (%) | Mineable $MgCl_2$ material (Mt) | Product tonnage (Mt) | NI 43-101 compliant | Estimated area (km$^2$) | Project or area | References |
|---|---|---|---|---|---|---|---|---|
| Patience Lake Member | 277.5 | 22.4 | 62.1 | 3.2[b] | Yes | 108.51 | Wynyard | Molavi and others (2010); Piché and others (2011); Rauche and others (2012, 2016) |
| Upper Belle Plaine Member | 335.7 | 24.7 | 82.8 | 4.3[b] | Yes | 108.51 | Wynyard | Molavi and others (2010); Piché and others (2011); Rauche and others (2012, 2016) |
| Lower Belle Plaine Member | 81.4 | 10.3 | 8.4 | 0.4[b] | Yes | 108.51 | Wynyard | Molavi and others (2010); Piché and others (2011); Rauche and others (2012, 2016) |
| Esterhazy Member | 2,092.7 | 2.7 | 76.2 | 12.4 | Yes | 108.54 | Wynyard | Molavi and others (2010) |
| Total for the Wynyard project | 694.6 | 22.1 | 153.3 | 7.9[b] | Yes |  | Wynyard | Molavi and others (2010); Piché and others (2011); Rauche and others (2012, 2016) |
| Patience Lake and Belle Plaine (combined) | nd | nd | nd | 20,000[b] | No | nd | None given | Fuzesy (1985) |
| Patience Lake Member | nd | 28[c] | nd | 13.4[a] | No | 1,036 | Near Quill Lake | Worsley (1975) |
| Belle Plaine Member | nd | 23[c] | nd | 20.9[a] | No | 1,554 | Near Quill Lake | Worsley (1975) |
| Patience Lake Member | nd | 29[c] | nd | 1[a] | No | 47 | Near Nakomis | Worsley (1975) |
| Belle Plaine Member | nd | 23[c] | nd | 0.65[a] | No | 47 | Near Nakomis | Worsley (1975) |
| Belle Plaine Member | nd | 27[c] | nd | 1.8[a] | No | 50 | Near Parkerview | Worsley (1975) |
| Patience Lake Member | nd | 40[c] | nd | nd | No | nd | Near Watrous | Worsley (1975) |
| Belle Plaine Member | nd | nd | nd | nd | No | nd | Near Watrous | Worsley (1975) |
| Patience Lake Member | nd | nd | nd | 35,000[a] | No | nd | Whole tract | Estimated in this study |
| Belle Plaine Member | nd | nd | nd | 35,000[a] | No | nd | Whole tract | Estimated in this study |
| White Bear Member | nd | nd | nd | 3,000[a] | No | nd | Whole tract | Estimated in this study |
| Esterhazy Member | nd | nd | nd | 42,000[a] | No | nd | Whole tract | Estimated in this study |
| Total |  |  |  | 185,000[a] | No |  | Whole tract | Estimated in this study |

[a] As carnallite.

[b] Reserves.

[c] From estimated concentration of carnallite.

and Swinehart, 1979), whereas others may be for the entire extent of Elk Point Basin potash in Saskatchewan (Holter, 1969) or in Canada (Stone, 2009). Others may include only the resources within the APD (Yang and others, 2009b; Saskatchewan Ministry of the Economy, 2016b; Stirrett and others, 2013), or individual permit or lease and mine areas in various NI 43-101 technical reports. Unless specifically stated, previous estimates of resources do not include which member or members were included or which stratigraphic part of a member was estimated. It is unknown whether some of the estimates included only the Patience Lake Member, part of the Patience Lake Member such as the A or B zone, or included other members in addition or instead of the entire Patience Lake Member.

In most of the regional estimates, potash grades are not included. Potash grades reported in the literature and in NI 43-101 technical reports are higher for operating mines than for the probable average potash grades for the entire member thickness because grades are reported for those mining intervals with the best potash grade and an established mining height. Intervals containing low-grade potash above and below the mining horizons from those reports are excluded from this report. Most early estimates probably did not include the White Bear Member, the salt interbeds between the potash members (as grades would have been too low to estimate), or the locally extensive carnallite-rich areas of any of the members.

NI 43-101 technical reports provide localized estimates and give the data, maps, and methods used to calculate or estimate the potash reserves and resources of each potash lease or permit (tables 7–9). These reserve and resource estimations are reasonably valid for the particular potash horizon(s)—or for a certain interval of that horizon—for which the estimate was calculated or estimated. Because of their limited geographic areas and their restrictions to particular economic or geologic criteria of selected potash horizons, those NI 43-101 technical reports do not estimate the total resources of potash contained in the Prairie Evaporite or in any of the individual members of the Prairie Evaporite. The grade data in early reports depend mainly on the few drill holes within each project area.

Halabura and others (2010) estimated the amount of solution-minable potash resources in the Belle Plaine and Esterhazy Members within the APD in Saskatchewan. They included the source of their data and, in general, state how their estimates were calculated. They calculated a total tonnage for these two members within the confines of one township from data obtained from seven drill holes in that township. Halabura and others (2010) then reduced that tonnage by subtracting known solution areas and buffer zones around those dissolution areas. That tonnage was then extrapolated to an area consisting of 85 townships that was underlain by both the Belle Plaine and Esterhazy Members to be amenable to solution mining based on depths to the Belle Plaine and Esterhazy Members of 1,500 m. The minable resource tonnages for the solution-mining area were expressed as measured and indicated resources. Their calculations assumed a constant mineral resource thickness of 30 m and an average grade of 16.7 percent $K_2O$ equivalent for an area of about 100 $km^2$. This calculation apparently totaled the thicknesses of both members. Variations in grade, thickness, or densities that could be obtained from drill hole data beyond the single township are not included in their estimates, nor do their calculations appear to include areas containing carnallite. The total $K_2O$ equivalent for this area exclusive of the Patience Lake Member was 0.359 Bt (or 0.579 Bt KCl) with 0.113 Bt being recoverable.

Halabura and others (2010) delineated additional areas for the parts of the Prairie Evaporite currently under conventional mining development and for an area in between those two areas that has no current mining method. Methodologies used for the calculations for those other areas are not as clear and appear to be based on data for the solution mining area. They estimated 64 Bt of KCl (or 40 Bt $K_2O$ equivalent) in the conventional mining area and 0.579 Bt KCl in the solution-mining area. This estimate is approximately similar to Holter's (1969) estimate of 69 Bt $K_2O$ equivalent. Using their data, estimates for total solution-minable potash in the Belle Plaine and Esterhazy Members within the APD would be about 2.7 Bt of $K_2O$ equivalent.

The tonnages calculated in this assessment report are dependent on different parameters than those considered in industry or government reports. The assessment results are considerably greater than previous estimates for the Prairie Evaporite. Also, this assessment differs from other estimates in that it defines: (1) the areal extent of the potash members based on measured drill hole intercepts; (2) volumes that are calculated based on the areal extents of the potash-bearing salt and contoured thicknesses from drill hole data; (3) potash grades that are calculated mainly from a published database; (4) the areal extent, volumes, and grades of both sylvinite and carnallitite areas from drill hole data; (5) the sylvinite and carnallitite densities that are used to estimate tonnages from measured grade-density relations; (6) dissolution areas and areas of non-deposition that are removed from tonnage estimations based on drill hole thickness contours and an estimate of their overall regional distribution; (7) the published known potash resources and reserves that are removed from the overall estimate; and (8) the amount of undiscovered potash, which is calculated using a Monte Carlo simulation that takes all of the parameters into consideration. The result is a probabilistic estimation of the total amount of undiscovered potash resources in the Prairie Evaporite above a predetermined depth that may be the lower limit of technically feasible mining.

# Discussion

This assessment estimates the amount of undiscovered potash resources in terms that are comparable with other world resources that are considered to be potentially recoverable. Users of this assessment should consider those differences and bear in mind that this assessment is for the total potash resources of each member of the Prairie Evaporite and not just for the current economically recoverable or presently mined potash. Furthermore, this assessment includes estimates of potash-bearing salt that was a minimum of 1 m thick and also includes estimates of potash-bearing salt that occur above and below current mining levels with a minimum $K_2O$ equivalent cutoff grade of 4 percent. The use of these parameters increased the area and the volume of each assessed member and reduced the average grade as compared with potash grades of active mines. The inclusion of these volumes of potash-bearing salt added resources to the assessment that may not be recoverable using the current conventional underground mining techniques used in the Elk Point Basin but that could be recovered using present or potential future solution mining methods. Areas that are considered to be unminable because they underlie population centers, critical utilities, or other natural resources such as reservoirs were not excluded during this assessment. Geologically similar potash resources which are of lower grades than those being mined in Saskatchewan, including carnallite-dominant resources, are being recovered at smaller deposits elsewhere in the world. This assessment included large volumes of potash-bearing salt that lie outside of Saskatchewan's Area of Potash Dispositions and that illustrate the potential for potash mining in this basin for a long time after the projected lifespan of the present and anticipated mining operations in Saskatchewan. Besides the current recovery of sylvite-bearing salts for $K_2O$, the carnallitic potash salts may prove to be an additional source of both $K_2O$ and $MgCl_2$.

Because of increasing global populations and decreasing amounts of arable land, the amount of fertilizers, especially potash-based fertilizers, is expected to increase in demand. Rawashdeh and Maxwell (2014) and Rawashdeh and others (2016) expect potash consumption to increase to around 38.3 Mt by 2022, with an annual growth rate of 2.9 percent. Other factors such as increasing rainfall in some areas and migration of farming regions in the northern and southern hemispheres (which is perhaps related to climate change) could require significant new fertilizer production to reinvigorate precipitation-depleted soils or to enhance soils in new regions opening to farming. Climate-change-related insect plagues have caused significant food shortages in eastern Africa, Pakistan, and India, and an increase in farm productivity aided by potash-based fertilizers has been essential to alleviate regional demand for agricultural-based foods (Wheeler and von Braun, 2013; Yager, 2016; Stone, 2020; Ogalla, 2021; Showler and others, 2022). Planned mines and expanded mining capacities in Saskatchewan—as well as in other potash producing countries such as Belarus (Cocker and others, 2017)—could accommodate the expected global demand for the foreseeable future.

The effects of the COVID-19 pandemic on the global population and its future fertilizer requirements are unknown. The pandemic has had a negative effect on the potash-mining industry in Saskatchewan and on the global mining industry since about March 2020, and future mining developments are uncertain at this point (Jowitt, 2020; Hitzman and others, 2020).

## Improving Potash Assessments

An assessment of potash on the scale of the Elk Point Basin could benefit from more published detailed geological studies of operating mines. Except for some isolated studies in a few underground mines or of drill holes discussed throughout this report, it was not until research by Holter (1969) and Fuzesy (1982) was published that a framework was provided for the geology of the potash-bearing salt in the Elk Point Basin. The detailed study by Boys (1990) provided an understanding of mine-level geology and supported the previous regional studies. Considerable basic information, such as reliable grade and tonnage data of the operating mines, was not available until 2005 when NI 43-101 technical reports began to be published. Historical drill hole data were limited in scope and availability, and grade and tonnage data for the operating mines were difficult to find and interpret in the context of Prairie Evaporite stratigraphy. Previous resource estimates for the Elk Point Basin could not be scientifically verified.

As proprietary drill hole and geophysical data are released to the public, Chao Yang and others in the SGS compile and publish that data (table 4). The USGS and the SGS have been working together since 2009 to assess the huge volume of data already available. The publicly available databases of the SGS and the USGS are used extensively by the potash industry for their exploration programs. Additional State (North Dakota) and Provincial (Manitoba) geological surveys have recently compiled and released potash-related geological data (Bamburak and Nicolas, 2009; Kruger, 2014). With industry and government institutions working together, more updated data and interpretations could provide increased benefits to the potash industry and ultimately benefit the global food supply.

Information that could support increased geologic knowledge of the Prairie Evaporite potash and improved future assessments include the following:

1. Determine better grade distributions for carnallite- and sylvite-rich areas;
2. Develop $K_2O$ equivalent grade-distribution maps for each member of the Prairie Evaporite;
3. Develop better seismic coverage of the potash-bearing salt;
4. Develop a more detailed seismic anomaly map or use the more limited seismic coverage to compile a statistical study of the occurrence, size, and spatial density of seismic anomalies;
5. Calculate the amount of undiscovered potash that occurs both within the Area of Potash Dispositions in Saskatchewan and in external areas. This may facilitate a better understanding of the salt anomalies' spatial relations and could be used to predict their occurrence and effect on the potash-bearing salt, as suggested by Boys (1990);

6. Examine the potential of additional potash-bearing strata where the salt above the Patience Lake Member is not as extensively removed by subrosion; and
7. Examine the extent and potential of carnallite-bearing salt beneath the presently defined base of the Esterhazy Member.

A spatial (and perhaps genetic) relation between the thickness of the Prairie Evaporite and potash thickness may be present. Developing an isopach map of the Prairie Evaporite and comparing that map to isopach maps of each member may aid in understanding the Elk Point Basin potash deposits and help serve as a model in other evaporite basins.

Development of the resource assessment methodology described in this report would not have been possible without the detailed drill hole information currently available and the ability to manage that data with current computing capabilities. The part of the Elk Point Basin containing the potash-bearing salt has a considerable amount of available data with which the assessment methodology could be further developed and tested. Because of the available data, parameters that could be calculated or reasonably estimated in the Elk Point Basin are more likely to be largely unknown or poorly documented in similar stratabound deposits. Parameters established in this assessment can be used to gauge or estimate values of the unknown or poorly documented parameters in other stratabound, potash-bearing salt basins.

## Summary

The Middle Devonian (Givetian) Prairie Evaporite consists of cyclic deposits of anhydrite, halite, and potassium-magnesium (K-Mg) salts. The evaporite deposits are stratabound and consist mainly of sylvite or carnallite in mixtures with halite. These were deposited within the large intracratonic Elk Point Basin, which extends southeastward across Alberta through Saskatchewan and into Manitoba, North Dakota, and Montana. Pre-evaporite geologic development of the basin strongly influenced the location and deposition of the potash-bearing salts and their subsequent modification. Paleotopographic highs divided the Elk Point Basin into the northern Alberta, central Alberta, and Saskatchewan subbasins. Reef complexes formed on these topographic highs and on the entrance to the basin and restricted the southeastward flow of increasingly saline marine water that was subjected to increased evaporation, eventually leading to precipitation of the K-Mg salts. Known potash-bearing salt occurs in the Saskatchewan subbasin within the upper 100 meters (m) of the Prairie Evaporite in the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members.

Members are separated by intervals of banded halite with minor amounts of potash salts. Each member consists of bedded cyclic evaporite sequences or cycles, and at least 11 cycles occur in the Patience Lake Member. Each of these cycles consists of halite grading upward into mixtures of halite plus sylvite and carnallite. The amount of insoluble minerals increases upward in each cycle, and the cycles are generally capped by a clay seam. Bedding is continuous with evaporite cycles and clay seams traceable from drill hole to drill hole and from mine to mine over tens of kilometers or more. Potash grades are consistent throughout much of the Prairie Evaporite, and the mine grades are among the highest for all potash basins, making the various potash-bearing members favorable targets for potash exploration and development.

Mining began in the Saskatchewan portion of the Elk Point Basin in the early 1960s, and the deposits have become the world's primary source of recoverable potash since that time. Most potash has been recovered from underground conventional mines located in the shallower, northernmost parts of the Saskatchewan subbasin, generally at depths of 900–1,100 m. These mines are expensive and time consuming to bring into production and require considerable long-term planning. Underground solution mining was initially limited to one mine in the 1960s, but two new solution mines have begun production with several others close to production startup. During the brief history of production in this basin, more than 1.5 trillion metric tons (Tt) of ore containing more than 576 million metric tons (Mt) of potassium chloride (KCl) or 365 Mt of potassium oxide ($K_2O$) equivalent were processed. Current production levels are on the order of 14–15 Mt $K_2O$ equivalent per year and will increase as new mines come into production. From 1962 to 2012, the total value of potash sales was approximately $68 billion (CAD) (Saskatchewan Ministry of Energy and Resources, 2009; Saskatchewan Ministry of the Economy, 2014b) and, based on recent sales, was estimated to be $100 billion (CAD) through 2018 (Saskatchewan Ministry of the Economy, 2018). Growing world populations and changing environmental factors have increased the demand for potassium-based fertilizers. Increasing prices and overall consumption of potash products during the first two decades of the 21st century favored increased production from existing mines along with faster and lower cost development of new mines.

Most of the production prior to 2015 was from conventional underground mines that developed the ore in the high-grade intervals of the Patience Lake and Esterhazy Members in parts of the basin at depths where this type of mining is technically feasible. Vast amounts of potash at deeper structural levels in the basin (and greater portions of the potash-bearing stratigraphy) are being evaluated for recovery by solution mining. This assessment attempts to estimate the amount of undiscovered potash that may be present in the Elk Point Basin.

Despite as many as 20 estimates of the contained potash resources in this basin during the past 70 years, no systematic documented assessment of the basin's total potash resources has been attempted. Until recently, estimates of contained potash in other evaporite salt basins had also not been attempted. Other basins recently evaluated were the Central Asia Salt Basin (Wynn and others, 2016) and the Pripyat and Dnieper-Donets Basins (Cocker and others, 2017). A global assessment of the world's potash-bearing basins attempted to use the same criteria for each basin. These criteria included potash-bearing salt with a minimum thickness of 1 m, depths above 3,000 m, and potash grades greater than 4 percent $K_2O$ equivalent. These criteria, along with certain geological criteria peculiar to the Prairie Evaporite, were used to define how Elk Point Basin potash resources were assessed. The geological foundation for this assessment is included in this report.

The results of this assessment suggested that the Patience Lake, Belle Plaine, White Bear, and Esterhazy Members may contain mean undiscovered amounts of 340, 220, 34, and 190 Bt of $K_2O$ equivalent, respectively, and may contain a total of 780 Bt of $K_2O$ equivalent. The estimated total of undiscovered potash plus the known amounts of potash is about 800 Bt of $K_2O$ equivalent. The results of this assessment of undiscovered $K_2O$ equivalent tonnages for the Prairie Evaporite exceed previous estimated tonnages. Reasons for the differences are attributed to expanded criteria used to define what is included as resources. Direct comparison of the present assessment to these previously estimated tonnages is not possible, because the data and the methods used to determine those estimated tonnages is generally undocumented. This assessment is a more inclusive compilation and interpretation of the geology and known extent of potash-bearing salt in the Elk Point Basin.

The potash-bearing salt strata extend to the south into North Dakota and Montana, but the grades and mineralogy are currently unknown. Depths to these strata are considerably greater (ranging from about 2,700 m to greater than 3,000 m) than the currently anticipated deepest solution mine (Milestone Mine, which has a depth of about 1,700 m) and may be beyond currently feasible recovery methods. Life expectancies of the current mines extend an additional 40–80 years beyond the present. The estimated tonnages in this report include resources that may be developed beyond the foreseeable future of mining in this basin and resources which may never be developed. The documented geological information included in this report can provide a model for the study and understanding of the world's other less-well-studied potash-bearing basins. Development and testing of an assessment methodology for stratabound, potash-bearing salt deposits was based on knowledge gained from studies of this basin.

## Outlook for Global Potash Deposit Development

After a substantial increase in global potash markets during the early part of the 21st century led to a substantial increase in potash exploration, demand and prices for potash declined abruptly in 2008 and 2009 (Stone, 2009). Some projects were put on hold as companies waited for a rebound in the potash market. Other exploration projects went into a period of consolidation or upgraded their mine facilities, and a few continued with their development to production status (Moore, 2006, 2010; Bruno, 2012a,b; Hopf and others, 2012; Spachtholz, 2013; Cocker and others, 2016, 2017; O'Rourke, 2017; Ziebarth, 2017). That was followed by a period of relative steady growth in interest and exploration from 2010 to 2019, particularly in the Elk Point Basin.

World potash demand was estimated at 38.3 Mt $K_2O$ equivalent in 2018 (Bartsch and others, 2014), and is expected to continue growing as the world's population and demand for higher quality food increases. Projects in other basins are expected to continue to advance depending, in part, on their potential market share as compared to the Saskatchewan potash industry's market share. Transportation costs are a major economic factor affecting the viability of a bulk commodity such as potash. Shallower, smaller, and lower grade deposits of potash than those in Saskatchewan have been and will continue to be profitably mined in or near countries that have a need for high-yield potash fertilizers. For example, costs of shipping potash from the Danakil Basin in Ethiopia (Cocker and Orris, 2014) to India would be less than that of shipping potash from the Saskatchewan deposits.

The continued use and development of solution-mining techniques for the extraction of lower grades of potash at greater depths and in order to generate greater amounts of the available potash (such as noted here for Saskatchewan) will influence the development of potash deposits in other parts of the world. Solution mining of potash deposits has been used in Saskatchewan, New Mexico, Utah, Michigan, and Germany, and has been proposed for shallow potash deposits in the Danakil Basin in Ethiopia and Eritrea (Rauche and van der Klauw, 2008, 2011) as well as in the Lower Congo Basin in the Republic of Congo (Rauche and van der Klauw, 2007; Cocker and Orris, 2014; Cocker and others, 2016). The results of this potash resource assessment may provide tools and knowledge to assess other potash-bearing salt basins that may currently be not viable opportunities for development.

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# Appendixes A–E

# Appendix A. Summary Descriptive Model of Stratabound Potash-Bearing Salt Deposits

By Mark D. Cocker and Greta J. Orris

## Introduction

Stratabound potash-bearing salt is associated with thick sections of evaporitic salt (halite) that form laterally continuous strata in marine evaporite basins. Deposits are extremely soluble and thus easily altered or destroyed over geologic time. Stratabound potash deposits range in size from several tens of millions to more than 30 billion metric tons (Bt) of potassium oxide ($K_2O$). Most of the world's potash resources are associated with this deposit type.

## Representative Deposits

Examples of stratabound potash-bearing salt deposits include those in the Givetian (Middle Devonian) Elk Point Basin in Canada, the Frasnian and Famennian (Upper Devonian) Pripyat Basin in Belarus, and the Lopingian (upper Permian) Solikamsk Basin in Russia (see fig. 2 of the main text for location of basins). Other basins, such as the Lopingian Zechstein Basin in Europe and the Central Asia Salt Basin, contain potash-bearing salt in both stratabound and halokinetic deposits (Orris and others, 2014).

## Brief Description

### Synonyms

Synonyms for this type of deposit include potash deposits, potash-bearing salt deposits, bedded potash, and marine potash.

### Principal Commodities and Byproducts

The principal products of potash mining are potassium chloride (KCl), which is referred to as muriate of potash (MOP), and potassium sulfate ($K_2SO_4$), which is referred to as sulfate of potash (SOP). Where carnallite ($KMgCl_3 \cdot 6H_2O$) constitutes a major part of a deposit, magnesium may be recovered in addition to potash. The main byproduct commodity of potash mining is halite, or rock salt.

### Relative Importance of the Deposit Type

Stratabound potash-bearing salt deposits may contain billions to trillions of tons of mineralized rock and are amenable to low-cost, bulk underground mining methods. Approximately 75 percent of the world's potash production is from stratabound potash-bearing salt deposits, and more than 25 percent of that production is from the Middle Devonian Prairie Evaporite of the Elk Point Basin in Saskatchewan, Canada (Orris and others, 2014; Wynn and others, 2016).

### Global Distribution

The largest and economically most important deposits of potash are found in North America, Europe, and Asia (fig. 2 of the main text). Newly explored deposits in Africa and South America are increasingly important (Orris and others, 2014; Wynn and others, 2016).

### Associated and Related Deposit Types

Stratabound potash-bearing salt deposits are associated with stratabound and bedded gypsum, anhydrite, halite, and sulfur deposits (Long, 1992).

## Descriptive and Genetic Synopsis

Potash-bearing salt is a chemically deposited sedimentary rock made up of fine- to coarse-grained potassium- and magnesium-chloride and sulfate minerals intergrown with halite. Beds of laterally continuous stratabound potash-bearing salt occur within thick sections of halite-dominant evaporite deposits. Potash-bearing strata range in thickness from centimeters to meters, and potash-bearing intervals may consist of one bed or numerous thin layers. These deposits are commonly attributed to evaporation of large volumes of seawater in hydrographically restricted or isolated basins under hyperarid climatic conditions (Warren, 2006, 2010; Kendall, 2010). Progressive evaporation of saline water—usually seawater—and salt precipitation contribute to increasingly hypersaline conditions, formation of bitterns, and eventual deposition of potassium- and magnesium-bearing minerals. Multiple episodes of saline-water inflow can result in the cyclic deposition of potash minerals and can yield deposits that are many tens of meters thick.

## Permissive Tract Delineation

The fundamental geologic feature used to delineate tracts that are permissive for stratabound potash-bearing salt is an evaporite-bearing sedimentary basin that contains halite-dominated areas and shows evidence that evaporation reached the bittern stage. Evidence of potash includes (1) reports of the presence of sylvite, carnallite, polyhalite, or other potassium saline minerals or (2) indirect evidence from downhole geophysical surveys.

Permissive tracts are outlined by selecting basins with known evaporites, restricting tract boundaries to areas likely underlain by salt at depths of 3 kilometers (km) or less and, if possible, by using drill hole data or other information to limit tracts to areas underlain by potash-bearing salt. Halite-rich layers are preferably many tens to hundreds of meters thick and are areally extensive. Thicknesses of potash-bearing salt that are economic to be mined are commonly reported as average thicknesses and vary considerably between basins. The established minimum U.S. Geological Survey standard for leasable potash ore is 1.2 meters (m; 4 feet) thickness (Aguilar and others, 1976; Cheeseman, 1978; John and others, 1978), and most industry reported thicknesses are at least approximately 3 m (British Sulphur Corp., Ltd., 1984). However, to compare potash tracts on a global basis, a minimum mined thickness of 1 m (such as that in the Pripyat Basin) was used as the minimum thickness of potash in a tract.

## Regional Geologic Attributes

Marine evaporite deposits are accumulations of salt minerals in structural sedimentary basins, such as cratonic basins (for example, Elk Point and Permian Basins) and grabens (for example, Pripyat and Dnieper-Donets Basins) (Adams, 1975; Orris and others, 2014; Cocker and others, 2017).

### Tectonic Setting of Basins

Stratabound potash-bearing salt is found in sedimentary basins that had access to episodic inflows of seawater and that formed in arid climates. Deposits have been described in continental and oceanic rift basins, foreland basins, intracontinental sag basins, and in transform basins that are products of the breakup (or failed breakup) of continents, the convergence or collision of continental plates, or the thinning and weakening of intraplate regions (Warren, 2010). Basin type is less critical than climatic conditions at the time of deposition. Hot, hyperarid climatic conditions are necessary to form brines from saline waters and deposit evaporites. These conditions may result from global-scale atmospheric wind-circulation patterns (Warren, 2010). Many of the world's deserts are in two belts centered on latitudes 15° and 45° north and south of the Equator and correspond to the boundaries between atmospheric circulation cells and increased aridity that were likely places for stratabound potash-bearing salt deposition (Warren, 2008).

### Depositional Systems

In an evaporite basin, near-shore, shallow clastic facies rocks grade to carbonate-rich, then sulfate-rich, then halide-rich rocks toward the central part of a basin or toward parts more distal from the point of seawater influx. Central parts of an evaporite basin may have facies representing shallow to deep water (Schmalz, 1969; Warren, 2006; Kendall, 2010). The resulting stratigraphic sequence begins with minor clastic red beds, followed by carbonate rocks, anhydrite or gypsum, salt, and ends with potash-bearing salt. Multiple episodes of evaporite mineral precipitation may be recorded in cyclic sequences of rock layers, with individual cyclic units ranging from a few centimeters to hundreds of meters thick.

### Age Range and Age-Related Features

Potash-bearing salt deposits are found in basins that are Neoproterozoic or younger in age (Zharkov, 1984, 2005; Goncharenko, 2006; Kovalevych and others, 2006; Warren, 2006, 2008). Half of the world's known potash-containing basins are Middle and Late Devonian, Permian, Cretaceous, or Paleogene to Neogene in age (Goncharenko, 2006).

Differences in deposit mineralogy likely reflect temporal changes in global seawater chemistry. During the Phanerozoic, marine brine chemistry appears to have oscillated between Na-K-Mg-Ca-Cl and Na-K-Mg-Cl-$SO_4$ types (Hardie, 1990, 1991, 1996; Holland and others, 1996; Horita and others, 2002; Kovalevych and others, 1998; Warren, 2006; Ries, 2010). Magnesium-poor sulfate deposits dominated by sylvite and carnallite are derived from the Na-K-Mg-Ca-Cl brines. Magnesium-rich sulfate type deposits, with variable amounts of potassium (K) and magnesium (Mg) sulfate minerals may form from Na-K-Mg-Cl-$SO_4$ brines. Local environmental conditions may be significant factors in basin brine geochemistry.

## Local Geologic Attributes and Deposit Characteristics

### Host Rocks

Host rocks are evaporitic sedimentary rocks, such as rock salt, sylvinite, carnallitite, kainitite, hartsalz, anhydrite, and gypsum. The mineralized rock strata consist of potash salt minerals, including chlorides, sulfates, and halite, in evaporite sequences.

### Deposit Form and Dimensions

Stratabound potash-bearing salt deposits are composed of one or more layers or beds of potash-bearing salt. The beds (or groups) of layers are commonly laterally continuous across large areas of a basin. Individual potash beds or layers commonly range in thickness from less than a meter to several tens of meters and rarely to almost a hundred meters. A sequence of potash-bearing salt beds can range from tens of meters to a few hundred meters thick. The areal extent of potash-bearing salt is ultimately limited by the basin size at time of deposition. Typical volumes of stratabound potash-bearing salt can range from hundreds to thousands of cubic kilometers.

# Mineralogy

## Potash Ore Mineral Assemblages

Primary potash ore minerals include sylvite, carnallite, kainite, polyhalite, and langbeinite (table A1). These minerals occur most commonly as intergrowths with halite.

The dominant potash ore-mineral assemblages contain sylvite and halite with minor (<6 weight percent) carnallite or carnallite plus halite with negligible amounts of sylvite. Some deposits may contain ore assemblages of kainite, langbeinite, polyhalite, kieserite, or bischofite mixed with halite and gypsum or with anhydrite.

## Gangue Mineralogy

Gangue minerals include halite, clay minerals, dolomite, anhydrite, gypsum, bischofite, epsomite, tachyhydrite, leonite, blödite, hexahydrite, vanthoffite, löweite, aphthitalite, picromerite, and borate minerals (table A1). Sonnenfeld (1991) noted the presence of halloysites, kaolinite, iron-chlorite, magnesium-chlorites, montmorillonite, palygorskite, illite, sepiolite, and muscovite in evaporite basins.

Primary mineral zoning may consist of an outer or stratigraphically lower zone dominated by sulfates such as anhydrite or gypsum, changing to a halite-dominated zone, and culminating with an inner or upper zone containing halite plus

**Table A1.** Common potash and evaporite minerals and their physical properties.

[t/m$^3$, metric tons per cubic meter]

| Mineral or material | Composition[a] | Potassium oxide ($K_2O$), percent[b] | Density, t/m$^3$ |
|---|---|---|---|
| Primary potash minerals | | | |
| Carnallite | $KMgCl_3 \cdot 6H_2O$ | 16.9 | 1.6 |
| Kainite | $MgSO_4 \cdot KCl \cdot 3H_2O$ | 19.3 | 2.1 |
| Langbeinite | $K_2Mg_2(SO_4)_3$ | 22.7 | 2.83 |
| Polyhalite | $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$ | 15.6 | 2.77 |
| Sylvite | $KCl$ | 63.2 | 2 |
| Primary potash ore materials | | | |
| Carnallitite | Mix of halite and carnallite | Typically <15 | Variable |
| Hartsalz | Mix of sylvite, halite, anhydrite, and kieserite | Typically <15 | Variable |
| Sylvinite | Mix of sylvite and halite | Typically <25 | Variable |
| Accessory potassium minerals | | | |
| Aphthitalite (glaserite) | $(K,Na)_3Na(SO_4)_2$ | 42.5 | 2.69 |
| Arcanite | $K_2SO_4$ | 54.1 | 2.66 |
| Douglasite | $K_2Fe^{2+}Cl_4 \cdot 2H_2O$ | 30.2 | 2.16 |
| Leonite | $K_2Mg(SO_4)_2 \cdot 4H_2O$ | 25.7 | 2.2 |
| Niter (saltpeter) | $KNO_3$ | 44 | 2.1 |
| Picromerite (schönite) | $K_2Mg(SO_4)_2 \cdot 6H_2O$ | 23.4 | 2.03 |
| Rinneite | $K_3NaFe^{2+}C_6$ | 34.5 | 2.35 |
| Syngenite | $K_2Ca(SO_4)_2 \cdot H_2O$ | 28.7 | 2.58 |
| Accessory non-potassium minerals | | | |
| Anhydrite | $CaSO_4$ | 0 | 2.98 |
| Bischofite | $MgCl \cdot 6H_2O$ | 0 | 1.59 |
| Blödite | $Na_2Mg(SO_4)_2 \cdot 4H_2O$ | 0 | 2.23 |
| Dolomite | $CaMg(CO_3)_2$ | 0 | 2.86 |
| Epsomite | $MgSO_4 \cdot 7H_2O$ | 0 | 1.677 |
| Gypsum | $CaSO_4 \cdot 2H_2O$ | 0 | 2.3 |
| Halite | $NaCl$ | 0 | 2.17 |
| Hexahydrite | $MgSO_4 \cdot 6H_2O$ | 0 | 1.757 |
| Kieserite | $MgSO_4 \cdot H_2O$ | 0 | 2.57 |
| Löweite | $Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$ | 0 | 2.36–2.42 |
| Tachyhydrite | $CaMgCl_6 \cdot 12H_2O$ | 0 | 1.67 |
| Vanthoffite | $Na_6Mg(SO_4)_4$ | 0 | 2.694 |

[a] Formulas from Back and Mandarino (2008).

[b] Average $K_2O$ content and specific gravity from Harben and Kužvart (1996) and Anthony and others (1997, 2003).

potassium chloride or potassium sulfate minerals. Under certain conditions at the end of an evaporation sequence, some other bittern minerals such as tachyhydrite or bischofite may also be present and preserved. These minerals are highly soluble and are commonly no longer present in most of these deposits.

### Effects of Alteration

Potash-bearing salt is highly soluble and susceptible to alteration, recrystallization, and dissolution by surface water, low-salinity brine, and groundwater (Warren, 2010). Groundwater dissolution can modify a deposit's mineralogy, layering, grain size, or porosity, or it can totally destroy a deposit. Dissolution of potash, salt, and potash-alteration zones may be only a few meters thick but can extend across hundreds of square kilometers. Salt dissolution, or subrosion, may remove considerable amounts of salt and potash-bearing salt, which can decrease overall salt and potash thickness or cause large dissolution embayments (Linn and Adams, 1963; Borchert and Muir, 1964; Schwerdtner, 1964; Jones and Madsen, 1968; McIntosh and Wardlaw, 1968; Wardlaw, 1968; Kislik, 1970; Fuzesy, 1982; Hite, 1982; Korenevskiy, 1989; Warren, 2010). Increased pressure and temperature related to burial metamorphism or thermal metamorphism can also lead to recrystallization and destruction of primary salt and potash textures and changes in grain size.

# Exploration Guides

## Geochemical Signature(s)

In many primary deposits, brines in boreholes may be anomalous in potassium, sodium, magnesium, bromine, chlorine, and sulfur (Rogers, 2011). Exceptionally saline wells and saline spring water are indicative of an evaporite sequence and have historically led to discoveries of concealed salt and potash deposits.

Bromine content of halite increases as the salinity of the brine increases; bromine profiles show increasing upward trends in unaltered evaporite cycles. Residual brines at this stage may contain hundreds of parts per million (ppm) bromine and can contain on the order of 1,000 ppm or more bromine during precipitation of potash minerals, although reported values are typically much lower owing to dilution and dissolution, diagenesis, and brine fluctuations (Garrett, 1996).

## Geophysical Signature(s)

### Radiometric Signatures

High gamma radiation signatures from the natural isotope potassium-40 ($^{40}K$) are used to map potassium content of salt in downhole geophysical surveys (Garrett, 1996).

### Seismic Signatures

Reflection seismic methods are used to delineate salt structures and layers (Fox, 1987; Simeonova and Iasky, 2005).

### Other Exploration Guides

Except for drilling to confirm potash, there are few sure indications of the presence of potash-bearing salt. Thick sections of halite, commonly greater than 100 m, are believed to be necessary prior to potash deposition (Harben and Kužvart, 1996), and this could be used in conjunction with other data to identify or rank the potash potential of basins with little exploration history.

# Typical Grade and Tonnage

Average reported potash grades in explored deposits of this type may range from 5.3 to 38 percent $K_2O$ equivalent (de Ruiter, 1979; Kumar and Bakliwal, 2005). Most reported grades in operating mines range from 11 to 25 percent $K_2O$. In general, the lowest average grade of potash that is currently being mined is in the range of 8–10 percent $K_2O$, with the lowest associated cutoff grade less than 4 percent $K_2O$ (Orris and others, 2014).

The minimum thickness of a leasable potash layer as defined by the U.S.Geological Survey is 1.2 m of $K_2O$ as sylvite (John and others, 1978). In Saskatchewan, minimal mining thicknesses range from 2.44 to 3.35 m because of the mining equipment used and the thickness of the highest grade ore in different mines (Moore and others, 2010a,b,c,d, 2011).

Reported tonnages for potash deposits range from a few tens of millions to 30 Bt (British Sulphur Corp., Ltd., 1984; Hardy and others, 2009). Reported tonnages since 2000 for greenfield potash projects that stated NI 43-101-compatible reserves and resources largely exceed 500 million metric tons and, commonly, 1 Bt of potash ore (Rauche and van der Klauw, 2010; BHP Billiton, 2010; Davis, 2010; Rauche and others, 2012; South Boulder Mines, 2012).

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# Appendix B. Glossary of Terms Used in the Description of Evaporites

By Mark D. Cocker and Greta J. Orris

### A

**Allochthonous salt** Sheetlike salt bodies emplaced at stratigraphic levels above the autoch jinm gmsdgmsfmvsdc thonous source layer. Allochthonous salt lies on stratigraphically younger strata; theoretically, allochthonous salt could overlie older strata, but such examples have not yet been reported (Jackson and Talbot, 1991).

**Autochthonous salt** Salt body resting on the original strata (or surface) on which it accumulated by precipitation and deposition of salt from brine by evaporation (Jackson and Talbot, 1991).

### B

**Brachyanticline** A short, broad anticline (Neuendorf and others, 2005). A short anticlinal fold of layers of rock having an oval map pattern. The layers of rock that form the brachyanticline slope away from the central part of its crest on all sides. A brachyanticline is represented on a geological map in the form of concentric oval rings, with the older rocks located in the center; rocks young toward the periphery (Prokhorov, 1970–1979).

### C

**Cap rock [tectonics]** In a salt dome, an impervious body of anhydrite and gypsum, with minor calcite and rare sulfur that overlies the salt body (or plug). It probably results from the accumulation of less-soluble minerals of the salt body during leaching in the course of its ascent (Neuendorf and others, 2005).

**Carnallite** A primary potash ore mineral, $KMgCl3 \cdot 6H2O$, that is also a source of magnesium in some deposits. Usually occurs as crystalline or granular masses. Occurs chiefly as a component of extensive thick sedimentary saline deposits, commonly associated with kieserite, halite, sylvite, and polyhalite (Roberts and others, 1974; Neuendorf and others, 2005).

**Carnallitite** A rock composed largely of a mixture of carnallite and halite (salt).

**Cycle** Many sedimentary sections exhibit (1) a kind of rhythmicity owing to regularly alternating beds traceable over long distance or (2) a repetition of larger units, which are referred to as sedimentary sequences or cycles. Rhythmic and cyclic sequences occur worldwide on various scales in presumably every environmental and stratigraphic system (Einsele, 2000).

### D

**Dewatering** The expulsion of water from sediments during diagenesis or metamorphism. The water may have been present in the form of interstitial pore waters or water bound to hydrous minerals, such as certain clays or gypsum (Friedman and others, 1992, p. 11; Neuendorf and others, 2005).

**Diapir [structural geology]** A dome or anticlinal fold in which the overlying rocks have been ruptured by the squeezing out of plastic core material. Diapirs in sedimentary strata usually contain cores of salt or shale (Neuendorf and others, 2005).

### E

**Evaporite** A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent. Examples include gypsum, anhydrite, other diverse sulfates, halite (rock salt), primary dolomite, and various nitrates and borates (Neuendorf and others, 2005).

### G

**Gypsum** A widely distributed mineral consisting of hydrated calcium sulfate ($CaSO4 \cdot 2H2O$). Gypsum commonly occurs as crystalline masses, fine to coarse granular. Textures range from fibrous to pulverent or concretionary. Occurs abundantly and widespread chiefly in sedimentary deposits, in saline lakes and playas, as efflorescence on certain soils, in the oxidized parts of ore deposits, and in deposits associated with volcanic activity (Roberts and others, 1974). It is the most common sulfate mineral and is frequently associated with halite and anhydrite in evaporites, forming thick, extensive beds interstratified with limestone, shale, and clay (especially in rocks of Permian and Triassic age; Neuendorf and others, 2005). It may alter to anhydrite under burial metamorphic conditions, releasing its water of hydration (Adams, 1970).

### H

**Halite** An abundant evaporite mineral ($NaCl$), most commonly interbedded or intergrown with various potash minerals. Usually occurs as crystalline masses that are granular and rarely columnar or stalactitic. Occurs widespread, chiefly as extensive sedimentary deposits ranging in thickness from a few centimeters to more than several thousand meters. Also occurs as efflorescence in playa deposits and as a sublimation product in areas of volcanism (Roberts and others, 1974; Neuendorf and others, 2005).

**Halokinesis** (1) A class of salt tectonics in which, in the absence of significant lateral tectonic forces, salt flow is powered entirely by gravity (Jackson and Talbot, 1991). (2) The deformation of halite by flowage and recrystallization. Causative forces cited for this process include gravity flow, tectonic thrusting, and diapirism (Kyle and Posey, 1991; Neuendorf and others, 2005).

**Hartsalz** Hard salt, typically a mixture of sylvinite and kieserite, with some anhydrite, found in the Stassfurt salt deposits in Germany (U.S. Bureau of Mines, 1996).

**Horizon** (1) In geology, any given definite position or interval in the stratigraphic column or the scheme of stratigraphic classification. (2) An identifiable rock stratum regionally known to contain or be associated with rock containing valuable minerals (Thrush, 1968; U.S. Bureau of Mines, 1996). (3) In the potash industry, a term widely used to identify and characterize potash-rich strata in potash basins throughout Africa, Asia, Europe, and North and South America (Holter, 1969; Garrett, 1996; Warren, 2006, 2016; Rauche and van der Klauw, 2011; Hardy and others, 2013; Cocker and others, 2017).

**Horse** A miners' term for a barren mass of country rock occurring within a vein (Neuendorf and others, 2005).

## I

**Intracratonic basin** A basin formed within the interior region of a continent, away from plate boundaries. It develops where there is subsidence of a part of a craton, probably owing to the thermal subsidence of an unsuccessful rift (Neuendorf and others, 2005).

## P

**Potash-bearing salt** A general term for a rock salt (usually dominated by the mineral halite but which may contain various amounts of clay and sulfate minerals) that contains variable amounts of potash minerals usually in the form of sylvite or carnallite (usage by Zharkov, 1984, and Prud'homme and Krukowski, 2006).

## R

**Rim syncline** A fold that has an arcuate or subcircular axial tract on the outer margin of a salt upwelling. Rim syncline is a nongenetic term but, in the context of salt tectonics, a rim syncline typically results from salt withdrawal in the source layer. Peripheral sinks of sediments accumulate within rim synclines (Nettleton, 1968; Jackson and Talbot, 1991; Neuendorf and others, 2005).

**Rock salt** Coarsely crystalline halite occurring as a massive, fibrous, or granular aggregate, and constituting a nearly pure sedimentary rock that may occur in domes or plugs or as extensive beds resulting from evaporation of saline water. It is frequently stained by iron or mixed with fine-grained sediments (Neuendorf and others, 2005).

## S

**Safety pillar** A significant thickness of salt, usually about 150 meters, that is left in place during mining below the brine-saturated caprock and surrounding water-bearing strata to act as a seal in a diapiric salt structure (Heim and Potthoff, 1983). See "salt-back."

**Saline giant** A term used to describe thick, basin-filling evaporite units; the term is synonymous with mega-evaporites. Mineralogies are dominated by halite or anhydrite, along with varying amounts of carbonates and potash salts (Warren, 2006, 2010).

**Salt** A general term for naturally occurring sodium chloride, NaCl. See "rock salt."

**Salt anticline** (1) A diapiric or piercement structure, like a salt dome, except that the salt core is linear rather than equidimensional, such as the salt anticlines in the Paradox Basin of the central Colorado Plateau (Neuendorf and others, 2005); (2) Elongated upwelling of salt having concordant overburden (DeGolyer, 1925; Harrison and Bally, 1988; Jackson and Talbot, 1991).

**Salt-back** A significant thickness of salt above the mining horizon maintained to ensure a water seal between mine openings and overlying strata that contain groundwater. The thickness of a salt-back depends on the mining method used and the nature of water saturation and rock competency in overlying beds (Holter, 1969).

**Salt diapir** A mass of salt that has flowed ductilely and appears to have discordantly pierced or intruded the overburden. In its broadest sense, "diapir" includes (1) lateral or vertical intrusion of any shape, (2) upwelling of buoyant or non-buoyant rock or magma, or (3) emplacement by passive piercement or by faulting of prekinematic overburden (Mrazec, 1907; Jackson and Talbot, 1991).

**Salt dome** (1) A diapir or piercement structure with a central, nearly equidimensional salt plug, generally 1–2 kilometers (km) or more in diameter, which has risen through the enclosing sediments from a mother salt bed (source layer) 5 km to more than 10 km beneath the top of the plug. Many salt plugs have a cap rock of less-soluble evaporite minerals, especially anhydrite. The enclosing sediments are commonly turned up and complexly faulted next to a salt plug, and the more permeable beds serve as reservoirs for oil and gas (U.S. Bureau of Mines, 1996); (2) An imprecise, general term for a domal upwelling comprising a salt core and its envelope of deformed overburden. The salt may or may not be discordant (Harris and Veatch, 1899; Jackson and Talbot, 1991).

**Salt glacier** Sheetlike extrusion of salt flowing from an exposed diapir and spreading subaqueously or subaerially (Jackson and Talbot, 1991).

**Salt horse** A dome-shaped barren zone generally consisting of halite that crosscuts potash-bearing salt beds. Bedding is continuous through the halite but is thinner than the potash-bearing salt beds. Halite is believed to have replaced the potash-bearing salt beds in the salt horse through upward movement of saline brines (Linn and Adams, 1966).

**Salt pillow** A subcircular upwelling of salt having concordant overburden (Jackson and Talbot, 1991).

**Salt plug** The salt core of a salt dome. It is nearly equidimensional (about 1–2 km in diameter) and has risen through the enclosing sediments from a mother salt bed (source layer) 5–10 km below (Neuendorf and others, 2005).

**Salt solutioning** A partial to complete dissolution of salts, commonly resulting in the collapse of overlying strata, and is attributed to ascending or descending low-salinity water or brine (Holter, 1969).

**Salt stock** A pluglike salt diapir having subcircular planform. See "salt plug." (Trusheim, 1957; Jackson and Talbot, 1991; Neuendorf and others, 2005).

**Salt tectonics** (synonomous with halotectonics) Any tectonic deformation involving salt, or other evaporites, as a substratum or source layer; this includes halokinesis (Trusheim, 1957; Jackson and Talbot, 1986, 1991).

**Salt wall** An elongated upwelling of diapiric (discordant) salt, commonly forming sinuous, parallel rows (Trusheim, 1960; Jackson and Talbot, 1991).

**Salt weld** Surface or zone joining strata that were originally separated by autochthonous or allochthonous salt. The weld is a negative salt structure resulting from the complete or nearly complete removal of intervening salt. The weld can consist of brecciated, insoluble residue containing halite pseudomorphs or of salt that is too thin to be resolved in reflection-seismic data. The weld is usually but not always marked by a structural discordance. Another distinctive feature of welds is a structural inversion above them (Jackson and Talbot, 1991).

**Salt withdrawal** Mass transfer of salt over time without obvious change in salt area in cross section. Examples are the migration of salt from the flanks of a salt pillow into its core as it evolves into a diapir or the flow of salt along a salt wall into local culminations that evolve into salt stocks. Synonomous with the term salt expulsion (Jackson and Talbot, 1991; Neuendorf and others, 2005).

**Source layer** (synonymous with mother salt) Layer supplying salt for the growth of salt structures; the source layer is a particular type of substratum (Jackson and Talbot, 1991).

**Stratabound** Descriptive term for a mineral deposit confined to a single stratigraphic unit (Neuendorf and others, 2005).

**Substratum** An underlying layer; in salt tectonics, substratum refers to the ductile layer below a brittle overburden and above the subsalt strata or basement. "Substratum" is a more general term than "source layer"; the substratum may or may not give rise to upwelling structures (Jackson and Talbot, 1991).

**Subrosion** (synonomous with post-burial dissolution) The process by which soluble rocks underground are dissolved by groundwater or by water penetrating from the surface. Subrosion takes place where soluble rocks are not protected by a layer of impermeable rocks (Rauche and van der Klauw, 2011).

**Subsalt strata** Sedimentary unit immediately underlying salt (Jackson and Talbot, 1991).

**Sylvite** The mineral sylvite (KCl) is the principal ore mineral of potassium. Sylvite usually occurs in compact to granular crystalline masses, as crusts, and columnar. Occurs chiefly as extensive thick sedimentary deposits, typically associated with halite, gypsum, anhydrite, carnallite, polyhalite, kieserite, and kainite (Roberts and others, 1974; Neuendorf and others, 2005).

**Sylvinite** A mixture of halite and sylvite, mined as a potash ore; sylvinite contains chiefly impure potassium chloride (Neuendorf and others, 2005).

### T

**Turtle-structure anticline** (1) Mounded strata between salt diapirs having a flat base and rounded crest over a local primary increase in sedimentary thickness; the anticline may or may not be cored by a low salt pillow. The turtle structure forms between diapirs whose flanks subside because of regional extension or between salt structures evolving from pillows to diapirs (Trusheim, 1957; Neuendorf and others, 2005); (2) The turtle structure forms by structural inversion of a primary peripheral sink when salt is withdrawn from the margins of the peripheral sink by growing diapirs. The planform of turtle structures is typically highly irregular, depending on the number, location, and relative vigor of the diapirs flanking it (Trusheim, 1960; Jackson and Talbot, 1991).

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# Appendix C. Adaptive Geometric Estimation for Stratabound Potash-Bearing Salt Deposits—Summary

By Greta J. Orris, James D. Bliss, Pamela Dunlap, and Mark D. Cocker

## Introduction

This summary describes a geometric estimation approach for assessing areally extensive bedded or stratiform mineral deposits and the use of this approach to estimate undiscovered potash in stratabound potash-bearing salt deposits. This methodology is adaptable to various types of data inputs and the resulting estimate is in a format compatible with results from the U.S. Geological Survey (USGS) three-part form of assessment (Singer and Menzie, 2010).

## Requirements for Methodology

An assessment methodology for stratabound deposits must meet several criteria:

1. The process must produce a probabilistic estimate of undiscovered resources as a distribution of expected grades and tonnages of the contained mineral or commodity (for example, potassium oxide [$K_2O$] equivalent for potash). A probabilistic distribution is compatible with outputs from areas assessed using the traditional USGS three-part form of assessment (Singer and Menzie, 2010) and indicates not only the best estimate but also the uncertainty of the estimate. A single number conveys a level of certainty unlikely to be achievable in this type of exercise.
2. The methodology must be appropriate for a stratabound deposit type; it should be based on volume (area multiplied by thickness) with appropriate adjustments for unmineralized areas, uncertainties and variability in input, and other factors that affect the estimate of the amount of mineralization.
3. The methodology must be adaptable to large variations in basin size and to highly variable input data volumes, formats, and densities across a tract.
4. The output must be adjustable for known reserves and resources.
5. The methodology needs to be easily implemented with readily available hardware and software, as well as be adaptable to new and different software, hardware, and estimation techniques.

These requirements led to the development of a methodology that can be adapted to highly variable inputs on a basin-by-basin basis, yet also provides a common underlying approach and results in a format that allows for comparison between areas.

## General Approach

A simplified description of mineral resource estimates that meet the Canadian Securities Administrators National Instrument (NI) 43-101 report standards for potash (Canadian Institute of Mining, Metallurgy, and Petroleum, 2003) starts with a volume estimate of mineralized material that is converted to tonnage using an appropriate bulk density. The estimated tonnage is then adjusted for unmineralized areas contained within the estimate area. An overview of mineral reserve and resource estimation standards for these reports, as well as some potash-specific guidelines, are available from the Canadian Institute of Mining, Metallurgy, and Petroleum (2003, 2004). The adaptive geometric estimation (AGE) methodology takes a similar approach to estimating undiscovered resources with the less-robust data inputs to be expected from underexplored areas and with an additional correction for known reserves and resources. Overall, the approach can be most simply stated as follows:

$$T=(VOL\times DENS)-NOMIN-RR \qquad (1)$$

where

$T$ is undiscovered in-place tonnage,
$VOL$ is volume of mineralized material,
$DENS$ is bulk density of mineralized material,
$NOMIN$ is correction for unmineralized areas, and
$RR$ is known reserves and resources.

It follows that the tonnage of the commodity of interest, potash calculated as potassium oxide ($K_2O$) equivalent, is

$$KT=T\times GRD \qquad (2)$$

where

$KT$ is tonnage of contained potash as $K_2O$, and
$GRD$ is potash grade as percent $K_2O$.

## Adaption of Reserves Estimation to Undiscovered Resources Estimation

The AGE methodology for assessing stratabound potash deposits consists of several steps. First, the prospective area for potash is identified using geologic maps, deposit models, and other data. Second, the volume of this area is then calculated using known or estimated thickness data. Third, a potash grade is selected from an appropriate grade-distribution model. If the dominant ore mineral is not known, then an assumption is made about the probable ore mineral based on the selected grade. The grade and ore mineral are used to determine an appropriate bulk density to convert the volume estimate to in-place tonnage for the delineated area. Fourth, the tonnage estimate is adjusted for unmineralized areas within the tract (anomalies) and along its edges (embayments) and for known mineralization, as appropriate. Finally, the contained potash in the mineralized material (in metric tons of $K_2O$) is determined from the tonnage and grade. The process is repeated for 5,000 iterations to produce a probabilistic estimate of contained potash. A flow chart of this process is shown in figure C1.

Although this approach is conceptually simple, implementation is complicated by incomplete and missing data in areas with undiscovered resources. Commonly, the extent of the potash-bearing salt (both in terms of area and thickness) is not well defined, and reported grade, bulk density, and similar data may not be representative of the entire assessment area. It is inevitable in areas with undiscovered resources that one or more data inputs will be unknown and must be estimated. These estimates can be based on analogy with similar, better explored areas; alternately, models can be constructed based on incomplete data from the area being studied.

This is a largely stochastic approach that requires simplifying assumptions along with the estimation of the missing data. Most estimates of missing data are not single numbers, but are distributions of possible values. These distributions are randomly sampled using a Monte Carlo simulation(s) in the AGE methodology. For our potash assessments, 5,000 simulation iterations were typically used. This process produces stable distributions of estimated undiscovered mineralized material and the contained commodity, with the medians of those distributions representing the most likely values.

This methodology for the potash assessment requires (1) a geographic information system (GIS) or other system to calculate areas and volumes and (2) statistical and modeling software. For this study, ArcGIS ver. 10 software was used to map data and estimate permissive tract volumes. Data distributions were constructed and tested using JMP ver. 8 and later JMP ver. 10 data analysis software. More complex statistical procedures, simulations, and estimations were programmed and executed using @RISK software (appendix D). Individual steps and some of the alternate estimation procedures are discussed more fully below.

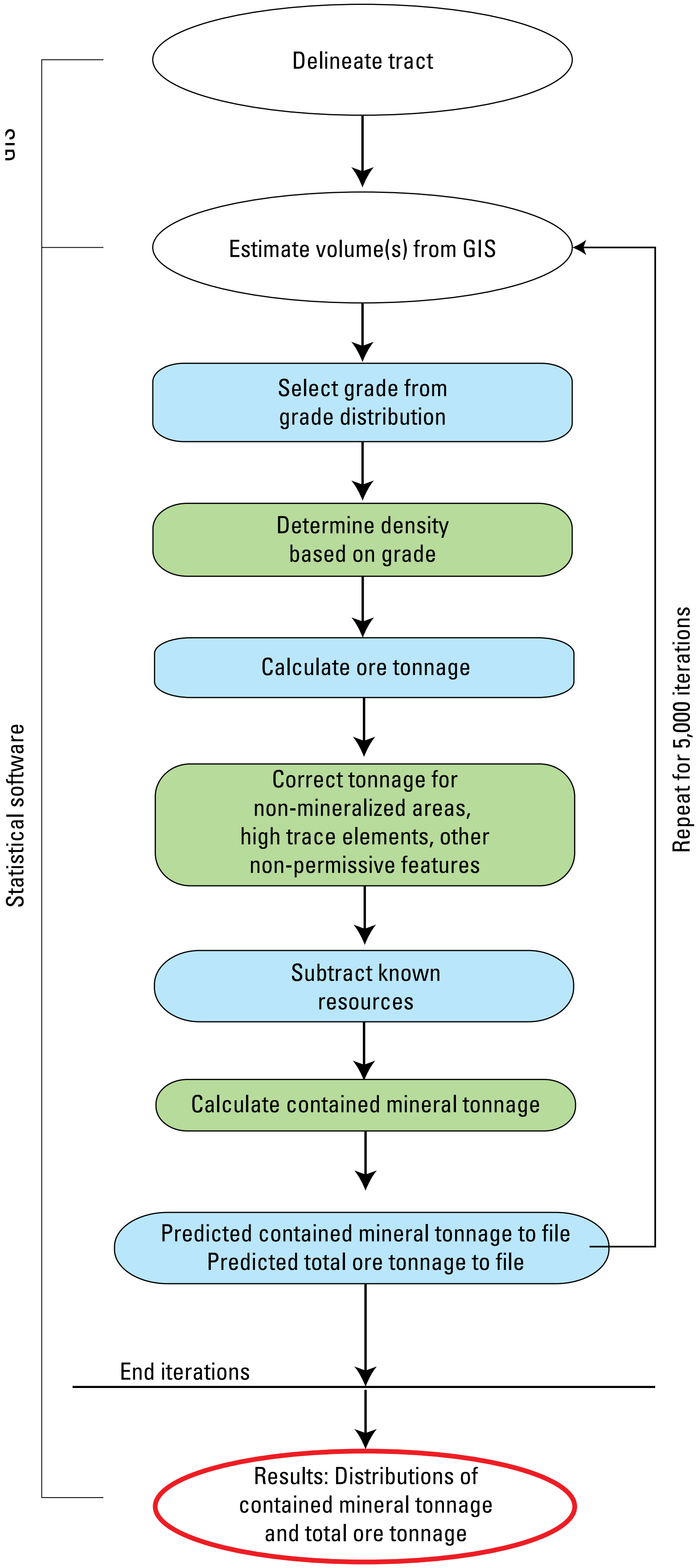

**Figure C1.** Flow chart showing generalized approach for assessing stratabound industrial mineral deposits. GIS, geographic information system.

## Tract Delineation and Volume

The first step in an assessment process is to delineate a tract, which is defined as the area containing the minerals of interest. Tract delineation is commonly done using a mix of geologic and other maps, geophysical data, and point data, such as drill holes and mineral occurrences. In addition, tract delineation may be constrained by criteria such as minimum thickness or grade or maximum levels of deleterious materials or contaminants. At an assessment scale of 1:1,000,000, uncertainties in potash tract boundaries can be substantial because of a lack of detail in the source materials used to delineate the mineralized areas, and assessors should account for this in their estimates. An Albers or other equal-area projection of the tract boundaries should be used for accurate area and volume calculations.

In relatively well-explored areas, thickness values can be extracted from drill hole data and the information can be contoured. In underexplored areas, thickness data might be a mix of drill hole and other point data of thickness. For these cases, a single volume can be calculated using a continuous raster surface of the total potash thickness and the lateral tract boundaries. Most tracts have multiple sources for thickness estimates, including drill-hole and isopach data, and these data are commonly unevenly distributed. In these cases, thickness isopachs can be constructed for the entire tract using the available data and informed judgment. Volumes can then be calculated using the isopachs.

In some areas, thickness data are not available as either point data or isopachs to allow calculation of volume. In these cases, an approximate average thickness can be estimated and used. If possible, a maximum, minimum, and modal estimate of thickness should be made. These values allow construction of a triangular distribution (Kotz and van Dorp, 2004). Use of triangular distributions is not an optimal choice because the tails tend to be overestimated and the relation between the maximum and minimum values and the mode are assumed to be linear (fig. C2). However, the triangular distribution is widely used in risk assessment and other areas where the underlying distribution is not known, and this distribution is commonly available in statistical software packages (Kotz and van Dorp, 2004; Wynn and others, 2016). The advantage of this distribution is that most scientists understand what the input values mean and can estimate these values consistently when provided with a given level of geologic information. However, the use of the triangular distribution is not considered to be as statistically rigorous as other distributions by some statisticians. In the case of potash thickness, we do not know the underlying distribution (normal, lognormal, exponential, or other) and published studies for thickness distributions for other lithologies are not in agreement. Therefore, use of the triangular distribution is commonly the best available option.

In assessments of undiscovered potash resources, the exact method of calculating the volumes is not considered to be an important issue compared to other uncertainties, and the assessor should use the tools available. Testing of calculated differences in volumes—such as comparing the outcomes of kriging and nearest neighbor in this study—showed maximum differences of 3–11 percent where the data points were unevenly distributed and the density of the data points was low. In most cases, the potential error from incomplete, missing, and widely and unevenly spaced data is substantially larger than differences arising from the volume-calculation technique.

## Grade and Bulk Density

For most potash tracts, grade was modeled using available grade data for thickness intervals of 1 meter (m) or greater. Grades of rock-forming commodities such as potash are normally distributed (as opposed to the lognormal distribution of commodities such as copper, gold, and lead; see Harris, 1984). Grade models were constructed using published potash horizon thicknesses and grades (Yang and others, 2009, 2018; Yang and Love, 2015; Yang, 2016), as well as data extracted from well logs (Saskatchewan Ministry of Energy and Resources, 2009). Grades and thickness determined by the USGS from well logs met the following criteria.

1. Contiguous extent of potash-bearing salt had a minimum thickness of 1 m and no maximum thickness;
2. Average grade within selected intervals was equal to or greater than 4 percent $K_2O$ equivalent; and
3. Unmineralized halite divides individual potash horizons.

Note that unmineralized halite consists of (1) halite horizons that were not sampled and analyzed by the drillers because of assumed low grade, (2) 1 m or more of halite that would drop the potash grade below the minimum grade if included in the potash horizon, and (3) halite outside of geophysically determined potash horizons. Most of the grade models constructed for potash tracts are distributed normally if $n>30$, where $n$ is the number of data points. For small datasets, the mean of the documented data and other information was

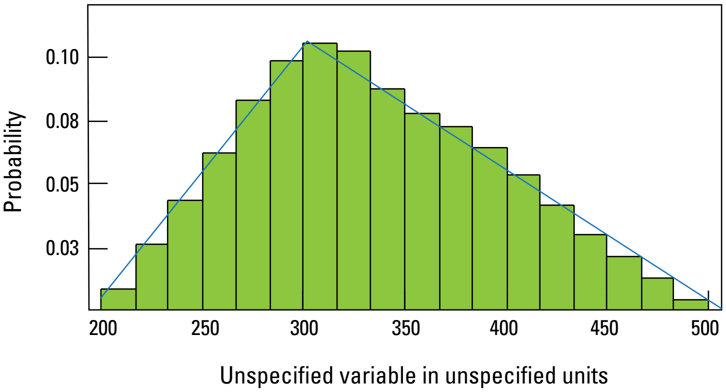

**Figure C2.** Plot of an example of a triangular distribution of an unspecified variable with a mode value of 300, a maximum of 500, and a minimum of 200.

used to create a normal distribution of $K_2O$ equivalent grade. For tracts with little data where correlation between potash horizons in different parts of the tract could not be determined and for tracts where reported data consisted of the aggregate thickness of all potash horizons and the average grade across all the horizons, potash resources were estimated as total potash without consideration of intervening halite.

To convert the estimated volume of potash-bearing salt to tonnage requires that a bulk density be known or estimated. In some areas, such as Saskatchewan, many companies use a standard average bulk density for conversion for sylvite ore based on knowledge or assumptions about the ore composition. For most of the potash tracts evaluated by the USGS, we estimate bulk density based on grade distributions constructed for each tract and modeled sylvinite or carnallitite grade and bulk density relations. Data released by Rauche and others (2013) allowed relations between carnallitite and sylvinite grades and measured bulk density to be modeled using linear regression (fig. C3). A Monte Carlo simulation was used to sample the grade distribution, and that grade was substituted in one of the following formulas based on regression of data from the Lower Congo and Danakil Basins (Rauche and van der Klauw, 2011a,b; Rauche and others, 2013) to determine the bulk density:

- Sylvinite: bulk density=2.177–0.003×grade; or
- Carnallitite: bulk density=2.044–0.027×grade.

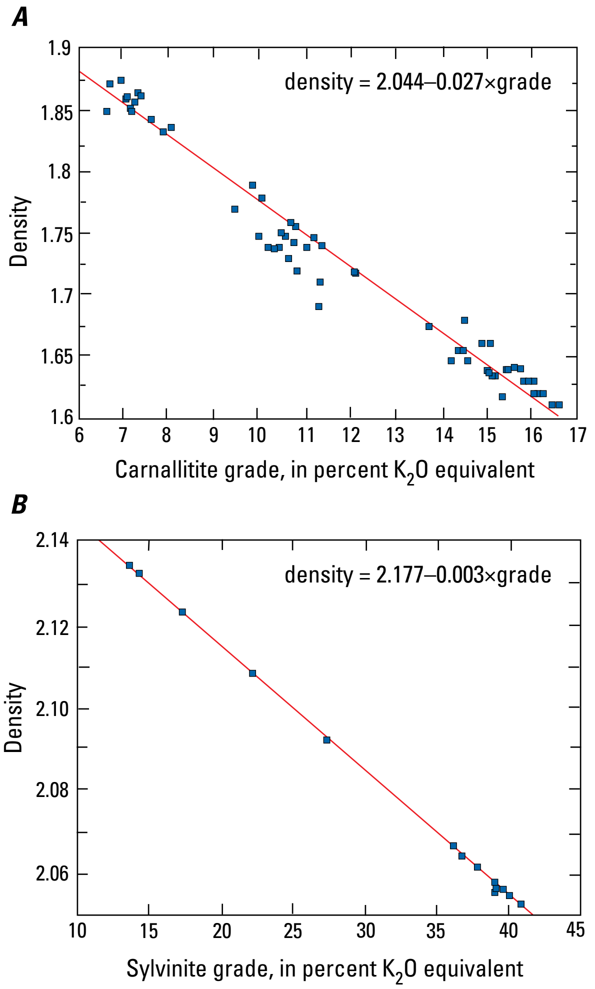

**Figure C3.** Plots of bulk density versus carnallitite (*A*) and sylvinite (*B*) grades in percent of potassium oxide ($K_2O$) equivalent content. The equation of the linear regression fit to the data is given.

These formulas are considered appropriate because the mean of the bulk density response for sylvinite in that regression is 2.08, a common average bulk density used for sylvinite ore tonnage calculations in Saskatchewan (Halabura and others, 2005; Myers and others, 207). Also, the carnallitite grade and bulk density relation provides bulk densities similar to a scattered handful of carnallitite grade and bulk density reports. Although region-specific relations would be preferred if the data were available, grade and measured bulk density are rarely reported together.

A major simplifying assumption is made in the absence of specific data on the type of potash. The resource is considered to be a mix of the potash mineral carnallite and halite (carnallitite) if the selected grade in an iteration is less than 16.9 percent $K_2O$ equivalent (the maximum $K_2O$ equivalent content of carnallite). For grades of 16.9 percent $K_2O$ equivalent or greater, the mineralized material is considered to be a mixture of sylvite and halite (sylvinite).

## Tonnage and Adjustments to Tonnage

After bulk density is determined, the in-place tonnage can be calculated by multiplying the volume of mineralized material by bulk density. Estimators need to ensure that the volume units and bulk density units are compatible.

There may be large non-mineralized areas within the tract boundaries. For potash, these areas may be because of non-deposition, dissolution, erosion, remineralization, or other factors that substantially decrease the size of the potential resource. Therefore, once a gross tonnage is determined for the potash mineralized area, the tonnage needs to be adjusted for what the potash assessment team has determined to be anomalies and embayments (for example, fig. C4), as well as for known reserves and resources.

Anomalies are defined as any barren areas inside the tract other than rocks that are too old to host potash-bearing salt and that would have been excluded from the tract during the initial delineation process. Anomalies include depletion, replacement, and halite zones; washout and leach or “salt horst” anomalies; or salt dissolution and collapse anomalies (Baar, 1973; Korenevskiy, 1989; Boys, 1990, Filippov, 1990; Kopnin, 1995; Abbott and Kuchling, 2009). Anomalies are interruptions in the normal continuity of potash-bearing beds and may range in size from less than a square meter to tens of square kilometers or more. The lack of potash-bearing salt may be because of dissolution, non-deposition, erosion, or another cause; halite is typically encountered in these areas rather than potash. Anomalies may constitute 5–25 percent or more of the mineralized area (Jones and Madsen, 1968;

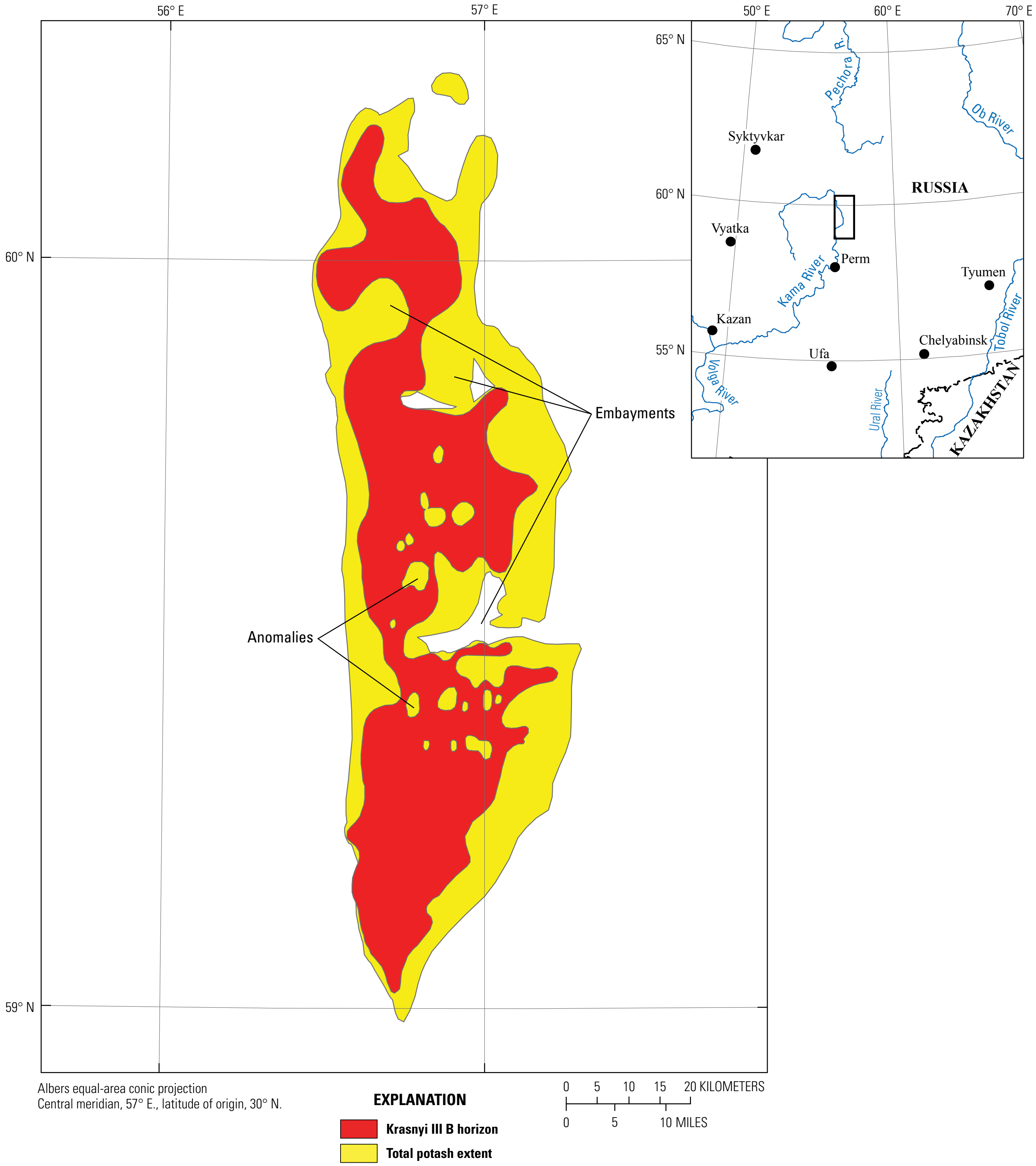

**Figure C4.** Map showing some of the anomalies and embayments of the Krasnyi III B horizon in the Solikamsk Basin, Russia (see fig. 2 of main text), relative to the maximum extent of potash as determined by all of the potash horizons.

Kopnin, 1995). Reported averages in the range of 20 to 25 percent include an adjustment to the anomalies that include buffer zones (Halabura and Hardy, 2007; Hardy and others, 2009). For most tracts, the effect of anomalies needs to be estimated, and there is commonly at least some information specific to each tract on which to base the estimate.

Embayments are a correction for actual edge irregularities in the potash-bearing salt that were not captured in the tract boundaries. These may form in part to dissolution but are largely because of non-deposition owing to topography, facies change, water or sediment incursion from the basin edges, or mechanical weathering. This correction is added because the effect of irregularities, dissolution, and non-deposition on volume and tonnage may be large; the effect is determined and estimated where appropriate on a tract-by-tract basis and considers how the tract boundary was delineated and the scale of the most detailed information. Potash-bearing tracts may show effects of just anomalies or just embayments, but, at common assessment scales such as 1:1,000,000, effects of both need to be considered. In places, the cumulative area of potash loss because of embayments and anomalies may be a large percentage of the overall potash mineralized area and may lead to a discontinuous pattern of potash distribution resembling Swiss cheese, such as found in the Krasnyi III B horizon of the Permian Solikamsk deposit, Russia (fig. C4; Zharkov, 1984).

The last adjustment to tonnage is to subtract known reserves and resources. For the potash assessment, this includes all proven, measured, recoverable, indicated, and inferred reserves and resources, as well as those classified as A, B, C1, and C2 under the Russian resource and reserve reporting system (Henley, 2004). All known reserve and resource figures are converted to in-place mineralized material and contained potash (as $K_2O$ equivalent content) before being subtracted from the estimate.

## Constructing a Distribution

The process outlined above is repeated for 5,000 iterations to create a probabilistic distribution of estimates of contained potash. This was done using the Monte Carlo simulation function of the SYSTAT ver. 12 software and tract-specific data. The SYSTAT software could not be used in the present assessment because it is incompatible with the Windows 10 operating system. Instead, the @RISK software package was used along with updated values for variables from the SYSTAT script.

## Summary

The adaptive geometric estimation (AGE) methodology produces a distribution of in-place mineralized material tonnage and contained potassium oxide ($K_2O$) equivalent tonnage for the assessed potash tracts and also provides an estimation of the uncertainty in the assessment. Input variables for the estimates that form distributions are sampled using successive Monte Carlo simulations; 5,000 iterations were performed for all tracts to produce stable distributions of estimated mineralized material and contained $K_2O$ equivalent tonnages. The most likely mineralized material tonnage and contained $K_2O$ equivalent estimates are centered near the mean of values; the values in the tails of these distributions are considered unlikely but help to quantify the uncertainty.

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# Appendix D. Generalized @RISK Script for Estimation of Undiscovered Contained $K_2O$ in Elk Point Basin Tracts

By Mark D. Cocker

This appendix contains a generalized @RISK script for the in-place mineralized material and potassium oxide ($K_2O$) equivalent estimates for stratabound tracts in the Elk Point Basin (table D1). This script is similar to the SYSTAT script used by Wynn and others (2016), but the variables are somewhat different because of the differences in available data from that study and the present assessment. The variables used in the script are discussed in the main text of this report and in the various tables therein. Because the SYSTAT software ver. 12 could not be successfully run on the current Windows 10 operating system, an alternative statistical software package was selected, which provided similar results obtained in a preliminary estimate run using the SYSTAT software (Michael Zientek, U.S. Geological Survey, oral commun., 2016). The @RISK software runs as an add-on to Microsoft's Office Excel application. Because the results were similar, it is believed that the estimates obtained in this study could be comparable to those obtained for the Central Asia Salt Basin by Wynn and others (2016).

The estimates were run in November 2018 and August 2019 using a defined relation between potash grade and bulk density. The revised simulations used data from the Congo Basin (Rauche and others, 2007, 2011a,b); these data allow a linear relation between potash grade and bulk density to be estimated using regression for both carnallitite and sylvinite (fig. C3 of appendix C).

**Table D1.** Script used in the 2019 simulation to estimate undiscovered potassium oxide ($K_2O$) using mean and standard error of the mean. Script was run using the @RISK software add-on in Microsoft Excel. Table is available as a downloadable Excel spreadsheet at https://doi.org/10.3133/sir20105090CC.

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# Appendix E. The Assessment Team

**Mark D. Cocker**, Ph.D., P.G., is a research geologist with the U.S. Geological Survey (USGS) in Tucson, Arizona. His background is in global potash assessment, lateritic deposits, supergene rare earth elements, precious and base metals in the western United States, industrial minerals in Georgia and Greater Antilles, pegmatite and magnesite deposits in Afghanistan, and hydrocarbon exploration in Alaska. His work has involved field mapping, drilling, geochemical sampling, petrography, geophysical surveys, and geographic information system (GIS) mapping and analysis. He has authored more than 170 papers, abstracts, maps, and digital publications. He has been a member of several mineral resource assessment teams.

**Greta J. Orris**, Ph.D., is a research geologist with the USGS in Tucson, Arizona. She specializes in industrial minerals and in tools and methodologies for quantitative assessment of these and other minerals, and conducts research in mineral economics. She has served as a leader of mineral resource assessment teams evaluating a wide range of commodities in North and South America, Europe, Asia, and Africa.

**Pamela Dunlap**, M.S., is a geologist with the USGS in Tucson, Arizona. She worked as an exploration geologist for several mining companies in Nevada, Montana, Idaho, and Washington and also as a research geologist for various State geological surveys (Idaho, Montana, and Washington) prior to joining the USGS. She has completed mineral resource assessment work in Idaho (phosphate) and Montana (oil shale) under contract to the USGS. She has prepared many geologic map and mineral resource assessment products in a GIS, including the GIS for this project, while with the USGS.

**Chao Yang**, Ph.D., is a senior oil and gas and evaporite geologist with Saskatchewan Energy and Resources, Regina, Saskatchewan, Canada. She has published reports and maps regarding potash and the stratigraphy of the Prairie Evaporite in Saskatchewan.

**James D. Bliss**, M.S., is an industrial mineral and spatial modeling specialist with the USGS in Tucson, Arizona. He has developed grade and tonnage models suitable for use in quantitative assessment for many industrial and metallic mineral-deposit types including diamonds, gold placers, graphite, low-sulfide gold quartz veins and pegmatites, among others. He has participated in numerous mineral resources assessment teams.

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