## SALT ANOMALIES IN POTASH BEDS OF THE ESTERHAZY MEMBER, DEVONIAN PRAIRIE EVAPORITE FORMATION, SASKATCHEWAN, CANADA

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SALT ANOMALIES IN POTASH BEDS OF THE ESTERHAZY MEMBER, DEVONIAN PRAIRIE EVAPORITE FORMATION, SASKATCHEWAN, CANADA

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Abstract

The Esterhazy Member of the western Canada Prairie Evaporite has been mined underground for sylvite (KCl) since the early 1960’s. Although the geology of the Esterhazy Member ore body is largely considered a regional flat lying continuous series of thin potash hosting beds, there are numerous occurrences where the ore has been either replaced or removed leaving behind uneconomical halite rich sections. An explanation of the underlying controls on the formation of these salt anomalies has been somewhat elusive although the overwhelming assumption remains that these features developed in lows on a salina. This paper proposes that salt anomalies formed because of two processes, early compaction of carbonate shoals of the Winnipegosis Formation and tectonics that resulted in multiple stages of block movement during the deposition of the upper Prairie Evaporite. Since these two processes can result in a significantly different size to a salt anomaly, encountering one or the other type can have a significant effect on the economics of the ore body. This paper looks at some of the geological methods that might provide geologists with means to predicting salt anomalies.

Key Words

Prairie Evaporite Formation, potash mining, salt anomalies, Winnipegosis Formation
Introduction

The Prairie Evaporite Formation of Saskatchewan, Canada is a Devonian evaporite deposit of Givetian age, and a world class source of sylvite (KCl). The formative Elk Point Basin which hosts the Prairie Evaporite was restricted to marine water to the northwest in northern Alberta. However, the basin was open to marine inflow which resulted in the deposition of predominantly halite and some anhydrite in the lower part of the Prairie Evaporite, and halite with potassium bitter salts in the upper part of the formation. The location of the Elk Point Basin and the potash evaporites in the Dominion of Canada is shown in Figure 1, and a compressed stratigraphic chart for the south eastern basin of the Province of Saskatchewan is shown in Figure 2. For a detailed description of the Saskatchewan potash deposits the reader is referred to Fuzesy (1982).

Potash bearing beds of the Prairie Evaporite have been mined in Saskatchewan since the early 1960’s, and although the Prairie Evaporite has proven to be an economical source of potassium chloride for over 50 years, challenges develop when potash salts of the ore zone have undergone replacement by halite. Typically, potash ore is extracted in the Esterhazy Member by rotary boring machines that take approximately 3 meter high cuts. Although the potash beds are structurally simple, they are not perfectly flat lying and rotary boring machines can be steered to efficiently follow the undulations of the ore zone.

More problematic are the accumulations of salt that reduce grade, affect the efficiency of the mechanized extraction, and reduce sylvite recovery from froth floatation. Typically, barren salt features have been probed with the boring machine for some distance at the Esterhazy mines.
The smaller salt features encountered in a drift tend to be less than 50 m long and do not impact mining or recovery operations to any significant extent. However, more expansive features have typically resulted in the abandonment of a room or rooms with a loss in production from that room and even large portions of a panel. Many occurrences of barren salt have occurred at most of the Saskatchewan operations, yet there have only been a handful of papers devoted to the subject of which the majority represent research more than 20 years old.

In many instances, the occurrence of anomalous salt replacing potash ore was thought to represent a high risk of water incursion into the mine with the potential for a calamitous outcome. Boys (1993) discussed the properties of collapse structures at the Potash Corporation Cory Mine. Macintosh and McVittie (1983) interpreted salt features to be genetically different in time and burial depth. They concluded that at least some salt diagenesis occurred very early from the playa surface after some degree of burial of the ore sediments. Baar (1974) suggested that salt replacement occurred near the playa surface in the Esterhazy Member of the Prairie Evaporite, and brine did not ascend from the underlying Winnipegosis. More recent work by Warren (2010) and Lowenstein et al. (2003, 2008) and Holt and Powers (2011) among others has increased the collective understanding of marine evaporites, important to unravelling the depositional history of the Devonian Prairie Evaporite Formation.

This paper focuses on research of the lowermost potash unit of the Prairie Evaporite, the Esterhazy Member, and the geology and genesis of the barren salt. Modern methods for evaporite exploration such as seismic reflection have proven frustrating for defining the ore
horizon in the Esterhazy Member and consequently the presence of barren salt. Resorting to new
ideas for evaporite formation and following some traditional methods of geological assessment,
there is new hope that models can be formulated to help define the occurrence of barren salt
features that might also apply to the Belle Plaine Member and the Patience Lake Member at the
other Saskatchewan potash mines.

Geology of the Esterhazy Member at the K1 and K2 Mosaic Mines

Although the stratigraphy of the Esterhazy ore zone has generally been considered simple and
predictable, there are unexplored geological features in the ore zone and associated underlying
carbonates that might provide insight into some of the depositional irregularities. Lithologically
the ore zone is not vertically homogenous with variation in bed thickness, insoluble mineral
content, colour, and grade especially where a salt anomaly is developed.

At the onset of mining at Esterhazy, Keys and Wright (1961) recognized the Esterhazy ore zone
stratigraphy to be of regional extent. The earliest mining rooms were 2.3m (7.5’) high and
extracted from a series of beds informally designated the 40, 45, and 50 beds descending through
the ore zone (Figure 3). Above the mining interval the beds with no economic value were named
35 and 30, and 29 to 1. Presumably the key economic unit at over 1.2m (4’) thickness was
designated the 40 Bed in recognition of the $^{40}$K isotope. Additionally, the visual differences in
the bedding made for easy marker recognition by mining machine operators. Visual recognition
has been the primary method for grade control at the mining face for mechanized mining at
Esterhazy in the absence of real time analyzers. The major differences of the four beds in the ore
zone are due to colour of the mineral assemblage, particularly dark red and orangey red for both sylvite and carnallite, and the olive-green colour of insoluble minerals. The higher content of insoluble minerals in the 45 bed made this unit the ideal marker for visual grade control at the mining machine. The overall reddish colour of the ore is noteworthy since this colour stems from either sylvite or carnallite, but the red minerals crystallized after the precipitation of colourless halite and sylvite.

The elevation of the ore zone can rapidly change over a few hundred feet of advancement by a mining machine which will severely affect grade. Over several thousand meters, elevation changes of 12 to 24 meters challenge the skills of the miner operator to cut on grade. Coupled with the elevation change is the potential for salt anomalies and enriched potash ore. An understanding of the controls on elevation and grade are key factors in dealing with ore variability.

Steep elevation changes in the Prairie Formation can be explained by only a few geological processes. Early on it was theorized that low spots on a dry salina were the likely sites for salt horses, a term that has since been replaced by salt anomaly or barren salt in the Canadian potash mining vernacular. In these depressions, rainwater accumulated and dissolved the potash leaving behind the low spots filled with salt. Duncan 1962 (internal company report) did not propose a model for the formation of these depressions, leaving the prediction for the location of salt anomalies for another day.

Both Boys (1993) and Barr (1974) provided detailed explanations for salt features in the Saskatchewan potash mines, concentrating on the general appearance of salt anomalies and
attempting to address the risk potential for water inflows. Their central theme was that salt
anomalies developed central to a playa low with inflow water resulting in linear washout
anomalies directed to the low and leach anomalies in the central part of the low.

Based on years of experience of potash mining over Winnipegosis mounds, and from 3D seismic
surveys, the ore zone over Winnipegosis mounds is usually structurally lower compared to the
off-mound position. Gendzwill (1978) proposed that porous Winnipegosis mounds resulted in
the dissolution of the overlying Prairie salt and subsidence at the ore zone. Later Gendzwill and
Wilson (1987) concluded that salt removal was subordinate to compaction within the
Winnipegosis mounds.

Some geologists in the potash industry believe that a gypsum to anhydrite conversion in the Shell
Lake Member provides a mechanism to explain the subsidence or anomalies at the ore zone
through the release of crystal water. However, this conclusion requires some scrutiny since less
than 5 meters of anhydrite has been found capping a large mound in the Esterhazy area and the
amount of water that could be generated from this amount of gypsum would only remove a
minute amount of salt. As Gendzwill and Wilson indicated, the amount of subsidence over
Winnipegosis mounds is as much as 30m and this is marginally more than the upper end of the
experience at Esterhazy. The gypsum to anhydrite conversion mechanism cannot be a credible
process to account for this degree of subsidence when the change in volume only accounts for
one meter of subsidence at best.

Salt Anomalies of the Esterhazy Member
The general practice at the Esterhazy mines has been to define salt anomalies by their length without any indication as to their genesis. Based on a simple set of observations of the anomaly, at least some degree of predictability was forthcoming to aid the production groups in making mining decisions. A good approximation for the length of short features was 30m or less, and long features generally exceeded 150m. Without a geological model for a salt anomaly, the longer features were generally explored for less than 150m and subsequently the room would be abandoned. Distance itself for these longer features provided little understanding to the origin of the salt anomaly.

However, since 2010, salt anomalies at the Mosaic operations have been scrutinized to a greater extent as it appeared that there were several morphological features to the Esterhazy Member salt bodies that would help to define different types of anomalies and the controls on their formation. Currently two major salt anomaly types have been defined with a probable subtype as described below.

**Halite Anomaly Type I**

A Halite Anomaly Type I is shown in Figure 4. Features of this salt anomaly include, 1) a gentle v or u-shaped zone replacing the normal bedded ore zone, 2) a basal accumulation of dark brown insoluble minerals often concentrated at the lower contact with unaffected evaporites, 3) very coarse crystalline salt and sylvite, and 4) the absence of primary bedding.
Two thirds of a circular shaped anomaly (Figure 4) was exposed on the roof of the excavation. The diameter of the anomaly was approximately 20m. These circular anomalies are generally the smallest salt features found at Esterhazy. The size of this anomaly produces only a minor disruption to mining. In many cases these small anomalies go unreported during excavation but at the same time provide significant geological information. The accumulation of dark brown insol at the lower contact requires a significant quantity of ore to be dissolved or a large amount of insol rich bedding to be dissolved such as the 45 bed. Boys (1993) identified the washout anomaly to be rich in insol, but at Esterhazy the Type I anomaly has limited extent and is more likely comparable to a “leach anomaly”.

Some Type I anomalies exhibit additional characteristics which may be sufficient to further classify the anomaly as a subtype of a Type I. Most notable of these features is the elongate shape of the anomaly which can be mapped extending to adjoining rooms, commonly normal to the strike of the basin. Other features of this subtype include:

- The base of the anomaly may extend below the room floor,
- dark brown insoluble mineral is dispersed throughout the anomaly and may include short horizontal stringers of insoluble minerals,
- generally devoid of sylvite, and
- halite crystallinity is similar to normal ore crystal size, but original bedding features are not preserved.

**Halite Anomaly Type II**
A Halite Anomaly Type II anomaly is shown in Figure 5 that was found in the upper part of the ore zone. The geological characteristics of this salt type include:

- Larger salt features than a Type I anomaly commonly with lengths of 60m to 600m, but retaining a round to elliptical shape,
- a halo of sylvite enrichment devoid of carnallite surrounds the anomaly,
- the salt front gradually descends through the ore zone, first appearing at the back of the excavation at the rim of the feature,
- as the anomaly thickens, sylvite may be progressively removed from the entire ore zone including the insoluble rich 45 Bed,
- remnant ore zone stratigraphy and sedimentary structures such as pressure ridges (Figure 6) are preserved. Remnant beds might be thinner than in unaltered ore (i.e. 45 Bed),
- insoluble mineral content is usually dark brown (i.e. 45 Bed and pressure ridges), including brown specks in the 40 Bed that has significantly less insol, and
- halite crystallinity is coarse but similar to the original ore zone.

The larger the salt feature is areally, the greater the ore zone is vertically altered and visa versa. Occasionally near the centre of the anomaly a zone of coarse crystalline halite might occur resembling a Type I anomaly, but it will be devoid of any sylvite which differs from the Type I anomaly.

Laterally Extensive Salt Anomalies
During recent mine development, a salt anomaly was encountered that exceeded 1500m in length. The length of this anomaly is inconsistent with the size of either a Type I or II anomaly. However, the diagenesis is consistent with a Type II anomaly but the gradual loss of sylvite to halite can extend for several 100 meters before the entire ore zone has been reduced to salt. It has been noted that the salt line will follow the top of the insol rich 45 bed for a considerable distance before it transgresses through the 45 bed. Currently 70% to 80% of the anomaly overlies a Winnipegosis shoal and the remainder extends beyond the edge of the shoal. There was no elevation change along the edge of the underlying shoal as mining advanced through the remnant ore zone. As the seismically defined edge of the shoal was encroached, the ore zone did not ramp up as would normally occur if compaction of the underlying Winnipegosis was at play as described in the next section. Another mechanism is required to account for potential subsidence at the salina surface.

Well logs and well site reports provided the data for a series of stratigraphic picks used to generate the isopach map in Figure 7. The isopach map is for the section from the top of the Devonian Bakken Formation to the top of the ore zone representing a period of approximately 26 Ma. The map shows a thick over the anomalous area, representing a significant period of sediment compensation in the area. Although not shown in this paper, a north to south thick was detected in the area for the upper potash section which includes the Esterhazy Member. At this point, mining had not progressed to the extent where the size of the anomaly could be evaluated against the depositional thick, but the feature has the potential to be extremely large.
Salt Anomaly Association to the Winnipegosis Formation

The association between Winnipegosis shoals and salt anomalies has long been recognized by potash miners and became important insight to mining of the Esterhazy Member. Isolated shoals were occasionally the site of small salt anomalies, but mining machine operators not recognizing the impending elevation change in the ore horizon were unable to guide their machines through these changes. In some cases, the off-grade results were interpreted as a salt anomaly and the mining room was abandoned. In reality though, not all shoals end up with an overlying salt anomaly and only about 30% of the shoals at Esterhazy are associated with an overlying salt anomaly. However, shoals remain a significant precursor for the occurrence of salt anomalies, and their location is a valuable predictor of large elevation changes of the ore zone.

From the Esterhazy study area, there is a limited amount of geological data on the Winnipegosis Formation except for some drill cuttings, and a 10 meter long core that was cut from the upper part of a Winnipegosis bank. On the other hand, seismic data has been a mainstay for several decades. As a result, there is a high reliance on drill hole data from SE Saskatchewan from petroleum exploration, and studies from south central Saskatchewan and western Manitoba to provide an understanding of the structure of the Winnipegosis carbonate features.

Located two hundred and sixty kilometers northeast of Esterhazy are several Winnipegosis mounds which have been extensively studied. The primary site is a Winnipegosis mound situated at the former Bluff fish station on the western shore of Lake Winnipegosis, in western Manitoba. Kent et al (1992) reported the results of 9 bore holes drilled into the Bluff mound
along with observations from outcrop. The significant features of the Bluff mound are its areal
dimensions that are similar to isolated shoals in the Esterhazy area, and the mound outcrops
along its margin with multiple cores have been taken across the mound.

There is only very limited core information from a Winnipegosis shoal in the Esterhazy area.
Therefore, a fundamental understanding of the potential lithologies that might be expected in the
Esterhazy area can only be provided from investigations elsewhere (McCabe 1987, Martindale et

Structure on a marine floor has long been considered key in promoting the colonization by reef
forming organisms. Core holes in the Bluff reef returned a thickened section (2 meters) of the
lower Winnipegosis (Kent et al, 1992) at the center of the reef thought to be sufficient to support
the initial colonization phase of the reef. The Bluff is also thought to be aligned with deeper
seated Precambrian structure of the Birdtail-Waskada Axis and the Nelson River gravity
anomaly.

The lower part of the Bluff and Tableland reefs (Martindale et al 1991) contain an assortment of
biota that are best classified as baffling organisms rather than reef builders. Although there are
differences in the biota diversity, both locations were well represented with peloids to indicate
that burrowing organisms were common to both regions, potentially foraging on the rich supply
of organic material in the baffled mud.
The biota described for the upper portions of both the Bluff and Tableland reefs are more typical of ecological or framework reefs that include branching coral and massive corals, hemispherical and bulbous stromatoporoids, and calcareous algae. In both regions, early marine carbonate cement was found in the interparticle porosity.

The final capping stage for the Tableland reef was interpreted to be a calcrete horizon, represented by a laminated dolostone with pisolites. In the Saskatoon area (Fu et al. 2004) there were 3 stages of pedogenic calcrete developed on the reefs. Although these calcrete zones might represent significant degrading neomorphism of the original sediments, the authors point out that there was a conspicuous absence of framework organisms emphasizing the point that these were mud mounds.

Within the Esterhazy area a complex mosaic of Winnipegosis shoal trends has been interpreted from 2D and 3D seismic surveys. Most of the shoals in the Esterhazy area which underlie the upper Prairie Evaporite (Figure 8) fall into three general geometries, namely, 1) isolated shoals that are approximately circular and 0.5 to 1.0 km in diameter, 2) long almost linear tracts that can extend for distances of several kilometers, and, 3) large banks that extend areally for several kilometers.

The linear shoaling tracts shown in Figure 8 may be peculiar to the Esterhazy area as they have not been recognized to this degree in the southeast or central Saskatchewan, nor in western Manitoba. Can these linear tracts be explained by structure on the Winnipegosis platform since structure albeit small has proven elsewhere to be critical to reef development? Further south in
the USA portion of the Williston Basin, work originally contracted by the U.S. Geological
Survey (Brown and Brown, 1987) proposed that wrench-style deformation produced
paleostructure which influenced sedimentation patterns. The study identified shear zones by
analyzing sedimentary patterns in the Mississippian Madison Formation to define a series of NW
to SE and NE to SW lineaments in the USA portion of the Williston Basin. In the case of the
Esterhazy area the shoal lineaments are well defined from the seismic data and trend NW to SE
and NE to SW but at a frequency far exceeding, by 10 to 20 times that determined in the
Madison Formation study (Brown and Brown, 1987). Outside the Esterhazy area, in southeastern
Saskatchewan and to the northeast in Manitoba, the genesis of the mounds appears to be similar.
However, the shoals at Esterhazy commonly have pronounced elongate ridges developed on their
tops that are a few to several meters high.

Considering the potential mud lithology of a Winnipegosis shoal, there is potential for the
overlying Prairie Evaporite sediments to undergo differential subsidence from compaction in the
Winnipegosis mounds prior to the deposition of the potash units. Logs from two wells that were
drilled 2.2km apart are shown in Figure 9. Well 13-11 was spotted at the edge of a carbonate
mound while 16-09 was spotted in an off-mound position. Several anhydrite beds that were
deposited in the upper salt prior to the deposition of the potash beds were correlated laterally in
the on and off-mound location. Halite interbeds that occur between anhydrite markers exhibit
thickening in all interbeds below the ore zone, and this theme extends above the ore zone to the
White Bear as well. These interbeds are 0.1m to 5m thicker in well 13-11 (Figure 9).
Modelling of Salt Anomalies

Operations at Esterhazy have long recognized the potential importance of the underlying Winnipegosis Formation on the undulations in the elevation of the ore zone. A rapid drop in elevation in the ore zone is usually related to an underlying isolated carbonate mound. In several cases this elevation change is supplemented by a halo of sylvite enrichment that may extend for several hundred meters around a salt anomaly. Figure 10 is a cross-section from a 3D survey with the interpretation of the structure over one of these mounds. Noteworthy is the expression of a positive element on the underlying mound referred to as a Shell Lake high which produces the “W” shaped profile. The use of the term Shell Lake high to explain the presence of the positive elevation change in the ore zone in the middle of the depression implies that the feature rightly or wrongly is structurally a result of Shell Lake deposition. However, considering that compaction is the primary mechanism (Gendzwill and Wilson, 1987) at play in some of these mounds, it seems more likely that an incompressible diagenetic or facies change in the mound could generate the structure referred to as a Shell Lake high.

When considering that most geologists working in the Prairie Evaporite have concluded that salt features required a depression on the salina to pond rainwater, the resounding question is what caused these depressions, and can their location be predicted? Mapping the first residual of the mine roof elevation provides some insight to this question.

Residual Mapping
Residual mapping of subsurface features was used by Evenick et al (2008) to explain some very complex geology of the Alberta Leduc reef trends. Flattening against an overlying or underlying stratigraphic unit is common practice in geology whether data is derived from well logs or seismic surveys. Theoretically, the Esterhazy Member represents the best example of a flat surface of regional extent, a product of salina deposition which makes virtually any stratigraphic unit within the Member a reliable geological flat surface. In the case of the Esterhazy mines, the elevation of the roof of the excavation provided the stratigraphic horizon for an assumed flat salina, although the cutting may not always be true.

Shown in Figure 11A is an area where a salt anomaly was encountered in non-carnallitic ore. Initially it appeared that the lateral expression of the salt anomaly tended to parallel elevation contours. Reprocessing the elevation data to remove the regional dip resulted in the residual shown in Figure 11B and illustrated the connection of salt anomalies to mappable depressions on the Esterhazy salina. However, the salt anomalies cover a rather small portion of the low that extends across the two panels. This might imply that an initial low that hosted the anomalies was more restricted coinciding with the salina that became the ore zone. Subsidence introduced later, even after the deposition of the Prairie Evaporite would account for the extension of the low beyond the salt anomalies.

Mapping of the room elevations utilizing the commercial software SURFER®, resulted in the first residual map that is shown in Figure 12. It compares the residual detail with the known geology. The second piece of data that is plotted in Figure 12 is the 1% carnallite concentration
in the ore zone, chosen as a clearer transition between sylvinitic and carnallitic containing beds than a zero contour. Trends that were observed from this data included, 1) larger salt anomalies are located above the edges of Winnipegosis shoals and banks, and 2) the area immediately surrounding salt anomalies is sylvinitic with no carnallite.

Both the first residual highs shown in the cooler blues and greens and first residual lows plotted in orange are central to carnallitic containing ore. The intermediate areas are sylvinitic and the sites of salt anomalies.

**Carnallite Anomalies**

Throughout the study area, carnallite occurs as dark red or orange intercrystalline cement between colourless halite and sylvite crystals, unless as pointed out earlier the carnallite was absent or replaced by sylvite with similar reddish or orangey hues. This replacement diagenesis results in red rims of sylvite around colourless sylvite. Red and orange coloured carnallite also occupies sites where halite and sylvite were locally dissolved as shown in Figure 13.

Carnallite also appears in large pods usually as white crystals as shown in Figure 14, although other colours of this mineral are in minority in these masses. However, there is no discernible insoluble content associated with these pods. Occasionally the pods host clear to slightly cloudy halite crystals 5cm or more in size. Some of the halite crystals may take on a light bluish hue when exposed to light as noted by Baar (1974) and even more rarely the halite may host dark
blue coloured patches. The pod may also be surrounded by a halo of red and orange carnallite as found in ore.

Pods can vary from a few meters to more than 10m in size and most carnallite pods extend upward from the 40 Bed. A mining room generally doesn’t intersect the top of the larger pods but when rehab is conducted to provide for roof stability, the top of the pod has been found to extend from 1.2m to more than 3m above the top of the ore zone as shown in Figure 14A. Little else is known about the genesis of the carnallite pods except that they are only located where the host ore zone is also carnallitic.

Observations underground suggest that there might be a genetic link between carnallite pods and Type I salt anomalies. Not all salt anomalies especially if they are small are recognized and reported during the mining of a room. And in some cases, the anomaly may be completely cut out without technical personnel being aware of an occurrence. However, there is a consistent theme to the location of Type I salt anomalies. They are in areas of sylvinitic ore with no carnallite and especially no indication of carnallite pods.

Stacking of Salt Anomalies

Within the Esterhazy Member several distinct informal stratigraphic or lithological units have been correlated for the upper Prairie Evaporite. In ascending order these units above the
Esterhazy Member are the 1st Clay, Whitebear, 2nd Clay, 3rd Clay, 4th Clay, and the Belle Plaine Member. The Whitebear Member is a thin (~1m) sylvinitic unit in the Esterhazy area. The Belle Plaine Member is a series of sylvinitic beds which vary in thickness and may be absent in the region due to non-deposition. Well 4-1 in Figure 15 shows a positive gamma response for the 3 key KCl bearing intervals, namely the Esterhazy, Whitebear and the Belle Plaine Members. There is no indication that sylvite was removed or replaced in the ore zone for wells 16-4 and 9-35. However, in the latter case the Belle Plaine Member may not have been deposited. In the log profiles of 5-21 and 1-23, sylvite is absent in some intervals. In well 1-23 the upper portion of the Esterhazy Member has a weaker gamma response than normal while the ore zone has a strong gamma response. Note that for both the Whitebear and Belle Plaine intervals for well 1-23, KCl has been removed but the remnant clastic sediments which appear as mine wide markers have a gamma response, albeit very small.

Discussion

Salt features at Esterhazy must have developed in depressions formed on the surface of the Prairie Formation salina due to subsidence derived from compaction in Winnipegosis mounds. The degree of lithostatic loading required to produce subsidence in carbonates is not substantial. Choquette and James (1987) point out that carbonate mud reacts to loading more quickly than grain supported carbonates with rates of compaction greatest at shallow depths and decreasing exponentially with depth. Anderson and Franseen (1990) identified differential compaction effects in Winnipegosis mounds in Saskatchewan from seismic data. The challenge will be to recognize the factors that single-handedly control the critical timing of subsidence, and not just...
the gross compaction. If different lithologies are a major factor, it is not simply the rim sediments versus the interior reef structure that contributes to subsidence at the mining level. For smaller mounds with a circular geometry, a minority of these mounds appear to produce salt anomalies at the ore zone. Timing appears to be critical as to when the depression was exposed to fresh rainwater which may also imply that the potash depositional cycles were of extremely short duration possibly as little as a few thousand years.

The compaction of Winnipegosis shoals is thought to be the primary mechanism for the formation of Halite Anomaly Type II salt features in the Esterhazy Member. Fresh water probably pooled in some of these depressions and resulted in leaching and removal of the potassic salts. Although shoals had undergone compaction, only a portion of the frontal areas of these shoals had undergone compaction during the deposition of the Esterhazy Member. Differential compaction would imply that the mounds were not lithologically uniform. Future studies may offer clues to the relative lithological homogeneity of mound structures and could provide further clues to salt anomaly genesis.

Non-uniform subsidence might also give the appearance of differential compaction. In this process compensation is delayed producing variations in the thickness of overlying beds. Ultimately this process could significantly limit the extent of anomaly development at the ore zone. As reported in this paper this process was detectable using well log data.
Halite Anomaly Type I features are the smallest salt anomalies found at the Esterhazy mines and they are only found in sylvinitic areas. Furthermore, carnallitic pods only exist in areas that have not been diagenetically altered to sylvite. It would seem that these two features are genetically linked in location but not in time. As others have suggested, a salt karst (Macintosh and McVittie, 1983) would help explain both the origin of carnallite pods which are sometimes observed in clusters, and the presence of the Type I anomalies. However, there are no other published reports that recognize salt karsts. Certain discrepancies can be explained within the existing model presented in this paper. Carnallite pods as shown in Figure 14 are free of insoluble minerals while Type I anomalies are not, and carnallite pods are significantly smaller than Type I anomalies. It follows that later stage differential subsidence could host the ponded water and provide the timing for the dissolution of carnallite and replacement with halite, including insoluble minerals as the area around the original karst is dissolved and insoluble material is concentrated at the base of the feature or within crude bedding. No blocks of overlying lithology have been detected in Type I features as might be expected if the anomalies were formed below the salina versus near the surface of the salina. As well, the sedimentary structures of a Type I anomaly have provided no evidence that moving water was part of the evolution.

For large anomalies such as those exceeding 1500 meters that don’t fit a Winnipegosis shoal compaction model, structural anomalies offer a possible explanation even for a stable intracratonic basin like the Elk Point. Thickened sections of sediments spanning a depositional period of some 120 million years suggests that differential subsidence was active for an extended period in specific areas which may have laid host to a large and early formed anomaly.
Differential compaction on the scale of a few hundred meters does not offer a suitable explanation for the formation of larger features which is better explained by subsidence induced from tectonic movement. Recall the section on the “stacking of salt lithologies” from exploration holes. Geophysical well logs exhibit similar stacked lithologies in the Esterhazy study area. However, salt has replaced potassium salts at different levels and in well 1-23 all three potash bearing units have undergone leaching with sylvite only present at the ore zone. The sequential deposition of the same stratigraphic units and markers, and the removal of sylvite and replacement with halite is consistent with a series of subsidence events affected by water ponded on the Prairie Evaporite salina. The location of well 5-21 is central to the thickened section and the entire thickness of the Esterhazy Member is replaced by halite.

Subsidence played a major role in establishing areas on the Prairie Evaporite salina where water could pool and subsequently replace potash salts with halite. The subsidence was generated from compaction in Winnipegosis mounds and for very large anomalies, subsidence probably originated from deeper seated tectonics. Ultimately, the depositional controls can be inferred from the relative dimensions of the anomaly, from mapping the position of Winnipegosis shoals, and the thickness variations in stratigraphic sequences above the Prairie Formation.

**Acknowledgments**

I wish to thank the management of Mosaic Potash for the opportunity to publish this paper, and to members of the Mine Engineering Department for their work in providing the many illustrations which were so important to the outcome of this paper.
REFERENCES


Figure 1: The location of this study is near Esterhazy, in southeastern Saskatchewan. Potash bearing beds in Saskatchewan and the adjacent US states of North Dakota and Montana are shown in red. (reproduced with permission from Holter 1969, and Cocker et al 2010)

Figure 2: Stratigraphic section for the Devonian of southeastern Saskatchewan (Modified from Saskatchewan Ministry of Economy, revised 2014).

Figure 3: The informal Esterhazy system that defines the bedding from bed 50 up to bed 30 in the ore zone is pictured in “A”. This bedding pattern is recognized mine wide (30 km by 18 km). Bed 40 is the highest grade and is generally 1.2m thick. In the photo the vertical section was swept of fine dust to expose the darker 45 bed with its greater insol and darker red sylvite, and the darker 40 bed which occurs from the oil like luster of the sylvite.

A partial Halite Anomaly Type II salt anomaly is pictured in “B” in the upper portion of the ore zone where the KCl has been replaced with NaCl. Note the change from the anomalous NaCl (white on top) to the pinkish potash ore of bed 40. The 285 is a distance reference.

Photos were modified in Microsoft Publisher; brightness and contrast increased by 10% and 20% respectfully.

Figure 4: Back to floor section from a production room cut through a Type I Halite anomaly shown with the insert enlarged. The anomaly includes recrystallized halite and sylvite, the dissolution of chlorides and the accumulation of insoluble minerals (dark brown). In the anomalous zone (to the right and above the dark insoluble patches) primary bedding is not recognized. The concentration of KCl in patches is common in this type of anomaly (oval) as opposed to normal disseminated crystals of sylvite and halite. Primary bedding is observed in the unaltered zone (bounded by two horizontal parallel lines) on the left side below the band of insoluble residue. The insoluble minerals are thought to have concentrated along a solution front. Scale: Hammer 14”.

Figure 5: Salt anomaly extends down approximately 1.4m (50%) from the back of a production room showing the subtype of a Halite Anomaly Type II salt anomaly. Insoluble minerals which appear black in the photo occur as dark brown patches, small dispersed blobs, and horizontal stringers with no indication of primary bedding. Sylvite is absent above the lower insol contact. Patches of large halite crystals occur in the white areas in the middle of the photo. The insoluble minerals were concentrated as the sylvite and halite were dissolved and removed from the ore zone. Insoluble minerals are dark brown associated with salt anomalies as pictured here but green in unaltered ore.

Figure 6: Primary sedimentary structures of hexagonal pressure ridges in the Esterhazy Member (photo A) which formed subaerially are found throughout the Esterhazy mines. However, they are not observed where thin (~2.5cm) rhythmic beds of NaCl and KCl occur. Pressure ridges are typically one meter across and extend vertically over several meters crossing several of the numbered beds. The pressure ridges are defined by insoluble carbonate and sulfate minerals, NaCl and carnallite. Photo A is of the back with a rotor cut ridge on the left side of the red paint mark. Photo was modified in Microsoft Publisher; brightness and contrast increased by 10% and 5% respectfully.
Photo B is a series of pressure ridges formed on a surface storage pond at Esterhazy. The polygon in the center of the photo is 2m in diameter. The black area above and to the left of the salt polygon is ponded brine.

Figure 7: This isopach map shows the interval from the top of the Bakken Formation to the middle of the Esterhazy Member in the study area. The depositional period spans approximately 26 Ma. A large area of thickening is prominently displayed near the south edge of the map. A north/south thick was also found in the interval from the top of the Prairie Formation (not shown) to the ore zone section. Specific well locations shown at the bottom are referenced in Figure 15. Map generated by SURFER® V10.

Figure 8: Complex geometries of the carbonate shoals (hatched) of the Winnipegosis Formation defined from Mosaic’s multi-year 3D and 2D seismic programs. Off-shoots are commonly developed at 90 degrees to the major elongate shoals. Ridges detected on the carbonate shoals from the seismic surveys are shown in red. The ridges generally run central to and along the long axis of the Winnipegosis shoals. Esterhazy is located approximately 16km west of the K2 mine.

Figure 9: Gamma ray and porosity logs from two wells located 2.2km apart. Well 13-11 was drilled at the edge of a Winnipegosis mound and well 16-9 was drilled in an off-mound location. A series of anhydrite beds below the Esterhazy ore zone from 1083m to 1098m in 13-11 are interpreted to be laterally continuous. The halite interbeds are consistently thicker in 13-11 suggesting that compaction in the underlying Winnipegosis mound was already in progress prior to deposition of the overlying potassium rich beds.

Figure 10: A production room was cut over this Winnipegosis shoal after a 3D seismic survey was shot. The room is approximately 20ms above the shoal top. Elevation changes in the room mimic the “W” shape of the Shell Lake Member (blue line) over the shoal, characteristic of the subsidence found over isolated shoals in the area. The profile was hung from the underlying Ashern Formation. TWTT = two way travel time.

Figure 11: Legacy mine elevation contour data is shown in Imperial units (ft) in “A” for the top of the ore zone. The survey data is taken from the roof of the mined room at approximately 200 ft intervals. Anomalous salt is shown in lime green. For map B the contours represent the survey data used to generate “A” minus the change in elevation from the regional dip which developed from subsidence essentially after the Esterhazy ore zone was deposited. The two salt features on the west side of map B correlate with the structural low of the residual paleo surface in “B”. Note that the contours at the Esterhazy mines adopted the arbitrary value of 10,000 ft for the elevation of sea level. Thus the 8600’ contour equals 1400’ subsea.

Figure 12: Legacy first residual plot of the ore zone elevation is shown in Imperial units (ft). Residual highs are predominantly blue and residual lows orange. Superimposed is the 1% carnallite contour (dark blue) which tends to be centralized on both the residual highs and lows. Note that the salt anomalies (cross hatched) outlined in orange are commonly developed between the residual highs and lows. The boundaries (shown with the symbols ???) of two salt features have not been determined as of the writing of this paper. Map width is approximately 25,000’.

Figure 13: Red carnallite was the last mineral to crystallize in this sample. Note the enhanced porosity that formed from the corrosion of both halite and sylvite crystals was followed by the
precipitation of red carnallite. In other areas of this specimen, carnallite appears to have cemented halite and sylvite primary intercrystalline porosity.

Figure 14: In photo “A” massive white carnallite stretches approximately 4 meters wide on the back of the excavation. The pod is rimmed with yellow carnallite and dark red carnallite (upper to mid left in photo). Carnallite pods are generally free of insoluble minerals but may include large (>5cm) halite crystals that change from a cloudy white colour to bluish on exposure to light. The pod in photo “B” is 0.6m thick and tabular in shape and was found in the ore zone. Carnallite pods tend to crumble and when exposed in the roof may require some type of ground support to maintain back stability.

Figure 15: Gamma ray well logs hung from the top of the Prairie Evaporite Formation. The well locations are shown in Figure 7. A series of clastic markers and the potash bearing White Bear and Belle Plaine members are found above the Esterhazy Member. Only the Esterhazy Member is mined locally. Sylvite may be associated with some clastic markers but where leaching of the marker has occurred, the gamma response is weak. Gamma ray wraps at 150 API units for each log.
Figure 1
Figure 2
Figure 3
Figure 6

Figure 7

https://mc06.manuscriptcentral.com/cjes-pubs
Figure 8
Figure 9

Prairie Evaporite

Winnipegosis Shoal

Ashern Formation

Figure 10
Figure 12
Figure 14
Figure 15