GEO
ST. JOHN'S
2019
UNDER LAND & SEA

The impact of a salt deposit's origin on its exploitation: three case-studies from underground mining operations

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ABSTRACT

Halite, commonly referred to as Rock Salt, presents remarkable and often unique mechanical behavior. Rock salt exhibits pronounced time dependent deformation under deviatoric stresses, denoted as creep. Rock salt also requires unconventional blasting methods due to its low blast wave impedance and very weak tensile strength. The mechanical behavior of salt deposits is largely influenced by the geological and geotechnical characteristics, and amount of impurities, which are all mainly governed by the origin of the deposit. This article presents a comparative summary of the main features of three salt deposits of very different origins, which are being mined for rock salt. The three deposits presented are: (i) the complex, fault-bounded Pugwash diapir located in the Carboniferous Maritimes Basin in Nova Scotia, (ii) the Ojibway tabular deposit located in the transition of the Silurian Michigan and Appalachian Basin in Ontario, and (iii) the Weeks Island salt dome located in the Jurassic Gulf Coast Basin in Southern Louisiana.

RÉSUMÉ

Le minéral halite, qui forme la roche appelée sel gemme, présente un comportement geomécanique unique. Le sel gemme, de par sa configuration crystalline, présente une tendance à déformer dans le temps sous une contrainte différentielle constante, communément appeler fluage. Le sel présent aussi des tendances bien particulières concernant le sautage avec explosifs. Le sel, étant charactérisé par une faible résistance en tension et compression, et une faible impédance face au ondes de vibrations, les designs de forage sautage dans le sel se doive d'être adapté en conséquence. Le comportement du sel gemme est grandement affect par les origines et la composition minéralogique du gisement. Le présent article porte sur une étude de cas comparative de trois différents sites miniers exploitant le sel gemme. Les gisements considérés sont (i) le diapir de Pugwash situés près du basin de carbonifèeres des maritimes en Nouvelle-Écosse, (ii) le dépôt tabulaire de Ojibway situés au dessous du lac Érié entre les basis des apallaches de l'Ontario silurien du Michigan, et (iii) le dome de sel de Weeks Island situé dans le bassin jurassique prèes du golfe du Mexique en Louisianne (É. – U.).

1 INTRODUCTION

The mineral halite, composed of sodium chloride (NaCl), naturally agglomerates to form rock salt deposits commonly mined for a wide variety of applications. Rock salt has been exploited for thousands of years as it evolved from a food conservation agent, to a multi-purpose chemical used in the agricultural, pharmaceutical, food and road de-icing industries. Rock salt, found in abundance around the globe, is extracted primarily through conventional mining and solution mining operations, and surface evaporation ponds.

Rock salt exhibits fascinating mechanical and chemical behavior which has led to extensive research and studies over the years. Halite draws its fundamental uniqueness from its mineral composition, which allows recrystallization at various temperatures that effectively tends to heal microfractures. As a result, rock salt traditionally exhibits low porosity (typically < 1 %), moderate elastic stiffness (modulus around 30 GPa), and characteristically low compressive (15 – 30 MPa) and tensile strength (< 1 MPa). Its low yield strength and recovery capacity also leads to time- and strain-dependent behavior, commonly observed through creep associated with continuous deformation under constant stress conditions.

Due to its mechanical uniqueness, rock salt often requires special considerations in terms of mine design. Blasting techniques, ground control practices and subsidence forecasting must be specifically adapted for rock salt features and to achieve proper results.

Given rock salt prevalence in modern day-to-day applications (e.g. road de-icing agent), it is often assumed to originate from similar geological sources, with comparable mechanical behavior. It can be shown however that the origins and mineralogical conditions of a rock salt deposit play a major role in its geotechnical behavior. This can lead to significant differences in operating standards and observed behavior from site to site.

This article presents a comparative case-study of three different underground rock salt mining operations. The presentation focuses on the deposit origins, geomechanical characteristics and mineralogical composition. Exploitation practices pertaining to rock fragmentation by blasting and ground control, and observed time-dependent convergence, are compared and discussed with respect to the geological and geotechnical settings. The study indicates how the origins of the deposit and its geological history explain the observed differences between the sites.

The three sites considered for this study are the Pugwash (Nova Scotia, Canada) and Ojibway (Ontario, Canada) mines (K+S Windsor Salt, Ltd.), and Weeks Island mine (Louisiana, USA: Morton Salt, Inc).

2 BACKGROUND

2.1 Rock salt deposits

Halite is a sedimentary mineral, member of the evaporites family characterized by solubility in water. Other evaporites include potash bearing minerals sylvite, sarnalite, and kainite; sulfates such as anhydrite and gypsum; and carbonates such as dolomite and calcite.

Evaporite formations are the result of precipitation and sedimentary deposition in sea water at or close to saturation. The typical sedimentation process of salt from sea water is the result of partial or complete seclusion of a water body that subsequently undergoes evaporation (Jeremic, 1994). Precipitation arises as mineral concentration increases following evaporation. The mineralogical content of the resulting deposit depends on the dissolved minerals and water seclusion conditions. When various minerals are in solution, the precipitation order depends on their respective solubility (i.e. least soluble minerals precipitate first). The different formation processes and seclusion conditions, and the resulting evaporite deposits are discussed at length by Babel and Schreiber (2014).

Evaporite deposition leads to tabular formations typically encountered at shallow depth (< 1 km). As additional sediment layers are deposited on top of salt, high pressures and temperatures lead to plastic deformation and buoyant rise of the lighter minerals through denser surrounding rocks. Many resulting formations exhibit dome like shapes, as is typically encountered in the Southern United States oil fields. The tectonic movements, combined with buoyant uplifting, can result in various salt deposit shapes associated with diapirs, which typically contain intertwined evaporite mineral bands (Kupfer, 1968; Jeremic, 1994) and other impurities (e.g. clay).

2.2 Mechanical and time dependent behavior

When subjected to sustained deviatoric stress conditions, rock salt exhibits plastic flow deformation resulting mainly from sliding of dislocations in halite crystals. Under a constant differential stress, inelastic deformation initially occurs with a higher strain rate, which then tends to decelerate as intracrystalline dislocations pileup and impede further plastic flow (a phenomenon known as strain-hardening). This first phase is termed primary creep (Skrzypek & Hetnarski, 1993). During the secondary creep phase that follows, dislocation pileups are counterbalanced by recovery processes and recrystallization of microfractures, leading to a constant strain rate (Carter & Hansen, 1983; Handin, et al., 1986; Senseny, et al., 1992). Tertiary (accelerating) strain rate arises when a sufficiently high differential stress is achieved and accumulated creep strain reaches a certain level (Hult, 1966; Sgaoula, 1997). Creep strains and strain rates are also favored by higher temperatures.

Figure 1 illustrates schematically two creep curves with the strain ε developing over time t (s), for two constant differential stress conditions. Both curves undergo primary (hardening) and secondary (steady-state) creep. Curve II results from a lower differential stress and thus exhibits lower strain rates. Only curve I, with a higher applied differential (deviatoric) stress undergoes tertiary creep with an accelerated strain rate (during the observation period).

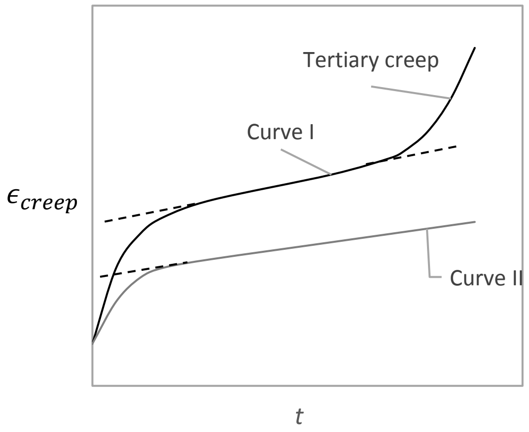

Figure 1: Creep strain over time for two different deviatoric stresses. Curves I and II exhibit primary and secondary creep; curve I also includes a tertiary creep phase (accelerating strain rate) associated with a stress level that exceeds the damage initiation threshold.

The relationship between the inelastic strain and strain rate and the stress (and temperature) conditions has been studied extensively by various authors, who have also proposed different models for predicting rock salt behavior around underground excavations, and related issues such as surface subsidence (Munson & Dawson, 1979; Carter & Hansen, 1983; Van Sambeek, 1986; Sgaoula, 1997; Julien, 1999; Bérest, 2013). Hampel et al. (2010) presents a thorough benchmarking comparison exercise considering different creep models and their numerical modelling applications.

Implementation of creep models for practical applications to analyze underground openings for rock salt mines is often limited to secondary creep, in part because of its assumed prevalence over primary creep for relatively long periods of time. Tertiary creep rate associated with failure beyond damage initiation is typically avoided by design (except very near the openings). The Bailey Norton law, or power creep law, represents the most common creep model in use (Sgaoula, 1997; Aubertin, et al., 2018); it can be written as follows (e.g. Carter and Hansen, 1983):

$$\dot{\epsilon}_{\iota} = A \cdot \sigma_d^n \qquad [1]$$

Where $\dot{\epsilon}_{\iota}$ (s^{-1}) is the inelastic strain rate due to secondary creep, A and n are material parameters, and σ_d (kPa) is the differential (deviatoric) stress.

2.3 Rock salt blasting

Rock salt has been shown to behave differently during blasting events compared to hard rocks (Nicholls & Hooker, 1962; Fornefeld, 1988; Aubertin, et al., 2018). These differences can be explained by the low density and moderate stiffness of rock salt (i.e. low blast wave impedance), and relatively small compressive and tensile strengths. The following statements summarize the main features of rock salt blasting:

- Large energy losses near the blasthole.
- Limited capacity to accumulate strain energy.
- High velocity of detonation (VOD) explosives tend to be less effective.
- Explosives settings with non-ideal detonation yield more efficient burden removal.

Years and experience and the observations behind the above statements have led underground rock salt mines to adopt special blast designs. Horizontal drill and blast development patterns incorporate additional free surfaces in the form of large boreholes or kerf cuts at the base of the faces. These extra free surfaces provide additional surface area for the blast waves to reflect and enhance localized fragmentation, and provide additional relief volume for the swelling rock masses.

Figure 2 presents the picture of a 4 meter long undercutter used at the Ojibway mine to generate a 15 centimeter kerf cut near the base of the face along its width.

Figure 2: Electric undercutter used at the Ojibway mine to create an undercut kerf at the base of the face. Undercutter bar is 4 meters long and creates a 37 cm thick kerf.

3 GEOLOGICAL SETTINGS

3.1 Ojibway

The Ojibway mine currently exploits a rock salt deposit from the Silurian Salina Formation. Sediments of the Salina formation were deposited in two major Paleozoic basins in North America: The Michigan Basin and the Appalachian Foreland Basin.

Figure 3 presents a map of Southern Ontario, Canada, highlighting the two basins, and tectonic elements pertaining to Paleozoic sedimentation around the Great Lakes region.

The Michigan and Appalachian basins are connected by an East-West striking synclinal structure, the Chatham Sag (CS in Figure 3), which intersects two anticlinal structures: the Algonquin and Findlay Arches (Sun, et al., 2018). Sediments in the center of the basins are buried up to 4 km below surface in the Michigan Basin, and about 12 km in the Appalachian Basin; sediments at the margin of both basins are however much more shallow (few hundred meters). The Ojibway mine is situated at the Eastern margin of the Michigan Basin, South of the Chatham Sag.

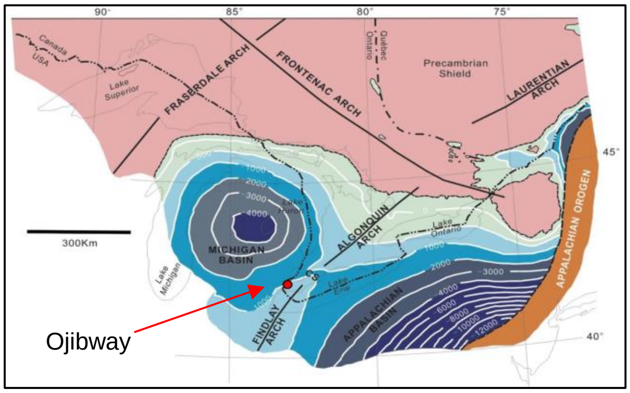

Figure 3: Locations of the Michigan Basin and the Appalachian Basin located (mainly) in Southern Ontario, Canada; adapted from Sun et al. (2018).

Evaporites in the Salina Formation consist of an alternating sequence of rock salt, dolomite, anhydrite and shale, which appear to have been deposited in seven evaporitic cycles (Landes, 1945). The Salina sediments in southwestern Ontario are horizontally bedded with very minor tectonic influence (Goodman, 1983). Only one salt bed is currently exploited at the Ojibway mine (Middle F-Salt) whereas up to 18 salt beds of the Salina B salt are exploited by solution mining in the adjacent Windsor brine field.

The depth of the mined rock salt horizon in the Ojibway mine is about 300 m. The medium-size grain rock salt of the currently mined Salina Middle F-Salt consists of 95 % to 99 % halite with very small amounts of impurities (anhydrite, dolomite and clay). A few areas show recrystallization with coarser-grained crystals up to 10 cm in diameter and almost no impurities.

Figure 4 shows an active face at the Ojibway mine. The typical halite (rock salt) and anhydrite beds can be discerned easily from the figure. Salt recrystallization can be observed along the face as well.

Figure 4: Active working face at Ojibway. Rock salt and anhydrite strata are present across the face and are discernable by coloration.

3.2 Pugwash

The Pugwash salt mine is located in the Cumberland Basin, a structurally complex sub basin of the late Paleozoic Maritimes Basin of Atlantic Canada. The Maritimes Basin is an extensive successor basin that formed in the wake of the Early to Middle Devonian Acadian Orogeny as part of the Appalachian Orogeny (Gibbling, et al., 1992).

Figure 5 illustrates the general paleographic settings of the Maritime basin where the Pugwash mine is located.

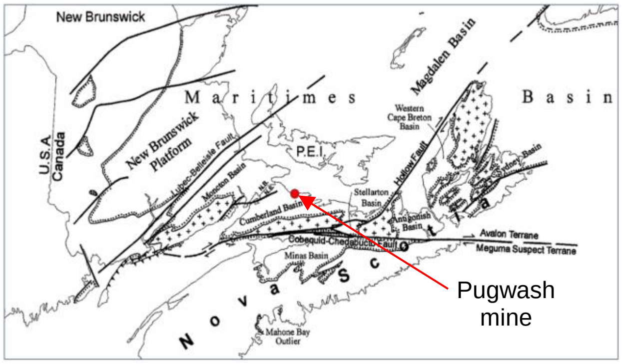

Figure 5: General paleogeographic and tectonic setting of the Martimes Basin, in Atlantic Canada; Modified from Gibling (1992).

The only major marine dominated depositional event in the late Paleozoic basin fill of the Maritimes Basin is represented by the deposition of the sediments of the Windsor Group (Giles & Boehner, 2001). Rock salt in the Pugwash deposit originated from the Lower Windsor Group (Giles, 2008), and is referred to as the Pugwash Mine Formation. The undisturbed Windsor Group rock salt succession is located at an estimated depth between 3.5 and 4.5 km.

The Lower Windsor Group itself represents the first evaporite deposit formed out of five Major Cycles (MC-1) in the Maritimes Basin (Ryan & Giles, 2017). The overlying Mabou and Pictou Groups, as well as the underlying Horton Group, are dominated by clastic deposits like sandstones, siltstones and conglomerates, with occasional coal intercalations.

The Pugwash deposit is in a fault-bounded parallelogram-shaped salt diapir, part of a series of structurally complex, en-echelon salt diapir anticlines (Boehner, 1987). The northern and southern boundary faults are striking NE-SW, whereas the eastern and western boundary faults are striking NNE-SSW. The shape of the salt diapir is interpretative and not supported by geophysical data.

The deposit is dominated by a steeply inclined sequence of argillite rock salt and partly isolated anhydrite cliffs. Carnallite and potash beds are also present, especially at the margin of the salt diapir. The rock salt body has been severely deformed during uplift and multiple tectonic overprinting (Evans, 1965). Plunging and non-plunging synforms and antiforms are common structures, as portrayed in Figure 6.

Figure 6: A series of folds at the Pugwash mine along a mined out drift. Deformed rock salt layers of different purity are intertwined with dark folded bands of massive anhydrite.

3.3 Weeks Island

The Weeks Island salt dome is part of the South Louisiana Salt Basin (Cunningham, et al., 2016) located in the northern Gulf of Mexico. , This area is part of the tectono-stratigraphic “Salt Dome-Mini Basin Province” (Diegel, et al., 1995). Weeks Island, Avery Island, Cote Blanche, Belle Isle and Jefferson Island form the Five Islands Salt Domes, representing two NW-SE striking syn-depositional counter-regional growth faults. The trend of the Five Islands Salt Domes is also aligned with the Terrebonne Transfer Fault (Stephens, 2009).

Figure 7 illustrates the so-called Salt Dome-Mini basin Province with the 5 rock salt deposits. The structural features of the overall regional fault system are highlighted to showcase the concurrent parallel fault systems.

Similar to the other four salt domes that have been mined in the region, the Weeks Island deposit consists of rock salt from the Jurassic Louann Salt Formation. The original Louann salt bed is located approximately 18 km below the surface, overlaid by other Mesozoic and Cenozoic sediments associated with the formation of the Gulf of Mexico and the progradation of the Mississippi Delta (Hoentzsch, et al., 2019).

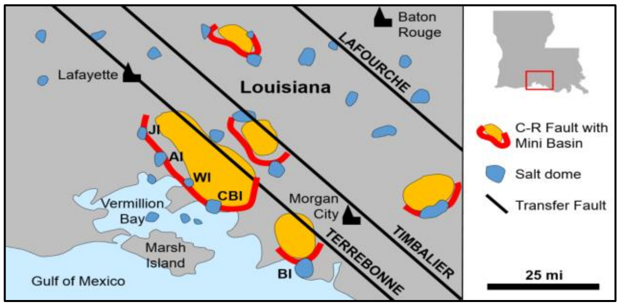

Figure 7: Structural framework of the southern Louisiana Gulf shore with the Five Islands Salt Domes. JI – Jefferson Island, AI – Avery Island, WI – Weeks Island, CBI – Cote Blanche Island, BI – Belle Isle. Taken from Hoentzsch et al. (2019), adapted from Stephens (2009).

The internal structure of the Weeks Island salt dome consists of more-or-less pure rock salt with minor impurities and varying grain sizes. Deformation is generally ductile (folding). The currently mined, high purity rock salt exceeds 99 % NaCl. Kupfer et al. (1998) identified specific geological features in the Weeks Island salt dome having a significant impact on salt quality and structural behavior. These so-called “anomalous zones” are characterized by unusual texture, inclusions or accumulated impurities, or unusual structures in the salt. These features can be traced throughout the salt dome and used as directional markers between different levels to map potentially problematic anomalous zones (i.e. brine pockets, anhydrite intrusions).

Weeks Island’s deposit is characterized by two mined zones along a North-East South-West trending shear zone. The rock salt in the North portion of the dome exhibits higher cohesion, and is characterized by smaller grained materials. The rock salt in the South portion of the dome is much more friable and contains lower amounts of impurities.

Figure 8 shows two samples taken from the Weeks Island mine. The left sample exemplifies the typical ore exploited at the Weeks Island mine, with coarse grained, friable, and interlocked crystals with varying edge geometry. The right sample represents recrystallized material typically found near and within anomalous zones, which constitute a valuable indicator for impurities and fluid intrusions.

Figure 8: Weeks Island rock salt samples: (left) coarse grained, high grade pure and friable rock salt, and (right) recrystallized rock salt (halite) crystals with fluid or gas intrusions. Taken from Hoentzsch et al. (2019).

4 SITE COMPARISON

4.1 Geomechanical characterization

4.1.1 Strength properties

The rock salt from the three considered sites exhibits very different strength properties due to mineralogical and granular differences. Figure 9 compares the uniaxial compressive strength, C_0 (MPa) of rock salt sampled at the three sites. The figure also displays the strength of the characteristic dolomitic shale encountered above and below the salt seam at Ojibway, and of the massive anhydrite intrusions encountered at the Pugwash mine. The rock salt from the Pugwash mine has a NaCl content between 88 and 92%, with the remainder as anhydrite intrusions. The C_0 values for the Weeks Island mine rock salt are given for the two domal sections respectively located North and South of the geological shear zone separating the exploited zones.

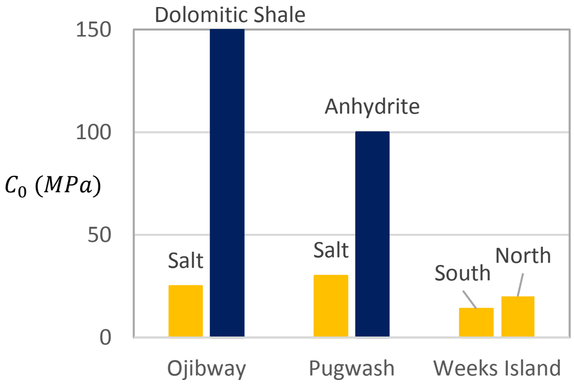

Figure 9: Compressive strength of rocks sampled at the Ojibway, Pugwash, and Weeks Island mines.

The results in Figure 9 indicate that the rock salt from the Weeks Island mine is the weakest, reflecting its interlocked coarse-grained structure, with relatively low intercrystalline cohesion. The rock salt from the Pugwash mine shows the highest compressive strength of the three sites, in part due to anhydrite intrusions binding crystals together and high level of tectonic deformation resulting in enhanced crystal interlock. Ojibway mine rock salt strength is influenced by traces of anhydrite intrusions and small amount of deformation of the deposit.

4.1.2 Elastic parameters

Young’s modulus E (GPa) and Poisson’s ratio ν (-) are commonly used to quantify the elastic behavior (and parameters) of rocks. Figure 10 presents a chart of compiled elastic properties for the three rock salt deposits. The data were provided by the respective sites, and are based on unconfined compressive tests performed on cored samples.

It can be observed that the rock salt from Pugwash mine exhibits the highest Young's modulus at about 25 GPa, due in part to the stiffer anhydrite intrusions. The modulus values for Weeks Island and Ojibway are in the range between 15 to more than 18 GPa. The latter Young's modulus values are in the lower range for data reported in the literature.

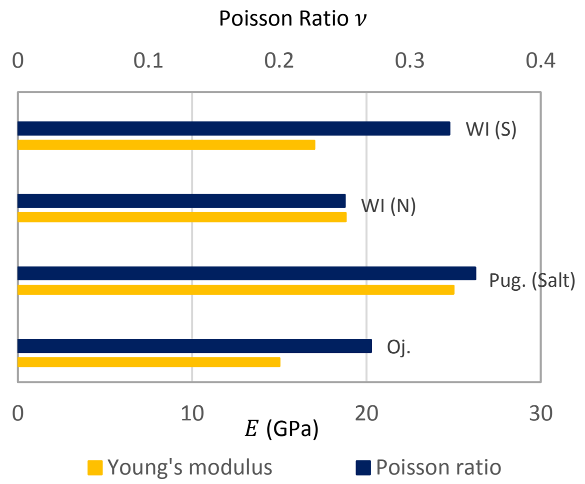

Figure 10: Elastic parameters for rock salt from the three mines: Weeks Island (WI) North (N) and South (S) section, Pugwash (Pug.), and Ojibway (Oj.).

4.2 Ground control requirements

The rock salt deposits at Weeks Island, Pugwash, and Ojibway mine exhibit different geomechanical characteristics as indicated in the previous sections. The deposits also feature quite different ground control requirements, primarily due to the deposits' origins, structural features and failure modes.

Table 1 compares the artificial ground control systems implemented at the three mine sites as part of normal operating practices. The table includes information about the rationale behind ground control practices and design, along with primary and secondary bolting, where required. It can be noted from

Table 1 that the three ground control systems have been designed to address different situations. The system at Ojibway's tabular deposit aims at maintaining a structurally sound rock salt support layer (behaving like a plate or beam) above the excavation. Below a certain thickness of this layer (due to drifting and narrowing of the seam), rebar is installed to add confinement and rigidity. Such confinement tends to increase the strength and stiffness of rock salt and its capacity to redistribute the stresses over time by maintaining the protective layer between the highly brittle dolomitic shale and the excavation.

Ground control at the Pugwash mine depends upon the structural features of the deposit. Vertical folds and horizontal bedding form the main structures encountered in active working zones, and these require no systematic bolting. Horizontal structures with massive and brittle anhydrite beds present a high potential for roof fall, so localized resin anchored bolting is implemented to support such structurally weak areas.

The high grade homogeneous deposit at Weeks Island mine is supported systematically via pattern bolting. End grouted anchored bolts are used to allow for rock salt strain and wall converge around the excavation, which tends to progressively increase the load on the bearing plates at the face. Artificial bolting thus aims at capitalizing on long term rock salt movement by using creep strains to increase confinement in the layer above the openings. Systematic bolting also provides enhanced support around undetected anomalous features (e.g. fluids).

4.3 Time dependent behavior

The three sites require robust pillar design to limit excavation convergence and surface subsidence. Rock salt tendency to deform inelastically overtime (in a ductile manner, without failure) is commonly quantified with the Norton power law (equation 1) describing stationary creep.

Table 1: Summary of artificial ground control systems used at the Ojibway, Pugwash and Weeks Island mines.

Mine	Ojibway	Pugwash	Weeks Island
Ground control rationale	Maintain integrity of horizontal salt layer	Structural gravity driven failure.	Systematic bolting.
Primary bolting	1.5 m x 1.5 m bolt pattern (salt thickness < 0.9m)	None.	5 bolts along drift.
Secondary bolting	Localized spot bolting for slabs (1.2 m long).	Resin bolts.	1.8 m x 1.8 m bolt pattern.
Bolt specifications	1.8 m fully grouted resin bolts.	Varies in the mine.	1.8 m, resin anchored.
Room dimensions	6 m high x 13 m wide	18 m high by 18 m wide	22 m high by 17 m wide

Figure 11 plots the measured stationary creep strain rates for a range of deviatoric stresses at the Ojibway, Pugwash and Weeks Island mines. Creep measurements at the Seleine mine (salt diapir, low grade anhydrite intrusion with massive interlayers) (Quebec, Cadana) are also presented for comparison purposes.

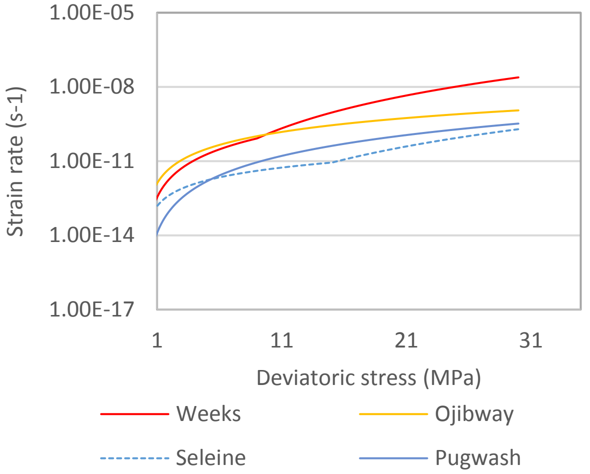

Figure 11: Stationary strain rates as a function of the deviatoric stress for different rock salt deposits (log-log plot) considering a Norton-Bailey power law function.

4.4 Blasting

The Ojibway, Pugwash and Weeks Island mines rely on similar blasting methods associated with kerf relief at the base of the face. Figure 12 presents the powder factor (kg of explosives per T of rock salt) for production rounds at the three mines. Ojibway's development occasionally relies on a modified design without kerf due to the presence of a low seam of hard dolomite near the floor that prevents the cut, but requires additional explosives. The advance at Pugwash mine is performed through two horizontal rounds, with the second cut including a kerf and a third free face at the top, yielding a lower explosives requirement. Both Pugwash and Ojibway mines use exclusively Amonium Nitrate Fuel Oil (ANFO) explosives. The face development at Weeks Island is performed using emulsion explosives, due to traces of brine that limit the use of ANFO near the perimeter of the dome. The bench conditions plotted in Figure 13 correspond to ANFO loaded blastholes.

Weeks Island mine presents the lowest explosives requirements when using ANFO with bench design. The large free face, combined with relatively low rock salt strength and granular cohesion, leads to lower powder factor requirements compared to the two other sites.

Pugwash mine exhibits a lower powder factor requirement than the Ojibway mine. This somehow counterintuitive practice was explicitly investigated and confirmed using single blasthole tests (Aubertin et al. (2018). This study indicates that rock salt at Pugwash exhibits a stiffer and more brittle response to loading, which affects the release of energy during blasting events.

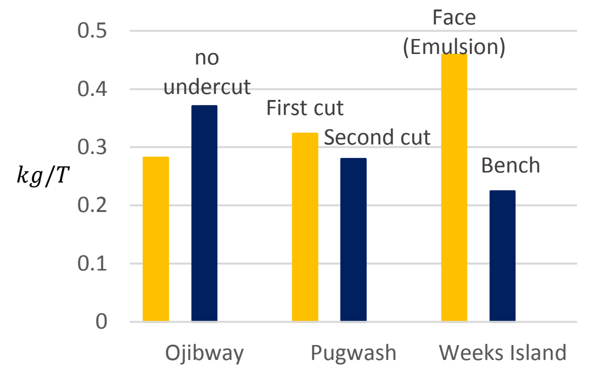

Figure 12: Powder factor for the use of explosives at the three salt mines.

5 SUMMARY AND CONCLUSIONS

Three different rock salt deposits currently under mine exploitation were characterized with respect to their origins and, geological features. The corresponding geomechanical properties and mine designs are compared to assess the respective influence of rock salt behavior.

The data presented above indicate that the rock salt in Weeks Island's homogenous dome deposit shows smaller strength and lower explosive requirements, and also higher creep strains under heavy deviatoric load. The coarse grained structure and low intercrystalline cohesion lead to more porous conditions with fluid intrusions resulting in localized weakness planes that require systematic bolting.

The Pugwash heavily folded, tectonically influenced deposit is characterized by a high level of impurities in the form of massive and dispersed anhydrite. The stiffer material serves as a binder which enhances the stability of the rock mass and its capacity to accumulate strain. The ground control systems used at the Pugwash mine focus on controlling the response of brittle structures with preferential planes that favor gravity driven structural roof falls.

The Ojibway rock salt deposit contains impurities, similar to Pugwash, but at lower concentrations. The overall rock salt homogeneity is comparable to Weeks Island. The ground control systems at Ojibway mine are driven by the tabular formations with brittle overlying layers of dolomitic shale. Excavations are designed to create a rigid horizontal beam of rock salt above the excavation, to support the brittle layer. Blasting conditions are influenced by the limited capacity to accumulate strain energy and the need for higher amount of explosives.

The three deposits are exploited primarily for the use of salt as a de-icing agent. Despite the same end use of the extracted ore, the three deposits exhibit quite different geological features, leading to different ground control and exploitation practices. This work confirms that rock salt can exhibit a wide range of geomechanical characteristics, which must be taken into account for the design of underground openings.

6 ACKNOWLEDGMENTS

The authors would like to express their gratitude toward K+S Windsor Salt and Morton Salt for access to data and support in completing the present work.

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