

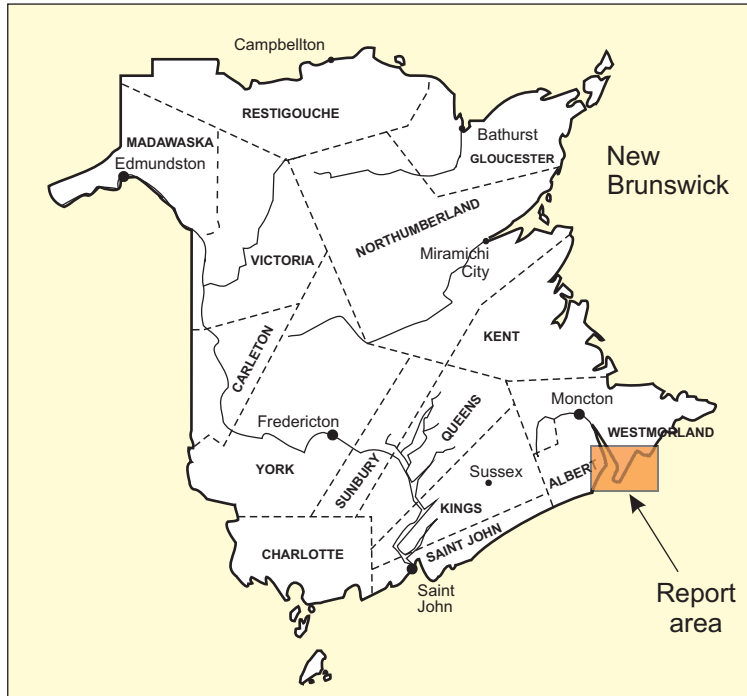
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Mineral Resource Report

BROMINE AS AN INDICATOR OF POTASH
MINERALIZATION IN CARBONIFEROUS
MARINE EVAPORITES, SACKVILLE SUBBASIN,
SOUTHEASTERN NEW BRUNSWICK



T.C. Webb and H.J. Stewart
2011



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Cover illustration	Contact between grey carbonate rocks of the Lime-kiln Brook Formation (Windsor Group) and red clastic sedimentary rocks of the Hopewell Cape Formation (Mabou Group) at Hopewell Cape in the Sackville Subbasin, southeastern New Brunswick. <i>Photograph courtesy of T.C. Webb, Geological Surveys Branch, New Brunswick Department of Natural Resources.</i>
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Hon. Bruce Northrup
Minister of Natural Resources

February 2011

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ABSTRACT

Located within the late Paleozoic Maritimes Basin of eastern Canada, the Sackville Subbasin of southeastern New Brunswick contains widespread subsurface indications of marine evaporites of the Early Carboniferous Windsor Group. The evaporites include chloride salt deposits considered stratigraphically equivalent to potash-bearing Windsor chlorides known to exist elsewhere in New Brunswick. Thus, the Sackville Subbasin represents a prospective area for potash exploration. However, the stratigraphy and depositional history of Windsor strata throughout much of the subbasin is not well understood. Regional gravity and seismic surveys and limited borehole data indicate substantial thicknesses of halite but demonstrate no evidence of potash.

Bromine distribution has long been considered a useful guide in determining the origin, diagenesis, and structural history of marine evaporites. When combined with other, supporting geological data, bromine can help to interpret paleosalinities in evaporite basins and to determine whether an evaporite deposit either is in its original depositional state or has undergone significant post-depositional change and subsequent recrystallization, resulting in altered primary mineralogical and textural characteristics.

Using halite drill cuttings from three boreholes in the northwestern part of the Sackville Subbasin, bromine profiles were constructed to help in determining whether conditions favoured deposition and preservation of potash. Preliminary results indicate that this part of the subbasin represents a marginal marine, platformal to shallow evaporite basin periodically flooded by both meteoric water and fresh seawater, and that resultant chloride deposits underwent multiple structural and diagenetic alterations. Such a depositional setting may not have favoured significant accumulation and preservation of potash in the northwestern area of the subbasin. Additional geological data are required to determine whether the Sackville Subbasin holds significant potential for potash resources.

RÉSUMÉ

Situé dans le bassin du Paléozoïque tardif des Maritimes dans l'Est du Canada, le sous-bassin de Sackville, dans le sud-est du Nouveau-Brunswick, renferme de vastes indices, sous la surface, de la présence d'évaporites d'origine marine du groupe de Windsor, du début du Carbonifère, ce qui comprend notamment des gisements de sel chloré qui correspondraient au plan stratigraphique aux chlorures de Windsor contenant de la potasse observés ailleurs au Nouveau-Brunswick. Ainsi, le sous-bassin de Sackville serait une zone prometteuse pour l'exploration des gisements de potasse. La stratigraphie et l'évolution sédimentaire des strates de Windsor dans la plus grande partie du sous-bassin de Sackville ne sont pas bien connues. Les levés gravimétriques et sismiques régionaux et des données de sondage limitées indiquent des épaisseurs caractéristiques du chlorure de sodium, mais ne contiennent aucun indice de potasse.

La répartition du brome a longtemps servi d'indice pour établir l'origine, la diagénèse et l'évolution structurale des évaporites marines. Combiné à d'autres données géologiques à l'appui, le brome peut aider à interpréter les traces paléosalines dans les bassins d'évaporites et à déterminer si un gisement d'évaporites se trouve dans son état sédimentaire d'origine ou si un changement important post-sédimentaire et une

recristallisation ultérieure ont eu lieu et ont modifié les caractéristiques minéralogiques et de texture primaires de ce minéral.

À la lumière des déblais de forage de chlorure de sodium de trois trous creusés dans la partie nord-ouest du sous-bassin de Sackville, des profils de brome ont été établis pour déterminer si les conditions ambiantes favorisaient la sédimentation et la préservation de la potasse. Les premiers résultats indiquent que cette partie du sous-bassin appartient à un bassin d'évaporites de milieu marin marginal, de plate-forme et à faible profondeur, qui subit à intervalles périodiques des inondations par de l'eau atmosphérique et des apports nouveaux en eau de mer. Les gisements de chlorure issus de ce phénomène ont subi de multiples altérations structurales et diagénétiques. Ce contexte sédimentaire peut ne pas avoir donné lieu à une forte accumulation et préservation de potasse dans la partie nord-ouest du sous-bassin. Il faudra compiler et examiner d'autres données géologiques pour déterminer l'importance des ressources possibles en potasse dans le sous-bassin de Sackville.

INTRODUCTION

Potash is the common name for sylvinite, a mixture of sylvite (KCl) and halite (NaCl), and is a key component of most commercial fertilizers. In New Brunswick, potash deposits are hosted by marine evaporites in the Early Carboniferous Windsor Group of the late Paleozoic Maritimes Basin of eastern Canada (Fig. 1). Exploration work in the early 1970s led to the discovery of economic-grade potash ore near Sussex in southern New Brunswick (Fig. 2). Deposits at Penobsquis and Salt Springs were subsequently developed into mines with processing facilities; a third deposit, at Millstream, was extensively explored (Fig. 2). New Brunswick has been a major potash producer since the 1980s and is scheduled to bring its newest potash mine into operation in 2012.

Worldwide potash demand has surged considerably over the last decade, due primarily to higher consumption of agricultural products such as food, fibre, and feed, as well as to an expanding biofuel industry. It is predicted that improved economic conditions in developing countries and increased demand for better quality, higher protein diets will further intensify the need for potash-based fertilizers.

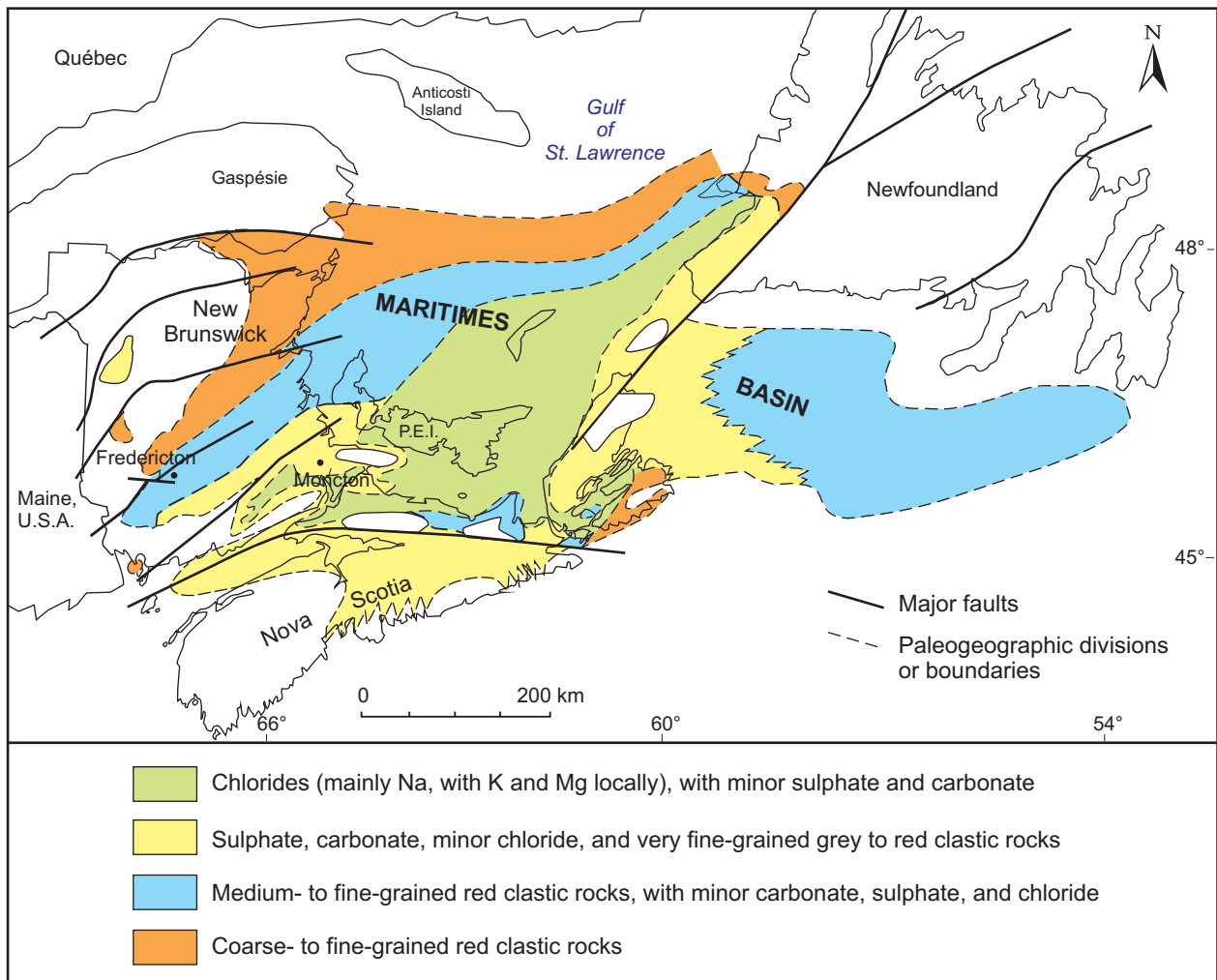


Figure 1. Paleogeographic distribution of sedimentary facies of the Early Carboniferous Windsor Group in the Maritimes Basin of eastern Canada (modified from Howie 1988; St. Peter and Johnson 2009).

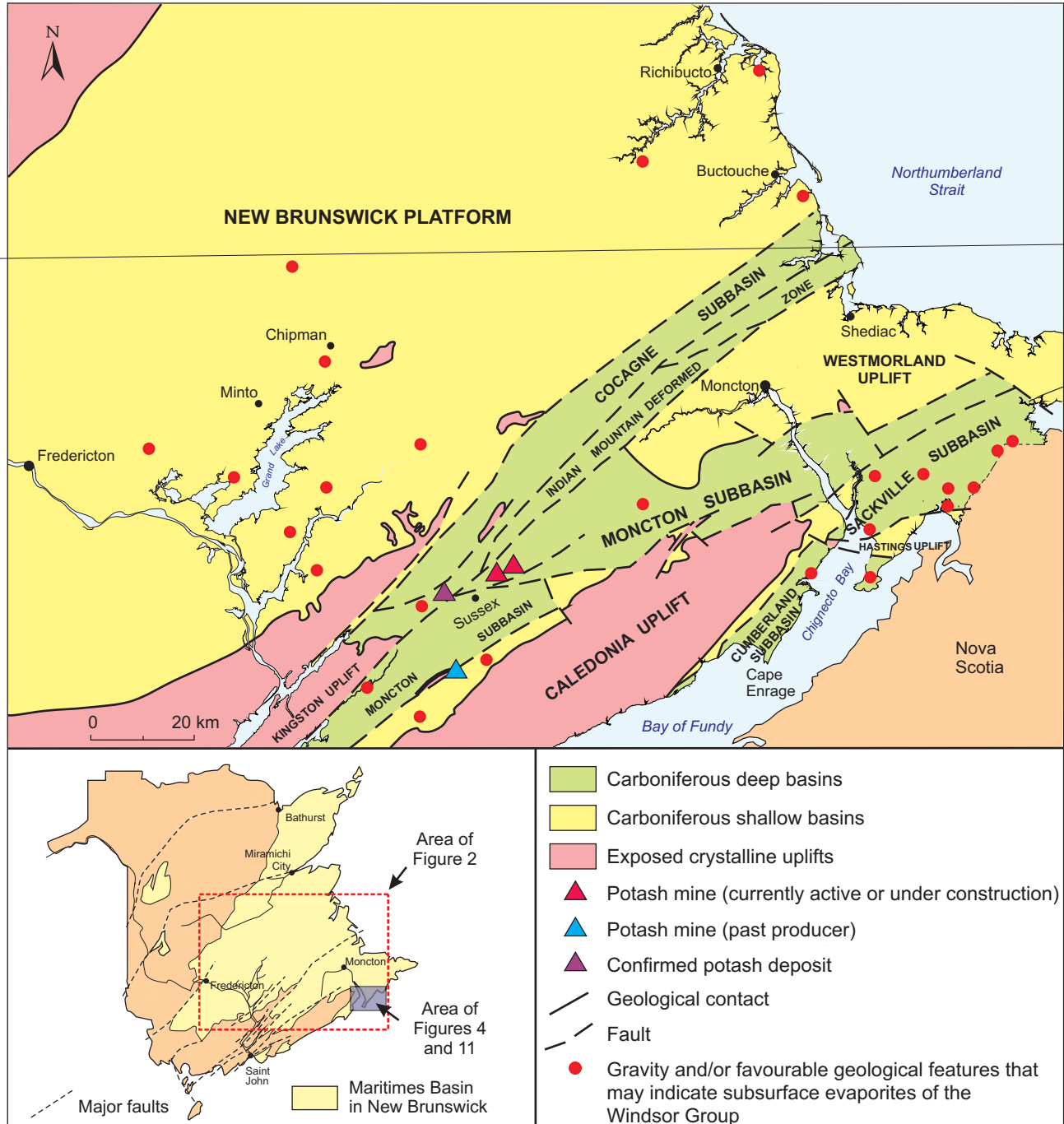


Figure 2. Carboniferous subbasins of southeastern New Brunswick and areas of known and potential evaporites of the Windsor Group.

The impending imbalance between global potash supply and demand has triggered brownfield expansion projects at several potash mines in western Canada. In New Brunswick, one such project is underway at Penobsquis, where PotashCorp is constructing a 2 Mt/yr potash mine and processing facility near its present potash operation (Fig. 2). Scheduled for start-up and initial production in 2012, this project represents an investment of CAD\$1.7 billion and is Canada's first new potash mine in almost a quarter of a century.

A key supply question relates to how the potash industry can expand to satisfy growing demand. Ultimately, some form of constraint on increased production is inevitable unless major upgrades are made to existing shaft-hoisting capacities in conventional mining operations. Potential limitations to expansion at current mines have prompted a global resurgence in greenfield potash exploration and development activities. Since 2006, several Canadian provinces have attracted new players and investors to the industry; other areas of the world with known but undeveloped potash resources have experienced similar attention.

Given the foregoing, it seems likely that potash exploration will be renewed within New Brunswick and elsewhere in Atlantic Canada. This report examines the distribution of bromine within Windsor marine evaporites of southeastern New Brunswick, specifically as it contributes to identifying geological conditions that may have favoured potash deposition and preservation.

REGIONAL GEOLOGICAL SETTING

Atlantic Canada lies within the northern Appalachian Orogen, a linear mountain belt extending from the northern tip of Newfoundland along the northeastern seaboard of North America. The orogen is characterized by complexly folded and faulted assemblages of igneous, sedimentary, and metamorphic rocks, the products of a protracted history of tectonic plate movement.

Several tectonic events within the orogen affected Proterozoic to late Paleozoic rocks in the Atlantic region (van Staal 2007). During the Late Devonian to Early Permian (from 360 Ma to 300 Ma), much of Atlantic Canada, including what is now southeastern New Brunswick, lay beneath a 148 000 km² terrestrial to marine basin termed the Maritimes Basin (Fig. 1; St. Peter and Johnson 2009). During the waning phases of the Devonian Acadian Orogeny, several northeast-trending, uplifted highlands and down-dropped basins formed within the Maritimes Basin, including the Cumberland, Sackville, Moncton, and Cocagne subbasins (Fig. 2). These subbasins became important depocentres for Early Carboniferous carbonates and evaporites, some of which are known to host potash deposits (Roulston and Waugh 1983; Roulston et al. 1995; St. Peter and Johnson 2009).

Economic potash deposits in Atlantic Canada are restricted to Early Carboniferous marine evaporites of the Windsor Group (Fig. 3). Regionally, the Windsor Group comprises basal clastic sedimentary rock succeeded by sequences of carbonate, sulphate, and various chloride salts that were partially preserved in the aforementioned subbasins (St. Peter and Johnson 2009). The chloride salts include sodium (halite or NaCl), potassium (sylvite or KCl, i.e., potash), and magnesium (in carnallite or $\text{KMgCl}_3 \cdot 6(\text{H}_2\text{O})$). In New Brunswick, potash deposits have been confirmed in the Moncton and Cocagne subbasins near Sussex (Fig. 2). Existing geotechnical information suggests that additional potash or related evaporite resources such as carnallite may occur as extensions of known deposits within these two subbasins.

Several exploration targets for subsurface Windsor evaporites have also been identified within the Sackville Subbasin (Fig. 2). Regional gravity data reveal a configuration of anomalies that

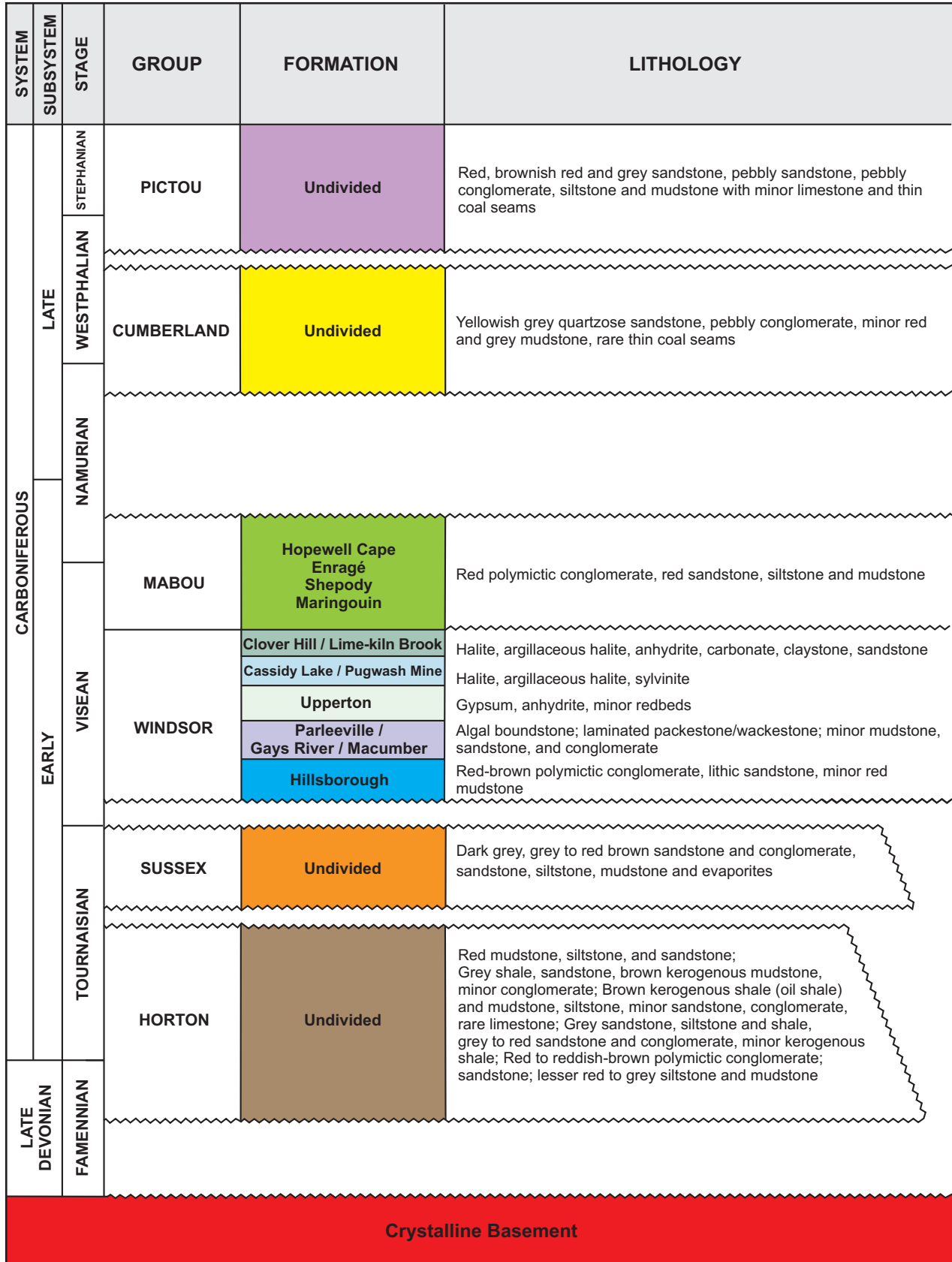


Figure 3. Late Devonian to Carboniferous stratigraphic chart for the Maritimes Basin of southern New Brunswick (modified after St. Peter 2006; St. Peter and Johnson 2009).

suggest subsurface evaporite bodies adjacent to major regional fault structures. Three boreholes—Shell Dorchester No. 1, Imperial Dorchester No. 1, and Columbia/Corridor Coppermine Hill—have intersected Windsor evaporites in the subbasin (Fig. 4). However, clear evidence of potash associated with these evaporites has yet to be confirmed; evaluating the potash potential of the Sackville Subbasin is difficult due to sparse outcrop and limited borehole control.

The classic work of Gussow (1953) and more recent works by St. Peter (1993, 2006) and St. Peter and Johnson (2009) provide comprehensive reviews of Carboniferous stratigraphy and structure in New Brunswick. Additional information pertaining to regional Carboniferous distribution is available in New Brunswick Department of Natural Resources (NBDNR) (2004, 2006, 2008), Smith (2005, 2006, 2008), and Smith and Fyffe (2006). These references can be ordered online from NBDNR in Fredericton, New Brunswick (NBDNR 2011).

GEOLOGY OF THE MARITIMES BASIN IN SOUTHEASTERN NEW BRUNSWICK

In New Brunswick, Late Devonian to Late Carboniferous strata of the Maritimes Basin are divided into six major lithostratigraphic groups (Fig. 3; St. Peter and Johnson 2009). These comprise

- Late Devonian (Famennian) to Early Carboniferous (early Tournaisian) clastic sedimentary rocks, including oil-bearing sandstones and shales, of the Horton Group,
- Early Carboniferous (late Tournaisian) clastic sedimentary rocks and minor carbonates, and lacustrine evaporites of the Sussex Group,
- Early Carboniferous (early to middle Visean) clastic sedimentary rocks, carbonates, and marine evaporites of the Windsor Group,
- Early Carboniferous (middle Visean to early Namurian) clastic sedimentary rocks of the Mabou Group,
- Late Carboniferous (late Namurian to Westphalian) clastic sedimentary rocks of the Cumberland Group, and
- Late Carboniferous (late Westphalian to Stephanian) clastic sedimentary rocks of the Pictou Group.

Horton and Sussex Groups

Proterozoic and early Paleozoic basement rocks underlying and bordering the Maritimes Basin are unconformably overlain by Late Devonian to Early Carboniferous rocks of the Horton Group. The Horton Group is composed of coarse- to fine-grained clastic sedimentary rocks, including economically important bituminous shales and hydrocarbon-enriched sandstones. Strata of the Sussex Group, which unconformably overlie the Horton Group, mostly comprise terrestrial clastic sedimentary rocks, but locally contain carbonates and impure glauberite and halite deposits. Given the fluviatile and fluviolacustrine depositional environment proposed for the carbonate, glauberite, and halite deposits (St. Peter 2006), it is unlikely that potash would be associated with the Sussex Group.

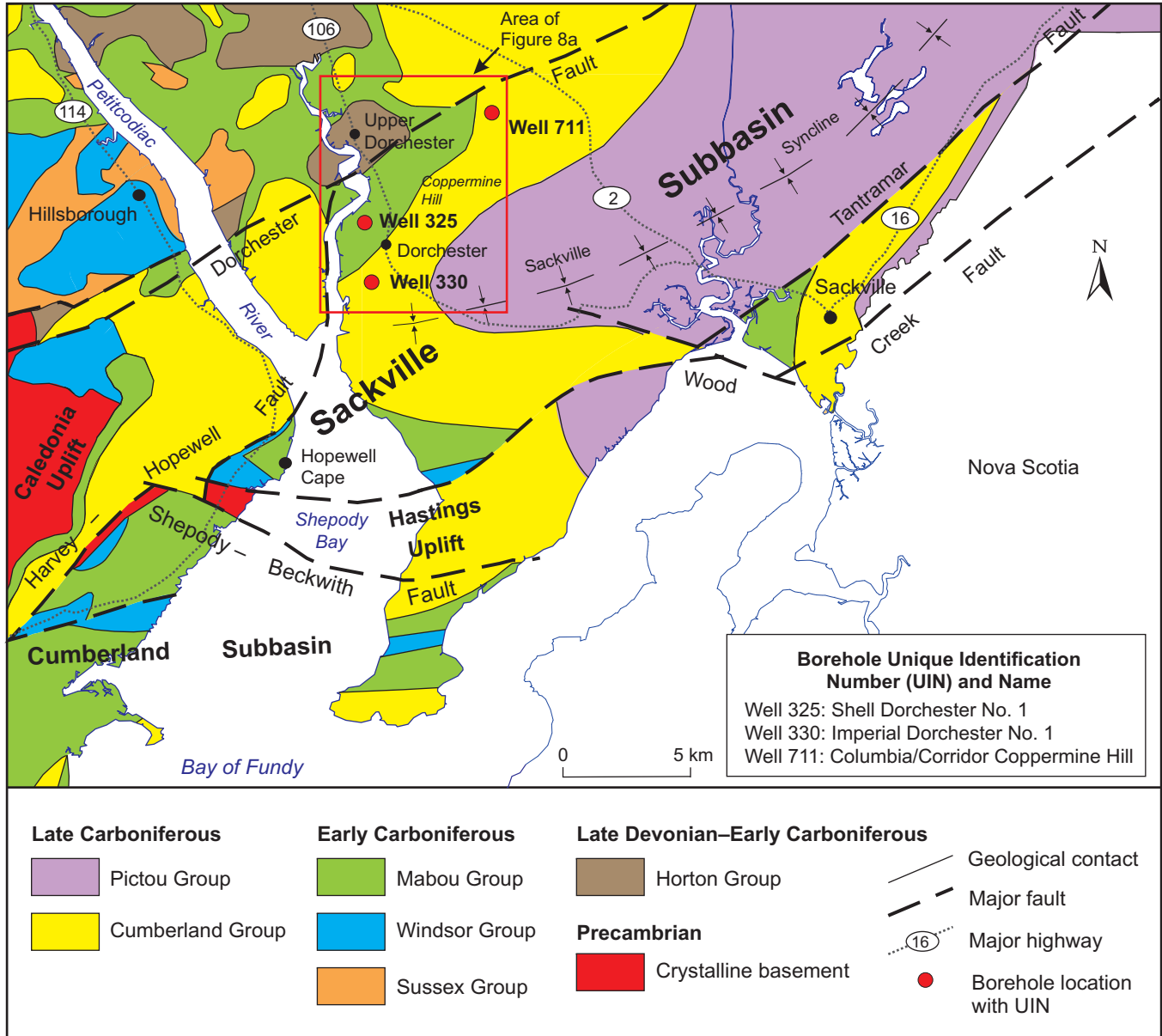


Figure 4. General geology and structure of the Sackville and Cumberland subbasins (after St. Peter and Johnson 2009), showing boreholes discussed in the text. See inset on Figure 2 for the location of this map area in southeastern New Brunswick.

Windsor and Mabou Groups

Sequences of Early Carboniferous coarse- to fine-grained clastic sedimentary rocks, carbonates, and evaporites, measuring several hundreds of metres in thickness (St. Peter 2006), have been identified by mapping, geophysical surveying, and subsurface drilling throughout southeastern New Brunswick. Collectively, these strata are referred to as the Windsor and Mabou groups.

Windsor rocks represent the only occurrence of marine sediments in the entire onshore portion of the Maritimes Basin in New Brunswick. The contact between the Windsor and

underlying Sussex Group is unconformable; the contact between the Windsor and overlying Mabou Group varies locally from gradational to erosional. Thin accumulations of Windsor strata lie along the southern margin of the Moncton Subbasin, where they overstep the margins of basement rocks of the Caledonia Uplift; and farther north, where they locally overstep the New Brunswick Platform (Fig. 2).

In the Moncton and Cocagne subbasins, the Windsor Group consists of the following strata in ascending order: basal clastic sedimentary rocks of the Hillsborough Formation; nearshore, platformal, and basinal carbonates of the laterally equivalent Parleeville, Gays River, and Macumber formations; sulphates of the Upperton Formation; chlorides (with or without potash) of the Cassidy Lake Formation; and chlorides, sulphates, carbonates, and clastic sedimentary rocks of the Clover Hill Formation (Fig. 3).

Rocks of the Windsor Group have undergone considerable structural alteration and erosion. Regionally, the thickness, lithofacies, and extent of Windsor strata vary markedly, reflecting the diverse structural evolution of each subbasin and the post-depositional deformation that affected Carboniferous rocks in the Maritimes. Windsor evaporites were characterized by limited compressive strength and structural competence, making them highly susceptible to deformation, such that they typically reacted like toothpaste being squeezed from a tube. The evaporites were also less dense and more buoyant than the surrounding sedimentary rock. This combination of characteristics tended to result in highly mobile, semifluid evaporite bodies moving up through the overlying sedimentary rock to an equilibrium position, where they formed domes, thickened lenses, diapirs, evaporite-cored anticlines, ridges, and walls. Thus, the subsurface distribution of Windsor evaporites represents the structurally thickened remnants of formerly horizontal, layered deposits.

Coarse- to fine-grained clastic sedimentary rocks of the Mabou Group lie conformably to unconformably above rocks of the Windsor Group and below rocks of the Late Carboniferous Cumberland and Pictou groups. Typically, the Mabou Group is a coarsening-upward succession of reddish brown mudstones to sandstones capped by conglomerates. The thickness of Mabou strata is fairly varied: up to a few thousand metres in the Sackville and Cumberland subbasins, up to 1000 m in the Moncton Subbasin, and only a few or tens of metres on the New Brunswick Platform.

Cumberland and Pictou Groups

Regionally, rocks of the Cumberland and Pictou groups overstep the Windsor Group and all other Carboniferous sequences in New Brunswick. The grey to green, coarse- to fine-grained clastic sedimentary rocks of these two groups represent the youngest Carboniferous strata in New Brunswick and underlie nearly one-third of the province. Thicknesses of these rocks may exceed a few thousand metres, but seldom exceed 1000 m on the New Brunswick Platform. The rocks reflect a semiarid, terrestrial setting. In the Chipman–Minto area (Fig. 2), the Pictou Group contains coal deposits that were mined for about three centuries.

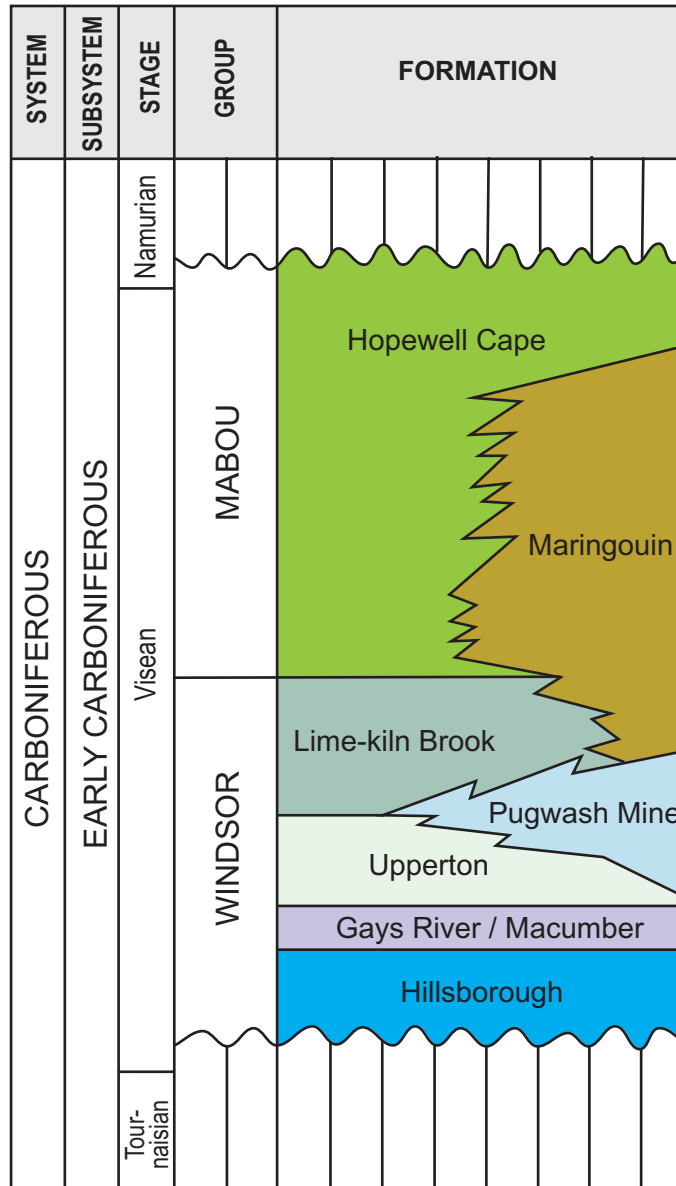


Figure 5. Early Carboniferous stratigraphic chart for the Sackville Subbasin in southeastern New Brunswick (modified after St. Peter and Johnson 2009). Vertical lines represent unconformities.

GEOLOGY OF THE SACKVILLE SUBBASIN

The Sackville Subbasin (Fig. 2, 4) is bounded by the Dorchester Fault and Westmorland Uplift to the north, Harvey–Hopewell Fault and Caledonia Uplift to the west, Wood Creek Fault and Hastings Uplift to the south, and Port Elgin Fault to the east (St. Peter and Johnson 2009). Covering approximately 1000 km², it is about 50 km long, has a maximum width of 20 km, and features a northeast-trending synclinal axis. The subbasin was filled primarily with terrestrial clastic sediments but also underwent a significant marine incursion during the Early Carboniferous, which resulted in the deposition of clastic sedimentary rocks, carbonates, and evaporites of the Windsor Group (Fig. 5).

Windsor Group

Comprehensive geological evaluation of the stratigraphy of the Windsor Group across the Sackville Subbasin has been restricted by sparse outcrop and limited subsurface data. Information on the group in the subbasin is derived mainly from a few boreholes; from regional gravity and seismic surveys; and from stratigraphic comparisons with equivalent Windsor strata within the Moncton and Cocagne subbasins in New Brunswick, and the Cumberland Subbasin in Nova Scotia (McCutcheon 1981a, 1981b; Martel 1987; Corridor Resources Inc. 1996; St. Peter and Johnson 2009; Webb 2010).

Hillsborough and Gays River/Macumber Formations

In the Sackville Subbasin, the stratigraphic base of the Windsor Group comprises several hundred metres of dark reddish brown, coarse-grained clastic sedimentary rock of the Hillsborough Formation (Fig. 5). Basinal and platformal marine carbonates of the laterally equivalent Macumber and Gays River formations disconformably overlie the Hillsborough clastic rocks. The Macumber Formation, characterized by olive grey to black, thin, parallel-laminated, even-bedded, allochthonous intraclastic and pelletoidal limestone, represents the erosional remnants of the updip platformal carbonates of the Gays River Formation.

The Gays River Formation represents basement-fringing, barrier reef or equivalent reefal build-ups of dark to light grey algal boundstone, bafflestone, wackestone, and packstone that either conformably overlie and interfinger with Macumber strata, or rest unconformably on pre-Carboniferous basement rocks (McCutcheon 1981a, 1981b). Gays River strata are locally associated with grey, coarse- to fine-grained clastic sedimentary rocks, bedded intraformational limestone, siliciclastic limestone, and limestone breccia.

Upperton Formation

The contact between the Gays River/Macumber formations and the overlying sulphates, carbonates, and fine-grained calcareous clastic sedimentary rocks of the Upperton Formation is gradational (McCutcheon 1981a, 1981b; St. Peter and Johnson 2009; Webb 2010). Dominant Upperton lithotypes comprise autochthonous and allochthonous sulphates, anhydrite, and gypsum. The allochthonous sulphate consists of replacement or displacement deposits in grey to greenish marlstone grading upward into bedded autochthonous sulphate. The latter sulphate is typically represented by anhydrite in the subsurface, various thicknesses of massive gypsum near the surface, and adjacent hydration features commonly associated with linear fault zones.

The contact between the Upperton sulphates and overlying Carboniferous rocks in the Sackville Subbasin is varied (St. Peter and Johnson 2009). At Hopewell Cape near the subbasin's western margin (Fig. 4), the Upperton is unconformably succeeded by coarse-grained clastic sedimentary rocks of the Hopewell Cape Formation (Mabou Group). In contrast, in the Dorchester area to the east, borehole data indicate that the Upperton is conformably overlain by evaporites, carbonates, and clastic sedimentary rocks of the

Pugwash Mine (St. Peter and Johnson 2009) and Lime-kiln Brook (Ryan and Boehner 1994) formations, both of the Windsor Group (Fig. 5).

Pugwash Mine Formation

Evaporites and associated rocks of the Pugwash Mine and Lime-kiln Brook formations in the Sackville Subbasin and western Cumberland Subbasin (in southeastern New Brunswick and northwestern Nova Scotia) are considered stratigraphically equivalent to similar strata of the Cassidy Lake and Clover Hill formations (Fig. 3) in the Moncton and Cocagne subbasins (Webb 2010). The Cassidy Lake Formation hosts significant potash resources; thus, the Pugwash Mine Formation may host similar potash deposits in the Cumberland and Sackville subbasins.

The nature and distribution of evaporites of the Pugwash Mine Formation in the Sackville Subbasin are not well understood. Most available information derives from three boreholes, hereafter referred to by their Unique Identification Number (UIN) in the NBDNR Borehole Database (NBDNR 2004) and more fully described therein: Shell Dorchester No. 1 or Well 325, Imperial Dorchester No. 1 or Well 330, and Columbia/Corridor Coppermine Hill or Well 711. Wells 325 and 330 lie 2.6 km apart near Dorchester, and Well 711 is situated about 6 km northeast of Dorchester in the vicinity of Coppermine Hill (Fig. 4).

About 977 m of Pugwash Mine evaporite, consisting almost entirely of colourless to white halite with varied amounts of sulphate (anhydrite stringers and selenite crystals), was encountered at a depth of 542 m in Well 325 (NBDNR 2004). Information concerning the purity of the halite is limited; however, a weighted average over a 25 m interval obtained by Wright (1950) indicated a purity of near 89% halite. Well 330 intersected about 795 m of halite interbedded with red to reddish brown to grey, fine-grained clastic sedimentary rock (shale to very fine-grained sandstone) and carbonate (NBDNR 2004). The more recent (2000) Well 711 intersected 150 m of Pugwash Mine Formation at a depth of 1962 m. The formation there was composed of pink halite with occasional thin bands of argillaceous halite, minor clasts of red claystone, and an interval of grey shale and anhydrite (NBDNR 2004).

Lime-kiln Brook Formation

Seismic profiles suggest that, in general, the Lime-kiln Brook Formation concordantly overlies the Pugwash Mine Formation in the central part of the Sackville Subbasin (Martel 1987) and represents the uppermost part of the Windsor Group in the subbasin (Fig. 5). Distribution is poorly documented, but borehole intersections indicate that the Lime-kiln Brook Formation is a variably mixed sequence of coarse- to fine-grained clastic sedimentary rock, carbonate, sulphate, and chloride (Fig. 6a–c).

St. Peter and Johnson (2009) state that the Lime-kiln Brook Formation is not present everywhere and is in part laterally equivalent to, and interfingers with, fine-grained clastic sedimentary rocks of the Maringouin Formation (Mabou Group). Near the western limit of the subbasin, the upper part of the Lime-kiln Brook Formation is exposed on the Shepody Bay coast at Hopewell Cape (Fig. 4). Lime-kiln Brook strata in that location comprise a 50 m thick

Figure 6a. Carbonate grainstone, siliciclastic wackestone, fine-grained calcareous sandstone, and siltstone of the Early Carboniferous Lime-kiln Brook Formation (Windsor Group) near Hopewell Cape, southeastern New Brunswick (see Fig. 4). Height of outcrop in the foreground is about 5 m.



Figure 6b. Algal stromatolites of the Lime-kiln Brook Formation near Hopewell Cape. Coin diameter is 1.9 cm.



Figure 6c. Oncolitic carbonate mudstone of the Lime-kiln Brook Formation near Hopewell Cape. Coin diameter is 1.9 cm.

section of fine- to medium-grained clastic sedimentary rocks and overlying carbonate (Fig. 6a–c). Carbonate and sulphate of the Lime-kiln Brook Formation are also exposed in narrow fault wedges along the Harvey–Hopewell Fault northwest of Hopewell Cape, and at a former quarry near Upper Dorchester (Fig. 4).

Well 325 intersected a 422 m thickness of Lime-kiln Brook anhydrite and gypsum at a depth of 121 m, gradationally overlying Pugwash Mine halite (St. Peter and Johnson 2009). According to St. Peter and Johnson (2009), Well 330 intersected 131 m of Lime-kiln Brook Formation at a depth of 1445 m, comprising predominantly fine-grained red and grey shale and mudstone with minor halite and anhydrite. Lime-kiln Brook strata were also intersected at a depth of 1085 m in Well 711, where the formation is 879 m thick and consists mainly of grey to reddish brown claystone and shale with significantly thick intervals of dolomite, anhydrite, and halite (St. Peter and Johnson 2009). The contact with the underlying Pugwash Mine Formation at a depth of 1962 m in Well 711 may be erosional, as the Pugwash Mine halite is much thinner there than in Well 325 (Fig. 4).

Mabou Group

The Lime-kiln Brook Formation in the Sackville Subbasin is conformably overlain by, and interfingers with, a sequence of coarse- to fine-grained clastic sedimentary rocks of the Hopewell Cape and Maringouin formations of the Mabou Group (Fig. 5; St. Peter and Johnson 2009). The Hopewell Cape and Maringouin formations are considered to be laterally equivalent by St. Peter and Johnson (2009).

In the western area of the Sackville Subbasin, the relative distribution of coarse- and fine-grained Mabou rocks differs, depending on their proximity to pre-Carboniferous upland areas of provenance. Reddish brown polymictic conglomerate, with minor amounts of sandstone and mudstone, constitute the proximal facies of the Hopewell Cape Formation (Fig. 7a), whereas a more distal, basinal facies is represented by red mudstone and siltstone of the Maringouin Formation (Fig. 7b). The Mabou Group in this area is conformably overlain by a mixed sequence of Late Carboniferous sedimentary clastic rocks of the Cumberland Group (Fig. 4).

EVAPORITE STRUCTURES IN THE SACKVILLE SUBBASIN

Seismic and gravity data, as well as limited borehole data, suggest that several evaporite structures may lie within the Sackville Subbasin, in addition to the one known to exist in the vicinity of Dorchester (Fig. 4, 8a–e, 9, 10).

Dorchester Evaporite Structure

Differing structural interpretations have been presented for the approximately 1000 m of halite and related evaporites intersected in boreholes near Dorchester (Fig. 8b–e). Some authors (Gussow 1953; Hamilton 1961; Potter 1967; Howie 1988) suggest that the evaporite structure is a thick, diapiric mass, whereas St. Peter and Johnson (2009) interpret it as a southward-plunging tabular body.

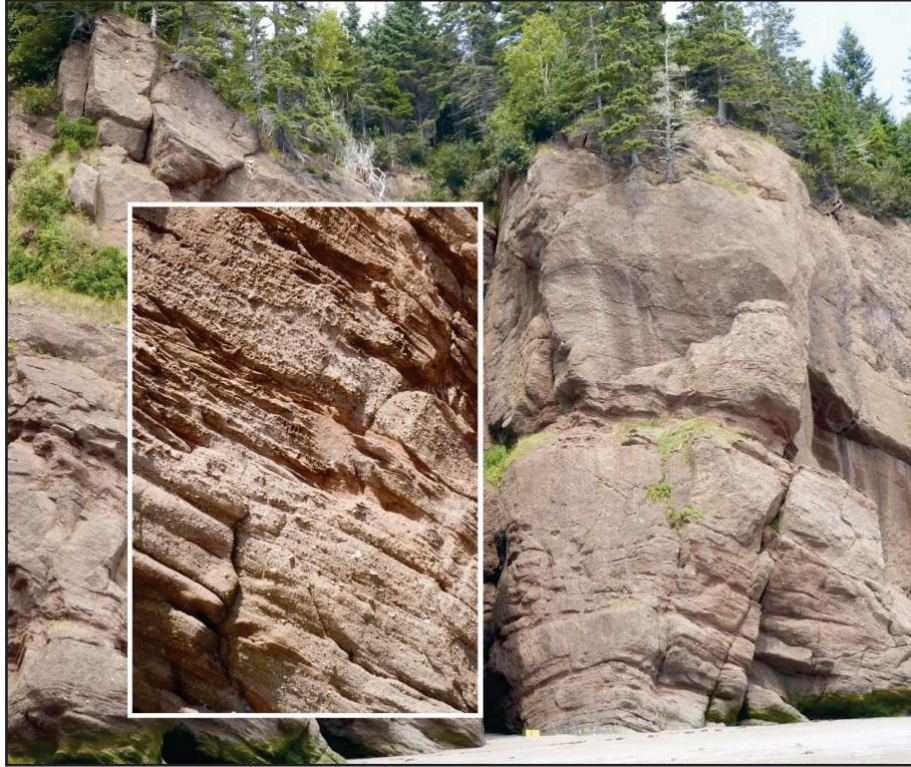


Figure 7a. Maroon to red, cross- and flat-bedded polymictic fluvial conglomerate and lithic sandstone of the Early Carboniferous Hopewell Cape Formation (Mabou Group) at Hopewell Cape, southeastern New Brunswick (Fig. 4). The cliff in the distance is approximately 25 m high; the outcrop in the close-up view is about 6 m high.



Figure 7b. Brick red to reddish brown mudstone and siltstone of the Early Carboniferous Maringouin Formation (Mabou Group) at Cape Enrage, southeastern New Brunswick (Fig. 2). The cliff in the distance is about 10 m high.

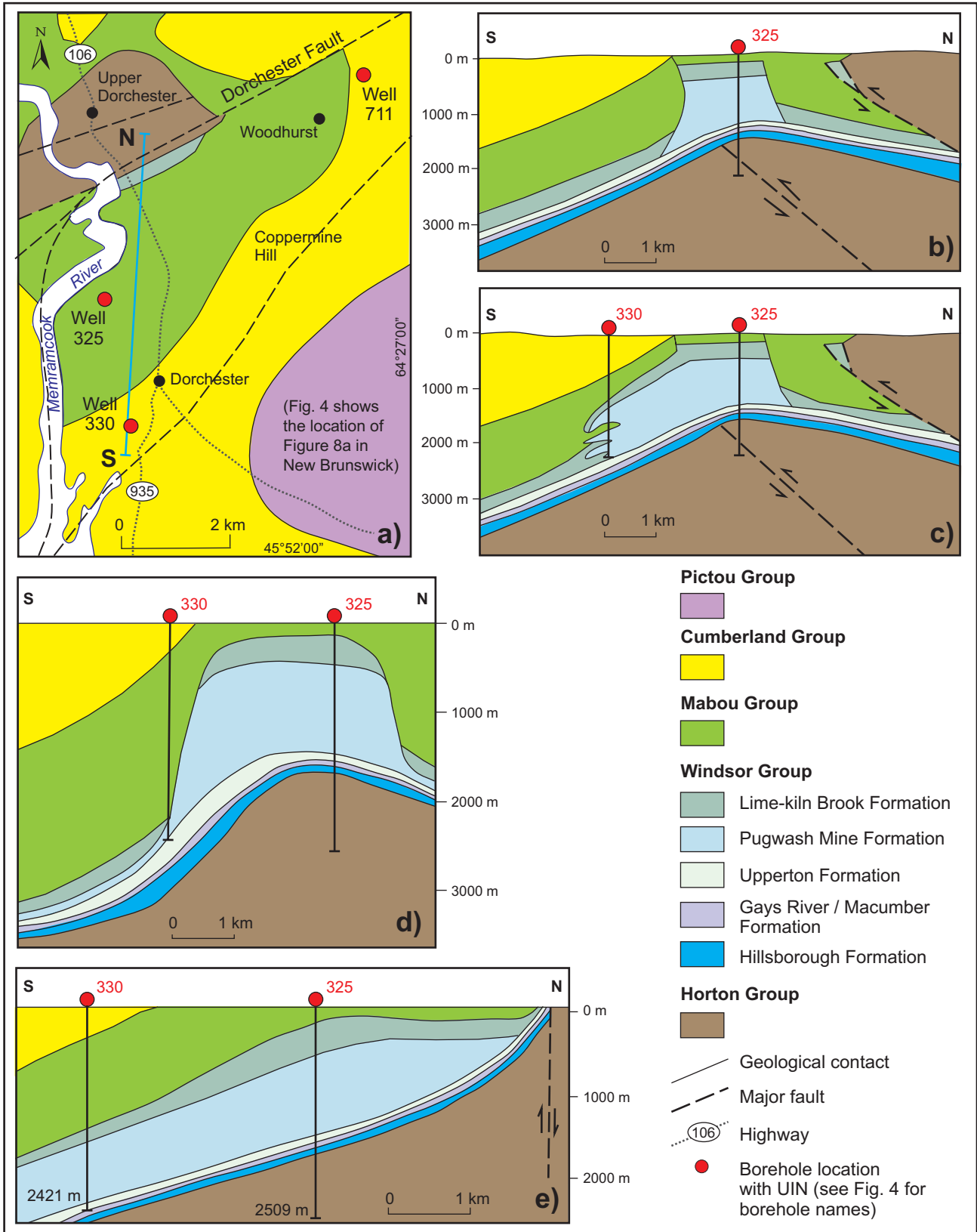


Figure 8. Subsurface geological cross-sections, indicating different stratigraphic and structural interpretations of the evaporite structure near Dorchester, southeastern New Brunswick. The approximate line of section N–S for Figures 8b to 8e is shown on Figure 8a. Interpretations are after Gussow (1953: Fig. 8b), Potter (1967: Fig. 8c), Howie (1988: Fig. 8d), and St. Peter and Johnson (2009: Fig. 8e).

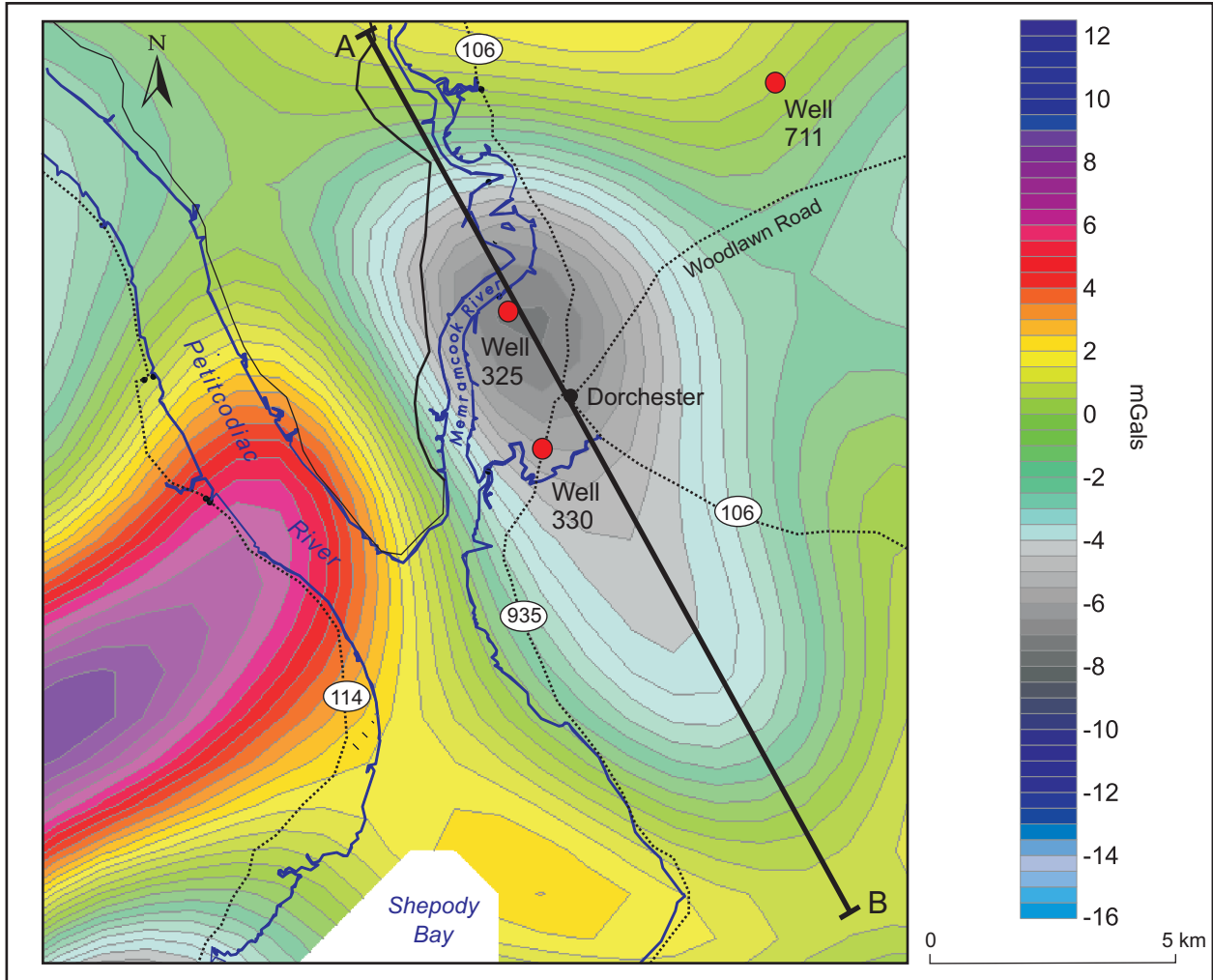
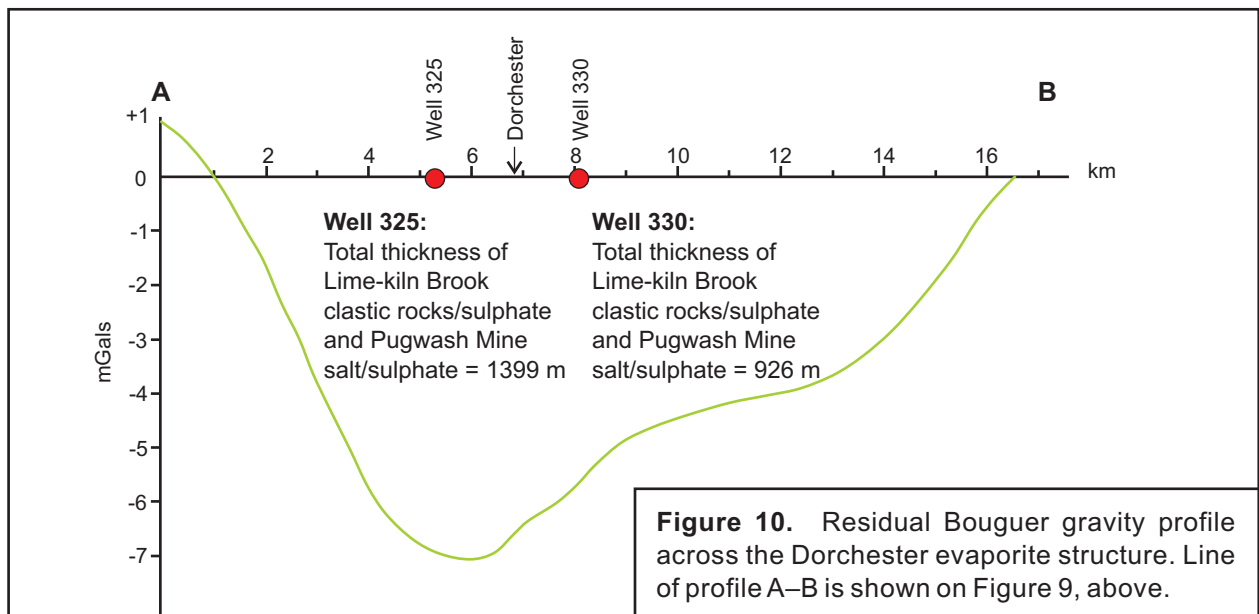


Figure 9. Residual Bouguer gravity map in the area of the Dorchester evaporite structure, with gravity data from Allard and Rennick (2009). Compare this figure with the Bouguer gravity profile on Figure 10 (below) and the geological maps on Figure 8a (facing page) and Figure 4.



Well 325 is positioned on the crest of the evaporite structure and intersected 977 m of generally clean halite interbedded with varied amounts of disseminated sulphate and argillaceous material of the Pugwash Mine Formation. Well 330, a short distance to the south (Fig. 4, 8a), intersected 795 m of impure halite interlayered with sulphate and silty to very fine-grained clastic sedimentary rocks. In the diapiric model (Fig. 8b–d), this argillaceous halite–sulphate sequence is part of the overlying Lime-kiln Brook Formation that was peripherally incorporated during the upward migration of the Pugwash Mine evaporites to an equilibrium position in the sedimentary pile. The evaporite structure dips steeply to the south in the area of Well 325 and steeply to the east in the area of Well 711.

In the tabular model (Fig. 8e), a major part of the argillaceous halite–sulphate sequence in Well 330 is considered to be a south-dipping extension of the upper portion of the Pugwash Mine Formation rather than part of the overlying Lime-kiln Brook Formation. As such, the drilled thicknesses of the Pugwash Mine Formation in Wells 325 and 330 (977 m and 795 m, respectively) are comparable, thereby giving the evaporite structure a tabular shape. The considerable lithological differences in the halite–sulphate–clastic interval between the two boreholes, particularly in the amount of salt, would require a facies variation over a distance of less than 3 km. To explain this variation, St. Peter and Johnson (2009) propose that the Dorchester evaporite structure experienced fault-related structural thickening accompanied by dissolution and differential collapse of the evaporite sequence.

Both the diapiric and tabular models support structural thickening (but to differing degrees) of the Pugwash Mine Formation and subsequent partial dissolution of the Pugwash Mine and Lime-kiln Brook evaporites, followed by collapse of the Lime-kiln Brook onto the underlying Pugwash Mine strata. It is interesting to note that similar evaporite deposits in the Moncton and Cocagne subbasins of New Brunswick, and particularly in the Cumberland Subbasin of northwestern Nova Scotia, also exhibit features resulting from periods of folding and faulting.

The regional residual Bouguer gravity map of the area (Fig. 9, 10) shows a north–south-elongated feature that helps to define the extent of the Dorchester evaporite structure. The circular to elliptical shape of closely spaced residual gravity contours in the area of Wells 325 and 330 delineates the boundary of a thick evaporite structure that lies fairly close to the surface and terminates rather abruptly to the north. South of Well 330, gravity contours become more elongated and widely spaced. Several possible scenarios may explain this gravity response: gradual plunging and deepening of a thick, increasingly impure evaporite structure to the south; rapid thinning and deepening of a high-purity evaporite structure to the south; or lack of adequate gravity control in key areas between Highways 106 and 935, and between Highway 106 and Woodlawn Road to the north (Fig. 9). Wider spacing of gravity contours and an increase in gravity values favour the interpretation of a rapid thinning and deepening of high-purity Pugwash Mine evaporite from Well 325 northeastward to Well 711 (Fig. 4).

Potential Evaporite Structures

Regional gravity data elsewhere in the Sackville Subbasin support a configuration of gravity lows suggestive of Pugwash Mine and Lime-kiln Brook evaporite remnants adjacent to, or

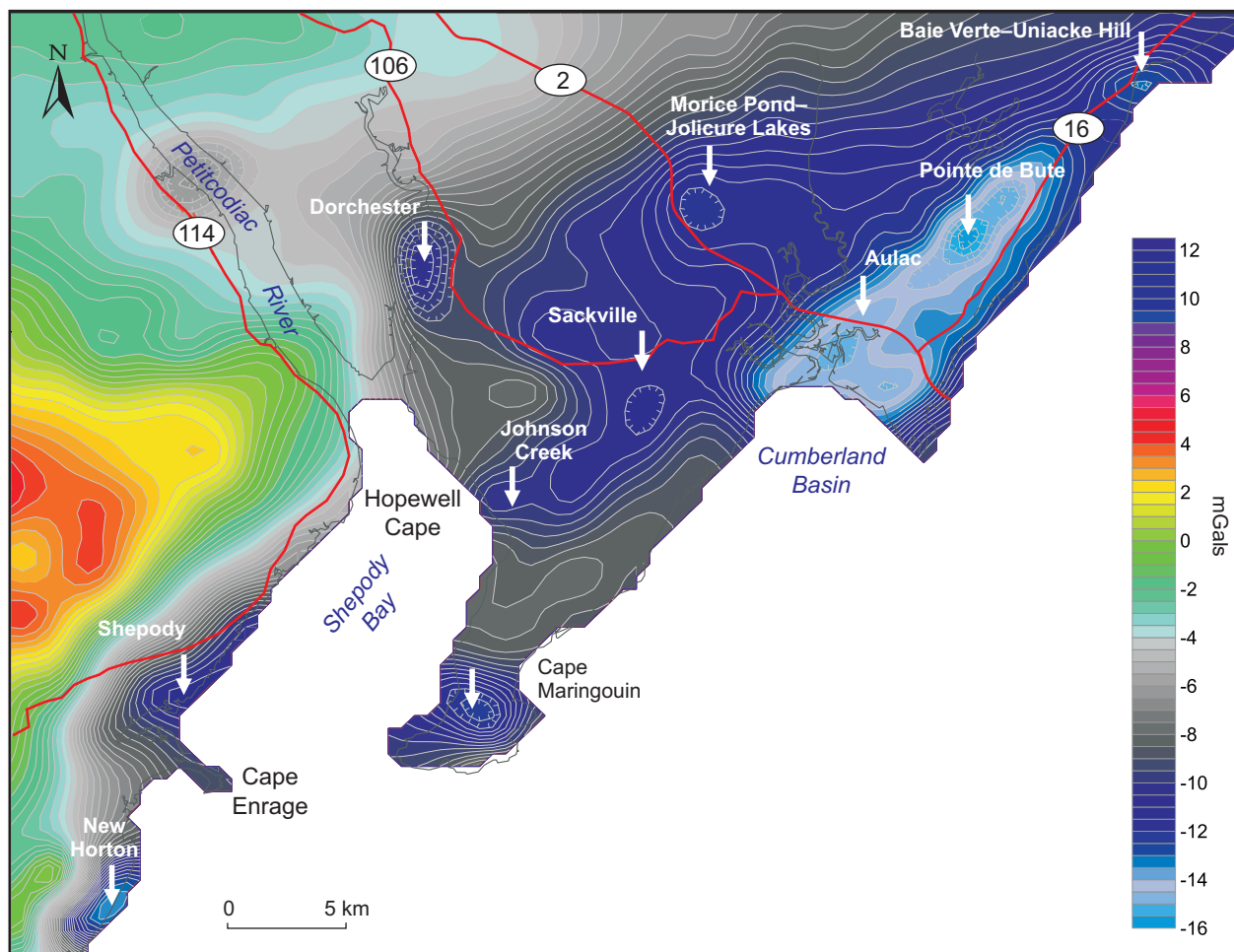


Figure 11. Regional residual Bouguer gravity map, showing the Dorchester evaporite structure and several potential subsurface evaporite bodies (white arrows) of the Windsor Group in the Sackville and Cumberland subbasins (gravity data from Allard and Rennick 2009). See inset on Figure 2 for the location of this map area in southeastern New Brunswick.

bounded by, major regional fault structures (Allard and Rennick 2009). Locations of interest include Johnson Creek, Morice Pond, Jolicure Lakes, Sackville, Aulac, Pointe de Bute, and the Baie Verte–Uniacke Hill area (Fig. 11). Although geological data relevant to these potential evaporite targets are limited, some information is contained in the following Oil and Natural Gas (ONG) reports of work, available at NBDNR in Fredericton, New Brunswick (St. Clair Pipelines Ltd. 1997; Intragaz Inc. 1998a–c, 1999a–c, 2000a, 2000b, 2001a–c, 2002, 2004, 2005a, 2005b).

The geological and geophysical data discussed above suggest that some modification is required to previous models proposed for the Dorchester evaporite body. Several regionally extensive, northeast-trending fault structures occur within the Sackville Subbasin, and it is reasonable to suggest that multiple crustal adjustments associated with these structures would be reflected in the region's evaporite deposits. Thickened evaporite bodies; coarsely crystalline and recrystallized, relatively clean halite; and dissolution and collapse textures (disseminated sulphate) within the Pugwash Mine and Lime-kiln Brook formations therefore indicate the occurrence of considerable diagenetic and post-depositional alteration (Fig. 12).

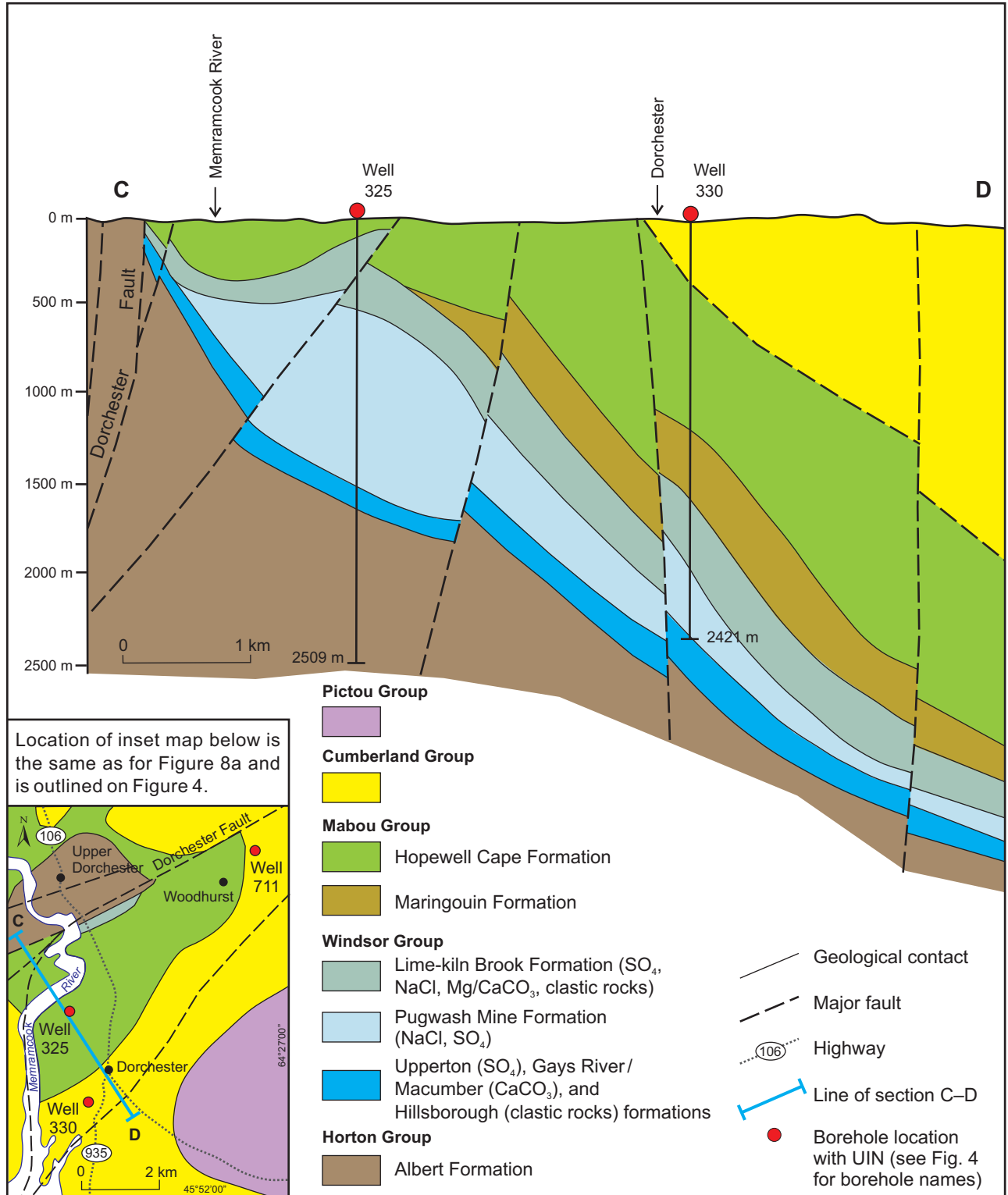


Figure 12. Cross-section illustrating interpreted fault structures that may have played a role in the preservation and distribution of Windsor evaporites in the Sackville Subbasin. Section shows the salt structure of the Pugwash Mine Formation thinning to the south and overlain by a thick sequence of the Lime-kiln Brook Formation. The fault structures are interpreted to have transected the evaporite strata, resulting in localized stratigraphic thickening, salt dissolution, and subsequent collapse of less soluble, overlying strata. Inset map shows the line of section C–D.

The schematic cross-section of the Dorchester evaporite structure (Fig. 12) differs from the tabular model of St. Peter and Johnson (2009), mainly in the increased thickness of the Lime-kiln Brook Formation and corresponding decreased thickness of the Pugwash Mine Formation in Well 330. See *Pugwash Mine/Lime-kiln Brook Contact in Well 330* (p. 29) for further details.

APPLICATION OF BROMINE GEOCHEMISTRY TO POTASH EXPLORATION

Introduction

Bromine concentration and distribution in marine evaporite deposits has been studied for almost a century. Several reports provide a basis for using bromine analysis in potash exploration (e.g., Valyashko 1956; Baar 1965; Braitsch 1966; Holser 1966; Raup 1966; Khun 1968; Raup et al. 1970; Holser et al. 1972; Raup and Hite 1978; Schramm et al. 2002; O'Driscoll et al. 2009). Bromine analyses can help to interpret paleosalinities in evaporite basins, to confirm whether an evaporite lies in its original depositional state, to determine diagenetic changes that affected an evaporite deposit, and to evaluate how diagenesis affected deposit preservation.

Boudreau (1975), Crosby (1975, 1982, 1983), Anderle et al. (1979), Waugh and Crosby (1979), and Webb et al. (2009) present bromine analyses that have helped to determine the paragenesis, as well to delineate the stratigraphy and structure, of several potash-bearing evaporite deposits within the Cocagne and Moncton subbasins of New Brunswick. The current report offers some preliminary analyses of bromine in evaporite rocks from the Sackville Subbasin.

Bromine Geochemistry

Marine evaporites precipitate in a specific sequence: first the carbonates, then the sulphates, and finally the chloride salts of sodium, potassium, and magnesium. Bromide is the fourth most abundant anion in seawater after chloride, sulphate, and bicarbonate. Bromine does not form its own evaporite mineral during the evaporation of seawater and subsequent crystallization of soluble chloride salts from that seawater. Instead, bromine (Br) typically becomes concentrated in two phases: in the liquid brine of dissolved chloride salts and other constituents, and as a solid solution replacement for the chlorine (Cl) ion in various sodium–potassium–magnesium (Na–K–Mg) chloride salts (Fig. 13). Bromine can substitute for chlorine in the crystal lattice of halite (NaCl) and other chloride salts, because the ionic size of Br (1.96 Å) is comparable with that of Cl (1.81 Å) (Warren 2006).

The amount of bromine that can be substituted into the solid phase of a chloride salt depends on the bromine concentration in the parent brine at the time of initiation of halite precipitation, and on the distribution coefficients of the salts, which in turn depend on temperature (Valyashko 1956). The distribution coefficient is defined as the ratio of Br/Cl (mineral) to Br/Cl (solution); it is low for halite and high for sylvite (KCl) and carnallite (KMgCl₃·6(H₂O)) (Braitsch 1971; Herrmann 1972).

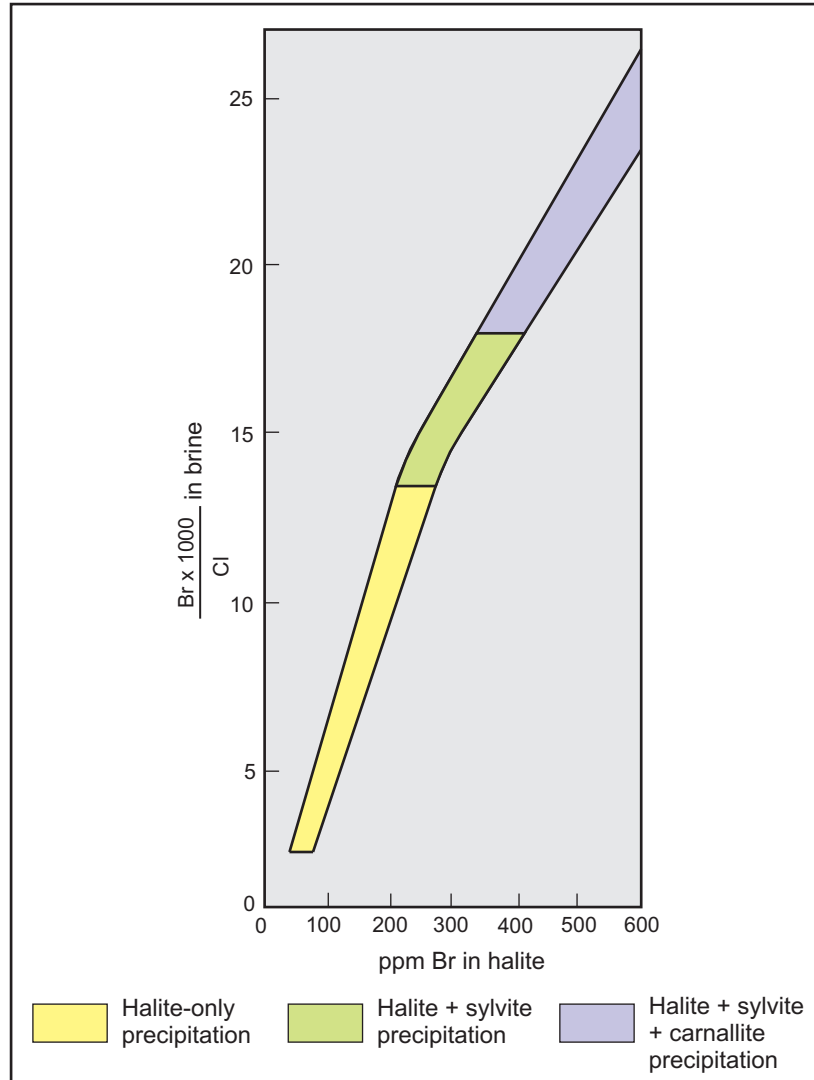


Figure 13 . Calculated bromine content in solid halite as a function of the Br:Cl ratio in residual brine (after Valyashko 1956). Coloured segments indicate the ranges of precipitation.

During evaporation, seawater becomes increasingly concentrated in bromine and chlorine within the residual brine. When halite saturation is achieved and crystallization begins, chlorine is removed preferentially over bromine from the parent brine. A small fraction of bromine is incorporated into the halite structure, but most of the bromine remains in the parent brine. As evaporation continues, the concentration of bromine, potassium, magnesium and other brine ions increases. The content of bromine rises in both the brine and the crystallizing salt. Only when saturation with respect to potassium, magnesium, and chlorine is reached do the high distribution coefficients of the resulting sylvite and carnallite allow for a significant amount of Br to be incorporated into their crystal structure.

The Br content of fresh seawater is near 65 ppm and is reported to increase to about 500 ppm as the first halite begins to crystallize from the brine solution (Valyashko 1956). During the halite-only depositional stage, Br concentration in the residual brines is reported to reach about 2300 ppm prior to the appearance of the first potash minerals (Valyashko 1956). The calculated

maximum amount of Br that can be incorporated into the initial solid halite phase during the halite-only depositional stage has been reported as approximately 75 ppm (Holser et al. 1972; Schramm et al. 2002). However, the actual maximum value has been observed to vary from 20 ppm to 100 ppm Br, according to Valyashko (1956), Braitsch and Herrmann (1963), Raup et al. (1970), Garrett (1995), and Warren (2006). Continued concentration of a brine increases Br accumulation in solid halite phases at successive stages of crystallization, such that calculated levels reach 230 ppm to 270 ppm (Fig. 13) before the accumulation of bittern (potassium and magnesium chloride minerals) (Valyashko 1956; Braitsch and Herrmann 1963; Holser et al. 1972; Raup and Hite 1978; Schramm et al. 2002; Warren 2006).

This discrepancy between the reported actual versus the calculated maximum values, as well as the very low Br concentrations (<5 ppm) in similar salts, is explained by localized dissolution by diluted ephemeral brine (i.e., new seawater); by upward moving intraformational brine; or by non-marine waters and subsequent post-depositional recrystallization of the chloride phase (Warren 2006). In some instances, bromine concentration in halite can thus result in misinterpretation of the parent brine's characteristics.

Bromine content in chloride salts may therefore be used with caution to reconstruct salinity variations in marine evaporite basins and to provide important information concerning stability of the brine and various chlorides at the time of accumulation. As potash-bearing salts are crystallized from highly concentrated brines, halite in and near potash beds should contain higher primary bromine concentrations than halite precipitated from less concentrated brines. Ideally, a bromine concentration profile should display a steady rise in Br as it slopes upward through the ranges of halite to overlying potash, and associated salts. However, such a bromine profile is seldom achieved, due to the sedimentary effects discussed above.

Bromine Geochemistry of Windsor Evaporites

Cuttings from the halite intersected in Wells 325, 330, and 711 near Dorchester (Fig. 4, 8a) were analyzed for bromine in order to augment the limited geological data for evaporites of the Windsor Group in the Sackville Subbasin. These analyses were then used to assist in determining the potential for economic potash deposits in the subbasin.

To minimize the influence of clay and sulphate impurities on bromine values, only clean halite was selected for analysis (Fig. 14a, 14b). Composite 10 g samples were hand-picked over spaced intervals of 15 m to 20 m in each borehole, and all samples underwent bromine and multi-element analysis. The prepared samples consisted of

- 64 samples selected over the 977 m halite interval of the Pugwash Mine Formation in Well 325
- 30 samples selected over the 795 m halite interval of the Lime-kiln Brook and Pugwash Mine formations in Well 330, and
- 9 samples selected over the 150 m halite interval of the Pugwash Mine Formation (excluding the bottom 27 m) in Well 711.



Figure 14a. Vials of salt cuttings from Well 325 (Shell Dorchester No. 1) near Dorchester, southeastern New Brunswick. See Figures 4 and 8a for the location of the borehole.



Figure 14b. Example of clean halite, hand-picked for analysis from vials of salt cuttings, shown in Figure 14a.

The analyzed elements consisted of Br, Ca, Cl, K, Na, S, Sr, and SO₄ and were quantified using three different analytical methods. Ion Chromatography (IC) was used to determine the concentrations of Br, Cl, and SO₄. Br was also analyzed using Instrumental Neutron Activation Analysis (INAA), and the remaining elements were analyzed by Induced Coupled Plasma–Optical Emission Spectrometry (ICP–OES). The resulting geochemical data are summarized in Tables 1 to 3, inserted at the end of this report before **References**.

DISCUSSION

Well 325 (Shell Dorchester No. 1)

The clean to sulphatic halite of the Pugwash Mine Formation in Well 325 has a drilled thickness of nearly 977 m, which represents the thickest accumulation of Windsor chlorides intersected in the Sackville Subbasin (and, incidentally, the thickest drilled indicated accumulation of halite in New Brunswick). Figure 15 plots the bromine concentrations of composite solid halite samples that generally correspond to the selected intervals.

Two atypical features stand out in the Well 325 bromine profile. First, the profile includes much lower than expected bromine values for halite; second, the low values remain fairly consistent over several hundred metres. Several authors (Valyashko 1956; Braitsch and Herrmann 1963; Rahimpour-Bonab and Kalantarzadeh 2005) suggest that halite originating as a precipitate from normal seawater should contain about 75 ppm Br, increasing to a maximum of 230 ppm to 270 ppm Br prior to the accumulation of major bittern. Yet Br levels in the halite section of Well 325 seldom exceed 20 ppm (Fig. 15), and 51% of the sampled intervals fall into the range of 15 ppm to 20 ppm Br. Maximum Br concentration reaches only 33 ppm, while concentrations below 5 ppm appear at nine different intervals throughout the sampled section.

The uncharacteristically low bromine values in Well 325 indicate that the Pugwash Mine evaporites are not primary marine evaporites. Rather, they may be the product of multiple cycles of solution and reprecipitation, possibly linked to contemporaneous brine mixing with fresh water or diagenetic and other post-depositional alteration caused by migrating fluids of drastically differing bromine concentration. Warren (2006) states that halite formed in a second cycle of solution and recrystallization in the presence of lower bromine content tends to show values of 20 ppm Br or less, particularly if the recycling waters were not of marine origin.

While studying evaporites with similarly low bromine values from the Lower Elk Point evaporite deposit in eastern Alberta, Holser et al. (1972) concluded that a process of solution and recrystallization, under the action of waters other than residual brines, was most likely responsible for the low bromine values. It was determined that the calculated bromine maximum (75 ppm Br) of halite crystallized from seawater could be reduced to 3 ppm Br during a second solution–crystallization cycle by the action of bromide-deficient waters. To yield such low values would require solution waters that were comparatively devoid of bromine.

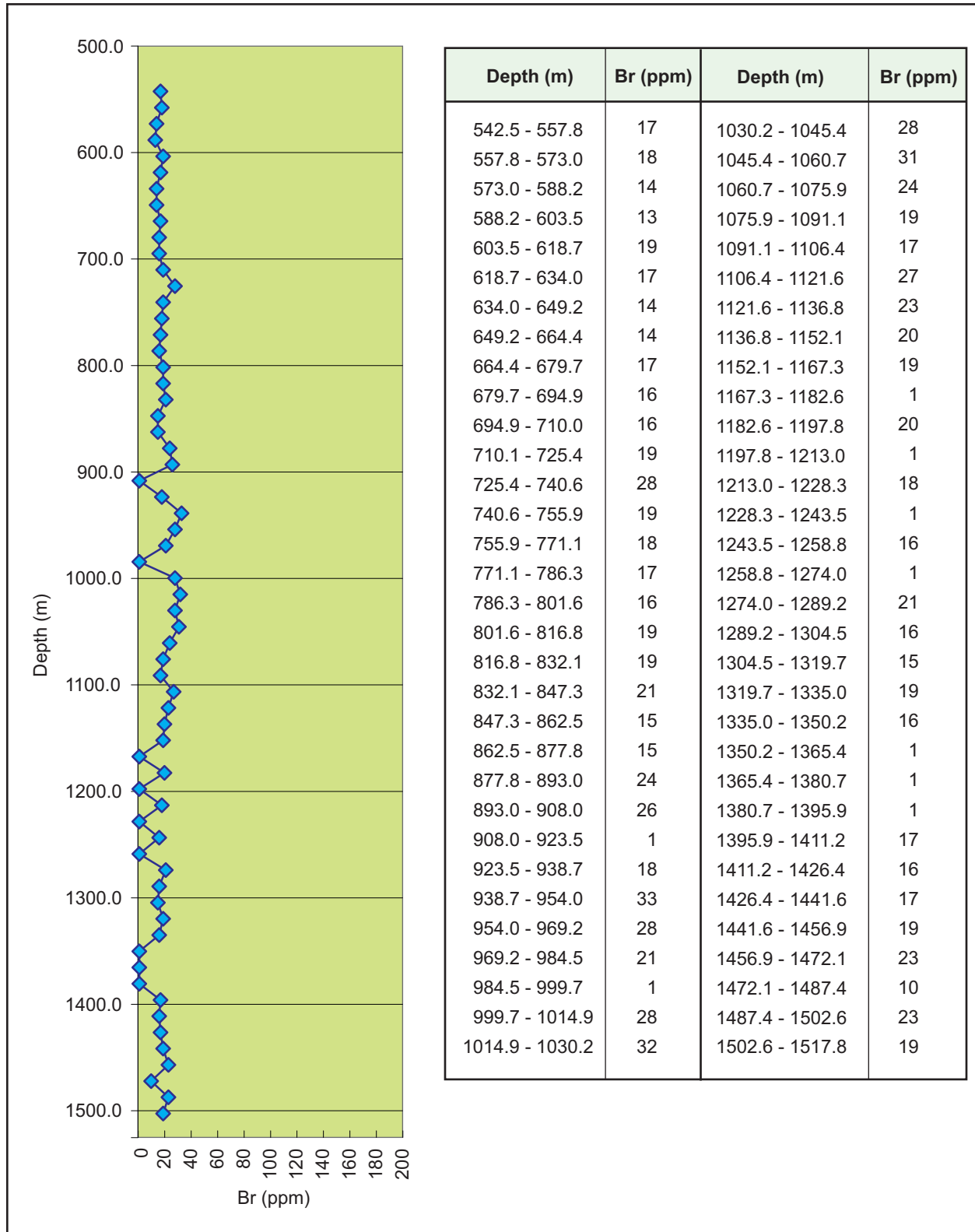


Figure 15. Bromine profile for halite of the Pugwash Mine Formation, Windsor Group, from Well 325 (Shell Dorchester No. 1) near Dorchester, southeastern New Brunswick. See Figures 4 and 8a for the location of the borehole.

Bromine geochemistry alone does not provide conclusive evidence on which to base a definitive depositional model for the extensive halite interval in Well 325. The typical 65 ppm Br content of normal seawater appears to contradict the likelihood of seawater freshening being the primary means in lowering bromine levels to those analyzed in chloride from this well. Dissolution involving possibly multiple interactions (i.e., leaching) with fresh water may be required to explain the low bromine values. Such a model would include the following stages: 1) halite deposition from seawater, 2) exposure of porous halite to fresh waters percolating downward or upward through the halite, 3) partial solution of the halite resulting in a saturated chloride solution with low secondary levels of bromine, 4) eventual solution equilibration with remnant halite crystals via new crystallization, coupled with gradual extraction of bromine from the crystal, and 5) disposal of the bromine-rich solution elsewhere (i.e., in the Moncton and Cocagne subbasins to the west).

It is important to note that any bromine leaching by a higher volume of fresh water is typically accompanied by halite dissolution and subsequent saturation of such water with NaCl while bromine is equilibrating in the halite. A corresponding volume decrease of the original halite interval also takes place. However, calculations by Holser et al. (1972) demonstrate that “slow differential leaching by the continuous flow of small amounts of fresh water result in a significant lowering of bromine with a minimized effect on the solution and subsequent volume reduction of halite...” (Holser et al. 1972, p. 71). Apart from any post-depositional structural thickening, the extensive thickness of halite in Well 325 suggests periodic, differential leaching with a minimal loss of halite. Interestingly, the insoluble residue of the dissolution process is reflected in the fairly concentrated and varied sulphate content in the halite section of this borehole, particularly in the interval from 550 m to 900 m.

Thus, the bromine profile of the Pugwash Mine evaporites in Well 325 reflects a structurally thickened interval of halite characterized by very low to low bromine levels. The interval possibly correlates to the basal halite member of the Cassidy Lake Formation in the Moncton and Cocagne subbasins (Fig. 2), neither of which have significant potash mineralization associated with that basal halite strata.

Well 330 (Imperial Dorchester No. 1)

The 795 m drilled thickness of halite in Well 330 is characterized by a relatively consistent Br concentration that seldom exceeds 30 ppm (Fig. 16). However, the concentration progressively increases between 1640 m and 1789 m, and again between 2002 m and 2066 m, the highest concentration being 185 ppm. Halite intervals in this borehole have bromine signatures typical of at least five hydrologic regimes; these are marked by the intervals between A and F in Figure 16.

- Interval A–B demonstrates a stable hydrologic regime of nearly constant salinity, although the average Br level of 16 ppm (ranging from 12–21 ppm) is exceptionally low for primary halite. The low and consistent bromine content of this interval is strikingly similar to the halite interval in Well 325 situated 2.6 km to the north, suggesting a similar

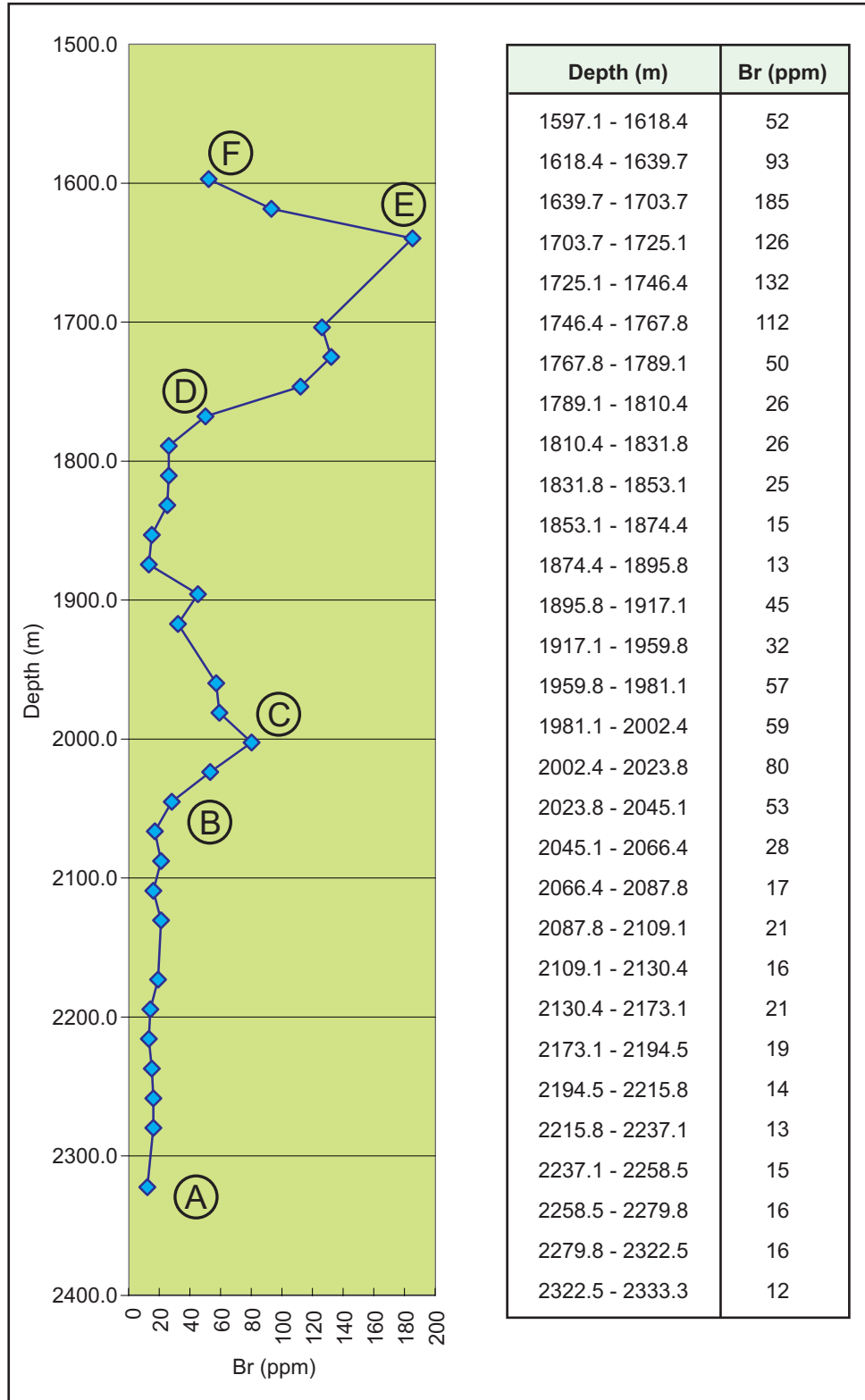


Figure 16. Bromine profile for halite of the Pugwash Mine Formation and Lime-kiln Brook Formation, Windsor Group, from Well 330 (Imperial Dorchester No. 1) near Dorchester, southeastern New Brunswick. See Figures 4 and 8a for the location of the borehole.

geological model of continuous bromine leaching with fresh waters and subsequent equilibration and concentration of bromine-rich brine elsewhere.

- The relatively sharp increase in bromine values in interval B–C corresponds to the section between 2002 m and 2066 m cited above. It may in fact reflect part of the aforementioned residual, bromine-enriched solution or may simply represent continued basin desiccation and gradual build-up toward bittern deposition.
- Interval C–D, characterized by a general decrease in bromine with some fluctuation, suggests the return to an influx of fresh water or seawater and subsequent lowering of evaporation rates.
- Interval D–E corresponds to the section between 1640 m and 1789 m cited above. It shows a sharp increase in bromine, with a maximum Br concentration of 185 ppm. Halite in this interval is slightly pinkish, similar to potash-bearing evaporites in areas of the Moncton and Cocagne subbasins. Potassium levels in interval D–E are directly proportional to elevated bromine, whereas strontium and sulphate concentrations display an inverse relationship (Table 2). The decrease in strontium values is indicative of increased progressive evaporation and the potential beginning of bittern precipitation (Crosby 1975). However, the elevated Br signatures of the halite are well below the minimum threshold (i.e., ~230–250 ppm) for primary precipitation of bittern chlorides (Rahimpour-Bonab and Kalantarzadeh 2005). Primary bittern deposits could have existed here and have been removed by some late diagenetic event, including but not restricted to recrystallization by non-marine (meteoric) inflows. The above scenario could be interpreted as a residual indication of potash mineralization that possibly was preserved elsewhere in the Sackville Subbasin. However, further work is required to reach a more definite conclusion concerning such preservation.
- The interval E–F features a sharp decrease in bromine concentration, suggesting an influx of fresh water or seawater.

Well 711 (Columbia/Corridor Coppermine Hill)

Well 711 lies northeast of Wells 325 and 330 and is named in part after the nearby Coppermine Hill (Fig. 4, 8a). Well 711 intersected two significant evaporite-bearing intervals at 1758 m and 1962 m (St. Peter and Johnson 2009). Only the 150 m thick halite interval between 1962 m and 2112 m, identified as the Pugwash Mine Formation, was analyzed for bromine (Fig. 17).

Bromine values over the analyzed interval were fairly consistent, averaging 127 ppm (ranging from 97–156 ppm). Such values are higher than ones from the stratigraphically equivalent halite deposits in Wells 325 or 330. The limited thickness of the Pugwash Mine halite section in Well 711 and the consistency of its bromine profile compared with those from Wells 325 and 330 nearer Dorchester suggest a significant loss of portions of the evaporite sequence in the vicinity of Coppermine Hill. The higher, and relatively narrow spread of, bromine values in Pugwash Mine evaporites in Well 711, coupled with a similar trend for potassium

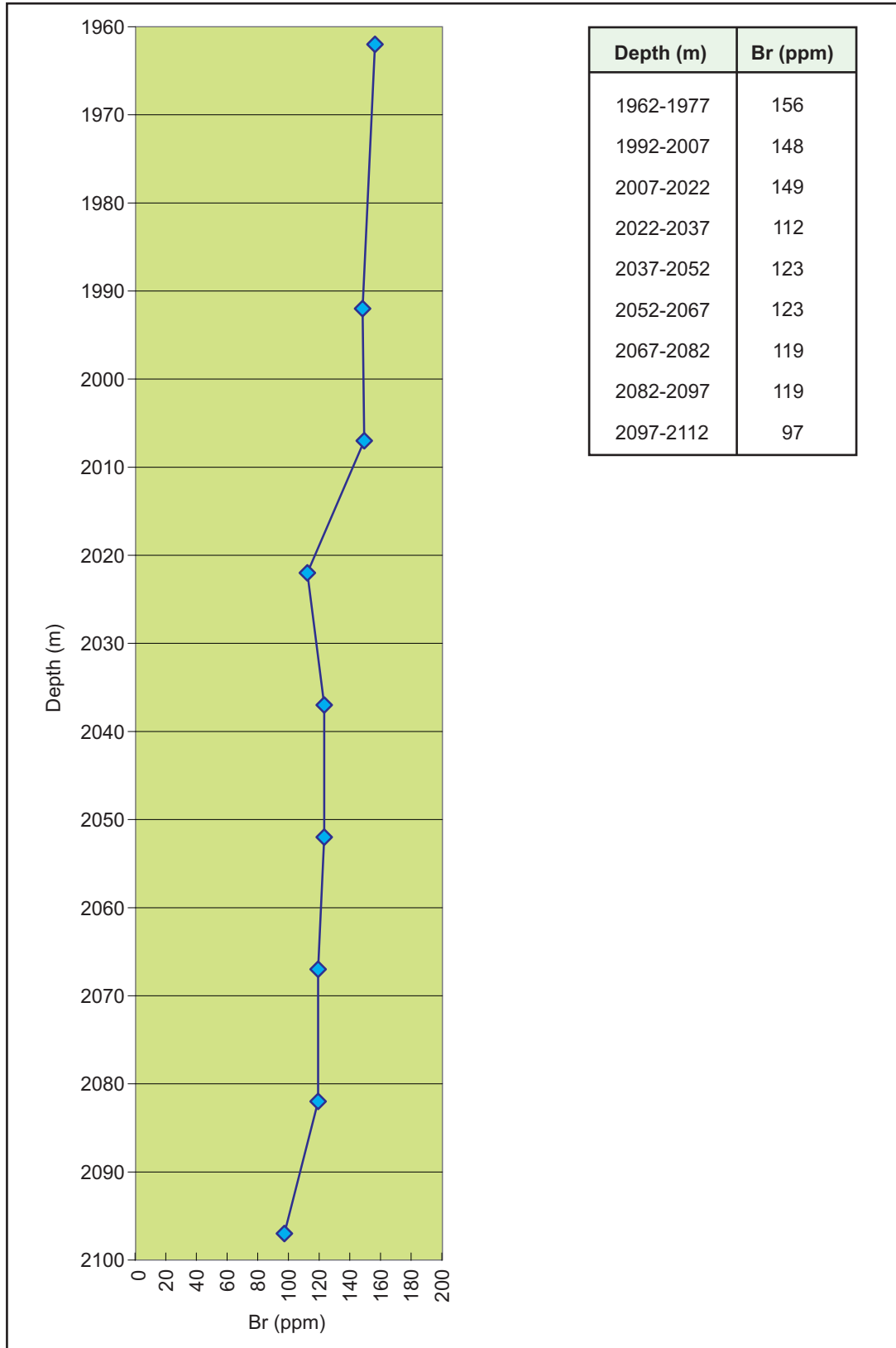


Figure 17. Bromine profile for halite of the Pugwash Mine Formation, Windsor Group, from Well 711 (Columbia/Corridor Coppermine Hill) near Coppermine Hill, southeastern New Brunswick. See Figures 4 and 8a for the location of the borehole.

for this well (Table 3), are interpreted as encouraging depositional indicators of potash potential within areas of the Sackville Subbasin.

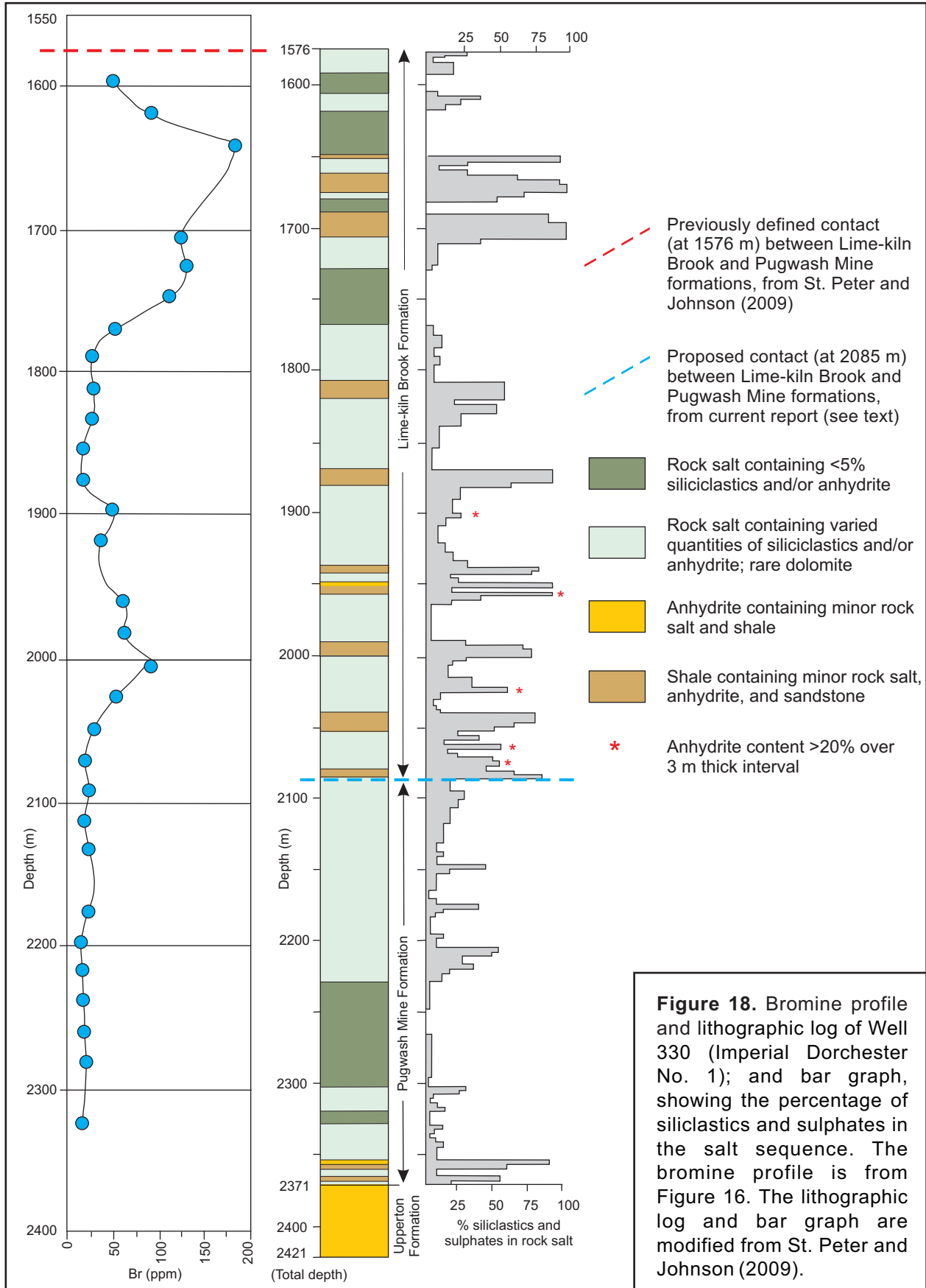
Potash-bearing evaporites are among the last products to precipitate from seawater. They tend to accumulate in the deepest areas of a basin, because concentrated (i.e., high-salinity) brines are dense and so migrate to depressions in the seafloor. If the orientation of increasing salinity can be determined for an individual evaporite horizon, then the location of potentially valuable potash deposits can be predicted. A salinity gradient, reflected by the lower to higher bromine concentrations between stratigraphically equivalent evaporite horizons at Dorchester and Coppermine Hill, could indicate a depression farther east in the Sackville Subbasin and a regional tendency to host higher bromine, higher density, potash-bearing brines.

Pugwash Mine/Lime-kiln Brook Contact in Well 330

As demonstrated above, the bromine profile for Well 330 evaporites offers a partial blueprint of the hydrologic regime in this area of the Sackville Subbasin. As well, it has helped to resolve apparent stratigraphic inconsistencies between the Windsor evaporite sequences in Wells 325 and 330. St. Peter and Johnson (2009) assign the entire 795 m thick evaporite sequence (1576–2371 m) in Well 330 to the Pugwash Mine Formation (Fig. 18). However, a reinterpretation of the drilled interval, discussed below, suggests that 509 m of this sequence instead correlates with strata of the overlying Lime-kiln Brook Formation.

An abnormally low, flat bromine profile in the lowermost 286 m (2085–2371 m) of relatively clean halite in Well 330 (Fig. 16) correlates closely with a similar halite-dominated interval in Well 325 (Fig. 15). The Pugwash Mine halite in Well 325 represents a drilled thickness (977 m) of more than three times that represented by the flat bromine profile (286 m) of Well 330. However, taking into account the interpreted substantial structural thickening of the evaporites in Well 325, the two sections could be directly correlated (Fig. 12). There is a significant increase in siliciclastic and other impurities (sulphate) in the halite intersected in Well 330 above 2085 m (Fig. 18). This halite–sulphate–clastic sedimentary sequence may represent a change to a less stable hydrologic regime with alternating terrestrial and shallow marine sedimentation (St. Peter and Johnson 2009). The sequence is also marked by a rise and fluctuation in bromine values within various halite-dominated units.

It is proposed herein that the 509 m section from 1576 m to 2085 m in Well 330, previously assigned to the Pugwash Mine Formation, is more representative of a fluctuating depositional environment such as that defined for the Lime-kiln Brook Formation. If this interpretation is correct, the proposed drilled thickness of 131 m for Lime-kiln Brook strata in Well 330 (St. Peter and Johnson 2009) can be increased to a total of 640 m. It is recognized that the clastic-dominated (shale, siltstone, sandstone) sequence considered part of the Lime-kiln Brook Formation in Well 330 is lithologically different from the 422 m of sulphate-dominated (gypsum, anhydrite), stratigraphically equivalent lithotype in Well 325 (Fig. 12). The difference in thickness of the Pugwash Mine Formation between Wells 325 and 330 can therefore be explained by lateral facies changes in combination with structural thickening of the evaporite section in the former well and erosion of the evaporite section in the latter. Data from Well 330



suggest that the Pugwash Mine evaporites in the Dorchester area may actually have a true thickness in the order of 300 m.

CONCLUSIONS

The Sackville Subbasin of the Maritimes Basin in southeastern New Brunswick is a prospective area for potash exploration. Seismic and gravity surveys, as well as limited borehole data, suggest that the subbasin potentially may contain several evaporite structures in addition to the one known near Dorchester. Yet despite widespread indications of subsurface evaporate deposits of the Early Carboniferous Windsor Group throughout the district, the deposits are less well understood than the stratigraphically equivalent, potash-bearing evaporites in other Early Carboniferous regions of southeastern New Brunswick such as the Moncton and Cocagne subbasins.

Three boreholes—Shell Dorchester No. 1 (Well 325), Imperial Dorchester No. 1 (Well 330), and Columbia/Corridor Coppermine Hill (Well 711)—provide key information on Windsor evaporites near Dorchester in the western Sackville Subbasin. Logs from these boreholes record substantial thicknesses of halite but document no potash. Nonetheless, such observations in three boreholes do not necessarily imply the absence of potash elsewhere in the subbasin.

Geochemical analyses of halite drill cuttings from the Pugwash Mine Formation (Windsor Group) in Wells 325, 330, and 711 reveal bromine concentrations that are considered abnormally low for primary halite. The low values suggest that seawater in this part of the subbasin may not have reached sufficient concentration for potash to precipitate. The low bromine content could also reflect a diagenetic depletion of bromine through secondary leaching and partial recrystallization of primary halite from intraformational, migrating low-bromine waters. In addition, the substantial drilled thickness of low-bromine, relatively clean halite in Well 325 (as opposed to the lesser thickness in Well 330) suggests that one or more deformational events resulted in considerable structural thickening, possibly accompanied by significant evaporite dissolution and subsequent recrystallization.

The upward transition from consistently low to erratically higher bromine concentrations in the evaporites of Well 330 may indicate proximity to a nearby potash horizon. These evaporites are included in the Pugwash Mine Formation by St. Peter and Johnson (2009), but are placed herein within the Lime-kiln Brook Formation (Windsor Group). The low bromine values of the relatively clean homogenous halite in the lower part of Well 330 correlate closely with those from similar Pugwash Mine strata in Well 325, reflecting stability of the original hydrologic regime with subsequent diagenetic alteration. Lithologic variation and lower to higher bromine levels in the reinterpreted Lime-kiln Brook strata indicate a fluctuating hydrologic regime. The lithologic and geochemical variations between Wells 325 and 330, combined with evidence from regional gravity data, suggest a thinning or even an absence of a significant evaporite structure to the south of the Dorchester area.

The consistently elevated bromine values, and the absence of any potash mineralization within the 150 m drilled thickness of Pugwash Mine halite in Well 711, suggest that a substantial portion of the evaporite structure is missing at this location. The 1962 m depth at which the Pugwash Mine Formation was intersected in Well 711 could indicate the presence of a deep depression in the evaporite basin to the east and northeast of the Dorchester area. In addition, the elevated, narrow range of bromine values over the halite interval could suggest a collection site for concentration of residual bromine from diagenetically altered chlorides elsewhere in the basin; it also could suggest a progressively increasing bromine profile indicative of a potential potash resource in other parts of the region.

Preliminary bromine studies of Windsor chlorides along the northwestern boundary of the Sackville Subbasin suggest a marginal, marine-fed, and platformal to shallow basin evaporite sequence that underwent a variety of physical and chemical alterations. Such a setting may not have favoured significant accumulation and preservation of potash in this particular area of the subbasin. However, potash occurs within stratigraphically equivalent and similar deposits in northwestern Nova Scotia, suggesting that it also could occur in adjacent districts of southeastern New Brunswick. Thus, additional geological investigations are required to determine whether potentially economic potash deposits exist in the Sackville Subbasin.

Table 1. Geochemical data for the Pugwash Mine Formation intersected in Well 325 (Shell Dorchester No. 1) near Dorchester, southeastern New Brunswick. All analytical data are in ppm.

Symbol	Br	Ca	K	Na	S	Sr	Cl	SO ₄
Analytical Method	INAA	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	IC	IC
Detection Limit (ppm)	2	5	5	5	50	0.5	0.03	0.03
Borehole Sample Interval (m)								
542.5–557.8	17	26900	<50	307000	23600	30.4	477000	107000
557.8–573.0	18	11200	69	392000	10200	32.5	606000	31300
573.0–588.2	14	14700	72	380000	13500	42.8	587000	42500
588.2–603.5	13	13800	<50	378000	13000	37.4	600000	41700
603.5–618.7	19	11400	59	380000	10600	33.2	627000	34500
618.7–634.0	17	12300	75	380000	10800	27.3	634000	35600
634.0–649.2	14	17600	<50	362000	16200	34.4	589000	57000
649.2–664.4	14	25600	<50	344000	23600	30.5	584000	96700
664.4–679.7	17	20500	81	352000	18800	30.5	593000	63300
679.7–694.9	16	21700	73	367000	19600	34.1	578000	69000
694.9–710.0	16	27900	77	344000	24800	36.3	552000	79000
710.1–725.4	19	43000	98	259000	35300	103	452000	126000
725.4–740.6	28	32500	102	332000	28500	63.2	558000	124000
740.6–755.9	19	11900	96	371000	11000	21.5	597000	34700
755.9–771.1	18	12700	76	366000	11600	24.9	598000	36000
771.1–786.3	17	28800	87	345000	25700	37.8	545000	92900
786.3–801.6	16	18100	110	349000	17400	32	564000	58300
801.6–816.8	19	17400	91	369000	15700	33.9	577000	49300
816.8–832.1	19	15300	96	385000	13000	26.9	595000	42100
832.1–847.3	21	22500	111	365000	20800	35.5	595000	68300
847.3–862.5	15	29000	88	310000	25000	34.2	479000	103000
862.5–877.8	15	32500	54	304000	28600	39.1	468000	108000
877.8–893.0	24	13700	93	379000	12900	33.6	594000	40200
893.0–908.0	26	10000	97	391000	8480	15.9	612000	26000
908.0–923.5	<2	33100	96	332000	29600	38.2	546000	113000
923.5–938.7	18	19200	72	359000	16800	23.6	584000	52500
938.7–954.0	33	22300	83	360000	19400	25.9	569000	60900
954.0–969.2	28	16700	110	370000	14100	21.8	587000	44300
969.2–984.5	21	13500	95	381000	10600	18.4	642000	35300
984.5–999.7	<2	17700	66	374000	15600	27.7	587000	50000
999.7–1014.9	28	18000	89	369000	15200	24	617000	48900
1014.9–1030.2	32	11400	84	379000	9540	14.7	603000	29600
1030.2–1045.4	28	15500	112	371000	13600	30	590000	42400
1045.4–1060.7	31	20400	103	370000	17400	26.9	609000	60000
1060.7–1075.9	24	18200	101	360000	16700	27.4	576000	53100
1075.9–1091.1	19	27700	75	366000	23100	34.5	608000	81400

Table 1 (cont'd). Geochemical data for the Pugwash Mine Formation intersected in Well 325 (Shell Dorchester No. 1) near Dorchester, southeastern New Brunswick. All analytical data are in ppm.

Symbol	Br	Ca	K	Na	S	Sr	Cl	SO ₄
Analytical Method	INAA	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	IC	IC
Detection Limit (ppm)	2	5	5	5	50	0.5	0.03	0.03
Borehole Sample Interval (m)								
1091.1–1106.4	17	29200	95	338000	25500	36	542000	84000
1106.4–1121.6	27	22300	96	356000	19900	32.2	580000	61400
1121.6–1136.8	23	12600	82	379000	10900	20.6	618000	35200
1136.8–1152.1	20	17500	98	361000	15700	31.1	575000	50300
1152.1–1167.3	19	20100	78	346000	18300	30	571000	57600
1167.3–1182.6	<2	15200	85	372000	13400	23.6	614000	45800
1182.6–1197.8	20	33500	142	330000	28100	38.9	535000	118000
1197.8–1213.0	<2	17000	104	337000	15700	24.4	578000	59100
1213.0–1228.3	18	19100	85	364000	15500	25.3	579000	61900
1228.3–1243.5	<2	17100	159	367000	15300	30.4	593000	56800
1243.5–1258.8	16	18600	103	369000	16000	30.6	589000	63600
1258.8–1274.0	<2	9460	95	384000	7600	17.7	616000	35700
1274.0–1289.2	21	16800	81	369000	14100	25.5	594000	55800
1289.2–1304.5	16	11900	74	374000	9860	20.8	609000	44600
1304.5–1319.7	15	14100	71	385000	11500	20.7	609000	45400
1319.7–1335.0	19	11600	73	381000	9790	20	613000	41400
1335.0–1350.2	16	18200	141	361000	15700	35.4	568000	60000
1350.2–1365.4	<2	13100	131	371000	11000	31.3	590000	44900
1365.4–1380.7	<2	13200	86	379000	10700	23.7	634000	47900
1380.7–1395.9	<2	11900	81	381000	9830	19.1	653000	45200
1395.9–1411.2	17	13300	94	388000	11900	25.3	596000	48500
1411.2–1426.4	16	7880	93	383000	6230	14.6	608000	32200
1426.4–1441.6	17	11000	69	370000	9240	20.3	630000	41700
1441.6–1456.9	19	10400	76	386000	8410	17.9	624000	40100
1456.9–1472.1	23	25400	138	359000	21000	63.7	542000	97300
1472.1–1487.4	10	28900	134	338000	22400	67	487000	108000
1487.4–1502.6	23	25700	100	345000	20900	60.5	555000	109000
1502.6–1517.8	19	30900	69	347000	26300	89.8	570000	114000

Note: Analyses were conducted by Activation Laboratories Inc. in Ancaster, Ontario.

Table 2. Geochemical data for the Pugwash Mine Formation intersected in Well 330 (Imperial Dorchester No. 1) near Dorchester, southeastern New Brunswick. All analytical data are in ppm.

Symbol	Br	Ca	K	Na	S	Sr	Cl	SO ₄
Analytical Method	INAA	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	IC	IC
Detection Limit (ppm)	2	5	5	5	50	0.5	0.03	0.03
Borehole Sample Interval (m)								
1597.1–1618.4	52	10700	219	395000	8130	35.1	507000	40400
1618.4–1639.7	93	6790	638	453000	4960	21.4	582000	22200
1639.7–1703.7	185	4690	729	471000	3640	8.5	614000	11600
1703.7–1725.1	126	4960	220	496000	3710	16.1	637000	12600
1725.1–1746.4	132	4550	1140	483000	3410	10.0	627000	11700
1746.4–1767.8	112	3040	588	481000	2360	7.9	632000	7970
1767.8–1789.1	50	13000	129	458000	9580	46.1	602000	42000
1789.1–1810.4	26	11300	129	459000	8480	32.0	590000	38400
1810.4–1831.8	26	13300	378	451000	9850	41.4	599000	42500
1831.8–1853.1	25	11700	170	465000	8900	32.7	600000	37300
1853.1–1874.4	15	14800	79	454000	11400	39.3	584000	42100
1874.4–1895.8	13	13300	103	461000	10200	35.4	592000	41300
1895.8–1917.1	45	11500	556	470000	8750	50.1	609000	35400
1917.1–1959.8	32	14500	224	464000	11300	48.9	595000	45700
1959.8–1981.1	57	4050	92	477000	3160	17.3	619000	10600
1981.1–2002.4	59	5090	102	485000	3760	19.5	623000	12800
2002.4–2023.8	80	7430	113	482000	5610	33.5	623000	20800
2023.8–2045.1	53	9660	276	474000	7210	48.6	613000	28500
2045.1–2066.4	28	18100	209	441000	13600	55.4	571000	57200
2066.4–2087.8	17	16700	101	462000	12700	46.5	578000	54300
2087.8–2109.1	21	14100	59	462000	10400	39.3	592000	43500
2109.1–2130.4	16	11900	69	463000	8730	33.8	591000	34200
2130.4–2173.1	21	8620	89	475000	6460	24.6	605000	26700
2173.1–2194.5	19	6780	<50	482000	5090	18.7	632000	18200
2194.5–2215.8	14	11400	<50	470000	8480	31.7	609000	36000
2215.8–2237.1	13	17100	60	436000	12400	43.7	577000	49300
2237.1–2258.5	15	17200	71	434000	13000	45.1	559000	53100
2258.5–2279.8	16	13800	53	457000	10400	36.4	590000	42700
2279.8–2322.5	16	11200	<50	468000	8640	31.8	603000	35100
2322.5–2333.3	12	16100	48	404000	11600	94.4	519000	47600

Note: Analyses were conducted by Activation Laboratories Inc. in Ancaster, Ontario.

Table 3. Geochemical data for the Pugwash Mine Formation intersected in Well 711 (Columbia/Corridor Coppermine Hill) near Coppermine Hill, southeastern New Brunswick. All analytical data are in ppm.

Symbol	Br	Ca	K	Na	S	Sr	Cl	SO ₄
Analytical Method	INAA	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	IC	IC
Detection Limit (ppm)	2	5	5	5	50	0.5	0.03	0.03
Borehole Sample Interval (m)								
1962–1977	156	9950	1090	384000	6670	55.2	502000	25100
1992–2007	148	10200	1140	333000	6610	63.3	441000	25000
2007–2022	149	11000	993	332000	7070	65.7	425000	28500
2022–2037	112	7540	710	387000	4910	46.4	507000	18300
2037–2052	123	8240	856	349000	5320	53.2	469000	21200
2052–2067	123	9650	960	323000	6110	59.6	433000	25100
2067–2082	119	10600	1190	314000	6530	69.0	416000	29400
2082–2097	119	8490	1210	276000	5000	61.7	376000	23000
2097–2112	97	18700	758	232000	13200	120.0	324000	53200

Note: Analyses were conducted by Activation Laboratories Inc. in Ancaster, Ontario.

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