Stratigraphic Comparison of the Mississippian Potash Deposits in New Brunswick, Canada

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ABSTRACT

Within the Fundy Basin, the Moncton Subbasin in southeastern New Brunswick contains two distinct salt deposits which have undergone extensive surface exploration, followed by detailed underground study, since potash was first discovered in the Sussex area in 1971.

This paper establishes a unified stratigraphy, based on lithology, geochemistry and geophysics, for these Mississippian (Windsor Group) deposits, located 25 km apart, at Penobsquis and Clover Hill. Two major evaporite cycles, represented by the Cassidy Lake Formation and the informal Plumweseep formation, are subdivided, described and interpreted.

The high order evaporites are considered to have been deposited in relatively deep troughs, within the subbasin, which gradually filled during the first evaporite cycle. A second transgression on to remnants of the original troughs led to localised shallow(?) water evaporite deposition which ended with continental red bed sedimentation.

The various lithological units within the evaporite sequence are interpreted to be the result of variable salinty and argillaceous influx, while differences in the stratigraphy of the two salt deposits may be explained by palaeogeographic location and variation in topography of the depositional troughs and surrounding shallower marginal areas.

INTRODUCTION

This paper compares and contrasts the stratigraphy of two salt and potash deposits in southeastern New Brunswick. It is also intended to provide an interpretation of the depositional environment in which Windsor Group marine sediments were deposited. Palaeoenvironmental models have, to date, been based largely on interpretation of carbonates, sulphates, or thick and incomplete halite sections, in which the stratigraphy was imperfectly known due to diapirism. This resulted in a local version of the shallow water/deep water controversy with, for example, Shenck (1967) describing the evaporite environment as a "flat, supratidal salt-flat, probably spotted with hypersaline lakes," while Evans (1970) compared it with the Dead Sea with "persistent subsidence, caused probably by movement on faults within the graben" as a more satisfactory way of explaining the thick halite and anhydrite sequence.

Based on information obtained from over 50 drill holes in the Penobsquis and Clover Hill salt deposits, as well as initial underground exploration, an interpretation can be drawn to show that neither extremist schools of thought was completely right or completely wrong.

Work to establish a unified Windsor Group stratigraphy encompassed a study of the extent and variation of features within the evaporite members. This was used to draw conclusions regarding the detailed depositional environment of the deposits and may be extended to other areas of the basin. Although conclusions dealing with particular features may be refined as work continues the general interpretation of evaporite units should not change.

GEOLOGICAL SETTING

Fundy Basin

The Carboniferous rocks of eastern Canada were deposited in a northeasterly trending depositional basin which extended from western Newfoundland to southern Nova Scotia and New Brunswick (Figure 1). This basin was referred to as the Fundy Basin (Bell 1944), whereas the deeper, fault-bounded part of the basin has been variously termed the Fundy Basin (Belt 1968, Schenk 1969), the Fundy Geosyncline (Poole, 1967) and the Fundy Taphrogeosyncline (Howie and Barss, 1975).

Post-Acadian sedimentation was initiated in the Fundy Basin by late Devonian to early Carboniferous time and was followed by a series of tectonic pulses termed the Maritime Disturbance (Poole, 1967). This tectonic activity resulted in fragmentation of the basin into individual sub-

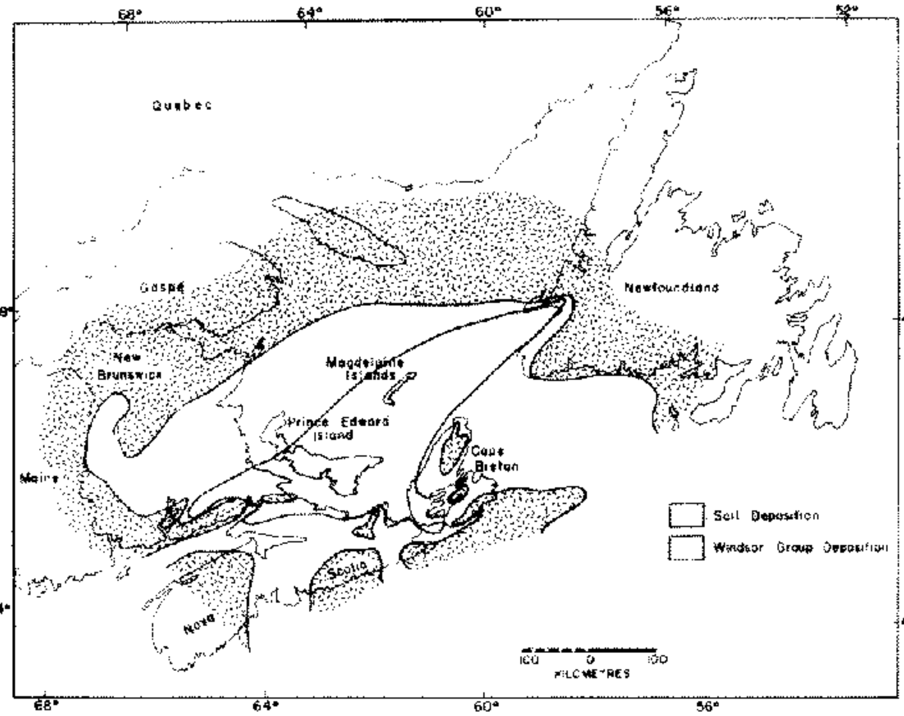

Figure 1. Map of Eastern Canada showing general distribution of Windsor Group sedimentation and area of salt distribution (after Howie, 1979).

basins and intervening uplifted areas. These semi-isolated depositional troughs, as described by Kelly (1970), are the St. George's and White Bay subbasins in Newfoundland; the Minas, Antigonish-Mabou and Cumberland subbasins in Nova Scotia; and the Moncton subbasin in New Brunswick.

These subbasins are largely filled with continental clastics with the exception of a thick carbonate-evaporite-red bed sequence resulting from an early Carboniferous (Viséan) marine incursion and named the Windsor Group by Dawson (1873) in Nova Scotia. This Group was later subdivided biostratigraphically by Bell (1929) in Nova Scotia and initially correlated by Gussow (1953) with the marine strata in New Brunswick.

Moncton Subbasin

The Moncton subbasin is a narrow northeasterly trending fault bound trough, approximately 120 km long (Figure 2). It is flanked on the north by the Kinston uplift and to the south by the Caledonian Mountains. Fault-controlled facies are typical (Gussow, 1953) with the present distribution of Carboniferous strata thought to closely reflect the palaeogeography of the subbasin (van de Poll, 1972).

To the southwest, along the border with Nova Scotia, the Cumberland subbasin also contains high order sodium and potassium salts, although commercial potash has only been found in three structures at the southern end of the Moncton subbasin. These are the Penobsquis, Clover Hill and Millstream deposits, which are located in the Dunsinane Synclinorium, Marchbank Syncline and Case Syncline respectively (Figure 2). These synclines are thought to represent original topographic depressions, acting as depositional troughs in which the thick sequences of evaporites accumulated, separated by extensive areas of shallow water.

In the Dunsinane Synclinorium, Potash Company of America has recently completed development of a salt and potash mine at the western end of a pronounced, northeasterly trending, narrow salt pillow (*sensu* Trusheim, 1960) known as the Anagance Axis. The evaporite core of this anticlinal feature in places displays early stages of diapirism, with salt, up to 1000 m thick, coming to within less than 100 m from surface. Salt is known to occur over a strike length of at least 27 km.

Denison-Potacan Potash Company has begun development of a potash mine 25 km to the southwest in the Marchbank Syncline. This structure contains an early stage pillow-like salt body, up to 750 m thick, with a minimum depth of 600 m. It has a northeasterly trending strike length of approximately 10 km and is 3.5 km wide.

Salt was also intersected by drilling near the centre of a gravity low in the Case Syncline, at a depth of over 900 m (Waugh, 1974). This structurally controlled deposit, which also follows the regional northeasterly trend, is presently undergoing surface exploration by British Petroleum Exploration (Canada) Limited.

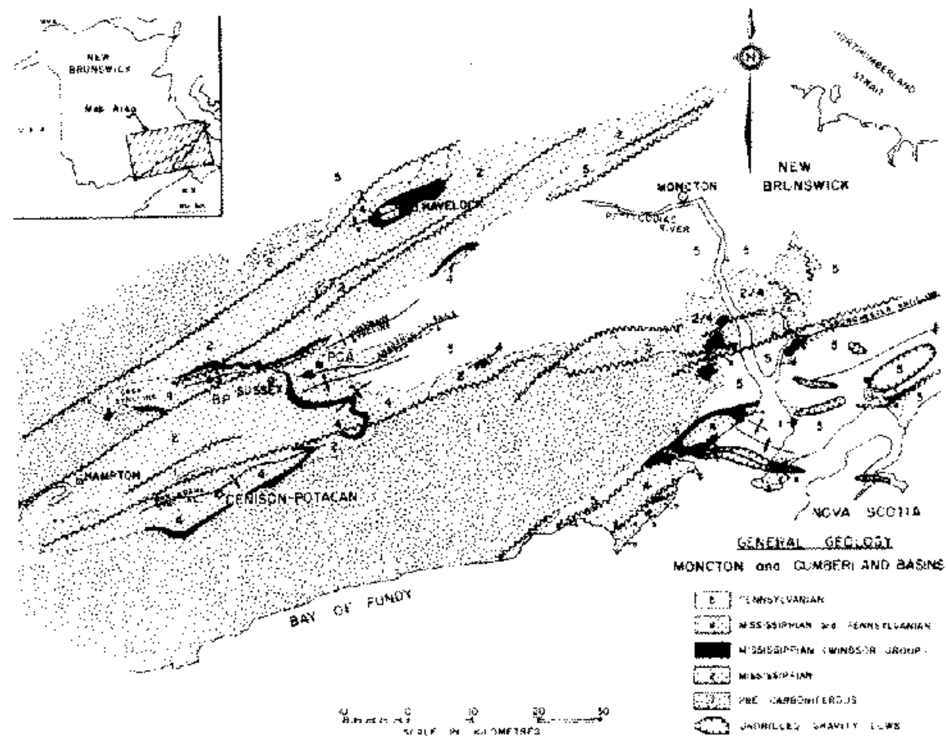

Figure 2. Geological map of southeastern New Brunswick showing location of Penobsquis and Clover Hill within the Moncton Subbasin (after Potter *et al.*, 1979).

Evaporite Stratigraphy of the Moncton Subbasin

The stratigraphic nomenclature used in this paper largely follows that established by Anderle *et al.* (1979) for the Clover Hill area, in which two major evaporite cycles are recognized and termed Sussex I and II. General correlation of their subdivisions with the Penobsquis area is shown in Figures 3 and 4. As the second evaporite cycle (Sussex II) is thicker and lithologically more complete in the Penobsquis area, this stratigraphic unit, the Clover Hill Formation of Anderle *et al.*, (*ibid.*) is informally changed to Plumweseep formation. Plumweseep is a place name just west of Penobsquis where the initial potash discovery was made. The absence of suberosion and brecciation on the flanks of the deposit in this area allow the formation to be divided into three lithostratigraphic units—the Upper Anhydrite Member, Penobsquis Salt Member and Grey Clay Member. At Clover Hill, the Penobsquis Salt Member is missing. (Figure 4)

UPHAM FORMATION

This formation was not studied in detail, as only one drill hole penetrates the complete section—at Penobsquis, where it is over 60 m thick. Based largely on outcrops and shallow drilling on the flanks of the basin, the formation may be divided into a lower carbonate member and an upper sulphate member.

Devine Corner Member

The limestone is characteristically a laminated to thinly-bedded, olive grey to dark grey wackestone—packstone with a near absence of fossils. Where the limestone overlies the Moncton Group a thin basal conglomerate may be seen.

Schenk (1967) considers lithostratigraphically equivalent rocks in Nova Scotia to be of shallow subtidal to supratidal origin, while Geldsetzer (1978) postulates a subtidal environment, and McCutcheon (1981) considers these, in New Brunswick, to be deeper water deposits. A relatively shallow water origin for these limestones is not unexpected as studies have concentrated on exposures along the margins of depositional troughs. Although we can offer no new insight, in the centres of the troughs a deeper water interpretation best fits the overall environmental concept for the overlying evaporites.

Upperton Member

In the deep subsurface this member varies from massively bedded anhydrite to claystone interbedded with anhydrite, while in shallower parts of the basin it is characterized by nodular to massive anhydrite in greenish grey mudstone. Anhydrite also occurs on surface but has undergone varying degrees of gypsification (Hamilton and Barnette, 1970). The contact with the underlying carbonates is gradational.

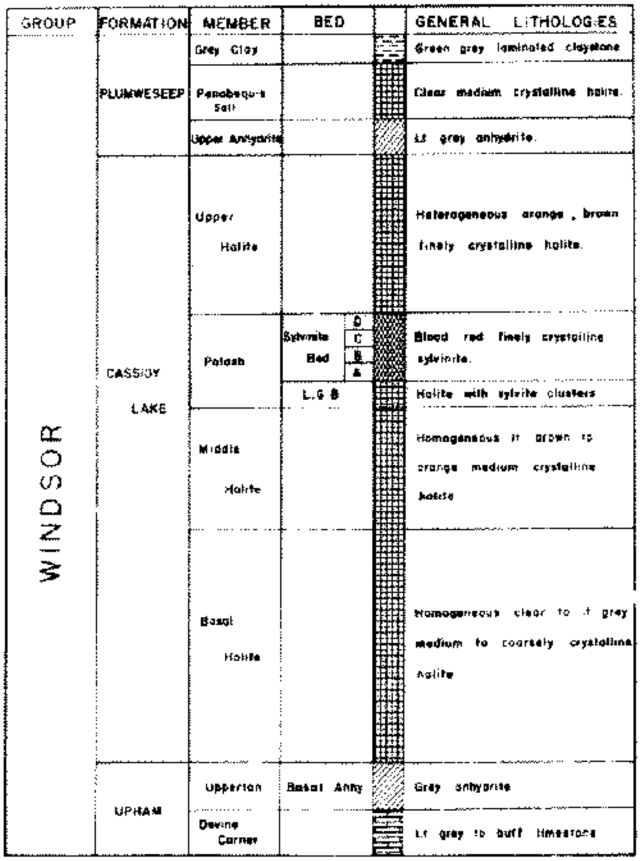

Figure 3. Stratigraphy of the Windsor Group in the Moncton Subbasin.

Although the depositional environment of this member is not known, it is conformably overlain by a thick sequence of deep water halite in the centres of the depositional troughs.

CASSIDY LAKE FORMATION

Basal Halite Member

Description. The Basal Halite rests generally conformably on the underlying anhydrite although an angular unconformity has been observed locally (Clover Hill) caused by décollement at the contact. The contact between the halite and anhydrite is quite distinct although fine anhydrite laminae extends up into the halite for up to 5 m. Subrounded to rounded anhydrite fragments have also been recognized in this lower part of the member at Clover Hill. The halite in this zone is frequently banded at Penobsquis with inversely graded salt bands (15 cm) often capped by a fine layer (less than 1 mm) of anhydrite.

This zone grades upwards into medium grained clear to very light grey halite which does not display distinct bedding features.

The basal halite varies in thickness from 0 m on the flanks of the basin to an estimated maximum true thick-

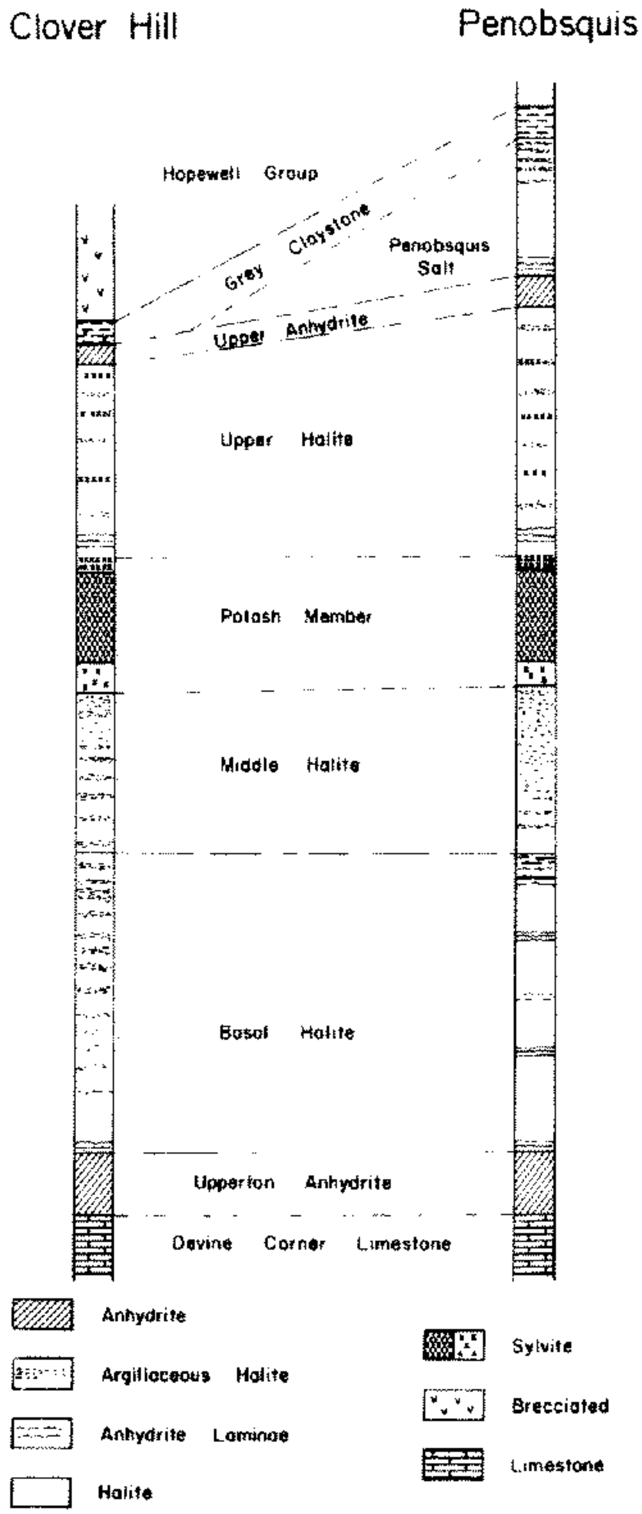

Figure 4. Idealized lithostratigraphic comparison of the Clover Hill and Penobsquis evaporite sequence.

ness of around 200 m. This thickness is difficult to estimate, however, due to post-depositional flowage resulting in thickening of the member—up to 1,000 m at Penobsquis and 750 m at Clover Hill.

Lithologically the Basal Halite member in both areas is composed predominantly of clear medium to coarse-grained halite, with an average grade in excess of 98.5% NaCl. The remainder of the unit is anhydrite laminae at Penobsquis and anhydritic claystone bands at Clover Hill. The anhydrite lamina occur in discrete zones of anhydrite/clear halite couplets, separated by thick layers of clear, medium grained halite. The anhydrite laminae range from 1–10 mm in thickness and average approximately 1 mm. They are of uniform thickness, at least over short distances and may be traced extensively underground. Individual laminae are bounded by smooth flat surfaces, rather than being draped over halite crystals. The halite portions of the couplets are clear, medium-grained and appear to show no colour or crystal size variation within the beds.

The Basal Halite at Clover Hill consists of repetitious beds of clean and argillaceous medium to coarse grained halite. The argillaceous halite layers are comprised of disseminated interstitial green grey anhydritic clays (2–5%) with occasional clay fragments to 1 cm in size. The contacts of the argillaceous halite do not show clear bedding planes but have diffused boundaries with the clean halite intervals. The beds vary in thickness from 5 cm to 1 m, and underground are seen to be laterally discontinuous. The argillaceous beds become more numerous upsection and on the north western edge of the deposit they are the only rocks present in some sections.

A prominent feature at Penobsquis, but not at Clover Hill, is the presence of a zone of interbedded anhydrite and clear halite beds just below the contact with the overlying argillaceous Middle Halite member. At Clover Hill a gradational contact with the Middle Halite member is marked by interbedded clear halite and light brown halite over a zone varying between 1 to 50 m. The Penobsquis zone ranges in thickness from 40 m in the center of the deposit to 8 m towards the south and is absent toward the northern edge of the deposit. The anhydrite beds, which average 15 cm in thickness, are weakly laminated with an irregular upper surface of elongated "grass like" subvertical crystals up to 5 mm high and averaging 2 mm. These crystals are generally partially replaced by anhydrite and halite.

Interpretation. The presence of a thick zone of anhydrite and halite beds close to the top of the Basal Halite member at Penobsquis and the fact that the anhydrite laminae lower in the sequence are not argillaceous, as they are at Clover Hill, may be explained by palaeogeographic positioning of the two areas within the Moncton Subbasin. With a marine source to the northeast (McCutcheon, 1981) the Penobsquis area would be most immediately affected by any influx of less concentrated brine.

At Clover Hill, the occurrence of irregular argillaceous halite beds with up to 5% disseminated green-grey clay, especially along the northwestern margin of the deposit, indicates proximity to shallow basin margins. Matthews and Egleson (1974, p. 27) show that, associated with exposed basin margins, water-borne clastics tend to form wedges within the evaporites. In the Moncton Subbasin, localised and repeated movements of faults which have been shown to be responsible for the clastic facies distribution throughout the Carboniferous (eg. van de Poll, 1972), can be expected to have remained active during transgressive periods, forming local source areas. McCutcheon (1981), in fact, describes a carbonate-siliciclastic unit to the north of the Case Syncline which he partially correlates with the sulphate and chloride phases of the evaporite cycle. This interpretation fits the observed clastic distribution at Clover Hill and implies that a lower halite interval, in the more proximal Case Syncline area, would be extremely argillaceous.

Wave base erosion along the margins would transport fine clastics into the basin at a very slow rate, as observed by the low percentage and local extent of disseminated clays at Clover Hill. Although these now appear as interbedded clean and argillaceous beds they are not necessarily the result of cyclic deposition. Richter-Bernburg (1980) describes the process of "descendence" (after Everding, 1907) in which dissolution of previously deposited argillaceous halite takes place at the sediment/brine interface. The halite is then redeposited as a clean bed, possibly disturbing or destroying primary bedding features. This process may have formed the bedded argillaceous halite at Clover Hill.

At Penobsquis, the fine anhydrite laminae draped over coarse-grained halite from the lower part of the Basal Halite member appear similar to features described by Nurmi and Friedman (1977) and Kendall (1979b) and interpreted as typical of deep water deposition. The zones of sulphate laminae higher in the sequence and traceable over long distances are similarly thought to be deep water features. Sulphate/chloride couplets have been reported from many deposits (e.g. Dellwig, 1955; Kunasz, 1970) and are generally interpreted as resulting from seasonal salinity changes (see Braitsch, 1971, pp. 251–258). If the couplets are in fact the result of seasonal changes then climatic conditions must have been benign during most of the Basal Halite deposition as the majority of the member does not display evidence of sulphate laminae development. The widely spaced zones of couplets, however, may represent fluctuations in the rate and/or salinity of influx brine, independent of seasonal conditions.

"Grass-like" crystal molds associated with the laminated anhydrite near the top of the Basal Halite at Penobsquis are interpreted as pseudomorphs after gypsum, based on crystal form, vertical growth position and comparison with other deposits. Similar crystal forms, replaced by anhydrite and halite, have been described from the Silurian Lower Salina Group in Michigan (Dellwig, 1955), the Upper Permian Salado Formation in New Mexico (Schaller and Henderson, 1932) and the Upper Miocene Gessoso-Solfifera Formation in Sicily (Schreiber and Kinsman, 1975). These have all been interpreted as being pseudomorphous after gypsum. Recent studies of modern salinas and solar salt ponds (e.g. Schreiber and Kinsman, 1975) show vertically oriented grass-like gypsum crystals to have originated at the water-sediment interface.

Middle Halite Member

Description. This member ranges from a maximum thickness of 80 m at the center of the basin at Clover Hill, to 25 m in the south, while at Penobsquis it ranges from 60 m to less than 1 m on the flanks. The gradational contact with the Basal Halite member similarly varies from 40 m to 30 m thick at Clover Hill and Penobsquis, respectively, to zero on the flanks.

The Middle Halite member consists of light red brown to orange, medium- to fine-grained halite with 3% to 10% interstitial green, grey and brown clays. In the lower half of the member it is represented by interbedded clean and argillaceous halite, becoming entirely argillaceous over the upper half. The clays have been determined by x-ray diffraction to be composed of illite and chlorite. The occurrence of greenish grey or reddish brown colouration of the clays appears to vary erratically, with occasional clay fragments showing zoning in both colours.

The clean and argillaceous beds vary from 10 cm to 60 cm in thickness. At Clover Hill the argillaceous segments consist of 3% to 5% disseminated clays with diffuse boundaries and are laterally discontinuous. The Penobsquis beds, however, contain 5% to 10% disseminated clays with more distinct boundaries, often capped by clay laminae that are laterally continuous.

According to Droste (1963, in Mossman *et al*, 1982), the prevalance of chlorite and illite among clay minerals is a typical feature of Palaeozoic evaporite rocks, and such clays also have a widespread distribution in the Carboniferous red beds of southern New Brunswick (personal communication, D. E. Barnett, March, 1981).

Interpretation. The change from the clear, clean Basal Halite member to the brown, relatively dirty Middle Halite member is attributable to a regional change in the amount of clastic material received by the subbasin. Matthews and Egleson (1974) have described similar lithologic changes from the Salina Group of Michigan and suggest that the clastic source was the expansive area of the basin edge exposed to sub-aerial erosion by evaporation drawdown. Similarly, at Penobsquis and Clover Hill, with salinities increasing toward the Lower Gradational bed of the overlying Potash member, as indicated by the bromine profile (Figure 5), contraction of the subaqueous basin may have occurred. This would have led to the development of extensive source areas resulting in concomitant argillaceous halite deposition throughout the basin. The higher percentage of clays observed in the Penobsquis Middle Halite member would seem to indicate the close proximity of more extensive salt mud flats (clastic source) than at Clover Hill, where the Middle Halite member is cleaner. Differences in lithology between the Clover Hill and Penobsquis areas (and between the Basal Halite and Middle Halite members) do not necessarily indicate major changes in the depth at which salt was being deposited, however, as relatively minor evaporation drawdown could lead to the development of extensive mud flats, along the shallow margins of the troughs. These source areas would then supply argillaceous material to the depositional trough in which salt was being deposited and where water depths had changed little. This characteristic persisted until deposition of the Upper Halite.

The formation of apparently cyclic repetitions of clean to dirty halite beds within the Middle Halite is similar to that observed in the Basal Halite at Clover Hill. It may be explained as being the result of varying amounts of clastics being transported into the basin or changing rates of halite precipitation or constant sedimentation with periodic dissolution and reprecipitation (Richter-Bernburg, 1980) previously described. Whichever mechanism was responsible for the repetitive cycles, it was probably the result of seasonal climate changes.

Potash Member

Description. The Potash members of both deposits, which also include gradational zones above and below the ore zone, have many similarities as well as some notable differences. They are of similar thickness (up to 50 m) and may be sub-divided into a number of zones on the basis of lithology (for details see Waugh and Urquhart, 1983). Mineralogically both deposits are alike, with the ore zone composed of fine-grained, blood-red sylvite, dark brown to light orange halite and minor grey clay. Clays associated with sylvite are generally grey because of the affinity of the hematite for the potassium minerals (Mitterer, 1969).

Carnallite is also present at Penobsquis, in the southern and eastern parts of the deposit, and is found rarely as scattered occurrences in the ore zone at Clover Hill. The carnallite mineralisation at Penobsquis appears to be a facies of the ore zone and also appears to be localized, occurring in areas of medium-grained sylvite and clear halite which have obviously been recrystallized. As it has not yet been observed in detail other than from several surface drill cores, a number of difficulties remain to be resolved:

(a) The stratigraphic position within the ore zones is not yet established as it has been found at different horizons, with contacts which are often sharp and slickensided.

(b) The lateral gradation being sylvinite and carnallite

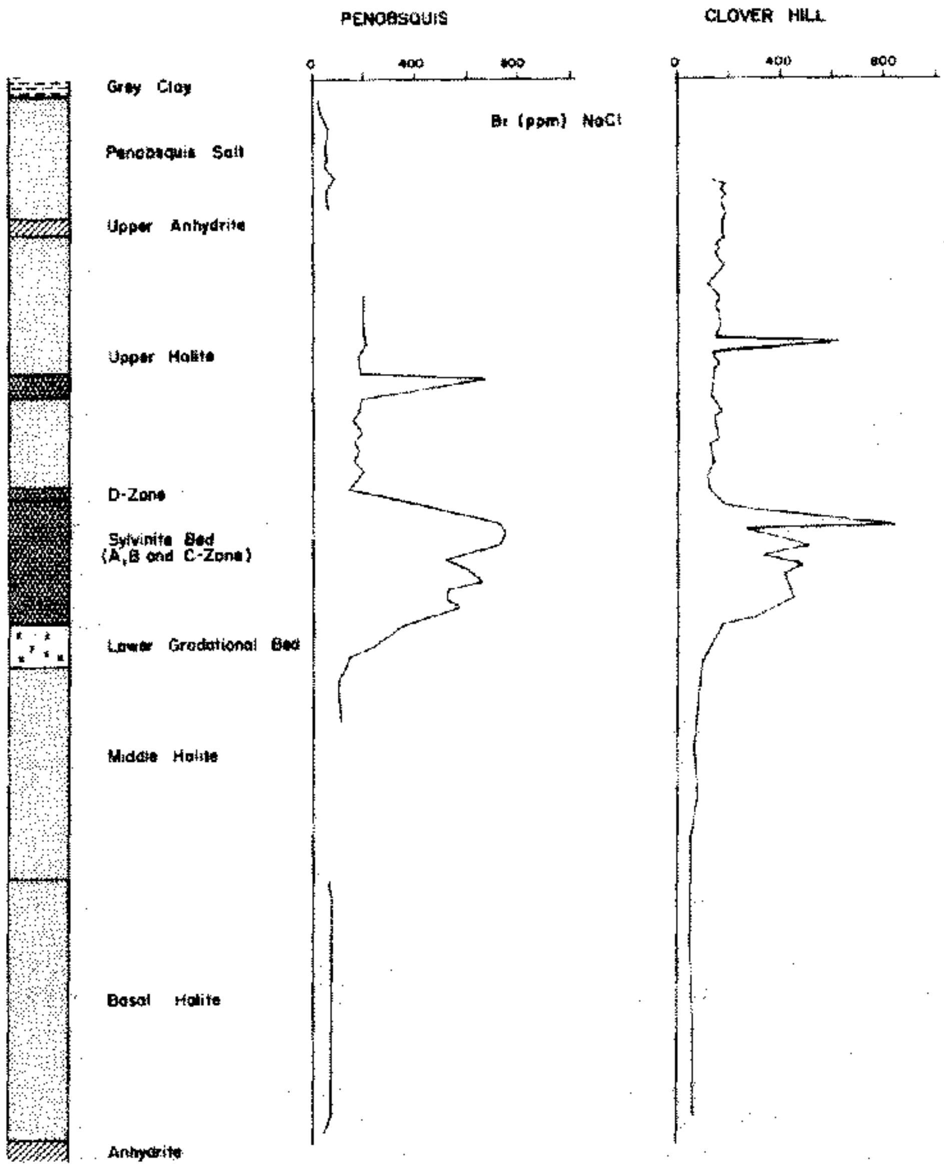

Figure 5. Comparison of composite bromine profiles from Penobsquis and Clover Hill.

has not yet been seen, so the form which this facies change takes is not known.

(c) The carnallite varies in colour from green to yellow and to white and the distribution of the various colours is not known.

Scattered, dark to light blue, very fine-grained halite, sometimes constituting over 5% of the total member, is also present in areas of both deposits where the sylvinite displays evidence of strain. Schwerdtner and Morrison (1974) refer to this as "schistose sylvinite" in which the highly inequant grains display transitions between ideally lineated and predominantly foliated rock. Slickensided bedding planes are frequently associated with this schistose ore (and thus the blue halite).

The Potash member of both deposits can be divided into two distinct beds—the Lower Gradational bed and the overlying Sylvinite bed. The Lower Gradational bed is a distinctive stratigraphic layer up to 20 m thick, and is composed of medium-grained light brown to orange halite, erratic clusters (up to 15 cm) and stringers of fine- to medium-grained, red-rimmed, clear to white sylvite crystals.

The Sylvinite bed is in gradational contact with the Lower Gradational bed over an interval of less than 1 m. This ore bed is thinly bedded at both deposits, although this feature is much more distinctive at Penobsquis, in part due to the highlighting effect of the higher clay contact. The bedding, which varies from 0.5 to 10 cm, is represented by repetitions of low to high grade, clean sylvinite and high grade dirtier sylvinite beds that are often capped

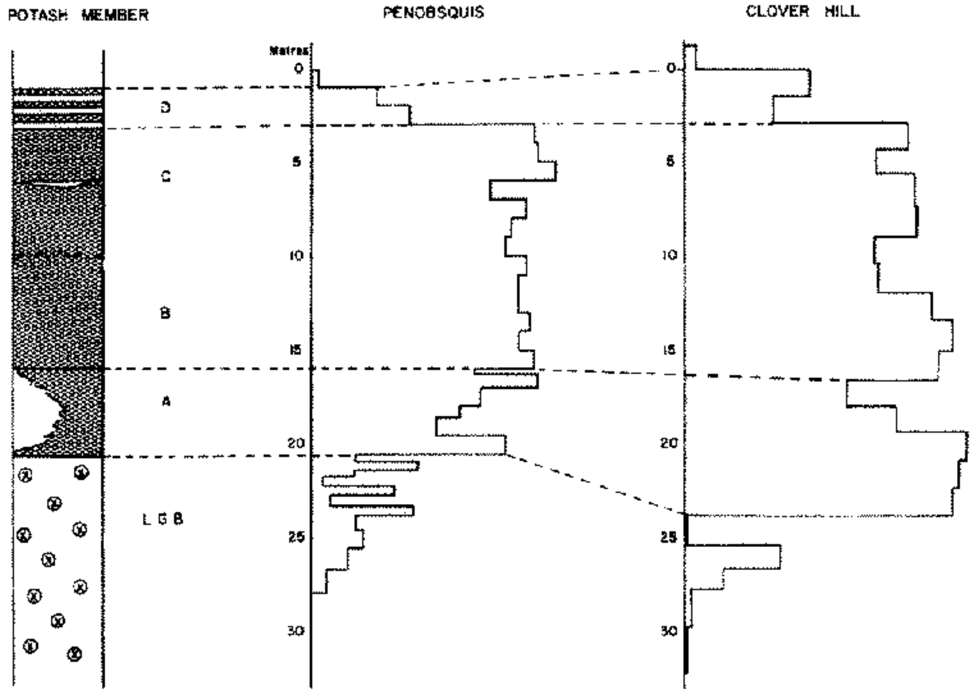

Figure 6. Comparative histograms showing the distribution of potash mineralization, in relative K_2O units, within the Sylvinite member at Penobsquis (cross-cut 86N) and Clover Hill (diamond drill hole #6).

by clay laminae or argillaceous beds. The clay content varies from 0.5 to 4% with the Penobsquis ore being several percentages higher than at Clover Hill. This feature is similarily reflected in the sylvite grade comparison between the deposit (Figure 6) with an average grade of 28% K_2O at Clover Hill and 26% K_2O at Penobsquis over an average thickness in both deposits of 12 to 15 m.

The Sylvinite bed has been subdivided into the A, B, C and D units or zones (Waugh and Urquhart, 1983), which have been observed at both deposits. The A zone consists of clear to red, fine-grained sylvite and light brown, fine-grained halite which varies laterally in sylvite mineralization. This zone varies from highly mineralized sylvinite through interbedded sylvinite and barren halite to completely barren halite. The overlying B and C zones comprise the main ore bed and are subtle divisions of an upward decrease in grade and increase in clay content with extensive lateral continuity. The D zone is an upper gradational interval consisting of interbedded sylvinite and barren halite. The number of sylvinite beds in the D zone vary laterally, although three beds are most commonly observed in both deposits. The Potash member is generally capped by an argillaceous halite bed (10 to 30 cm thick) with several distinct green-grey clay laminae, and is overlain by the Upper Halite member.

Interpretation. Similarities in mineralogy, textures and layering of the ore zone in both deposits strongly suggests deposition under comparable conditions. The low grade Lower Gradational bed represents the gradual increase in brine concentration from the Middle Halite member to Sylvinite bed deposition which is also verified by the increase in bromine values over this zone.

The deposition of the thick, mineralogically homogeneous, high grade, uninterrupted Sylvinite Bed confirms the existence of a static depositional environment not easily influenced by fluctuations of influx and/or seasons. These conditions would be best met in a large body of water which would act as a buffer to minor salinity changes.

A major contrast between the two areas is the higher clay content at Penobsquis, which is of interest as both deposits were obviously laid down during the same regional potassium event in the evaporite cycle. The relatively higher percentage of clay may well be directly related to the aerial extent of subaerially exposed clastic source regions, or wave base erosion along the shallow margins supplying argillaceous material to the deeper parts of the troughs, as discussed in the interpretation of Middle Halite member deposition.

Upper Halite Member

Description. Above the Potash member in both deposits is a distinctive, heterogeneous interval designated as the Upper Halite member. This interval is composed of distinctly interbedded, orange, brown and clear, fine-grained, clean and argillaceous halite; red fine-grained sylvinite; claystone and grey anhydrite laminae. The beds appear to be laterally continuous, although the lack of persistent marker beds, salt flowage and removal by suberosion along the upper contact at Clover Hill, has made correlation and subdivision difficult.

The Upper Halite member consists of zones of varying lithology up to 5 m in thickness which can be broadly grouped into three divisions. Overlying the potash member in both deposits is a fine-grained clear to light orange halite with numerous anhydrite laminae (less than 5 mm). The overlying division is characterized by several beds of sylvinite varying from 5 cm to 6 m in thickness with as yet unknown lateral continuity; and a diagonostic suite of borate minerals (Figure 7).

This interval is overlain at Penobsquis by thin halite beds composed largely of inclusion-rich, vertically oriented halite crystals. The salt beds, which are less than 5 cm in

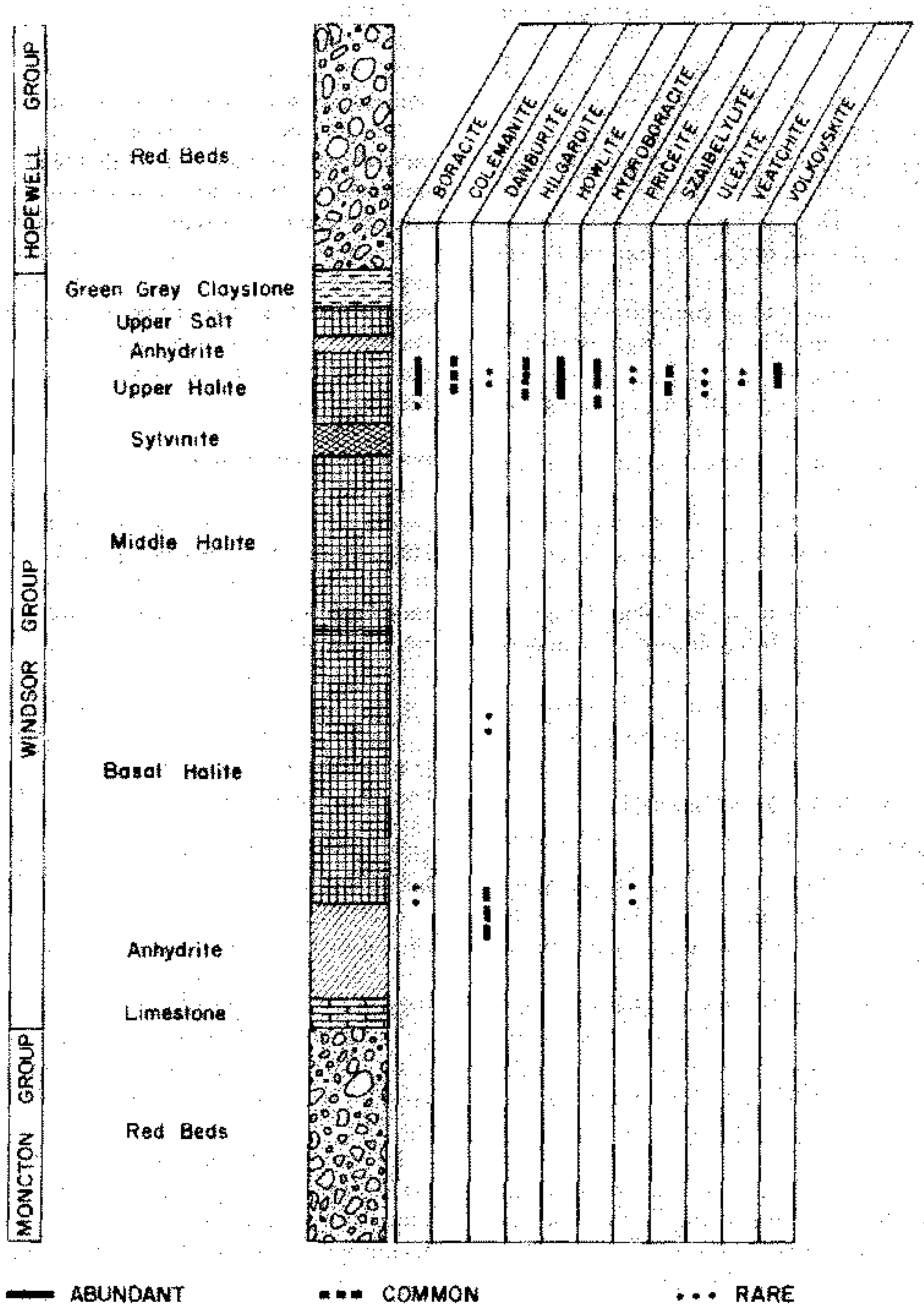

Figure 7. Location and range of borate minerals identified from Penobsquis and Clover Hill.

thickness, sometimes contain thin beds or scattered lenses of sylvite crystals. The beds alternate with thin (less than 0.05 mm) often highly irregular anhydrite laminae.

At Clover Hill this division is missing, probably due to suberosion. It may be represented by a residual bed composed of claystone, anhydrite, borate crystals, halite and sylvite, which occurs at the contact with the overlying Upper Anhydrite member of the Plumweseep formation.

Interpretation. The Upper Halite member lithotypes represent a marked change in brine concentration and static conditions which existed during the major potassium depositional event of the evaporite cycle. This "recessive salt above the potash" (Matthews and Egleson, 1978, p. 29) was deposited from a relatively high brine concentration, as indicated by comparatively high bromine values (averaging 150 ppm) and the presence of several sylvinite beds, as well as trace disseminated sylvite through most of the Upper Halite member. The interbedded sylvinite/barren halite marking the gradational contact between the Potash member and the Upper Halite member also seems to point to a slow, gradual reduction in brine concentration.

The diverse and widespread borate mineral assemblage found in the Upper Halite member of both deposits has been interpreted as being the result of syndepositional volcanism modifying the geochemistry of the brine in the subbasin by the addition of boron to the system (Roulston and Waugh, 1981). This was then concentrated by evaporation.

Finely laminated halite at the top of the member is different from anything seen lower in the sequence. It appears closely similar to salt described by Dellwig (1953) and Nurmi and Friedman (1977) from the Salina Group of Michigan and interpreted as being deposited in shallow water where the volume of brine was small, possibly representing the infilling of the depositional troughs which existed during the previous part of the evaporite cycle.

PLUMWESEEP FORMATION

Upper Anhydrite Member

Description. This member is termed the Upper Anhydrite member, despite the fact that it is at the base of the second evaporite cycle, as it is the uppermost anhydrite in the evaporite sequence. Although members may extend from one formation to another, stratigraphically it may not be an ideal name, *senso stricto*. However, it is a useful term as widespread suberosion has removed much of the second evaporite cycle and this anhydrite stratum generally represents the top of the evaporite sequence as now seen.

The Upper Anhydrite member reaches a maximum thickness of more than 20 m at Penobsquis, overlying the area where the Potash member is also best developed. It thins outward from this area and does not appear to have been deposited over the western part of the basin. At Clover Hill, it ranges from 0–8 m in thickness, but, as it is often extensively brecciated, an isopach reconstruction has not been possible.

The contact with the Upper Halite member appears sharp and comformable at Penobsquis, although the anhydrite may be separated from the finely laminated halite by coarse-grained clear to dark grey halite, locally up to 3 m thick. At Clover Hill, the contact between these members has always been observed as erosional, with a residual bed (0.2 to 1 m), formed by concentration of the insolubles in the underlying halite, generally occurring just under the anhydrite.

Lithologically, this member is composed of massive anhydrite with occasional thin argillaceous laminae (1 mm) and areas of scattered, small, clear halite crystals.

Interpretation. Both Penobsquis and Clover Hill apparently experienced a sudden influx of low salinity brine, as indicated by an abrupt termination of the gradually increasing bromine content of the Upper Halite member.

The measured thickness of anhydrite reflects general topographic control with the beds thinning toward the edge of the depositional troughs. This does not define a shoreline, however, as the actual extent of any evaporite facies only marks the limits of a transgressive body of brine (Schmalz, 1969).

Penobsquis Salt Member

Description. This salt unit has been intersected in a number of surface drill holes at Penobsquis while at Clover Hill it appears to be missing, probably due to suberosion. It has a maximum measured thickness of almost 50 m, although the variation in thickness and aerial extent of this salt is imperfectly known due to suberosion along the elevated axis of the Penobsquis deposit and incomplete core recovery through this section in some drill holes.

The lower contact with the Upper Anhydrite member is gradational over 10 m with light grey, nodular anhydrite beds, averaging 10 cm in thickness but ranging from less than 1 cm to over 1 m, alternating with coarse-grained, argillaceous halite. The anhydrite beds often display enterolithic folding.

Unlike the Upper Anhydrite member this gradational zone does not show a tendancy to thin in any direction. However, there is a consistent trend in the ratio of anhydrite to halite, ranging from 70% anhydrite in the east to just over 10% in the west. Unfortunately, a correlation of individual beds, even between drill holes less than 500 m apart, is not apparent, despite the interbedded nature of the zone.

Above the gradational zone the halite is coarse-grained, clear to reddish brown, with up to 30% interstitial reddish brown clay fragments. The percentage of clay decreases slightly toward the top of the member and becomes slightly anhydritic. These anhydritic clays display distinct bedding, while lower in the member the clay is entirely interstitial.

The upper contact is also gradational, with finely laminated, grey claystone containing scattered halite crystals interbedded with halite that becomes increasingly argillaceous. Individual halite crystals can be found in the grey claystone up to 10 m above the contact.

Bromine concentrations in this member are consistent throughout the lower gradational zone and the argillaceous halite (average 60 ppm) but drop to less than 30 ppm in the interbedded halite/claystone. The most noticeable trend is a consistent increase in bromine values from east to west.

Interpretation. An environmental interpretation based on varying anhydrite forms cannot be given, as they have not yet been examined in detail. However, the fact that the anhydrite/halite beds are not laterally extensive, and an apparent similarity with nodular anhydrite from deposits interpreted as being deposited in shallow water (Kendall, 1979a; Nurmi and Friedman, 1977) may indicate similar conditions at Penobsquis.

The coarse-grained halite with interstitial clay grading up into laminated claystone may represent displacive halite formed in supratidal sediments and depressions on broad coastal flats. The decrease in bromine values in the upper gradational zone would indicate that halite was being reprecipitated here after being dissolved from older salts along the basin margins.

Increasing bromine values to the west may tentatively be interpreted as a normal concentration toward more distal parts of the basin remnants, away from a marine source.

Grey Clay Member

Description. This finely laminated, greenish-grey claystone is only a few metres thick but occurs throughout both deposits. Minor internal brecciation indicates that it may have once been interbedded with halite, similar to the underlying 10 m gradational zone.

The claystone is overlain gradationally by non-laminated, fine-grained, red mudstones, which at Penobsquis have anhydrite pseudomorphs after gypsum and occasional contorted anhydrite beds.

Interpretation. The finely laminated claystone appears similar to mudstones described from the Silurian Ruff formation of southeastern Michigan by Budros and Briggs (1977). There, "thinly laminated mudstones" from their Lithofacies D are interpreted as having formed in a high intertidal to subtidal environment. They describe a very thinly laminated, argillaceous, non-algal, carbonated mudstone exhibiting "poker chip" partings which appears similar to the finely laminated claystone and is thought to represent quiet, shallow subtidal deposits.

The gradationally overlying red beds of the Hopewell Group display caliche layers and displacive gypsum crystals—features typical of a playa lake environment, and represents the end of the marine evaporite sequence in the Moncton subbasin.

ENVIRONMENTAL RECONSTRUCTION

The evaporite stratigraphy in the Clover Hill—Penobsquis deposits is illustrated in Figure 4. Correlation between these areas is based not only on lithostratigraphy but also on geophysics and geochemistry (Figures 5 and 6). Such a correlation shows that both deposits were formed (contemporaneously?) under very similar conditions, and also allows the reconstruction of their paleoenvironmental setting.

The initial Windsor marine transgression over older Carboniferous and Precambrian strata was rapid and widespread. Carbonates were deposited throughout the subbasin, with algal build-up along shallow margins possibly contributing to the development of restrictions to marine circulation in the Moncton subbasin (McCutcheon, 1981), as well as elsewhere in the Fundy Basin. Tectonic activity may also have been a factor influencing marine circulation. The paleogeographical situation appears similar to that described by Borchert and Muir (1964, p. 47) and Wardlaw and Schwerdtner (1966) in which brines become progressively more concentrated as they move over "bar zones and fore basins" toward an inner depositional basin. This is caused by differential hydrostatic pressure due to greater evaporation within the inner basins (Kunasz, 1970), leading to a modified "tear drop" evaporite distribution pattern (Hsü *et al.*, 1973), as demonstrated by the Windsor Group facies distribution in the Fundy Basin (Howie, 1979).

In the Moncton subbasin the great thickness of clear halite deposited after the sulphate phase in the depositional troughs at Penobsquis and Clover Hill shows that a constant influx of brine continued for some time. Widespread transgressive conditions must have existed throughout the depositional period of the Basal Halite member, covering any potential source area and leading to the formation of a uniform and relatively "clean" halite member. The increase in clay content observed along the northwestern margin of the Clover Hill area is the result of local conditions as opposed to a more regional event. The localized argillaceous source may be the result of proximity to basin margin and/or tectonic activity along fault zones.

Near the end of Basal Halite member deposition, a zone of interbedded anhydrite and halite was formed at Penobsquis, probably resulting from a pulse of lower concentrated brine in the subbasin which did not affect the more distal Clover Hill area. Despite these minor fluctuations, concentrations were slowly increasing, as indicated by the bromine profile. The extent of the evaporating body must have been contracting, probably due to evaporation drawdown with a reduced rate of brine influx, resulting in the exposure of surrounding margins to wave base activity or to subaerial erosion. These exposed areas would have provided a source of the clays found in the Middle Halite member. The apparent absence of any arenaceous material suggests that the shallow margin, or salt flats, were

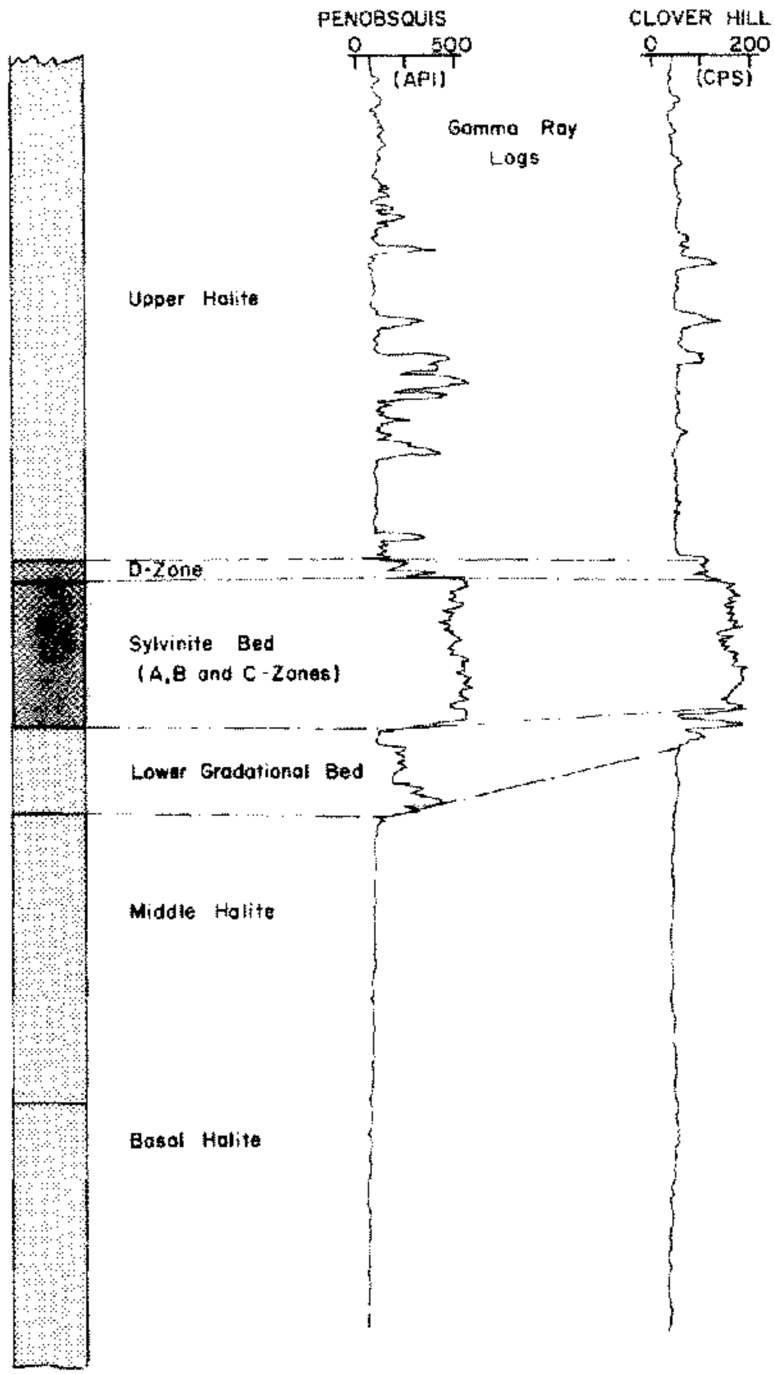

Figure 8. Comparison of gamma ray logs from Penobsquis and Clover Hill.

widespread and that clastic source areas were not in close proximity. A higher clay content at Penobsquis, compared with Clover Hill, may be related to the variable aerial extent of surrounding flats, resulting from differences in local gradients on the edge of the depositional trough.

The advent of potash deposition is quite gradual, as reflected by the progressive increase in bromine concentration through the Lower Gradational bed. This would indicate that barriers to influx became more restrictive and remained in place for some time to allow the deposition of an uninterrupted thick Sylvinite bed. The thickness of this unit, in such geographically confined deposits, reflects the retorting effect of fore basins in which a large portion of the lower order evaporites was decanted during potassium deposition in the Moncton Subbasin. Local topography of the basin would also be reflected by the thickness of the evaporite units, with brines concentrating by evaporation on the shallow water margins or intervening subaqueous ridges and sinking into the deeper depositional troughs. Relatively rapid thickness changes of the Potash member towards the margins reflect this feature, although halokenesis may have been a contributing factor in some areas.

The upper gradational contact (D zone) of the Potash member seems to point to a relatively slow reduction in brine concentration in the subbasin caused by the increase and dilution of the influx brine, which may also have been accompanied by the beginning of reflux from the subbasin. This is capped by a dirty halite bed (10–30 cm thick) with several green-grey clay laminae, possibly representing a short hiatus in evaporite deposition, or even erosion of part of the previously deposited sylvinite/halite beds.

The Upper Halite member, overlying the potash, contrasts markedly with the lower part of the evaporite sequence, and represents a distinctive change in brine concentration and depositional conditions. This "recessive salt" member is composed of a series of small scale cycles, less than 10 m thick, with similar lithologies to those seen lower in the section, i.e., clear halite + orange (argillaceous) halite + sylvinite. Individual beds are not always distinct so that a precise count of cycles has not been possible, although in some drill holes at Penobsquis, through an apparently undisturbed sequence, at least six were apparent.

There is a general increase in brine concentration throughout the Upper Halite member, with occasional periods of short duration when sylvinite was deposited, as represented by "spikes" on the bromine profile. Additionally, the member changes lithologically, becoming finely bedded with inclusion-rich halite alternating with very thin irregular anhydrite laminae near the upper contact. Such finely laminated salt is typical of the last stages of an evaporite cycle with very shallow water conditions, representing a shallowing trend through the Upper Halite member, possibly due to an infilling of the depositional troughs.

Shallow water deposition was brought to an abrupt halt by a second major transgression, (Sussex II of Anderle *et al.*, 1979). Although not as widespread as the first transgressive cycle (Sussex I), the marine influx deposited a thick evaporite sequence (Plumweseep fm.) in low-lying areas of the depositional troughs that still existed in the Sussex area. Spores from the Grey Claystone member of this cycle have been identified as equivalent to Windsor Group sub-zone A or B of Bell (1948) and Gussow (1953) in McCutcheon *et al.* (1980). In part of Nova Scotia the faunal subzones have been equated by Giles (1981) to five major transgressive-regressive cycles, suggesting that the Plumweseep formation may represent part of a regional event. The lack of a well developed carbonate unit at the base of the cycle can be related to the continued decanting effect of the fore basins, as second cycle carbonates are known from other parts of the Fundy Basin.

Conclusions regarding the detailed palaeogeography of the Plumweseep formation are, of necessity, circumstantial, due to a paucity of diagnostic features. However, the fact that these Sussex II cycle evaporites are underlain by salt interpreted as indicative of a shallowing trend and overlain by terrestial red beds suggests that conditions did not change substantially.

This conclusion is reinforced by the limited geographical extent of the Upper Anhydrite member, rapid facies changes, nodular anhydrite and displacive halite with low bromine values in the upper part of the Penobsquis formation. All of these features, including the finely laminated clays, suggest shallow water or even subareal deposition.

The termination of the second evaporite cycle represents the end of Carboniferous marine transgressions in New Brunswick, although younger Windsor Group evaporites continued to be deposited in more central parts of the Fundy Basin.

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