

A BORATE MINERAL ASSEMBLAGE FROM THE PENOBTSQUIS AND SALT SPRINGS EVAPORITE DEPOSITS OF SOUTHERN NEW BRUNSWICK

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ABSTRACT

A number of borate minerals have been identified during exploration of two Windsor Group (Mississippian) salt and potash deposits in southern New Brunswick. Borates not previously reported from eastern Canada include boracite, colemanite, hilgardite, hydroboracite, priceite, szaibelyite, veatchite and volkovskite. These minerals are found in association with halite, sylvite, anhydrite and red mudstone. Such occurrences have apparently not been documented from elsewhere in North America, although they have been reported from the Permian evaporite deposits of northern Germany and eastern England. In southern New Brunswick the borate-mineral assemblages occur in specific stratigraphic intervals. Within these intervals the borates are a common feature of the lithology, frequently forming clusters over 5 cm across and representing up to one-third of a cored section. The addition of boron from volcanic activity, rather than an increase through evaporation, is postulated to account for the deposition of these minerals.

Keywords: southern New Brunswick, Mississippian, Windsor Group, evaporites, salt, potash, borates, volcanism, boracite, colemanite, hilgardite, hydroboracite, priceite, szaibelyite, veatchite, volkovskite.

SOMMAIRE

Plusieurs borates ont été identifiés lors de l'étude de deux gisements de sel et de potasse situés dans le groupe Windsor, dans le Nouveau-Brunswick méridional. Parmi ceux-ci, plusieurs n'avaient jamais été signalés dans l'Est du Canada, à savoir: boracite, colemanite, hilgardite, hydroboracite, priceite, szaibélyite, véatchite et volkovskite. On les trouve associés à la halite, la sylvite, l'anhydrite, et des argillites rouges. De telles associations semblent courantes dans les évaporites permiennees du Nord de l'Allemagne et de l'Est de l'Angleterre,

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mais les gîtes du Nouveau-Brunswick en fournissent le premier exemple en Amérique du Nord. Elles apparaissent dans des intervalles stratigraphiques bien définis; les borates, qui y forment des agrégats répétés de plus de 5 cm de diamètre, sont caractéristiques de la lithologie et représentent jusqu'au tiers de la carotte de sondage. Une activité volcanique serait à l'origine de l'addition du bore plutôt qu'une simple concentration par évaporation d'eau.

(Traduit par la Rédaction)

Mots-clés: Nouveau-Brunswick méridional, Mississippien, groupe Windsor, évaporites, sel, potasse, borates, volcanisme, boracite, colemanite, hilgardite, hydroboracite, priceite, szaibélyite, véatchite, volkovskite.

INTRODUCTION

The presence of borate mineralization in eastern Canada was first documented by How (1857), who identified ulexite $\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$ in the Mississippian Windsor Group of Nova Scotia. Since then, small quantities of other calcium-sodium borates have been widely recognized in rocks of similar age (Viséan) throughout eastern Canada (Fig. 1). Danburite $\text{CaB}_2\text{Si}_2\text{O}_8$, ginorite $\text{Ca}_2\text{B}_{14}\text{O}_{23} \cdot 8\text{H}_2\text{O}$, howlite $\text{CaB}_5\text{SiO}_9(\text{OH})_3$ and inyoite $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 13\text{H}_2\text{O}$ have been found in association with gypsum and anhydrite.

Recent exploration work by the Potash Company of America at Penobtsquis and by the International Minerals and Chemical Corporation (Canada) Limited at Salt Springs (Fig. 1) has resulted in the drilling of more than 50 holes over an area of 15 km² in two separate, but closely related, salt and potash deposits. Borate minerals in the salt core obtained from this drilling (Fig. 2) were initially identified by X-ray diffraction supplemented with, in some cases, chemical analyses (Sutherland 1976). This work was later confirmed and expanded upon by Murowchick (1978), who used X-ray diffraction and optical properties to examine

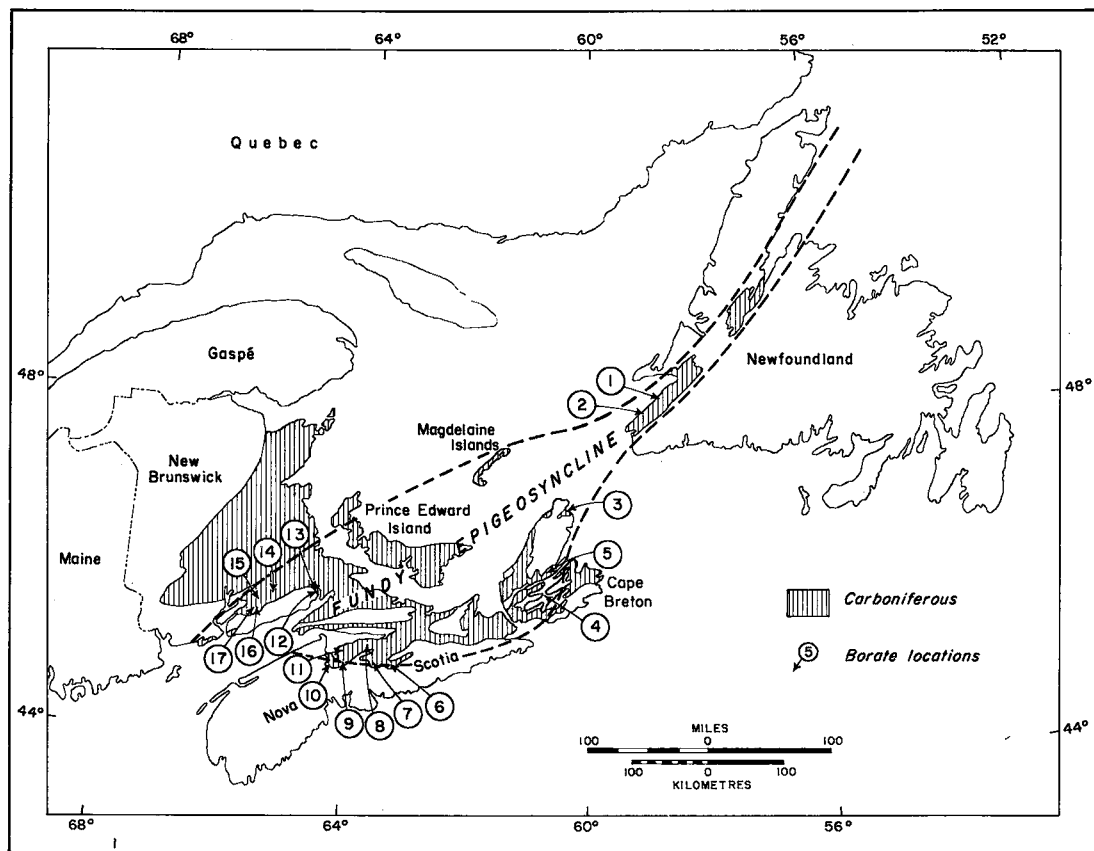


FIG. 1. Location map of borate occurrences in the Windsor Group of southeastern Canada.

the mineralogy of the water-insoluble fraction of the salt.

As well as danburite, ginorite, inyoite, howlite and ulexite, boracite $Mg_5B_7O_{13}Cl$, colemanite $Ca_2B_6O_{11} \cdot 5H_2O$, hilgardite $CaB_3ClO_3(OH)_2$, hydroboracite $CaMgB_6O_{11} \cdot 6H_2O$, priceite $Ca_4B_{10}O_{19} \cdot 7H_2O$, szaibelyite $MgBO_2(OH)$, veatchite $Sr_2B_{11}O_{18}(OH)_5 \cdot H_2O$ and volkovskite $(Ca,Sr)B_8O_{10} \cdot 3H_2O$ have been isolated. These borates had not been identified previously in this evaporite basin.

GEOLOGICAL SETTING

The Carboniferous rocks of eastern Canada were deposited in a complex, northeasterly trending depositional basin, which extended from White Bay, Newfoundland, to southern New Brunswick and Nova Scotia (Belt 1964). This was originally 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 1962) and the Fundy epigeosyncline (Poole 1967). In this paper, "basin" is used in the more restricted "geosynclinal" sense, *i.e.*, implying a "composite of individual troughs, basins and intervening, uplifted source areas which has a complex non-uniform history of positive and negative movements" (Poole 1967).

The Windsor Group described by Bell (1927, 1958) consists of the sediments deposited during Viséan to early Namurian marine events; in the Moncton sub-basin of southern New Brunswick it is represented in part by a thick sequence of evaporites. The uppermost beds of the Windsor Group in the Moncton sub-basin are characteristic of Utting's Assemblage Zone I, Lower Windsorian (McCutcheon *et al.* 1980) of late Viséan age (Mamet 1970).

LOCAL STRATIGRAPHY

The Windsor Group evaporites in the Monc-

	BORONATE, Mg ₃ B ₇ O ₁₃ Cl COLEMANITE, Ca ₂ B ₆ O ₁₁ ·5H ₂ O DANBURITE, Ca ₂ B ₆ O ₁₁ ·5H ₂ O GIBBSITE, Ca ₂ B ₆ O ₁₁ ·5H ₂ O HILLSBOROUGHITE, Ca ₂ B ₆ O ₁₁ ·5H ₂ O HOWLITE, Ca ₂ B ₆ O ₁₁ ·10H ₂ O NITROBORACITE, Ca ₂ B ₆ O ₁₁ ·5H ₂ O IHWITE, Ca ₂ B ₆ O ₁₁ ·18H ₂ O PHOSITE, Ca ₂ B ₆ O ₁₁ ·18H ₂ O SEABOROVITE, Mg ₂ B ₄ O ₇ ·7H ₂ O ULEXITE, Na ₂ B ₄ O ₇ ·10H ₂ O WEARTONITE, Sr ₂ B ₄ O ₇ ·10H ₂ O UNIDENTIFIED KALIBORONATE, (Ca ₂ B ₆ O ₁₁) ₂ ·10H ₂ O																				
1 Flat Bay										G										F	
2 Fishnell's Brook										G										F	
3 Dingwall																					C
4 Bevis Point																					C
5 Iona			C,D																		E
6 Gays River																					G
7 Milford																					G
8 Noel										A(ii) A(iv)											
9 Wentworth												C		C							
10 Windsor																					A(i) C
11 Cheverie				C																	C
12 Hillsborough														B							B
13 Chemical Creek																					
14 Penobsquis		H	H	H			H	H	H						H						H
15 Hammondvale					H																
16 Salt Springs		H	H	H			H			H				H	H						H
17 Upham							H														

FIG. 2. Summary of borate minerals identified in the Windsor Group. A(i) How (1877), A(ii) How (1861), A(iii) How (1868), A(iv) How (1877), B Walker (1921), C Goodman (1957), D Hey & Bannister (1952), E Sabina (1965), F Fong (1974) [*N.B.*: the borates are not identified in this report], G Papezik & Fong (1975), H Roulston & Waugh (this report), I J.A. Mandarino (pers. comm. 1980).

ton sub-basin are in paraconformable contact with underlying red-brown siltstone, sandstone and conglomerates of the Moncton Group, and in primary gradational contact with the overlying, lithologically similar, red to red-grey clastic sediments of the Hopewell Group. Recent potash exploration in the Sussex area of southeastern New Brunswick has revealed that the Penobsquis and Salt Springs evaporite deposits have a similar internal stratigraphy. Despite extensive drilling, the true thickness of these evaporite sequences, comprised mainly of anhydrite and gypsum as well as salt, is difficult to estimate owing to postdepositional halokinetic movement. In the Sussex area, where drilling has been most intensive, the total evaporite thickness is in the order of 500 m.

STRATIGRAPHY OF THE EVAPORITE SEQUENCE

The stratigraphy of the evaporite sequence

observed in the Moncton sub-basin has recently been informally subdivided by Kingston & Dickie (1979), Anderle *et al.* (1979) and McCutcheon *et al.* (1980). These stratigraphic divisions are similar, differing only in some of the terminology used, and are incorporated in the description below.

The Basal Limestone at the base of the evaporite sequence varies from laminated to massively bedded, is locally fossiliferous and appears to be lithologically equivalent to the surface exposures. The surface exposures of limestone have been interpreted by Gussow (1953) and Hamilton (1961, 1965) as representing Windsor Group Subzone A and Member 1 of Subzone B as defined by Bell (1927), although the lack of chronostratigraphic control in rocks other than those of Lower Windsor age renders use of Bell's subdivisions questionable in the New Brunswick context.

Overlying the Basal Limestone is a light grey,

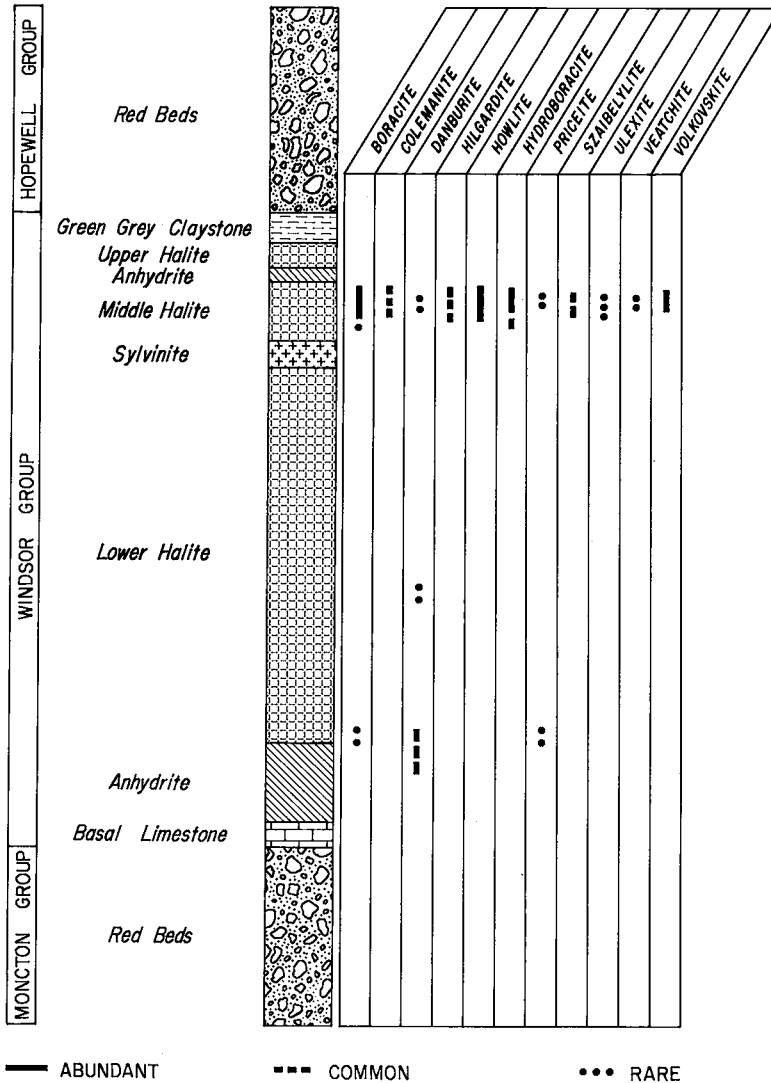


FIG. 3. Generalized stratigraphy of the Penobsquis and Salt Springs evaporite deposits showing location and range of borate minerals.

massive to thinly laminated Basal Anhydrite (Fig. 3). The Lower Halite, which is in sharp but conformable contact with the underlying Basal Anhydrite, forms a homogeneous sequence of medium grained clear halite interbedded with argillaceous halite. The argillaceous halite consists of clear halite with interstitial green-grey claystone, which becomes more predominant towards the overlying sylvinite interval. The Sylvinite bed generally consists of a mixture of equigranular, fine- to medium-grained red sylvinite and grey-brown

halite, and is in gradational contact with the overlying Middle Halite.

The Middle Halite is a distinct heterogeneous interval, contrasting strongly with the more homogeneous Lower Halite. It varies in color from white to orange to light brown, and includes argillaceous halite and sylvinite beds as well as thin laminae of claystone and anhydrite. It is within this interval that the majority of the borates are found.

A 5–15 m thick anhydrite unit overlies the heterogeneous halite interval, differing from the

Basal Anhydrite only in thickness and a general absence of anhydrite claystone laminae.

The Upper Anhydrite grades upwards into Upper Halite, consisting of coarse grained clear halite, which in turn is replaced by more argillaceous halite and is overlain by finely laminated, very slightly calcareous, grey-green claystone. This represents the end of the evaporite cycle. Red clastic rocks of the overlying Hopewell Group are interbedded with and gradationally overlie the claystone.

BORATE OCCURRENCES

Basal Anhydrite

Scattered, but significant, borate mineralization has been observed in the Basal Anhydrite at Salt Springs, Chemical Creek, Hammondvale and Upham. At these locations danburite forms 1–5 mm white, earthy, microcrystalline nodules unevenly distributed within the anhydrite. These nodules were previously identified as alabaster (Crosby & Waugh 1975). Danburite has not been observed in surface exposures, although the anhydrite–gypsum unit outcrops throughout the Sussex area (Hamilton & Barnett 1970).

Lower Halite

Borates in the Lower Halite have been identified only from Salt Springs. Danburite is the most common mineral, with rare occurrences of priceite and boracite. The danburite is found chiefly in medium- to coarse-grained clear halite; within 20 m of the Basal Anhydrite contact, although a few nodules have been noted 100 m above the contact. These nodules occur in the same form as those in the Basal Anhydrite and, like the latter, appear to be unevenly distributed with regard to size and stratigraphy.

Crystals of priceite and boracite have been observed in only one intersection, within 2 m of the salt–anhydrite contact. The priceite occurs as 5–16 mm white to very light orange clusters unevenly distributed over a 50 cm interval. This is also the only boracite occurrence observed in the Lower Halite. It is found as small (0.5 mm) cubic crystals unevenly distributed throughout the interval.

Sylvinite

Borate minerals have not been identified in

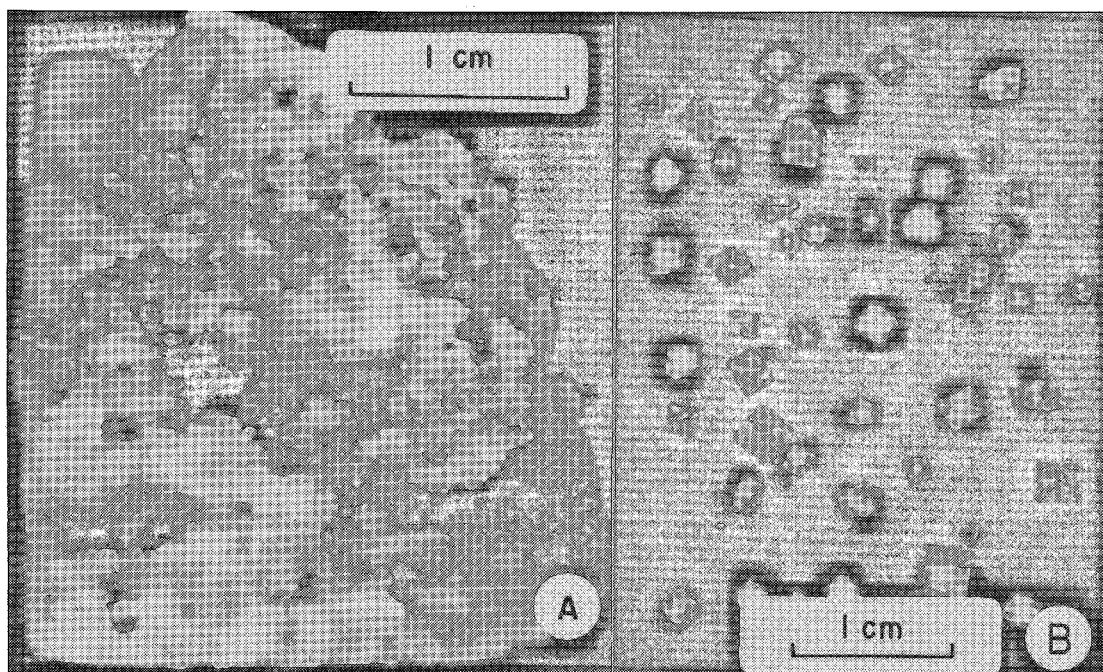


FIG. 4. Boracite. (A) Aggregates of 1–2 mm boracite crystals. (B) Individual boracite crystals. Locality: Salt Springs.

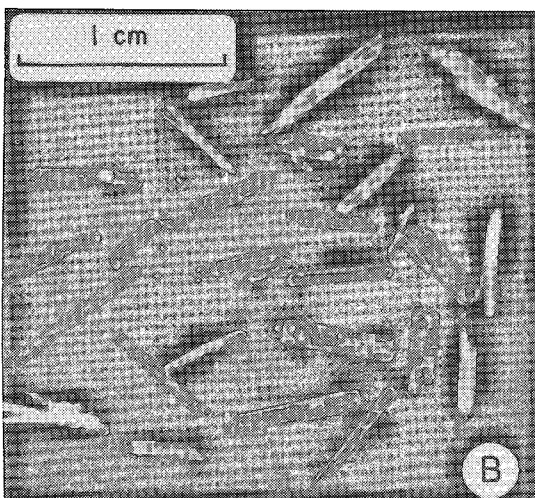


FIG. 5. Borate minerals. (A) Clusters of boracite crystals. (B) Individual hydroboracite crystals. Locality: Salt Springs.

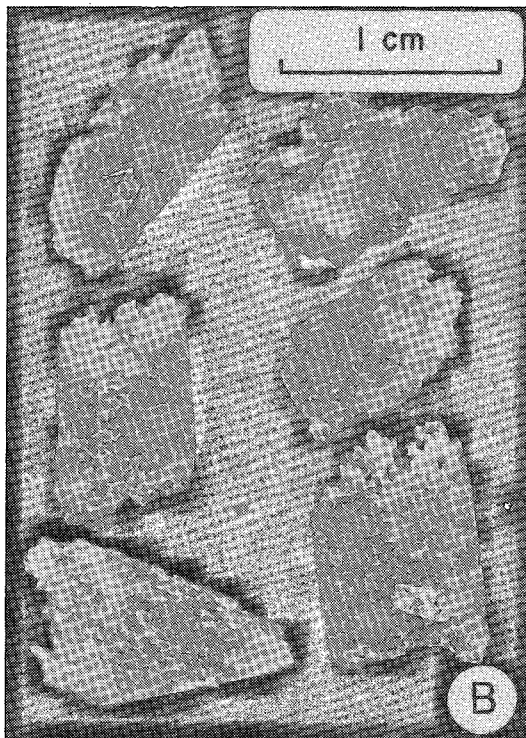
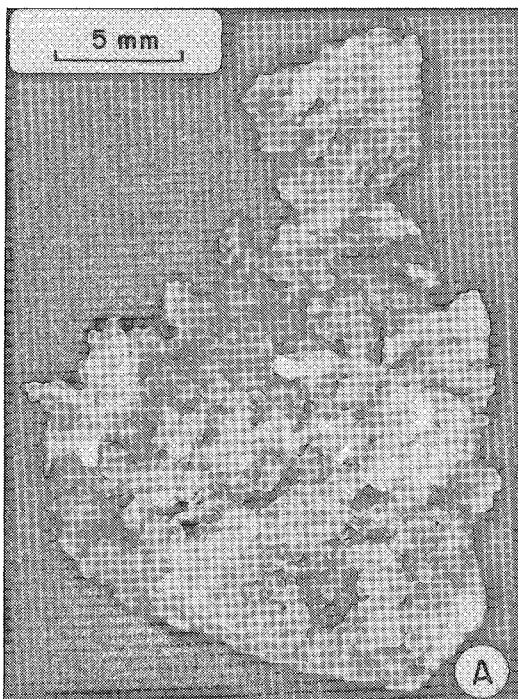


FIG. 6. Volkovskite. (A) Crystal aggregate. (B) Individual crystals. Locality: Penobscis.

the upper part of the Lower Halite or in the Sylvinite interval.

Middle Halite

In contrast to the Lower Halite, the Middle Halite interval contains the greatest concentration of borates, as well as the complete range of minerals found. Seven of the borates appear to be restricted to this interval (Fig. 3) and are therefore useful stratigraphic markers. Boracite, howlite, hydroboracite and volkovskite are the most common, although they occur in different concentrations throughout this stratigraphic horizon. Boracite tends to be more common at Salt Springs than at Penobsquis, where howlite predominates. Although there are also considerable variations within each deposit, in general these borates are found abundantly throughout the Middle Halite interval, except for a barren 15 m zone just above the Sylvinite interval.

The boracite crystals (Figs. 4, 5) occur as colorless to pale green or blue single cubes or aggregates, frequently found as laminations, associated with argillaceous halite beds. The single cubes vary from 0.8 to 2 mm in size, whereas the aggregates or clusters range from 4 to 2 cm. These boracite clusters appear to be similar to those described by Kühn (1968) and Elert (1976) from the salt deposits of northern Germany.

At Salt Springs, boracite, the major borate mineral, occurs in association with hydroboracite, hilgardite, szaibelyite, priceite, ulexite, colemanite and danburite. Although boracite has been commonly identified at Penobsquis, howlite is the most common mineral in association with hydroboracite and volkovskite as well as rarer (although locally common) occurrences of hilgardite, danburite, szaibelyite, colemanite and veatchite.

Howlite occurs as patches and bands of pustulose white nodules up to 1.5 cm in diameter, but generally ranging from 0.5 mm to less than 1 cm. It is associated with argillaceous beds and is often found concentrated in areas with anhydritic claystone laminae. Howlite has been reported widely in anhydrite beds of the Fundy basin, forming nodules up to 15 cm across (How 1868, Papezik & Fong 1975).

Hydroboracite (Fig. 5B) occurs as clear to light brown to greenish prismatic crystals up to 1 cm long, often forming rosettes or "swallow tails" up to 2 cm in length, resembling gypsum crystals. The crystals are unevenly distributed in the salt and do not appear to be concentrated

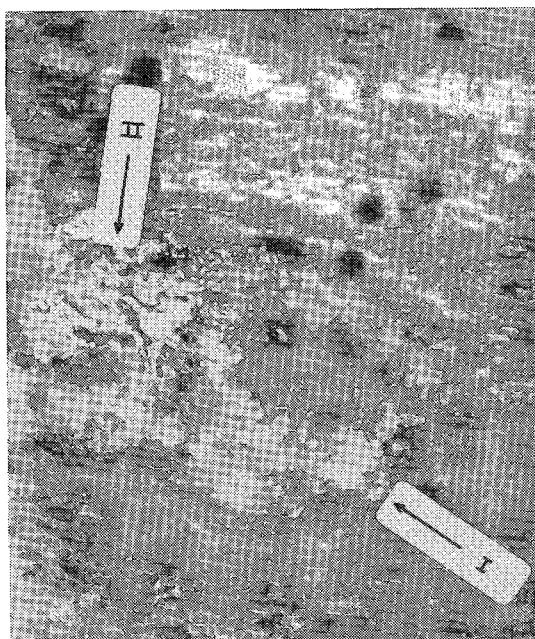


FIG. 7. Borate cluster. Hilgardite (I) and szaibelyite crystals (II). Note distortion of interstitial clays above borate cluster. Locality: Salt Springs.

in the argillaceous beds.

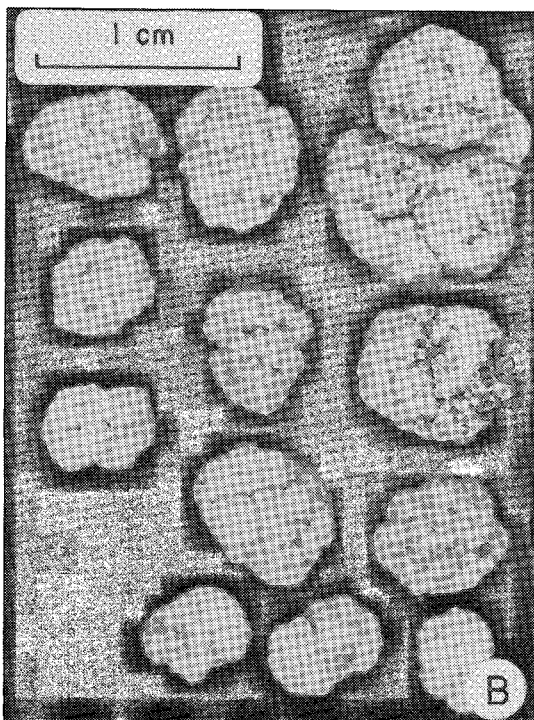
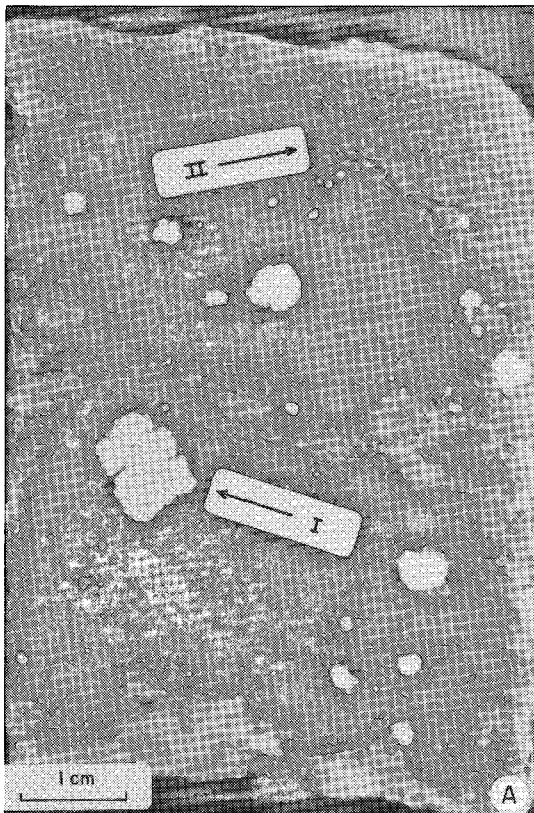
Volkovskite (Figs. 6, 8A) is abundant in the Middle Halite overlying the Sylvinite at Penobsquis and forms the largest borate aggregates that were identified. Some of these are light orange, subspherical, granular masses up to 5 cm in size. They occur most commonly in the argillaceous beds in association with howlite and, to a lesser extent, hydroboracite.

Hilgardite (Fig. 7) occurs as clusters of brownish, triangular-shaped crystals, often in parallel multiple growths, in association with other borates. Individual crystals vary from 0.5 to 5 mm, although clusters up to 2 cm have been measured.

Szaibelyite (Fig. 7) occurs as very fine, radiating, acicular white crystals that form "cotton-ball" aggregates. These disseminated aggregates range up to 9 mm in size and are generally associated with hilgardite and boracite.

Priceite, which occurs rarely in the Lower Halite, is found in one intersection at Salt Springs. It occurs as soft, chalky white nodules up to 1 mm in size, resembling danburite, and is associated with boracite and hydroboracite.

Although ulexite is one of the most common borates found throughout the Fundy basin (Fig.



2), where it occurs as white nodules 1–3 cm in size, it was only identified rarely in cores from Salt Springs. It occurs as very fine, fibrous, small white aggregates (Murowchick 1978).

Colemanite forms white to pale brown single crystals up to 1 mm, but also occurs as crystal aggregates up to 1 cm.

Danburite (Fig. 8) forms earthy to microcrystalline nodules 1–8 mm in size, similar to those described from the lower segment of the evaporite sequence. It is common at Penobscquis and rare at Salt Springs in the Middle Halite interval.

Veatchite occurs as brownish to red platy crystalline aggregates resembling volkovskite. It has been identified rarely in the Penobscquis deposit and has not been observed in the Salt Springs deposit.

Upper Anhydrite

Borate minerals have not been observed in the Upper Anhydrite or Upper Halite units.

ORIGIN OF BORATES

The extensive marine evaporite deposits of North America, which include the Silurian Salina Formation of Michigan, the Devonian Prairie Evaporite Formation of Saskatchewan, the Mississippian Hermosa Formation of Utah and Colorado and the Permian Salado Formation of New Mexico, all contain abundant late-stage (high-order) evaporites, but only trace occurrences of borates (*e.g.*, Schaller & Henderson 1932). However, widespread evaporite borate deposits have been recorded elsewhere.

Recent deposits have been documented by Muessig (1966) from the Andes in northwestern South America. There, ulexite, borax $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ and inyoite $\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 13\text{H}_2\text{O}$ occur as cones and aprons around hot springs, as well as in thin discontinuous beds and nodules in a salt and gypsum matrix in playas. Muessig (1966) discounted the possibility of leaching from a source in underlying or peripheral rocks, and conclude that the boron (and chloride) is of volcanic origin.

The thick Miocene borate deposits at Kramer, California, are also closely associated with volcanic rocks, being underlain by the

FIG. 8. Borate minerals. (A) White nodules of danburite (I) and very fine-grained aggregate of volkovskite (II). (B) Individual nodules of danburite. Locality: Penobscquis.

Saddleback Basalt and overlain by beds of volcanic ash. The borates have been shown to have originated from thermal springs discharging into a basin of restricted drainage (Barnard & Kistler 1966, Bowser & Dickson 1966). Bowser & Dickson (1966) also suggested that variations in the type of borates formed, mainly borax, ulexite and colemanite, in association with less common minerals (Morgan & Erd 1969), could have resulted from changes in the chemistry of the spring water as well as from postdepositional alteration.

The extensive Middle Oligocene Emet borate deposits of Turkey are interpreted by Helvacı & Firman (1976) as having been derived from weathering of volcanic rocks or from thermal springs. After extensive study of nonmarine lacustrine deposits, Borchert & Muir (1964) have similarly concluded that "borates are usually derived either from adjacent igneous rocks or from hot springs."

A direct relationship between borate minerals and an external thermal or magmatic source appears to be well documented. Also, in North America, there is a general segregation of borates and marine salt sequences, although combined occurrences are common elsewhere.

In the Danakil area of Ethiopia, for example, Quaternary marine evaporites have been mineralogically altered by boron-rich hydrothermal waters (Holwerda & Hutchinson 1968). The best-documented occurrences, however, are those of the Permian Zechstein evaporites of northern Germany, Poland and northeastern England, where boracite, stassfurtite (boracite aggregates), ascharite $MgHBO_3$ and other rarer borates have been identified. These borates have been studied extensively, and various interpretations have been suggested for the origin of the boron.

Harder (1959) suggested that the boron content of the Zechstein salt deposits is low enough to be explained by concentration due to the evaporation of salt water. However, the observed fissure filling by ascharite in the Zechstein 2 (Alteres Steinsalz), the large clusters and aggregates of "stassfurtite" and the random occurrence in low-salinity evaporites (anhydrite) have compelled D'Ans & Kühn (1960), Kühn (1968) and others to argue against primary mineralization. In their opinion, the irregular distribution of boracite and ascharite is related to pneumatolytic and hydrothermal activity. They stated that a volcanic source might be indicated, as an extensive felsic porphyry occurs below the saline Zechstein at Wolfsburg/Gilhorn, and acid volcanic rocks are present

in Rotliegender sandstone in the Hannoverian region.

Borchert & Muir (1964) and Braitsch (1971) agreed that the borates are the result of secondary mineralization, but suggested that they were derived from boron-enriched diagenetic brines formed by the concentration of interstitial solutions, without any external source of boron.

A modification of previous theories was suggested by Elert (1976), who undertook an extensive study of boron concentrations as well as borate minerals (mainly ascharite and "stassfurtite") of the Zechstein 2. He concluded that boron was expelled from the rock salt prior to deposition but remained in solution to be later introduced into the formation by telethermal processes.

In conclusion, the origin of nonmarine borates has been shown to be directly related to volcanism; although the association of borates and marine evaporites is obviously still open to interpretation, many workers have suggested that volcanism is a controlling factor.

DISCUSSION

The Mississippian Windsor Group evaporites of eastern Canada appear to be similar in many respects to the cratonic North American marine deposits (Kinsman 1974), but differ significantly by containing an extensive borate mineral assemblage and in being intimately associated with volcanic activity, both in space and time (Schenk 1969, van de Poll 1967, 1972, Gagnon & Carbonneau 1979). It is theoretically possible that the borate minerals could have been produced by the evaporation of sea water, which has an average composition of 0.026% H_3BO_3 , although no deposits are known to have originated in such a way. In fact, the world's major borate deposits have been shown to be the products of hydrothermal solutions derived from volcanic activity and concentrated by evaporation.

At Penobsquis and Salt Springs, the majority of the borates are concentrated in a specific stratigraphic unit. They also occur in association with sulfates but have never been identified in the sylvinitic. The presence of this unique mineral assemblage and its relationship to the evaporites can be explained by the occurrence of syn-depositional volcanism, which was a ready source of boron for the evaporite basin. It is suggested that this mechanism was responsible for the primary formation of borates in eastern Canada, although subsequent mineralogical alteration may also have occurred owing to diagenetic processes.

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