

BORATE MINERALS OF THE PENOBSQUIS AND MILLSTREAM DEPOSITS, SOUTHERN NEW BRUNSWICK, CANADA

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ABSTRACT

The borate minerals found in two potash deposits, at Penobsquis and Millstream, Kings County, New Brunswick, are described in detail. These deposits are located in the Moncton Subbasin, which forms the eastern portion of the extensive Maritimes Basin. These marine evaporites consist of an early carbonate unit, followed by a sulfate, and finally, a salt unit. The borate assemblages occur in specific beds of halite and sylvite that were the last units to form in the evaporite sequence. Species identified from drill-core sections include: boracite, brianroulstonite, chambersite, colemanite, congolite, danburite, hilgardite, howlite, hydroboracite, kurgantaite, penobsquisite, pringleite, ruitenbergite, strontioninorite, szaibélyite, trembathite, veatchite, volkovskite and walkerite. In addition, 41 non-borate species have been identified, including magnesite, monohydrocalcite, sellaite, kieserite and fluorite. The borate assemblages in the two deposits differ, and in each deposit, they vary stratigraphically. At Millstream, boracite is the most common borate in the sylvite + carnallite beds, with hilgardite in the lower halite strata. At Penobsquis, there is an upper unit of hilgardite + volkovskite + trembathite in halite and a lower unit of hydroboracite + volkovskite + trembathite–congolite in halite–sylvite. At both deposits, values of the ratio of B isotopes [$\delta^{11}\text{B}$] range from 21.5 to 37.8‰ [21 analyses] and are consistent with a seawater source, without any need for a more exotic interpretation. The assemblage at Penobsquis is consistent with a fore-basin deposition by evaporation, whereas that at Millstream, a more inland and restricted basin, is indicative of a late-stage periodic influx of concentrated brines from the fore-basin. The evaporites are intensely folded, but the degree of metamorphism remains unknown.

Keywords: borate minerals, boron isotopes, marine evaporite, chemical composition, Penobsquis, Millstream, New Brunswick.

SOMMAIRE

Les borates trouvés dans deux gisements de potassium, Penobsquis et Millstream, dans le comté de Kings, au Nouveau-Brunswick, sont ici décrits en détail. Ces gisements sont situés dans le sous-bassin de Moncton, qui forme la portion orientale du vaste bassin des Maritimes. Ces évaporites marines sont faites d'une unité précoce riche en carbonates, suivie d'une séquence riche en sulfates, et ensuite en halite. Les assemblages de borates sont présents dans des couches spécifiques de halite et de sylvite, dernières à se former dans la séquence évaporitique. Les espèces minérales identifiées dans les carottes incluent: boracite, brianroulstonite, chambersite, colemanite, congolite, danburite, hilgardite, howlite, hydroboracite, kurgantaite, penobsquisite, pringleite, ruitenbergite, strontioninorite, szaibélyite, trembathite, veatchite, volkovskite et walkerite. De plus, 41 espèces autres que les borates ont été identifiées, y inclus magnésite, monohydrocalcite, sellaite, kieserite et fluorite. Les assemblages de borates dans les deux gisements diffèrent, et dans chacun, il y a une zonation stratigraphique. A Millstream, la boracite est le borate le plus répandu dans les couches à sylvite + carnallite, et la hilgardite est prédominante dans les strates inférieures à halite. A Penobsquis, il y a une unité supérieure à hilgardite + volkovskite + trembathite dans la halite et une unité inférieure à hydroboracite + volkovskite + trembathite–congolite dans la halite + sylvite. Dans les deux gisements, les valeurs du rapport des isotopes de bore, $\delta^{11}\text{B}$, dans l'intervalle 21.5 à 37.8‰ [21 analyses], concordent avec un milieu marin, sans besoin de recours à une interprétation plus exotique. L'assemblage à Penobsquis concorde avec une déposition dans un bassin proximal par évaporation, tandis qu'à Millstream, un bassin plus interne à accès plus restreint, il y a évidence de remplissage périodique tardif par des saumures provenant du bassin proximal. La séquence évaporitique est fortement plissée, mais le degré de métamorphisme demeure méconnu.

(Traduit par la Rédaction)

Mots-clés: minéraux boratés, isotopes de bore, évaporite marine, composition chimique, Penobsquis, Millstream, Nouveau-Brunswick.

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INTRODUCTION

Borate mineralization in eastern Canada was first documented by How (1857), who identified ulexite and ginorite in the gypsum deposits of Windsor, Nova Scotia. How (1868, 1877) later reported a new mineral from Noel, Hants County, Nova Scotia, which he named "silicoborocalcite" (now howlite). It occurs as nodules in the gypsum unit. Goodman (1957) reported finding danburite at White Head, Victoria County, and inyoite from Wentworth area, Hants County, Nova Scotia. Howlite and ulexite have been reported from several other localities in the gypsum-rich horizons of Nova Scotia, New Brunswick and Newfoundland (Papezik & Fong 1975).

In 1971, in the context of a provincial government exploration project for high-grade salt deposits to be used in the chemical industry, geologists made the initial discovery of potash in the Sussex area of New Brunswick. The importance of the potash discovery as a source of potassium for the fertilizer industry precluded any immediate interest in halite. Further exploration outlined three important sylvite (potash) deposits (Fig. 1): (1) Penobsquis, 12 km NE of Sussex, formerly owned by the Potash Company of America, is now owned and operated by Potash Corporation of Saskatchewan Incorporated (New Brunswick Division); (2) Clover Hill (Salt Springs), formerly owned

by Potacan prior to Denison-Potacan, is now owned by Potash Corporation of Saskatchewan Incorporated (New Brunswick Division), but not presently operating; (3) Millstream, 10 km west of Sussex, has never been mined, and the mining lease is held by the provincial government of New Brunswick. As these deposits were mined or developed, it became evident that they contain a significant concentration of borate minerals. The assemblage of borate minerals was discussed by Roulston & Waugh (1981) for the Penobsquis and Salt Springs (Clover Hill) deposits.

In the present study of the Penobsquis and Millstream deposits (drill core for the Clover Hill deposit was not available), we examined the various assemblages in several cores and correlated them with the host strata. The mineral species are identified, described, many are analyzed, and their distribution determined in the two deposits. Differences between the deposits and within a deposit are discussed. Boron isotopes analyses are used to answer the question of origin of the boron; was it a volcanic or a marine environment? Metamorphism of the deposits is briefly discussed.

GEOLOGICAL SETTING

The geology of the Maritimes Basin was discussed in detail by Papezik & Fong (1975), Waugh & Urquhart (1983), and Webb & Roulston (1994). The Carbonife-

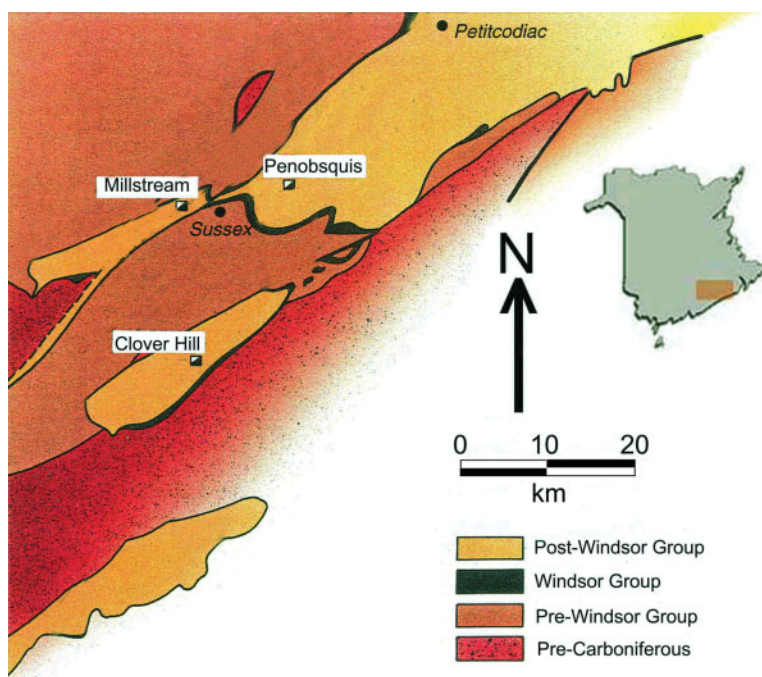


FIG. 1. Location of the potash deposits within the Windsor Group evaporites in the Sussex area of New Brunswick (after Webb & Roulston 1994).

rous (300 m.y.) sedimentary rocks of eastern Canada extend from southern New Brunswick to the western margin of Newfoundland. This large, complex depositional trough is referred to as the Maritimes Basin. Tectonic activity throughout the Upper Devonian to Lower Carboniferous resulted in a series of northeast- to east-trending troughs or subbasins. These troughs were largely filled by continental clastic sediments, but as well a series of marine evaporites such as carbonates, sulfates and chlorides was developed.

The Moncton Subbasin underwent two distinct cycles of evaporite deposition. The earlier and longer cycle resulted in a lower carbonate unit, followed by a sulfate sequence and, lastly, the residual salts of sodium (halite), potassium (sylvite), and magnesium (carnallite) (Fig. 2). In Figure 2 and in what follows, the term "sylvinite" refers to an evaporite rock rich in sylvite and halite. The second depositional event is characterized by a series of shallow-water evaporites, including an anhydrite unit with localized occurrences of halite and clay. The entire Windsor evaporite sequence was subsequently buried by continental sediments. In the Moncton Subbasin near Sussex, New Brunswick, the deposits alluded to earlier occur in the three local depositional troughs: Penobsquis, Clover Hill and Millstream. In all three deposits, there is a diverse and extensive accumulation of borate minerals in the upper units of the first evaporite cycle. These borate minerals are the main subject of this paper.

ANALYTICAL METHODS

Sampling

All samples from the evaporite deposits were collected from drill core (Fig. 3), as there are no outcrops of the mineralized horizons. The Potash Corporation of Saskatchewan Incorporated (New Brunswick Division) and the New Brunswick Department of Natural Resources and Energy generously provided access to their core sheds for the Penobsquis and Millstream deposits, respectively. They also made available the logs of their core, greatly reducing the amount of time necessary to obtain good representation of the borate-bearing zones for each deposit. For Penobsquis, 144 samples, and for Millstream, 42 samples were taken. Each sample consisted of a length of 2 to 6 cm of 1.5 or 2 cm in diameter core. Initially, several thin sections were specially prepared using acetone to prevent dissolution of any minerals. No borate minerals that are water-soluble were identified in these thin sections, so the remainders of the samples were prepared by dissolving the salt minerals in water and examining the residues. The grain size of insoluble fractions, consisting of borates and other minerals, generally ranged from 0.5 mm to 6 mm.

X-ray diffraction

The standard technique for identification was to take an X-ray powder-diffraction pattern using Cu radiation and a 114.6 mm camera having Debye-Scherrer or Gandolfi geometry. A total of 915 diffraction patterns were taken. For mineral samples that appeared to be new or could not be identified solely by X-ray diffraction, electron-microprobe analyses were performed. X-ray-diffraction data for new minerals first described from these deposits (brianroulstonite, penobsquisite, pringleite, ruitenbergite, trembathite and walkerite) are given a reference in the Mineral Descriptions below.

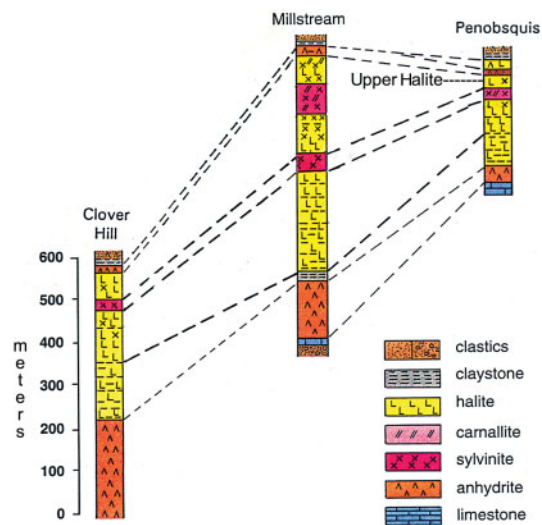


FIG. 2. Correlation of stratigraphic sections of the three potash deposits in the Sussex area of New Brunswick (after Webb & Roulston 1994).



FIG. 3. Photograph of a section of drill core from the Penobsquis deposit. The borate minerals are white spheroids within the orange-colored halite.

TABLE 1a. SUSSEX, NEW BRUNSWICK, CANADA: REPRESENTATIVE CHEMICAL COMPOSITIONS OF THE BORACITE GROUP

	Boracite		Millstream Deposit Trembathite		Congolite		Boracite		Penobsquis Deposit Trembathite		Congolite	
	Ave. (n = 84)	Range	Ave. (n = 6)	Range	Ave. (n = 13)	Range	Ave. (n = 18)	Range	Ave. (n = 13)	Range	Ave. (n = 15)	Range
MgO wt. %	28.92	(18.39-33.73)	16.05	(14.23-18.03)	8.48	(1.59-13.45)	24.18	(19.08-33.18)	16.33	(13.60-18.17)	5.99	(0.27-12.55)
MnO	0.14	(0.00-1.95)	0.40	(0.05-0.55)	1.50	(0.39-7.97)	0.64	(0.00-6.59)	0.16	(0.07-0.34)	3.94	(0.12-10.27)
FeO	5.83	(0.46-19.21)	22.20	(18.92-24.55)	30.96	(25.52-39.11)	11.67	(0.62-18.87)	21.88	(19.73-25.31)	31.23	(27.31-38.17)
CaO	0.16	(0.00-0.81)	0.03	(0.00-0.12)	0.16	(0.00-0.81)	0.07	(0.00-0.22)	0.08	(0.00-0.18)	0.38	(0.00-0.82)
Cl	8.26	(3.61-9.68)	8.38	(7.94-8.85)	7.88	(6.68-8.58)	7.08	(4.09-9.54)	7.53	(6.29-8.42)	7.21	(6.66-7.74)
(B ₂ O ₃)	64.05		57.89		54.06		60.74		57.06		52.03	
O=Cl	-1.86		-1.89		-1.78		-1.60		-1.70		-1.63	
Total	105.50		103.06		101.26		102.79		101.34		99.15	
<i>Formula contents on the basis of 14 anions</i>												
Mg <i>apfu</i>	2.73		1.68		0.95		2.41		1.73		0.70	
Mn ²⁺	0.01		0.02		0.10		0.04		0.01		0.26	
Fe ²⁺	0.31		1.30		1.94		0.65		1.30		2.04	
Ca	0.01		0.00		0.01		0.00		0.01		0.03	
Cl	0.89		1.00		1.00		0.80		0.91		0.95	
B	7		7		7		7		7		7	

TABLE 1b. SUSSEX, NEW BRUNSWICK, CANADA: REPRESENTATIVE CHEMICAL COMPOSITIONS

	Brianroulstonite Penobsquis		Chambersite Penobsquis		Colemanite Penobsquis		Hilgardite Millstream		Hilgardite Penobsquis		Hydroboracite Penobsquis	
	Ave. (n = 4)	Range	Ave. (n = 1)	Range	Ave. (n = 26)	Range	Ave. (n = 7)	Range	Ave. (n = 58)	Range	Ave. (n = 14)	Range
K ₂ O wt. %	0.05	0.05-0.06										
CaO	32.85	29.24-34.50	0.83		26.67	26.36-26.94	32.64	31.60-33.38	32.38	28.40-33.82	12.95	12.67-13.22
SrO							0.92	0.09-2.44	0.97	0.00-7.97		
MgO			6.33								10.19	10.00-10.37
MnO			21.73									
FeO			12.58								0.20	0.10-0.42
Cl	13.79	13.28-14.31	7.73				10.26	9.64-11.05	10.68	9.77-10.93		
(B ₂ O ₃)	33.92		53.07		49.67		51.21		51.34		50.81	
(H ₂ O)	40.44						5.3		5.31			
O=Cl	-3.11		-1.74				-2.32		-2.41		26.30	
Total	117.99		100.53		97.76		98.02		98.27		100.44	
<i>Formula contents on the basis of a fixed, total anion sum</i>												
K <i>apfu</i>	0.01											
Ca	3.00		0.07		2.00		1.98		1.96		0.95	
Sr							0.03		0.03			
Mg			0.72								1.04	
Mn			1.41									
Fe			0.80								0.01	
Cl	1.99		1.00		6		0.98		1.02			
B	5		7		10		5		5		6	
H	23						2		2		12	
Σanion	23		14		16		11		11		17	

TABLE 1c. SUSSEX, NEW BRUNSWICK, CANADA: REPRESENTATIVE CHEMICAL COMPOSITIONS

	Kurgantaite Penobsquis		Penobsquisite Penobsquis		Pringleite				Strontioginorite Penobsquis		
	Ave. (n = 3)	Range	Ave. (n = 3)	Range	Millstream Ave. (n = 6)	Range	Penobsquis Ave. (n = 34)	Range	Millstream Ave. (n = 1)	Ave. (n = 9)	Range
CaO wt. %	16.19	15.85-16.66	17.27	17.20-17.36	25.30	24.94-26.02	24.66	24.02-25.46	7.86	7.47	6.66-8.10
SrO	25.51	24.91-26.32							11.68	12.23	11.30-13.69
MgO			1.82	1.37-2.25							
MnO			0.23	0.20-0.25							
FeO			7.48	6.79-8.08							
Cl	9.22	9.11-9.35	5.77	5.62-5.86	5.72	4.60-7.00	5.36	4.08-6.70			
(B ₂ O ₃)	46.29		48.50		43.76		44.22		61.62	61.22	
(H ₂ O)	4.79		19.52		21.78		22.40		18.22	18.10	
O=Cl	-2.08		-1.30		-1.29		-1.21				
Total	99.92		99.29		95.26		95.44		99.38	99.02	
<i>Formula contents on the basis of a fixed, total anion sum</i>											
Ca <i>apfu</i>	1.08		1.99		9.33		9.00		0.89	0.94	
Sr	0.93								1.11	1.06	
Mg			0.29								
Mn			0.02								
Fe			0.67								
Cl	0.98		1.05		3.34		3.09				
B	5		9		26		26		14	14	
H	2		10		50.78		50.91		16	16	
Σanion	11		24		75		75		31	31	

TABLE 1d. SUSSEX, NEW BRUNSWICK, CANADA:
REPRESENTATIVE CHEMICAL COMPOSITIONS

	Szaibélyite Penobsquis		Veatchite Penobsquis		Volkovskite				Walkerite* Penobsquis		
	Ave. (n = 8)	Range	Ave. (n = 10)	Range	Millstream Ave. (n = 4)	Range	Penobsquis Ave. (n = 30)	Range	Ave. (n = 18)	Range	
K ₂ O wt. %					3.69	3.63-3.77	3.64	3.51-3.74	0.07		
CaO			4.34	1.30-6.63	18.26	17.84-18.51	18.25	17.32-18.87	23.05	21.52-24.79	
SrO			25.21	21.25-30.45	0.49	0.07-0.90	0.51	0.00-1.66			
MgO	49.20	47.11-50.24							0.58	0.16-0.88	
MnO	tr.										
FeO	0.84	0.23-3.07	0.10	0.00-0.21	0.04	0.00-0.16	0.03	0.00-0.21	0.32	0.16-0.44	
Cl					2.79	2.73-2.88	2.72	2.50-2.87	4.91	3.33-5.68	
(B ₂ O ₃)	42.90		61.66		62.98		62.87		47.17*		
(H ₂ O)	11.10		10.15		13.37		13.36		25.48		
O=Cl					-0.63		-0.61		-1.11		
Total	104.04		101.47		100.99		100.77		100.72		
<i>Formula contents on the basis of a fixed, total anion sum</i>											
K <i>apfu</i>					0.95		0.94		0.06		
Ca			0.48		3.96		3.96		15.60		
Sr			1.51		0.06		0.06				
Mg	0.99								0.55		
Mn											
Fe	0.01		0.01		0.01		0.01		0.17		
Cl					0.96		0.94		5.26		
B	1		11		22		22		51.42		
H	1		7		18.04		18.06		107.34		
Σanion	3		22		47		47		14		

* in walkerite, the concentration of B₂O₃ was determined by ICP-MS; in addition, it contains 0.12% Li₂O and 0.13% Na₂O, corresponding to 0.31 *apfu* Li and 0.16 *apfu* Na.

Electron-microprobe analysis

The chemical analyses were performed with a JEOL 733 electron microprobe in wavelength-dispersion (WD) mode using Tracor Northern 5500 and 5600 automation. Data reduction was done with a PAP routine in XMAQNT (C. Davidson, CSIRO, *pers. commun.*). The operating voltage was 15 kV, and the beam current was 20 nA. The beam diameter varied from 20 to 40 μm . The following standards were used: albite (NaK α), rubidian microcline (KK α), danburite (CaK α), celestine (SrL α), dolomite (MgK α), almandine (FeK α), tephroite (MnK α), phlogopite (FK α) and tugtupite (ClK α). Only those elements detected are reported in the tables of chemical composition of the various species. Data for all elements in the samples were collected for 25 s or 0.50% precision, whichever was attained first. One-hundred-second energy-dispersion (ED) scans were performed on many of the samples to check on levels of trace elements and, where detected, they are mentioned in footnotes to the tables. A total of 637 electron-microprobe analyses were performed, and a summary of these results is presented in Table 1.

Boron isotopes: method

Samples were chosen for boron isotopic analyses from both deposits, with fifteen samples from Millstream and six samples from Penobsquis. Sample sites within each deposit were selected from core sections varying in areal extent, depth and mineral species.

Each monomineralic sample consisted of 5–10 mg of hand-picked crystals.

Boron isotope measurements were made at the Geological Survey of Canada (Grégoire 1987) with the following procedure. Milligram quantities of sample were dissolved in 50 mL of concentrated HCl. Following evaporation to dryness, the sample residue was dissolved in 5 mL of water. The resulting solution was diluted 1000-fold prior to inductively coupled plasma – mass spectrometry (ICP–MS) measurement. For each solution, the boron isotope composition was measured on four replicate aliquots and averaged. Instrumental mass-discrimination was corrected using a solution of NIST SRM 951 isotopically analyzed boric acid. The precision of the boron isotope value measured is 0.2%. Results of these analyses are presented in Table 2.

BORON ISOTOPES: RESULTS

Table 2 includes the borate species chosen for analysis along with the fraction of borate polyhedra in trigonal and tetrahedral coordination in their structure. For the Millstream deposit, the seven samples of hilgardite have values of the boron isotope ratio $\delta^{11}\text{B}$ from +24.2 to +37.8‰ (mean value 28.6‰), and the eight samples of boracite have $\delta^{11}\text{B}$ values from +21.5 to +35.8‰ (mean value 30.5‰). For the Penobsquis deposit, four different species were chosen with varying proportions of the two types of polyhedra. The six samples have $\delta^{11}\text{B}$ values from +25.3 to +36.4‰ (mean value 30.7‰). Combining both deposits, there is a large range of $\delta^{11}\text{B}$ values, from +21.5 to +37.8‰ (mean value 29.9‰).

The average boron isotopic composition for Sussex samples, $\delta^{11}\text{B} = 29.9\%$, falls within the range of values of $\delta^{11}\text{B}$, +18.2 to +31.7‰, given by Barth (1993) for marine borate minerals. Barth (1993) gave the $\delta^{11}\text{B}$ range –30.1 to +10.2‰ for non-marine borate minerals, and the range –0.9 to 21.4‰ for fumarolic condensates. Thus the borate mineral assemblages within the Sussex deposits are consistent with a marine evaporite origin on the basis of the boron isotopes. This is in contrast to the proposal of Roulston & Waugh (1981), that the borate assemblages are due to syndepositional volcanism. In the Sussex data, no correlation is apparent between the boron isotope composition and the ratio of boron in triangular coordination to that of boron in tetrahedral coordination; such a correlation was described by Oie *et al.* (1989).

MINERAL DESCRIPTIONS

The 19 species of borate minerals that have been identified in the Sussex deposits are listed in Table 3. Those first described from this area are highlighted, and a reference to the description of the type material is given in the text. Table 3 also includes the mineral

TABLE 2. SUSSEX, NEW BRUNSWICK, CANADA:
BORON ISOTOPE RATIO FOR SELECTED MINERALS

Species	Polyhedra	Fraction*	Drill hole	Sample number	$\delta^{11}\text{B}^{\dagger}$
Millstream deposit					
boracite	1 Δ 6 \square	0.14	BP 1A	F94/3/2	34.7
boracite	1 Δ 6 \square	0.14	BP 1A	F94/3/5	27.4
boracite	1 Δ 6 \square	0.14	BP 1A	F94/3/10	35.8
boracite	1 Δ 6 \square	0.14	BP 2	F94/3/11	30.7
boracite	1 Δ 6 \square	0.14	BP 7	F94/3/18	32.1
boracite	1 Δ 6 \square	0.14	BP 7	F94/3/22	21.5
boracite	1 Δ 6 \square	0.14	BP 8	F94/3/31	32.4
boracite	1 Δ 6 \square	0.14	BP 9	F94/3/35	29.4
hilgardite	2 Δ 3 \square	0.40	BP 1A	F94/3/3	37.8
hilgardite	2 Δ 3 \square	0.40	BP 1A	F94/3/7	24.2
hilgardite	2 Δ 3 \square	0.40	BP 1A	F94/3/9	32.9
hilgardite	2 Δ 3 \square	0.40	BP 2	F94/3/15	25.0
hilgardite	2 Δ 3 \square	0.40	BP 4	F94/3/42	28.7
hilgardite	2 Δ 3 \square	0.40	BP 8	F94/3/32	24.5
hilgardite	2 Δ 3 \square	0.40	BP 8	F94/3/33	26.9
Penobsquis deposit					
boracite	1 Δ 6 \square	0.14	PCA M4	F94/3/57	32.1
hydroboracite	1 Δ 2 \square	0.33	PCA M4	F94/3/60	30.2
hydroboracite	1 Δ 2 \square	0.33	PCA H5	F94/3/67	25.3
hilgardite	2 Δ 3 \square	0.40	PCA M4	F94/3/43	32.5
volkovskite	4 Δ 2 \square	0.67	PCA M4	F94/3/46	36.4
volkovskite	4 Δ 2 \square	0.67	PCA V4	F94/3/71	27.5

* Fraction: the ratio $n\Delta / (n\Delta + m\square)$, where n and m are the number of each type of polyhedron. \dagger The value of $\delta^{11}\text{B}$ is reported in ‰.

formula, relative abundance, cation : anion ratio, and the structural classification for each species.

Boracite, $Mg_3B_7O_{13}Cl$, *orthorhombic*

Boracite (chemical data in Table 1a) is commonly found at both Penobsquis and Millstream deposits. It occurs as pseudocubic, pseudododecahedral, or pseudotetrahedral crystals of millimetric size (Fig. 4) and as stepped or multifaceted spheroids of fine-grained aggregates up to 40 mm across. It is colorless, white, gray, pale yellow to orange and pale blue to pale green. The crystals are translucent to transparent, with a vitreous luster. In thin section, boracite crystals have an undulatory extinction. Boracite is brittle, without cleavage; it has an uneven to conchoidal fracture. In the Millstream deposit, boracite is associated with hilgardite and, in some cases, it occurs as inclusions in hilgardite, rarely with anhydrite, kieserite and szaibélyite. In the Penobsquis deposit, boracite is uncommon relative to trembathite and congolite; it is associated with hydroboracite, hilgardite and volkovskite. Samples that are chemically zoned invariably have the more Fe-rich phase (trembathite or congolite) in the core, and the more Mg-rich phase (boracite) is the last to crystallize.

Brianroulstonite, $Ca_3B_5O_6(OH)_7Cl_2 \cdot 8H_2O$, *monoclinic*

Brianroulstonite (chemical data in Table 1b) was first described by Grice *et al.* (1997) from the Penobsquis deposit. This remains the only known locality. It is very rare in that deposit, being found as a few flakes in two samples. It is found in halite intimately associated with hilgardite, pringleite, trembathite, sellaite, fluorite, hematite, penobsquisite, a mica-group mineral and a

clay-group mineral. It occurs as cleavable masses to 2 mm with individual micaceous crystals to 0.2 mm. The thin, colorless to white {010} lamellae are flexible, transparent to translucent, with a vitreous luster and a white streak. It has a perfect {010} cleavage. It has a unique sheet structure among borate minerals (Grice *et al.* 1999).

Chambersite, $Mn_3B_7O_{13}Cl$, *orthorhombic*

Chambersite (chemical data in Table 1b), a member of the boracite group, was found in only one sample from the Penobsquis deposit. It is found in orange halite associated with hydroboracite, hilgardite, volkovskite, szaibélyite, anhydrite, a mica-group mineral, magnesite and quartz. It occurs as 0.5 to 1.5 mm, euhedral, light-blue, flattened tetrahedra. There is no cleavage, and the fracture is uneven.

Colemanite, $Ca_2B_6O_{11} \cdot 5H_2O$, *monoclinic*

Colemanite (chemical data in Table 1b) is found as a common accessory mineral in the Penobsquis deposit, but it has been found in only one sample at Millstream. It occurs as single, pseudorhomboidal to short prismatic crystals up to 3 mm (Fig. 5) in size and as groups of crystals or nodules to 10 mm. It is colorless, pale yellow, pale to dark orange and brown. Crystals are translucent to transparent, commonly etched and with a vitreous to dull luster. It has a perfect {010} cleavage.

Congolite, $Fe_3B_7O_{13}Cl$, *orthorhombic*

Congolite (chemical data in Table 1a), a member of the boracite group, occurs as zones within trem-



FIG. 4. Photograph of boracite cubes (2 mm across) on hydroboracite from the Penobsquis deposit. Photograph by Q. Wight.

bathite crystals. Although it occurs at both deposits, it is much more common at Penobsquis. It is found as perfect pseudocubes a few mm across (Fig. 6) and is commonly colorless to grey or mauve in color. In the Penobsquis deposit, congolite is associated with volkovskite, hilgardite, trembathite, hydroboracite, danburite and strontionorite. At Millstream, congolite

is associated with hilgardite, strontionorite, anhydrite and magnesite.

Danburite, $\text{CaB}_2(\text{SiO}_4)_2$, *orthorhombic*

Danburite occurs as massive, fine-grained, white nodules up to a few cm across (Fig. 7) in the Penobs-

TABLE 3. SUSSEX, NEW BRUNSWICK, CANADA: LIST OF BORATE MINERALS

Mineral ¹	Abundance ²	Formula	Ca : Other : B : H ³	Structure ⁴
Boracite	a	$\text{Mg}_3\text{B}_7\text{O}_{13}\text{Cl}$	0 : 1 : 2.3 : 0	Framework: 1Δ 6□
* Brianroulstonite	vr	$\text{Ca}_3\text{B}_5\text{O}_{16}(\text{OH})_7\text{Cl}_2 \cdot 8\text{H}_2\text{O}$	1 : 0 : 1.6 : 7.6	Sheet: 6Δ 6□
Chambersite	vr	$\text{Mn}_3\text{B}_7\text{O}_{13}\text{Cl}$	0 : 1 : 2.3 : 0	Framework: 1Δ 6□
Colemanite	rc	$\text{CaB}_2\text{O}_4(\text{OH})_3 \cdot \text{H}_2\text{O}$	1 : 0 : 3 : 5	Chain: 1Δ 2□
Congolite	c	$\text{Fe}_3\text{B}_7\text{O}_{13}\text{Cl}$	0 : 1 : 2.3 : 0	Framework: 1Δ 6□
Danburite	rc	$\text{CaB}_2(\text{SiO}_4)_2$	1 : 0 : (4) : 0	Framework: 10□
Hilgardite	a	$\text{Ca}_2\text{B}_5\text{O}_{13}\text{Cl} \cdot \text{H}_2\text{O}$	1 : 0 : 2.5 : 1	Framework: 2Δ 3□
Howlite	r	$\text{Ca}_2\text{B}_6\text{SiO}_9(\text{OH})_5$	1 : 0 : (3) : 2.5	Framework: 1Δ 6□
Hydroboracite	c	$\text{CaMgB}_3\text{O}_4(\text{OH})_3 \cdot 3\text{H}_2\text{O}$	1 : 1 : 3 : 9	Chain: 1Δ 2□
Kurgantaitite	r	$\text{CaSrB}_2\text{O}_9\text{Cl} \cdot \text{H}_2\text{O}$	1 : 0 : 2.5 : 1	Framework 2Δ 3□
* Penobsquisite	r	$\text{Ca}_7\text{FeB}_9\text{O}_{18}(\text{OH})_6\text{Cl} \cdot 4\text{H}_2\text{O}$	1 : 0.5 : 4.5 : 7.0	Framework: 10Δ 11□
* Pringleite	r	$\text{Ca}_9\text{B}_{26}\text{O}_{34}(\text{OH})_{24}\text{Cl}_4 \cdot 13\text{H}_2\text{O}$	1 : 0 : 2.9 : 5.6	Framework: 8Δ 7□
* Ruitenbergite	vr	$\text{Ca}_9\text{B}_{26}\text{O}_{34}(\text{OH})_{24}\text{Cl}_4 \cdot 13\text{H}_2\text{O}$	1 : 0 : 2.9 : 5.6	Framework: 8Δ 7□
Strontionorite	c	$\text{SrCa}[\text{B}_{14}\text{O}_{20}(\text{OH})_6] \cdot 5\text{H}_2\text{O}$	1 : 0 : 7 : 8	Sheet: 8Δ 6□
Szaibélyite	rc	$\text{MgBO}_2(\text{OH})$	0 : 1 : 1 : 1	Cluster: 2Δ
* Trembathite	c	$(\text{Mg}, \text{Fe})_3\text{B}_7\text{O}_{13}\text{Cl}$	0 : 1 : 2.3 : 0	Framework: 1Δ 6□
Veatchite	c	$\text{Sr}_2\text{B}_{11}\text{O}_{16}(\text{OH})_5 \cdot \text{H}_2\text{O}$	1 : 0 : 5.5 : 3.5	Sheet: 4Δ 2□
Volkovskite	c	$\text{KCa}_4\text{B}_{22}\text{O}_{32}(\text{OH})_{10}\text{Cl} \cdot 4\text{H}_2\text{O}$	1 : 0 : 4.4 : 3.5	Sheet: 4Δ 3□
* Walkerite	r	$\text{Ca}_8\text{MgB}_{26}\text{O}_{34}(\text{OH})_{24}\text{Cl}_3 \cdot 14\text{H}_2\text{O}$	1 : 0.1 : 3.3 : 6.5	Sheet: 10Δ 10□

1) * indicates a species first described from Sussex. 2) Abbreviations: a abundant, c common, rc relatively common, r rare, vr: very rare. 3) Proportion of Calcium : cations other than Ca : Boron : Hydrogen. 4) Structure classification of Grice *et al.* (1999).



FIG. 5. Photograph of colemanite crystals, 10 mm long, from the Penobsquis deposit. Photograph by Q. Wight.

quis deposit. Nodules are difficult to distinguish from similar nodules of fine-grained strontioginorite, anhydrite or boracite-group minerals. It was found

only at Penobsquis in association with howlite, volkovskite, hilgardite, strontioginorite, hydroboracite and boracite.



FIG. 6. Photograph of aggregates of concolite crystals that attain 17 mm across from the Penobsquis deposit. Photograph by L. Horváth.



FIG. 7. Photograph of danburite nodule 10 mm in diameter from the Penobsquis deposit. Photograph by L. Horváth.

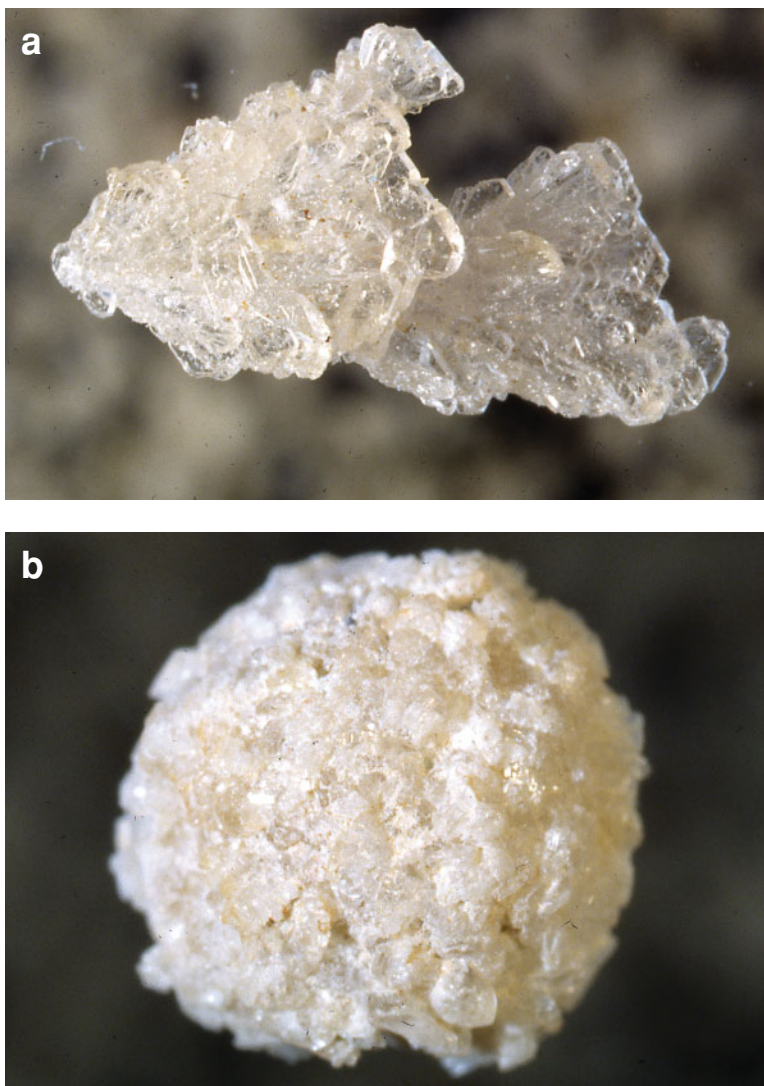


FIG. 8. Photograph of hilgardite; (a) arborescent cluster, 7 mm long; (b) nodule 10 mm in diameter from the Penobsquis deposit. Photograph by Q. Wight.

Hilgardite, $\text{Ca}_2\text{B}_5\text{O}_9\text{Cl}\cdot\text{H}_2\text{O}$, *triclinic or monoclinic*

Hilgardite (chemical data in Table 1b) is very common at Penobsquis and common at Millstream. At the Millstream deposit, only hilgardite-3A has been found, associated with the boracite group of borate minerals. In contrast, the Penobsquis deposit has all three polytypes, hilgardite-1A, hilgardite-3A and hilgardite-4M. The monoclinic polytype hilgardite-4M was first recognized from Sussex by Rachlin *et al.* (1986), and Burns & Hawthorne (1994) refined the crystal

structure of hilgardite-1A from Penobsquis. These two polytypes, -4M and -1A, occur in the margins and at depth in the halite-“sylvinite” sequence associated with hydroboracite and volkovskite. Hilgardite-3A is ubiquitous at Penobsquis, and it is occasionally associated with the other two polymorphs. The hilgardite group forms complex, tabular to platy crystals up to 5 mm across, occasionally occurring as arborescent clusters or multiple parallel growths forming spheres to 10 mm in diameter (Fig. 8). It is colorless, tan, pale yellow and pale to bright orange. Crystals are transparent and vitreous. The Mohs hardness is 5, and it has perfect

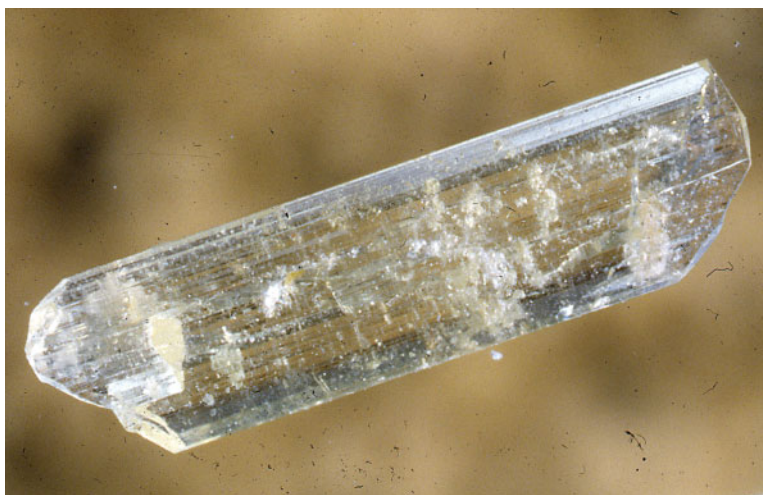


FIG. 9. Photograph of hydroboracite, doubly terminated crystal 15 mm long from the Penobsquis deposit. Photograph by Q. Wight.



FIG. 10. Photograph of penobsquisite crystals up to 1.5 mm from the Penobsquis deposit. Photograph by Q. Wight.

{010} and {100} cleavages. At Millstream, hilgardite has inclusions of boracite.

Howlite, $\text{Ca}_2\text{B}_5\text{SiO}_9(\text{OH})_5$, *monoclinic*

Howlite occurs rarely at Penobsquis. It is associated with danburite, boracite, hydroboracite, hilgardite and volkovskite. It forms elongate [001], flattened {010} and striated crystals up to 0.3 mm and nodules to 15 mm across. Crystals are transparent, colorless with a vitreous luster, and nodules are a porcelainous white. The Mohs hardness is 3, and it has a perfect {010} cleavage.

Hydroboracite, $\text{CaMgB}_6\text{O}_8(\text{OH})_6 \cdot 3\text{H}_2\text{O}$, *monoclinic*

Hydroboracite (chemical data in Table 1b) is very common at Penobsquis, but rare at Millstream. It is commonly associated with volkovskite, hilgardite and trembathite. It forms prismatic crystals that are heavily striated, flattened on {100}, and elongate on [001], and up to 20 mm in length (Fig. 9), commonly with serrated terminations and double terminations. It is transparent, colorless, light to dark yellow, light orange and light green with a vitreous to silky luster. It has a Mohs hardness of 3, and is fibrous if crushed, with a perfect {001} cleavage. It may be "cavernous" with large fluid inclusions or solid inclusions of boracite, clay, and mica. Aggregates of densely packed, randomly oriented crystals are common. Strontioginorite has been observed impaling hydroboracite. Hydroboracite is difficult to distinguish from strontioginorite in small crystals.

Kurgantaite, $\text{CaSrB}_5\text{O}_9\text{Cl} \cdot \text{H}_2\text{O}$, *triclinic*

Kurgantaite (chemical data in Table 1c) has been found in a single drill-core in the northernmost portion of the Penobsquis deposit. It forms single, equant crystals with triangular faces to 2 mm across, and groups of crystals to several mm across. The crystals are transparent, light to dark yellow with a vitreous luster. Associated minerals are hydroboracite, boracite, walk-erite, veatchite, szaibélyite and a clay-group mineral. Kurgantaite, a member of the hilgardite group, was originally described as a new species by Yarzhemskiy (1952), discredited by CNMMN in 1982 as a mixture



FIG. 11. Photograph of pringleite crystal 2 mm long, from the Penobsquis deposit. Photograph by L. Horváth.

of tyretskite and celestine, and revalidated by Pekov *et al.* (2001). “Strontiohilgardite” (Braitsch 1959) is now regarded as a synonym of kurgantaite. Bright, transparent to translucent crystals are light yellow-orange to orange in color. Complex crystal forms are triangular in habit. Kurgantaite is associated with boracite, congolite, hydroboracite, szaibélyite, veatchite, pringleite and walkerite.

Penobsquisite, $\text{Ca}_2\text{Fe}[\text{B}_9\text{O}_{13}(\text{OH})_6]\text{Cl}\cdot 4(\text{H}_2\text{O})$,
monoclinic

Penobsquisite (chemical data in Table 1c) has been found only at Penobsquis. It forms hemimorphic, triangular single crystals to 1.5 mm in length (Fig. 10). It is elongate on [010] and flattened on {100}. Forms observed are: pinacoids {100}, {101} and {101} and the sphenoids {111}, {110}, {110}, {221} and {121}. It is dark yellow to dark orange, transparent to translucent, with a vitreous luster. It has a Mohs hardness of 3 and is brittle, with a conchoidal fracture. It was first described from the Penobsquis deposit by Grice *et al.* (1996).

Pringleite, $\text{Ca}_9\text{B}_{28}\text{O}_{34}(\text{OH})_{24}\text{Cl}_4\cdot 13\text{H}_2\text{O}$, *triclinic*

Pringleite (chemical data in Table 1c) has been found at both Penobsquis and Millstream deposits; it is much more common at Penobsquis, however. It occurs in a matrix of halite and minor sylvite as colorless, pale orange to tan, platy, subhedral to anhedral cleaved masses to 4 mm in size. It forms single crystals to 2.5 mm, flattened on {010} and groups of crystals to

4 mm; it is transparent and colorless to translucent white (Fig. 11). Crystals have a pearly to satin luster, and are brittle with a good cleavage {110}. The Mohs hardness is estimated to be 3 to 4. In many instances, pringleite is included with hilgardite and rarely with volkovskite. The mineral was first described by Roberts *et al.* (1993), and the crystal structure was determined by Grice *et al.* (1994).

Ruitenbergitte, $\text{Ca}_9\text{B}_{28}\text{O}_{34}(\text{OH})_{24}\text{Cl}_4\cdot 13\text{H}_2\text{O}$,
monoclinic

Ruitenbergitte has a polymorphic relationship with pringleite, and its physical properties are nearly identical. It is platy with a perfect {100} cleavage. The mineral was first described by Roberts *et al.* (1993) from Penobsquis, the type locality. It is not known to occur at the Millstream deposit.

Strontioginorite, $(\text{Sr},\text{Ca})_2\text{B}_{14}\text{O}_{23}\cdot 8\text{H}_2\text{O}$, *monoclinic*

Strontioginorite (chemical data in Table 1c) is found commonly in small amounts at Penobsquis associated with hilgardite, volkovskite, hydroboracite and trembachite. It occurs as colorless, transparent to translucent (frosted) crystals, elongate on [001], flattened and with a perfect {010} cleavage. Small crystals up to 1 mm may display the forms {111}, {010}, and {100}; larger crystals commonly display double terminations with fine striations parallel to [001]. Many crystals are twinned, with (010) as the twin plane (Fig. 12).

Szaibélyite, $\text{MgBO}_2(\text{OH})$, *monoclinic*

Szaibélyite (chemical data in Table 1d) is found as a rare constituent in several sections at Penobsquis, associated with hilgardite, walkerite, hydroboracite and pringleite. At Millstream, it is associated with boracite and commonly impales hilgardite. It occurs as fine acicular to flattened crystals on {010} (Fig. 13). It is colorless, transparent to translucent, with a silky luster. Dense nodules average 4 mm in diameter, with some attaining 10 mm; single crystals are <1 mm and are associated with a mica-group mineral and thin films of Fe oxides. It is fibrous if crushed.

Trembathite, $(\text{Mg,Fe})_3\text{B}_7\text{O}_{12}\text{Cl}$, *trigonal*

Trembathite (chemical data in Table 1a), first described by Burns *et al.* (1992) from the Salt Springs deposit, is relatively common at Penobsquis, but rare at Millstream. Crystals a few mm across are transparent to translucent, colorless, white, gray, very pale green and most commonly in shades of pale blue (Fig. 14). Rarely, transparent colorless, generally translucent,

pseudocubic single crystals and groups with repeated interpenetrative twinning give the appearance of a dodecahedron. Tetrahedra show other modifying forms and occasional interpenetrating twins. Simple pseudocubes modified by {111} occasionally show epitactic growths on corners; rarely, compact, perfect spheres showing no forms at all are observed. Colorless to pale green spheres are concentrically zoned about congolite. Single crystals are described with the pseudocubic forms {100}, {010} and {001} most common, and {111} and {110} less common. Some specimens display exaggerated {111} forms modified by {110}. The type locality for trembathite is the nearby Clover Hill deposit (Burns *et al.* 1992). In the Penobsquis deposit, trembathite is



FIG. 12. Photograph of strontioginorite prism 1 mm long, from the Penobsquis deposit. Photograph by L. Horváth.



FIG. 13. Photograph of szaibélyite fibers on hydroboracite, 5 mm long, from the Penobsquis deposit. Photograph by L. Horváth.



FIG. 14. Photograph of cluster of trembathite crystals 3 mm across, from the Penobsquis deposit. Photograph by L. Horváth.

associated with hilgardite, volkovskite, hydroboracite, szaibélyite, veatchite and danburite. At Millstream, it is associated with hilgardite and strontioinorite.

Veatchite, $\text{Sr}_2\text{B}_{11}\text{O}_{16}(\text{OH})\cdot 5\text{H}_2\text{O}$, *monoclinic*

Veatchite (chemical data in Table 1d) was observed in several core-sections at Penobsquis as a rare constituent associated with hilgardite, boracite, strontioinorite and danburite. Translucent, platy, rhombic crystals up to 2 mm have a vitreous to pearly luster and are light to dark orange to orange-red in color (Fig. 15).

Volkovskite, $\text{KCa}_4\text{B}_{22}\text{O}_{32}(\text{OH})_{10}\text{Cl}\cdot 4\text{H}_2\text{O}$, *triclinic*

Volkovskite (chemical data in Table 1d) is abundant at Penobsquis and rare at Millstream. At Penobsquis, it is associated with hydroboracite, hilgardite and many minor borate minerals, whereas at Millstream, the main association is with hilgardite and trembathite. It occurs as granular masses to 5 cm, as single, pseudo-hexagonal, equant to elongate platy crystals, in some cases with double terminations and as aggregates of subparallel plates forming rosettes (Fig. 16). Crystals are vitreous, transparent to translucent, colorless and from pale to deep orange and pale red.

Walkerite, $\text{Ca}_{16}\text{MgB}_5\text{O}_{68}(\text{OH})_{48}\text{Cl}_6\cdot 28\text{H}_2\text{O}$, *orthorhombic*

Walkerite (chemical data in Table 1d) was first described from the Penobsquis deposit by Grice *et al.* (2002); it remains the only known locality. Although rare, it was found in several parts of this deposit. It is found in halite associated with hilgardite, hydroboracite, volkovskite, boracite, szaibélyite, a mica-group mineral, a clay-group mineral and anhydrite. It occurs as white bundles of fibers to 7 mm and more rarely as colorless single, acicular crystals elongate parallel to the c axis (Fig. 17). It is translucent to transparent with a vitreous luster. It is brittle with no apparent cleavage and a splintery fracture. It shares some crystal-structure similarities with pringleite, ruitenbergite and penobsquisite.

DESCRIPTION OF THE BORATE OCCURRENCES IN THE SUSSEX AREA

The Millstream deposit

In an Exploration Agreement with the Government of New Brunswick, BP Resources Canada Limited (BPRC) drilled 11 holes between 1981 and 1983 (Webb 1994). In 1993, BPRC relinquished its mining lease on the Millstream property. Of the 11 holes drilled, two holes (numbers BPM 3 and BPM 10) did not intersect the halite horizon, and a third hole (number BPM 5) did not have any observed borate minerals. Samples of borate minerals were collected from the remaining

eight holes, which covered the entire areal extent of the deposit. The most common borate minerals are members of the boracite group; boracite and, less commonly, congolite and trembathite, and secondly hilgardite-3A. Much less common is szaibélyite, and there are rare occurrences of hydroboracite, strontioinorite, volkovskite and pringleite. Non-borate minerals of interest include magnesite, sellaite, kieserite and monohydrocalcite.

In the Millstream deposit, the borate minerals occur throughout the entire halite horizon formation between the Lower and Upper Anhydrite members (Fig. 2). In central portions of the basin, in the earliest precipitated halite and sylvite sequences (drill holes, from southwest to northeast, BP 11, BP 7 BP 1A, BP 2), the most common borate minerals are hilgardite and congolite, trembathite or Fe-rich boracite. Above this unit, boracite is the main borate in the upper carnallite and sylvite units. In the center and deepest portion of the basin (drill holes BP 1a and BP 7), the last salt sequences to precipitate are slightly more complex because they have a larger number of borate species; they include the primary phases boracite and congolite, but also have lesser amounts of volkovskite, hydroboracite, hilgardite and pringleite. These more complex upper borate sequences resemble those of the Penobsquis deposit described below. On the periphery of the basin (drill holes BP 6, BP 8 and BP 4 in the north and drill hole BP 9 in the south), the northerly holes contain primarily boracite, trembathite or congolite, with some hilgardite in the lower "sylvinite" unit, whereas in the southern hole, there is a distinct change, with the more Fe-rich members of the boracite group, trembathite and congolite, in association with hilgardite and strontioinorite at depth. Generally speaking, where hilgardite is the most abundant borate, it is found in thick beds of halite, whereas the boracite is usually associated with carnallite or sylvite or both (Fig. 18).

The Penobsquis deposit

The Potash Corporation of Saskatchewan (New Brunswick Division) made available seven drill-core sections with the core logs. Only those sections where "borate" mineralization had been noted were sampled. The cores were drilled in 1979 by Potash Company of America (PCA) prior to mining. These cores were critical to the present project, as the mining activities do not intersect the evaporite unit (upper halite unit), which contains concentrations of borate minerals. The labeling for the drilling pattern at the Penobsquis deposit relies on a letter-and-number designator system such that going west to east, letters A to Z then AA to DD, and from south to north, numbers 1 to 6 are used; thus drill hole A-1 was in the southwestern corner of the deposit, and drill hole DD-6, in the northeastern corner. Five sampled drill holes extend approximately 5 km east to west from drill hole H-5 to DD-4. The

remaining two holes were on the southern (P-1) and northern flank (X-6), approximately 9 km apart. In all sections containing these complex borate minerals, there is invariably a multiphase assemblage with major amounts of hilgardite, volkovskite, hydroboracite, boracite – trembathite – congolite, with minor amounts of colemanite, pringleite–ruitenbergitte, strontioginorite, szaibélyite and walkerite, and rarely, brianroulstonite, chambersite, danburite, howlite, penobsquisite and veatchite. Most of the borate minerals are Ca–Cl-bearing hydrated phases, and where there is a boracite-group mineral, it is Fe-rich (*i.e.*, trembathite or congolite). Non-borate minerals of interest include magnesite, sellaite, kieserite and monohydrocalcite.

In the seven cores sampled, the borates are contained within the Upper Halite Member, which lies below the Upper Anhydrite Member and above the Potash Member; the Potash Member includes the sylvinitic bed mined for potash ore. Because there is little mining activity above the Upper Halite Member, there are only bore-hole samples to yield information on the borate assemblages. Just above the sylvinitic bed in the lower portion of the Upper Halite Member, the first borate minerals to appear are congolite, then trembathite, then boracite, followed immediately or coevally with hilgardite and hydroboracite. The hydroboracite and hilgardite extend upward into a unit containing volkovskite. Further progression in the crystallizing sequence is marked by the disappearance of hydroboracite. The last assemblage of borates before precipitation of the anhydrite layer consists primarily of hilgardite, with lesser amounts of volkovskite and trembathite. In this upper section, the silicoborates howlite and danburite commonly appear. The Sr-bearing borates strontioginorite and veatchite appear in the later stages of evaporation throughout the basin, whereas kurgantaite is only found in the most northerly drill-hole (X-6), which was the most restricted portion of the basin.

The section DD-4 has carnallite, which is unique to the Penobsquis deposit. The exotic and rare Ca–Cl-bearing hydrated borates brianroulstonite, penobsquisite, pringleite, ruitenbergitte and walkerite, are late in the crystallization sequence in each of their assemblages, but they may be found in any portion of the Upper Halite Member. Colemanite is a late-stage mineral found in the youngest (uppermost) portions of the Upper Halite Member, whereas szaibélyite occurs in the center and southern portions of the deposit, in halite-rich units. In Figure 18, we compare the two deposits, Millstream and Penobsquis, in a very general overview of the major borates within the salt sequences.

In two of the drill cores (M-4 and X-6), folds could be documented by the “inversion” of the sedimentary layers and the corresponding “inversion” of the borate assemblages. Webb & Roulston (1994) indicate briefly that there are metamorphic features such as folds, dislocations, boudinage, and halite recrystallization, but they do not comment on the effects of this metamorphism

on mineral assemblages. It is difficult to draw any conclusions as to metamorphic grade of a salt deposit. Its plastic behavior under stress may not require a very high temperature or pressure to attain such dramatic folding as is observed in these deposits.

COMPARISON OF SUSSEX DEPOSITS TO OTHER SALT EVAPORITES

Borate minerals from sedimentary deposits of economic interest are primarily composed of Na–Ca-bearing hydrated borates related to Neogene nonmarine basins and volcanism. Such lacustrine deposits, found in the United States, South America, Turkey and China, are playa-lake or deep lake environments that received a supply of boron-rich fluids from thermal springs or hydrothermal fluids. The deposits at Sussex are very different from these both in origin and mineralogy.

Boron isotopes within the Sussex potash deposits are consistent with a marine evaporite and not a lacustrine evaporite associated with volcanism. Other marine evaporites include the large Zeichstein Formation, which extends from England to Germany, the Russian deposits of the Inder region, Caspian area, and Siberian Plateau, and in the United States, the salt dome formations in Alabama, Louisiana, Mississippi, New Mexico, Oklahoma, Texas and Utah (Garrett 1998). In salt formations, the majority of borate minerals are Ca–Mg–Cl borates, an assemblage quite different from that in the lacustrine evaporites.

The Sussex deposits most closely resemble the Permian potash deposits in Germany. Both are marine evaporites that have been metamorphosed, to some degree, since the time of deposition. Kühn (1962) reported that boracite is common with lesser amounts of danburite, szaibélyite (referred to as “ascharite”) and rarely pinnoite, kaliborite, kurgantaite (referred to as “strontiohilgardite”), veatchite and strontioginorite. In contrast to Sussex, the German deposits include a series of phosphates; wagnerite, isokite and lüneburgite as well as heidornite, a borate–sulfate. Some of the boron in the German deposits seems to have a volcanic source, but this does not seem to be the case for Sussex. The boracite crystals in both these deposits form pseudocubes that display birefringent microstructures that are visible in polarized transmitted light. These microstructures are interpreted as indicators of a phase transition on cooling (Burns & Carpenter 1996). This cubic-to-orthorhombic phase transition occurs at 265°C for boracite and higher for more Fe-rich boracite-group minerals (Burns & Carpenter 1996). One might conclude from this finding that the Sussex area deposits were subjected to metamorphic temperatures above this minimum. This conclusion is certainly in contrast to that expressed by Braitsch (1971) and Kühn (1962), who stated unequivocally that the German deposits never reached such temperatures. In the present study, we have not seen any evidence that clearly solves the problem

of the degree of metamorphism in these deposits. We do recognize the possibility that boracite crystallizing below 265°C could assume a pseudocubic morphology because of its pseudocubic crystal-structure; the microstructures could merely be a consequence of the structure's propensity to twin. Thus we believe that the microstructures observed optically in boracite from Sussex provide inconclusive evidence with regard to a minimum temperature of formation.

SUMMARY AND CONCLUSIONS

Two deposits in the Sussex area have been studied in detail; the Millstream deposit is a near-shore, isolated basin, whereas the Penobsquis deposit is an outer fore-basin (Roulston *et al.* 1995). The two deposits differ in salt contents and borate assemblages. Roulston *et al.* (1995) proposed that bitterns from the later stages of infilling of the Penobsquis depression were periodically flushed into the more remote and isolated Millstream depression. Support for this hypothesis comes from the higher concentrations of potassium and magnesium salts, sylvite and carnallite, in Millstream, whereas Penobsquis has greater thicknesses of the less soluble sodium salt, halite. The distribution of borates also supports this hypothesis in that borate mineralization occurs throughout the lower halite and "silvinite" beds of Millstream, whereas at Penobsquis, the borates only appear in the upper halite unit. The most common borate minerals at Millstream are boracite and hilgardite-3A, whereas at Penobsquis, the common borate minerals are trembathite + congolite, hilgardite-1A, -3A, -4M, hydroboracite and volkovskite. The significance of the distribution of the various polytypes of hilgardite is

not fully understood, as there are no phase diagrams available for this system. It is apparent though that hilgardite-3A occurs in later sequences of evaporites than hilgardite-1A or hilgardite-4M. In addition to these common borate minerals, there are several minor borate minerals. At Millstream, there are occurrences of szaibélyite and rarely hydroboracite, pringleite and volkovskite, whereas at Penobsquis, there are several complex Ca-Cl borate minerals such as brianroulstonite, hydroboracite, penobsquisite, pringleite + ruitenbergitte and walkerite. Sodium borates are notably absent, which contradicts the opinion of Roulston *et al.* (1995).



FIG. 15. Photograph of veatchite plates (total width of field of view 12 mm) from the Penobsquis deposit. Photograph by L. Horváth.



FIG. 16. Photograph of volkovskite in subparallel plates measuring 3 mm across, from the Penobsquis deposit. Photograph by Q. Wight.



FIG. 17. Photograph of walkерite fibers in halite with a separate bundle of fibers (total width of field of view is 25 mm), from the Penobsquis deposit. Photograph by L. Horváth.

In these assemblages, one can see distinct differences in geochemical trends: (1) at Millstream, Mg (boracite) dominates the boracite group, whereas at Penobsquis, Fe is major to dominant in this mineral group (trembathite + congolite); (2) at Millstream the activity of H in the borate phases is much less than that at Penobsquis; (3) at Millstream, the activity of Ca in the borate phases is much less than that at Penobsquis; (4) at Millstream, Cl is almost always present in the borate phases, whereas at Penobsquis, there are notable, common exceptions to this rule, with major hydroboracite and lesser amounts of colemanite, danburite, howlite, strontioginorite and veatchite; (5) at Millstream, there is a notable lack of Sr and Si in the borate phases, whereas at Penobsquis, these elements are widespread in borate phases late in the crystallization sequence; (6) at Millstream, the borate phases are dominantly framework-type structures, whereas at Penobsquis, framework structures dominate, but less highly polymerized structures of the sheet and chain type are common; (7) at Millstream, the activity of K in the borate phases is very much less than that at Penobsquis; (8) at Penobsquis, there is a notable increase in the amount of Ca and H₂O as crystallization proceeds, and in the final stages, Sr then K enters the borate phases as an essential constituent, whereas at Millstream these features are not evident.

At the two deposits, some trends of crystallization are developed in common: (1) Fe-enriched boracite crystallizes before Mg-enriched boracite; (2) the earliest assemblages of borates have Ca and H₂O in their crystal structure, (3) Sr is essential in some crystal structures (kurgantaite, strontioginorite and veatchite) in late-crystallizing borate phases in halite and commonly with

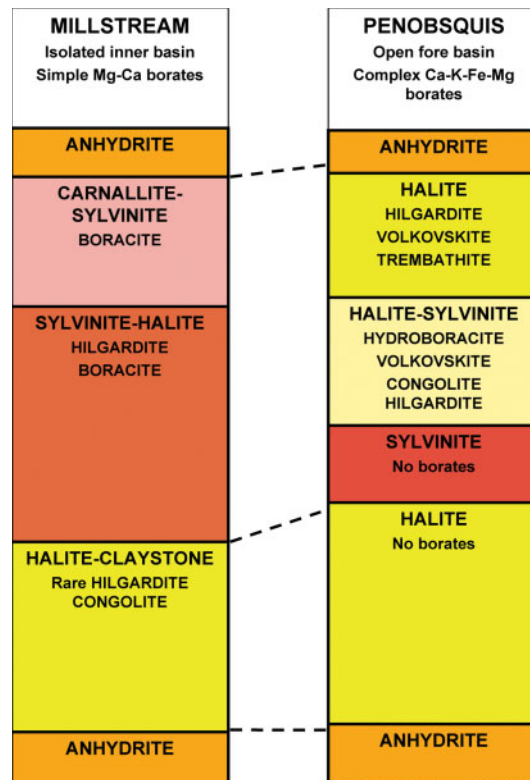


FIG. 18. A simplified stratigraphic section for the Millstream and Penobsquis deposits showing the distribution of borate minerals.

sylvite; (4) the silicoborates, danburite and howlite, are at the very end of the crystallization sequence of all borate minerals.

Schindler & Hawthorne (2001) drafted a series of pH versus log [H₂O] diagrams and outlined the stability fields of borate minerals. In these activity–activity diagrams, several trends may be seen. They highlight three broad geological occurrences of borates that span the full range of log [H₂O], but that have restricted ranges in pH. Skarn deposits are characterized by the highest values of pH, evaporites and low-temperature hydrothermal deposits occupy the range of the mid-pH values, and fumaroles, the lowest values of pH. Explaining the existence of all borate minerals present in the Sussex deposits would necessitate a span of the entire range of pH and log[H₂O] activities. Concentrating on the most common borate minerals in the deposits gives a better idea of the factors important to the stability of the borate assemblages. In the Millstream deposit, the change in assemblage from hilgardite at depth to boracite in the upper layers is indicative of an increase in pH in a field of low activity of [H₂O]. In the Penobsquis deposit, [H₂O] is somewhat higher than at Millstream, but it is still relatively low compared to non-marine evaporites. The phase-change progression from trembathite to hilgardite–hydroboracite to volkovskite indicates a decreasing pH. At the end of the crystallization sequences, there is a reversal of this trend, to increasing pH, with the reappearance of hilgardite and trembathite and several more exotic species like penobsquisite, pringleite and walkerite. Overall in the Sussex marine evaporites, the borate assemblages are rich in highly polymerized structures, with most of the minerals having framework structures and some with sheets or chains (Table 1). This finding, consistent with the saturation in other marine evaporites, indicates the influence of pH–[H₂O] on the mode of occurrence as well as the atomic structure.

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