

Geological Setting and Fluid Inclusion Study of Celestite Mineralization, Beckwith (NTS 11E/13), Nova Scotia

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Introduction

Celestite and minor galena occur as isolated pods in an unconsolidated clay unit of Early Carboniferous age in the Cumberland Basin of southern Nova Scotia (Fig. 1). Felderhof (1978) suggested that the Beckwith occurrence resulted from a combination of fault-related and vein mineralization, but exploration in the late 1980s revealed that this deposit is not a vein, but instead is spatially related to nearby faulting (Felderhof, 1986). In this paper we outline the geological setting of this unusual celestite-galena occurrence, review previous work, and present the first results of fluid inclusion studies carried out on celestite samples. Although not currently economic, the deposit provides a unique opportunity to examine the mechanism responsible for this unusual type of mineral occurrence and, as such, may have implications for other, larger and more promising celestite deposits in the province (e.g. Lake Enon) and elsewhere.

General Geology

The Beckwith deposit lies adjacent to a fault between Upper Carboniferous terrestrial sandstones (Cumberland and Pictou groups) and Lower Carboniferous marine evaporites (Windsor Group) in the Cumberland Basin, northern Nova Scotia (Fig. 1). The basin is a segment of the Maritimes Basin, a large upper Paleozoic basin in eastern Canada (Fig. 1a), which hosts significant resources of fossil fuels, precious metals, base metals and industrial minerals. The Permo-Carboniferous system of eastern Canada comprises a post-Acadian molassic suite of coarse- and fine-grained terrestrial and volcanic rocks, as well as shallow marine clastic, carbonate and evaporitic rocks. It underlies an irregular area of lowland extending from the Bay of Fundy through the Gulf of St. Lawrence to offshore Newfoundland. The onshore distribution extends from eastern Maine to Newfoundland and southern mainland Nova Scotia to Quebec (Fig. 1).

Cumberland Basin Geology

The Cumberland Basin is an east-west depocentre which

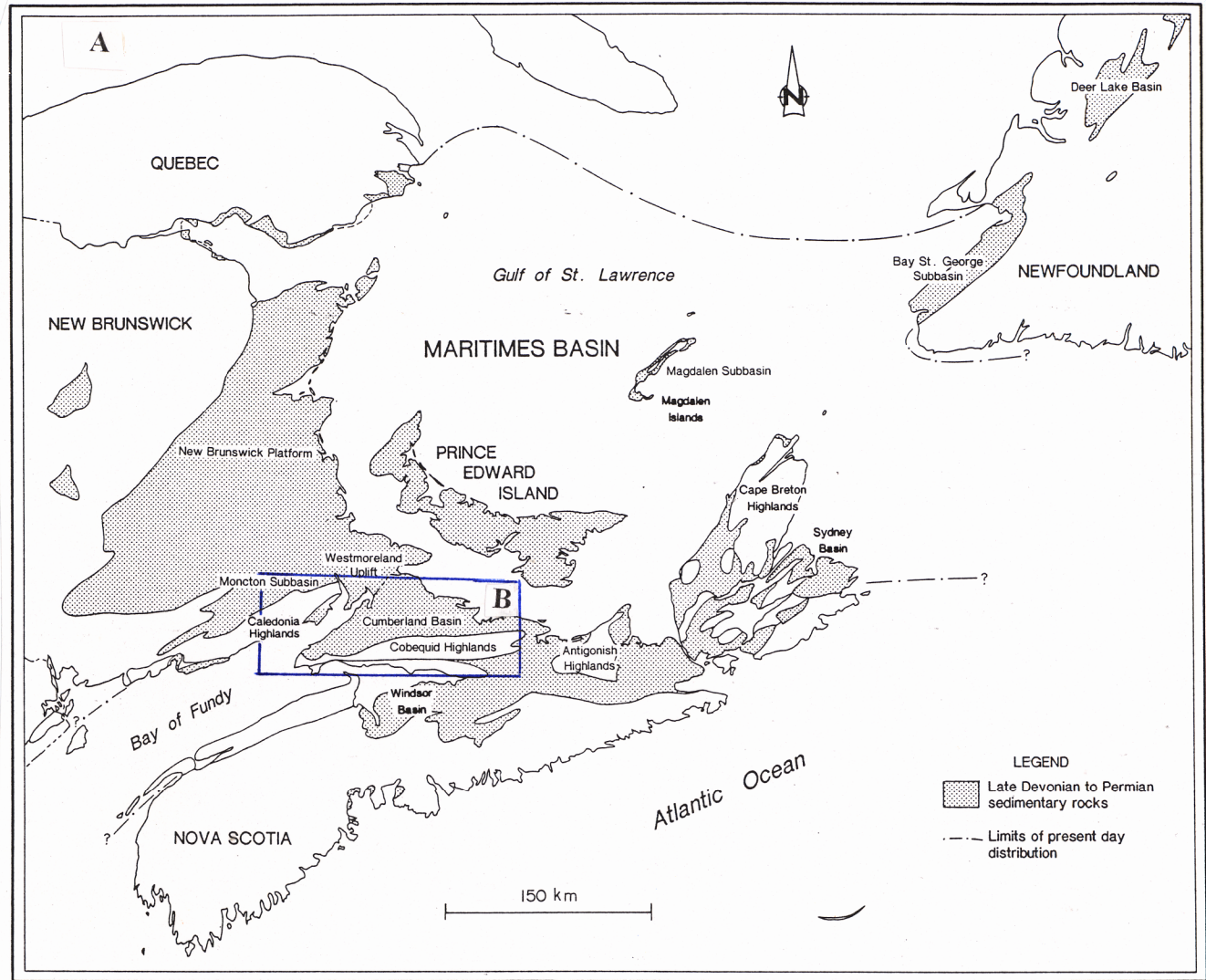
contains a succession of sedimentary strata in excess of 7 km thick (Fig. 1b). The internal structure of the basin is a broad, east-west synclinorium enclosing two parallel, diapiric anticlinal structures. The basin has a Devonian-Carboniferous redbed and volcanic sequence referred to as the Fountain Lake Group at the base, succeeded by fluvial/lacustrine red and grey shale and sandstone of the Horton Group. The Horton Group is overlain by marine clastics, evaporites and carbonates of the Windsor Group. The unit of most interest to this paper is the thick (300 m) anhydrite/gypsum beds of the Pugwash Mine and Lime Kiln Brook formations and their laterally equivalent halites (Pugwash Formation).

Overlying the Windsor Group are strata of the Mabou Group, which are divided into two formations. The lower unit is red-brown mudstone, siltstone and sandstone with rare, thin, polymictic conglomerate interbeds (nonmarine). The upper unit is greenish-grey sandstone with minor calcareous conglomerate, mudstone and siltstone.

The Mabou Group is overlain by the Cumberland Group, which consists of red and grey boulder to pebble polymictic conglomerate, grey sandstone, grey to reddish-brown mudstone, siltstone, coal seams from 0.01 m to 3.5 m thick, and thin, bituminous black limestone and shale. The Cumberland Group is overlain by the redbed-dominated rocks of the Pictou Group, in which varying proportions of sandstone and mudstone occur.

Location and Previous Work

The Beckwith celestite occurrence is located adjacent to Dickson Brook (Hayes and Bell, 1938) ca. 1.3 km south of Beckwith and approximately 6 km southwest of Highway 6 at Port Howe, Cumberland County, Nova Scotia (Fig. 2). The area has low relief with elevations ranging from 25 to 40 m above sea level and outcrop is rare. The celestite-galena occurs near a fault boundary where Windsor Group evaporites are juxtaposed next to the red and grey sandstone and shale of the upper part of the Cumberland Group (Fig. 2).



The first reported work on the occurrence dates to 1911 when H. G. Elliot discovered what he thought to be barite and a 9 m shaft was sunk in the bank of the brook. Little work took place on the property until 1941 when Springer Sturgeon Gold Mines Limited carried out some trenching in order to expose the bedrock; however, only one trench encountered bedrock. The next work was carried out by F.M.C. Limited in 1969 and 1970. This company exposed 5 m of celestite in a trench and followed this up with geophysics, rotary drilling (over 1500 m in 42 holes) and diamond-drilling (over 1000 m in 36 holes). Drilling indicated that the “vein” was discontinuous and occurred within or near a fault gouge.

The latest work on the occurrence, carried out in 1985-1986 by ACA Howe International for Timminco Ltd., consisted of trenching, mapping, bulk sampling and both rotary- and diamond-drilling. There were nine diamond-drill holes totaling 300 m length and 27 percussion holes that totaled 110 m. The trenching was

extensive and a pit measuring approximately 60 m by 45 m was excavated to a depth of greater than 10 m (Fig. 3).

Deposit Geology

The host rocks of the deposit area have been variably described by previous workers as faulted sandstone and mudrocks. The excavation in 1986 revealed that red and grey sandstone, siltstone and pebble conglomerate occupy the east side of the pit, whereas gypsum was encountered in drillholes to the west and north sides of the pit (Fig. 3a). The sandstone and clastic sedimentary rocks to the east are part of the Cumberland Group and the gypsum is part of the Windsor Group. Celestite can be found associated with brecciated sandstone along the eastern side of the deposit, but it is more commonly found in poorly consolidated grey and red clay units (Fig. 3c).

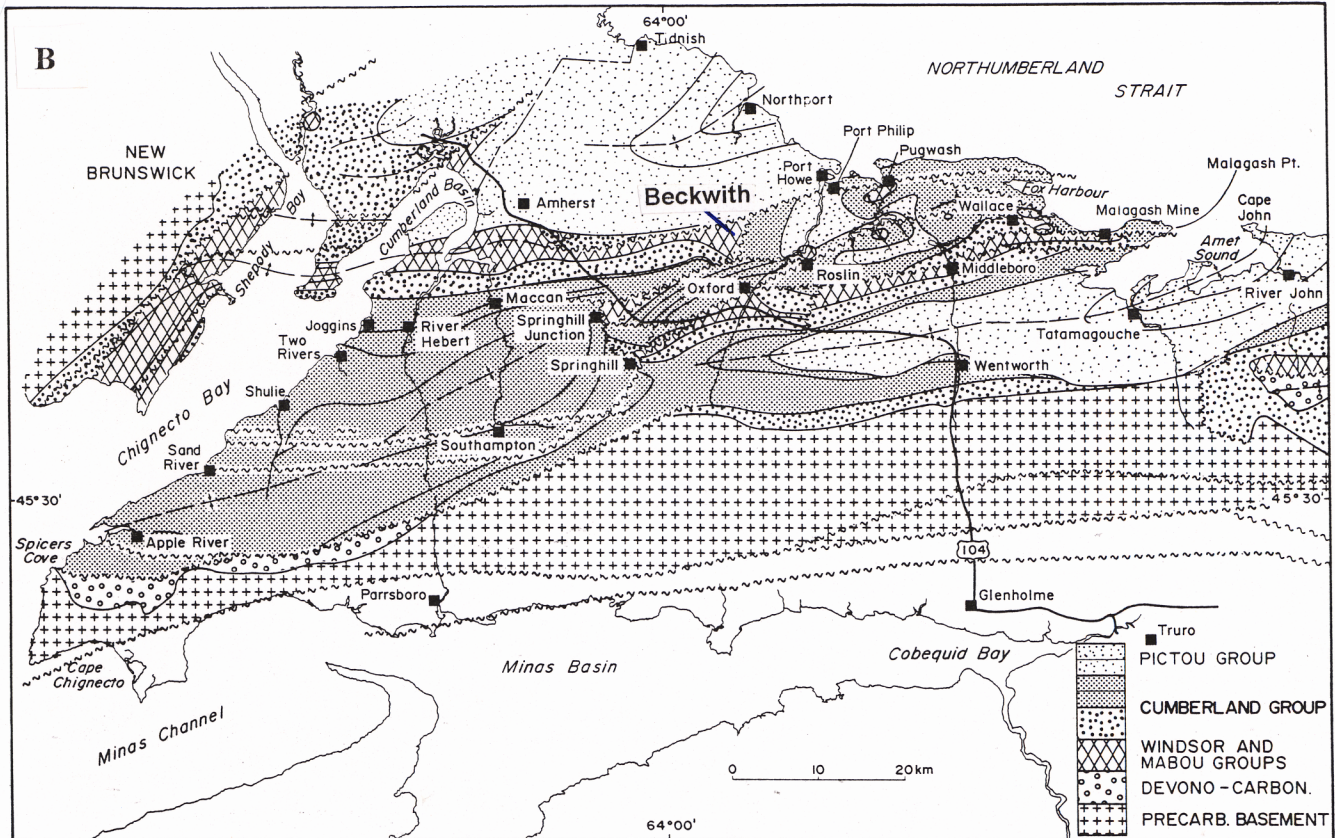


Figure 1. (a; previous page) Location map of the Maritimes Basin in eastern Canada with a location of Figure 1b. (b) Generalized geology map of the Cumberland Basin with the location of the Beckwith celestite occurrence (from Ryan and Boehner, 1994).

Contacts between the Upper Carboniferous clastic strata and the Windsor Group rocks can only be rationalized as faults. Ryan *et al.* (1990) indicate that there are faults both north and south of the occurrence and, given the nature of other Windsor Group outcrops in the Cumberland Basin, it is reasonable to assume that the evaporites are part of a diapiric structure (Fig. 4). In fact, just west of the Beckwith area there is a significant negative Bouguer gravity anomaly interpreted to reflect the presence of salt at depth (Boehner, 1986).

Celestite Mineralization

The long-standing theory of the occurrence of celestite on the property was that it was a fault-related vein deposit. The exploration and pit development undertaken in the 1980s by ACA Howe International suggest that this is erroneous (Felderhof, 1986). Drilling and excavation revealed that the celestite occurs as isolated pods within poorly consolidated red and grey clay (Figs. 3a, b). These pods are up to 8 m in length, 4 m in width, and up to 3 m in thickness (e.g. Fig. 3b).

This mode of occurrence greatly reduces the economic viability of the property, but it is of scientific significance because of the unusual morphology of the celestite.

The large masses or pods of celestite are generally surrounded by grey clay, although red clay is common proximal to the pods (Fig. 3c, d). Minor amounts of celestite have been observed in brecciated red sandstone on the east side of the pit. The celestite can also occur as pebble- to sand-sized crystals which appear to be displacing the clay host. The smaller celestite crystals are almost always hosted in the grey clay. It is unclear as to whether the grey coloration of the clay is related to alteration during mineralization or if the mineralization preferentially occurred within the grey (reducing) clay zones.

Celestite at Beckwith ranges in colour from translucent to light cream and celestial blue. The individual crystal blades can be up to 2.5 cm in length. Ore in the large pods exhibits numerous open vugs between the crystals, which are usually filled with the

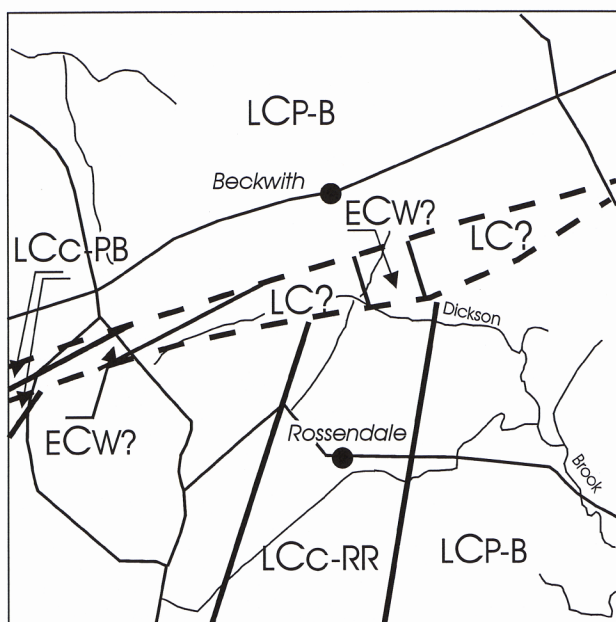


Figure 2. Geological map of the area around the Beckwith celestite occurrence. Abbreviations are as follows: ECW is Windsor Group, LC and LCC-RR are Cumberland Group strata, and LCP-B refers to Pictou Group strata.

surrounding clay. In a few areas in the pit minor amounts of galena were observed. Galena occurs as small (less than 5 mm) cubic crystals growing on the celestite blades of the coarse ore. Barite has also been reported in minor amounts within the more massive celestite pods. Felderhof (1978) reported an average BaSO_4 content of 2.5 wt. % within 87 wt. % celestite (SrSO_4) ore.

The size of the celestite resource at Beckwith remains unclear. Exploration on the property was predicated with the assumption that the occurrence was a mineralized vein, whereas it is now clear this is not the case. Felderhof (1986) suggested that the resource defined by drilling and excavation was only 1150 tonnes of ore-grade celestite.

A palynological sample taken from the pit was determined to be of Viséan age (Ryan and Boehner, 1994) suggesting, therefore, that the clays are either Windsor Group sediments or derived from them. Red and grey siltstone and silty shale are common within the Windsor Group; however, the presence of thick clay or claystone has not been reported. The lack of visible bedding, unconsolidated nature of the host clays of the Beckwith property, and the fine grain size of the unit are all atypical of Windsor Group clastic strata. Thin clays are common in the evaporites of the Windsor Group and karst features are ubiquitous on the top of the evaporites

where they are exposed in the Cumberland Basin. If evaporites are dissolved in the near-surface environment, the end result is an accumulation of insoluble residues after dissolution. In this case, the residuum would be derived from the thin clays interlaminated with salt and gypsum of the Windsor Group evaporite sequence. These clays would be expected to contain spores of Windsor age.

Fluid Inclusion Studies

Samples of coarse celestite from mounds in the excavated trench were crushed, and hand-picked celestite crystals were mounted on glass slides for petrographic observation. The celestite is inundated with inclusions; thus, several chips were made into doubly polished fluid inclusion sections of ca. 150 μm thickness for subsequent petrographic and thermometric study. Results of these studies are summarized below.

Thermometric measurements of the relevant freezing and heating changes of inclusions were made with a U.S. Geological Survey gas flow heating-freezing stage (FLUID INC.) at the Nova Scotia Department of Natural Resources [see Kontak (1998) for details]. The equipment was initially calibrated and is routinely checked with synthetic fluid inclusions. Accuracy for the equipment is estimated at $\pm 0.2^\circ\text{C}$ for low temperature runs and $\pm 1.0^\circ\text{C}$ for high temperature runs, whereas precision determined from replicate runs is $\pm 0.2^\circ\text{C}$ or better. In addition, a single celestite chip inundated with fluid inclusions was rapidly heated on the fluid inclusion stage in order to induce thermal decrepitation of the inclusions, which causes formation of precipitate mounds. These mounds were subsequently imaged and analyzed with the electron microprobe at Dalhousie University in order to determine the chemistry of the solute component of the inclusions.

Fluid Inclusion Petrography

Fluid inclusions in celestite occur: (1) decorating growth faces (Fig. 5a, b), (2) along healed fracture planes (Fig. 5f) and (3) as random clusters within the host mineral (Fig. 5c). Type 1 are considered primary, whereas type 2 and 3 are possibly pseudosecondary and primary/secondary, respectively, following criteria of Goldstein and Reynolds (1994). The size, shape and composition (i.e. L:V ratio) of the inclusions vary considerably suggesting, therefore, post-entrapment modification of the inclusions. There is no correlation of these features with the types 1, 2 or 3 mentioned above. Hence, the description of the inclusions below applies to all types.

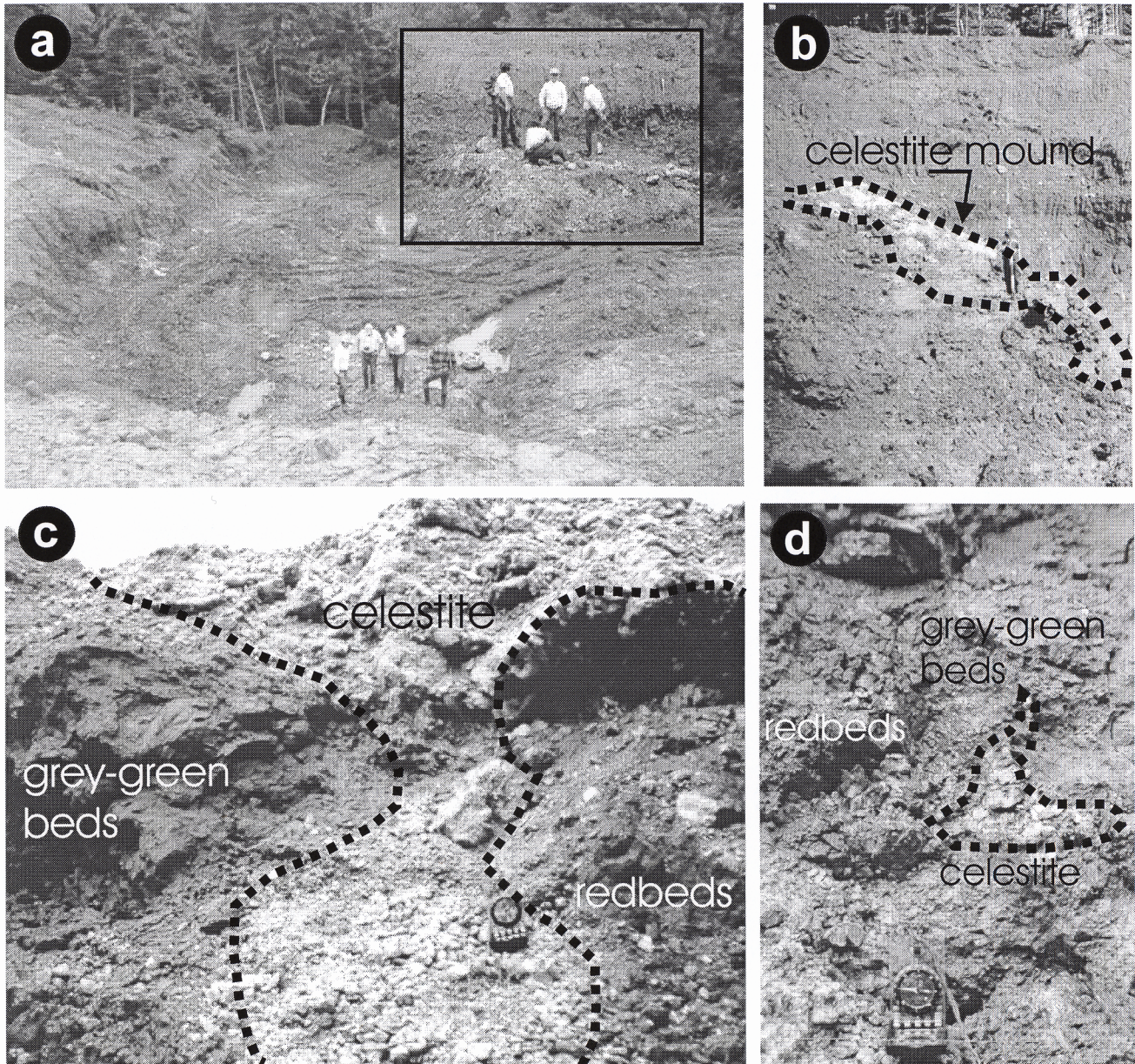


Figure 3. Photographs of the open pit at Beckwith showing the nature of the host rocks and the mineralization. (a) View of open pit looking southeast. People are standing on pod of celestite mineralization, which is enlarged in the inset photo. (b) View of another celestite pod. Person standing for scale. (c) Celestite mineralization in red sediments with grey-green halo around the mineralization. (d) Close-up of celestite mineralization and host rocks.

Inclusions are up to 100-150 μm long, with most $\leq 10\text{-}20\ \mu\text{m}$ (Fig. 5c, d, g). The larger inclusions tend to be elongate or acicular with tapered ends, and have regular to highly irregular outlines (e.g. Fig. 5d, h). Smaller inclusions vary from regular to equant (Fig. 5g), in some cases with negative crystal form, to very irregular; regular-shaped inclusions are dominant. The presence of healed fracture planes decorated with abundant, equant-shaped inclusions indicates necking down was common (Roedder, 1984). The L:V ratio of

inclusions is highly variable, such that there is a complete gradation from L-rich to V-rich inclusions (compare fluid inclusions in Fig. 5c), and this is attributed to necking, which is extensive within the celestite (Fig. 5e, h). However, planes of regular to equant inclusions with monophasic L-rich inclusions occur, and less commonly planes with uniform L:V ratios. Rare occurrences of unidentified trapped solid phases were noted. Fluid inclusions were examined in ultraviolet (UV) light for the presence of liquid

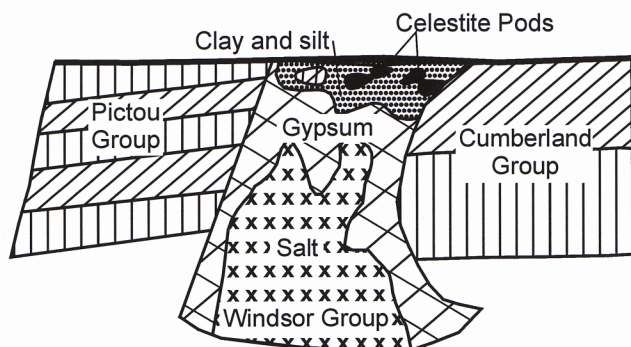


Figure 4. Schematic cross-section of the Beckwith property showing the celestite pods with clay and silt derived from karstification of Windsor Group rocks.

petroleum, but no evidence of petroleum was found.

Fluid Inclusion Thermometry

Measurements reported below were made on single, isolated inclusions and groups of inclusions concentrated along healed fracture planes and rare growth zones. Initial measurements of homogenization temperatures suggested results were unreliable for the following reasons. (1) Homogenization temperatures were considerably higher than expected given the L:V ratio of inclusions and assuming a simple aqueous system (Roedder, 1984), which suggested that stretching occurred in the inclusions during heating (Bodnar and Bethke, 1984). (2) Results varied widely for a fluid inclusion assemblage, given their similar L:V ratios. Thus, the results reported below are restricted to observations made during freezing runs only.

Inclusions were frozen to -100 to -120°C and subsequently observed during controlled heating until all phases had melted. During freezing, the vapor bubble froze suddenly (i.e. collapsed) at ca. -40°C to -52°C with the exception being two isolated inclusions that froze at -35 and -30°C (Fig. 6a). In exceptionally large L-V inclusions (ca. $100\ \mu\text{m}$) and large (ca. $30\text{-}50\ \mu\text{m}$) V-rich inclusions, freezing of the vapor phase was observed specifically to examine for evidence of condensed gases such as CH_4 or CO_2 (e.g. clathrate development). However, the only phase observed during freezing was formation of ice along edges of the V-phase. During warming the majority of inclusions first darken and then become grainy in appearance before developing an onionskin-type texture in the -55° to -50°C range, which is generally considered indicative of recrystallization and initial melting (Goldstein and Reynolds, 1994). In the -40° to 45°C range, definite melting occurs with ice coexisting with abundant, small, high-relief microlites

considered to be hydrohalite (HH). The HH phase persists until -26° to -22°C (Fig. 6b). In a few large inclusions (to $100\ \mu\text{m}$), temperature cycling (see Goldstein and Reynolds, 1994) was performed and in these cases hydrohalite melting was easily observed and it dissolved at -22°C . Ice is the last phase to melt in all the inclusions; melting occurs between -16.5° to -0.1°C , with the majority above -8.0°C (Fig. 6c). In those inclusions where HH was not observed, first melting occurs near -8° to -3°C with subsequent rapid melting of ice.

Fluid Composition from Thermometry

The composition of the fluid phase is inferred from the freezing and melting of inclusions and comparison to modelled chemical systems (Roedder, 1984; Goldstein and Reynolds, 1994; Bodnar and Vityk, 1994). Freezing runs indicate that condensed gases such as CO_2 and CH_4 are not present, since neither double freezing of the inclusions nor clathrate formation were noted. Crushing of inclusions confirms the absence of detectable condensed gases. The development of graininess and onionskin texture, and clear melting in the -50° and -40°C range, suggest the presence of solute(s) other than Na in order to depress the eutectic point in the $\text{NaCl-H}_2\text{O}$ system (-21.2°C ; Sterner *et al.*, 1988). Less reliable, but empirically valid, is the depressed point of freezing of inclusions in the -40° to -55°C range, which is well below what is normally observed for fluid inclusions in the $\text{NaCl-H}_2\text{O}$ system. Although the observations are suggestive of CaCl_2 , the melting of hydrohalite and ice suggests low $\text{CaCl}_2/(\text{CaCl}_2+\text{NaCl})$ ratios (ca. <0.2), based on phase equilibria in the $\text{CaCl}_2\text{-NaCl-H}_2\text{O}$ system (Vanko *et al.*, 1988; Oakes *et al.*, 1990). In the few large inclusions that were cycled, the melting of HH at -22°C is only slightly below the eutectic in the system $\text{H}_2\text{O-NaCl}$ (i.e. -21.2°C). Thus, for the inclusions examined the fluid is clearly dominated by NaCl with only minor amounts of another solute, probably CaCl_2 .

Fluid salinities, as equivalent wt. % NaCl, were calculated using the equation of Bodnar (1993; table in Bodnar and Vityk, 1994). Salinities range from 0.2 to 19.8 wt. % eq. NaCl, but the majority fall below 11 wt. % eq. NaCl with a continuum down to near 0 wt. % (Fig. 6c). These salinities are noted to be significantly lower than most Carboniferous Pb-Zn-Ba-F assemblages in a variety of occurrences in Nova Scotia (e.g. Ravenhurst *et al.*, 1989; Kontak, 1998; Chi and Savard, 1995; Chi *et al.*, 1995; Kontak and Macdonald, 1995; Kontak and Sangster, 1998).

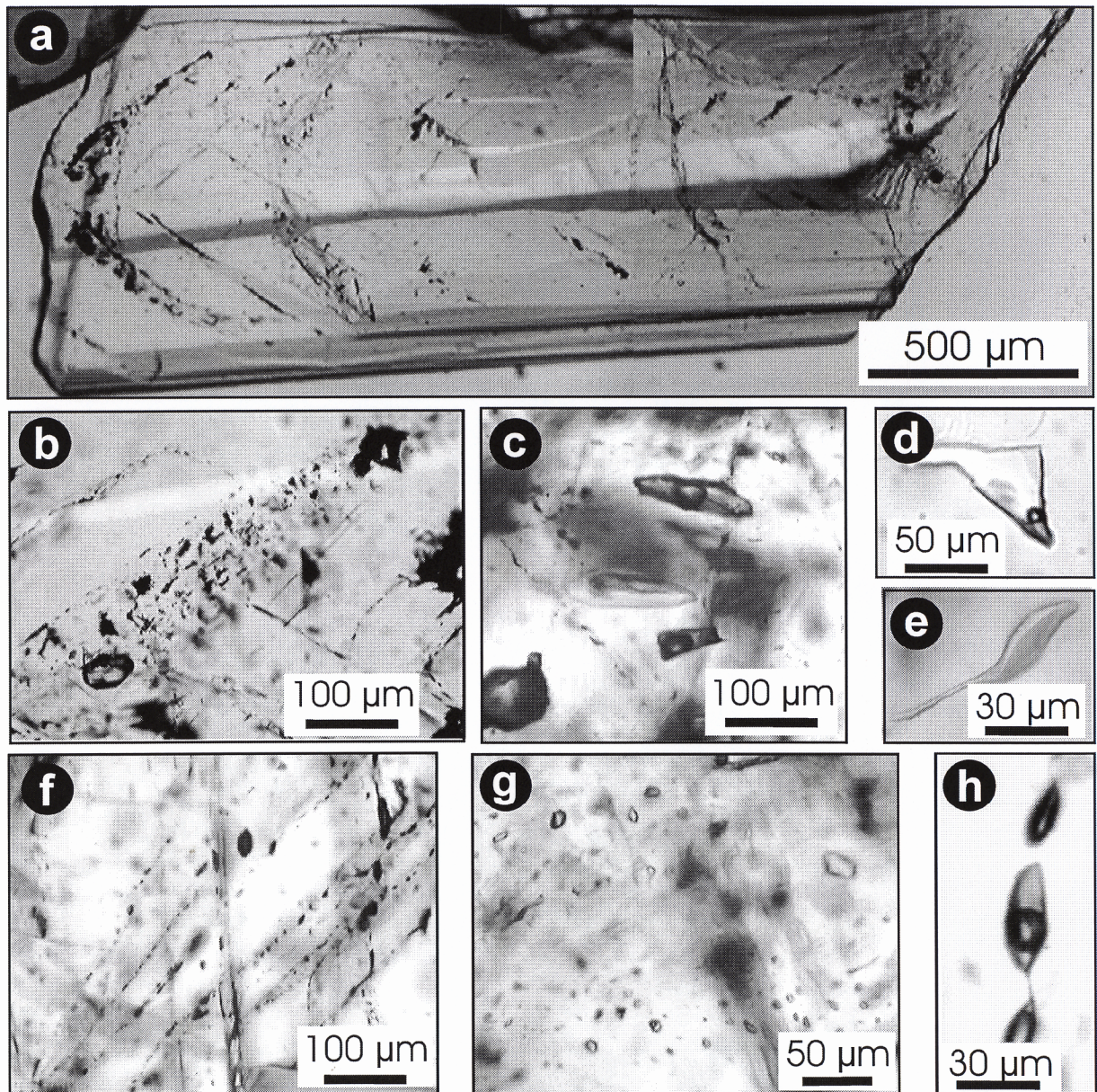


Figure 5. Photomicrographs of fluid inclusions in celestite from Beckwith. (a) Celestite chip showing primary growth zones decorated by fluid inclusions. (b) Growth zone in celestite with primary fluid inclusions. Note the irregular shapes of the inclusions and V-rich nature. (c) Large, randomly oriented L-V and V-rich inclusions in celestite. Note healed fracture planes with smaller inclusions in the background. (d) Isolated L-V inclusion. Cycling of this inclusion indicated hydrohalite melting at -22°C and ice melting at -2.8°C . (e) Tadpole-shaped, L-rich inclusion that originated from necking down. (f) Secondary fluid inclusions decorating a series of subparallel healed-fracture planes in celestite. (g) Planes of secondary fluid inclusions in celestite. Note that most of the inclusions are equant with negative crystal shapes. (h) Example of necked fluid inclusion which is now three separate inclusions with variable L:V ratios (top to bottom: V-rich, L+V, V-rich).

Fluid Inclusion Decrepitate Analysis

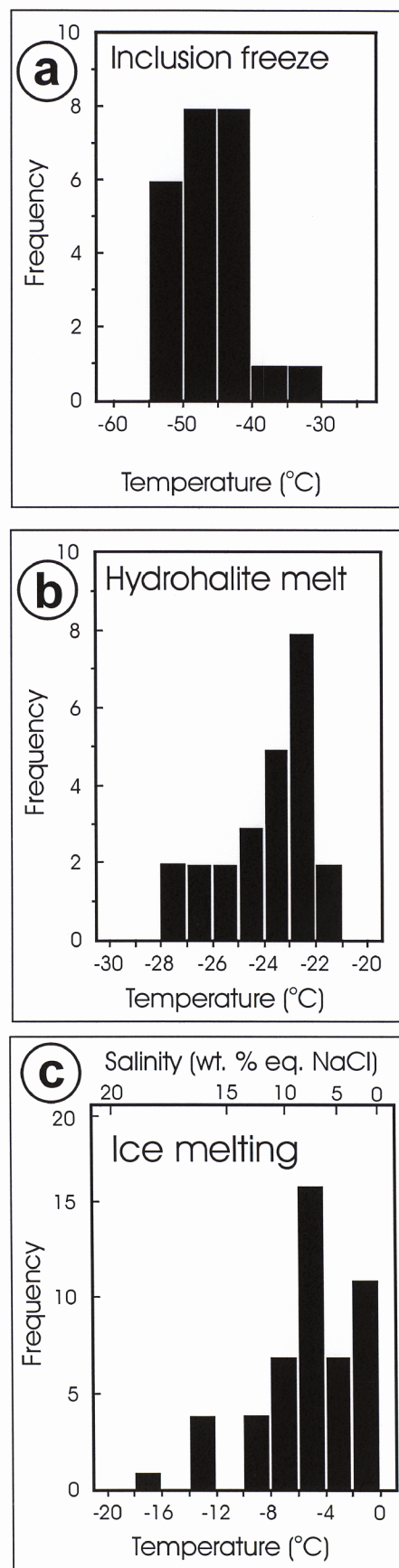
Analysis of fluid inclusion decrepitate mounds (Haynes *et al.*, 1988) was carried out to complement the thermometric data discussed above. Decrepitate mounds were first imaged and then analyzed using an energy dispersive system (EDS) with a 1-10 μm electron beam. Imaging of the samples indicates the presence of open cavities without associated mounds and also ones with mounds (Fig. 7b, c). Whereas the latter reflect precipitation of solutes from saline inclusions, the former probably represent evacuated inclusions with very low salinities (i.e. 0 wt. % eq. NaCl; see Fig. 6c). Results of EDS analysis of the mounds indicate three chemically distinct groupings (1, 2, 3), as summarized in the Si-Ca-Na and Cl-Ca-Na ternary plots of Figure 8. Group 1 consists of Na-Ca-Cl mounds which also have erratic amounts of Mg ($\leq 3-4$ wt. %), K ($\leq 1-2$ wt. %) and Ba (≤ 1 wt. %). Group 2 consists of Ca-Si mounds with erratic Ba (≤ 3 wt. %) and without detectable amounts of either Mg or K. Finally, group 3 consists of Si-rich mounds with minor amounts of Ca and a noted absence of any Cl. The proximity of these different mounds to each other is illustrated in Figure 9, which shows groups 1, 2 and 3 mounds within an area of ca. 0.015 mm².

A chemically unusual type of mound was encountered during routine analysis of the decrepitates. These mounds, shown in Figure 7a, are enriched in Ni (to 62 wt. %) and Fe (to 36 wt. %), have variable Si and Ca, and are deficient in Cl. Hence, these mounds equate to group 2 mounds mentioned in the paragraph above.

Summary of Fluid Inclusion Data

Thermometric measurements of fluid inclusions and analysis of decrepitate mounds hosted by celestite indicate a variety of fluids infiltrated the mineralized site at Beckwith. These fluids are variably saline with 0 to 18 wt. % eq. NaCl, and semiquantitative analyses indicate three distinct chemical groups, namely Na-Ca (-K-Mg-Ba), Ca-Si(-Ba), and Si. Unfortunately, it is not possible at present to discern temporal or spatial relationships among these different fluid types. We also note the presence of the unusual Ni- and Fe-rich fluids, as

Figure 6. Histogram plots summarizing thermometric data for fluid inclusions hosted by celestite from Beckwith. (a) Temperature at which inclusions freeze during cooling, a determined by sudden collapse of vapor phase in the inclusions. (b) Temperature of dissolution of hydrohalite in fluid inclusions. (c) Temperature of ice melting in fluid inclusions.



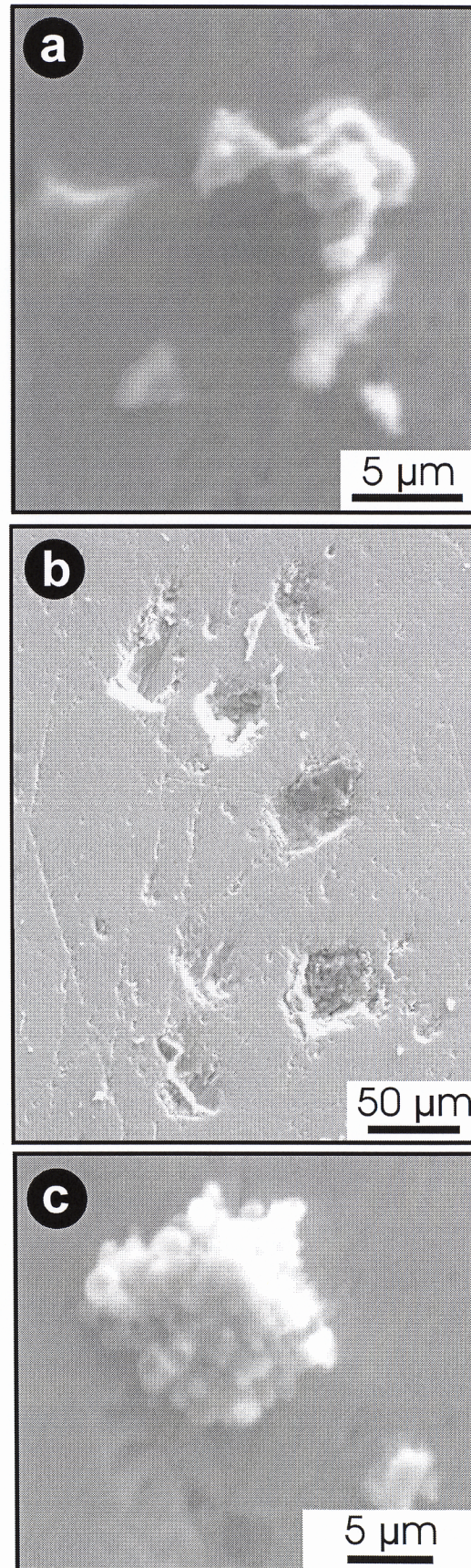
indicated from the decrepitate analysis, which have not been noted previously in Carboniferous mineral deposits of Nova Scotia.

Discussion

The occurrence of isolated pods of massive celestite in a clay unit containing spores of Windsor Group age is unusual. Elsewhere in Nova Scotia celestite occurs either as a replacement of carbonate rocks or as veins. The clay host itself is not typical of the Windsor Group strata, which are known to lack thick clay units. Instead, the mottled and unconsolidated nature of the host clay beds is consistent with what one might expect to see in a residuum derived from karstification of the Windsor Group evaporites due to infiltration of either basinal fluids or descending surficial water. The Windsor Group gypsum and anhydrite units contain an average of 800 ppm Sr and have been found to contain as high as several thousands of ppm Sr (Adams, 1991). Therefore, dissolution of the evaporitic beds would result in liberation of considerable quantities of Sr in solutions that would also be enriched in Ca and SO₄.

Fluid inclusion studies indicate that the fluids present in celestite are of variable salinity (i.e. 0 to 18 wt. %) and of mixed chemistry (Na-Ca-Si-Cl). The chemistry of these fluids can be explained by the alteration of the surrounding clastic and evaporitic strata. In general, the fluids are similar to basinal brines associated with carbonate-hosted Zn-Pb-Ba-F mineralization in Maritime Canada, although the salinities are slightly lower (Chi and Savard, 1995; Chi *et al.*, 1995; Sangster *et al.*, 1998). However, the Si-rich nature of the fluids, in addition to traces of Ni and Fe, are noted to be anomalous and differ in this respect from the fluids associated with Carboniferous mineralization in Nova Scotia where decrepitate analyses are available (Savard and Chi, 1998; unpubl. data of Kontak). This difference may relate to the formation of kaolinite in the clastic strata given the low temperature of fluid:rock interaction and formation of kaolinite during alteration, which would liberate Si. The Ni and Fe may reflect breakdown of nickeliferous pyrite in the redbed sequences of the Cumberland Group.

Figure 7. Combined secondary electron and back scattered electron images of different features of decrepitated fluid inclusions hosted by celestite. (a) A Ni-, Fe-, Si- and Ca-type decrepitate mound. (b) Empty cavities without proximal mounds possibly indicating that a very low salinity brine once occupied the inclusions. (c) A Na-, Ca-, K-, Cl-type decrepitate mound. Note the distinct, sub-micron scale crystal-like features that comprise this mound.



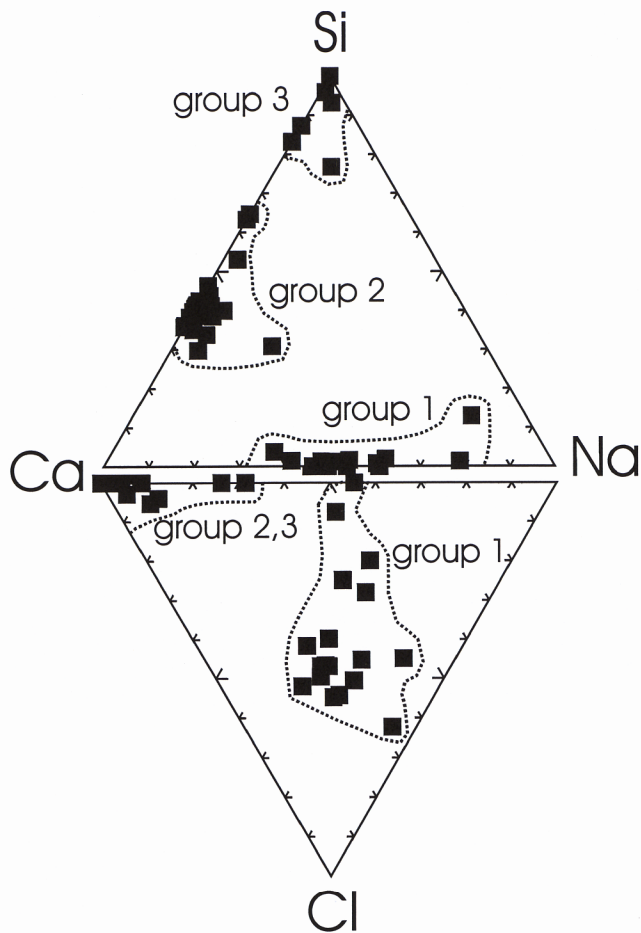
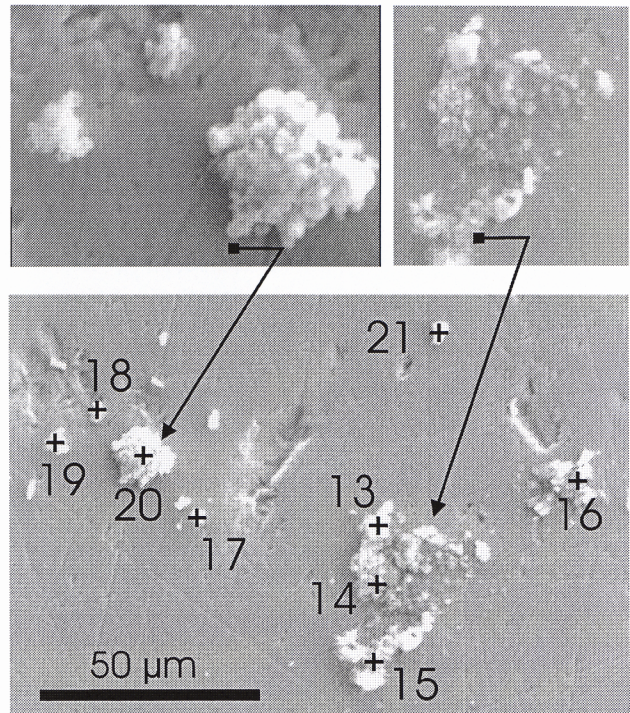


Figure 8. Ternary plots of Ca-Si-Na and Ca-Cl-Na illustrating the chemistry of the decrepitate mounds in celestite. Note that three distinct chemical groupings, designated group-1, 2, and 3, are distinguished.

A preliminary model, therefore, for the celestite mineralization involves karstification of the evaporites due to infiltration of groundwater and/or basinal brines along fault zones. The fluids would have interacted with the permeable red sandstone surrounding the Windsor Group strata in the area. Water moving through the red sandstone was likely oxidizing and carried Si and Pb derived from the kaolinitization of feldspars in the sandstone, as well as Fe and Ni derived from the oxidation of the Ni-bearing, early diagenetic pyrite common in the Upper Carboniferous strata of the Cumberland Basin (Ryan and Boehner, 1994; Fig. 4). Given that the essential components of this model are present throughout the study area, additional centres of celestite mineralization might be expected.

The age of dissolution of the Windsor Group evaporites would provide a constraint on the timing of



| mound | chemistry |
|-------|-----------|
| 13 | Si(Ca) |
| 14 | Ca-Si |
| 15 | Ca-Si |
| 16 | Ca-Si |
| 17 | Ca-Si(Na) |
| 18 | Ca-Na- |

Figure 9. Combined secondary electron and back scattered electron images of decrepitate mounds with corresponding chemistry, as determined by electron microprobe analyses. Note that the three groupings identified in previous Figure are distinguished in this area.

mineralization, but this is difficult to constrain given that the history of karstification is complex, multigeneration, and has occurred over a long period of time. The best that can be offered at this time is that a maximum age for the event is Permian, which coincides with the age of redbed copper mineralization that may have been remobilized to give the anomalous Ni-Fe signature of the fluid inclusions.

References

Adams, G. C. 1991: Gypsum and Anhydrite Resources in Nova Scotia; Nova Scotia Department of Natural Resources Economic Geology Series 91-1, 293 p.

Bodnar, R. J. 1993: Revised equation and table for determining the freezing point depression for H₂O-NaCl fluid solutions; *Geochimica et Cosmochimica Acta*, v. 57, p. 683-684.

Bodnar, R. J. and Bethke, P. M. 1984: Systematics of stretching of fluid inclusions I: Fluorite and sphalerite at 1 atmosphere confining pressure; *Economic Geology*, v. 79, p. 141-161.

Bodnar, R. J. and Vityk, M. O. 1994: Interpretation of microthermometric data for H₂O-NaCl, in *Fluid Inclusions in Minerals: Methods and Application, Short Course on the Working Group (IMA) "Inclusions in Minerals"*, ed., B. De Vivo, B. and M.L. Frezzotti; Virginia Polytechnic Institute, Blacksburg, Virginia, p. 117-130.

Boehner, R. C. 1986: Salt and potash resources in Nova Scotia; Nova Scotia Department of Mines and Energy, *Bulletin 5*, 346 p.

Chi, G.-X. and Savard, M. M. 1995: Fluid evolution and mixing in the Gays River carbonate-hosted Zn-Pb deposit and its surrounding barren areas, Nova Scotia; *Atlantic Geology*, v. 31, p. 141-152.

Chi, G.-X., Savard, M., and Héroux, Y. 1995: Constraints from fluid-inclusion data on the origin of the Jubilee carbonate-hosted Zn-Pb deposit, Cape Breton, Nova Scotia; *Canadian Mineralogist*, v. 33, p. 709-722.

Felderhof, G. W. 1978: Barite, Celestite and Fluorite in Nova Scotia; Nova Scotia Department of Mines, *Bulletin No. 4*, 463 p.

Felderhof, G. W. 1986: Report on the machine trenching and drilling program, Beckwith Celestite Property, Beckwith Nova Scotia; Nova Scotia Department of Natural Resources Assessment Report 86-168, 53 p.

Goldstein, R. H. and Reynolds, T. J. 1994: Systematics of fluid inclusions in diagenetic minerals; *Society for Sedimentary Geology Short Course 31*, 199 p.

Hayes, A. D. and Bell, W. A. 1938: Oxford sheet, Cumberland and Colchester Counties, Nova Scotia; Geological Survey of Canada, Map 409A.

Haynes, F. M., Sterner, S. M. and Bodnar, R. J. 1988: Synthetic fluid inclusions in natural quartz, IV. Chemical analysis of fluid inclusions by SEM/EDA: Evaluation of method; *Geochimica et Cosmochimica Acta*, v. 52, p. 969-977.

Kontak, D. J. 1998: A study of fluid inclusions in sulfide and non-sulphide mineral phases from a carbonate-hosted Zn-Pb deposit, Gays River, Nova Scotia; *Economic Geology*, v. 93, p. 793-817.

Kontak, D. J. and Macdonald, A. S. 1995: Initial results of a fluid inclusion study of fluorite from Lake Ainslie barite-fluorite deposits, Cape Breton Island, Nova Scotia; *in* Mines and Minerals Branch Report of Activities 1994; ed. D. R. MacDonald; Nova Scotia Department of Natural Resources, Report 95-1, p. 99-106.

Kontak, D. J. and Sangster, D. F. 1998: Aqueous and liquid petroleum inclusions in barite from the Walton deposit, Nova Scotia, Canada: a Carboniferous carbonate-hosted Ba-Pb-Zn-Cu-Ag deposit; *Economic Geology*, v. 93, p. 845-868.

Oakes, C. S., Bodnar, R. J. and Simonson, J. M. 1990: The system NaCl-CaCl₂-H₂O: I. The ice liquidus at 1 atm total pressure; *Geochimica et Cosmochimica Acta*, v. 54, p. 601-610.

Ravenhurst, C. E., Reynolds, P. H., Zentilli, M., Krueger, H. W. and Blenkinsop, J. 1989: Formation of Carboniferous Pb-Zn and barite mineralization from basin-derived fluids, Nova Scotia, Canada; *Economic Geology*, v. 84, p. 1471-1488.

Roedder, E. 1984: Fluid Inclusions; *Reviews in Mineralogy*, v. 12, 644 p.

Ryan, R. J. and Boehner, R. C. 1994: The geology of the Cumberland Basin, Cumberland, Colchester and Pictou Counties, Nova Scotia; Nova Scotia Department of Natural Resources, Mines and Minerals Branch, *Memoir 10*, 223 p.

Ryan, R. J., Boehner, R. C. and Deal, A. 1990: Cumberland Basin Geology Map, Oxford and Pugwash, Cumberland County; Nova Scotia Department of Natural Resources Map 90-13, 1:50 000.

Sangster, D. F., Savard, M. M. and Kontak, D. J. 1998: A genetic model for mineralization of Lower Windsor (Viséan) carbonate rocks of Nova Scotia, Canada; *Economic Geology*, v. 93, p. 932-952.

Savard, M. M. and Chi, G. 1998: Cation study of fluid inclusion decrepitates in the Jubilee and Gays River (Canada) Zn-Pb deposits - Characterization of ore-forming brines; *Economic Geology*, v. 93, p. 920-931.

Sterner, S. M., Hall, D. L. and Bodnar, R. J. 1988: Synthetic fluid inclusions. V. Solubility relations in the system NaCl-KCl-H₂O under vapor-saturated conditions; *Geochimica Cosmochimica Acta*, v. 52, p. 989-1006.

Vanko, D. A., Bodnar, R. J. and Sterner, S. M. 1988: Synthetic fluid inclusions: VII. Vapor-saturated halite solubility in part of the system NaCl-CaCl₂-H₂O with application to fluid inclusions from oceanic hydrothermal systems; *Geochimica Cosmochimica Acta*, v. 52, p. 2451-2456.