Targeted Geoscience Initiative 2000-2003

Geological Mapping for Mineral Development in South-central Cape Breton Island

Windsor Group Stratigraphy and Structure, Drill Core Orientation Field Trip 2001*

May 22-23, 2001

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Introduction

This two day Windsor Group Stratigraphy and Structure Drill Core Orientation field trip has been organized as part of the South-central Cape Breton Targeted Geoscience Initiative (TGI) Project. The Geological Mapping for Mineral Development, South-central Cape Breton TGI Project, is a joint project of Natural Resources Canada, Geological Survey of Canada and the Province of Nova Scotia, Department of Natural Resources and operates between 2000 and 2003. The purpose of the field trip and guidebook is to introduce industry, government and academic geologists to the Windsor Group of the project area by examining diamond-drill core sections representative of the Windsor Group in south-central Cape Breton Island. The drill core is located in the Nova Scotia Department of Natural Resources, Mineral Resources Branch, Core Library at 105-109 Acheron Court, Stellarton Industrial Park, Stellarton, Nova Scotia.

The plan is to look at a series of deep core holes (186-1191 m) with representation of Windsor Group stratigraphy and structure using examples from the Malagawatch salt deposit and Loch Lomond Basin (Figs. 1, 2, 3). This will include salt, potash and anhydrite/gypsum, which are economically important, dissolution collapse relations, key marine carbonate member markers and simple and complex folds. Malagawatch is selected to represent the deep saline basin facies with most of the major cycles present and locally very complex structure. The Loch Lomond Basin is selected because it contains the thin marginal basin facies, with typically locally developed complex structure, and, also Major Cycle 1 is absent, due to onlap/overstep. The drill core available for the Windsor Group in the Carboniferous basins of southern Cape Breton Island offers an opportunity to observe the substantial variation in lithology, thickness and salinity of marine evaporites and related strata. Dramatic change occurs in the basin fill over distances of tens of kilometres in a depositional area with considerable change in paleotopographic relief.

Figure 1. General geology and composite Bouguer gravity anomaly map, south-central Cape Breton (Canso-Bras d’Or area).
Figure 2. Windsor Group stratigraphy and correlation in Nova Scotia.

After Roehnner and Prime (1993); modified after Giles (1981a)
Figure 3. Schematic representation of some Windsor Group facies relationships.
The following information guidebook is assembled mainly from previous publications on Windsor Group geology and mineral resources. The Early Carboniferous age (Viséan) Windsor Group, historically, has been one of the more difficult, mysterious and sometimes controversial units of the Carboniferous basins. This, in large part, has been due to the recessive erosional character of the evaporite dominated lithology. The burial beneath thick surficial deposits in the lowland areas has resulted in extremely limited outcrop which is further compounded by the scarcity of deep drill core sections. The availability of drill core increased dramatically in the early to mid 1970s driven by base metal exploration for carbonate hosted deposits in the Windsor Group, especially the basal Windsor Group carbonate (Macumber Formation or Gays River Formation). Deep potash and salt exploration drilling as well as gypsum mining and drilling (Fig. 4) have added substantially to the information and knowledge and have contributed to major advances in understanding the geology of these strata.

The Windsor Group (Figs. 2, 3) is the most significant, distinctive and widespread lithostratigraphic marker for correlation throughout the Maritimes Basin of Atlantic Canada. It comprises an excellent representation of a marine evaporite basin at a scale comparable to giant saline basins in the world (e.g. Zechstein/North Sea). The Windsor Group is a primary source for the industrial minerals salt, potash, gypsum, anhydrite, limestone and dolomite as well it is a host for base metal and barite, celestite and fluorite deposits. The current and past production of these has dominated the mineral economy of the Province for the past three decades and will remain a stable base for the future. Exploration and development potential have not been exhausted and substantial areas remain to be explored. The use of salt deposits for underground storage is encouraging and hydrocarbon exploration has barely been undertaken in the region. Understanding the geology of the Windsor Group is critical to the future exploration and development activities in the region.

The intent of this core review and guidebook is to provide participants with background information on the stratigraphy and structure of the Windsor Group as well as illustrate very basic information on the drill core sections to be examined. This guidebook includes previously published material and unpublished, new and developing information and interpretations on the central Cape Breton area. It should not be considered a comprehensive treatment of the geology of the drillholes and the areas they are selected to represent. Users are directed to associated publications and references for more in depth treatment, including detailed lithologic and geophysical logs where available.

Figure 4. Five geological block diagrams illustrating gypsum deposit types in Nova Scotia. Deposit type 1 shows shallow surface hydration of massive ‘basal anhydrite’, with gypsum development limited by permeability, e.g. permeable carbonate interbeds or fracturing. Deposit type 2, a variation of type 1, shows surface hydration and deeper hydration along the contact with the underlying ‘basal carbonate’ of the Windsor Group and older strata with gypsum development enhanced by increased permeability, e.g. permeable carbonate/siliciclastic interbeds or fracturing associated with this disrupted contact zone. Deposit type 3 shows surface hydration and deeper hydration enveloping the anhydrite along the contacts with permeable carbonate and siliciclastic strata of the Windsor Group. Deposit type 4, a variation of type 3, shows enhanced hydration enveloping the anhydrite associated with structural deformation and faults creating increased permeability in carbonate/siliciclastic interbeds or fracturing. Deposit type 5 shows massive disruption of the original strata, especially at the contact between the ‘basal anhydrite’ and the B Subzone (Major Cycle 2) of the Lower Windsor (a local and regional decollement fault zone). Hydration development extends to depths exceeding 100 m, and typically occurs updip from variably deformed stratigraphic sections dominated by salt, but with significant anhydrite interbeds (e.g. ‘main salt’ of Major Cycle 1). Note that salt is typically preserved only below depths of 300-400 m.
Figure 4. See caption on facing page.

After Adams (1991)
Representative Windsor Group Stratigraphy and Structure Drill Core Sections

Malagawatch Drillhole Sections

Major Cycle 1: ‘basal carbonate’ and ‘basal anhydrite’

Drillhole Chevron C9-78 (CB9) (Figs. 3, 4, 5, 6), total depth 186.2 m (611 feet), at Malagawatch illustrates the lowermost Windsor, Major Cycle 1 units informally referred to as the basal anhydrite and the underlying basal carbonate (correlative of the Macumber or Gays River Formations). Synoptic section: 0-6 m (0-20 feet) overburden- not recovered; 6-22.9 m (20-75 feet) hydration karst zone of gypsum with cavity fill mud and pebbles; 22.9-181.4 m (75-595 feet) anhydrite with thin petroliferous limestone interbeds (0.9-4 m (3-13 feet)) dips 20°-45°; 181.4-184 m (595-604 feet) limestone, peloidal lime mud (Gays River/Macumber Formation); 184-186.2 m (604-611 feet) ‘basement’ weathered calcitized granite? saprolite?. A similar hole C3/3A-78 drilled approximately 1.5 km to the northwest intersected a show of light oil associated with a petroliferous carbonate interbed.

Major Cycle 1: ‘main’ salt unit and includes ‘main’ potash

Drillhole Chevron CM-8 (M8) (Figs. 5, 6), interval 640-850 m, represents the upper part of Major Cycle 1 dominated by the ‘main’ salt unit and includes ‘main’ potash unit (687.1-700.4 m). A very high grade section of halite typical of the basal salt of Major Cycle 1 was intersected beneath the main potash in the interval 715-897 m. A major antiform fold axis is present in this section and is inferred at a depth of approximately 835 m with an overturned fold repetition of the main potash at 969.2-984.5 m.

Major Cycle 2 - Major Cycle 4

Drillhole Chevron CM-5/5a (M5/5a) (Figs. 5, 6), 0 m to total depth 1191 m, represents Major Cycles 2-4. It represents one of the very few sections in the region where there is continuous, right way up stratigraphic succession. CM-5 was lost at 363.32 m before reaching the top of the salt and was redrilled as CM-5a at a location 7 m away. Major Cycles 3 and 4 of the Upper Windsor were intersected to 460 m at the base of the Herbert River Limestone Member (Chevron marker 1-0). The top of salt was picked at approximately 415 m indicating any salt formerly present above in the Upper Windsor has been removed by dissolution and the stratigraphic section telescoped, but not severely disrupted. A section of Major Cycle 2 (B Subzone) was intersected from 460-1046.8 m and then the upper part of Major Cycle 1 (A Subzone) to the total depth at 1191.1 m.

Major Cycle 2 fold repeat

Drillhole Chevron CM-4 (M4) (Figs. 5, 6), has a short selected interval, 457-716 m, which represents a complex fold structure in the upper part of Major Cycle 1 (B Subzone) that is typical of the deformed saline Windsor Group in the region. A thin marine carbonate marker (Chevron marker 1-5) is intersected multiple times in descending order intersections at: 480.36-486.46 m rwu (right way up), 504.75-505.7 m ovt (overturned), 520.3-523.04 m rwu, (major antiform fold axis at 530.6 m), 541.32-548.7 m ovt, (major synform fold axis at 560.0 m), 569.4-573.55 m rwu. The drillhole intersects a continuous rwu section to a depth of 716 m, including Chevron carbonate markers 1-6, 2-1, 2-2, and 3-1.
Loch Lomond Drillhole Section

Major Cycles 2-5 with a major overturned fold

Drillhole Scotia Prime LL-01-91 (Black and Miller, 1991) total depth 456 m, is selected to represent the near basin margin onlap facies (Major Cycles 2-5) with a major overturned fold (Figs. 1, 7). It also is used as an illustration of the origin and relationship of gypsum to parent anhydrite and permeable carbonate and siliciclastic interbeds as well as fractures and faults.

General Geology and Carboniferous Stratigraphy

The Maritimes Basin of Atlantic Canada is a successor basin dominated by nonmarine (alluvial, fluvial and lacustrine) siliciclastics. The basin fill, that may exceed 8000 m (late Devonian to early Permian), occurs as an overstep sequence on the Appalachian Orogen as a series of large and small erosional remnants centred in the Gulf of St. Lawrence. The basin fill is locally, highly disrupted by complex fault systems that produce many smaller structural basin features (especially in the onshore region). In ascending order, the major lithostratigraphic units are assigned to the Horton, Windsor, Mabou, Cumberland and Pictou Groups. The Windsor Group has played a key role in the development of the basins and is a primary economic unit serving as a source of mineral resources, a host for base metal deposits, as a regional and local correlation reference, and as a petroleum system seal. It represents the only major marine dominated depositional event in the late Paleozoic basin fill. The stratigraphic and basin nomenclature at all levels is complex and evolving as new subsurface data become available. The Windsor Group serves as a key for basin scale correlation of lithostratigraphic and chronostratigraphic units in the Maritimes Basin.

The south-central Cape Breton area (Fig. 1) occurs near the present day southern limits of the Maritimes Basin and includes the Bras d’Or Sub-basin of Bell (1958) and the southern part of the Sydney Sub-basin of Bell (1958). The initial surface and subsurface data that were available indicated the stratigraphy and structure were rather complex. The Carboniferous rocks, in this area, occur in a series of interconnected outcrop areas that primarily form the lowlands (e.g. Bras d’Or Lakes, River Denys). The highlands, that separate the areas of Carboniferous outcrop, comprise pre-Carboniferous crystalline rocks (e.g. Creignish Hills, North and Sporting Mountains). The geology of the Windsor Group in this area was poorly understood until the early 1980s because of the lack of deep subsurface data.

The south-central Cape Breton area generally has a similar geological configuration to those described in other Carboniferous basins in Nova Scotia. It differs dramatically, however, in the presence of thick saline dominated evaporite rocks of the Windsor Group (Figs. 2, 3). Major structures, in the area, are characterized by the complexity faulted contacts of Carboniferous basins in the lowlands and the basement highland blocks. This structure and landforms, define a series of northeasterly to easterly trending fault blocks and structural basins. The Carboniferous basins are gently to complexly folded depending upon the stratigraphic unit, presence of saline evaporites (e.g. salt) and location with respect to the major fault structures.

Carboniferous rocks are successively exposed on the angular unconformity on the northwestern borders of the pre-Carboniferous basement blocks forming distinct highlands such as the Creignish Hills, North and Sporting Mountains as well as smaller features such as the Washabuck block. These older Carboniferous rocks are represented mainly by Windsor Group and Horton Group. The northwestern borders of North and Sporting Mountains differ in that the Horton Group is apparently not well developed or it is onlapped/overstepped by the younger Windsor Group or both. These borders are probably faulted and folded locally. The southeastern borders of the Creignish Hills, North and Sporting Mountains, in contrast, are major faults with northeastward-southwestward trends that give the adjacent lowland structural basins the general configuration of half grabens (Fig. 1). Apparent dip slip on these northeastward-southwestward trending
Figure 5. General geology and location map, Malagawatch deposit area, central Cape Breton Island. Please note that Chevron Standard Ltd.'s (1982) drillholes M3 to M10 are labelled CM-3 to CM-10.
Figure 6. Detailed cross-section through the Malagawatch deposit (east to west).
Sketch of one possible interpretation of the structure cored in LL-01-91. A high-angle reverse fault is the preferred interpretation because of the difficulties imposed by the necessity to fold granitoid basement in a fold-interpretation alone.

The facing of the basal Upper Windsor Group limestone is uncertain. If overturned, the larger fold structure is preserved in the upper overturned limb, and the interpretation would be slightly different in detail. Fragments of Middle Windsor Group limestone in the breccia apparently beneath the basal Upper Windsor Group carbonate in the well, suggest that the breccia may be a fault breccia incorporating material from the Middle Windsor Group, and that the reverse fault was actually penetrated by the core.

Figure 7. Drillhole plot of Scotia Prime LL-01-91, Loch Lomond Basin. (For location see Figures 1 and 11).
faults is inferred to exceed 1000 m based upon drilling data and may exceed 2000 m based upon geophysical interpretations in the Orangedale-River Denys area.

The younger Carboniferous strata in the area comprise broad synclinal outcrop areas of Mabou Group and Cumberland Group. These are apparently less complex structurally, typically occurring as gently dipping and plunging synclines, especially in the southern part of the area near the Strait of Canso. The outcrop patterns are complicated by faults that juxtapose these upper Carboniferous strata with the Windsor Group as well as the Horton Group.

Windsor Group rocks form broad outcrop belts in the northern part of the area, especially in the River Denys basin area between the Creignish Hills and North Mountain and extend to the northeast into the Baddeck area. Boehner (1992) indicated that the compression that caused the fragmentation and complex adjustments of the smaller basement blocks in central Cape Breton Island may have produced complex deformation of the very thick, salt dominated Windsor Group. Thrust and slide fault tectonics, as well as evaporite diapirism, were considered to be the extreme products of this compressive-transpressive deformation. Giles and Lynch (1993) and Lynch and Brisson (1996) identified the Ainslie Detachment primarily in the basal Windsor Group, but stepping through to both higher and lower stratigraphic levels. This regional decollement produced the well recognized complex deformation and stratigraphic omission, especially within the evaporitic Windsor Group and bounding units (Horton and Mabou Groups).

The pre-Carboniferous basement rocks comprise complex intrusive and metamorphic massifs of Early Paleozoic to Proterozoic age (Hadrynian to Devonian). These basement blocks typically occur in the highland areas and are unconformably overlain by, in fault contact with and surrounded in whole or in part by Carboniferous sedimentary strata. The sedimentary strata occur in variably deformed structural basins that typically underlie the lowland areas. The lowermost strata comprise Lower Carboniferous Horton Group siliciclastic rocks, a complex succession of interstratified sandstone, mudrock, shale and conglomerate. The stratigraphy and sedimentology of the Horton Group have been studied in some detail by several workers including Murray (1960), Kelley (1967a, b), Hamblin and Rust (1989) and Giles et al. (1997a, b, c) who described the basic stratigraphic subdivisions in Cape Breton as the Creignish, Strathlorne and Ainslie Formations. In addition, the Fisset Brook Formation, with interstratified coarse and fine siliciclastics and volcanics including basalt and minor rhyolite and gabbroic intrusions, locally occurs in a section immediately beneath the Creignish Formation (e.g. southwestern end of the Creignish Hills, Lynch and Brisson, 1996).

Kelley (1967a) presented an isopach map showing original thicknesses of the Horton Group in central and western Cape Breton Island. The major areas of deposition and the approximate area of pinchout and Windsor Group onlap are readily seen on this map. Major deposition occurred to the west of the Creignish Hills and also in the Whycocomagh-Lake Ainslie area. The thickness and stratigraphy of the Horton Group in the River Denys Basin area southeast of the Creignish Hills, however, is unknown.

Although not contoured by Kelley (1967a), the Strait of Canso-St. Peters area may also be inferred to have substantial sections of Horton Group rocks (Ferguson, 1946; Ferguson and Weeks, 1950; Weeks, 1954). The induration of the Horton Group is abnormally high in some outcrop areas near the Strait of Canso (e.g. Sugar Camp) where fracturing cuts through both matrix and clasts in very hard conglomerates. In its thickest sections, such as in Graham River, Kelley (1967a) measured in excess of 3000 m. These sections may thin drastically by pinchout and onlap to less than a few hundred metres or to nil in the vicinity of pre-Carboniferous basement highs. In areas of such extreme thinning and Windsor Group onlap, it has been a mapping difficulty to determine which siliciclastic rocks are Horton Group and which are Windsor.
An example of this situation occurs along the southeastern contact of the River Denys Basin. This border of the Basin is defined by the pre-Carboniferous basement rocks of North Mountain (Fig. 1). Along the border, Kelley (1967a) mapped a band of red sandstone and conglomerate, and assigned the unit to a marginal facies of the Horton and/or Windsor Groups in a fashion after Weeks (1954). Weeks (1954) indicated the Windsor Group, in the southeastern part of Cape Breton, occurred in two distinct relationships with underlying rocks, the ‘central basin succession’ and ‘marginal basin succession’. The marginal basin succession occurs in an onlap relationship with pre-Carboniferous rocks. It is invariably associated with coarse, ill-sorted conglomerate and interpreted as marginal facies of the more basinal sections which rest on Horton Group rock. Although mapped by Kelley (1967a) as marginal facies of the Horton Group, R. Ryan (personal communication, 2001) indicated that these siliciclastics are probably a deeply weathered granitoid saprolite remnant beneath the Windsor Group and updip from stratified Horton Group. This saprolitic Horton Group unit occurs in a narrow outcrop band between Big Brook through River Denys Station to McKenzie Brook.

Bell and Goranson (1938a) introduced the term Grantmire member and applied it to coarse siliciclastic rocks beneath Lower Windsor marine strata in the Sydney map area, which were believed to have been marginal basal Windsor Group facies. Boehner and Giles (1986) separated some of the upper coarse facies and included them in the Windsor Group and assigned the bulk of the Grantmire type area conglomerates and sandstones to the Horton Group. Weeks (1954) applied the name Grantmire Formation to a conglomerate and sandstone unit in the St. Peters map area and considered it part of the Windsor Group. Weeks (1954) also mapped the unit in the Iona-Washabuck area. More recently Kelley (1967a), in the adjoining map area, recognized typical Horton Group rocks rather than Grantmire introducing a nomenclature conflict. In this specific area, modification and reassignment of the coarse siliciclastic map unit to the Horton Group is not a problem, because a typical basal Windsor carbonate and lower sulphate succession are apparent at the topographic and mapped boundary. Petroleum exploration drilling nearby in the Little Narrows-Jubilee area by Little Narrows Petroleum in the 1940s established that the Horton Group exceeded 600 m (2000 feet) in thickness (McMahon et al., 1986). In other areas, the problem is not so easily resolved however, especially where conglomerate is interstratified with the marine carbonates of the Windsor Group in the Loch Lomond area (Boehner, 1981; Boehner and Prime, 1993).

Boehner (1984, 1986a, b) documented that the most important interval with regard to thick salt occurs above the lower sulphate-basal Windsor limestone section (Major Cycle 1) and beneath the interstratified siltstone, sandstone, gypsum-anhydrite, and limestone dolostone that comprise the middle and upper parts of the Windsor Group (Figs. 2, 3). Thinner and possibly significant salt horizons, however are also known to occur at any level in the Windsor Group and may also occur above the highest Windsor Group carbonate member (Giles and Boehner, 1979; Giles, 1981a).

In central and southern Cape Breton Island the basal limestone-evaporite section is well represented. It was referred to as ‘basal laminated limestone’ by Weeks (1954) and Ferguson (1946) and ‘A1 Windsor limestone’ by Kelley (1967a, b). This unit concordantly and probably conformably overlies the Horton Group (Kelley 1967a, b; Ferguson, 1946). The unit was originally described by Ferguson (1946) as a fine grained, dull grey rock with individual laminae one-quarter inch thick and a maximum total thickness of approximately 20 m (65 feet). Weeks (1954) reported that the lower most bed in his ‘central basin succession’ is a characteristic black, laminated, sandy, unfossiliferous limestone with a maximum thickness of approximately 21 m (70 feet). Kelley (1967a) described the A1 limestone as thinly laminated, fine grained, medium to dark grey with quartz or gypsum and anhydrite grains scattered on bedding planes.

A thick section of anhydrite normally overlies the basal Windsor limestone and has been informally referred to as the basal anhydrite or as other formation names in other structural basins, e.g. Carrolls Corner Formation. Broad outcrop belts of anhydrite and gypsum are evident on maps and drilling has established thick anhydrite sections (typical of the basal anhydrite locally exceeding 300 m) near Little Narrows at Jubilee, Alba and at Big Brook in the River Denys area.
The stratigraphic section of the lowermost Major Cycle 1 or A Subzone of the Lower Windsor Group will be examined in the representative drill core from Chevron Standard Ltd. (1978) C9-78 drilled in the Malagawatch area (total depth 186 m (611 feet)).

In some areas, the basal part of the Windsor Group oversteps the Horton Group and onlaps intrabasinal highs such as along the northwestern side of North Mountain where Kelley (1967a) and Ferguson (1946) reported basal limestone overlying thin conglomerate on pre-Carboniferous rocks. More extreme onlap and the appearance of coarse siliciclastic facies are evident in the Mira Hills-East Bay Hills area. Here the middle and upper Windsor sections have overlapped the basal Windsor section and were deposited directly on deeply incised pre-Carboniferous basement. This line of onlap occurs in the vicinity of the Bras d’Or Lake-East Bay shoreline along the northwestern side of the East Bay Hills between Johnstown and Glen Morrison. Similar onlap of lowermost Windsor over Horton and pre-Carboniferous basement also is evident in the Black River-Dundee area and along the northern and northwestern borders of North Mountain between Big Brook and Malagawatch. Spectacular onlap of Middle and Upper Windsor as well as Mabou and Cumberland Groups strata onto steep terrain is well developed in the Loch Lomond-Enon area (Figs. 2, 3, 4, 5, 8, 9, Boehner and Prime (1993)).

The stratigraphy of the middle and upper parts of the Windsor Group has not been well understood in the area prior to the deep potash exploration drilling by Noranda and Chevron in the early 1980s. No stratigraphic columns or measured sections of the Windsor Group were described by previous workers with the exception of the aforementioned Loch Lomond area. The substantial deep core drilling now allows a greater understanding and documentation of the stratigraphy and structure of these rocks (Giles and Boehner, 1982a; Boehner, 1986a, b; Boehner, 1992) and correlation to well established stratigraphy in the Shubenacadie Basin (Figs. 8, 9) as described by Giles and Boehner (1979). Extreme variations in thickness may be present in the central and southern Cape Breton area due to rapid changes in topography, paleotopography, basin depth, as well as postdepositional structural adjustments that are also severe in most areas. Fairly undisturbed areas with gently deformed stratified salt sections are probably rare in the central Cape Breton area because of extensive tectonism. The Boularderie deposit appears to be quite undeformed, however it is known only from one deep drillhole.

This stratigraphic section of the middle to upper part of the ‘main salt’ section including the ‘main potash’ unit comprising the uppermost part of Major Cycle 1 or A Subzone of the saline basinal facies of the Lower Windsor Group, will be examined in the representative drill core from Chevron CM-8 (M8) drilled in the Malagawatch area (interval 640-850 m) (Chevron Standard Ltd., 1982). The stratigraphic section of the saline basinal facies of the B Subzone, Major Cycle 2 and the Upper Windsor Subzones C and D will be represented in drillhole Chevron Malagawatch CM-5/5a (M5/5a), TD at 1191 m (Chevron Standard Ltd., 1982). Basin margin and onlap facies of less saline Major Cycles 2-5 will be represented by the Scotia Prime drillhole LL-01-91 (Black and Miller, 1991) in the Loch Lomond Basin where the regionally typical Major Cycle 1 is absent due to basin margin onlap/overstep.

The Windsor Group in the central Cape Breton area, as in other areas of Nova Scotia, is overlain conformably to disconformably by younger, typically nonmarine strata assigned to the Mabou (Canso) Group and Cumberland (Riversdale) or Pictou Groups. The section above the Windsor Group has a complex history of stratigraphic subdivisions and age assignments by a variety of workers including Norman (1935), Bell (1944, 1958), Ferguson (1946), Weeks (1954), Belt (1964, 1965, 1968a, b), and Kelley (1967a, b). These rocks are currently being mapped and investigated by P. S. Giles as part of the Cape Breton TGI Project. In general, these Upper Carboniferous strata comprise stratified red and grey shale, sandstone, conglomerate and rare coal.
The thickest and most complete Upper Carboniferous sections occur near the Strait of Canso, St. Peters and Kingsville. Bell (1944) indicated approximately 610 m (2000 feet) of Canso Group in the type section at the Strait of Canso. Belt (1962, 1964, 1965), who incorporated the Canso and Riversdale Groups in this same section assigned more than 2743 m (9000 feet) to his new Mabou Group including 914 m (3000 feet) considered by Ferguson (1946) to be Canso Group and more than 1829 m (6000 feet) considered by Ferguson (1946) to be Riversdale Group. Kelley (1967a) calculated a minimum total thickness of 2134 m (7000 feet) for the section of Upper Carboniferous, Mabou Formation (Canso-Riversdale Groups equivalent) in the Maple Brook Syncline near Kingsville. Ryan et al. (1991) proposed a revised lithostratigraphic nomenclature for Upper Carboniferous strata and would include in their expanded Cumberland Group part of the strata formerly included in the abandoned Riversdale Group. Kelley (1967a) reported that, along the western border of the Maple Brook Syncline, the Windsor Group A1 limestone is overlain concordantly by 4.6 m (15 feet) of red siltstone, which in turn is overlain by Mabou Formation. Further to the north the Mabou Formation overlies apparently younger Windsor Group strata.

Ferguson (1946) reported that the thickness of the Windsor Group beneath the Mabou (Canso) Group varied and attributed this to erosion of parts or, in some instances, nearly all of the original Windsor Group section. Kelley (1967a) suggested this erosion may have been contemporaneous with some Mabou Formation deposition. Areas, where the Windsor Group is extremely thin, occur mainly in the vicinity of the Strait of Canso, but also occur along the southeastern border of the Antigonish Basin. In the latter areas this

Figure 8. Correlation of Windsor Group carbonate members Major Cycles 2-5, Windsor Group type area, Shubenacadie Basin and Glengarry/Loch Lomond Basin.
Figure 9. Windsor Group reference sections correlation, Shubenacadie Basin (SB-1) and central Cape Breton Island composite section (CCBI Malagawatch and McIntyre Lake).
discrepancy may be fault related with high and/or low-angle faulting suspected along at least part of the contact between the Windsor and Mabou Groups as well as low angle decollement faults (Ainslie Detachment) within the Windsor Group (Lynch and Brisson, 1996; Lynch et al., 1998; Giles and Lynch, 1993, 1994).

The complex stratigraphy in the central Cape Breton area is further complicated by faulting and folding. One major fault occurs on the northwestern side of the River Denys structural basin and brings the Windsor Group in contact with Horton Group and pre-Carboniferous rocks of the Creignish Hills between Diogenes (Glen) Brook-Melford area and Baddeck (Lynch and Brisson, 1996; Lynch and Lafrance, 1996). The southeastern Cape Breton area is also marked by major faults that extend from Lennox Passage northeastward to the Loch Lomond area. Faulting in the area is dominated by a series of major northeastward trending faults and fault systems that can be traced from the Strait of Canso-Chedabucto Bay area to Mira Bay (e.g. Lennox Passage and Grand River Faults, Boehner and Prime, 1993) (Fig. 1). Many major faults have been mapped by previous workers and more recent subsurface and geophysical data indicate others are probable. The highland blocks of the Creignish Hills, North Mountain, Sporting Mountain and the Washabuck block appear to be fault bound on their southern contact with Carboniferous strata in the adjoining lowlands and their extension beneath the Bras d’Or Lakes. Interpretations of tectonics and sedimnetation are included in the reports by Belt (1968a, b), Kelley (1967a, b), Bell (1958), Ferguson (1946), and Weeks (1954), White and Barr (1998), and Barr et al. (1996). The reader is directed to these for more detailed descriptions.

**Windsor Group Major Cycles Distribution and Correlation**

The Major Cycles of the Windsor Group described by Giles (1981a) extend to many areas in Nova Scotia (Figs. 1, 2, 3). Major facies changes and stratigraphic onlap locally complicate the picture, especially in areas near basement blocks such as Mahone Bay, Eureka and Loch Lomond (Fig. 2, Sections 1, 8 and 16). Typical Major Cycle 1 rocks are widespread throughout Nova Scotia and are well represented in the Antigonish-Mabou, south-central Cape Breton (Canso-Bras d’Or) and Sydney areas where its thickness ranges from 300-600 m. Halite with siliciclastic and anhydrite interbeds is known to occur with Major Cycle 1 in most areas and it forms the most important salt resource in Nova Scotia.

Potash salt, sylvite and minor carnallite are known to be associated with halite in Major Cycle 1 in the Antigonish area and especially in the south-central Cape Breton area (Fig. 2, Sections 10, 11, 12 and 14). Although encouraging for further exploration, economic deposits have yet to be defined. Potash salts are not known to occur on the Nova Scotia (Meguma) Platform south of the Cobequid-Chedabucto Fault System. Major Cycle 1 rocks in this platform area were inferred by Giles (1981a) to have been deposited adjacent to seaways connected to a major Viséan sea through a shallow marine carbonate shelf on the Nova Scotia Platform. Successive Carboniferous structural basins in a northwesterly direction generally contain increasingly saline evaporite suites indicating significant lateral facies change and important paleogeographic control on evaporite deposition. Paleogeographic reconstructions across the Cobequid-Chedabucto Fault System are extremely uncertain at this time.

The distribution, thickness and facies variation of evaporites in Major Cycle 1 are unknown in most areas because of the scarcity of deep drilling. Stratigraphic thicknesses of up to 600 m are present in some areas with the thickest sections in the highly deformed saline Windsor Group facies of the Canso-Bras d’Or area. Major Cycle 1 is the major target for potash exploration in Nova Scotia as it is in New Brunswick.

The thick halite-anhydrite-siltstone sequence in the highly deformed diapiric Windsor Group in the Cumberland area described by Carter (1990, 1994) is of uncertain stratigraphic assignment (Fig. 2). Drillhole sections and mine stratigraphic sections (Evans, 1972) are incomplete and their relationship to the
outcrop sections of Bell (1958) are uncertain. The stratigraphy of the evaporites in the Cumberland area is virtually unknown and therefore stratigraphic comparisons to well established sections in other areas is not as yet clear, however they appear to be similar to sections of Major Cycles 1 and 2.

Major Cycle 2 is more widespread than Major Cycle 1. Major Cycle 2 displays major facies change regionally ranging from evaporite dominated to terrigenous dominated. It locally oversteps Major Cycle 1 to onlap onto pre-Carboniferous basement rocks (Figs. 2, 3, 8) in marginal basin areas including Loch Lomond and Salmon River. Similar changes are indicated by Giles (1981a) in the Mahone Bay and Eureka areas (Figs. 2, 3, Sections 1 and 8). The Mahone Bay area is similar to the Musquodoboit Basin (Fig. 2, Sections 1 and 2). Shallow marine shelf facies in Major Cycles 1, 2 and 3 indicated that these areas may have been proximal to a seaway connecting the Viséan inland sea on the Nova Scotia Platform to the major Viséan sea to the southeast (Giles, 1981a). The major evaporite deposition appears to have been localized in deeper, more northerly parts of the inland sea.

Halite, stratigraphically above Major Cycle 1, was first recognized with several carbonate-anhydrite minicycles within Major Cycle 2 in the Shubenacadie Basin. The stratified halite and interbedded anhydrite horizons rarely exceeded thicknesses of 15 m, but subsequently thicker and more numerous halite beds have been confirmed in the highly deformed sections in the Cano-Bras d’Or area (Giles, 1981b; Chevron Standard Ltd., 1982). Exploration drilling at McIntyre Lake, Malagawatch and Orangedale has intersected potash (sylvite and minor carnallite) in one carbonate-anhydrite-halite minicycle within Major Cycle 2. The presence of potash, although in subeconomic quantities in at least one horizon in this cycle, was previously unknown and may provide an additional potash exploration target. Gypsum deposits are notably concentrated at or near the Major Cycles 1 and 2 contacts in Nova Scotia. They occur in a variety of types (Fig. 4) described and illustrated by Adams (1991). A description of these types is included in a following section.

Major Cycle 2 at Malagawatch (e.g. Chevron drillhole CM-5/5a (M5/5a), Figs. 5, 6, 8, 9, 10) is dominated by halite and is up to three times (500 m versus 160 m) as thick as in the Hants-Colchester area (SB-1). Approximately 45% of the Malagawatch section is halite and 30% anhydrite. Corresponding sections in the Shubenacadie Basin are 14% halite and 51% anhydrite (Boehner, 1984). The majority of the increase in stratigraphic thickness at Malagawatch is contributed by the halite (230 m versus 22 m). These very saline sections are frequently recumbently folded with multiple repetition of stratigraphic intervals defined by distinctive carbonate members (e.g. Orangedale, Fig. 10 and Malagawatch, Fig. 6).

Major Cycles 2, 3, 4 and 5 are more widely distributed than Cycle 1 (Figs. 2, 3). Onlap relationships have been documented by Boehner and Prime (1985) near Loch Lomond and Salmon River (Fig. 2, Sections 16 and 17) in southeastern Cape Breton Island and near Knoydart Point in northeastern mainland Nova Scotia by Giles (1981b). Although salt was locally present in Major Cycle 5 in the Shubenacadie Basin it did not occur in Major Cycles 3 and 4. It was found, however, to be a substantial component in Major Cycles 3 and 4 in the Cano-Bras d’Or area. Here the Major Cycle 3 section is nearly four times as thick as corresponding sections in the Shubenacadie Basin (270 m versus 70 m) and consists of 34% halite and 28% anhydrite. Corresponding values are 0% and 10% respectively in the Shubenacadie Basin. As with Major Cycle 2 in the Malagawatch area, most of the increase in thickness is contributed by the halite (Figs. 8, 9, 10).

**Gypsum and Anhydrite Deposit Types (Adams, 1991)**

The following section of text has been adapted from Adams (1991) (adaptations appear in italics) to describe and illustrate the range of gypsum deposit types in the Province. In addition the text includes a synopsis of gypsum and anhydrite deposit geology with major source information references for those with further interest in the subject.
The upper part of the overturned fold structure in Scotia Prime LL-01-91 has been selected to illustrate the types 3 and 4 relationship between parent anhydrite and the secondary hydration to gypsum typical of many gypsum deposits mined in the Province. (Note: inserts in italics have been added by Giles and Boehner, this report).

From Adams (1991):

>Although evaporites have been the subject of extensive studies elsewhere in the world, the Windsor Group evaporites in Nova Scotia have not been studied in similar detail. Bell (1929) proposed that the thick basal sulphates were deposited in sea lagoons connected to a sea by a restricted channel. Goodman (1952) believed that the Province’s calcium sulphate deposits were originally laid down as anhydrite in lagoons “...rhythmically replenished with marine waters…” Schenk (1969) concluded the evaporites of the Windsor Group represented diagenetic deposition in a coastal sabkha-salina environment (supratidal CaSO₄) and halite in a landward salt flat playa environment.

More recent work by Evans (1972) on the evaporites found in the salt mine at Pugwash, Cumberland County, has examined in detail the deposition and diagenesis of calcium sulphates in the mine section. He concluded that the calcium sulphate horizons in the lower part of the Windsor (Cycle 1) (Major Cycles 1(?) and 2(?)) were deposited in a restricted sea under water of <150 m depth as gypsum crystals forming within carbonate sedimentary rock. Shortly after deposition the gypsum was replaced by anhydrite. Evans (1972) also
suggested, as does Boehner (1986) (1986a), that the thinner, interbedded calcium sulphate horizons found in Cycles 2-5 of the Windsor Group may have been produced in a different environment, probably the sabkha environment described by Schenk (1969) rather than entirely in restricted sea lagoons. Boehner (1986) (1986a) concluded that both sabkha displacive nodular evaporite deposition and shallow subaqueous (saline pan) evaporite deposition coexisted during Major Cycles 2-5.

Two different depositional environments and lithological associations for Cycle 1 and Cycle 2 calcium sulphate deposits have led to modern gypsum and anhydrite deposits with distinctly different character. Complex structural deformation (tectonic and solution collapse) of those original deposits has greatly increased the complexity of modern deposits and occurrences. This in turn makes the delineation of economically viable deposits more difficult. Boehner (in press) (1992) suggests that the more ductile nature of the evaporite dominated Windsor Group has amplified the effects of tectonism on these strata. Intensity of deformation varies within the Group, as well as within basins depending on basin depth, abundance of salt and tectonic-sediment setting. Boehner (in press) (1992) proposes that three mechanisms produced much of the evaporite tectonism observed in the Carboniferous basins “... (1) decollement: gravity slides and thrusts, (2) compressive-transpressive, and (3) diapiric, tectonic and density contrast driven...”

The differing depositional environments and resulting lithology in combination with the varied degrees of deformation (tectonic setting) have yielded distinctly different types of gypsum deposits in Nova Scotia. Lewis and Holleman (1983) made the first attempt to stratigraphically locate the Province’s major gypsum and anhydrite production sites. Using Bell’s (1929) subzones, they placed all active mines within the A and B Subzones (Giles, 1981a, Cycles 1 and 2). Several factors which localized these units include: (1) large component of CaSO₄, (2) influence of structure concentrated at this level (decollement-collapse, etc.), (3) enhanced permeability due to structure and paleodrainage (geomorphology).

Although gypsum has been observed in drillcores from today’s Windsor Group basins at depths up to 300 m below surface, virtually all gypsum horizons in the Province grade to anhydrite with increasing depth. In contrast to the primary depositional model proposed by Goodman (1952), it is generally accepted by most investigators (i.e. Schenk, 1969) that present day gypsum deposits primarily are the result of rehydration of anhydrite bodies. Whether the anhydrite is primary or secondary after original depositional gypsum is unclear. The spatial relationship and association with near surface environment, fracture-permeability aquifer zones and inferred burial depth below the stability of primary gypsum, as well as abundant replacement textures of gypsum after anhydrite, leave little doubt as to the origin of the gypsum. The time of rehydration varies from area to area and could have occurred at any time between the Carboniferous and the present as is evidenced by multiple episodes of karstification and associated solution infilled materials found in the Cycle 1 and Cycle 2 horizons at various locations in the Province. Giles (1980) suggested that the Lakevale Formation found in the Antigonish Basin was probably deposited in karst features in Cycle 1 evaporites at some time not later than Namurian (Late Carboniferous Canso Group). Similarly Boehner’s (1980a) (1980) discussion of solution infill material found in the same basal sulphate horizon at Crystal Cliffs, Antigonish County, reported spores of Stephanian (Late Carboniferous Pictou Group) age extracted from infill material.

Much younger Triassic material infills solution features studied by Clifton (1967) in the Windsor Basin. Unconsolidated Cretaceous aged deposits of clay, sand and lignite were
reported by Dickie (1987) to be preserved in solution features in Cycle 1 and Cycle 2 at the following areas around the Province: Gays River, Halifax County; West Indian Road, Hants County; McKay Settlement, Hants County; and Diogenes Brook, Inverness County. All deposits of gypsum quarried at present in Nova Scotia have innumerable karst features over their upper surfaces infilled by Pleistocene aged materials and annually cases of sinkholes suddenly opening up on properties around the Province graphically show that dissolution of gypsum and anhydrite continues at present.

Sonnenfeld (1984) stated that “secondary gypsification requires meteoric waters.… “The hydration appears to be enhanced by the presence of porous interbeds adjacent to the anhydrite bodies, faulting of the anhydrite which may have enhanced its permeability, and differing patterns of overlying cover and drainage. Sonnenfeld (1984) also suggested that "the presence of barium, calcium, strontium or trivalent metal ions in the water will accelerate the hydration.” It is also known that the presence of other substances such as calcium hydroxide will inhibit hydration.

Theoretically, mole for mole hydration of anhydrite to gypsum results in a 61% volume increase which could, in part, be responsible for some of the structural deformation which is observed within the Windsor Group strata. It is more likely that much of the excess gypsum is removed in solution as part of the throughgoing fluid system during the hydration process. Observations that chloride content of gypsum is usually lower than in the original anhydrite support this idea (removal of CaSO₄ and NaCl). Lewis and Holleman (1983) noted that the highest concentration of soluble salts are found in gypsum adjacent to anhydrite often as haloes 2-3 m in width. Sonnenfeld (1984) determined that solutions containing higher concentrations of salt will precipitate anhydrite rather than gypsum. It may be that meteoric water which hydrated anhydrite and flushed salts as they moved downward, gradually became saturated so that they no longer hydrated the anhydrite until additional meteoric water was introduced.

A number of gypsum deposit types were recognized and described during the course of this study by Adams (1991). Two are seen in the Cycle 1 (A Subzone) and three are present in Cycle 2 (B Subzone). Type 1 surface rind/envelope involves the hydration of the massive basal anhydrite from the surface down (Fig. 1-2) (Fig. 4). Hydration usually extends 10-20 m below the top of the gypsum to an irregular interface with underlying anhydrite. This irregularity may reflect fracture/fault structures cutting the anhydrite, surface groundwater patterns or overburden cover having differing permeability. Interbeds of carbonate and clastics are rare, have limited permeability and thus have little influence as hydration fluid pathways. Examples of this type of deposit are Georgia-Pacific Corporation’s Big Brook site at River Denys, Inverness County, and Fundy Gypsum Company Ltd.’s White Quarry at Wentworth, Hants County. Gypsum produced from these Quarries is a white, highly pure product. These deposits are usually of lesser volume than other types.

Deposit type 2 of Cycle 1 (A Subzone) is a modification of type 1. In addition to having thin surface hydration over the top of basal anhydrite, these deposits contain a much deeper (+30 m) trough of hydration which roughly conforms to the contact between the basal sulphate and the underlying basement (Fig. 1-3) (Fig. 4). At many places around the Province there is evidence that these features existed, the gypsum was removed by dissolution and the resultant trench was partially or totally infilled by younger material. Deposits like Domtar Gypsum’s McKay Section Quarry in Hants County, Georgia-Pacific Corporation’s Sugar Camp Quarry, Inverness County, and the drilled, but undeveloped
deposits at Long Hill, Victoria County, held by Republic Gypsum and Domtar Gypsum all are this type. Gypsum from these deposits is a white, highly pure variety equal in quality to the first type; the volume of these deposits depends on how deep hydration extended and how much of this trench material has remained in place. Due to the enhanced hydration thickness from water concentration down the basal contact, they tend to be larger than the first type, but still are smaller than the deposits of Cycle 2.

There are (at least) three separate types of gypsum deposits found in Cycle 2 (B Subzone). Primarily, they differ in the degree and style of deformation of the strata in which they are confined. All three types are confined to the lowermost portion of Cycle 2 where the calcium sulphate interbeds comprise up to 75% of the geological section. Carbonate and clastic interbeds make up the remainder and are considered as waste material to be discarded during the mining process.

Deposit type 3 consists of gently-dipping interbedded calcium sulphate horizons with interbeds of carbonates and fine grained clastics (Fig. 1-4) (Fig. 4). These deposits are rare since most of the Cycle 2 sections in most of the subbasins are moderately to highly deformed. Calcium sulphate beds 10-20 m thick, dip gently (8-10°) to the northeast in the Meadows Road area, Cape Breton County. Hydration extends downdip to a point approximately 30 m below surface. A few drillholes have been put down into this section at Meadow Road, however insufficient information is available to comment on the volumes of gypsum which might be extractable. This deposit type would most likely be amenable to underground, room and pillar mining only and as such would be more expensive than any of the other deposit types. Gypsum quality is good here and is generally white to light grey in colour.

Deposit type 4 is comprised of type 3 strata structurally deformed to produce a folded and faulted section (Fig. 1-5) (Fig. 4). Structural mechanisms previously mentioned enhance the permeability of these sections which results in greatly increased depths of hydration in excess of 100 m. Degree of deformation varies from a broad plunging syncline in the Little Narrows Gypsum Company Ltd.’s Magazine Quarry at Little Narrows, Victoria County, to a recumbently folded and faulted section at Fundy Gypsum Company Ltd.’s Miller Creek Quarry. Gypsum taken from this type of deposit is usually light to dark grey in colour and varies from very fine grained to selenitic. Interbeds of carbonate and clastic materials are usually removed from the quarry during the mining operation and some fine grained waste material is screened after crushing has occurred. Final products are dark and less pure than those generated from all previously described deposit types.

Type 5 occurs in the same strata near the base of Cycle 2 (B Subzone) as is seen in types 3 and 4, however the deformation and disruption of the beds is so complete that little remains of the original beds which made up the section (Fig. 1-6) (Fig. 4). The mechanisms which produced these deposits are still unclear; Boehner (in press) (1992) and Moore (1967) proposed faulting, either thrusting or decollement, and Howie (1986) proposed brecciation after the dissolution of halite horizons; perhaps both processes were involved. Whatever the mechanism, these deposits are generally large (+50 Mt thick), with +100 m depths of hydration. They are quite homogeneous in composition and thus are less complicated and more straightforward to mine than any other type. The grade and character of the gypsum is the same as in type 4, however all impurities (carbonates and clastics) must be removed in the crushing and screening process rather than by the selective mining practiced in type 4. Occasionally, larger blocks of carbonate can be avoided in mining, but generally everything
is removed from the quarry. National Gypsum (Canada) Ltd.’s East Milford Quarry in Halifax County is an example of type 5 and a similar deposit has been outlined nearby at Dutch Settlement, Halifax County, by Fundy Gypsum Company Ltd. Type 5 deposits are also known to exist adjacent to the Big Brook and Sugar Camp Quarries of Georgia-Pacific in Inverness County.

Undoubtedly there are more types of deposits of gypsum and anhydrite present in the variably deformed Windsor Group basins in the Province. Recognition of these deposit types as well as the stratigraphic and structural parameters and processes which have produced them should aid in extending the reserves of present quarries and help to delineate new ones.

### Salt Dissolution Features

The details of salt dissolution features have not been investigated or described, however the following general observations are made. The interrelationship with stratigraphic distribution, tectonics and gypsum deposit formation is not completely understood, but is of great economic importance (Adams, 1991). Boehner (1986a) described the geology of the saline Windsor Group salt deposits using an alphabetic identifier based on a variety of characteristic parameters including basin depth/thickness, salt abundance, tectonic setting, deformation and fold structure. The classification ranged from type ‘A’ with slight to gentle folding and structural deformation through moderate and severe types ‘B’ and ‘C’ to type ‘D’ where diapiric intrusive features were evident. In the near surface environment the highly soluble salt is generally dissolved by circulating groundwater to depths exceeding 400 m. The residual, less soluble strata remain as a type of caprock or karst dissolution collapse deposit with variably intact stratigraphy and structure. These rocks are closely related to major gypsum deposits, especially types 3, 4 and 5 described by Adams (1991). Salt dissolution and primary and secondary structural enhancement of porosity/permeability are key factors in deep and extensive hydration of residual anhydrite units to form gypsum.

Caprock development of the Gulf Coast type described by Martinez (1974, 1978) is not known to occur in association with Windsor Group salt in Nova Scotia. Residual collapse breccia is common in areas where saline Windsor Group comes to the surface. The residual breccia is well developed in the Pugwash and Nappan deposits (Cumberland area Type D). Here blocks of gypsum and carbonate resistates are found in poorly consolidated to unconsolidated mud forming an irregular cap to the evaporite diapirs. Giles (1981b) described telescoped sections of highly deformed saline Windsor Group in the McIntyre Lake deposit (Canso-Bras d’Or area, Type C). In this area, halite has been preferentially dissolved to a depth of 200-300 m leaving the original stratigraphic succession intact, but thinned. The collapse breccia comprises quite insoluble, brecciated anhydrite-gypsum, siltstone and carbonate infiltrated by mudstone (Fig. 6). A similar situation has been described nearby in the Malagawatch deposit area by Chevron Standard Ltd. (1982) where salt is removed to depths locally exceeding 400 m (Fig. 6).

Salt removal, residual accumulation and collapse brecciation and economically important hydration of anhydrite to gypsum may be expected in the vicinity of faults and permeable strata in areas where they are in contact with the Windsor Group. The absence of salt springs and seeps in many areas of these features indicates salt dissolution has been reduced or halted, possibly by the sealing action of residual clay and mud. The abundance of salt springs, seeps and saline formation water regionally, however, indicates most salt areas are not stable or completely sealed.

In addition to the dissolution of salt, there has been locally extensive dissolution of anhydrite and gypsum that has produced a variety of karst features. These are evident in large and small scale surface
landforms as well as subsurface features including filled and unfilled cavities. Representation of subsurface bedrock interface features of this process (including gypsum/anhydrite relations) will be presented in drillholes LL-01-91, C9-78 and CM-5.

Central Bras d’Or - the Saline Basin Centre - Malagawatch Salt Deposit

NTS 11F/15B, C UTM 659870 E 5081170 N

The Malagawatch salt deposit is situated along the western shore of Bras d’Or Lake near Malagawatch, Inverness County (NTS 11F/15, Fig. 1). Malagawatch is located approximately 40 km northeast of Port Hawkesbury and 20 km southeast of Whycocomagh. The area is accessible by paved and unpaved roads connected with Highways 104 and 105. The Canadian National Railway (former) mainline between Port Hawkesbury and Sydney is situated 10 km to the west.

The topography in the area is dominated by the North Mountain which rises abruptly to 230 m. The Carboniferous lowlands are largely submerged beneath Bras d’Or Lake and rarely have elevations that exceed 50 m.

Historical Background

Although salt springs are not known in the Malagawatch area, several have been reported by Hayes (1931) in the Orangedale, Whycocomagh and West Bay areas (Fig. 1). The recent discovery of salt and potash near Malagawatch was complicated as well as serendipity (Dekker, 1982). Chevron Standard Ltd. (1978) unexpectedly encountered light crude oil in two base metal exploration drillholes (C3-78 and twin C3A-78) near Malagawatch (Figs. 1, 5, 6). The minor amount of oil recovered from a shallow and thin carbonate in the basal anhydrite was a sweet light 40.4° API crude with low sulphur 0.24%. The area became a petroleum prospect that was drilled in 1979-80 under a joint venture between Chevron Standard Ltd. and Irving Oil Company Ltd. Chevron acquired petroleum reservations of 1.2 million acres in the region and undertook a major petroleum exploration program. Two wells, Chevron Irving Bras d’Or CIB-1 and CIB-2 were drilled in the area of the discovery drillholes at Malagawatch (Chevron Standard Ltd., 1979). The third well, Chevron Irving Malagawatch CIM-1 was drilled on a small gravity low near Malagawatch Point and unexpectedly intersected a significant section of salt and potash (Chevron Standard Ltd., 1980). The potash zone was recognized in the geophysical logs as a high gamma ray log response coincident with a washout and very low density zone in the well over an interval of 75 m at a depth of 487 m. Core analysis over an 11 m interval gave a grade of 28.3% K₂O. Interpretation from gamma ray, density and neutron logs indicated additional intervals of 58.5 m grading over 25% between 490 m and 560 m. A twinned cored well, CIM-2 was drilled adjacent (20 m away) to CIM-1 to recover a complete core section from the rotary drilled section of potash intersected by CIM-1 (Chevron Standard Ltd., 1980). An ore grade section of 18 m was assayed in the drill core 463-525 m grading 22.3-26.4% K₂O. Structural correction to true thickness reduced these intersections to 23.3 m in CIM-1 and 8.2 m in CIM-2.

The Malagawatch area then became a very promising potash prospect that encouraged further potash exploration in the central part of Cape Breton Island by Chevron Standard Ltd. and Noranda Exploration Co. Ltd.

Geology

The geology in the Malagawatch area (Fig. 5) was described by Kelley (1967a) and Weeks (1955). The area
is included on a recent Geological Survey of Canada geological map, Whycocomagh 11F/14 by Lynch and Brisson (1996). The Malagawatch deposit is located on a narrow lowland area at the northeastern end of the North Mountain highland block that comprises Devonian and possibly older quartz monzonite, granodiorite and minor granite. These have intruded older, (possibly Hadrynian) George River Group rocks which comprise quartzo-feldspathic and micaceous quartz schist, quartz gneiss, limestone, quartzite, minor volcanic rocks and greywacke.

Thin siliciclastic rocks including sandstone, conglomerate and mudrock assigned to the Lower Carboniferous Horton Group, onlap the older rocks of the North Mountain highlands, and occur in a narrow outcrop band along its northwestern border. These strata are not present beneath the basal Windsor carbonate and basal anhydrite of Major Cycle 1 at the northeastern end of the highlands near Malagawatch. In these onlap areas there is preserved, locally, deeply weathered granitoid saprolite remnant beneath the Windsor Group and updip from stratified Horton Group (R. Ryan, personal communication, 2001). This saprolitic Horton Group unit occurs in a narrow outcrop band as a marginal facies of the Horton Group between Big Brook through River Denys Station to McKenzie Brook.

The Horton Group section is overlain by a thick section typical of the basal anhydrite and Macumber Formation (basal Windsor Group carbonate) along the northern border of North Mountain. It also extends into the Malagawatch area where it is little more than a thin weathering profile on the basement granitoids and the Macumber Formation essentially rests on the basement rocks (Chevron Standard Ltd. (1978) drillholes C1-78, C2-78, C7-78, and C9-78, and the Chevron-Irving Bras d’Or wells CIB-1 and -2 (Chevron Standard Ltd., 1979), Figs. 5, 6). The dip of the fairly undisturbed Macumber Formation and overlying basal anhydrite of Major Cycle 1 in these correlated drillhole sections is approximately 20° to the northeast. This geology and structure appear to be typical of the immediate periphery of the northeastern end of North Mountain adjacent to the Malagawatch deposit.

Windsor Group rocks rarely outcrop in the immediate Malagawatch area, however there are a few outcrops in the area of Valley Mills (B Subzone, Major Cycle 2), and McKenzie Brook to the west. The abrupt narrowing of the basal anhydrite outcrop area that is apparent near Valley Mills (in contact with Major Cycle 2) probably indicates an intervening fault relationship. This outcrop pattern is similar to that in the Windsor Group strata occurring to the southwest near Big Brook (e.g. Bestwall deep drillhole near Georgia-Pacific gypsum quarry).

Detailed information regarding the geology of the salt and potash in the Malagawatch deposit including the stratigraphy and structure of the salt and potash in the area is contained in a major exploration project report by Chevron Standard Ltd. (1982). The Chevron Standard Ltd. (1982) description of the Windsor Group geology at Malagawatch is generally similar to that in the adjacent Orangedale deposit and the McIntyre Lake deposit area near Port Hawkesbury. Potash occurred at three stratigraphic levels (Fig. 9), one in Cycle 2 (upper potash) and two near the top of Cycle 1 (middle not shown and lower potash) with the lower potash the major economic horizon. For further information the reader is directed to the summary report on the Malagawatch Project by Chevron Standard Ltd. (1982).

The potash exploration drilling by Chevron Standard Ltd. (1982) defined the Malagawatch deposit as having a structure and stratigraphy that is very complex and different from that associated with the basal section of Major Cycle 1 of the Windsor Group around North Mountain in the drilling to the southwest and west. Eight deep potash exploration core holes (CM-3 to CM-10) were drilled by Chevron with depths ranging from 877-1220 m (Chevron Standard Ltd., 1982). Please note that the CM-3 to CM-10 drillholes are also labeled M3 to M10. Most drillholes have fold repeated sections of salt dominated stratigraphy that is well documented both in the lithological logs of the cores and in the geophysical logs of the drillholes (Figs. 6, 9, 10). The folds have varied inferred dips and plunges with tight isoclinal limbs and limb intersections ranging from 10s to 100s of metres (Figs. 6, 10).
The complex structural geology of the Windsor Group saline evaporites in the Pugwash Salt Mine in Cumberland County was well documented by Evans (1972) and subsequently mapped in more detail by Carter (1994) and references therein. This work should serve as a reference for the geological complexity that may occur within highly deformed deposits like those in southern Cape Breton Island. Giles (1981b) illustrated a very complexly folded section of saline Windsor Group strata in a series of holes through the McIntyre Lake deposit near Port Hawkesbury. This type of deformation has now been documented at Malagawatch and Orangedale based upon deep core drilling by Chevron and Noranda in the early 1980s.

Chevron Standard Ltd. (1982) reported the following conclusions on the geology of the Malagawatch deposit based upon their exploration drilling. A composite stratigraphic column was pieced together from the following four drillholes: CM-5a, CM-8, CM-1 and CM-10. Noranda’s Orangedale N225-3 was used by Chevron Standard Ltd. (1982) to establish the stratigraphic section between CM-5a (upper parts of the Windsor Group) and the lower part of the Windsor Group in CM-8, CM-1 and CM-10. Carbonate interbeds and other distinctive lithologic units were identified as a series of key markers to establish stratigraphic sequence and younging directions. The composite section from the Macumber Formation at the base to the Herbert River Limestone Member (base of the Upper Windsor) at the top is indicated to be nearly 1200 m with most of this section comprising the Lower Windsor Group (Subzones A and B). These stratigraphic markers were coded and tabulated for all drillholes in the Malagawatch area and summarized in the Chevron Standard Ltd. (1982) report. For the deep saline potash exploration drillholes, only CM-5/5a and CM-6 intersected normal upward facing Windsor Group sections from top to the total drilled depth. All others encountered complex and overturned folded sections evidenced by repetition of stratigraphic sections.

Saline evaporites, including salt (halite and potash), occur at all stratigraphic levels including the Upper Windsor in drillhole CM-6 (Fig. 6). Potash salts occur only in the Lower Windsor Group. A zone of solution collapse and brecciation extends throughout the drilled area containing saline evaporites (Fig. 6) and occurs from surface to a depth from 181 m (CM-9) to 415 m (CM-5a). The correlations and stratigraphic identifications are difficult because of the section reduction, brecciation and collapse due to the removal of the highly soluble halite as well as anhydrite. Although the lowermost Windsor section, including the Macumber Formation and the basal anhydrite, was intersected in the base metal exploration drilling at the edge of North Mountain, they were not completely penetrated in the subsequent potash and petroleum exploration drilling.

Chevron Standard Ltd. (1982) described three significant potash zones in the Lower Windsor in ascending order as follows: the lower potash zone, middle potash zone and upper potash zone (Table 1). The lower (or main) potash zone located in the middle part of the main salt in the A Subzone/Major Cycle 1 was the most significant zone with the greatest thickness and grade, but only attained economic thickness and grade where structurally thickened. The middle potash zone in the upper part of Major Cycle 1 and the upper potash zone in the lower part of Major Cycle 2 are described by Chevron Standard Ltd. (1982) as low grade and uneconomic. No drillhole contained all three zones and the upper and middle zones were not intersected in continuous section in the Malagawatch area. Noranda N225-3 did intersect both zones near Orangedale. The middle zone occurs with the main (lower) zone in drillholes CIM-1 and CIM-2, but was absent from CM-8 and CM-9.

All three potash zones consist of sylvinite, a mixture of sylvite and halite. Carnallite occurs in very minor amounts in the lower or main potash zone grading from < 0.5 to 2.0%. Carnallite may comprise up to 7.5% of the upper zone. The insoluble content is high in some of the potash intersections. The insoluble material occurs as inclusions, clots and fragments of greenish-grey siltstone and mudstone, reddish-brown siltstone and clots and wisps of grey, very fine grained anhydrite/gypsum.
Table 1. Summary of potash assay results from Chevron Standard Ltd. (1982) drilling at Malagawatch and St. Patricks Channel.

<table>
<thead>
<tr>
<th>Hole</th>
<th>Upper</th>
<th>Middle</th>
<th>Lower</th>
<th>Interval (m)</th>
<th>Length (m)</th>
<th>Dip°</th>
<th>True (m)</th>
<th>K₂O%</th>
<th>Insol%</th>
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<tr>
<td>CM-1</td>
<td></td>
<td></td>
<td></td>
<td>*342-351</td>
<td>9</td>
<td>45?</td>
<td>6.3</td>
<td>2.0</td>
<td>?</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*486-533</td>
<td>47</td>
<td>70</td>
<td>15.8</td>
<td>&gt;25</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*543-560</td>
<td>17</td>
<td>70</td>
<td>5.7</td>
<td>&gt;25</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td></td>
<td></td>
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<td>70</td>
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<td>8</td>
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<td></td>
<td>337-348</td>
<td>11</td>
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<td>290.9-300.2</td>
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<td>6.1</td>
<td>40</td>
<td>4.2</td>
<td>&lt;1</td>
<td>?</td>
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NOTES: Dip in degrees to horizontal
Upper = Upper Potash Zone, Middle = Middle Potash Zone, and Lower = Lower or Main Potash Zone
Length = Sample interval length
Calculations based upon a 0.63% K₂O cutoff (=1% KCl)
*GammaRay Log Calculated Assay Result
The upper contact of the upper potash zone is a gradation of low grade sylvinite with abundant mudstone fragments upward into reddish-brown mudstone brecciated with dark orange fibrous halite veins. The lower contact is sylvinite grading downward into clear, honey and pale orange coloured, fine- to coarse-grained euhedral halite with very minor insolubles. The sylvite is typically less than 20% with clear, brownish to orange halite greater than 60%. The sylvite is clear to reddish orange, fine- to medium-grained with minor opalescent augen up to 2 cm. The crystals typically have red rims associated with greater insolubles. Carnallite is very fine grained, coppery red with flecks of hematite. Insolubles comprise up to 20% pale olive to dark greenish grey clay, mudstone and siltstone clots and fragments. The average K₂O content is less than 15%.

The middle potash zone is the least well documented and most of its character is described from drillhole CM-2. The upper contact of the middle potash zone is gradational from a breccia of olive greenish-grey siltstone with dirty orange brown halite and a matrix of very low grade sylvinite down into veins. The lower contact is sylvinite grading downward into clear, honey and grey coloured, fine- to coarse-grained halite (80% of the zone). The sylvite is typically reddish orange and fine grained. Carnallite was not assayed, but may occur in trace amounts. The K₂O content is less than 9% in CM-2.

The lower or main potash zone is the highest grade and most consistent of the three zones. The upper contact of the lower potash zone grades abruptly upward from high-grade sylvinite containing up to 65% sylvite to clear to grey, dirty orange brown halite with abundant reddish-brown mudstone. The lower contact of the high grade sylvite is gradational downward over a short interval into banded halite (diffused to distinct bands over several metres). The halite varies from clear to milky white to light orange to dark grey with minor disseminated dark orange sylvite. The transition zone has a K₂O content of 2-15%. The high grade sylvite has dark orange red sylvite with a few clear crystals. It is mostly massive and finely crystalline, euhedral to slightly acicular. Milky white to opalescent to reddish orange ‘augen’ of sylvite are also abundant. Insolubles comprise less than 10% pale olive to dark greenish grey clay, mudstone and siltstone clots and fragments. The high grade potash also includes a massive lower grade sylvinite zone 0.5-1.0 m thick. It comprises a mixture of clear to light orange to dark orange, fine to medium crystalline sylvite with 50-80% milky white halite crystals up to 2 cm. The high grade zone locally has a strong foliation/lineation emphasized by conspicuous blue halite inclusions in clear, finely crystalline halite. The blue halite is associated with lower K₂O grades. The K₂O content in the lower main potash zone varies from 20-40%.

Chevron Standard Ltd. (1982) concluded the upper and middle potash zones were too low grade to be economically important. The middle potash zone in Noranda N225-3 approached economic thickness and grade (2.3 m true / 20.7% K₂O), however it was not laterally persistent. The contact relationships for the three zones were very similar with an upper contact gradational from mudstone breccia down into sylvinite. The lower contacts typically grade down into halite with minor impurities. These contacts were useful in determining facing directions. The lower or main potash zone is the only zone with economic potential and has 20-45% sylvite and 12.6-41% K₂O. The insoluble content may be high to the detriment of potential ore grade (e.g. 1% insoluble to 1% grade degrade).

A structural boundary oriented approximately northwest-southeast through Malagawatch Harbour is inferred to separate the basal Windsor Group (Macumber Formation and basal anhydrite of Major Cycle 1) and North Mountain block from the highly disturbed saline Windsor Group (Major Cycles 1 (upper part) and 3, 4 and 5) intersected in the potash exploration drilling CIM-1, -2 and CM-3 to CM-10 to the east. It is not clear whether this is simply an easterly to northeasterly dipping decollement surface at the top of the basal anhydrite with a dip of approximately 20° steepening to approximately 45° (calculated and interpolated). Alternatively and/or additionally the contact could be complicated by a later(?) high angle fault with a northwesterly orientation. This northwesterly orientation is nearly parallel to the fault in the McKenzie Brook area immediately to the southwest.
Chevron Standard Ltd. (1982) constructed a series of cross-sections through this drilling and also used inferred high angle, sharp faults to separate some of the interpreted folded blocks (e.g. between CM-5a and CM-8/CIM-9, CM-6 and CM-7 and CM-9/CIM-2/CIM-1 and CM-3). P. S. Giles (personal communication in 2001) indicated the geology may be reconciled in these cross-sections without these faults which are not typically associated with the highly mobile and incompetent deformation of salt dominated evaporite strata (Figs. 5, 6). This type of geology also occurs in the Orangedale deposit to the northwest (Figs. 1, 10). The final cross-sections and structural interpretation by P. S. Giles will be included in the TGI project when completed.

**Geophysics**

The area in the vicinity of the Malagawatch deposit is included on Bouguer anomaly maps by Noranda Exploration Company Ltd. (1981) and Chevron Standard Ltd. (1982). The discovery drillhole is situated near the northern side of a very large gravity trough centred beneath the south-central part of the Bras d’Or Lake. The gravity contours are steep (very close together) in the Malagawatch area indicating a juxtaposition of contrasting blocks of higher and lower density rocks. Chevron Standard Ltd. (1982) concluded there were no clear, simple relationships of quantity-thickness of salt or potash, the depth of salt and the Bouguer gravity anomalies. Geological continuity with the Estmere deposit to the north is probable and consequently only a small percentage of the salt mass presumed to have produced the gravity low is located on land. The Bouguer gravity anomaly indicates that saline evaporites probably extend throughout much of the Bras d’Or Lake area. The Malagawatch deposit appears to be bounded to the northwest by a northeasterly trending fault structure extending from near Estmere, West Alba to Iona Rear where it forms the southeastern boundary of the Washabuck Block. The Orangedale deposit to the northwest is very similar and occurs on the opposite side of the inferred northwestern fault through the Malagawatch area. In the Orangedale area, this inferred fault separates thick saline Windsor Group from a thinner section of Lower Windsor in the area of Alba to the northeast (analogous to the relationship of Malagawatch with North Mountain).

The possible occurrence of a northwestern cross structure at the northeastern end of North Mountain is indicated by an area of coincident magnetic and gravity highs separating the inferred Alba high from the deep saline evaporite basin section in the Orangedale area to the southwest. Very steep contours are evident along the western side of the gravity low at Malagawatch where the inferred northwesterly-trending fault forms the boundary with Horton Group and pre-Carboniferous basement rocks along the valley of McKenzie Brook in the adjoining highlands of North Mountain. It is unclear if the fault is a low angle or a high angle fault, or both.

**Geochemistry**

Salt springs have not been described in the immediate area of Malagawatch or in the adjoining Estmere area. They are present in the nearby St. Patricks Channel deposit and Orangedale deposit areas to the north and northwest. Chemical analyses of bromine was completed on selected salt from many of the drilled salt sections by Chevron Standard Ltd. (1982). In addition, Boehner (in preparation) completed detailed sampling of a section representative of Major Cycle 1 and the lower part of Major Cycle 2 (CM-5a and CM-8). This sampling overlapped with the wider spaced sampling by Chevron and significant variations in the Br profile were discovered in the Major Cycle 2 and the upper part of Major Cycle 1 in drillhole CM-5a. The values in both sets of analyses were very similar for the CM-8 drillhole that intersected the middle to lower part of the Major Cycle 1 salt. Exceptions were a few samples having discrepancies of double the value. The CM-5a drillhole section, however, was very different with Chevron Standard Ltd. (1982) values two to three times the values across the entire section of the upper part of Major Cycle 1 and the lower part of Major Cycle 2. These Chevron values were generally in the range of 150-200 ppm and anomalous in comparison to correlative sections at Orangedale and Boularderie (Kempt Head). In general the bromine values of Boehner
(in preparation) are typical of the saline Windsor Group in the region with higher bromine values indicative of potash salt precipitation occurring in proximity to the lower potash zone.

Although assays of the salt intervals were not undertaken, assays of the potash zones were included by Chevron Standard Ltd. (1982). Chevron Standard Ltd. (1982) concluded potash beds reached economic grade and thickness in structurally thickened sections e.g. CIM-1 and CIM-2 or as single beds e.g. CM-8 and CM-9 that are similar to Noranda N225-3. The drilling was unable to establish sufficient lateral extent or continuity of grade and thickness for an economic deposit. Although there were structural complexities from faulting and folding, and geophysical methods, e.g. seismic, gravity and magnetic surveys, were unable to resolve detailed geology, Chevron considered the local basin area to be an attractive exploration target. The potential for less complicated geology with potash could be targeted using additional gravity and new seismic techniques to target drilling sites.

**Economic Considerations**

The Malagawatch deposit comprises a complexly folded, thick section of saline Windsor Group evaporites with numerous significant intersections of potash in thick sequences of salt. The broad Bouguer gravity anomaly in the region indicates saline Windsor Group probably occurs at depth throughout the area, especially beneath a large part of Bras d’Or Lake to the north, east and south of the drilled area of the deposit. This, together with the drill data available, indicates the presence of a potentially large salt deposit with significant intersections of potash at depths of 500 m to nearly 1000 m and potential at depths extending below 1000 m (Table 1). Chevron Standard Ltd. (1982) concluded the structural complexity, variable thickness and limited land-based resource area diminished the potential for developing an economic potash deposit at Malagawatch. They concluded further exploration was warranted in the region where the prospective potash stratigraphy was under land and potentially less structurally complex and more consistent in thickness. The Malagawatch deposit is probably geologically related to the Orangedale deposit 15 km to the northwest, as well as the Estmere deposit immediately to the north (extending beneath the Bras d’Or Lake and under Boom Island).

**Loch Lomond Basin - the Basin Margin Onlap**

*The following sections are adapted from Boehner and Prime (1993) (adaptions appear in italics) with additional information on drillhole Scotia Prime LL-01-91 from Black and Miller (1991).*

From Boehner and Prime (1993):

> The Loch Lomond Basin and Glengarry Half Graben are connected structural basins in southeastern Cape Breton Island (*Figs. 1, 11*) comprising strata that range in age from Early to Late Carboniferous (Viséan to early Westphalian D). This sedimentary succession is dominated by siliciclastic strata and has an estimated stratigraphic thickness of up to 2000 m in the Glengarry Half Graben, but less than 1000 m in the Loch Lomond Basin (Map 85-2, in pocket). The strata within the area progressively onlap Hadrynian to Devonian rocks of the Fourchu Block, which collectively form an igneous and metasedimentary basement (*Figs. 2, 3, 12*). The L’Ardoise Block, comprising deformed siliciclastics that correlate with the Horton Group (in part), is interpreted to be an allochthonous block emplaced by strike-slip fault movement.

The basal part of the succession comprises an uncertain thickness, probably exceeding several hundred metres in the Grand River area southwest of the Loch Lomond Basin, of red and green conglomerate, mudstone and sandstone. These rocks were not mapped extensively in this study and were assigned to an undivided basal conglomerate map unit. The basal conglomerate units record the early stages of development of a continental basin
Figure 11. Simplified geological map of the Loch Lomond Basin and location of Scotia Prime LL-01-91 and the Passage Bridge cross-section (For section AA see Figure 12).
Figure 12. Geological cross-section, Passage Bridge, Loch Lomond Basin. (See Figure 11 for location of section AA1)
with piedmont alluvial and fluvial deposition as local marginal facies of the Lower Windsor Group. The thick evaporites that typically constitute Major Cycle 1 of the Windsor Group (Giles, 1982) are not present in the basins and are apparently represented by coarse redbed alluvial fan deposits which are overlain by strata typical of Major Cycle 2 (Fig. 7) (Figs. 2, 7, 12). The continental alluvial fan to alluvial plain sedimentation at the basin edge was eventually inundated by the Windsor seas during deposition of Major Cycle 2. In this situation there is interbedding of the coarse grained alluvial siliciclastics with the marine deposits including carbonates and evaporites.

Regionally, Major Cycle 2 comprises a package of interstratified gypsum, anhydrite (locally salt and potash), limestone, dolostone, and red siltstone and sandstone. This represents repeated marine transgressions and regressions individually recorded by fossiliferous marine carbonates overlain by nodular sulphate and continental clastics. The marine carbonates and related evaporite and redbed facies of the middle Viséan age Enon and Loch Lomond formations (record a complex interaction of evaporitic marine and continental alluvial deposition. In this environmental setting), indicate that the marine transgressions occurred over a terrain with substantial local paleotopographic relief and was (were locally) accompanied by significant input of marginal basin siliciclastics (coarse grained siliciclastics near the basin margin). The marine carbonate rocks are shallow water algal, oncotic, oolitic and argillaceous micritic packstone, wackestone and mudstone. Buildup facies of the B2 Member were deposited on elevated topographic highs formed by basement rocks both within and peripheral to the depositional basin (Figs. 9, 12 and 14) (Figs. 11, 12). This type of carbonate facies distribution (Fig. 18) was previously described in the Gays River Formation of the Shubenacadie and Musquodoboit Basins (Giles and Boehner, 1979; Boehner, 1987, 1988). The Loch Lomond Basin is a key area in defining a similar relationship at a higher stratigraphic level. In the marginal siliciclastic-dominated sections (typically conglomeratic) the carbonates are extensively recrystallized and are locally recycled calcirudite. The nodular sulphate and fine-grained redbeds represent regressions with the development of sabkha type hypersaline mudflats and evaporite deposition in hypersaline lagoons (subaqueous) in basinward sections.

There is a close relationship between fine- and coarse-grained alluvial redbed sediments (marginal alluvial fan conglomerate and breccia to basinal mudstone and sandstone) and the evaporites. In areas peripheral to the basin, the Enon and Loch Lomond formations undergo profound and rapid facies change (over a few kilometres) from evaporite-dominated to alluvial fanglomerate-dominated. In the area of the MacRae celestite pit northeast of Enon, the Enon and Loch Lomond formations are characterized by abundant redbed paraconglomerate interbedded with highly recrystallized limestone, which is locally recycled calcirudite (Fig. 12). Evaporites are absent. To the southwest, near the Amaic and Enon celestite deposits, the paraconglomerate and sandstone fine to mudstone and sandstone redbeds, and interbeds of evaporites are typical. Farther southwest of Enon, near Loch Lomond, the section is dominated by evaporites with minor fine-grained redbeds. The paraconglomerate-dominated section of the Loch Lomond and Enon formations and the undivided basal conglomerate unit represent alluvial fan deposition along the changing margin of the basin. Regressive periods between the marine transgressions are recorded by prograding alluvial fan conglomerate and sandstone to mudstone, with subaerial erosion and weathering at the top of the limestone interbeds. The absence of evaporites indicates that the area of deposition was elevated above the restricted hydrology required for sabkha evaporite deposition.
The Enon and Loch Lomond formation package is overlain by a similar package of interstratified red siltstone, marine carbonate and minor evaporite constituting the middle Viséan Uist Formation. With the exception of an overall decrease in evaporite content and fining of the constituent red beds in the Uist Formation, the depositional regime is similar to that described for the Enon and Loch Lomond formations.

The Uist Formation records the last marine carbonate deposition in the area and is succeeded by grey (minor red) shale, minor sulphate evaporites, and thin algal carbonate of the late Viséan MacKeigan Lake Formation of the Mabou Group. These strata represent the residual evaporitic conditions of the underlying Windsor Group and the return of the basin to continental conditions. A large lake or system of saline lakes is inferred to have developed following retreat of the Windsor seas.

Paleotopography and tectonism greatly influenced sedimentation in the area especially during deposition of the Windsor and Mabou groups. The influence of topography decreased with time as erosion and successive deposition of onlapping strata buried the basement relief. The sequence to the top of the Mabou Group displays a generalized pattern of fining upward and basinward. Coarse alluvial facies are developed at all stratigraphic levels up to the top of the Windsor Group.

Paleotopography and tectonism appear to have greatly influenced deposition in the area, especially in the Windsor Group and older units. The importance of paleotopography decreased with time as local erosion and deposition of successive units buried the surrounding landscape. Coarser alluvial fanglomerates are marginal facies of most levels within the Windsor Group only. Sections representing Major Cycles 2 through 5 (Subzones B, C, D and E) display locally profound facies change over distances of less than 3 km, from evaporite-dominated to marginal alluvial fanglomerate-dominated. Carbonate facies show related facies change to calcirudite (limestone conglomerate) in areas of high energy terrestrial influence. Elsewhere, carbonate buildups (bioherm-biostrome) are developed on basement paleotopographic highs (Figs. 12 and 14) (Fig. 12). The change from coarser fanglomerates to sand-silt red beds is especially dramatic in the area between Enon and the Terra Nova Fault (Figs. 4, 5 and 12) (Fig. 11).

Stratigraphic, structural and mineral deposit studies of the Windsor Group are hindered and complicated by several factors, including: (1) solution collapse and brecciation (multigenerations related in part to faults) (and folds, Figs. 7, 12) in the evaporitic sections of the Loch Lomond and Enon formations along the southeast border, (2) coincidence of later (possible) fault re-activation with earlier (inferred) block faulting, (3) typical minimal outcrop, and (4) bias toward the high density of drill data at the basin margin with few deeper (>200 m) drillholes in the basinward areas.

Passage Bridge Section (Fig. 12)

The Windsor Group in the Loch Lomond Basin and Glengarry Half Graben is especially interesting because this is one of the best areas to document geological interaction along an expanding basin margin where the unconformity landscape has significant relief (Figs. 8 and 9) (Figs. 2, 12). The coincidence with extensive mineralization makes it important in understanding and predicting the mineral potential in the area as well as in other basins with potentially similar geology (e.g. West Bay-Dundee area in Richmond County). The level of stratigraphic onlap is of particular interest in view of the relationship of mineralization with carbonate buildup facies in the Windsor Group (e.g. Gays River Formation, Giles et al., 1978 (1979)). The basal carbonate of the Windsor Group has been
a traditional exploration target. The term ‘basal carbonate’ is a general term which typically has been restricted to the A Subzone (Major Cycle 1) Macumber Formation (and equivalents) and during the mid-1970s included the correlative buildup facies, Gays River Formation, which onlaps basement. The Loch Lomond Basin was one of the few areas identified where the B Subzone (Major Cycle 2) overstepped Major Cycle 1 and was deposited directly on basement. The basement onlap of Major Cycle 1 was previously well documented in many basins by Giles et al. (1979) and Boehner et al. (1989a) (1989).

Cross-sections A-A1 (Passage Bridge) and B-B1 (MacRae Pit) (Fig. 12) (Figs. 11, 12) illustrate the general geology and structure of the Windsor Group and the two basic end-member facies in the Loch Lomond Basin. Generally the stratigraphic section consists of the following three lithologic packages: (1) pre-Carboniferous basement, (2) the undivided basal conglomerate, Enon and Loch Lomond formations, and (3) the Uist and MacKeigan Lake formations.

The basal contact with basement rocks is a major angular unconformity or nonconformity with progressive stratigraphic onlap and locally developed carbonate buildups (Figs. 11 and 18). The Loch Lomond-Uist contact is a disconformity and in the marginal subcrop areas there is a disrupted brecciated zone at or near the top of the evaporitic Loch Lomond Formation. Strata in the Loch Lomond and Enon formations have dips of 15 to 20° and tend to steepen basinward (Fig. 12). The dips in the overlying Uist Formation are generally similar, except in the area above the breccia at the basin margin where dips are only 5 to 10°. This coincides with the disrupted evaporite dissolution zone and is interpreted to be due to downward tilting and foundering of the Uist Formation. The collapse was apparently accompanied by small scale faulting and perhaps is related to block faulting associated with the Grand River-Lennox Passage faults. The solution collapse process post-dates (at least in part) celestite mineralization (Fig. 12); however, an upper age limit is not clear. It may be related to the pre-Silver Mine Formation disconformity, or may be much younger (possibly Mesozoic), or may be a complex multi-generation paleokarst process. Boehner (1981, 1983) speculated on a potential relationship between karstification and mineralization with base metals and celestite.

**Loch Lomond Structure**

The Loch Lomond Basin and Glengarry Half Graben (Map 85-2, in pocket) are identified as structural features (Keppie, 1982) and not necessarily as depositional basins. These disrupted structural remnants are contiguous and have a prominent northeast-southwest structural trend. This trend reflects the regional Appalachian structural fabric and is emphasized by the Lennox Passage Fault, the major basin-bounding fault. The extension to the northeast is truncated by the Mira River Fault (the south boundary of the adjacent Sydney Basin) which converges with the Lennox Passage Fault (Fig. 4). (Figs. 1, 5, 11). The Loch Lomond Basin and Glengarry Half Graben are essentially fault-truncated synclines and are typical of the numerous small structural elements that constitute late Paleozoic structural basins in Atlantic Canada. They are bounded to the northwest by the Lennox Passage Fault, a northwesterly-trending, high-angle fault which separates the basins from Hadrynian to Devonian igneous basement of the East Bay Block. In the middle of the map area is the Terra Nova Fault, a northwesterly-trending, high angle, transverse fault which separates the Glengarry Half Graben from the Loch Lomond Basin. The southeastern boundary of the basins is a profound angular unconformity with rocks of the Fourchu Block Hadrynian to Devonian basement (Figs. 5 and 8) (Figs. 1, 2, 11, 12).
Strata within the basin areas form asymmetric synclines in which bedding generally dips gently (10°) toward the basin centre, but with very steep to overturned dips along the Lennox Passage Fault which truncates the basins to the north. Dips on the basement unconformity, as interpolated from drilling data, are in the range of 10 to 15° in the more central parts of the basin and from 20 to 35° along parts of the southern margin. These steeper dips reflect, in part, the greater erosional relief and perhaps are related to early block faulting. The slope on the present day ground surface updip from the unconformity is also typically less than the mean dip on the unconformity, suggesting that post-Carboniferous erosion has probably occurred and that the updip landscape may not necessarily be the unaltered Carboniferous paleotopography as interpreted by Sangster and Vaillancourt (1990a and b).

**Folds**

Rocks in the Loch Lomond Basin and Glengarry Half Graben have been folded into two asymmetric synclines, the Enon and Glengarry synclines (Map 85-2, in pocket). The major fold features are probably related to movement on the major faults and represent the remains of a fault-truncated, synformal basin. Small scale folding is rarely recognizable in outcrop but locally complex and chaotic folding is probably present adjacent to the faults. A significant fold structure was recently encountered during drilling **LL-01-91 by Scotia Prime** (Figs. 7, 11) in the Loch Lomond Basin near Lake Uist (Black and Miller, 1991). At this location, an isoclinal recumbent fold involving the MacKeigan Lake, Uist and Loch Lomond formations was intersected in the area immediately northwest of the Passage Bridge Section (Figs. 11 and 12) and is the first documentation of this type of structure in southeastern Cape Breton Island. Although it was unexpected, it is not totally surprising given the proximity to the highly disrupted geology adjacent to the Lennox Passage and Grand River faults and the L’Ardoise Block. A similar structure was previously described in the northern part of the Shubenacadie Basin (Giles, 1977) confirming the radical change in structural character possible over short distances in these basins (Boehner, 1992).

**Faults**

The major faults in the Loch Lomond Basin and Glengarry Half Graben may be subdivided into several categories using criteria such as their orientation and latest apparent sense of movement, and they include: high-angle longitudinal faults with northeast-southwest orientation (transcurrent wrench), high-angle transverse faults, and high-angle block faults with northwest to north trends. High-angle longitudinal faults (e.g. Lennox Passage, Grand River and nearby Big Pond Fault) are responsible for the pronounced northeast-southwest linearity in the borders of the basins (Fig. 5 and Map 85-2, in pocket) (Fig. 11). These major faults converge with and are genetically related to the east-west Bateston Fault, on the south border of the Sydney Basin, and the Mira River Fault. They are extensions or components of a complex structural system extending from the Strait of Canso-Chedabucto Bay area, situated north of the Cobequid-Chedabucto Fault System.

All the high-angle longitudinal faults have components of dextral strike-slip and dip-slip offset. The details of the movement kinematics are rarely described, except in the adjacent Big Pond area by Bradley and Bradley (1986) who described evidence for dextral offset. Apparent strike-slip movement on the Lennox Passage and related faults is difficult to estimate. However, the anomalous structural relationships with the L’Ardoise Block and related Windsor Group Major Cycle 1 in the Lochside-Hay Cove area indicate movements
in the order of kilometres. Relative dip-slip movement is inferred to be in the range of 1000 m on the basis of the offset evident in adjacent stratigraphic units. The amount of strike-slip movement on the Lennox Passage, Grand River and Bateston system may be in the order of tens of kilometres or more. Although the faults are interpreted as nearly vertical normal faults, some or all may entirely have a high-angle reverse geometry. Drill intersections and outcrops of near vertical to overturned strata along the northwest border contact, together with the isoclinal recumbent fold in a recent exploration drillhole near Lake Uist, offer support for the reverse fault or local overthrust configuration. This may be related to emplacement of the L’Ardoise Block and/or the faulted contact to the north with the East Bay Hills. Northeasterly-trending longitudinal faults are also inferred to be present in the East Bay Hills area south of the Big Pond Fault extension (Bradley and Bradley, 1986). These appear to be a genetically related set and are probably subsidiary to the Lennox Passage Fault.

**NOTE:** This document has received no formal scientific review and minimal editing. Major cited references are provided, and additional references are provided for further information. The references and content should not be considered comprehensive, complete or current.

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