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LITHOSTRATIGRAPHIC SETTING OF DIAGENETIC, ISOTOPIC, AND GEOCHEMISTRY STUDIES OF IBEXIAN AND WHITEROCKIAN CARBONATE ROCKS OF THE ST. GEORGE AND TABLE HEAD GROUPS, WESTERN NEWFOUNDLAND

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ABSTRACT

Diagenetic, isotopic and geochemical studies of Ibexian and Whiterockian carbonate rocks of the St. George and Table Head groups in western Newfoundland, are ongoing. This article summarizes the lithostratigraphy that plays host to the succession of shallow-shelf carbonates examined in shoreline sections near Port au Choix, and drill cores from Port au Choix and the Port au Port peninsulas.

Ibexian to Whiterockian carbonate rocks of the upper St. George Group form a disconformity-bounded, third-order onlap-offlap sequence; this being the last sequence to be deposited on the passive margin of Laurentia (in Newfoundland). Rocks of the Table Head Group preserve Whiterockian carbonate shelf deposits of the succeeding Anticosti foreland basin. The transition between the sequences is marked by the St. George Unconformity, an erosional karst unconformity fashioned by the dynamic interplay of Taconic orogenesis and eustatic sea-level fluctuation upon the local paleo-geography.

The dolomitization of significant parts of the sequence is described within the context of the regional lithostratigraphy, and some geochemical, petrographic and isotopic results are summarized and presented here.

INTRODUCTION

The lower Paleozoic shelf rocks in western Newfoundland underlie a long, sinuous terrain that extends over 400 km from Cape Norman in the north to the Port au Port Peninsula in the southwest (Figure 1). These shallow-water, autochthonous and parautochthonous, siliciclastic and carbonate rocks fringed part of the paleo-southern margin of Laurentia from the late Early Cambrian through to the early Middle Ordovician. The shelf was deposited close to the apex of the St. Lawrence Promontory and along the Newfoundland Embayment (Hibbard *et al.*, 2006). A long-lived passive margin (~50 My), host to the Labrador, Port au Port and St. George group rocks, was succeeded by a rapidly evolved foreland basin (4-7 My) in which shelf carbonates of the Table Head Group were deposited before the shelf foundered and was smothered by the influx of siliciclastic flysch of the Goose Tickle Group. A regional erosional unconformity, the St. George Unconformity, is the most prominent and well known feature of the transition from the passive margin to the foreland basin (Knight *et al.*, 1991). The transition was, however, marked by regional tectonic instability that overlapped with falling sea level, as the last sediments of the St. George Group were deposited and with later local sea-level rise that accommodated the deposition of the younger Table Head Group (Knight *et al.*, *op cit.*; Stenzel *et al.*, 1990). The interplay of tectonism and sea-level change reflects the passage of a Taconian peripheral bulge across the margin at a time of eustatic sea-level fall (Knight *et al.*, *op. cit.*).

The St. George Group is a complex succession of limestone and dolostone, divided into two, long-lived third-order sequences of Tremadocian and Ibexian (Arenigian) age; Knight and James (1987) referred to the sequences as megacycles. Each megacycle is characterized by three-part architecture of generally thin, lower peritidal, thick middle subtidal and thick upper peritidal units (Knight and James, 1987). The younger Arenigian sequence is bounded by the Boat Harbour disconformity at the base and by the St. George Unconformity at the top (Figure 2). It comprises the Barbace Cove Member, Boat Harbour Formation (lower peritidal),

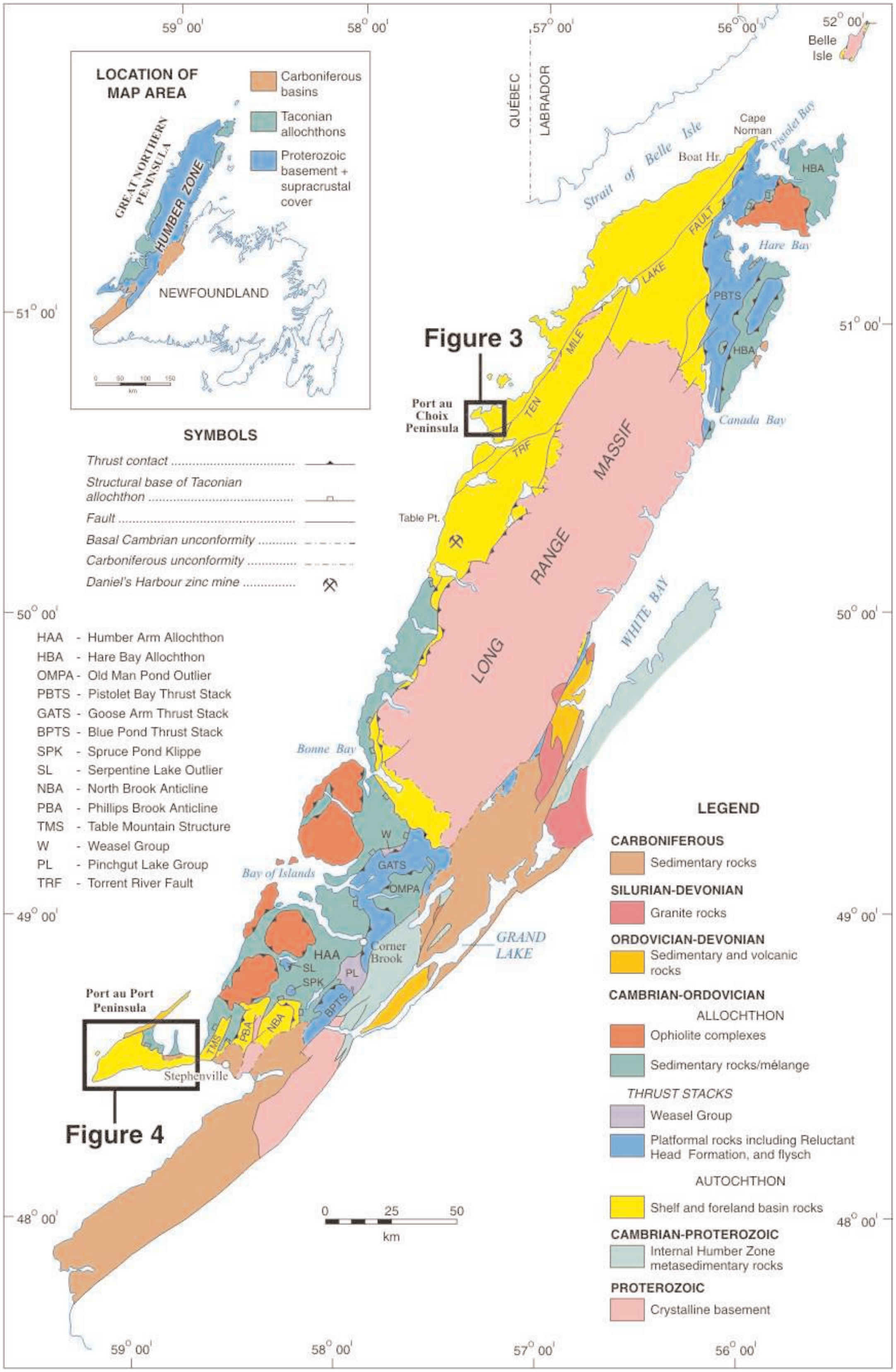

Figure 1. *Regional geological map of western Newfoundland showing major terranes, distribution of lower Paleozoic shelf rocks and location of study areas.*

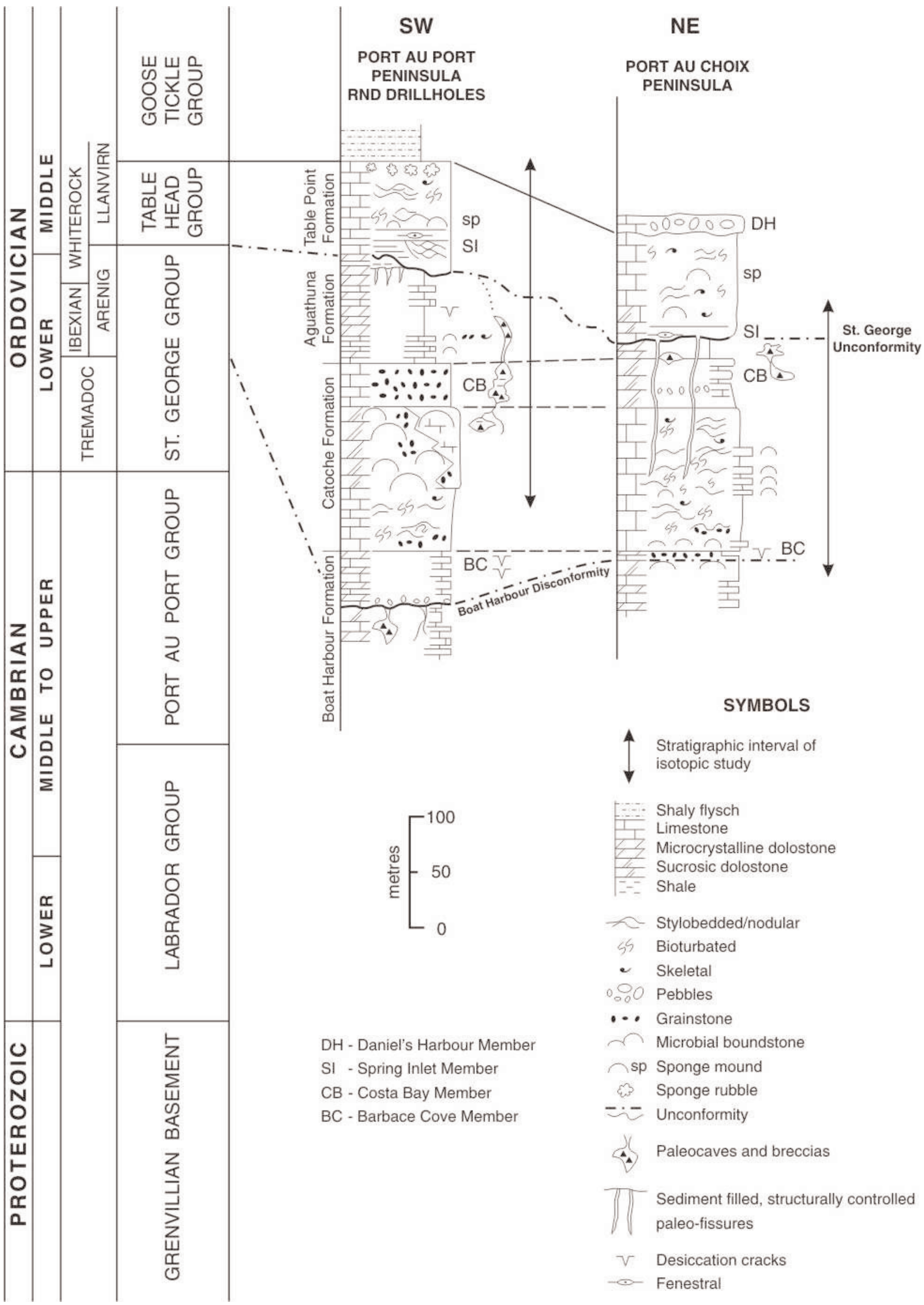

Figure 2. *Comparative lithostratigraphy of the two study areas of Port au Choix Peninsula and Port au Port Peninsula.*

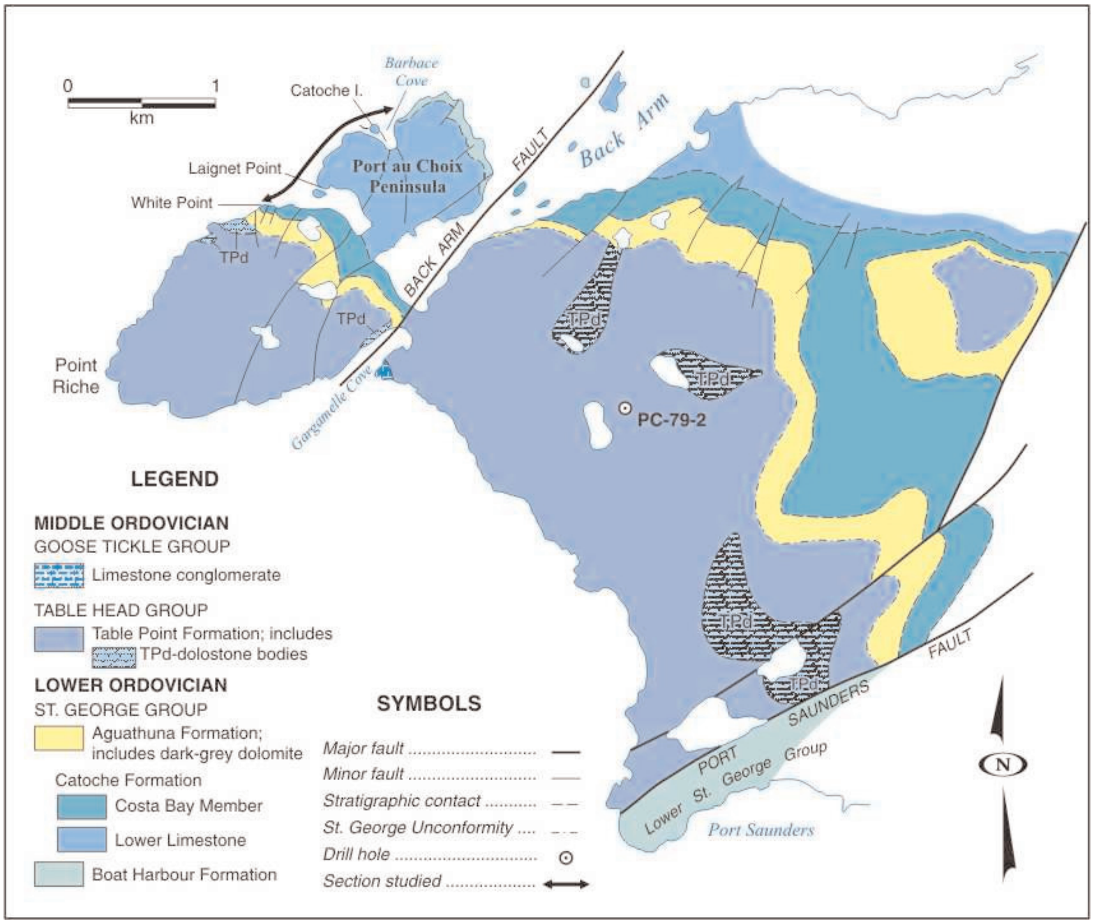

Figure 3. *Geological map of the Port au Choix area (based on mapping of Knight, 1991; I. Knight unpublished data, 1996) showing location of coastal section and drillhole PC79-02 used in study.*

the Catoche Formation (middle subtidal) and the Aguathuna Formation (upper peritidal). Regional erosion below the St. George Unconformity can locally remove up to 60 m or more of the Aguathuna Formation.

The Table Head Group buries the St. George Unconformity and is essentially a deepening-upward succession of peritidal to subtidal shelf limestone of the Table Point Formation to slope ribbon limestone and shale of the Table Cove Formation (Stenzel *et al.*, 1990; Knight, 1991). Large thickness variation characterizes the formation, in part, reflecting paleo-topography on the St. George Unconformity and active tectonism that affected the basin at this time (Knight *et al.*, 1991). The Table Head Group is disconformably to locally conformably overlain by basinal shale and flysch of the Goose Tickle Group (Figure 2).

Petrographic, geochemical, diagenetic, fluid inclusion and isotopic studies are ongoing on the rocks of the Arenigian megacycle and the overlying Table Point Formation. The sequence was studied and sampled, in detail, in two areas over two field seasons, the first in 2005 in the Port au Choix area, and the second in 2006 from drill core drilled at the west end of Port au Port Peninsula. The study at Port au Choix investigates the shoreline section along the shore of the Port au Choix Peninsula from Barbace Cove to Laignet Point (*see* Knight, 1991) and also includes study of a BX diameter mineral-exploration drill core (Dickie and Lyn, 1979) located in the limestone barrens southeast of Port au Choix (PC-79-2, Figure 3). Two, large-diameter, mineral-exploration drillholes located just east of Round Head near Lourdes (Westminer, 1992) provide the sections logged and collected from the Port au Port Peninsula (Figure 4).

The two areas were selected to provide access to the most complete succession of the Arenigian sequence and the overlying, post-unconformity Table Head Group (Figures 5 and 6). As such, they provide access to overlapping parts of the Arenigian sequence that are host to discordant and stratabound bodies of early and late dolostone, and some examples of high-temperature dolomite (HTD) complexes. Late dolostone bodies, that replace lower parts of the Table Head Group, are also present at Port au Choix as are joint- and fault-controlled dolostone-filled fissures that cut the

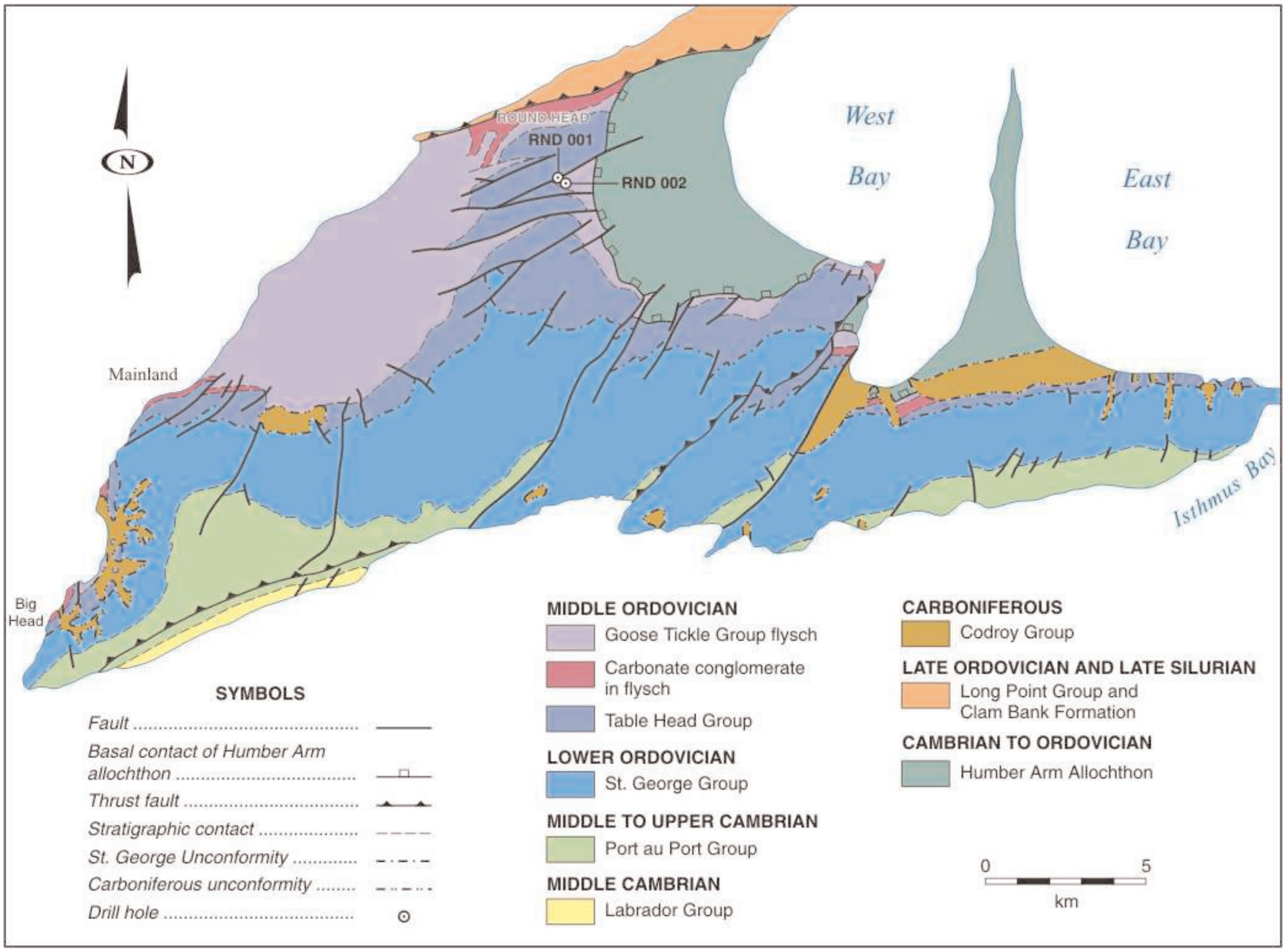

Figure 4. *Geological map of the Port au Port Peninsula showing location of two drillholes, RND 001 and RND 002, used in study (based on unpublished mapping of Knight, 1996).*

middle part of the Arenigian sequence. These fractures are infilled by fine dolostone believed to have been washed into the fractures from the St. George Unconformity (Knight, 1991; Knight *et al.*, 1991).

The study seeks not just to establish a petrogenetic history of the succession, but also to generate an isotopic curve for the pre- and post-unconformity sequences that can be linked to the local lithostratigraphy, and can also be compared to isotopic curves established in coeval successions globally. In addition, the area around Port au Choix is interpreted to be an exhumed oil field of large size (Baker and Knight, 1993; Cooper *et al.*, 2001, Figure 21) and the succession on Port au Port Peninsula straddles the stratigraphic interval known to host hydrocarbon reservoirs (the Garden Hill discovery well of Hunt and PanCanadian (Newfoundland Hunt Oil Company Inc., 1996)). The Garden Hill discovery lies in the footwall to the high-angle Round Head Fault (Cooper *et al.*, 2001), an Acadian thrust that carries the rocks of the western end of the peninsula, including the rocks cut by the Round Head drillholes, as its hanging wall (Stockmal and Waldron, 1993). Thus, the present study is also designed to better appreciate the relationship of the reservoir potential of the succession to the generation of stratigraphic and diagenetic dolomite and other diagenetic features.

LITHOSTRATIGRAPHY

UPPER ST. GEORGE GROUP

The succession studied in the upper St. George Group begins at the Boat Harbour disconformity and continues to the St. George Unconformity. The description that follows is a synthesis of the sequences incorporating details of the two sections studied (Figures 5 and 6) together with published and unpublished work, where appropriate.

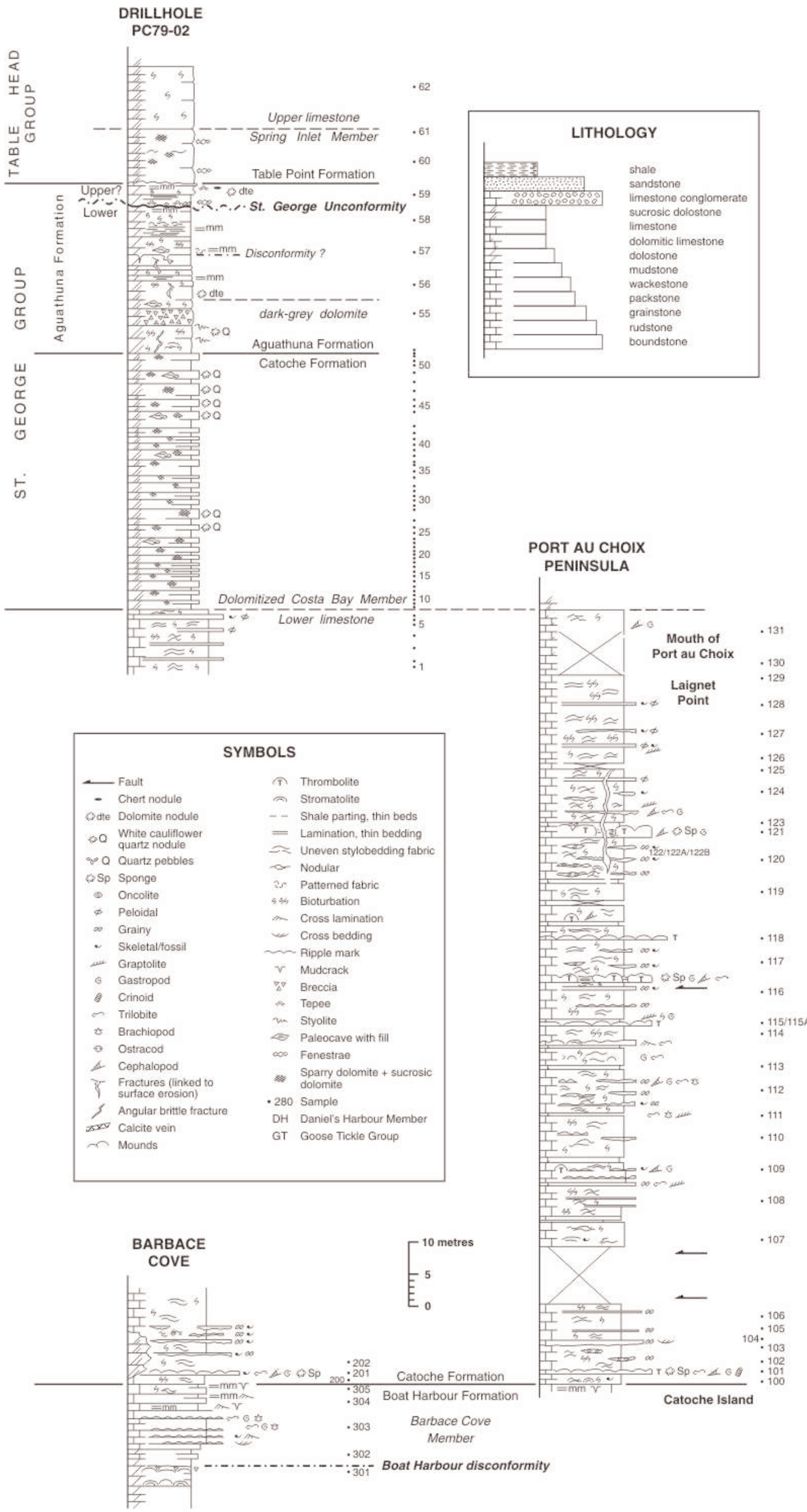

Figure 5. *Detailed stratigraphic log of the upper St. George Group at Port au Choix based on the coastal section and drill-hole PC79-02.*

Boat Harbour Disconformity

The Boat Harbour disconformity is a cryptic to readily recognized, regionally developed surface that was first noted at Boat Harbour on the Northern Peninsula (Knight, 1977; Boyce, 1989) where it is a subtle, truncating surface that can be traced for more than 250 m along strike. The surface has locally developed, small-scale karren and pinnacles and is draped by a veneer of intraformational quartz and chert pebbles and sand and by a thin grey shale layer (Plate 1) The disconformity was called the Boat Harbour "pebble bed" by Boyce (1989) and earlier Pratt (1979) identified some of the quartz as evaporitic in origin. Below the surface, a burrowed limestone is dolomitized for a few tens of centimetres and locally hosts spherical bodies of crystalline dolostone. Vugs occluded by geopetal dolostone and dolomite spar are also present. Only 10 km to the south, the disconformity is overlain by an intraformational quartz- and dolostone-pebble conglomerate that is 2 m thick (Knight, 1987).

At Port au Choix, the disconformity occurs just north of Barbace Cove where it truncates stromatolitic dolostone of the middle part of the Boat Harbour Formation and is veneered, locally, by pockets of breccia (Plate 2; Knight, 1991); silicification is common immediately below the surface. Dolomite spar neomorphically replaces the very fine crystalline, glassy dolostone matrix of the breccia and intercrystalline and vuggy porosity, the latter partially occluded by geopetal dolostone and by sparry dolomite, occur in the dolomitized stromatolite.

On Port au Port Peninsula, the disconformity occurs in the well-exposed section on the west shore of Isthmus Bay, about 50 m below the top of the Boat Harbour Formation (I. Knight, unpublished data, 1986; Knight and Cawood, 1991). There, it is marked by an erosional surface, which is overlain by a bed of dolomite- and quartz-pebble conglomerate above dolomitized and fractured carbonates of the middle part of the Boat Harbour Formation (Plate 3). Silicification, including red chert masses, is also common below the disconformity. Karst is developed at the top of at least three of the metre-scale peritidal parasequences immediately below the disconformity. Features such as sub-karst paleocaves, extensive fracturing with accompanying geopetal sediment and shallow collapse structures infilled by subtidal limestones of the succeeding parasequence are associated with the karsted tops.

The disconformity marks a significant change in both macro- and micro-faunas between the overlying Arenigian sequence from that of the underlying Tremadocian sequence of the middle Boat Harbour Formation (Stouge and Boyce, 1983; Boyce, 1989; Ji and Barnes, 1994; Boyce and Stouge, 1997).

Boat Harbour Formation

Barbace Cove Member

Northern Peninsula

The Barbace Cove Member is regionally developed throughout western Newfoundland; it was first recognized at Boat Harbour and Port au Choix where it is characterized by metre-scale, shallowing-upward, tidal-flat parasequences of which there are 9 and 6 in number, respectively (Knight, 1991, unpublished data, 1988; Boyce, 1989). In the Boat Harbour area, a marker bed of thrombolitic boundstone and grainstone occurs just above the Boat Harbour disconformity, whereas in the Port au Choix area (Figure 5) the disconformity is overlain by flaser-bedded, lime mudstones. Above the basal units, parasequences begin with sharp, locally scoured bases overlain by burrowed and stylonodular, sparsely fossiliferous lime mudstone to wackestone (Plate 4), intercalated with sheet-like beds of centimetre-thick, intraclastic and skeletal grainstone, pebbly grainstone and rudstone, many of which have tops with exquisitely preserved ripple marks (Plate 5). Gutter casts and small bulbous and domal stromatolites, locally decapitated by scours, are common in the facies association. Parasequences are capped by flaser-bedded to flat-laminated dolomitic limestone and some dololaminite beds. Fissure cracks and mud cracks are common in the laminated facies that can reach up to 1.75 m thick in some sequences (Plate 6). The top of the member is mapped regionally as the top of the last laminated unit and detailed mapping in the Port au Choix area suggests this contact is slightly diachronous.

Boyce (1989) has described a mixed skeletal fauna of trilobites, brachiopods, crinoids, gastropods and cephalopods of early Arenigian age. Conodonts recovered from the member belong to Midcontinent Fauna D (Stouge and Boyce, 1983; Boyce and Stouge, 1997).

The member is only 10 to 15 m thick in the sections from the Daniel's Harbour to Port au Choix to Boat Harbour but doubles in thickness as it is traced eastward through the Pistolet Bay thrust stack (Figure 1). Boundstone mounds associated with peloidal and oolitic grainstone form a significant part of the member in this thrust stack.

Port au Port Peninsula

The Barbace Cove Member in the coastal section of Isthmus Bay is approximately 52 m thick and consists of 26 shallowing-upward parasequences (I. Knight, unpublished data, 1987) above a basal conglomerate (Plate 3; *see* Boat Harbour disconformity discussion above). Each sequence sports a basal scour, above which microbial mounds, both

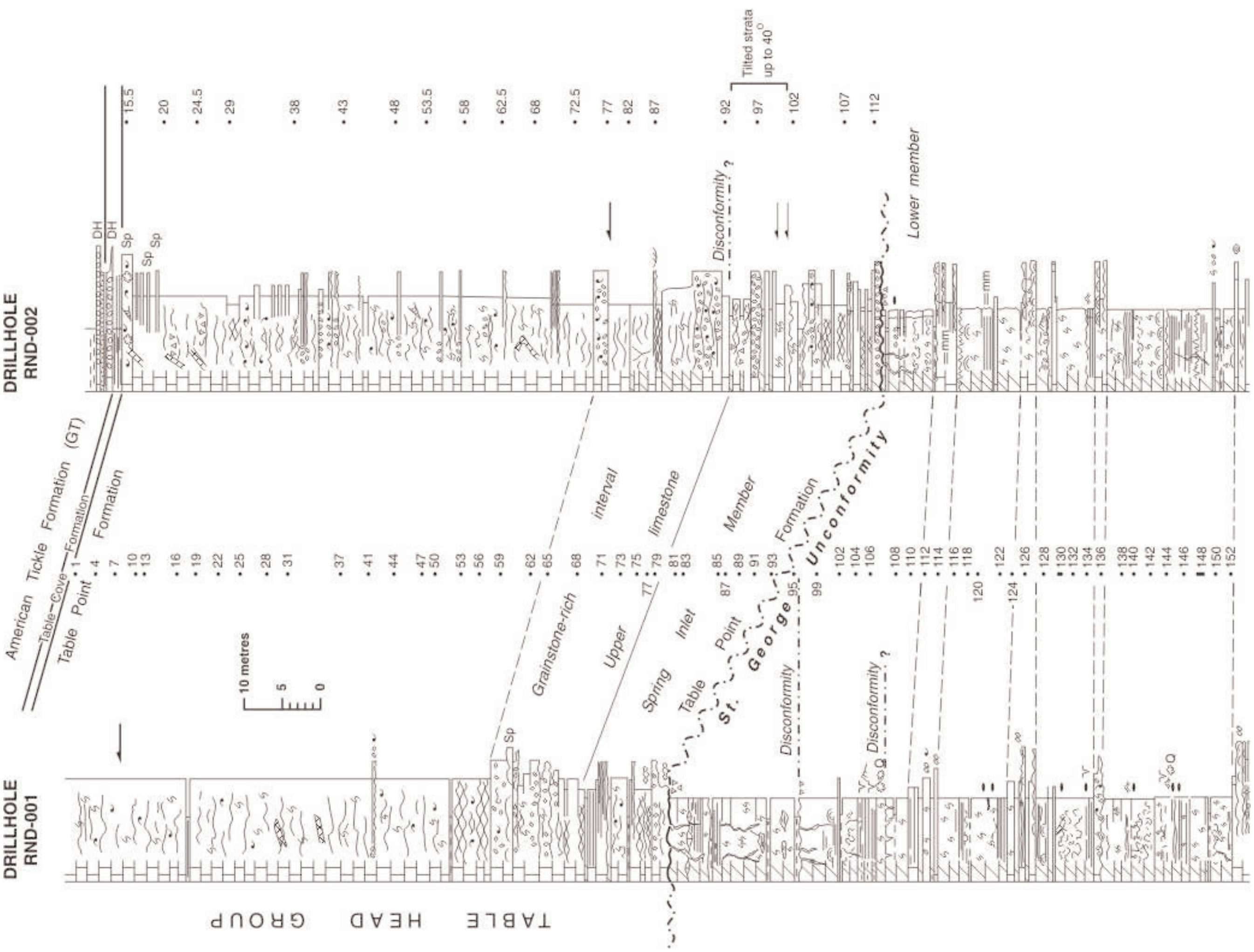

Figure 6. Caption below.

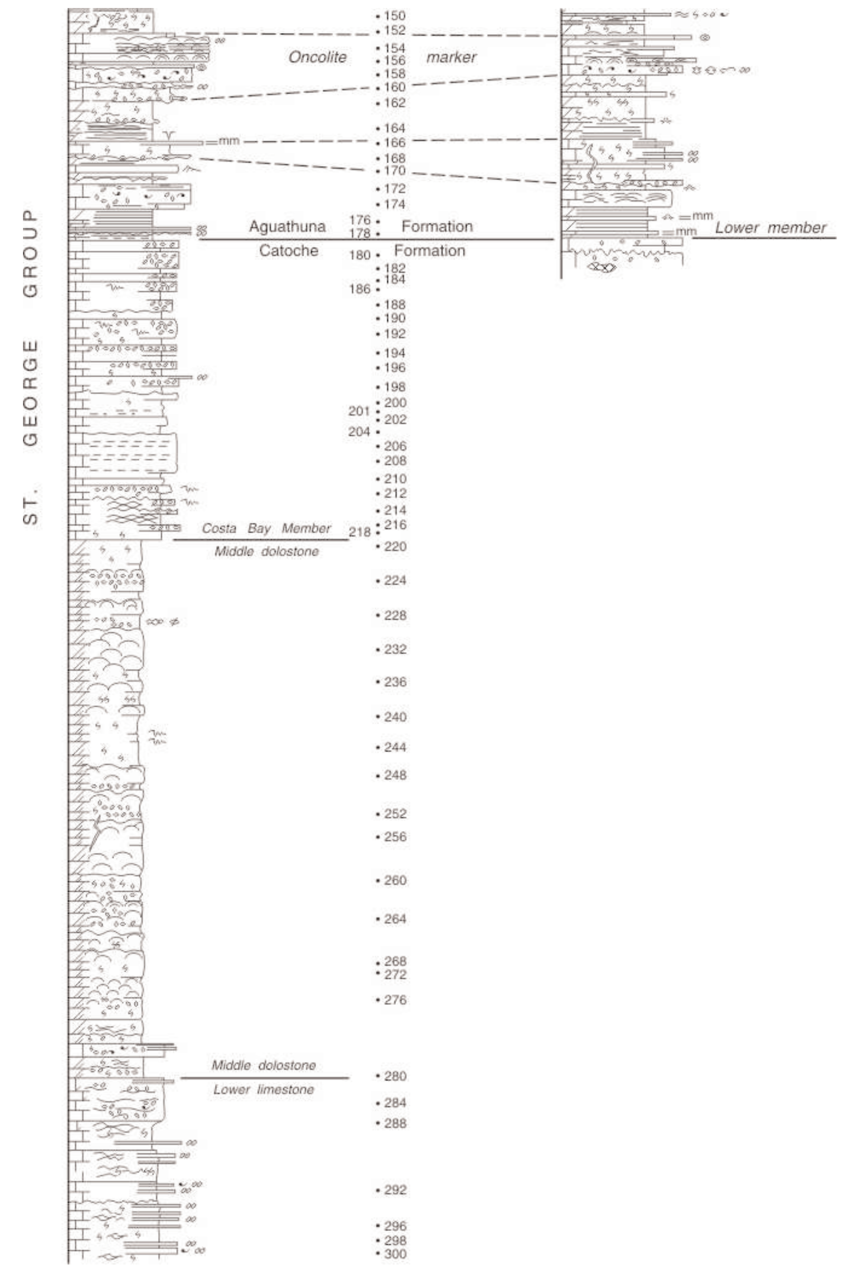

Figure 6. *Detailed stratigraphic logs of the two drill cores RND 001 and RND 002 from near Round Head, Port au Port Peninsula. Logs are correlated using the contact of the Catoche Formation with the Aguathuna Formation.*

Plate 1. *Boat Harbour disconformity, base of Barbace Cove Member, Boat Harbour Formation, 4 km southwest of Cape Norman. The irregular surface caps a dolostone in which are found scattered white quartz and chert pebbles. The surface is draped by a thin shale. Lens cap is 5.5 cm.*

Plate 2. *The Boat Harbour disconformity at Barbace Cove, Port au Choix is marked by a rubble layer of dolostone breccia (lens cap). It rests upon the irregularly truncated top of a dolomitized stromatolitic boundstone bed that marks the top of the middle part of the Boat Harbour Formation. Lens cap is 5.5 cm.*

thrombolitic and stromatolitic, are associated with plentiful grainstone and rudstone. Most of these grainy beds are intraclastic and skeletal rich but there are also beds of oolitic and peloidal grainstone; oncolites are present in some beds. A single erosion surface of deeply incised depressions and pedestal-like highs truncates a bed of mounds and grainstone in the lower part of the member. Its architecture compares favourably with that of a coastal karst.

Burrowed, fossiliferous, dolomitic lime wackestone may dominate the lower parts of some parasequences where mounds and grainstones are weakly developed, but in many sequences, the burrowed facies is thinly developed above, or intermixed with, the mound-grainstone association. The wackestone facies is thickest in the three topmost parasequences where it is intercalated with grainstone/rudstone sheets and lenses. Intraclastic, centimetre-size, discoidal pebbles of pinkish lime mudstone occur in the rudstones. Laminated, dolomitic limestone and/or dololaminite, generally ranging from 10 to 60 cm thick, cap the parasequences. Planar to crenular lamination, mudcracks, laminar fenestrae and spar-lined vugs are characteristic of most of these laminite caps. Beds (20 to 50 cm thick) of green-grey shale overlie the laminite in three parasequences midway through the

Plate 3. *Boat Harbour disconformity (arrow and dashed line), base of Barbace Cove Member, Boat Harbour Formation, shoreline of Isthmus Bay, eastern Port au Port Peninsula. A basal dolomitic conglomerate of chert, quartz and dolostone pebbles rests upon broken dolostone. Knife is 9 cm.*

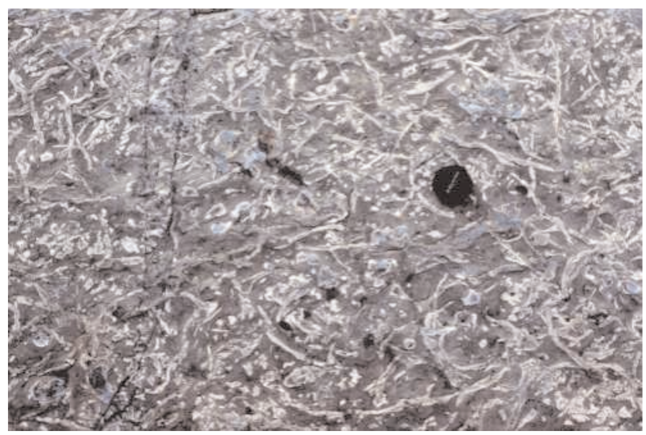

Plate 4. *Dolomite burrows in a bioturbated dolomitic lime mudstone/wackestone, Barbace Cove Member, Boat Harbour Formation, Barbace Cove, Port au Choix. The burrowed limestone mark the lower part of shallowing-upward metre-scale sequences that are intercalated upward with beds of intraclastic-skeletal grainstone (*see *Plate 5). Lens cap is 5.5 cm.*

Plate 5. *An impressive bedding plane of long sinuous ripple marks developed on the top of a bed of intraclastic-skeletal grainstone/rudstone in the Barbace Cove Member, Boat Harbour Formation, north of Port au Choix. Arrow points to metre stick.*

Plate 6. *Desiccation cracks on top of a laminated dolomitic limestone at the top of the Barbace Cove Member, Boat Harbour Formation, Barbace Cove, Port au Choix. Brunton compass is 7 cm diameter.*

unit. The thickest laminites occur in the top two sequences of the member, where they attain a thickness of 2.2 m. Like their stratigraphic counterparts throughout western Newfoundland, the uppermost laminites of the Port au Port Peninsula are extremely well laminated with limestone, dolostone and argillaceous planar laminae, cut by mudcracks and some deeply penetrating, tapering, fissure cracks.

Shelly fossils are rare from the section at Isthmus Bay, but the member has yielded conodonts of Midcontinent Fauna D (Ji, 1989; Ji and Barnes, 1994).

Catoche Formation

The Catoche Formation forms the middle subtidal interval of the Arenigian sequence, lying conformably upon the Barbace Cove Member (Figure 5). The formation is well exposed along the west shore of Port au Choix Peninsula and along the shoreline, north of the town, where it has a measurable thickness of about 160 m (Knight, 1991). Here, it consists of two unnamed informal units, a Lower limestone that is 120 m thick, and an Upper dolostone that is 40 m thick (Figure 5). Kluyver (1975) informally named the dolostone as the Port au Choix formation, but this name was not adopted in later studies by Knight and James (1987), Knight (1991) and Baker and Knight (1993) because it is a body of replacement dolostone for part of the formation that can be correlated with the Costa Bay Member. The latter is an interval of distinctive, white limestone that is widely mapped and described on the Port au Port Peninsula and adjacent areas, as well as in the three, thrust stacks that deform the shelf rocks.

On the Port au Port Peninsula, the Catoche Formation consists of the Lower limestone of uncertain thickness (possibly up to 80 m thick), a Middle dolostone, 40 to 53 m thick, and the Costa Bay Member, 38 m thick, at the top. The Middle dolostone was called the Pine Tree unit by DeGrace (1974). It replaced a thick interval of Catoche Formation, comprising large thrombolitic boundstone mounds and associated grainstone, which is time equivalent to part of the Lower limestone in the Port au Choix area. The Costa Bay Member was called the White Hills unit by DeGrace (1974).

Both macrofauna and microfauna indicate that the Catoche Formation is exclusively Ibexian (Upper Canadian; Fortey, 1979; Stouge, 1982; Stouge and Boyce, 1983, 1989; Williams *et al.*, 1987; Ji, 1989; Ji and Barnes, 1994; Boyce and Stouge, 1997).

Lower limestone

The Lower limestone is a succession of well-bedded, dark-grey, bioturbated, dolomitic limestone that weathers, as a series of low cliffs and step-like benches, as the sequence is traced upward along shoreline sections (Plate 7), and also across inland limestone barrens on the Port au Port Peninsula. Only the top few metres were logged in the core at Round Head, so that the following description is based largely on the succession at Port au Choix augmented by other pertinent data.

Rubbly weathering, skeletal, peloidal wackestone and packstone, which display a stylonodular to uneven fabric outlined by slightly argillaceous dolomitic partings, is the dominant facies at both Port au Choix (Plate 7) and in the Round Head drill core of the Port au Port Peninsula (Plate 8). Gastropods, large straight and coiled cephalopods, brachiopods, crinoids, and trilobites dominate the macrofossil fauna (Fortey, 1983; Boyce, 1989); simple tubular burrows are almost ubiquitous. Lenses and beds of intraclastic skele-

Plate 7. *Typical bedded limestones of the Lower limestone, Catoche Formation, Port au Choix Peninsula. Metre stick lies on an isolated thrombolite mound in the foreground.*

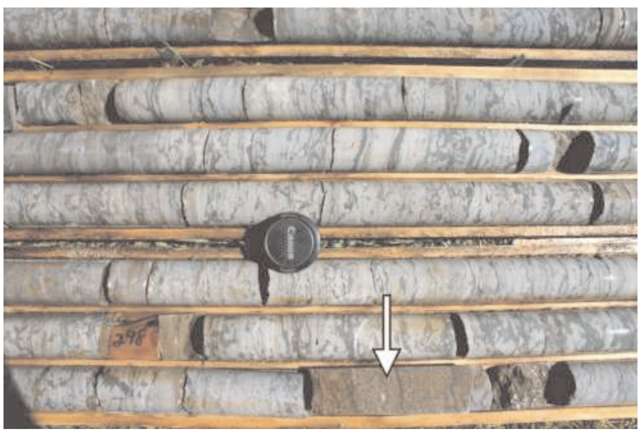

Plate 8. *Bioturbated dolomitic limestone from the Lower limestone, Catoche Formation, DDH RND 001, Port au Port Peninsula. The slabbed core in the lowest run (arrow) is an intraclastic, skeletal grainstone bed. Lens cap is 6 cm diameter.*

tal, grainstone, pebbly grainstone and rudstone are frequently interspersed with the dominant muddier facies. Starved ripple marks, and large, sinuous to straight, ripple marks, some of which are planed, are common features of the grainy facies (Plate 9). Rounded discoidal, centimetre-size pebbles of pink to red lime mudstone are common in the rudstones in the first 20 m of the sections in both study areas. At Port au Choix, one such bed (Plate 10) is 65 cm thick, planar crossbedded, with shingled rudstone foreset intervals of imbricated pebbles interleaved with spaced wackestone foreset drapes, indicating a staggered history of lateral accretion. Recessively weathering beds of sparsely bioturbated, nodular to flaser-bedded to massive lime mudstone associated with a low-diversity fauna of large trilobites and rarely graptolites are periodically intercalated in the bedded limestone. Some of these beds are extensively dolomitized.

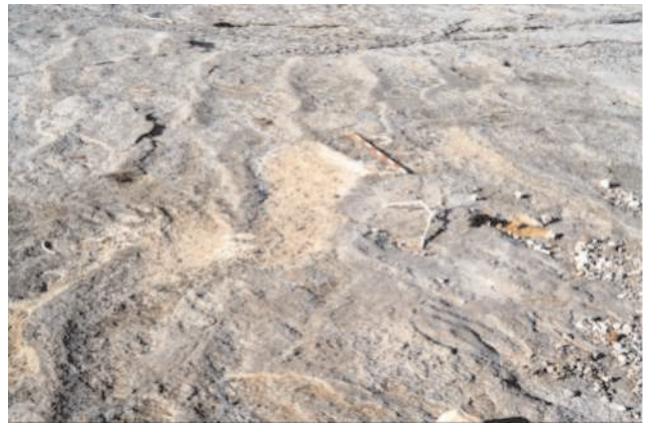

Plate 9. *Long sinuous, widely spaced, ripple marks composed of intraclastic-skeletal grainstone and rudstone. Lower limestone, Catoche Formation, Bustard Cove, north of Port au Choix. Metre stick for scale.*

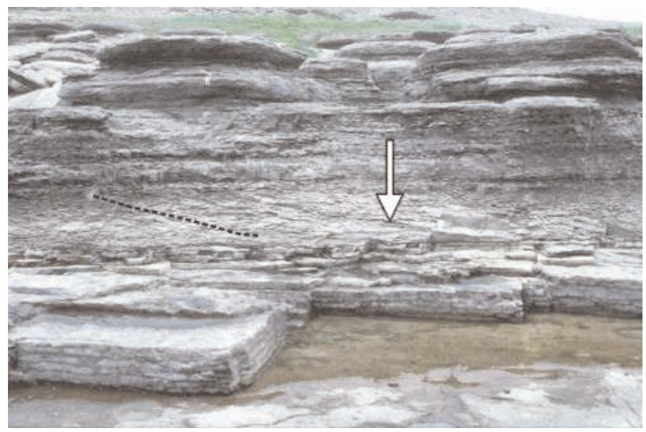

Plate 10. *A cross-stratified rudstone, 65 cm thick, bounded by planar surfaces and flat-lying burrowed dolomitic lime wackestones. The crossbeds, which consist of foreset layers (dashed line) of imbricated discoidal lime mudstone shingle pebbles interrupted by wackestone drapes (arrow), migrates to west. The base of the Lower limestone, Catoche Formation, Port au Choix.*

Several beds of large mounds of microbial, thrombolitic boundstone are present in the Lower limestone, especially in the Port au Choix area where one mound bed forms a marker just above the basal contact of the formation. Most of the mound beds, however, cluster in the upper half of the member in the coastal section where they range from large mound complexes (Plate 11) to isolated, elongated biostroms spaced at regular intervals upon bedding planes. Sponges, receptaculitids, trilobites, and large molluscs are common in the mounds. Grainstone commonly fringes the mounds and infills the intermound channels. The grainstone fringe of the elongated mounds passes outward, into bioturbated wackestone.

Plate 11. *A thick, hummocky-weathering, thrombolitic boundstone mound bed in upper part of the Lower limestone of the Catoche Formation. Port au Choix Peninsula. Dolostone replaces intermound sediment (paler rock near hammer). Hammer is 29 cm long.*

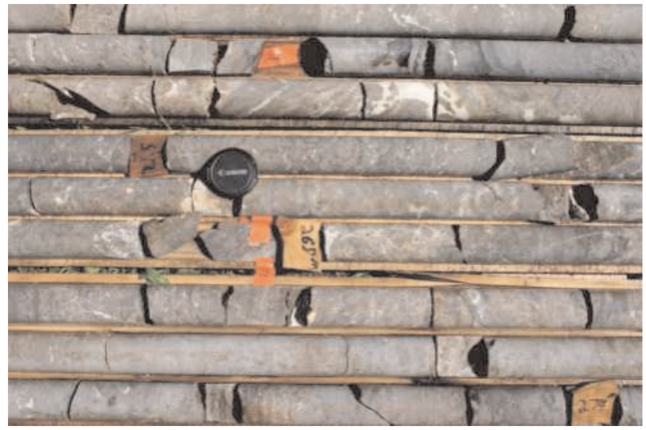

Plate 12. *Mottled sucrosic dolostones of the Middle dolostone, Catoche Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

Middle dolostone or Pine Tree unit (of Port au Port Peninsula)

This 50-m-thick, tan-grey-weathering, mottled, dark-grey, sucrosic dolostone (Plate 12) is a unit mapped from the east end of Port au Port Peninsula to a few kilometres south-west of the Round Head drillholes, a strike distance of at least 30 km. At its western edge, the dolomite rapidly feathers out into a succession of grey, subtidal limestone with a few beds of undolomitized microbial mounds. In outcrop, the dolostone preserves large domal mounds associated with intermound dolarenite, as well as some burrow-mottled dolostone. Porosity in this unit is variable but includes intercrystalline, vuggy, cavernous and breccia porosity (Baker and Knight, 1993); the best porosity in the dolostone is associated with the dolarenite. A thick interval of dolomitized boundstone mounds (Plate 13) also occurs in the middle of the Catoche Formation in the Cape Norman area, Northern Peninsula (Knight and Cawood, 1991; Baker and Knight, 1993).

Logging of the Round Head core (Figure 6) confirms the impression gathered from outcrop exposures that the mound-grainstone facies formed largely as a vertically stacked and amalgamated mound complex rather than being discrete mound beds separated by other rock types. This is comparable to thick stratigraphic intervals of stacked, metazoan-thrombolitic limestone mounds mapped extensively in the middle part of the Catoche Formation along the eastern side of the Northern Peninsula from the Pistolet Bay thrust stack to the Goose Arm thrust stack (Knight, 1986, 1987). Large trumpet-shaped sponges, *Archaeoscypha*, and sheet-like primitive stromatoporoids, are present in these mounds. The Middle dolostone thus may be part of a belt of mounds

Plate 13. *Dolomitized thrombolitic mounds in the middle part of the Catoche Formation at Cape Norman on the Northern Peninsula. The sucrosic dolostone is about 20 m thick in this area. Similar dolomitized mounds outcrop on the Port au Port Peninsula. Hammer is 32 cm long.*

that probably formed a substantial barrier complex on the shelf, along the Newfoundland margin throughout the middle to later stages of the third-order Arenig sequence. The northernmost part of the barrier complex outcrops at the very tip of the Northern Peninsula near Cape Norman, where it is also dolomitized (Plate 13).

Costa Bay Member

The Costa Bay Member is a succession of well-bedded, off-white, clean, grainy limestone that is readily mapped along strike for more than 30 km, westward from the east end of Port au Port Peninsula. The member is quarried for high-purity limestone at Lower Cove. However, at the west end of the peninsula, the member, where properly defined, appears to feather out into a cyclic, fossil-rich succession of limestone of deeper water aspect overlain by a thick porous dolostone that replaced crossbedded grainstone (Boyce *et al.*, 2000). The transition appears to roughly coincide with the zone of the rapid feathering of the underlying Pine Tree dolomite into limestone.

The member has been mapped elsewhere in western Newfoundland, particularly in the three thrust stacks (Knight, 1986, 1987, 1994, 1997), but it is less easy to identify in two large anticlinal structures just east of Port au Port Peninsula. There, in parts of the Phillips Brook and North Brook anticlines (Figure 1), the white limestones are either absent or intercalated with thick dolostones typical of the Aguathuna Formation and are more properly mapped as the latter. This suggests that the member may be better placed in the Aguathuna Formation. On the western side of the Northern Peninsula, from Daniel's Harbour to Port au Choix, the member is pervasively dolomitized with vestiges of limestone, preserved locally (Figure 5). This dolostone unit was host to the Daniel's Harbour zinc mine where it is rich in HDT sparry hydrothermal dolomite complexes. It was also host to the exhumed oil field at Port au Choix (Baker and Knight, 1993; Cooper *et al.*, 2001).

Port au Port Peninsula

On the Port au Port Peninsula, the Costa Bay Member consists of white to cream, and uncommonly pink and green, stylolitic limestones that range from crossbedded, peloidal grainstone, to burrowed packstone, to peloidal and fenestral limestone laminite, to nodular to burrow-mottled lime mudstone and wackestone (Figure 6; Plates 14 and 15). In the Round Head drillholes, the member comprises at least 16 coarsening- and shallowing-upward parasequences of burrowed wackestone to grainstone. Dolostone locally caps a few cycles. Glossy, bright chrome green shale partings are common in some beds especially along stylolites. The shale also infiltrates vugs and rubble zones where limestones appear to be partly dissolved. These latter features are believed to relate to later sub-unconformity karst.

Upper Dolostone (Port au Choix)

The Upper dolostone at Port au Choix is a 40-m-thick unit that is correlated with the Costa Bay Member. The dolostone was studied extensively by Baker and Knight (1993) in both coastal sections and several drill cores to examine its cyclicity, dolostones and porosity. In the present study, only one drill core (PC-79-2, Newfoundland Core Library inventory reference number 12I/11 09) was sampled.

The dolostone comprises 26 metre-scale cycles of dark-grey, massive, finely crystalline, tight dolostone overlain by light-grey-weathering, sucrosic, grey dolostone rich in porosity (Figure 5; Plates 16 and 17). Burrow mottling is

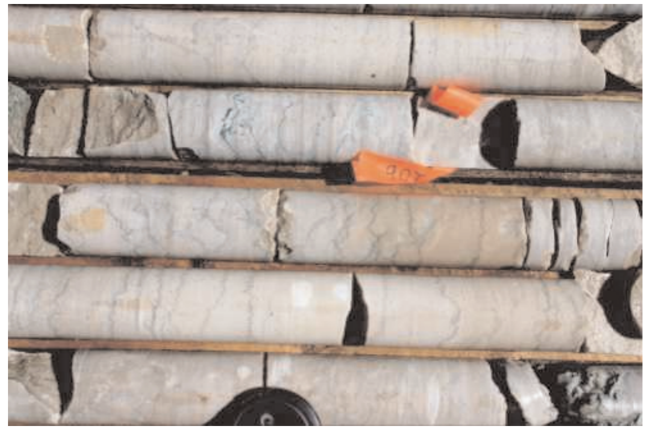

Plate 14. *Off-white, stylolitic clean limestone of the Costa Bay Member, Catoche Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

Plate 15. *Peloidal, fenestral laminated limestone (upper run) of the Costa Bay Member, lying next to slabbed core of white, stylolitic, fine-grained peloidal grainstone. Note the spar-cemented stromatactoid cavities (arrow) in the laminite. Catoche Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

variably developed in the sucrosic dolostone including markers of intense burrow development at the top of some cycles; ghosts of gastropods also occur. White sparry dolomite partially lines the intercrystalline to vuggy porosity. Upper contacts of the cycles are generally sharp but there is commonly a rapid transition between the lower and upper rock types. Vestiges of burrowed lime mudstone/wackestone in the dark-grey dolostone and of burrowed to crossbedded, off-white, peloidal grainstone and packstone in the sucrosic dolostone, indicate that these cycles reflect cleaning-, coarsening- and shallowing-upward mudstone to grainstone parasequences. A few dololaminite beds, which pinch out between drillholes, cap some of the cycles, and irregular upper surfaces to some cycles suggest locally developed karst or erosion (Baker and Knight, 1993).

Plate 16. *The dolomitized Costa Bay Member, Catoche Formation, Port au Choix. The section comprises decametre- to metre-scale cycles of recessively burrow-mottled, finely crystalline dolostone alternating with resistant weathering ledges of porous, light-grey, sucrosic dolostone.*

Plate 17. *Close up of a sucrosic dolostone cap, Costa Bay Member, Catoche Formation at Back Arm, north of the Port au Choix. The porosity in the dolostone is accentuated by modern weathering. Hammer is 29 cm long.*

The unit is mapped over a distance of more than 80 km, from Port au Choix to south of Daniel's Harbour, where it plunges below younger shelf and foreland-basin rocks and below the northern edge of the allochthonous Cow Head Group.

Aguathuna Formation

The Aguathuna Formation is a unit of metre-scale, peritidal cyclic carbonate that is mapped throughout the autochthon of western Newfoundland. In the area between Port au Choix and Daniel's Harbour, the formation is exclusively finely crystalline dolostone and minor shale (Knight and James, 1987). Elsewhere, however, limestone is intercalated with the dolostone and shale and this is typical of the succession on the Port au Port Peninsula (Figure 6).

Detailed studies of the Aguathuna Formation in the Port au Choix to Daniel's Harbour area show that the formation consists of two informal members separated by the St. George Unconformity (Lane, 1990; Knight *et al.*, 1991). The Lower member of the Aguathuna Formation is mapped throughout western Newfoundland although it is very variable in thickness, largely because of erosion at the St. George Unconformity (Knight *et al.*, 1991). The Upper member of the Aguathuna Formation is, however, restricted to the area between Daniel's Harbour and Port au Choix.

The upper part of the Lower member in the Daniels Harbour mine area shows widespread evidence of penecontemporaneous, karst-related subsidence as sedimentation was ongoing (Lane, 1990). This part of the succession was defined as the Middle member of the formation and was thought to be confined to the area near the Daniel's Harbour zinc mine (Knight *et al.*, 1991). However, more recent unpublished lithological studies supported by conodont studies (Stait and Barnes, 1991) indicate that rocks and microfauna similar to those logged at the Daniel's Harbour mine and at Table Point are present on the Port au Port Peninsula. The use of the term, Middle member, is therefore discontinued in this study, and all rocks below the St. George Unconformity are reassigned to the Lower member.

Port au Choix to Daniel's Harbour

The Lower member in the Port au Choix to Daniel's Harbour area consists of metre-scale sequences of burrow-mottled dolostone, dololaminite which is locally shaly, rare beds of stromatolitic dolostone and some units of green-grey shale; chert nodules layers are also present. The member is approximately 50 m thick near Table Point and Daniel’s Harbour but ranges between 6 and 28 m thick in drillholes and coastal sections in the Port au Choix area. This thickness variation largely reflects the effect of erosion at the St. George Unconformity (Baker and Knight, 1993). A distinctive burrow-mottled, basal marker, 4 to 12 m thick, known at the Daniel's Harbour zinc mine as the "dark grey dolomite", occurs at the base of the member in this area. In drillhole PC79-2, the dolostones of the Lower member, above the dark-grey dolomite, are typically burrow-mottled, patterned and laminated. The patterned dolostone varies between lumpy fabrics with irregular wispy argillaceous seams to those that have a distinctly soft-sediment deformed aspect after burrows. Large bodies of collapse breccia occur low in the member in the section at Table Point.

The Lower member in this area is generally unfossiliferous. Rare didymograptid graptolites (Williams *et al.*, 1987, 2000) and high-spired gastropods and opercula (Rohr *et al.*, 2000) are the only macrofossils known. Conodont studies of the member, however, indicate that it is host to

Midcontinent Fauna E and 1 of late Ibexian (Canadian) to early Whiterockian age (Stait, 1989). The faunal change occurs about 30 m above the base of the member, at a marker bed of stromatolitic dolostone, which is locally brecciated and silicified, and is overlain by green-grey shale (Stait and Barnes, 1991).

In the Daniel's Harbour zinc mine area, Lane (1990), using numerous exploration drill cores and an intimate knowledge of the local geology, defined and mapped an interval of cyclic, burrow-mottled, laminated and shaly dolostone near the top of the member, which he showed varied widely in thickness as the cycles were mapped throughout the mine area. Knight *et al.* (1991) defined this interval as the Middle member of the formation (its usage is now discontinued). The interval is up to 45 m at its thickest in the mine area, but rapidly thins away from the mine. Distinctive burrow-mottled dolostone units in this interval can be traced to the section at Table Point and as far south as the Port au Port Peninsula (*see* discussion below). The thickest parts of the interval are interpreted to be deposited synchronously within structurally controlled, elongate, collapse basins (doline), several kilometres in length. These dolines formed above areas of subsurface dissolution of limestone in the Catoche Formation, and where tectonic instability occurred along large northeast-trending faults that cut through the mine area. The interval is unconformably overlain by the Upper member of the formation suggesting that the collapse basin and its fill formed before the unconformity. Conodont studies (Stait, 1989; Stait and Barnes, 1991) indicate that the interval is host to a Whiterockian microfauna equivalent of Midcontinent Faunas 1 and 2.

Lane (1990) elegantly showed that many of the parasequences in the Lower member on the Northern Peninsula are deepening-upward cycles. This cycle motif begins with a basal truncation surface, sharply overlain by mudcracked shales and/or dololaminites, and succeeded transitionally by burrowed dolostones that are terminated abruptly by the next erosional surface. In some instances, extensive brecciation and silicification mark the top of the cycles.

The Upper member of the Aguathuna Formation outcrops near Table Point where it is approximately 15 to 20 m thick. It rests disconformably upon brecciated Lower member dolostone, and above an irregular surface that is overlain by shale; the surface is correlated with the St. George Unconformity. Dololaminites, intercalated with burrow-mottled dolostone, characterize the member but there are also thin layers of quartz- and chert-pebble sand and pebbles interspersed in the laminites. The member is largely confined to the Daniel's Harbour–Table Point area and also occurs as a thin veneer, about 4 m thick, as far north as Port au Choix, where it locally rests paraconformably to locally erosively upon the dark-grey dolomite (Knight *et al.*, 1991). Conodont studies of the Upper member, recovered Midcontinent Fauna 4 elements from the member at Daniel's Harbour, Table Point and Port au Choix and confirm the unconformable relationship at Port au Choix (Stait and Barnes, 1991).

Port au Port Peninsula

The Aguathuna Formation on the Port au Port Peninsula is a complex succession of dolostone, limestone and shale, all belonging to the Lower member. It is at its thickest, in sections, at the west end of the peninsula, including drillhole RND 001, where it reaches 103 m in thickness. Nonetheless, the large number of drillholes and outcrop sections on the peninsula demonstrate that substantial erosion of the upper part of the formation has occurred, as illustrated in Figure 6, which correlates drillhole RND 001 with drillhole RND 002.

The presence of limestone and shale intercalated with the dolostone provides tight correlation between the two drillholes studied. Limestone forms six marker units between 2 and 5 m thick in the lower 85 m of the formation. Several thin beds of limestone from 10 to 100 cm thick also occur isolated within thick dolostones that exhibit similar depositional fabrics. Limestone is more common in the lower part of the formation at the east end of Port au Port Peninsula (Knight and James, 1987; Stait, 1989).

The limestone in the formation is generally grey to off-white. They range from burrow-mottled, unfossiliferous, lime mudstone and wackestone to fossiliferous and peloidal, wackestone and packstone, skeletal, peloidal, oolitic and oncolitic grainstone and floatstone, intraclastic rudstone and stromatolitic boundstone (Figure 6; Plate 18). Trilobites, brachiopods and ostracods are recognized in the fossiliferous limestones of the cores. The most prominent and distinctive limestone occurs 20 m above the base of the formation where it is host to fossils, stromatolites and oncolites (Oncolite marker, Figure 6). This marker can be traced about 15 km to the southwest to a section near Mainland (Boyce *et al.*, 2001). In general, stromatolitic limestones become more common upward in the lower part of the formation, a feature also illustrated in the section near Mainland.

Dolostones of the formation are characterized by burrow-mottled, stromatolitic, patterned and laminated depositional fabrics (Plates 19 and 20). The patterned dolostone varies between varicoloured striped fabrics, to lumpy fabrics that have irregular wispy argillaceous seams to those with a distinctly soft-sediment deformed aspect after burrows. Mudcracks, small tepee structures, rare, white cauliflower quartz nodules, crosslamination, thin beds of dolorudstone

Plate 18. *Oncolites (arrow) at the top of a thick grainstone that dominates the middle part of a shallowing-upward limestone unit, 20 m above the base of the Aguathuna Formation. A green shale rests on the oncolite bed. The grainstone is associated with stylolitic, laminated and stromatolitic limestone, DDH RND 001, Port au Port Peninsula. A rudstone occurs to the right of the lens cap, which is 6 cm diameter.*

and local pockets of intraformational breccia characterize the dololaminites.

Green and green-grey shales occur scattered as partings and centimetre-thick beds mostly associated with the dololaminites; the thickest shale is 75 cm thick. It occurs at the 85 m mark just 17 m from the top of the formation in drillhole RND 001. The shale rests upon a very irregular surface below which the dolostone is extensively brecciated and fractured for several metres, suggesting a disconformity at this level. Above the shale (at the 85 m mark), the member is almost exclusively dolostone (Plate 21). The latter includes very distinctive, burrow-mottled units that can be

Plate 19. *Dololaminite and burrow-mottled dolostone, Lower member, Aguathuna Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

Plate 20. *Delicately patterned dolostone cut by a compacted fracture infilled by dark dolostone silt; about 75 m above base of the Aguathuna Formation, DDH RND 001, Port au Port Peninsula. Quarter of lens cap is 3 cm wide.*

Plate 21. *Burrowed dolostone lying above the shale interval at 85 m, Aguathuna Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

traced as far east as the section at the Aguathuna quarry, 22 km away, where they occur immediately below the St. George Unconformity. These same, distinctive, burrow-mottled dolostones, which are characterized by grey wormy burrows in a buff-coloured to light-grey matrix, also occur immediately below the unconformity, 220 km to the north at Table Point on the Northern Peninsula.

Thin limestone beds do occur in the upper dolostone-dominated interval in the east of the peninsula, at Aguathuna. However, the limestone beds disappear between sections only a few kilometres apart, and their stratigraphic position is replaced by bedding plane caves (*see* Figure 14, Knight *et al.*, 1991) that suggest paleo-dissolution of the limestone beds. Small vestiges of limestone that are bound by irregular surfaces in drillhole RND 001 a few metres from the top of the formation in drillhole RND 001 are, therefore, probably remnants of thin limestone interbeds that were incompletely dissolved.

Conodonts recovered from this upper dolostone interval at Table Point and the east end of Port au Port Peninsula includes Whiterockian elements of Midcontinent Fauna 2 (Stait, 1989; Stait and Barnes, 1991). This suggests that the section above the green shale correlates with the upper part of the Lower member affected by the penecontemporaneous development of doline basins near Daniel's Harbour.

Our knowledge of the lower part of the section near Aguathuna is, at present, incomplete, and hinders a better correlation of the Port au Port east sections with the two drillholes, RND 001 and RND 002. Nonetheless, conodonts recovered from Aguathuna quarry and shoreline sections nearby, suggest that below a surface readily correlated with the shale-draped disconformity at 85 m in drillhole RND 001, there is at least 28 m of section, that is host to Whiterockian Midcontinent Fauna 1 conodonts, below which conodonts are characteristic of the late Ibexian Midcontinent Fauna E (Stait, 1989; Stait and Barnes, 1991). The faunal change occurs at a shale-draped bed of breccia (Knight and James, 1987; Stait, 1989; Stait and Barnes, 1991). This suggests that the lower 85 m of the formation in drillholes RND 001 and 002 probably includes Whiterockian Midcontinent Fauna 1 and the underlying late Ibexian Midcontinent Fauna E.

St. George Unconformity

The St. George Unconformity is the most significant, regional erosional surface in the carbonate shelf sequence of western Newfoundland (Knight *et al.*, 1991). Not only does the surface have pronounced paleo-relief of many tens of metres (*see* Figure 6), but there are significant surface and sub-surface karst features as well as evidence that the sub-surface karst is locally structurally controlled.

Port au Choix

The Port au Choix area is interpreted as a strongly eroded structural high that lay northwest of the Torrent River Fault that was active when the high was formed and was eroded (Knight *et al.*, 1991; Knight, 1991). Southeast of the fault, at least 60 m of the Lower member of the Aguathuna Formation lies unconformably below the Upper member. At Port au Choix 25 km to the north, however, the Upper member rests unconformably upon the dark-grey dolomite, *i.e.*, the very base of the Lower member, whilst a few kilometres southeast of the town, at least 20 m of the Lower member is preserved below the unconformity. This implies, that in this area, prior to the deposition of the Upper member, there was at least 50 m of erosion on the unconformity as well as local low-relief topography on the unconformity.

Northeast-trending, dolostone-filled joints and chert-sand filled open space along minor faults (Plates 22 and 23) are widespread near, and south of, Port au Choix (Knight, 1991). The solution-widened fractures cut the Lower limestone of the Catoche Formation as much as 120 m below the unconformity. An anastomosing network of dolostone-filled fractures also cut the basal dark-grey dolomite of the Lower member of the Aguathuna Formation along the trace of the Back Arm Fault (Knight, 1991; I. Knight unpublished data, 1996), *i.e.*, about 10 m below the unconformity. Paleocaves, small and large bodies of matrix breccia, local bedding collapse and localized dolomitization along the faults are all important in the area. On a smaller scale, millimetre-wide angular fractures, occluded by fine sucrosic dolostone and by white sparry dolomite, are common in outcrop and drill core below the unconformity throughout the area (Knight, 1991; Baker and Knight, 1993). All support the importance of a strong structural control contemporaneous

Plate 22. *A centimetre-wide, northeast-trending paleo-fissure (lower arrow) infilled by fine dolomite silt cutting the Lower limestone, Catoche Formation, Port au Choix Peninsula. The fissure, which is one of many throughout this area, lies approximately 120 m below the St. George Unconformity with which it is believed to be linked. Light coloured dolomitization effects the limestone 10s of centimetres either side of the fissure (chevron arrow). Metre stick for scale.*

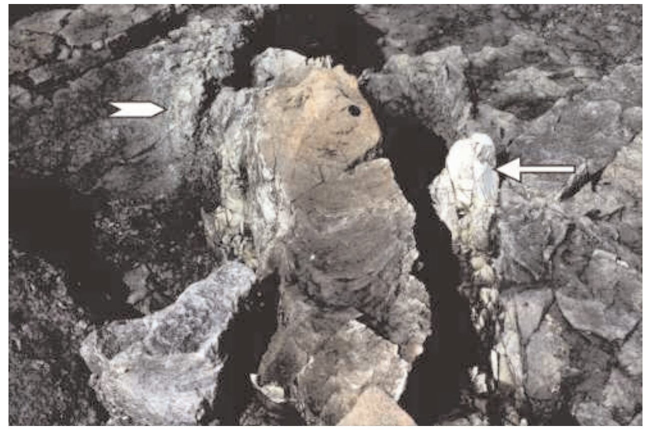

Plate 23. *A vertical body of stratified sandstone composed of chert quartz sand infills an open space along a minor fault cutting flat-lying Lower limestone of the Catoche Formation, south of Port au Choix. Wedges of fine-grained dolostone (arrow to the right of the sandstone) also form part of the fault fill. Narrow, localized areas of dolomitization (chevron arrow) affect the limestone wall rock left of the fault. Lens cap is 5.5 cm diameter.*

Plate 24. *Brecciated dolostone, Aguathuna Formation, just below the St. George Unconformity, DDH RND 002, Port au Port Peninsula. Isopachous pyrite coats clasts in the breccia. Lens cap is 6 cm diameter.*

with the timing of the unconformity and that the Back Arm Fault, and by implication other faults, was probably active at the time of the unconformity.

Port au Port Peninsula

Erosional topography with paleo-relief of more than 30 m over about a kilometre distance is the chief characteristic of the St. George Unconformity on the Port au Port Peninsula, as shown in Figure 6. In the drillhole RND 002, the unconformity cuts downward to 7.5 m below the intraformational disconformity logged in drillhole RND 001, at 85 m mark. A metre-wide zone of broken and fractured dolostone occurs locally below the unconformity (Plate 24). Just 10 to 20 m below the unconformity, paleo-caves developed along bedding by dissolution of limestone beds intercalated in the dolostone of the Aguathuna Formation (*see* Figure 14, Knight *et al.*, 1991). There are also numerous metre-size paleo-caves, many of which are filled or partly filled by green shale and/or dolostone rubble. The paleo-caves occur in the Aguathuna Formation, the Costa Bay Member and the Middle dolostone indicating that subsurface karst was effective down to at least 140 m below the unconformity. Caves developed in the Middle dolostone imply that the dolomites were early burial, in origin. Irregular bodies of matrix breccia with locally derived clasts set in a matrix of shale and dolomite occur cutting the Aguathuna Formation and the Costa Bay Member at the quarry at Aguathuna (I. Knight, unpublished data, 1996). Paleocaves and collapse breccias have also been described in the section south of Mainland (Boyce *et al.*, 2000). Although there is no obvious evidence for structural control of the unconformity on the peninsula, a rectilinear, anastomosing network of fine dolostone-filled, brittle fractures, like those noted near Port au Choix, pervade the Aguathuna Formation in the two drill cores examined. Centimetre-scale vugs, infilled by green shale, also occur in the two drill cores studied.

TABLE HEAD GROUP AND OVERLYING FORELAND BASIN STRATIGRAPHY

The Table Head Group buries the St. George Unconformity. This deepening-upward succession of peritidal to subtidal shelf limestone of the Table Point Formation and slope ribbon limestone and shale of the Table Cove Formation was most recently studied by Klappa *et al.* (1980), Stenzel *et al.* (1990) and Stenzel (1993). The Table Point Formation is divided into two members, the basal peritidal unit called the Spring Inlet Member (Ross and James, 1987) and an unnamed Upper limestone.

SPRING INLET MEMBER

The Spring Inlet Member is a complex of small-scale, shallowing-upward parasequences of fenestral-rich and non-fenestral lithofacies associations (Stenzel *et al.*, 1990; Knight, 1991). The large, variation in thickness, and facies distribution, as well as the local development of intra-member disconformities (*see below*) that mark the member, largely reflect the response of sedimentation to the local paleo-topography on the St. George Unconformity (Knight *et al.*, 1991) and on-going regional tectonism.

The fenestral facies are dominantly light grey to off-white, lime mudstone and peloidal wackestones to grainstones with burrowed as well as crossbedded and laminated subfacies, each characterized by fenestrae and vugs of different types. Laminar, keystone and tubular fenestrae cemented by clear spar are common, as are numerous stromatactoid-like vugs, occluded by geopetal carbonate silt and pendant cements (Knight, 1991). The non-fenestral facies association comprises dark-grey, stylonodular to parted, sparsely bioturbated, dolomitic limestone overlain by laminated limestone and/or dololaminite. Brachiopod coquina beds occur in the association locally on the Northern Peninsula, and are also seen in core from drillhole RND 002. A basal conglomerate is also present upon the unconformity in many localities on the Northern Peninsula and in drillhole RND 002.

In the Port au Choix to Daniel's Harbour area, the Spring Inlet Member locally attains 50 m in thickness, although it is generally much thinner. The unit is dominated in most sections by the fenestral facies association with only a lesser role played by the non-fenestral association (Knight, 1985, 1992, unpublished data, 1996). This is in contrast to the member in the Pistolet Bay thrust stack where some of the thicker intervals are dominated by cycles of the non-fenestral association (Knight, 1986, 1987). The fenestral lithofacies is well exposed along the shore at Gargamelle Cove and at White Point, and is present in the drillholes of the Port au Choix area. The facies is easily recognized even when overprinted by dolomitization as it is at Gargamelle Cove, White Point and in several drillholes in the area.

The non-fenestral facies dominates the Spring Inlet Member in the Port au Port Peninsula drillholes, where it partly infills the pronounced topographic low sculpted in the unconformity. Most of the member in the drillholes consists of thick beds of stylonodular limestone, and 10- to 60-cm-thick interbeds of skeletal-intraclastic grainstone and rudstone and some thin beds of dololaminite. Only scattered thin beds of fenestral limestone are present in the two cores (Plate 25). A basal conglomerate occurs in drillhole RND 002 (Plate 26), but is absent in drillhole RND 001, where a fenestral laminite rests upon the unconformity. A number of beds of finely laminated, green-grey, calcareous and dolomitic mudstone that host scattered thin-shelled fossils and pea-sized chert quartz pebbles, are also present in drillhole RND 002, but absent in RND 001. The facies, which is hackly-weathering, (the cores are exposed to the elements and are now weathered), was also described immediately above the unconformity in the Big Head area of the western shore of the Port au Port Peninsula, some 20 km to the southwest (Knight *et al.*, 1991). There, like in the core, it is associated with thin layers of scattered quartz pebbles and sand.

Plate 25. *Laminated and fenestral, peloidal limestone near the base of the Spring Inlet Member, Table Point Formation, DDH RND 001, Port au Port Peninsula. Lens cap 6 cm diameter.*

Plate 26. *Basal conglomerate (arrow, middle core), Spring Inlet Member, Table Point Formation, DDH RND 002, Port au Port Peninsula. Underlying dololaminite and shale of the Aguathuna Formation occurs in the core to right and overlying nodular Table Point Formation limestone marks the core to left. Lens cap is 6 cm diameter.*

Plate 27. *Stylonodular, dolomitic lime mudstone-wackestone of the Upper limestone member, Table Point Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

Throughout western Newfoundland, a number of intramember erosional disconformities occur in the Spring Inlet Member (Knight *et al.*, 1991). One such disconformity is present in drillhole RND 002, where it caps a 7 m interval of tilted strata that have dips of up to 40°. A number of faults occur at the base of, and below, the tilted interval but no fault separates flat-lying strata that sits atop the tilted interval, *i.e.*, the upper contact looks depositional. If this structural relationship is correctly interpreted, then it suggests that there were penetrative and disruptive faults active in this area during the deposition of the member.

UPPER LIMESTONE

The Upper limestone consists of predominantly thick-bedded, dolomitic and argillaceous, dark-grey limestones. The limestones range from stylonodular and burrowed, fossiliferous and peloidal wackestone that have thin, fossil-rich peloidal packstone and grainstone lenses, to stylonodular lime mudstone to burrowed wackestone, which are often chert rich and fossil poor (Plate 27). Lithistid sponge biostroms occur locally (Klappa and James, 1990) and horizons of slumped bedding occur locally especially in the Table Point area. A diverse macrofauna of trilobites, brachiopods, crinoids, gastropods, cephalopods, ostracods and sponges occur in the limestones (Stenzel *et al.*, 1990). The above rock types dominate the member in the two drillholes logged on the Port au Port Peninsula (Plate 27; Figure 5). Core from drillhole RND 001 also has thin shale interbeds, two of which are putty-like, suggesting possible bentonite clays.

Grainstone bodies, a few metres to tens of metres thick, are widely developed in the lower part of the Upper limestone immediately above the Spring Inlet Member (Stenzel, 1993; Knight, 1991, 2003; Knight and Boyce, 2000). The grainstones are principally peloidal, but also include oolitic, intraclastic and skeletal allochems. Many of the bodies are rich in large, high-spired gastropods; crossbeds are ubiquitous. Several, thick, aerially extensive grainstone bodies occur at the west end of Port au Port Peninsula (I. Knight, unpublished data, 1996), in the Phillips Brook and North Brook anticlines (Knight and Boyce, 2000; Knight, 2003), and are present in the two drillholes logged near Round Head (Plate 28). Skeletal-rich sponge biostroms occur locally in the facies at Phillips Brook and are also present in the grainstone body in drillhole RND 001. However, the biostroms do not occur in either of the two grainstone intervals in drillhole RND 002, less than a kilometre away. At Port au Choix, crossbedded grainstone at the base of the member is dolomitized along the shore of Gargamelle Cove (Plate 29).

Rubble layers of sponges and other robust skeletal elements occur locally at the top of the Upper limestone and are present in drillhole RND 002. Stromatactoid mud mounds are also locally seen on the Port au Port and Northern peninsulas (Stenzel and James, 1995). Dolomitization, silicification and pyritization widely affects the top few centimetres of the member at many sections in western Newfoundland.

Traced eastward into the Blue Pond and Goose Arm thrust stacks, the Upper limestone become less fossiliferous, texturally lumpy and is interspersed with thin beds to locally metre-thick units of thin-bedded, ribbon limestone, and lenses of intraformational conglomeratic to brecciated limestone (Knight, 1995, 2003, 2006).

Both the Spring Inlet Member and the Upper limestone host Whiterockian conodont Midcontinent Fauna 4 (Stouge, 1984; Stait and Barnes, 1991). The Upper limestone hosts Anomalorthis zone brachiopods and trilobites of zone M (Ross and James, 1987; Whittington and Kindle, 1963) whilst the Spring Inlet Member hosts a sparse shelly fauna of the Orthidiella zone.

Plate 28. *Skeletal intraclastic grainstone in the base of the Upper limestone member, Table Point Formation, DDH RND 001, Port au Port Peninsula. Lens cap is 6 cm diameter.*

Plate 29. *Crossbedded dolostone that replaces a grainstone unit just above the Spring Inlet Member at Gargamelle Cove, Port au Choix. The grey to salt-and-pepper-coloured, sucrosic, hydrothermal dolostone occurs as a narrow, vertical wall-like body on the north side of the Back Arm Fault. Unaltered limestone occurs in the background. Hammer is 29 cm long.*

POST-TABLE POINT FORMATION

Ribbon limestones and shales of the Table Cove Formation locally overlie, conformably, the Table Point Formation. Interpreted as slope facies rocks by Stenzel *et al.* (1990), it varies greatly in thickness and is only thickly developed in the Table Point area (Stenzel *et al., op. cit.*) and the west side of the Phillips Brook Anticline (Knight and Boyce, 2000). Where the formation is absent at several localities in western Newfoundland, it is replaced by a local disconformity at the top of the Table Point Formation that is characterized by erosion, deeply penetrating shale-filled fractures, cementation and diagenetic alteration below a range of rock types and stratigraphy of the Goose Tickle Group flysch (Stenzel *et al.*, 1990; Knight and Cawood, 1991). The latter includes sandy and shaly flysch of the American Tickle Formation above a widely developed but generally thin, black shale of the Black Cove Formation (Quinn, 1995). Carbonate conglomerate, rich in Table Point detritus, named the Daniel's Harbour Member, was largely derived by erosion of the Table Point Formation from fault-controlled horsts within the foreland basin. The conglomerates of the Daniel's Harbour Member are intercalated widely throughout western Newfoundland as thin to thick sheets and lenses, in both the black shale and the overlying flysch. The member locally also lies disconformably upon the Table Point Formation (Stenzel *et al.*, 1990; Stenzel, 1992) as, for example, at Port au Choix (Plate 30).

Plate 30. *Daniel’s Harbour Member limestone conglomerate resting on Table Point Formation limestone, south shore of Gargamelle Cove, Port au Choix. Hammer is 29 cm long.*

The most spectacular example of such tectonically linked conglomerate is the Cape Cormorant Formation, a thick unit of carbonate conglomerate, grainstone, ribbon limestone and shale that outcrops only at the western end of the Port au Port Peninsula. Conglomerates in this unit indicate that erosion cut deeply down through the underlying Lower Ordovician shelf into Cambrian carbonates that were uplifted along a penecontemporaneous fault scarp, the forerunner of the Round Head Fault (Stockmal and Waldron, 1993). Stenzel *et al.* (1990) placed the formation in the Table Head Group but its erosional base, stratigraphic setting, and its distinct depositional setting in the tectonically shaped foreland basin, suggest that it is more stratigraphically compatible with the Daniel's Harbour Member and should be included in the Goose Tickle Group.

Drillhole RND 2 intersects thin beds of these units and nicely illustrates the complexity of the stratigraphy in the post-Table Point Formation succession (Plate 31). Dark-grey shale with isolated thin ribbon limestone beds, 1 m thick, probably belongs to the Table Cove Formation. It rests conformably upon a skeletal grainstone that marks the top of the Table Point Formation. The Table Cove Formation is erosively overlain by 85-cm-thick limestone conglomerate of the Daniel's Harbour Member. This is succeeded in turn by 40 cm of black shale (probably the Black Cove Formation) intercalated with a single, thin bed of green shale below a green-grey sandstone that must define the base of the American Tickle Formation. The sandstone is immediately overlain by a second limestone conglomerate (Daniel’s Harbour Member) that is succeeded by grey shale.

Plate 31. *Top of the Table Point Formation limestone (upper core) overlain by dark-grey shale of the Table Cove Formation (lens cap) and limestone conglomerate Daniel’s Harbour Member (below lens cap), DDH RND 002, Port au Port Peninsula. Lens cap is 6 cm diameter*.

A BRIEF REVIEW OF DOLOSTONES AND DOLOMITE TYPES

Dolostones have been studied in the St. George Group by both Haywick (1984) and by Lane (1990). Both of these authors recognized that dolostones ranged from microcrystalline to very fine grained to sucrosic and are often rich in sparry/saddle dolomite veins and open-space cements, the latter equated with hydrothermal high temperature dolomite.

The microcrystalline dolostones that dominate formations such as the Aguathuna Formation near Table Point and Port au Choix and mostly the tops of shallowing-upward peritidal sequences in the Aguathuna Formation at Port au Port Peninsula and in the Barbace Cove Member are characterized by excellent preservation of sedimentary structures and have been interpreted as essentially synsedimentary to early shallow burial, in origin. Burrow dolomite that is so ubiquitous in the subtidal limestones of most formations is also understood in much the same vein. Sucrosic dolostones that preserve burrow-mottle and mound fabrics, however, are interpreted as deeper burial dolostones, likely associated with mixing zone processes, formed early enough to be included as clasts in collapse breccias where they cut the dolostones intervals and in some Cape Cormorant Formation carbonate conglomerates that are interbedded low in the Goose Tickle Group. Sparry dolomite complexes are the product of hydrothermal processes. They appear to be in some instances, spatially linked to known active fault systems that deformed the shelf sequence as the foreland basin was developing. It is also clear, however, that the stratiform bodies of sucrosic and sparry dolomite are generally deformed by the later large faults and folds that are the main structures through the autochthonous terrain. This is in contrast to some sucrosic dolostones that spatially lie along the trace of major and minor faults that are clearly formed later than, or at least penecontemporaneous with, the development of the main structures.

As illustrated by the sections sampled for this study, dolomite selectively to pervasively replace subtidal limestones of both the St. George and Table Head groups. This replacement can range from simple sedimentary fabrics such as burrows or parts of mounds (Plate 4) in most limestone stratigraphic units to substantial intervals of a limestone unit. Some bodies of dolostone are spatially linked to faults as, for example, the near vertical decametre-wide wall of dolostone that occurs close to the Back Arm Fault in Gargamelle Cove, Port au Choix (Figure 3A).

In the upper St. George Group, stratabound, stratiform bodies of many square kilometres, and tens of metres thick form units as, for example, the dolomitized Costa Bay Member in the Port au Choix to Daniel's Harbour area (Figure 3; Plates 16 and 17) and the Middle dolostone and correlative boundstone mound units in the middle of the Catoche Formation on the Port au Port Peninsula and at Cape Norman on the Northern Peninsula (Plates 12 and 13). These dolostones are characterized predominantly by fine- to medium-grained crystalline, sucrosic dolomite that displays primary depositional fabrics even if in a somewhat vague manner. In the case of the Middle dolostone and the dolomitized mounds at Cape Norman, the sucrosic dolostones are massive, inconsistent in porosity and poor in sparry dolomite veins and open-space fillings.

Overprinting the stratabound dolostones of the Costa Bay Member in the Port au Choix to Daniel's Harbour area, however, is the widespread development of hydrothermal white sparry and saddle dolomite complexes (*e.g.*, HTD). These HTD complexes are best developed over a wide area near Table Point and Daniel's Harbour (Plate 32), where they hosted the now-mined-out Daniel's Harbour sphalerite deposit. They can be seen as small, spherical to rectangular bodies, a few metres thick, replacing individual limestone beds in the Catoche Formation immediately below the stratabound dolostones and are common locally in other parts of the St. George Group succession (Plates 33 and 34). HTD dolomite occurs as veins and cements in open space and replaces matrix in collapse and matrix breccias throughout the western part of the Northern Peninsula area, north of Daniel's Harbour.

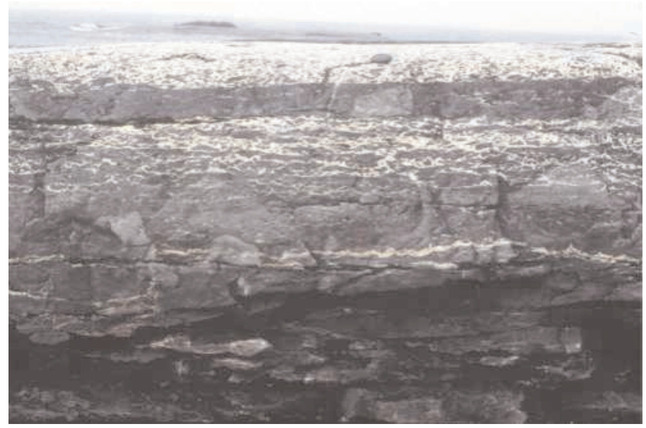

Plate 32. *HTD dolomite (white spar) partially replacing sucrosic dolostone essentially parallel to bedding, Costa Bay Member, Catoche Formation, north of Table Point. The outcrop lies in the hanging wall of the Torrent River Fault that occurs in the surf zone in the background. Lens cap is 5.5 cm diameter.*

Plate 33. *A small, bedding parallel body of hydrothermal sparry and sucrosic dolostone replacing Lower limestone of the Catoche Formation at Cape Norman. The body has no apparent structural control although a network of high-angle faults are projected to occur just offshore to the right. Hammer is 32 cm long.*

In the Port au Choix area, the hydrothermal dolomite is less common, although it does form as millimetre-thick, isopachous cement rinds in porosity within sucrosic dolostones that replace the peloidal grainstone and packstones that form the top of the metre-scale shallowing-upward parasequences earlier (*see* descriptions of Catoche Formation and Costa Bay Member). The Port au Choix dolostones illustrate the importance of initial lithology to later porosity development in suitable burial dolomites to facilitate the development of HTD complexes in regionally mapped stratabound and stratiform dolostone units. This is also

Plate 34. *A body of hydrothermal dolostone that replaces a single bed of boundstone mounds in the Boat Harbour Formation, north of Port au Choix. The dolostone is bounded by limestone beds and can be traced westward (to the left) where it abruptly ends in the lime boundstone. Hammer is 29 cm long.*

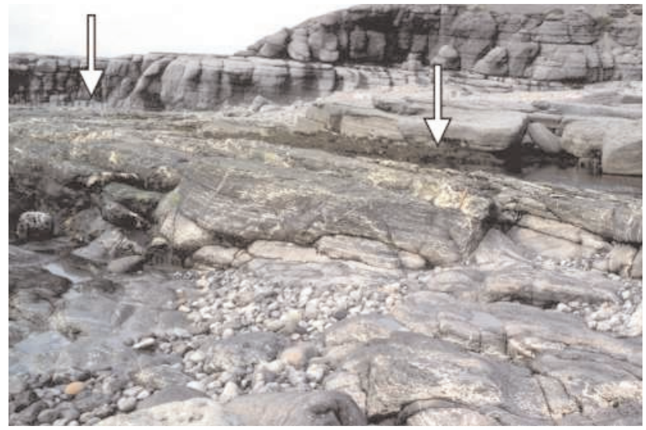

Plate 35. *The upper contact (arrow just above hammer) of a hydrothermal sparry and sucrosic dolostone body that replaces the lower part of the well-bedded, Upper limestone of the Table Point Formation just south of White Point, Port au Choix. Hammer is 29 cm long.*

reflected in the sucrosic dolostone that replaces much of the Spring Inlet member in the Port au Choix area. Generally, highly porous, sucrosic dolomites replace the fenestral facies association's peloidal limestones, and encroach as large bodies of sucrosic and sparry dolomite up into lower stratal parts of the Upper limestone of the Table Point Formation (Figure 3A; Plate 35). These higher dolomite bodies are not always stratiform but rather form irregularly shaped to elongate or room-shaped bodies abruptly enclosed by its host limestone. As described by Baker and Knight (1993) and noted earlier, the dolostone bodies of the upper St. George Group and lower Table Head Group at Port au Choix have excellent porosity and were host to a large petroleum field (Cooper *et al.*, 2001).

Based on a variety of geochemical and petrographic tools, several stages of dolomite have been documented in earlier studies (Lane, 1990). However, the current study, focused on the Port au Choix carbonate rocks, suggests five major dolomite generations, which have been summarized in Table 1.

DOLOMICRITE (D1)

Dolomite 1 ranges in size from 5 to 40 microns and consists mainly of tightly packed anhedral to subhedral crystals. It is Fe-rich (based on staining) and exhibits a dull luminescence under cathodoluminoscope (CL). In thin-section, D1 appears laminated, either displaying a preserved relict texture after replacement of micritic calcite or its original depositional fabric.

The average concentrations of Ca, Mg, Mn, Sr and Fe are 131714, 77216, 92, 42, and 1549 ppm respectively. The average $\delta^{18}O$ (PDB) and $\delta^{13}C$ values ‰ are -7.38 and -0.83 ‰. (VPDB), respectively (Table 1)

DOLOMITE 2 (D2)

Dolomite 2 ranges in size from 55 to 270 microns and is anhedral to subhedral in shape while displaying tight packing. Similar to D1, D2 is also Fe-rich (based on staining) and displays a dull reddish-orange luminescence. Unlike D1, D2 displays inclusion-rich turbid cores that may represent former replaced peloids.

Dolomite 2 averages Ca concentrations of 189460 ppm and average Mg concentrations of 102989 ppm. Average concentrations for Mn, Sr and Fe are 142 ppm, 61 ppm, and 3722 ppm, respectively. An average $\delta^{18}O$ (PDB) value of -9.13‰ and a $\delta^{13}C$ (PDB) value of -0.68‰ were obtained from this dolomite.

DOLOMITE 3 (D3)

Dolomite 3 ranges in size from about 60 to 175 microns while displaying a subhedral to euhedral crystal shape. D3 exhibits cloudy, Fe-rich cores that have slightly Fe-poorer rims and displays dull luminescence at its core to slightly bright reddish-orange luminescence at it rims. D3 is usually bounded by stylolites and associated with similar organic matter associated with the stylolites.

Table 1. Average trace-element concentrations and isotope analysis results from the Catoche Formation of the Port aux Choix area, western Newfoundland

Dolomite Type	Avg. Size (μm)	$CaCO_3$	$MgCO_3$	Mn (ppm)	Sr (ppm)	Fe (ppm)	$\delta^{18}O$ ‰ (VPDB)	$\delta^{13}C$ ‰ VPDB)
Dolomicrite								
N=18	15	29.90	24.19	78	40	844	-7.38	-0.83
St dev	-	4.16	3.41	12	16	-	1.35	0.44
Dolomite 2								
N=13	120	47.65	35.73	142	61	3722	-9.13	-0.68
St dev	-	5.69	3.91	27	55	4341	1.16	0.38
Dolomite 3								
N=11	90	53.13	32.76	164	151	9691	-8.29	-1.23
St dev	-	6.42	7.40	60	88	7551	1.46	0.46
Dolomite 4								
N=15	600	NA	NA	NA	NA	NA	-10.03	-1.20
St dev	-	NA	NA	NA	NA	NA	0.41999	0.24864
Dolomite 5	500	NA	NA	NA	NA	NA	NA	NA
St dev	-	NA	NA	NA	NA	NA	NA	NA

Note: VPDB = ???

Average concentrations of Ca and Mg were obtained and are 211275 ppm and 94429 ppm. Manganese, Sr, and Fe recorded average concentrations of 164 ppm, 151 ppm, and 9691 ppm, respectively. An average $\delta^{18}O$ (PDB) value of -8.29‰ and a $\delta^{13}C$ (PDB) value of -1.23‰ were obtained for dolomite 3.

DOLOMITE 4 (D4)

Dolomite 4 ranges in size from about 300 microns to 2.5 millimetres and exhibits a planar to saddle dolomite shape. D4 is primarily Fe-poor but commonly observed are Fe-rich rims. This generation of dolomite lines vugs but usually does not completely occlude pore space. Sweeping extinction is common with D4.

Trace-element analysis for Dolomite 4 is presently not available. However, isotope analysis indicates an average $\delta^{18}O$ (PDB) value of -10.03‰ and a $\delta^{13}C$ (PDB) value of -1.20‰.

DOLOMITE 5 (D5 - FISSURE FILLING DOLOMITE)

Dolomite 5 (vein or fracture filling) ranges 450 to 650 microns and is anhedral to rarely planar in shape. The turbid crystals of D5 are blue to dark blue (Fe-rich) when stained and dull reddish-orange under CL. It is difficult to determine the relative timing of the crystallization of D5, in relationship to D4, because the two distinct dolomites were not observed together. However, cathodluminescence and staining suggest the dolomite may be related to Dolomite 2.

Results for trace-element and isotope analysis are presently not available.

The C-isotope profiles, reconstructed from primary C-isotope signatures, have been successfully used for chemostratigraphic correlation of sequences from different sedimentary basins (*e.g.*, Halverson *et al.*, 2005). Trace-element concentrations in carbonate rocks have been used as indicators for degree of diagenetic alteration *vs.* preservation (*e.g.,* Azmy *et al.*, 2006). During diagenesis, Sr is significantly depleted in the secondary carbonate, whereas Mn is enriched. Alternatively, if the diagenetic waters do not contain much dissolved CO_2, there is only minimal impact on the $\delta^{13}C$ of the carbonate. This, in many cases, results in insignificant resetting of the $\delta^{13}C$ signature, although the effect is severe on the $\delta^{18}O$ signature. Therefore, the variations between $\delta^{13}C$ and Mn/Sr are used to evaluate the degree of preservation of the $\delta^{13}C$ signatures of carbonates (*e.g.*, Azmy *et al.*, 2001).

Many of the fine-grained St. George Group carbonates show fabric preservation and insignificant correlation between their $\delta^{13}C$ and Mn/Sr values, thus suggesting a high degree of preservation of their c-isotope composition (Fig-

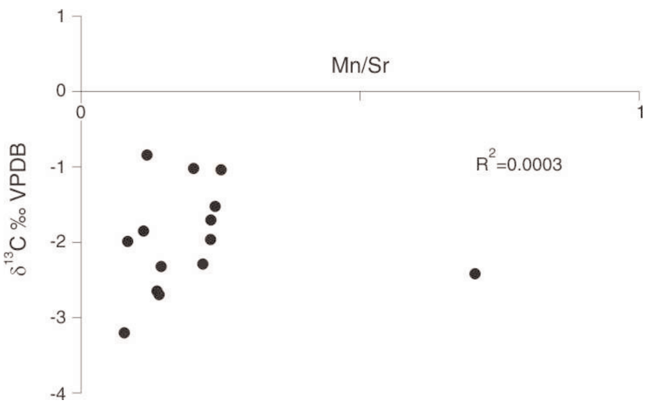

Figure 7. *Scatter diagram of δ^{13}C vs. Mn/Sr showing insignificant correlation.*

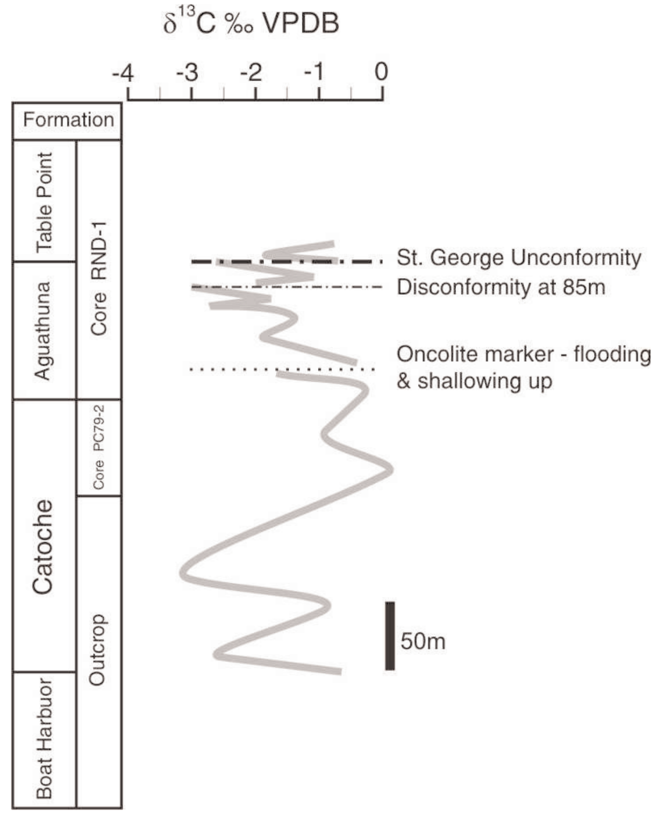

Figure 8. *Variations in the δ^{13}C profile of the St. George Group showing the major swings correlated with sedimentary events.*

ure 7). Their C-isotope profile exhibits remarkable shifts over short-time intervals (Figure 8), which correlate with the major St. George Unconformity and other minor disconformities and shallowing-up events. These shifts can be used, with high reliability, for correlating the equivalent potential reservoir beds throughout the boreholes in the entire western Newfoundland area, a significant issue in a region severely affected by tectonism.

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REFERENCES

Azmy, K., Veizer, J., Jin, J. and Copper, P.
2006: Paleobathymetry of a Silurian shelf: oxygen isotope test. Canadian Journal of Earth Sciences, Volume 43, pages 281-293.

Azmy, K., Veizer, J., Misi, R., De Olivia, T. and Dardenne, M.
2001: Isotope stratigraphy of the Neoproterozoic carbonate of Vazante Formation Saõ Francisco Basin, Brazil. Precambrian Research, Volume 112, pages 303-329.

Baker, D. and Knight, I
1993: The Catoche dolomite project, Anticosti basin, eastern Canada. Centre for Earth Resources Research Report, Memorial University of Newfoundland, St. John's, Newfoundland, 174 pages.

Boyce, W.D.
1989: Early Ordovician trilobite faunas of the Boat Harbour and Catoche formations (St. George Group) in the Boat Harbour-Cape Norman area, Great Northern Peninsula, western Newfoundland. Government of Newfoundland and Labrador, Department of Mines, Geological Survey of Newfoundland, Report 89-2, 175 pages.

Boyce, W.D., Knight, I., Rohr, D.M., Williams, S.H. and Measures, E. A.
2000: The upper St. George Group, western Port au Port Peninsula: lithostratigraphy, biostratigraphy, depositional environments and regional implications. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Division, Report 2000-1, pages 101-125.

Boyce, W.D. and Stouge, S.
1997: Trilobite and conodont biostratigraphy of the St. George Group at Eddies Cove West, western Newfoundland. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, Report 97-1, pages 183-200.

Cooper, M., Weissenberger, J., Knight, I., Hostad, D., Gillespie, D., Williams, H., Burden, E., Porter-Chaudhry, J., Rae, D. and Clark, E.
2001: Basin evolution in western Newfoundland: New insights from hydrocarbon exploration. American Association of Petroleum Geologists Bulletin, Volume 85, No. 3, pages 393-418.

De Grace, J.R.
1974: Limestone Resources of Newfoundland and Labrador. Newfoundland and Labrador Department of Mines and Energy, Report 74-2, 117 pages.

Dickie, G.J. and Lyn, I.
1979: Diamond drilling at Port au Choix. Brinex-Riofinex-Freeport Joint Venture geological drilling report #79003. Unpublished report, 8 pages (Nfld File No. 12I/127).

Fortey, R.A.
1979: Lower Ordovician trilobites from the Catoche Formation (St. George Group), western Newfoundland. Geological Survey of Canada, Bulletin 321, pages 61-114.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C. and Rice, A.H.N.
2005: Toward a Neoproterozoic composite carbon-isotope record. Geological Society of America Bulletin, Volume 117, pages 1181-1207.

Haywick, D.W.
1984: Dolomite within the St. George Group (Lower Ordovician), western Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's Newfoundland, 281 pages.

Hibbard, J.P., van Staal, C.R., Rankin, D.W. and Williams, H.
2006: Lithotectonic map of the Appalachian Orogen, Canada-United States of America. Geological Survey of Canada, Map 2096A, scale 1: 1 500 000.

Ji, Z.
1989: Lower Ordovician conodonts from the St. George Group of Port au Port Peninsula, western Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 576 pages.

Ji, Z. and Barnes, C.R.
1994: Lower Ordovician conodonts of the St. George Group, Port au Port Peninsula, western Newfoundland, Canada. Palaeontographica Canadiana, Number 11, 149 pages.

Klappa, C.F. and James, N.P.
1980: Lithistid sponge bioherms of Middle Ordovician age, Table Head Group, west Newfoundland. Bulletin of Canadian Petroleum Geology, Volume 28, pages 425-451.

Klappa, C.F., Opalinski, P.R. and James, N.P.
1980: Middle Ordovician Table Head Group of western Newfoundland: a revised stratigraphy. Canadian Journal of Earth Sciences, Volume 17, pages 1007-1019.

Kluyver, H.M.
1975: Stratigraphy of the Ordovician St. George Group in the Port-Au-Choix area, western Newfoundland. Canadian Journal of Earth Sciences, Volume 12, pages 589-594.

Knight, I.
1977: Cambro-Ordovician platformal rocks of the Northern Peninsula, Newfoundland. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 77-6, 27 pages.

1986: Ordovician sedimentary strata of the Pistolet Bay and Hare Bay area, Great Northern Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Report 86-1, pages 147-160.

1987: Geology of the Roddickton (12I/16) map area. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 343-357.

1991: Geology of Cambro-Ordovician rocks in the Port Saunders (NTS 12I/11), Castors River (NTS 12I/15), St. John Island (NTS 12I/14) and Torrent River (NTS 12I/10) map areas. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, Report 91-4, 138 pages.

1994: Geology of the Cambrian-Ordovician platformal rocks of the Pasadena map area (NTS 12H/4). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 94-1, pages 175-186.

1997: Geology of Cambro-Ordovician carbonate shelf and co-eval off-shelf rocks, southwest of Corner Brook, western Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Report 97-1, pages 211-235.

2003: Geology of the North Brook Anticline, Harry's River map area (NTS 12B/09). *In* Current Research. Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Report 2003-1, pages 51-72.

Knight, I. and Boyce, W.D.
2000: Geological notes on the Cambro-Ordovician rocks of the Phillips Brook anticline, north of Stephenville. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 2000-1, pages 197-215.

2002: Lower Paleozoic carbonate rocks of the northern closure of the North Brook Anticline and the Spruce Ponds Klippe, Georges Lake (12B/16) and the Harrys River (12B/9) map areas: collected thoughts on unconnected rocks. *In* Current Research. Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Report 02-1, pages 121-134.

Knight, I. and Cawood, P.A.
1991: Paleozoic geology of western Newfoundland: an exploration of a deformed Cambro-Ordovician passive margin and foreland basin, and Carboniferous successor basin. A field-based short course for industry, June 1991. Centre for Earth Resources Research, Department of Earth Sciences, Memorial University of Newfoundland, St. John's. Part 1, 229 pages.

Knight, I. and James, N.P.
1987: Stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: the interaction between eustasy and tectonics. Canadian Journal of Earth Sciences, Volume 24, pages 1927-1951.

Knight, I., James, N.P. and Lane, T.E.
1991: The Ordovician St. George Unconformity, northern Appalachians: the relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe sequence boundary. Geological Society of America Bulletin, Volume 103, pages 1200-1225.

Lane, T.E.
1990: Dolomitization, brecciation and zinc mineralization and their paragenetic, stratigraphic and structural relationships, upper St. George Group - Ordovician - Daniel's Harbour, western Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John’s, Newfoundland, 565 pages.

Newfoundland Hunt Oil Company Inc.
1996: Final well report for onshore well NHOC/Pan Canadian Port au Port No 1.

Pratt, B.R.
1979: The St. George Group (Lower Ordovician), western Newfoundland: sedimentology, diagenesis and cryptalgal structures. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 254 pages. [NFLD/1248]

Quinn, L.
1995: Middle Ordovician foredeep fill in western Newfoundland. *In* Current Perspectives in the Appalachian-Caledonian Orogen. *Edited by* J.P. Hibbard, C.R. van Staal and P.A. Cawood. Geological Association of Canada, Special Paper 41, pages 43-64.

Rohr, D.M., Measures, E.A., Boyce, W.D. and Knight, I.
2000: Ongoing studies of Late Cambrian and Early Ordovician gastropods of western Newfoundland. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Division, Report 2000-1, pages 241-250.

Ross, R.J. Jr. and James, N.P.
1987: Brachiopod biostratigraphy of the Middle Ordovician Cow Head and Table Head groups, western Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 70-95.

Stait, K.A.
1988: Upper Canadian to Whiterockian (Ordovician) conodont biostratigraphy of the Upper St. George Group, western Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 493 pages.

Stait, K.A. and Barnes, C.R.
1991: Conodont biostratigraphy of the upper St. George Group (Canadian to Whiterockian), western Newfoundland. *In* Advances in Ordovician Geology. *Edited by* C.R. Barnes and S.H. Williams. Geological Survey of Canada, Paper 90-9, pages 125-134.

Stenzel, S.R.
1992: Carbonate sedimentation in an evolving Middle Ordovician foreland basin. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 575 pages.

Stenzel S.R. and James N.P.
1995: Shallow-water stromatactis mud-mounds on a middle Ordovician foreland basin platform, western Newfoundland. *In* Carbonate Mud-Mounds: Their Origin and Evolution. *Edited by* C.L.V. Monty, D.W.J. Bosence, P.H. Bridges and B.R. Pratt. Special Publication of the International Association of Sedimentologists, Volume 23, pages 127-149.

Stenzel, S.R., Knight, I. and James, N.P.
1990: Carbonate platform to foreland basin: revised stratigraphy of the Table Head Group (Middle Ordovician), western Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 14-26.

Stockmal, G.S. and Waldron, J.W.F.
1993: Structural and tectonic evolution of the Humber Zone, western Newfoundland, 1. Implication of balanced cross sections through the Appalachian structural front, Port au Port Peninsula. Tectonics, Volume 12, No. 4, pages 1056-1075.

Stouge, S.
1982: Preliminary conodont biostratigraphy and correlation of Lower to Middle Ordovician carbonates of the St. George Group, Great Northern Peninsula, Newfoundland. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 82-3, 59 pages.

1984: Conodonts of the Middle Ordovician Table Head Formation, western Newfoundland. Fossils and Strata, Number 16, 145 pages.

Stouge, S. and Boyce, W.D.
1983: Fossils of northwestern Newfoundland and southeastern Labrador: conodonts and trilobites. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 83-3, 55 pages.

Westminer Canada Ltd
1992: Drill logs for RND 001 and RND 002 holes, Port au Port Peninsula.

Whittington, H.B. and Kindle, C.H.
1963: Middle Ordovician Table Head Formation, western Newfoundland. Geological Society of America Bulletin, Volume 74, pages 745-758.

Williams, S.H., Boyce, W.D. and James, N.P.
1987: Graptolites from the Lower-Middle Ordovician St. George and Table Head groups, western Newfoundland, and their correlation with trilobite, graptolite, brachiopod and conodont zones. Canadian Journal of Earth Sciences, Volume 24, pages 456-470.

Williams, S.H., Boyce, W.D., Knight, I., Measures, E.A. and Rohr, D.M.
2000: Early Ordovician (Arenig) graptolites from the upper St. George Group, Port au Port Peninsula, western Newfoundland: preservation, correlation and paleoenvironmental and stratigraphic implications. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Division, Report 2000-1, pages 291-298.