THE UPPER ST. GEORGE GROUP, WESTERN PORT AU PORT PENINSULA: LITHOSTRATIGRAPHY, BIOSTRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS AND REGIONAL IMPLICATIONS

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ABSTRACT

Shallow-water carbonate rocks of the upper part of the Early Ordovician St. George Group outcrop in several roadside exposures at the west end of the Port au Port Peninsula, western Newfoundland. The succession contains a previously undocumented, fairly abundant and diverse shelly fauna that includes ostracodes, trilobites, articulate brachiopods, ?bryozoa, cephalopods, crinoids, gastropod shells and opercula, machaeridians, sponges and calcispheres. The fauna occurs within metre-scale parasequences of open-shelf, muddy carbonates overlain by grainy carbonates that are commonly rich in small oncolites, and which are assigned to the Costa Bay Member, Catoche Formation. Well-preserved graptolites occur in the upper 20 m of the member, an interval marked by a shoaling sequence of subtidal muddy carbonate to crossbedded, now dolomitized, grainstone.

In contrast, peritidal cyclic carbonates of the overlying Aguathuna Formation yield mainly a mixed molluscan fauna of cephalopods, gastropod shells and silicified gastropod opercula although grainstone beds contain as yet indeterminate articulate brachiopods and trilobites.

The abundant and diverse faunas in shoaling, subtidal, limestone parasequences of the Costa Bay Member support an open-shelf, marine environment, seaward of a major grainstone barrier complex. The presence of graptolites at the top of the Costa Bay Member suggests that a significant oceanic flooding event may have marked the shelf at the transition from the open-shelf Costa Bay Member to the broad development of peritidal flats preserved in the Aguathuna Formation.

Two trilobite faunas occur in the Costa Bay Member, western Port au Port Peninsula, a lower Gignopeltis rarus fauna and an upper Cybelopsis speciosa fauna. The former is also known from the member at Burnt Island, Pistolet Bay but the upper fauna is newly discovered in western Newfoundland. It is correlated with a similar fauna in the Nunatami Formation of northern Greenland and with the Pseudocybele nasuta Zone (Zone J) of western Utah. The presence of D. bifidus zone graptolites in the upper Cybelopsis speciosa fauna, the Nunatami Formation and the Utah sections further strengthens this correlation. The trilobite and graptolite faunas, each support an older transition from Costa Bay Member to Aguathuna Formation in the north compared to the south of the western Newfoundland Arenig shelf. The Goniotelina and pliomerid trilobites in the subtidal muddy carbonates of the Costa Bay Member are tentatively assembled as a new biofacies, the Goniotelina-Cybelopsis biofacies.

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INTRODUCTION

Recently exposed sections through the upper part of the Early Ordovician St. George Group outcrop in a number of roadcuts along Route 463 between Cape St. George and Mainland, at the west end of the Port au Port Peninsula, western Newfoundland (Figure 1). The roadcut sections preserve strata from the Costa Bay Member, Catoche Formation, and the overlying Aguathuna Formation (Knight and James, 1987, 1988). This upper St. George Group stratigraphy is repeated by high-angle reverse faults that strike northeast and dip to the west. Two logged sections separated by one of these faults are correlated bed by bed using lithology and fauna (Figures 2 and 3).

The succession preserved in the west Port au Port Peninsula area is unique in western Newfoundland in that there is an abundance of fossil-bearing, unaltered limestones through a stratigraphic interval that elsewhere in western Newfoundland is commonly extensively dolomitized and/or sparsely fossiliferous. A diverse and common shelly fauna in the Costa Bay Member includes ostracodes, trilobites, articulate brachiopods, ?bryozoa, cephalopods, crinoids, gastropod shells and opercula, machaeridians, sponges and calcispheres. Graptolites are present in a 2.5 m interval within 20 m of the top of the Costa Bay Member and are the focus of an accompanying short paper (Williams et al., this volume). Molluscan faunas, which are commonly silicified, dominate the overlying Aguathuna Formation.

The faunas described herein were collected by W.D. Boyce, D.M. Rohr and E.A. Measures in 1998 and 1999; I. Knight measured detailed sections to complement the systematic macrofossil sampling.

LITHOSTRATIGRAPHIC SETTING

The St. George Group is a succession of Early Ordovician to lower Middle Ordovician subtidal and peritidal carbonate rocks that are subdivided into the Watts Bight, Boat Harbour, Catoche and Aguathuna formations (Knight and James, 1987, 1988). This succession is recognized to preserve at least two unconformity-bounded sequences (James et al., 1989), which consist of transgressive to regressive sedimentation, termed megacycles by Knight and James (1987). The upper megacycle includes rocks of the Barbace Cove Member of the Boat Harbour Formation, the Catoche Formation and the Aguathuna Formation. It is bounded below by the Boat Harbour disconformity ("pebble bed" of Knight, 1978; Boyce, 1978) and above by the St. George Unconformity (Knight et al., 1991). Carbonate rocks from the lower part of the upper megacycle preserve strata of transgressive and highstand system tracts (i.e., Barbace Cove Member and lower to middle part of the Catoche Formation) and are well documented faunally and lithologically, especially on the Great Northern Peninsula (Fortey, 1979; Stouge, 1982; Boyce, 1989; Knight, 1991; Stait and Barnes, 1991; Ji and Barnes, 1994; Boyce and Stouge, 1997). The upper, essentially regressive part of the megacycle is poorly known faunally, except through conodonts and some scattered graptolites (Williams et al., 1987; Stait, 1988; Stait and Barnes, 1991; Ji and Barnes, 1994), although it is well described lithologically on the Great Northern Peninsula (Knight, 1977, 1991; Knight and James, 1988; Stait, 1988; Knight and Cawood, 1991) and less so on the Port au Port Peninsula (Pratt, 1979; Pratt and James, 1986; Stait, 1988). This preliminary paper aims to address both the lithological and macrofaunal character of the upper part of the megacycle in a small area of the western end of Port au Port Peninsula and set this section within a regional Port au Port and western Newfoundland context.

The Catoche Formation on the Port au Port Peninsula consists of a lower limestone, a middle mound member and the Costa Bay Member. The lower limestone essentially consists of grey, bioturbated, peloidal and muddy, dolomitic limestone having thin storm beds and lenses of skeletal, intraclastic rudstone–grainstone. The middle mound member comprises stacked thrombolite mounds and grainstones and is pervasively dolomitized through much of the Peninsula (see Knight, 1996; Knight and Cawood, 1991). However, the mound member loses its massive character at the west end of the Peninsula (including the study area), so that mound beds are rather interbedded with bioturbated limestones like those of the lower member and the strata remains limestone.

The Costa Bay Member, which conformably overlies the mound member, is a well-bedded, white to cream, chemically pure limestone that predominantly comprises peloidal and intraclastic grainstone, and fenestral grainstone and grainy, fenestral microbial laminites. This apparently massive but well-bedded unit appears to lack cyclicity (Knight and James, 1988; I. Knight, unpublished data) although future detailed logging may change this impression. This grainy facies dominates the member from Aguathuna quarry west to the sections at Lower Cove limestone quarry in the centre of the Peninsula (Stride Consulting, 1988,1989) and White Hills limestone barrens (Tuach Geological Consultants, 1990) just 3.5 km east of the sections described in this paper (Figure 1).

The Costa Bay Member is conformably succeeded by the Aguathuna Formation, consisting of peritidal limestones and dolostones. Known from fairly detailed sections at the east end of the Peninsula, e.g., Aguathuna quarry and the East Bay coastal section (Pratt, 1979; Pratt and James, 1986; Knight and James, 1988; Stait, 1988), the Aguathuna For-
Figure 1. Geological map of the Port au Port Peninsula showing the location of the new section at the western end of the Peninsula and other important sections through the Costa Bay Member, Catoche Formation. Map based on Stockmal and Waldron (1993).
Figure 2. Detailed graphic logs of sections through the Costa Bay Member, Catoche Formation and the Aguathuna Formation, Route 462, western Fort au Port Peninsula.
Figure 3. Ranges of trilobite and graptolite taxa in the Costa Bay Member, Catoche Formation, section along Route 463, western Port au Port Peninsula.
LITHOSTRATIGRAPHY OF THE STUDY AREA

The upper St. George Group succession is characterized by a metre-scale cyclicity in both the Costa Bay Member and the Aguathuna Formation (Figure 2). The Costa Bay Member is at least 50 m thick and consists of a lower sequence of limestone and an upper unit of crystalline dolostone and minor limestone. The lower limestone comprises lithologically distinct facies by comparison to the type section at Aguathuna quarry. The upper dolostone unit is possibly also unique to the western end of the Peninsula although this must be verified by additional studies.

The lower limestone consists of 33 m of at least nineteen repetitive metre-scale cycles ranging in thickness from 0.35 to 7.5 m. The cycles consist of a basal, rubbly weathering, stylonodular, fossiliferous, dolomitic and argillaceous mudstone–wackestone having minor thin lenses of packstone, gradationally overlain by variably bioturbated and dolomitic, fossiliferous, peloidal wackestone–packstone–grainstone that is capped by oncolitic, skeletal, intraclastic-peloidal floatstone–rudstone–grainstone at the top of the cycle (Figure 2; Plate 1). The peloidal and oncolitic packstone–grainstone–rudstone are characteristically pale grey reflecting their generally clean and undolomitized state, similar to the limestones in the type section at Aguathuna. Sedimentary structures are rarely visible in the upper coarser facies of the cycles but rather skeletal and oncolitic allochems are commonly seen floating in a finer grained matrix (Plates 2 and 3). The tops of the cycles are generally sharp and planar but lack evidence of erosional truncation surfaces discounting the likelihood of erosion of lithified carbonate sediment.

Preservation of the shelly faunas in the limestones is excellent, with abundant complete articulate brachiopod valves, large robust straight and coiled cephalopods (Plate 2) and trilobite parts and (locally) almost complete trilobite carapaces, especially in the more stylonodular, muddier carbonates. Disarticulated crinoid ossicles, stem lengths and spines are scattered ubiquitously throughout the cycles.

The oncolites in the coarser facies generally average about 1 cm in diameter. They are oval in shape, mostly structureless and micritic (Plates 2 and 3), but rarely oncoids comprise peloidal packstone (some displaying cortices of a single microbial laminae), Girvanella or fenestral laminated fabric. Centimetre-sized sponges (Plate 3) are common in the upper part of the cycles.

The uppermost parasequences of the lower limestone consist of four decametre-scale cycles of rubbly weathering, stylonodular, dolomitic lime mudstone–wackestone capped by centimetre-thick intraclastic rudstone (Plates 4, 5 and 6).
This interval, which is 2.2 m thick, is exceptionally rich in shelly fossils. Graptolites are hosted by the topmost parasequence in the lower limestone, a sequence 1.6 m thick (see Williams et al., this volume).

The upper dolostone of the Costa Bay Member follows directly the graptolitic limestones of the top of the lower limestone (Plate 6). It comprises very finely to finely crystalline, dark grey to grey, burrow-mottled dolostone and crossbedded dolarenite (Plate 7), the latter hosting porosity and a faint petroliferous odor. Vestiges of limestone in the dolostone suggest that the unit is still part of the Costa Bay Member rather than part of the overlying Aguathuna Formation. The burrowed dolostone, which is 3 m thick, hosts the uppermost graptolite horizon in the section, 47 cm above its base. It is overlain by 11 m of crossbedded dolostone and the member is completed by a limestone, 3.7 m thick, of grainy, laminated, burrowed and possibly thrombolitic limestone below the first dololaminitic bed of the Aguathuna Formation. White cauliflower megaquartz nodules occur in the top of the lower burrowed dolostone and are present near the top of the dolarenite.

The Aguathuna Formation is characterized by limestone, dolostone and shale and its base is defined at the first thick dololaminitic bed (see Knight and James, 1987, 1988). The section measured to date is incomplete at 39 m; it will be completed to the St. George Unconformity in future field studies. The formation consists of 0.5 to 2.5 m parasequences comprised essentially of dololaminites, many of which host mudcracks, fissure cracks, sheet cracks, in situ brecciation, tepees and crosslamination (Plates 8 and 9), interbedded with peloidal, micritic and stromatolitic limestones, some oncotic–peloidal and oolitic grainstones and beds of laminated and fenestral limestone. Most of the stromatolites consist of biostromes of decametre-scale heads of laterally linked hemispheroidal laminated structure (Plate 10). Oncolites in contrast to those in the Costa Bay Member reach 2 to 3 cm in diameter, are beautifully laminated, display multiple asymmetrical growth stages and locally nucleate vertical digitate stromatolite suggesting that the oncoid had become immobilized in the rudstone–floatstone bed (Plate 11). Opercula form the nuclei of some of the oncolites.

Shales are intercalated with dololaminites higher in the formation but have yet to be logged in any significant thickness. However, shale forms the matrix to broken and brecciated carbonate at the top of one parasequence. Burrowed and crossbedded, very finely to finely crystalline, grey and dark grey mottled dolostones (Plate 12) commonly containing distinctive chert layers (Plate 13) and cauliflower chert nodules also occur. Cephalopods and silicified gastropod opercula are common in the oncotic and dolomitic beds and cross sections of trilobites and brachiopods occur in some of the peloidal grainstones.

Paleocaves filled by oligomictic breccias and geopetal laminated dolomite siltstone occur associated with dissolution of select limestone beds within the section (Plate 14).
Their presence, plus fairly widespread development of angular and irregular hairline fractures, are probably related to karstification of the succession below the St. George Unconformity. They are cut by subvertical fractures filled by red Carboniferous mudstone and siltstone.

**BIOSTRATIGRAPHY**

The preservation of a diverse and abundant shelly fauna in unaltered limestones of the Costa Bay Member in the west Port au Port Peninsula area is unique in western Newfoundland. The fauna includes ostracodes, trilobites, articulate brachiopods, ?bryozoan, cephalopods, crinoids, gastropod shells and opercula, machaeridians, sponges and calcispheres. Brachiopods and trilobites dominate the lower muddy strata of the Costa Bay parasequences where they may also be mixed with orthocones, ostracodes and crinoid ossicles. These faunas are also associated with robust coiled and straight cephalopods, gastropods and sponges in the grainier upper strata of the parasequences. A monospecific *Didymograptellus bifidus* (J. Hall, 1858) graptolite fauna occurs at a number of levels over a 2.5 m interval within 20 m of the top of the Costa Bay Member. The graptolites are preserved in predominantly burrowed muddy to grainy limestone and are concentrated just below the rudstone at the top of the lower limestone unit. They also occur in burrow-mottled dolostone 35 cm above the base of the upper dolostone unit (see Williams et al., this volume).

Two trilobite faunas are recognized in the limestones of the Costa Bay Member in the Route 463 sections at the west end of Port au Port Peninsula. The faunas include a lower *Gignopeltis rarus* fauna and an upper *Cybelopsis speciosa* fauna, which is partially illustrated in Plate 15.

The lower *Gignopeltis rarus* fauna (98F068) includes:
- **Arthropoda-Trilobita**
  - *Cybelopsis* sp. undet.
  - *Gignopeltis rarus* (Billings, 1865) - pygidium (+)
- **Brachiopoda-Articulata**
  - *Hesperonomia?* sp. undet.
  - Gen. et spp. undet. - at least two (2) species
- **?Bryozoa?**
  - Gen. et sp. undet.
- **Echinodermata-Crinoidea**
  - Gen. et sp(p). undet.
- **Mollusca-Cephalopoda**
  - Gen. et sp. undet. - straight form
- **Mollusca-Gastropoda**
  - *Maclurites* sp(p). undet.

The higher *Cybelopsis speciosa* fauna (98F069 to 98F011) includes:
- **Arthropoda-Ostracoda**
  - *Bivia?* sp. undet. - "wings" extend outward from shell (Plate 15D)
Arthropoda-Trilobita
asaphid? gen. et sp. undet.
Cybelopsis speciosa Poulsen, 1927 (Plate 15C)
Gen. et sp. undet.
Goniotelina sp(p). undet. (Plate 15A)
Ischyrotoma sp. undet.
Isoteloides? sp. undet.
Presbyniles sp. cf. P. latifrons Dean, 1989 (Plate 15E)
Pseudocybele sp. undet. (Plate 15B)
Raymondaspis? sp. undet. - cranidium (+, -)
Stroctacinus ?salteri (Billings, 1865) (Plate 15G)

Brachiopoda-Articulata
Hesperonomia? sp. undet. (Plate 15H)
Gen. et spp. undet. - at least two (2) species
Pomatotrema sp. cf. P. semiconvexum (Poulsen, 1927)

Echinodermata-Crinoidea
Gen. et sp(p). undet.

Hemichordata-Graptolithina
Didymograpteus bifidus (J. Hall, 1858) (see Williams et al., this volume)

Machaeridia
Plumulites sp. undet. (Plate 15F)

Mollusca-Cephalopoda
Buttsoceras? sp. undet.
Centrotarphyceras sp. undet. (Plate 2)
Gen. et sp. undet. - straight form

Mollusca-Gastropoda
Maclurites sp(p). undet.
Ophileta? sp. undet.

Porifera
Zittelella? sp. undet.

Subtidal shelf limestones and boundstone mound limestones of the lower part of the Catoche Formation of neighbouring areas to the road sections have yielded a fauna characteristic of the lower Catoche Formation elsewhere in western Newfoundland (Boyce, 1989; Boyce and Stouge, 1997). The lower Catoche fauna collected from Route 463 roadside outcrops and from the limestone barrens overlooking the road includes:

Arthropoda-Trilobita
?Benthamaspis sp. undet.
Bolbocephalus convexus (Billings, 1865)
Ischyrotoma anataphra Fortey, 1979
Jeffersonia angustimarginata Boyce, 1989
Jeffersonia sp. undet.
Jeffersonia timon (Billings, 1865)
Petigurus nero (Billings, 1865)
Petigurus sp. nov. A of Boyce (1989, pages 53-54; Plate 29, figure 7)
Strigigenalis caudata (Billings, 1865)

Brachiopoda-Articulata
Gen. et sp(p). undet.

Echinodermata-Crinoidea
Gen. et sp(p). undet.

Mollusca-Cephalopoda
Cassinoceras wortheni (Billings, 1865)
Centrotarphyceras sp. undet.
Gen. et sp. undet. - straight form
Protocycloceras lamarchi (Billings, 1859)

Mollusca-Gastropoda
Gen. et sp(p). undet.
Maclurites oceanus (Billings, 1865)
Maclurites sp(p). undet.
operculum illustrated by Billings (1865, page 243; Figure 229)
Pleurotomaria normani Billings, 1865
Pleurotomaria numeria Billings, 1865

Mollusca-Rostroconchia
Euchasma blumenbachii (Billings, 1859)

Porifera
Archaeoscyphia ?minganensis Billings, 1865
Calathium? sp. undet.

The above species are indicative of the late Canadian (Cassinian) Strigigenalis caudata to Benthamaspis gibberula zones of Boyce (1989, 1997a) and Boyce and Stouge (1997) and compare closely with faunas recovered from the bulk of the formation in sections on the Great Northern Peninsula.

The presence of Gignopeltis rarus (Billings, 1865) in the Costa Bay Member at Port au Port Peninsula indicates that the lower fauna correlates with the Late Canadian (Cassinian) Gignopeltis rarus Zone of Boyce (1997a). The fauna is also developed in the upper part of white limestones of the Costa Bay Member on Burnt Island, Pistolet Bay (Boyce et al., 1988). There G. rarus is part of a fairly diverse trilobite fauna that includes species recovered from a lower interval of grainy and bioturbated limestone and those recovered from an upper interval of dominantly thrombolitic mounds. The fauna includes the following trilobites:

Bathyurellus platypus Fortey, 1979****
Benthamaspis gibberula (Billings, 1865)**
Jeffersonia spp undet.***
Illaenus sp. nov.**
Strontacticus insularis (Billings, 1865)
Isoteloides canalis Whitfield, 1886****
Peltabellia glandicephalus (Whitfield, 1890)****
Catocchia glabra Fortey, 1979****
?Raymondaspis sp. undet.****
Bolbocephalus convexus (Billings, 1865)*
Uromystrum affine (Poulsen, 1937)*
Bolbocephalus kindlei Boyce, 1989*

* trilobites found only in the upper thrombolitic mound interval
** trilobites found predominantly in the upper mounds but also in the underlying bioturbated and grainy limestone interval
*** trilobites found only rarely in the mounds but common in other rock types
**** trilobites found only in the lower bioturbated and grainy limestone interval

1 formerly identified as I. latimarginatus Fortey, 1979
The trilobite fauna on Burnt Island therefore appears to be divisible into a lower assemblage that is compatible with a late faunal assemblage of the upper part of Zone I (Boyce et al., 1988; Boyce and Stouge, 1997). The mound-hosted fauna in the upper part of the section, which includes the zone fossil *G. rarus*, however, may mark the lower part of Zone J in western Newfoundland, since it also carries the Zone J (to later) trilobite genus *Kawina*.

The upper *Cybelopsis speciosa* fauna has not been identified in abundance anywhere else in western Newfoundland, although isolated elements of the fauna (i.e., *Bivia?* sp. nov.) have been recovered from undolomitized vestiges of upper Catoche limestone at Freshwater Cove near Table Point, Great Northern Peninsula (Boyce, 1985).

Based on the presence of *Cybelopsis speciosa* Poulsen, 1927, *Pomatotrema* sp. cf. *P. semiconvexum* (Poulsen, 1927) and *Didymograptellus bifidis* (J. Hall, 1858), the *Cybelopsis speciosa* fauna is correlated with the fauna of the Nunatami Formation of western North Greenland (see Appendix 1), and by extension with the *Pseudocybele nasuta* Zone (Zone J) of western Utah. The Nunatami Formation contains light grey, clean limestones that resemble the limestones of the section described in western Port au Port Peninsula (see Poulsen, 1927; W.D. Boyce, observation of samples and faunas of the Nunatami Formation housed at the Geological Museum, Copenhagen). The Zone J *P. nasuta* fauna of Utah is hosted by argillaceous and silty, fine-grained and grainy carbonates of the Wah Wah Formation (Jensen, 1967; Ethington et al., 1995) and the upper cherty member of the Garden City Formation (Ross, 1951). Yellow-weathering, thin-bedded, quartzose silty calcisiltites and tan-coloured calcareous shales intercalated with ledges of massive calcarenite characterize the Wah Wah Formation (Jensen, 1967; Ethington et al., 1995). The cherty member of the Garden City is similarly argillaceous and silty, cryptocrystalline limestones that have a stylo nodule aspect (interpreted from Ross’s description) (Ross, 1951).

*Isoteloides polaris* Poulsen, 1927 is common to the Nunatami Formation of western North Greenland and the *Pseudocybele nasuta* Zone (Zone J) of western Utah (see Appendix 2). Consequently, the *Cybelopsis speciosa* fauna of the Costa Bay Member readily correlates with the *Pseudocybele nasuta* Zone (Zone J). The correlation of the Route 463 Costa Bay sequence with Utah is strengthened by the presence of *Didymograptellus bifidis* (J. Hall, 1858) in Zone J correlative sections in Utah and Nevada (Ross and Berry, 1963).

This suggests that the Zone J fauna is hosted by lithofacies similar to those of the Costa Bay Member of western Port au Port Peninsula. The common association of Goniotelina and Cybelopsis in similar rocks of these three geographically distant areas, further suggests a common trilobite biofacies, tentatively designated here as the
Goniotelina-Cybelopsis biofacies. This Goniotelina-Cybelopsis biofacies marks it as a subfacies within the broader Bathurid biofacies of Fortey (1975).

DISCUSSION

DEPOSITIONAL SETTING OF THE UPPER ST. GEORGE GROUP, PORT AU PORT PENINSULA

The diverse fauna, the repetitive upward-coarsening cycles consisting of stylonodular and bioturbated, peloidal, muddy carbonate overlain by clean fossiliferous, peloidal, oncolitic and intraclastic grainy limestones suggest that the Costa Bay Member, at the western extreme of the Port au Port Peninsula, was deposited in an open-shelf setting. Here, the shelf was characterized by high carbonate production rates and moderate to low energy conditions that favoured proliferation of abundant calcareous organisms. Argillaceous and dolomitic stylonodular mudstone and wackestone are lithologically similar to fine-grained stylonodular carbonates described widely in the Middle Ordovician Table Point Formation (Stenzel, 1992; Stenzel et al., 1990) and were probably deposited below wave base, where they hosted mostly trilobites and brachiopods, crinoids and ostracodes. The carbonate mudrocks became cleaner as the shelf shallowed and the somewhat coarser and more mixed peloidal carbonates becoming extensively burrowed as the macrofauna became more diverse to include abundant crinoids, molluscs and sponges. The tops of the parasequences are marked by a mixture of floatstones, rudstones and packstone–grainstones. The general unsorted and featureless floatstones and rudstones, many with oncinites floating in a finer grained matrix along with robust molluscs and sponges, suggest storm deposits with little reworking by later bottom currents and/or an organic gravel-strewn sea floor, the preferred environment for prolific growth of sponges, molluscs and algal oncinites. The better sorted grainstones and very locally rudstones, still importantly devoid of observable current structures however, suggest sorting and reworking by bottom currents as the sea floor prograded toward wave base.

The coarsening-upward muddy to grainy, metre-scale parasequences characterize a zone of unknown width where repetitive sedimentation was controlled by repeated progradation of the leading edge of carbonate sand shoals over a muddy shelf bottom. However, the zone may be as wide as 10 km allowing for its extension south to Cape St. George. The lack of interbedded laminites, stromatolites, crossbedding or truncation surfaces at the cycle tops suggests the prograding lime sand shoals were never emergent, subject to tidal currents or extensively lithified in this area although the sharp planar tops to the cycles suggest that bottom currents scoured the top of the grainy shoals before the shelf was again drowned.

These characteristics, plus regional lithostratigraphic relationships, suggest that the area lay seaward of a broad peloidal carbonate barrier sand body (represented by the type Costa Bay lithofacies of the Aguathuna quarry to White Hills sections) that supplied much of the sand-sized detritus to the shelf. The generally consistent thickness and facies
architecture of the metre-scale cyclicity throughout the lower limestone suggests that the major facies belts remained essentially stable in this area throughout the Costa Bay Member although influenced by 5th order sea-level fluctuations. The barrier complex geographically occupied the centre and eastern part of the Port au Port Peninsula. It consists of stacked bodies of clean, peloidal and intraclastic, fenestral grainstones that characterize the high-purity limestone of the member quarried at Lower Cove and Aguathuna and which is last seen in the area of White Hills, 3.5 to 5 km to the east of the study area.

The graptolite-rich interval, 20 m from the top of the Costa Bay Member is part of a thick prograding sequence that began at its deepest in muddy, fossiliferous and burrowed, low-energy carbonates and was completed by a high-energy, crossbedded grainstone barrier complex. At least 75 percent of this thick sequence was later dolomitized. At its simplest, this sequence marks a transition from the open-shelf setting of the lower Costa Bay Member to the more restricted peritidal flat complex of the Aguathuna Formation. The unusually plentiful and diverse shelly fauna that includes deeper water shelf trilobites, the presence of didymograptids, and the predominance of deeper shelf carbonates in the lower half of the interval with little evidence of cyclicity may indicate a marine flooding event onto the shelf at this time.

The abundance of graptolites at the top of the Costa Bay Member may also, however, signal the stressful confluence of normal marine and saline shoal conditions along the seaward front of the barrier. It is probable that the briny waters of the shallow, hypersaline lagoon and tidal flat in the lee of the Costa Bay barrier complex were periodically flushed seaward by storms through tidal channels and storm-generated breaches across the barrier. The evacuation of the brines into the normal marine setting offshore of the barrier poisoned the pelagic graptolites and effected mass extinctions such as the graptolitic laminae described by Williams et al. (this volume). Turbulence, which would have been greatest in front of the barrier, possibly also lead to significant mortality in itself as well as perhaps sorting the pelagos into some of the graptolite beds (see Williams et al., this volume).

The extensive dolomitization that marks this interval may also be a reflection of the transitional position of a carbonate barrier complex between an open-shelf having normal marine salinity and carbonate chemistry and a very extensive, very shallow-water back-barrier tidal-flat complex with accompanying heightened salinity. The fine-grained crystallinity of the dolomite, the preservation of sedimentary textures (burrows, crossbedding, allochems) as well as some fossils and cauliflower chert nodules in the dolostone suggest that early shallow burial dolomitization, possibly the product of mixing zone diagenesis, marked the barrier complex as it was buried (compare to Haywick, 1984).

The Aguathuna Formation, characterized largely by metre-scale cyclicity and rocks that support peritidal deposition of carbonates, preserves a mix of tidal flats, shallow lagoons, oolitic and peloidal lime sand shoals and stromatolitic mound banks adjacent to tidal flats. Importance of mudcracked, broken and tepeed dololaminites, restricted faunas and of dolomitized burrowed carbonate, some with nodular chert layers possibly after evaporites, suggest a more restricted hypersaline setting for the much of the formation with zones of early dolomitization. Karstification at the top of one cycle supports local subaerial exposure of the tidal-flat complex. Apart from the obvious molluscan fauna, only the clean grainier limestones in the Aguathuna Formation contain some trilobites and brachiopods, suggesting short-lived open marine flooding at the margins of the flats.
Plate 15. Selected shelly fossils of the upper Cybelopsis speciosa fauna of the Costa Bay Member, Route 463, western Port au Port Peninsula.

A. Goniotelina sp. undet. Free cheek (top left) and hypostome (bottom centre). 12 mm from front to back tips of free cheek. Small pliomerid cranidium immediately to right of free cheek. Specimens from 98F095, (equivalent to 98F010, but on opposite side of Route 463) in same piece of rock as "F".

B. Pseudocybele sp. undet. Pygidium, 8 mm long. Specimen from 98F095 (equivalent to 98F010, but on opposite side of Route 463).

C. Cybelopsis speciosa Poulsen, 1927. Large, flattened and broken pygidium, 18 mm long. Specimen from 98F010.

D. Bivia? sp. nov., 4 mm horizontal length. Specimen from 98F010, in same piece of rock as "E".

E. Presbynileus sp. cf. P. latifrons Dean, 1989. Pygidium, 7 mm wide. Specimen from 98F010, in same piece of rock as "D".

F. Plumulites sp. undet. 2.3 mm long. Specimen from 98F095 (equivalent to 98010, but on opposite side of Route 463) in same piece of rock as "A".

G. Strotactinus ?saltleri Billings, 1861. Pygidium, 2.4 mm long. Specimen from 98F010, in same piece of rock as "H".

H. Hesperonomia? sp. undet., 6.5 mm long. Specimen from 98F010, in same piece of rock as "G".
THE COSTA BAY TRILOBITE FAUNAS – THEIR SIGNIFICANCE AND BIOFACIES

Ordovician trilobite assemblages have been subdivided into four broad biofacies, the inshore Bathyrurid biofacies, the mound-hosted Illaenid-Cheurirud biofacies, the slope-hosted Nileid biofacies and the deep-water Olenid biofacies (Fortey, 1975; Fortey and Droser, 1996). The Lower Ordovician carbonate shelf of western Newfoundland hosts only faunal assemblages of the Bathyrurid and Illaenid-Cheurirud biofacies (Boyce, 1986, 1989, 1997b). The trilobites of these biofacies are illustrated by Boyce (1989) in the rocks of the Barbace Cove Member, Boat Harbour Formation and the overlying lower limestone and mound sequence of the Catoche Formation. In particular, Boyce (1997b) was able to subdivide the Bathyrurid biofacies into two biofacies, the nearshore Isoteloides-Strigigenalis biofacies hosted mostly by ripple-marked grainstones, and the Jeffersonia biofacies that dominated much of the Catoche succession of bioturbated lime wackestones and packstones. The mound-hosted Illaenid-Cheurirud biofacies was refined to better reflect the Newfoundland mound fauna and was called the Illaenus-Bolbocephalus biofacies.

The biofacies model of Fortey (1975) is ideally suited to the characteristics of the Ordovician carbonate shelf during the deposition of the lower limestone and mound member of the Catoche Formation (Figure 4, section A). The trilobite faunas of this sequence correlate with Utah Zones G2, H and perhaps I, and belong to the Strigigenalis caudata and Benthamaspis gibberula Zones of Boyce (1989, 1997a; Boyce and Stouge, 1997). The lower Strigigenalis caudata Zone assemblages are essentially hosted by rocks that mark the transgressive system tract of the Arenig megacycle of Knight and James (1987) and comprise the Isoteloides-Strigigenalis and Jeffersonia biofacies. Individual mound beds in this part of the 3rd order sequence contain Bolbocephalus but lack illaenid trilobites (Boyce, 1989, 1997b). Carbonates of the hightand system tract which is marked by a stable subtidal shelf of outer barrier and inner subtidal shelf seaway (Figure 4, Section A) occurred in the higher B. gibberula Zone. A thrombolite-sponge mound barrier complex developed from Cape Norman in the north over 400 km to the Port au Port Peninsula in the south (Knight and Cawood, 1991) and dominated the outer parts of the exposed Newfoundland shelf during trilobite Zones H to I. The barrier hosts trilobites of the Illaenus-Bolbocephalus biofacies (Boyce, 1986, 1997b; Boyce et al., 1988). Inboard of this barrier complex (i.e., to the west and north), the Early Arenig–Late Canadian shelf was characterized by a broad subtidal lagoon/seawaway dotted with a patchwork of isolated thrombolite mounds (Knight, 1991; Knight and Cawood, 1991). The wide inboard lagoon/seawaway was the depository of subtidal shelf bioturbated muddy carbonates that host the Bathyrurid–Jeffersonia biofacies while the Illaenus-Bolbocephalus biofacies trilobites inhabited the patch reef-like thrombolite mounds that studded the seaway (Boyce, 1986, 1997b; Knight, 1991; Knight and Cawood, 1991).

The distribution of the trilobite biofacies in the upper part of Zone I and in Zone J of the upper St. George Group is, however, in marked contrast to the distribution of biofacies during trilobite Zones H to I in the lower part of the Catoche Formation (Figure 4). The Gignopeltis rarus and Cybelopsis speciosa faunas in the Costa Bay limestones of the west end of Port au Port Peninsula are viewed as new and important facies-controlled faunas that probably inhabited the more open-shelf setting seaward of a shoreline-hugging barrier on the late Canadian (Arenig) Newfoundland shelf (Figure 4, Section B and C).

Trilobites of the time-equivalent and lithologically comparable Utah sections, however, have been characterized as inshore shelf Bathyrurid biofacies (Fortey and Droser, 1996). The association of common Goniotelina and pliomerid trilobites in the Costa Bay Member as in the lithologically similar Nunatami Formation, Greenland and the Utah sections, together with the D. bifidus graptolites, strongly suggest an open-marine influence dominated the western Port au Port shelf and suggest that no outer barrier complex occurred during Zone J of this late Canadian stage in the development of the shelf. Rather in the Port au Port area, a shoreline barrier complex of high-energy carbonate sands marks the shoreline edge of this open shelf, protecting a very broad back barrier zone of peritidal flats (Aguathuna Formation).

At Burnt Island, Northern Peninsula, the nearshore barrier separating offshore shelf from back barrier peritidal flats is not a grainstone complex but a thrombolitic reef complex. The fauna and succession in the Costa Bay Member at Burnt Island is interesting for several reasons. First, it includes elements of both the Illaenus-Bolbocephalus biofacies that is predicted to dominate mound sequences in Newfoundland and elsewhere, and elements of the inshore shelf Bathyrurid biofacies (Boyce et al., 1988; Boyce and Stouge, 1997; Fortey, 1975; Fortey and Droser, 1996). The presence of the deeper water trilobite Kawina sp. undet. in the mound sequence however, appears to predict that the Burnt Island section lies just inboard of an open shelf (Figure 4, Section B). Second, the fauna appears to straddle Zones I to J. Lastly, the sequence occurs immediately below the contact with the Aguathuna Formation because the Costa Bay Member is overlain by a few metres of dololaminites of the Aguathuna Formation below the St. George Unconformity at the top of the Burnt Island section (see Knight et al., 1991).
Figure 4. Early Ordovician biozones related to lithofacies in the lower and upper parts of the late Canadian (Arenig) shelf in western Newfoundland. Based on Fortey, 1975; Fortey and Droser, 1996 and modified to include Newfoundland faunal zones and biozones of Boyce (1997a and b), Boyce and Stouge, 1997.
This indicates that the development of Aguathuna Formation peritidal flat complexes that marks the top of the St. George Group occurred sooner on the Northern Peninsula than to the south on Port au Port Peninsula. The transition in the south occurs after the proliferation of the later Zone J Cybelopsis speciosa fauna in the open shelf limestones of the upper part of the Costa Bay Member. A similar conclusion was reached for this Costa Bay–Aguathuna transition based on graptolite distribution on the Northern and Port au Port Peninsulas (see Williams et al., this volume). Nonetheless, regardless of timing or geographical areas, the widely separated sections (400 km apart) each illustrate a common theme of inboard tidal flat that mostly hosts a molluscan biofacies, a shoreline barrier complex that may host locally in mounds the Illaenus-Bolbocephalus biofacies and then offshore an open shelf of unknown width that was host to a specialized Bathyruid biofacies trilobite fauna, the Goniotelina-Cybelopsis biofacies.

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Note: Geological Survey file numbers are included in square brackets.
APPENDIX 1

Faunas of the Nunatami Formation of western North Greenland

Poulsen (1927) subdivided the Nunatami Formation into four members; in ascending order, these are:

Bifidus shale
Angustifolius limestone
Gastropod limestone
Ostracod limestone

The faunas of the members are listed below.

**Bifidus Shale**

Hemichordata-Graptolithina
- dichogaptid? genus et sp. ind. Poulsen, 1927
  Didymograptus *(Didymograptellus) bifidus* (J. Hall, 1858)

**Angustifolius Limestone**

Arthropoda-Trilobita
- *Goniotelina?* sp. ind. (Poulsen, 1927; Plate XX, figure 3)
  *Isoteloides polaris* Poulsen, 1927

Hemichordata-Graptolithina
- *Phyllograptus angustifolius* Hall, 1858

Mollusca-Cephalopoda
- Genus et sp. ind. Poulsen, 1927

Mollusca-Gastropoda
- *Raphistomina latiumbilicata* Poulsen, 1927

Associated brachiopod. Associated low spired gastropod.

**Gastropod Limestone**

Arthropoda-Trilobita
- *Psephosthenaspis* sp. ind.

Brachiopoda-Articulata
- *Deltorthis* sp. Poulsen, 1927

Mollusca-Gastropoda
- *Hormotoma* sp. ind.
  *Turritoma* sp. ind. I. Poulsen, 1927
  *Turritoma* sp. ind. II. Poulsen, 1927

Troelsen (1950, page 53) suggested that the Gastropod limestone merely occurs as lenses or thin layers within the Nunatami Formation.

**Ostracod Limestone**

Arthropoda-Ostracoda
- *Isochilina arctica* Poulsen, 1927
- *Isochilina egressa* Poulsen, 1927
- *Isochilina perporosa* Poulsen, 1927
- *Isochilina suavis* Poulsen, 1927

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1 *Didymograptus bifidus* (Hall, 1858)
Arthropoda-Trilobita
   *Bathyurellus tenuis* Poulsen, 1927
   *Bolbocephalus angustisulcatus* Poulsen, 1927
   *Cybelopsis speciosa* Poulsen, 1927
   *Goniotelina boggildi* (Poulsen, 1927)
   *Goniotelina crassicornis* (Poulsen, 1927)
   *Illaenus/Presbynileus glaber* (Poulsen, 1927)
   *?Isoteloides* sp. Poulsen, 1927
   *Jeffersonia exterminata* Poulsen, 1927
   *Kanoshia insolita* (Poulsen, 1927)
   *Psephosthenaspis?* sp. ind.

Brachiopoda-Articulata
   *Clitambonites trivialis* Poulsen, 1927
   *Pomatotrema semiconvexum* (Poulsen, 1927)
   *Syntrophia rhombica* Poulsen, 1927

Mollusca-Cephalopoda
   *Buttsoceras? modestum* (Poulsen, 1927)

This unit also contains crinoids.

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2 *Pliomera insolita* Poulsen, 1927
3 *Pliomera dactylifera* Poulsen, 1927
APPENDIX 2

Taxa of the *Pseudocybele nasuta* Zone (Zone J) of Utah and Nevada, U.S.A.

Ross (1951, pages 27-28) listed the following from the Garden City Formation of northeastern Utah:

**Arthropoda-Trilobita**

*Carolinites genacinaca* Ross, 1951
*Goniotelina williamsi* (Ross, 1951)
*Ischyrotoma caudanodosa* (Ross, 1951)
*Isoteloides?* sp.
*Kawina sexapugia* Ross, 1951
*Lachnostoma latuclsum* Ross, 1951
*Pseudocybele nasuta* Ross, 1951
*Ptyocephalus delevita* (Ross, 1951)

**Brachiopoda-Articulata**

*Diparelasma* sp.
*Hesperonomia dinorthoides* Ulrich and Cooper, 1938
*Syntrophopsis* sp. cf. *S.polita* Ulrich and Cooper, 1938
*Tritoechia* sp. nov.

Hintze (1952, page 18, Table 10), Jensen (1967), Braithwaite (1976), Ross *et al.* (1993), and Ethington *et al.* (1995, pages 16-17) listed the following from the Wah Wah Formation (Pogonip Group) of western Utah and eastern Nevada:

**Arthropoda-Trilobita**

*Benthamaspis diminutiva* Hintze, 1952
*Carolinites genacinaca* Ross, 1951
*Cybelopsis* sp. cf. *C. speciosa* Poulsen, 1927
*Goniotelina brighti* (Hintze, 1952)
*Goniotelina brevis* (Hintze, 1952)
*Goniotelina sp. D* (Hintze, 1952)
*Goniotelina wahlwahensis* (Hintze, 1952)
*Ischyrotoma caudanodosa* (Ross, 1951)
*Isoteloides polaris* Poulsen, 1927
*Kanoshia* sp. cf. *K. insolita* (Poulsen, 1927)
*Kawina sexapugia* Ross, 1951
*Kawina webbi* Hintze, 1952
*Lachnostoma latuclsum* Ross, 1951
*Presbynileus* sp.
*Presbynileus utahensis* (Hintze, 1952)

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4 *Eleutherocentrus williamsi* Ross, 1951
5 *Dimeropygiella caudanodosa* Ross, 1951
6 *Kirkella delevita* Ross, 1951
7 *Goniotelus brighti* Hintze, 1952
8 *Goniotelus brevis* Hintze, 1952
9 *Goniotelus sp. D* Hintze, 1952
10 *Goniotelus wahlwahensis* Hintze, 1952
11 *Dimeropygiella caudanodosa* Ross, 1951
12 *Paranileus* sp.
13 *Paranileus utahensis* Hintze, 1952
Psephosthenaspis? sp.\(^{14}\)

*Pseudocybele nasuta* Ross, 1951

*Ptyocephalus declevita* (Ross, 1951)\(^{15}\)

*Ptyocephalus* sp. cf. *P. vigilans* Whittington, 1948\(^{16}\)

*Stenorhachis genalticurvatus* (Hintze, 1952)\(^{17}\)

*Theamataspis* sp.\(^{18}\)

*Trigonocercella acuta* Hintze, 1952

**Brachiopoda-Articulata**

*Diparelasma* sp. cf. *D. transversa* Ulrich and Cooper, 1938

*Diparelasma typicum* Ulrich and Cooper, 1936

*Hesperonomia dinorthoides* Ulrich and Cooper, 1938

*Hesperonomia fontinalis* (White)

*Hesperonomia subtransversa* Ulrich and Cooper, 1938

*Syntrophopsis* sp. cf. *S. polita* Ulrich and Cooper, 1938

*Tritechia sinuata* Ulrich and Cooper, 1938

**Bryozoa?**

**Echinodermata-Cystoidea**

cystid plates

**Hemichordata-Graptolithina**

*Callograptus* sp.

*Desmograptus* sp.

*Dichograptus octobrachiatus* (J. Hall, 1858)

*Didymograptus extensus* (J. Hall, 1858)

*Phyllograptus anna* J. Hall, 1865

*Phyllograptus anna longus* (Ruedemann, 1947)

*Phyllograptus griggii* Ross and Berry, 1963

*Phyllograptus ilicifoliusmajor* Ruedemann, 1947

*Phyllograptus loringi* White

*Tetragraptus agilis* Braithwaite, 1976

*Tetragraptus ibexensis* Braithwaite, 1976

*Tetragraptus pogonipensis* Braithwaite, 1976

**Mollusca-Cephalopoda**

*Campbellloceras?* sp.

*Catoraphiceras* sp.

*Endoceras* sp.

**Mollusca-Gastropoda**

*Bellerophon*-like sp.

*Lesuerilla?* sp.

*Raphistomina* sp.

**Porifera**

*Zittelella* sp. cf. *Z. clarae* Howell

\(^{14}\) Unassigned pygidium of Hintze (1952, page 18; Plate XV, figure 19)

\(^{15}\) *Kirkella declevita* Ross, 1951

\(^{16}\) *Kirkella* sp. cf. *K. vigilans* (Whittington, 1948)

\(^{17}\) *Isoteloides genalticurvatus* Hintze, 1952

\(^{18}\) "*Barrandia?* sp." Walcott