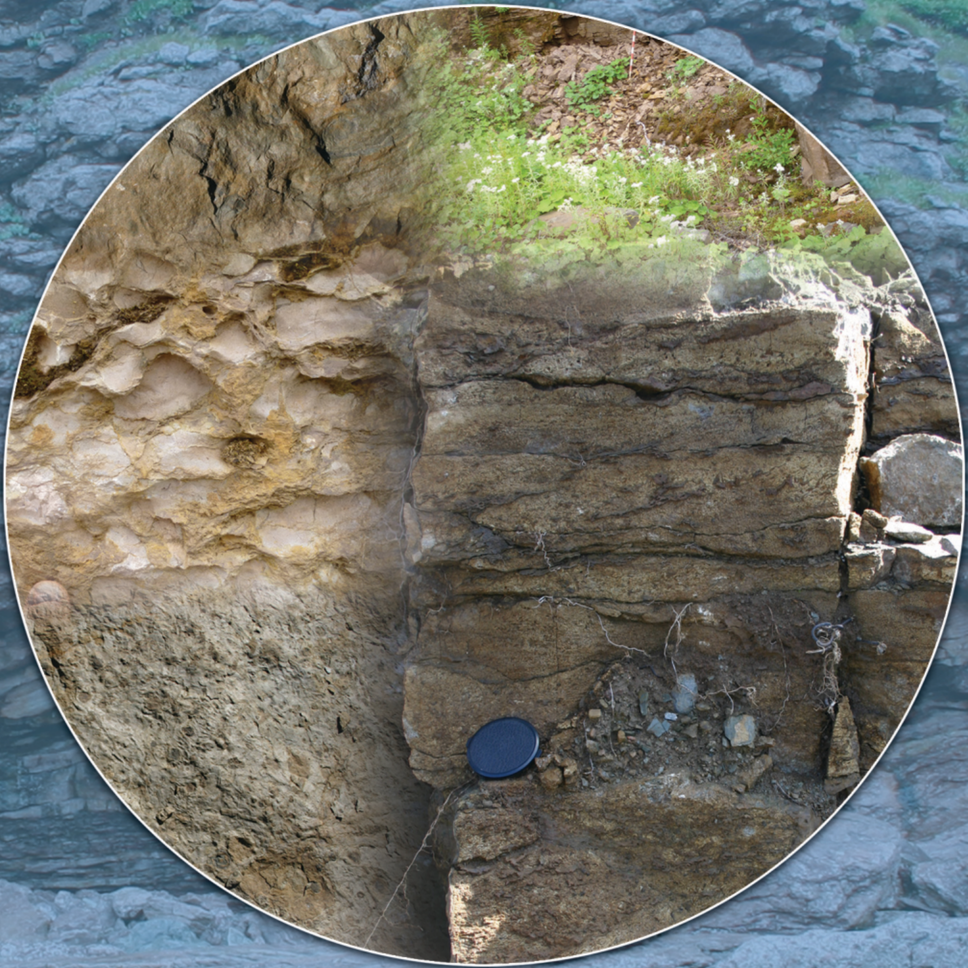
Newfoundland Labrador
Natural Resources

# THE LOWER CAMBRIAN FORTEAU FORMATION, SOUTHERN LABRADOR AND GREAT NORTHERN PENINSULA, WESTERN NEWFOUNDLAND: LITHOSTRATIGRAPHY, TRILOBITES AND DEPOSITIONAL SETTING



I. Knight, W.D. Boyce, C.B. Skovsted and U. Balthasar
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## NOTE

## DISCLAIMER

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Newfoundland Labrador

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Mines

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# ABSTRACT

*The upper Lower Cambrian Forteau Formation in southern Labrador and the Great Northern Peninsula (GNP) is a succession of shale, limestone, siltstone and sandstone accommodated by rising sea levels during the early drift stages of Newfoundland's Laurentian passive margin. Its Dyeran trilobite fauna, characterized by* Elliptocephala logani *(Walcott, 1910) that ranges throughout the formation, indicates it was mostly deposited in the middle* Bonnia–Olenellus *Zone. Its three lithostratigraphic divisions, the Devils Cove member, Middle shale and Upper limestone, preserve a transgressive system tract (TST; Devils Cove and lower part of the Middle shale) and the early stages of a regressive high-stand system tract (HST; upper Middle shale and Upper limestone) that hosts a carbonate ramp shelf.*

*A mudstone-dominated succession characterizes the TST, comprised of an inner belt of archeocyathid patch reef and cyclic, well-stratified, fine-grained mixed clastic and carbonate shelf rocks in southern Labrador. To the southeast on the GNP, the shale succession along with minor limestone and no reefs suggests a deeper water shelf basin in which shale accumulated across the GNP. Maximum flooding on the GNP is linked to dark shale midway through the basinal succession, and to a thick shale bed that overlies the reefal strata in Labrador.*

*Thin-bedded siltstone, sandstone and limestone in Labrador, and extensively bioturbated siltstone, sandstone and rare limestone on the GNP, support a shelf shallowing above storm-wave base as it prograded during the early stages of regression. Shallow-water carbonate of the Upper limestone supports a prograding shelf, at first dominated by an archeocyathid reefal tract and oolitic shoal complex. The reef tract and carbonate sand shoal complex prograded southeastward to just beyond the northeast-trending Ten Mile Lake–Long Range fault system. Evidence of slumping in the underlying fine clastic sediment in the same area suggest that this fault zone may coincide with a hinge zone, beyond which the shelf steepened into mostly deep-water clastic sedimentation. The archeocyathid tract in southern Labrador is a broad biostromal complex confined within an erosional recess in the shelf. On the GNP, however, the tract is characterized by high-energy bioherms associated with crossbedded grainstone channels that can be traced for over 60 km along a northeast strike length.*

*East of the reef tract–shoal complex, the succession appears to be dominated by deeper water shelf mudrock, nodular carbonate and little evidence of shallow-water carbonate facies. The facies transition suggests the Forteau Formation in southern Labrador and the GNP was laid down in a high-energy shallow-water, inner ramp setting that was up to 75 km wide. Above the carbonate sand shoal complex, the succession is marked by decametre-thick parasequences of intercalated carbonate and clastic intervals. The sequences support a shelf of fine grained to grainy carbonate deposited on an open shelf ramp overlain by intervals dominated by coarsening upward high-energy siliciclastics that suggest barrier complexes along the landward margin of the ramp. Thick units of crossbedded quartz arenite, in the upper half of the Upper limestone, suggest terrigenous sediments initially encroached along the inner part of the shelf, and eventually smothered the Forteau shelf leading to the low-stand deposits of the overlying Hawke Bay Formation. Trilobites recovered from this transition throughout the GNP, indicate that it occurred very late in the upper part of the* Bonnia–Olenellus *Zone, likely between the* Bristolia mohavensis *Biozone and the top of the zone.*

# INTRODUCTION

The Forteau Formation, middle Labrador Group, is part of a 3rd order, transgressive–regressive megasequence that formed the first, shallow-water, craton-fringing shelf of Newfoundland's Laurentian passive margin in the late Early Cambrian (James *et al.*, 1989b). Mapped throughout western Newfoundland and locally in southern Labrador (Figure 1), the late Early to early Middle Cambrian Labrador Group and its three formations, Bradore, Forteau and Hawke Bay, was first described by Schuchert and Dunbar (1934; Labrador series) and remains the preferred stratigraphic definition of most regional studies (*e.g.*, James *et al.*, 1989b; Knight *et al.*, 1995). The formation was originally documented as "division B" of the Potsdam Group by Logan *et al.* (1863).

The Labrador Group rests unconformably upon Proterozoic crystalline basement (1600 to 900 Ma) in southern Labrador and much of western Newfoundland. Locally at Canada Bay and Belle Isle, however, it sits paraconformably to unconformably, upon flat-lying to tilted Ediacaran rift basin rocks of the Bateau and Lighthouse Cove formations (Williams and Stevens, 1969; Bostock *et al.*, 1983; Knight, 1987; Gower *et al.*, 2001).

In southern Labrador, the group's type area, the formation, a succession of limestone, shale, siltstone and sandstone named after Forteau, Forteau Bay, is incomplete (~ 55 to 70 m thick). However, beneath the southern shore of the Strait of Belle Isle, Great Northern Peninsula (GNP), the full formation attains 120 m thickness (drillhole NF-1B, Figure 2; *see* also Cumming *in* Bostock *et al.*, 1983). Other easily accessible stratigraphic sections are rare. The section logged along the precipitous Frenchmans Brook, Highlands of St John (HSJ) in 1920 by Lovering and Dunbar (Figure 3, Schuchert and Dunbar, 1934) is unsuitable as it is steep, overgrown and not easy to access. The cored section logged by Lam and others (Cumming *in* Bostock *et al.*, 1983) at Yankee Point near Flowers Cove is descriptively useful, but the core is lost. Fortunately, cored drill holes (inclined at 30° angle) were recently drilled through the Labrador Group at nearby Savage Cove by Nalcor Energy in 2009-2010, and one of these cores (such as drillcore DH-NF-1B, Figure 2) would make an ideal type section for the group and for the Forteau Formation.

The formation is mapped at 1:50 000 scale throughout the Cambro-Ordovician shelf sequence in western Newfoundland (*e.g.*, Knight, 1977, 1986, 2013). Its succession changes from an inboard, dominantly shallow-water succession in southern Labrador and northwest Newfoundland, to a deeper water, outboard succession in the east and southern exposures of the formation. The outboard succession, exposed in Gros Morne, Canada Bay, White Bay, and near Deer Lake and Stephenville is described elsewhere (Knight, 2013).

The inboard Forteau succession is rich in thick units of variegated shale and siltstone, fine- to coarse-grained sandstone, oolitic and skeletal grainstone to packstone, skeletal and burrowed wackestone, thin-bedded fine-grained limestone, and locally archeocyathid buildups. The outboard succession as recorded in Gros Morne (Knight, 2013) is dominated by mudrocks (shale and mudstone, now largely slate) and fine-grained ribbon-bedded siliciclastics. Limestone in the outboard succession is mostly limestone nodules, thin beds of fine-grained and skeletal rich, stylonodular limestone, a few thick beds of stylonodular skeletal limestone, and the odd thin bed of oolitic limestone. No archeocyathid limestone occurs and only one thick oolitic limestone is mapped at Canada Bay (Knight, 1987; Knight and Boyce, 1987). The outboard succession becomes increasingly shale rich to the east suggesting deposition on an eastward deepening ramp (James *et al.*, 1989b).

Previously, detailed studies of the formation concentrated upon the famous cliff exposures of archeocyathid reef complexes in southern Labrador (James and Kobluk, 1978; Hughes, 1979; Debrenne and James, 1981). However, stratigraphic and sedimentological studies are scant apart from those focused on the reefs. Mapping studies on the GNP provide general observations of the disparate outcrops exposed in the area (Knight, 1985a, b, 1986, 1987, 1991; Knight *et al.*, 1986a, b; Snow and Knight, 1979). Macrofaunas (brachiopods, hyolithids, salterellids, small shelly fossils and trilobites) are listed in various publications (Billings *in* Logan *et al.*, 1863; Billings, 1861, 1865; Schuchert and Dunbar, 1934; Betz, 1939; Resser, 1937; Resser and Howell, 1938; Yochelson, 1970, 1977; Stouge and Boyce, 1983; Fritz and Yochelson, 1989; Skovsted, 2003; Skovsted and Peel, 2007; Skovsted *et al.*, 2010; Knight and Boyce, 2015a). Unpublished acritarch studies yielded a Vergale flora (E. Burden, personal communication, 2003).

The formation figures prominently in studies that correlated the Newfoundland Paleozoic shelf sequence with that in Central-East Greenland and Scotland. Swett and Smit (1972a, b) correlated the formation with the Bastion and Ella Ø formations in Greenland and the Fucoid beds of the An T'Sron Formation in Scotland and brought attention to the shale's high $K_2O$ content.

This study focuses on the inboard succession in southern Labrador and the GNP. It attempts to integrate recent field studies (2007, 2008 and 2012) to investigate small shelly fossils and trilobites throughout western Newfoundland (Skovsted *et al.*, 2010; *in press*) and logging of the Nalcor

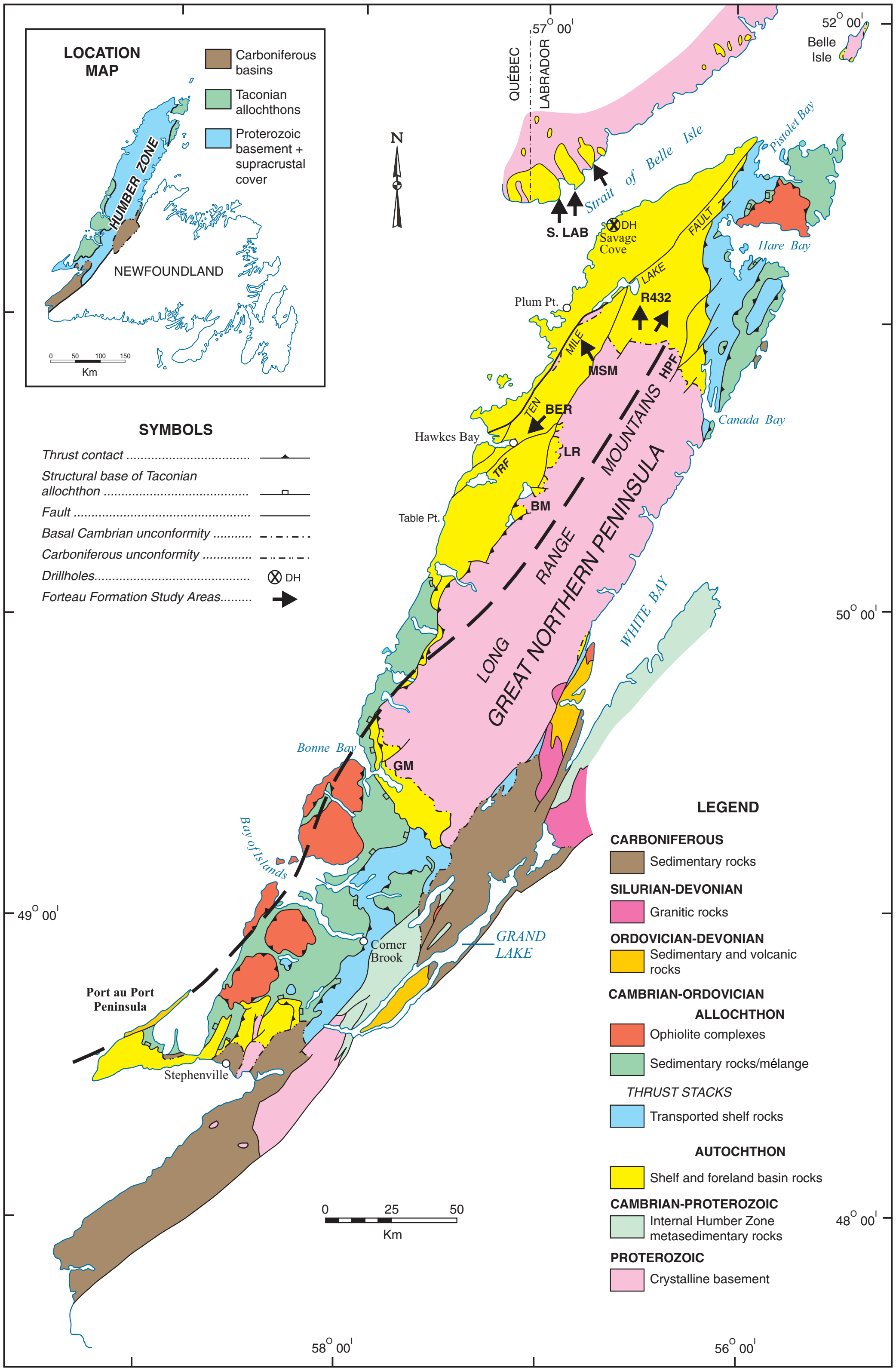


**Figure 1.** *Geology map of western Newfoundland showing its main geological terranes and the location of study areas (arrows) hosting rocks of the Lower Paleozoic shelf succession. S. Lab – southern Labrador, MSM – Mount St. Margaret, R432 – Route 432, BER – Big East River resource road, and DH – Drillhole DH-NF-1B (Savage Cove). TRF – Torrent River Fault. HPF – Hatters Pond Fault. LR – Long Range Cambrian Outliers. BM – Blue Mountain. GM – Gros Morne National Park. The heavy dashed line marks the approximate divide between the inboard and outboard zones of the Forteau shelf.*

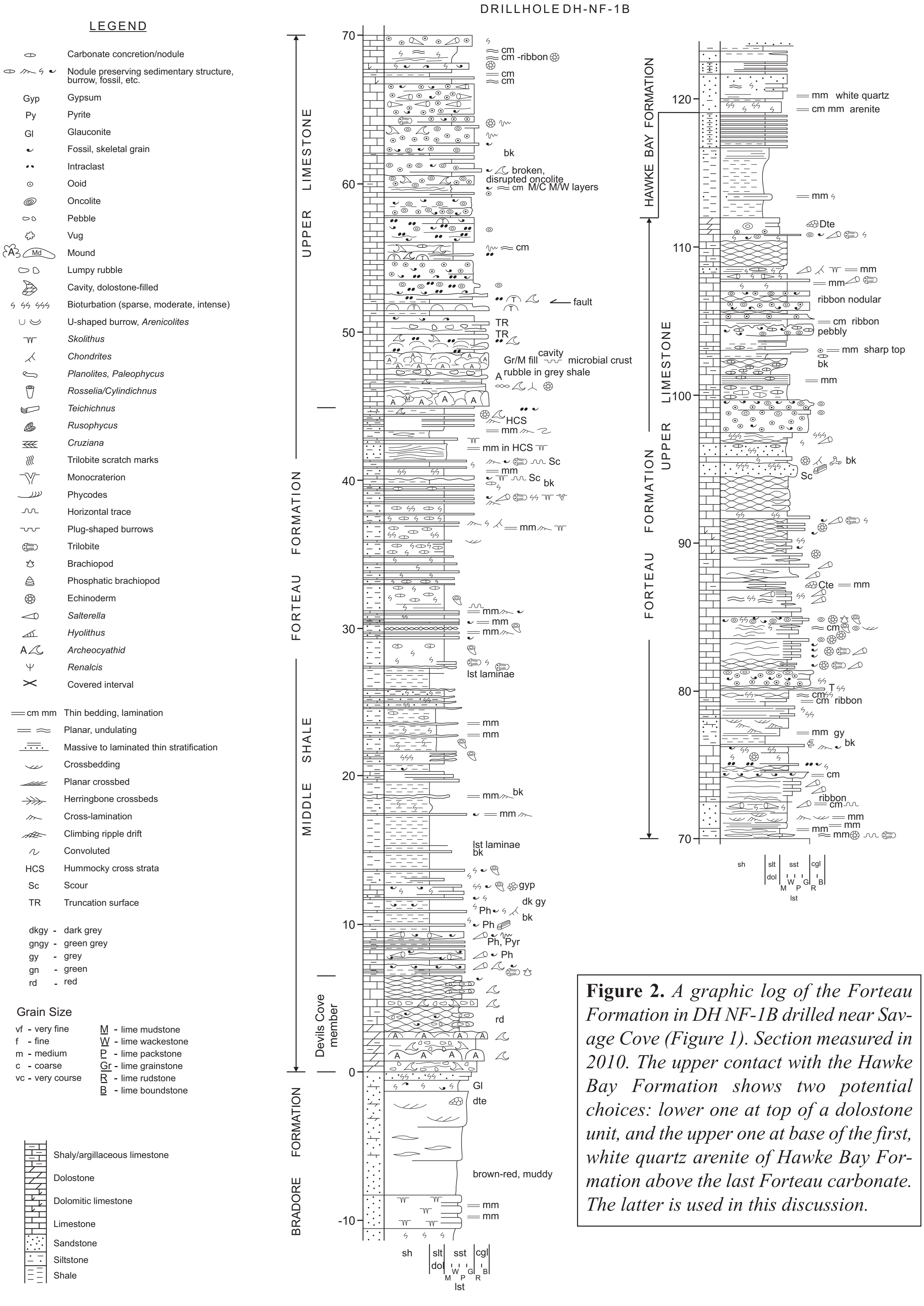


**Figure 2.** *A graphic log of the Forteau Formation in DH NF-1B drilled near Savage Cove (Figure 1). Section measured in 2010. The upper contact with the Hawke Bay Formation shows two potential choices: lower one at top of a dolostone unit, and the upper one at base of the first, white quartz arenite of Hawke Bay Formation above the last Forteau carbonate. The latter is used in this discussion.*

Energy drillcore DH-NF-1B at Savage Cove in 2010 (Figure 2) with the earlier studies listed above. The formation was examined in three areas (Figure 1), namely: 1) Paleozoic outliers along the Labrador shore of the Strait of Belle Isle (Figure 3); 2) Mt. St. Margaret quarry (MSM) and road side outcrops and quarries along Route 463 east of Ten Mile Lake (Figure 4); and 3) small quarry and roadcut outcrops along resource roads striking northeast into the Newfoundland forest from Hawkes Bay, informally named the Big East River (BER) sections (Figure 5). Southeast of Hawkes Bay, observations were made during 1:50 000-scale mapping in 1982 to 1984 (Knight, 1985b, 1991) and along newly developed woods roads near Blue Pond and Blue Mountain (I. Knight, unpublished data, 2012).

Drillcore DH NF-1B (Figure 2) forms the basis of the lithostratigraphic framework of the inboard succession. Most sections measured during the field study are short (rarely exceeding 10 m in thickness) and geographically isolated from each other. They were measured using a graduated measuring stick, 1.5 m long, and positioned by standard mapping techniques (measured bedding strike and dip coupled with field station location by Garmin GPS plotted on existing geological maps of the areas). Macrofossil collections and samples col-

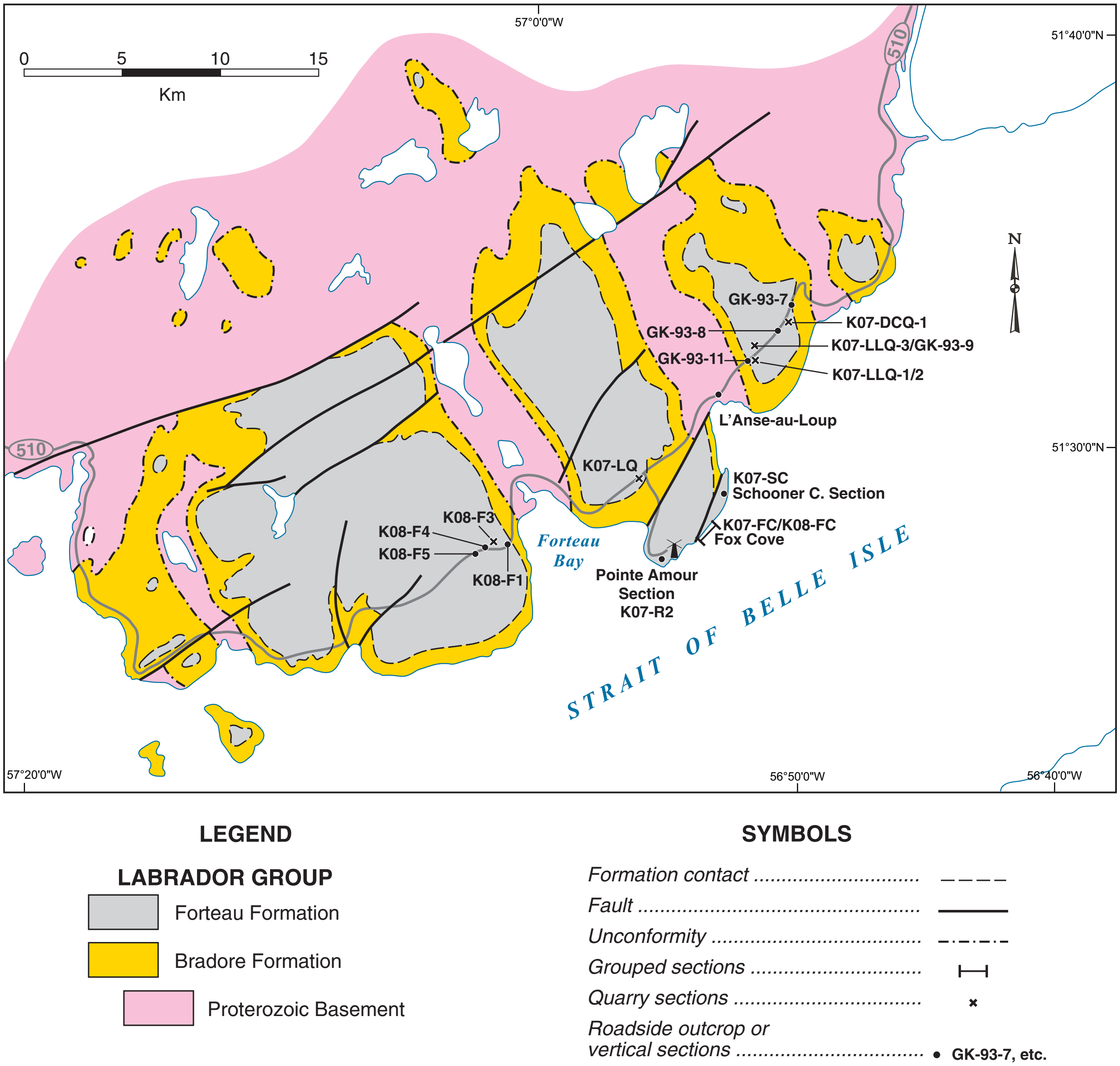


**Figure 3.** *Geology map of the south coast of Labrador showing localities in the Forteau Formation, Labrador Group that were studied (map based on Bostock* et al.*, 1983 and Gower, 2010). LLQ – L'Anse au Loup quarry, DCQ – Diablo Cove quarry, K07, K08 studies in 2007, 2008. GK-7 and the others – studied in 1993 with C.F. Gower.*

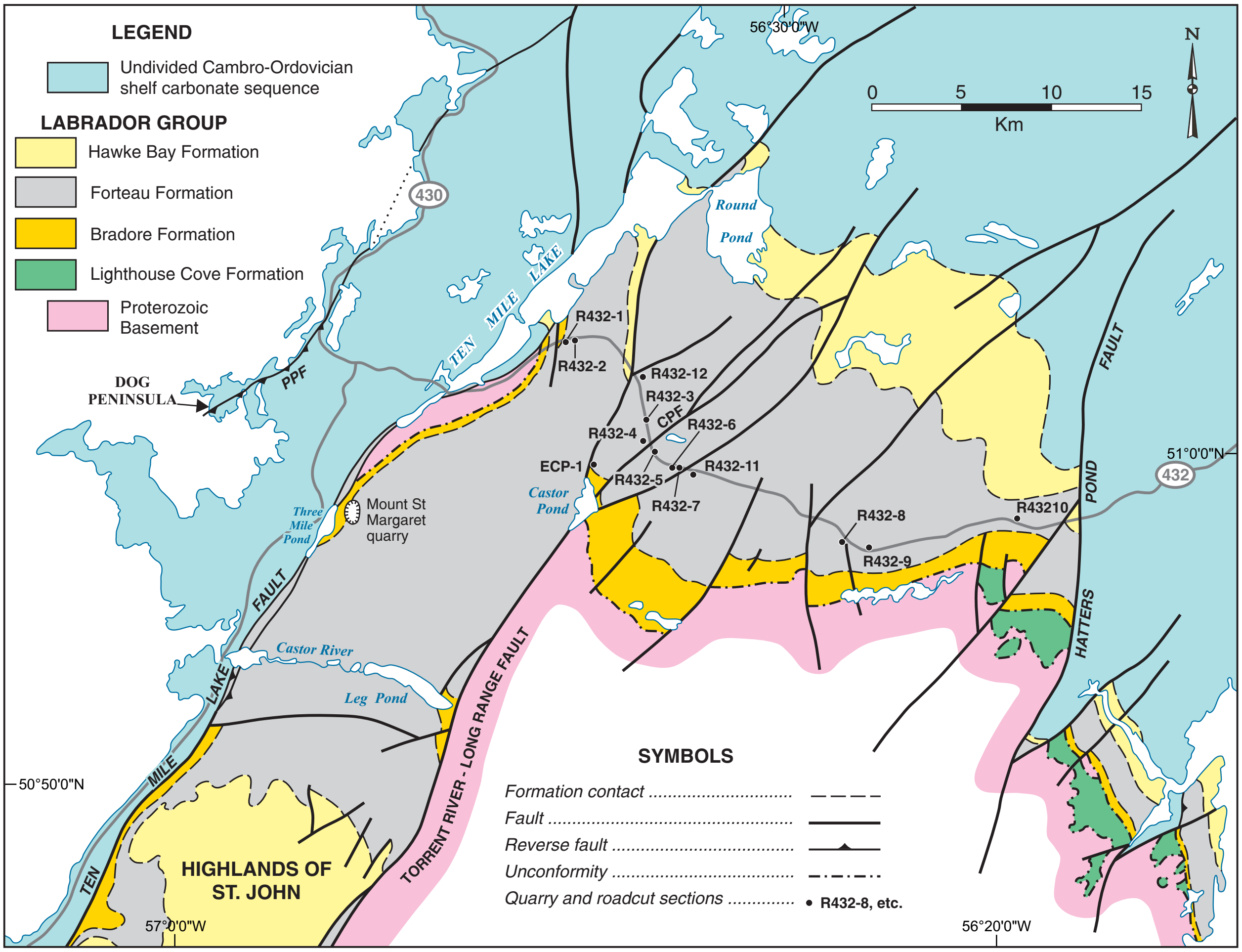


**Figure 4.** *Geology map of Ten Mile Lake to Canada Bay area of the Great Northern Peninsula showing localities studied in the Forteau Formation at Mount St. Margaret quarry, East Castor Pond road (ECP), and Route 432 (*e.g.*, R432-1). CPF – Castor Pond fault, PPF – Plum Point fault.*

lected for processing were located precisely during sectioning and fossil samples relevant to trilobite faunas are shown in this study.

## REGIONAL GEOLOGY AND SETTING

Lower Paleozoic shelf strata occur widely throughout western Newfoundland in the outer Humber Tectonostratigraphic Zone (Hibbard *et al.*, 2006) where it occurs as a sinuous belt snaking around Proterozoic basement massifs and transported Taconic allochthons (Figure 1). The inboard shelf succession occurs both in the foreland to, and in, the northwest of the Humber Zone, the Appalachian deformational front coinciding with either the Ten Mile Lake Fault system (Williams, 1978; Hibbard *et al.*, 2006) or the Plum Point fault, 10 km west of the Ten Mile Lake Fault (Knight and Boyce, 2015a).

The foreland succession in southern Labrador and the southern Strait shore of the GNP rests upon Proterozoic crystalline basement, is gently dipping to broadly warped and is offset by east-northeast trending faults (Figure 2). Southeast of the Appalachian frontal fault (Figures 3 and 4), the terrain is dominated by northeast to north-trending sinuous, braided, northwest-verging, reverse faults that have hundreds of metres of vertical throw, some component of lateral displacement, and can be traced over tens to hundreds of kilometres (Grenier and Cawood, 1988; Knight, 1991). Between the faults the strata are gently dipping except for narrow zones adjacent to the faults where the beds steepen to the near vertical and locally invert (Knight, 1991; Knight and Boyce, 2015). East of the Ten Mile Lake Fault, the Paleozoic rocks plunge to the north around the northern closure of the Proterozoic Long Range Inlier. The rocks throughout the area preserve sedimentary structures and fossils. The most easterly exposures of the formation near the Hatters Pond Fault (Knight, 1987) are penetrated by low-angle faults and a light penetrative cleavage (*this study*).

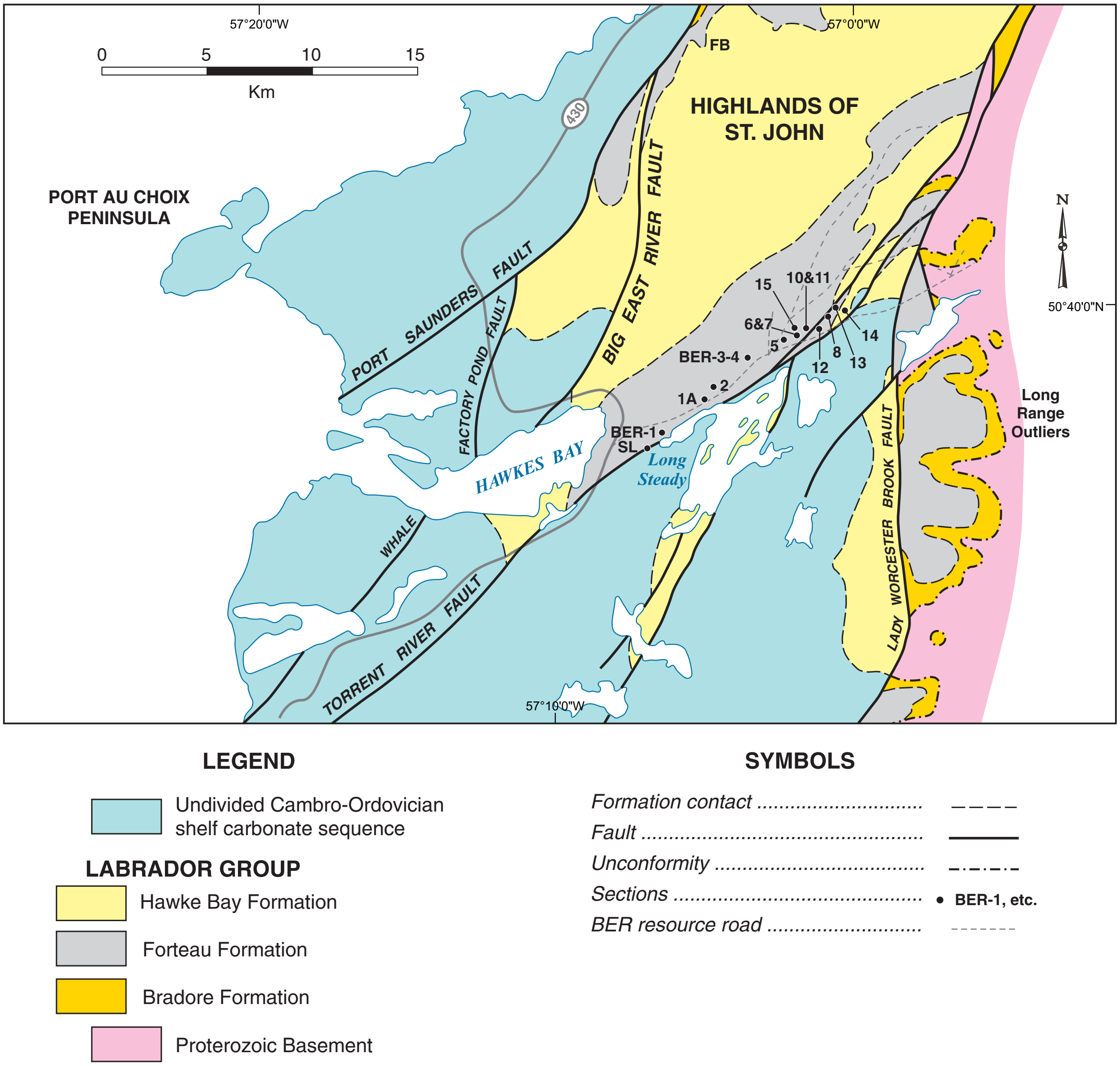


**Figure 5.** *Geology map of Hawke Bay–Highlands of St. John area of the Great Northern Peninsula showing localities studied in the Forteau Formation along the Big East River (BER) resource road. SL–Torrent River salmon ladder.*

## STRATIGRAPHY OF THE FORTEAU FORMATION: INBOARD SHELF SEQUENCE

The Forteau Formation in the inboard shelf succession of southern Labrador and the western side of the GNP has a three-part architecture, expressed in full, in drillcore DH-NF-1B, near Savage Cove, and consisting of three members: Devils Cove member, Middle shale and Upper limestone (Knight, 1991). The units are mapped from Blue Mountain to MSM, and eastward around the northern plunging closure of the Long Range Inlier (Figures 1 and 4). However, 10 km east of Castor Pond fault, the sporadically exposed succession appears to be dominated by mudrock and abundant carbonate nodules, stylonodular, fine to grainy, dark grey limestone and lesser sandstone, somewhat similar to the succession in Gros Morne National Park (Knight, 2013). This suggests that the succession in the east consists, perhaps, only of the Devils Cove member (DCL) and an overlying succession of unnamed nodular mudrocks, and is comparable to that mapped in Canada Bay (Knight, 1987).

In southern Labrador, James and Kobluk (1978) and Debrenne and James (1981) described the incomplete succession as a basal dolomite, lower biohermal patch reef complex, an interval of shale, siltstone and limestone and an upper biostrome. These strata fit the three members as follows: the dolomite is the DCL, the lower bioherm and overlying of shale, siltstone and limestone is the Middle shale, and the upper biostrome belongs to the Upper limestone.

## DEVILS COVE MEMBER

The basal DCL (Plate 1), a regional marker throughout western Newfoundland, is characterized by its red, purple and white colour, its nodular fabric with abundant shale partings, and its mix of grainy and fine-grained carbonate. In much of western Newfoundland, it is limestone, but in southern Labrador, MSM and HSJ, it is fully to partially dolomitized. First named as an informal formation by Betz (1939) at Devils Cove, Canada Bay, it was later amended to a member of the Forteau Formation (Schuchert and Dunbar, 1934).

The member ranges from 3 to 7 m in thickness in southern Labrador (Plate 1; Figure 6) and western GNP and is generally in sharp, conformable contact with the Bradore

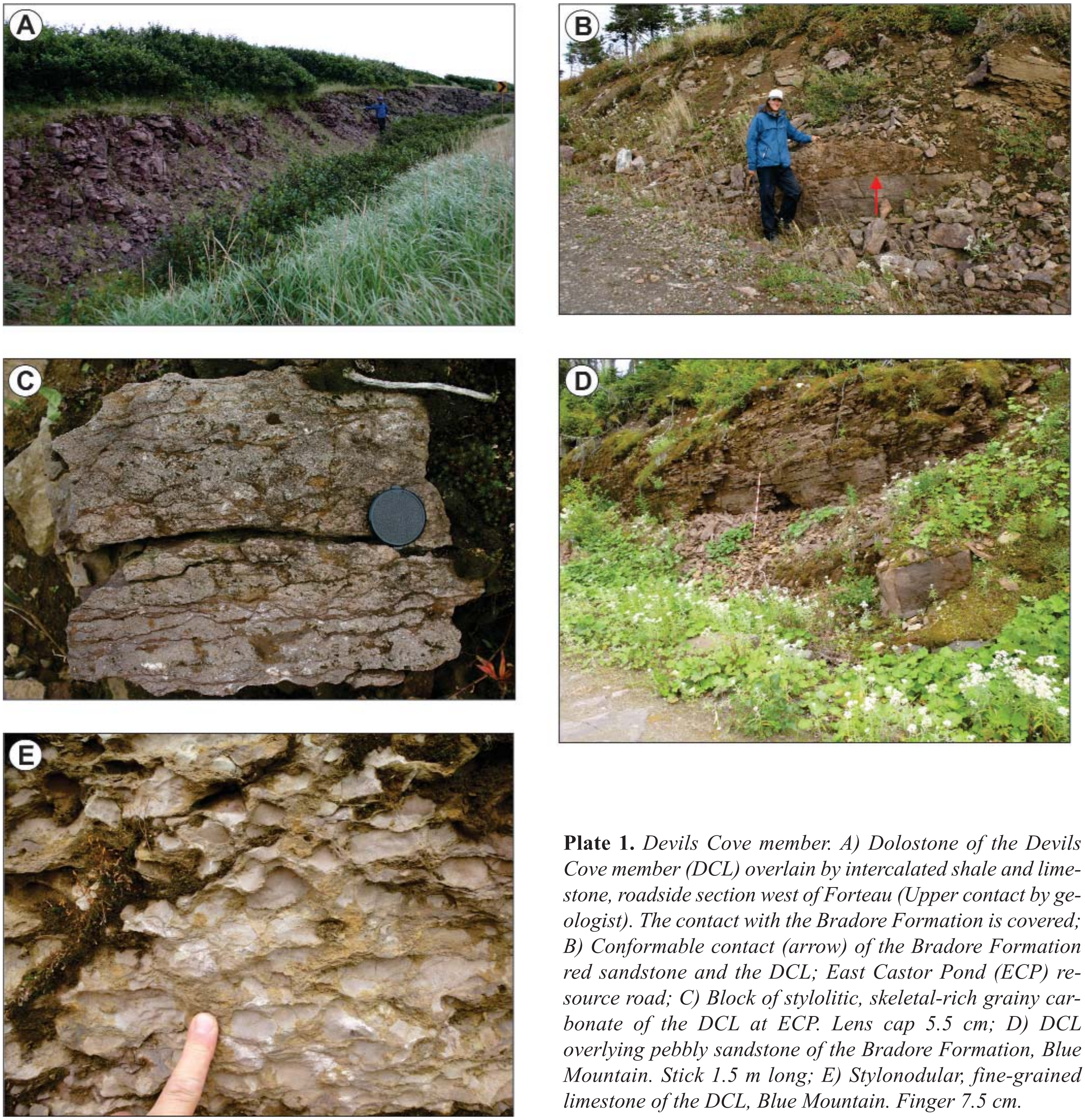
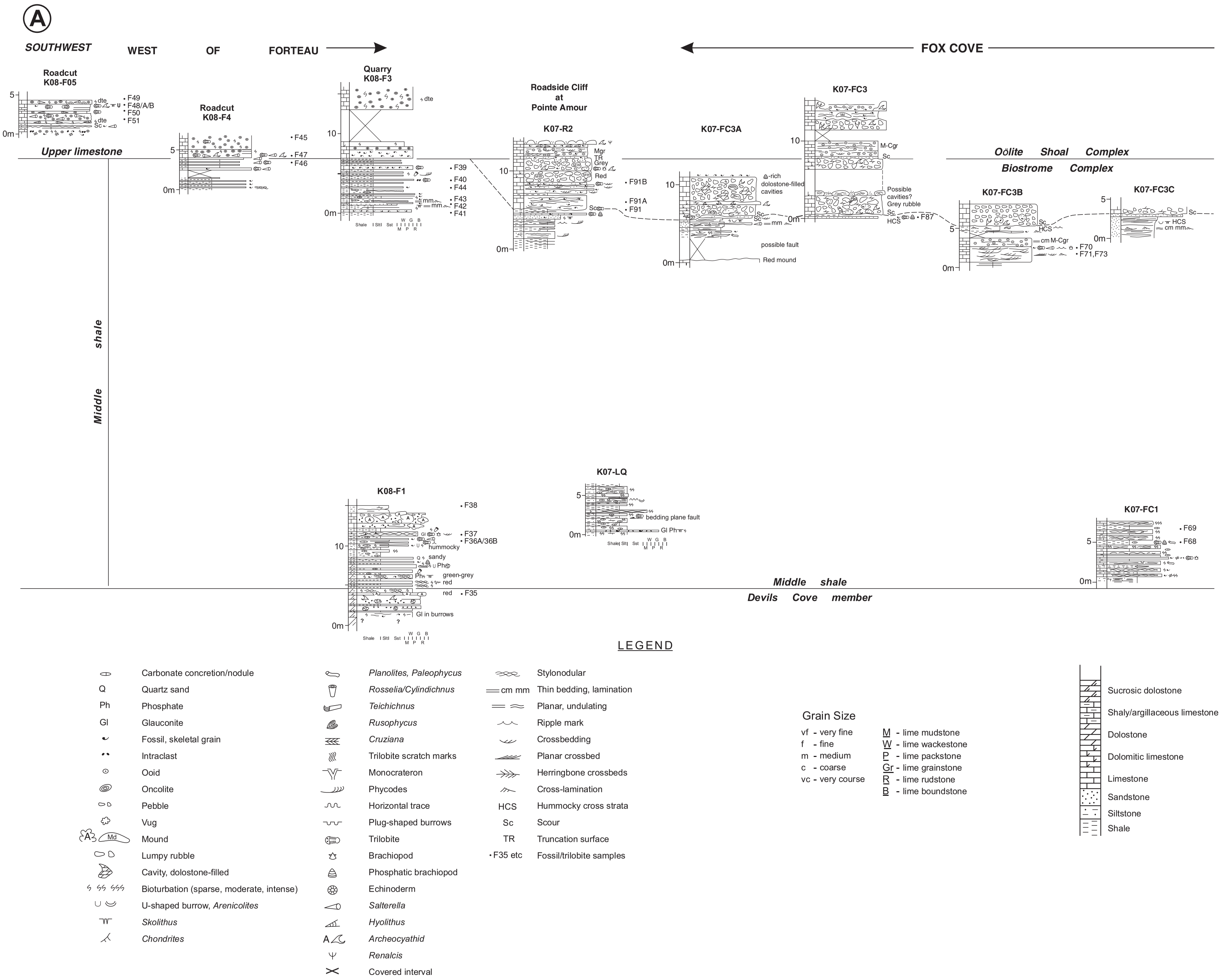


**Plate 1.** *Devils Cove member. A) Dolostone of the Devils Cove member (DCL) overlain by intercalated shale and limestone, roadside section west of Forteau (Upper contact by geologist). The contact with the Bradore Formation is covered; B) Conformable contact (arrow) of the Bradore Formation red sandstone and the DCL; East Castor Pond (ECP) resource road; C) Block of stylolitic, skeletal-rich grainy carbonate of the DCL at ECP. Lens cap 5.5 cm; D) DCL overlying pebbly sandstone of the Bradore Formation, Blue Mountain. Stick 1.5 m long; E) Stylonodular, fine-grained limestone of the DCL, Blue Mountain. Finger 7.5 cm.*


A
SOUTHWEST
WEST OF FORTEAU
FOX COVE
Roadcut K08-F05
Roadcut K08-F4
Quarry K08-F3
Roadside Cliff at Pointe Amour
K07-R2
K07-FC3A
K07-FC3
K07-FC3B
K07-FC3C
K08-F1
K07-LQ
K07-FC1
Upper limestone
Middle shale
Oölite Shoal Complex
Biostrome Complex
Middle shale
Devils Cove member
F49
F48/A/B
F50
F51
F45
F47
F46
F39
F40
F44
F43
F42
F41
F91B
F91A
F91
F87
F70
F71,F73
F38
F37
F36A/36B
F35
F69
F68
dte
Mgr
TR
Grey
Red
M-Cgr
Sc
HCS
cm mm
Δ-rich dolostone-filled cavities
possible fault
Red mound
Possible cavities? Grey rubble
hummocky
sandy
green-grey
red
Gl in burrows
bedding plane fault
Gl Ph
0m
5
10
Shale
I Stl
Sst
W G B
M P R
LEGEND
Carbonate concretion/nodule
Q Quartz sand
Ph Phosphate
Gl Glauconite
Fossil, skeletal grain
Intraclast
Ooid
Oncolite
Pebble
Vug
Md Mound
Lumpy rubble
Cavity, dolostone-filled
Bioturbation (sparse, moderate, intense)
U-shaped burrow, Arenicolites
Skolithus
Chondrites
Planolites, Paleophycus
Rosselia/Cylindichnus
Teichichnus
Rusophycus
Cruziana
Trilobite scratch marks
Monocrateron
Phycodes
Horizontal trace
Plug-shaped burrows
Trilobite
Brachiopod
Phosphatic brachiopod
Echinoderm
Salterella
Hyolithus
A Archeocyathid
Renalcis
Covered interval
Stylonodular
cm mm Thin bedding, lamination
Planar, undulating
Ripple mark
Crossbedding
Planar crossbed
Herringbone crossbeds
Cross-lamination
HCS Hummocky cross strata
Sc Scour
TR Truncation surface
•F35 etc Fossil/trilobite samples
Grain Size
vf - very fine
f - fine
m - medium
c - coarse
vc - very course
M - lime mudstone
W - lime wackestone
P - lime packstone
Gr - lime grainstone
R - lime rudstone
B - lime boundstone
Sucrosic dolostone
Shaly/argillaceous limestone
Dolostone
Dolomitic limestone
Limestone
Sandstone
Siltstone
Shale

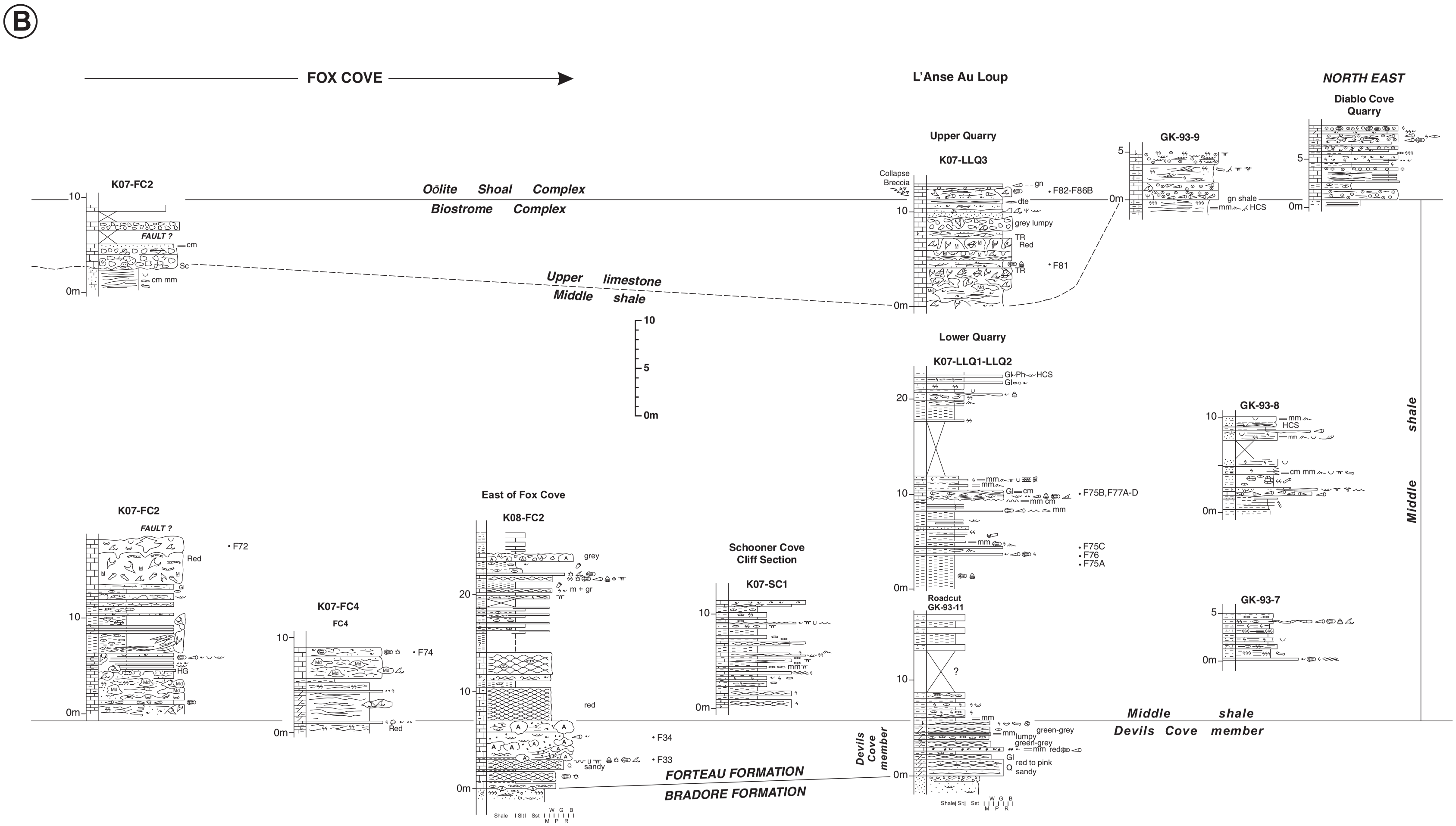


**Figure 6A and B.** *Sections measured in the Forteau Formation of south Labrador coast. Open shelf and biohermal patch reef facies lie adjacent to each other on the foreshore at and east of Fox Cove. Section FC2 comprises a lower and upper part separated by a sub-vertical fault that cuts out most of the Middle shale. The base of the Upper limestone (Biostrome complex) has an erosional base that can be traced for more than 50 m at Fox Cove supporting the hypothesis of Hughes (1979) that the Biostrome occupies a recess. Sections K07-FC1* etc. *measured in 2007, K08-F1* etc. *measured in 2008. Fossil samples shown on sections also collected in same years. GK-93-11* etc. *measured in 1993.*

Formation throughout the inboard shelf succession (Cumming *in* Bostock *et al.*, 1983; Knight, 1991, unpublished data, 2012, *this study*). In Labrador and northern GNP, it rests upon quartz arenite of the L'Anse au Claire member, Bradore Formation (Hiscott *et al.*, 1984). Elsewhere, on the GNP, it overlies small pebble conglomerate and granular sandstone that caps a succession of red arkosic sandstone and green-grey, glauconitic and micaceous, sandstone (Knight, 1991, unpublished data, 2012). Just east of Fox Cove, Labrador, small dolomitized archeocyathan mounds, 10 to 15 cm high and 25 cm in diameter lie directly on the uppermost Bradore Formation below quartz sand-rich grainy dolostone. At East Castor Pond (Plate 1B), basal Devils Cove carbonate is intercalated with red, very coarse-grained, Bradore sandstone, for 2 m, indicating a transitional contact and supporting a conformable but likely diachronous contact with retreating Bradore clastics throughout the region (*see* also Knight, 2013). The upper contact of the member is sharp everywhere in the region.

### Lithology

The DCL consists dominantly of nodular to lumpy, commonly shaly, skeletal grainstone, packstone and wackestone and its dolomitized equivalents. In general, it is host to densely packed skeletal remains, principally trilobite, hyoliths brachiopod, echinoderms, sponge spicule, chancelloriid and regular archeocyathids (Betz, 1939; James and Debrenne, 1980a; James *et al.*, 1988). Archeocyathids recovered from the DCL in Gros Morne include *Cordilleracyathus blussoni* Handfield, 1971, *Sekwicyathus nahanniensis* Handfield, 1971 and *S. tillmani* Debrenne and Zhuravlev 2000 (James and Debrenne, 1980a; McMenamin *et al.*, 2000). However, archeocyathids, found in the member in the study area have not been examined, so it is premature to imply that the Gros Morne species are applicable to the biostratigraphic studies in southern Labrador and GNP.

#### *Labrador*

Crystalline, often vuggy or sandy dolostone dominates the basal 3 m of the formation in Labrador. Tapering, plug and U-shaped burrows and scattered archeocyathids and brachiopods occur in the dolostone. Centimetre-sized vugs reflect dissolution of isolated archeocyaths at Forteau. Crossbedded, skeletal and intraclastic dolostone enclosing metre-scale archeocyathid reefs, 4 m thick, occur above sandy dolostone near Fox Cove. Two recent drillholes, east of Point Amour lighthouse, have scattered archeocyathid remains in a basal sandy dolostone and grainy limestone. Mounds are present in one hole but absent in the other. Archeocyathid mounds occur high in the member just east of Fox Cove (Figure 6).

At a roadside outcrop west of Forteau (Plate 1A), the dolostone is overlain by 4.6 m of intercalated beds of red and green-grey shale overlain by red, stylonodular to lumpy, shaly dolostone and limestone. The lumpy beds are generally bioturbated by *Arenicolites*, *Rossellia* and *Skolithos*, and some contain the fossils *Salterella* and hyoliths.

#### *Western Newfoundland*

In drillcore DH-NF-1B, the member comprises intraclastic-skeletal rudstone and scattered archeocyathids, small archeocyathid buildups, red and grey, stylonodular lime mudstone and skeletal wackestone with lenses, and a single bed of intraclastic grainstone and rudstone; most skeletal debris is recrystallized. Lumpy, nodular to lenticular carbonate that ranges from skeletal floatstone, grainstone to wackestone occurs at MSM and East Castor Point (ECP) (Knight, 1991; Plate 1B, C). Fringing fibrous calcite cements the skeletal framework of grainstone, some echinoderm grains are micritized and voids are cemented by sparry calcite. Phosphate and glauconite also occur in the limestone. Interbeds of sandstone characterize the member at ECP (*see* above).

A well-exposed, 5.45 m thick section at the foot of Blue Mountain (Plate 1D) begins with a basal, 90 cm, vuggy, yellow-weathering, calcareous, fossiliferous sandstone, host to *Salterella* below 4.55 m of red to grey, shaly (lower part) and dolomitic (upper part), stylonodular lime wackestone and mudstone (Plate 1E; I. Knight, unpublished data, 2012); phosphatic brachiopods, *Salterella* and trilobites are scattered in the limestone.

### MIDDLE SHALE

The Middle shale is recognized in southern Labrador and the northwest GNP. It is about 40 m thick in southern Labrador (James and Kobluk, 1978; Figure 6), drillcore DH-NF-1B at Savage Cove (Figure 2), and about 60 m thick at MSM quarry (Knight and Boyce, 2015a; Figure 7). The thicker MSM section may imply some overlap and duplication of lower parts of the member measured in the poorly exposed benches of the outer quarry or that the member thickens as it is traced 35 km southeast across depositional strike. The Middle shale is estimated at approximately 70 m thick on the north face of Blue Mountain (altimeter readings, I. Knight mapping 1983 and 1984) supporting southeastward thickening.

The Middle shale is sharply conformable upon the DCL in both Labrador and the GNP. The upper contact is locally marked by a crosscutting erosional base to the overlying Upper limestone in southern Labrador and MSM. Elsewhere, however, the contact is gradational and conformable (*see* Upper limestone for details).

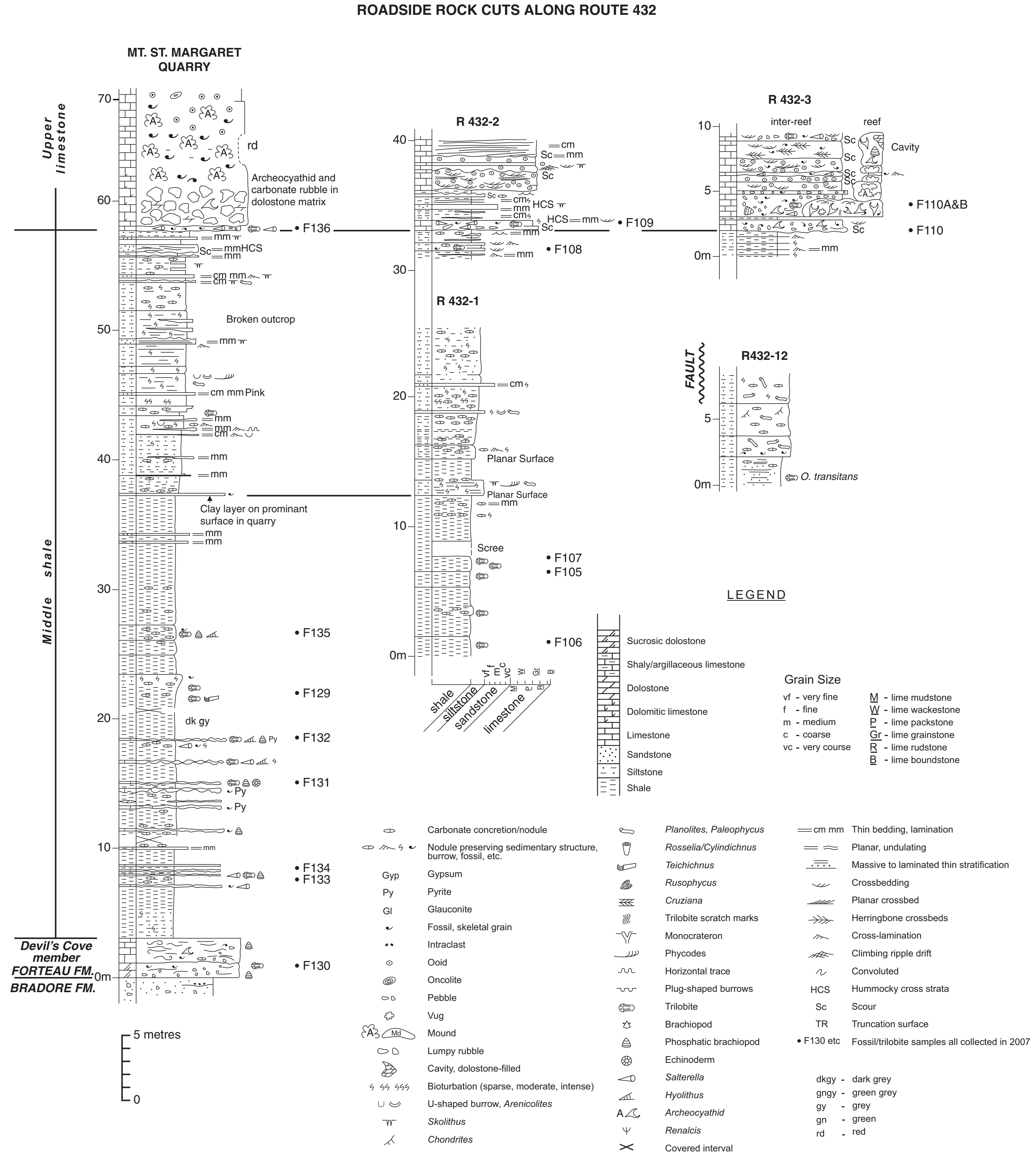


**Figure 7.** *Stratigraphic sections through the incomplete Forteau Formation at Mount St. Margaret quarry (MSM) and at roadside rock cuts along Route 432 just east of Ten Mile Lake (*see *Figure 5). The archaeocyathid interval at top of MSM quarry section is partly based on scattered roadside outcrops above the quarry.*

## Lithology

The succession in the member differs, in detail, from southern Labrador to the GNP. In southern Labrador, it is characterized by a lower succession built around two contrasting facies: 1) biohermal archeocyathid patch reefs and their companion sediments; and 2) an open-shelf facies of well-bedded, fine-grained siliciclastic and carbonate facies (James and Kobluk, 1978; Debrenne and James, 1981). Overlying the lower succession, the rest of the member consists of grey shale interbedded with skeletal grainstone, rudstone, siltstone and sandstone. Debrenne and James (1981) estimated that the lower bioherm-open shelf complex was between 15 and 20 m thick, the upper interval about 20 m.

In northwest GNP, the member is dominated by a lower interval of shale characterized by nodular carbonate interbeds and an upper interval where shale passes upward to intensely bioturbated siltstone interbedded with some sandstone and limestone (Knight, 1991; Knight and Boyce, 2015a).

### ***Labrador***

#### *Lower Archeocyathid Biohermal Buildups and Bedded Open-shelf Facies Interval*

The lower part of the succession is documented by many studies that primarily focused on the archeocyathid biohermal patch reefs (James and Kobluk, 1978, 1979; Kobluk and James, 1979; James and Debrenne, 1980b; Debrenne and James, 1981; James and Klappa, 1983). The grey and red patch reefs, are associated with fringing grainstone and red and green, calcareous mudstone (Plate 2A). They pass laterally into the open-shelf facies (Plate 2B, C) of extensive, upward-coarsening cycles (?parasequences) of green-grey shale, shaly nodular to lenticular, calcareous siltstone and limestone and calcareous siltstone-very fine sandstone or silty, intensely bioturbated limestone; glauconite is noted in the succession.

Two, closely spaced, Nalcor Energy drillholes, mid-way between Fox Cove and Pointe Amour illustrate the rapid switch from the one facies association to the other. Drillcore DH LAB-1 penetrated only 6 m of open-shelf facies above a few metres of DCL, whilst in drillcore DH LAB-02, 8 m of archeocyathid buildups rests upon the DCL below about 5 m of open-shelf facies. The abrupt switch from one facies to the other is also seen at Fox Cove, where, clustered patch reef bioherms interspersed with narrow zones of fringing facies pass abruptly into the open-shelf facies (*see* James and Kobluk, 1978; Debrenne and James, 1981; *this study*; Plate 2B, C). East of the Fox Cove reefs, cliff high buildups, 10 to 15 m wide are separated by zones of bedded open-shelf strata, 10 to 30 m wide. The reefs end abruptly 150 m to the northeast (Plate 2B) beyond which the open-shelf facies dominates a long, raised cliff northeast for several kilometres to Schooner Cove; some archeocyathid mounds locally occur high in the section near Schooner Cove (*see* also James and Kobluk, 1978). No bioherms are present at L'Anse-au-Loup and eastward implying that the open-shelf facies lay largely outboard of the reef complexes as the margin flooded. The succession comprehensively described by James and Kobluk (1978), Kobluk and James (1979), Debrenne and James (1981), James and Klappa (1983) and James *et al.* (1989a) is summarized below.

*Archeocyathid–microbial Bioherms* The archeocyathid–microbial bioherms occur as solitary to clustered, oval to oblate to irregular, largely unoriented, loaf- to pillow-shaped mounds, each a few metres thick. At Fox Cove, stacked smaller mounds coelesce into upward-expanding buildups at least 15 m thick (Plate 2A, B). Synoptic relief of individual bioherms however was only a few metres above the surrounding seafloor (James and Kobluk, 1978).

The mounds are dominated by *Metaldetes profundus* and lesser contributions by *Archaeocyathus atlanticus*, *Archaeosycon billingsi*, *Arrythmocricus kobluki*, *M. simpliporus* and *Retilamina amourensis* (Debrenne and James, 1981). The dominant *M. profundus* is polymorphic ranging from stick to cone, cup, bowl, and sheet forms; *R. amourensis* is sheet-like, whilst the others are all stick-like (Debrenne and James, 1981). Although *M. profundus*, in its various forms, is the primary reef association, distribution of the archeocyaths is not consistent from one mound to another and different reef builders may comprise neighbouring mounds. Secondary associations include: 1) *M. profundus* cups associated with *Retilamina* and *Renalcis*-lined cavities, 2) *Archaeocyathus atlanticus* and *Archaeosycon* sticks low in some mound, and 3) mounds constructed almost entirely of small archeocyath sticks dominated by *M. profundus* with local *Archaeocyathus* and *Arrythmocricus*.

Microbial algae particularly *Renalcis*, *Renalcis*-like forms, *Epiphyton*, *Girvanella* and infrequent *Serligia* are important elements in the buildups, where they encrust frame builders such as sheet-like *R. amourensis*, line reef cavity roofs often with pendant form, and locally attach to skeletal debris (James and Kobluk, 1978; Kobluk and James, 1979; Debrenne and James, 1981). Skeletal remains in the buildups include organism that dwelled in the shelter of the reefs, and thrived as coelobionts in reef cavities where they attached to other reef builders and reef cements. The fauna includes hyolithid cones, trilobite carapaces, brachiopods, echinoderm plates, sponge spicules, the sponge-like coeloscleritophorid *Chancelloria*, and cnidarians *Bija* and *Archeotrypa* (Debrenne and James, 1981). Other coelobionts living in reef cavities include fungi and the benthic foraminifera *Wetherdella*. Fine-grained, massive microspar host some skeletal remains and fine terrigenous detritus form the matrix of the buildups; both matrix limestone and laminated geopetal calcareous mudrock infills cavity and shelter porosity; some reef sediment is bioturbated (Pemberton *et al.*, 1979). Early and late fibrous and sparry cements lined and occluded porosity and open space (James and Kobluk, 1978; James and Klappa, 1983). Evidence of borings is common and at least one hardground surface is present at Fox Cove (James *et al.*, 1977; James and Kobluk, 1977, 1978). Kobluk and James (1979) and James and Klappa (1983) described microbial and faunal elements of reef cavities and cement microfabrics. Recent statistical analysis of the skeletal carbonate associated with the bioherms (Pruss *et al.*, 2012) confirmed the conclusions of James and others (*see* above) that the reefs were the primary site of carbonate productivity in the Forteau seas, dominated by echinoderms and trilobites.

*Bioherm-fringing Facies* Wedge-shaped, inclined thin stratified skeletal grainstone is banked against the bioherms in the Fox Cove area (Plate 2A). The wedges thin from a metre at their thickest to nothing, over a few metres; the thickness of the grainstone bank is locally assymetrical on opposite sides of buildups. The grainstone consists mostly of abraded trilobite and echinoderm debris and detrital clastic silt (*see* also Pruss *et al.*, 2012). Calcareous mudstone drapes some inclined grainstone stratification and also forms massive to crudely bedded zones associated irregularly with the buildups. Traced away from and locally, between the buildups, a crude mudstone–grainstone cyclicity is developed.

*Open-shelf Facies* This facies comprises cycles of green-grey shale (fissile mudrock of James and Kobluk, 1978) overlain by bioturbated shale and nodular carbonate below burrowed calcareous siltstone or silty limestone and rare sandstone (Plate 2C, D). The cycles generally average between 65 and 95 cm in thickness and can be traced for several kilometres (James and Kobluk, 1978; Debrenne and James, 1981). The shale, mostly up to 15 cm thick, is overlain by generally intensely bioturbated, structureless, calcareous siltstone to silty limestone, the latter mostly skeletal and peloidal wackestone and packstone. Nonetheless, remnant lamination and cross-lamination survive locally and a grainstone at section K07-LQ (Figures 3 and 6) showed both lamination and small-scale crossbeds. Glauconite and phosphate sand and layers of shell debris are also present. The sharp cycle tops are generally lumpy because of bioturbation. Long horizontal burrows and small-scale ripple marks occur locally and some cycles grade up into overlying shale of the next cycle.

The open-shelf facies is host to scattered skeletal material that includes *Salterella*, hyolithids, trilobites, calcareous brachiopods, phosphatic cones and a rare archeocyathan. Its ichnofauna includes *Chondrites*, *Monocraterion*, *Monomorphichnus*, *Paleophycus*, *Planolites*, *Rusophycus*, *Skolithos* and *Teichichnus* (Pemberton *et al.*, 1979); Debrenne and James (1981) added *Anemonichnus*, *Stipsellus* and *Cruziana* citing Pemberton *et al.* (1979) who listed these fauna from the Bradore Formation only. Near vertical, downward-tapering cone (funnel) to cylindrical burrows and long horizontal burrows, both lined by concentric–laminar fill, in many cycles suggest *Rossellia–Cylindrichnus* association.

### *Upper Interval*

Thick grey to green-grey shale, 3.75 m thick, marks the base of the upper interval. The shale, exposed in the lower quarry, east of L'Anse-au-Loup (Plate 2E), can be traced from Pointe Amour northeast towards Fox Cove as a low grassy and schrub-covered terrace of shaly soil. It has high $K_2O$ (~8-10%) content (James and Kobluk, 1978) and is host to olenellid trilobites and bradorid arthropods.

Above the thick shale bed, the succession is dominated by cycles of shale, siltstone, limestone and sandstone that broadly resemble the cyclic open-shelf facies of the lower half of the member but are nonetheless distinctive (Plate 2E). Shale beds (22 to 100 cm thick) display little structure except limestone nodules, bioturbation, some thin bioturbated mudstone, and scattered, irregular lumps to lenses of crosslaminated, calcareous siltstone that become more common upwards. Some siltstone lenses, up to 14 cm thick, resemble starved ripple marks, others have an incised scour base, a planar to gently curved convex top and thin rapidly to zero in outcrop suggesting gutter casts (*see* Myrow, 1992; Mángano *et al.*, 2002).

Above the shale, beds, 5 to 140 cm thick, of coarse siltstone to very fine sandstone commonly display thin shale partings, crosslamination and planar to undulose lamination. *Skolithos*, *Planolites*, bow-shaped *Arenicolites*, *Teichichnus*, *Phycodes*, *Cylindrichnus* and *Cruziana* traces bioturbate the facies (Plate 2F, G). The thickest sandstones are clean and laminated with some *Skolithos*.

Interbeds of skeletal grainstone dominated by *Salterella*, trilobites, hyolithids and brachiopods also occur above the thick shale. Generally, 5 to 20 cm thick low in the interval, they attain 75 to 170 cm in thickness higher in the interval at Fox Cove beach and the roadside cliff at Pointe Amour where they are characteristically white and rich in skeletal remains including *Olenellus crassimarginatus*. The thicker grainstone beds low in the interval at L'Anse-au-Loup are characterized by green shaly stylo partings, planar and inclined lamination, possible hummocky cross stratification (HCS) and small-scale crossbedding (Plate 2H). Glauconite sand marks the top of some beds. Thick beds near Diablo Bay and west and north of Forteau Bay include oolitic and skeletal grading to oolitic immediately below the Upper limestone. *Cruziana*, arthropod scratch marks (*Dimorphichnus*) and long, gently meandering, horizontal traces commonly grace the base of sandstone and

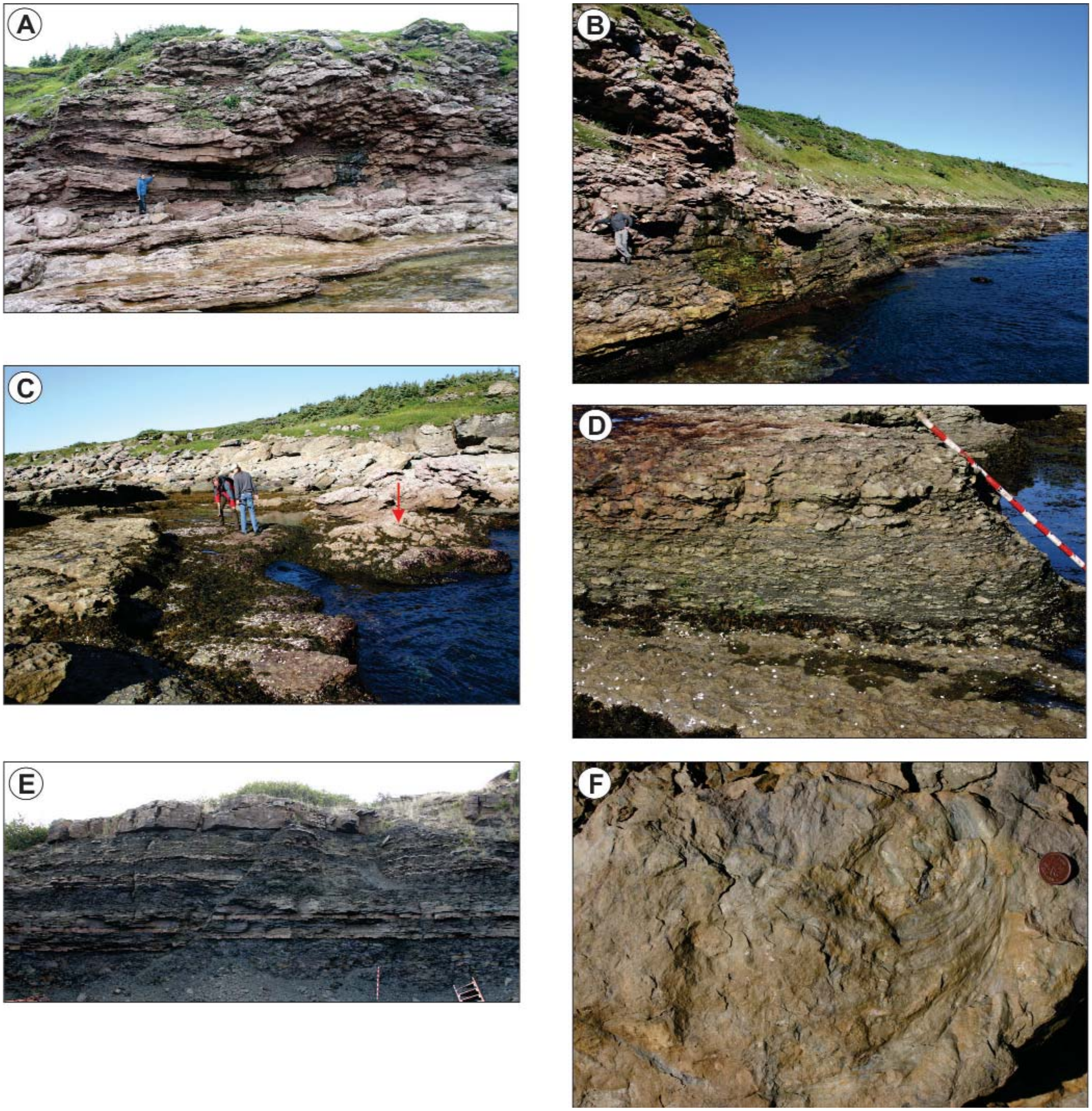


**Plate 2.** *Caption on page 15.*

grainstone beds. Sparse bioturbation within beds is dominantly narrow, lined, vertical funnels and horizontal tubes. One vertical burrow that penetrates through a siltstone into an underlying grainstone terminates in meniscate silt-filled chambers suggesting possibly *Zoophycus*.

Thin beds of skeletal grainstone near Forteau Bay are characterized by densely concentrated skeletal debris such as *Salterella* and paterinid brachiopods and host angular floating intraclasts of laminated dolostone and shale. Other thin grainstone beds grade vertically into crosslaminated, calcareous siltstone. Sections logged over a decade in the active lower quarry at L'Anse-au-Loup indicate that grainstone beds thicken and thin, and wedge out as they pass laterally into calcareous siltstone. Similar lithological and thickness variation was also noted in the Diablo Bay area.

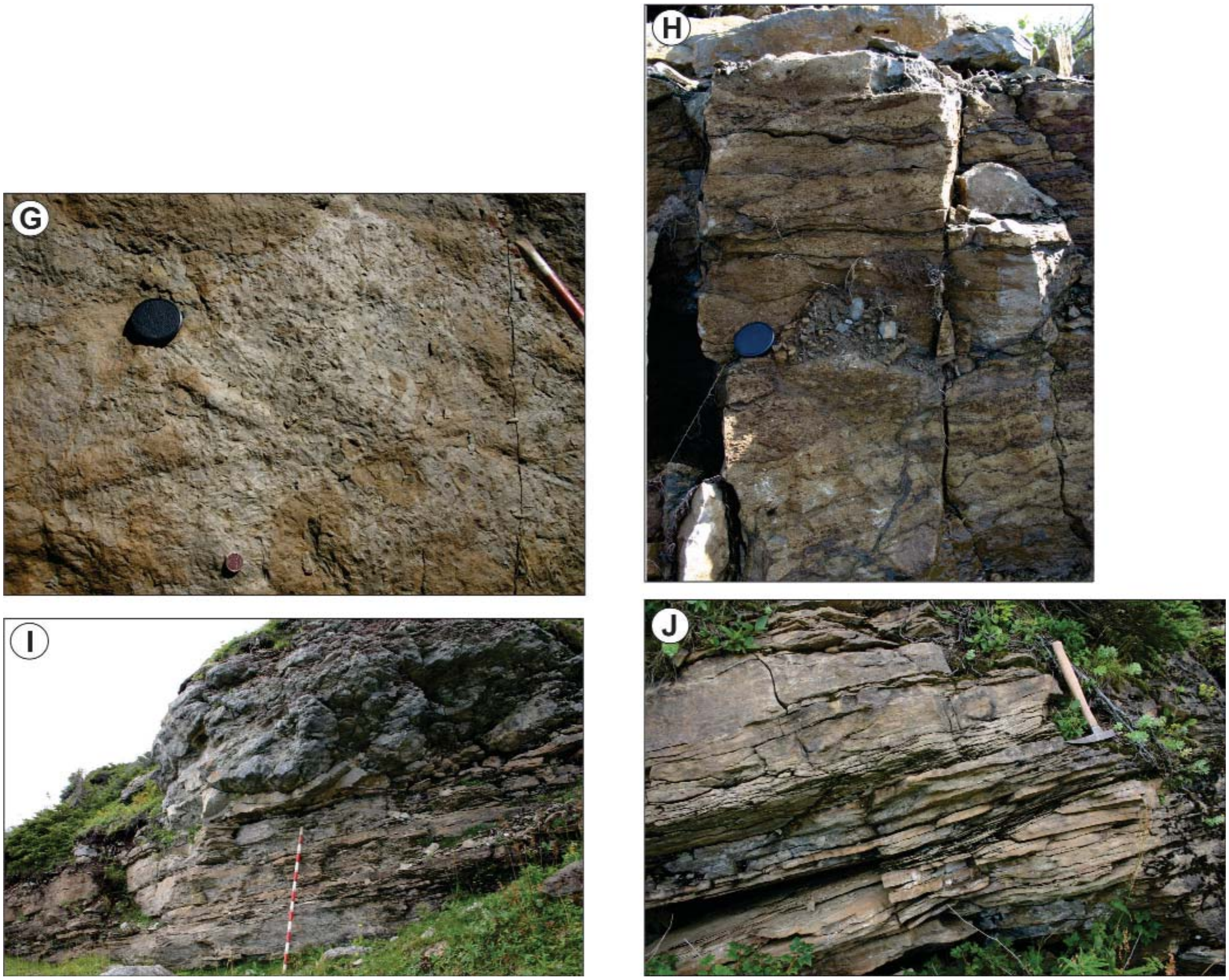


**Plate 2.** *Middle shale, Labrador. A) Archeocyathid bioherms flanked by cyclical shaly calcareous mudstone and grainstone, east of Fox Cove; B) Bedded open-shelf strata abruptly abutting a bioherm, northeast of Fox Cove; C) Abrupt lateral transition from small bioherms (arrow to right of geologists) to cyclic fine-grained open-shelf facies, east of Fox Cove; D) Close up of the open-shelf facies. Its sharp base is overlain by shale and nodular limestone that grades up into bioturbated, skeletal limestone. Stick in 10 cm intervals; E) The shale dominated base of the upper interval of the Middle shale, L'Anse-au-Loup lower quarry. Beds of siltstone cap shale in a number of cycles below a thick grainstone bed at top of quarry face. Measuring stick is 1.5 m long; F) The feeding trace* Phycodes *on the base of siltstone bed, fallen block, L'Anse-au-Loup lower quarry. Coin 19 mm; G)* Cruziana *(below lens cap),* Rusophycus *(below coin) associated with* Skolithos *and small horizontal burrows, fallen siltstone block, lower L'Anse-au-Loup shale quarry. Lens cap 5.5 cm, coin 19 mm; H) Thick bed of crossbedded, skeletal grainstone lower L'Anse-au-Loup shale quarry. Lens cap 5.5 cm; I and J) Flaggy, planar to uneven thin-bedded siltstone and sandstone at Fox Cove; I), just below the irregular crosscutting contact with carbonate rudstone of Upper limestone; J). Note wedge-shaped sandstone with convex-upward lamination suggesting HCS below hammer (Measuring stick is 1.5 m 2I; hammer 33 cm).*

Thin-bedded shale and siltstone-very fine sandstone dominates in the Fox Cove area immediately below the base of the Upper limestone (Plate 2I). However, one very thick bed, 2.5 to 2.6 m thick, appears to coarsen upward from dominantly very fine in the lower part to cleaner fine grained in the upper 60 cm. Lamination and crosslamination are succeeded by wedge-like, non-parallel, discordant sets of gently upward-curved to inclined lamination, each 5 to 10 cm thick, that are interpreted as HCS (Plate 2J); *Arenicolites* and *Skolithos* occur scattered in the facies.

### *Great Northern Peninsula*

The Middle shale on the GNP is a succession of fine-grained siliciclastics lacking the reefs and the lithological diversity of southern Labrador's succession. Overall, it coarsens upward from lower shale to upper bioturbated siltstone and shale host to scattered sandstone (Figures 2 and 7); the succession appears to thicken southeastward (*see* above).

The succession in drillcore DH-NF-1B and MSM and Route 432 quarries (Section R432-1) begins with 6 m of burrowed silty mudstone, shale and scattered carbonate nodules intercalated every 10 to 100 cm with 10 to 20 cm thick interbeds of fossiliferous, lumpy and nodular, grey, fine-grained limestone (Plate 3A). The latter are rich in comminuted phosphatic shell debris and are intensely churned by coarse bioturbation. Pyrite is common in the shale, in burrows and locally encrusts and replaces skeletal debris. The fossils, which are generally thin shelled, include phosphatic inarticulate brachiopods, *Salterella*, hyolithids, olenellid trilobites and rare echinoderms.

Dark grey, fossiliferous, trilobite-bearing shale, rare siltstone or limestone ribbons and some horizons of scattered yellow-weathering, centimetre-sized carbonate nodules and mud-filled tubular burrows dominates the next 10 to 20 m of the member (Figure 3B). Partial to complete, juvenile and mature olenellid trilobites *Olenellus thompsoni* (Hall, 1859) and *O. transitans* (Walcott, 1910), and the eodiscid *Calodiscus lobatus* (Hall, 1847) are abundant. The nodules range from structureless to those that preserve lamination, crosslamination, burrows and fossils including hyolithids and a partial thorax and pygidium of *Elliptocephala logani* (Walcott, 1910) (*see* Plate 12B; Knight and Boyce, 2015a).

Well-stratified, decimetre-thick beds of intensely bioturbated, muddy siltstone and lesser shale, 22 m thick, sharply overlies the lower shale (Plate 3B–E). Remnants of lamination and crosslamination and scattered limestone nodules occur. Resistant beds and lenses of laminated, crosslaminated and burrowed, coarse-grained siltstone to very fine-grained sandstone and limestone punctuate the siltstone upwards. Sandstone beds, up to 50 cm thick, characterized by scoured bases, internal lamination, HCS and locally ripple-marked tops occur near the top of the member (Plate 9G in Knight and Boyce, 2015a). Metre-wide lenticular HCS sandstone bodies occur immediately below the upper contact in MSM quarry (Plate 3F).

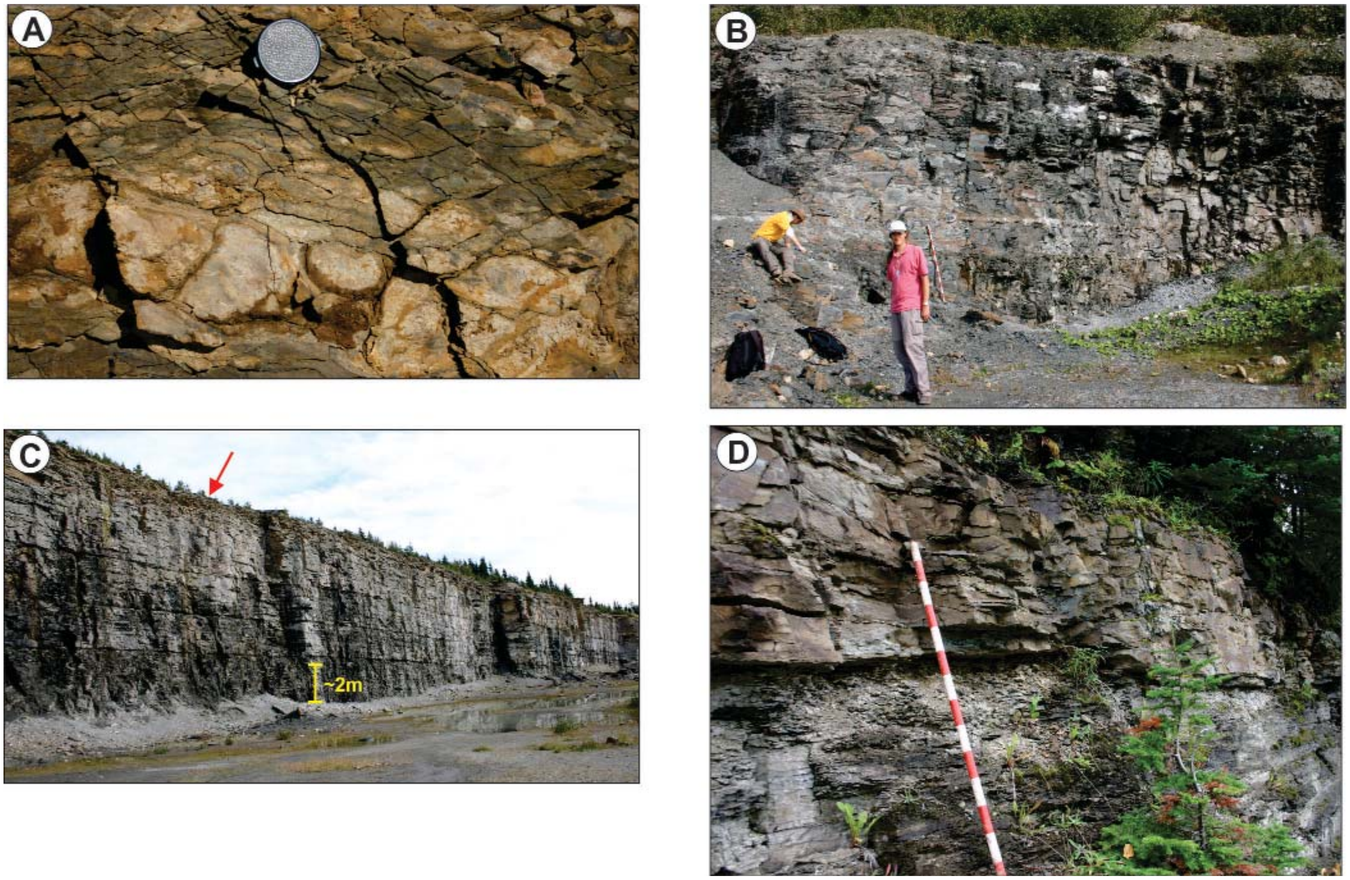


**Plate 3.** *Caption on page 17.*

Burrows include *Planolites*, *Chondrites*, *Teichichnus*, *Phycodes* and vertical to inclined, concentric-lined tubular burrow, possibly *Cylindrichnus* and/or *Rossellia* (Plate 3G, H). The laminated HCS sandstone hosts *Skolithos*, *Arenicolites*, *Cruziana*, *Rusophycus* and scratch marks. Fossils (trilobites, archeocyathids and molluscs) occur in the limestone beds immediately below the top of the member.

Grey and green-grey shale overlain by hackly-weathering mudstone quarried at section BER-12 northeast of Hawkes Bay (Figure 5; Plate 4A–E) contains horizons of yellow-weathering calcareous siltstone, grey limestone nodules, yellow-weathering, thin and thick beds of calcareous siltstone, beds of skeletal packstone, and intraformational pebbly mudstone of locally disoriented, yellow-weathering calcareous siltstone lumps in a mudstone matrix. The calcareous siltstone is laminated and crosslaminated and includes some convex-upward curved lamination (possibly small-scale HCS). There is a large-scale recumbent fold in the lower half of the shale associated with potential small-scale slide surfaces and a zone

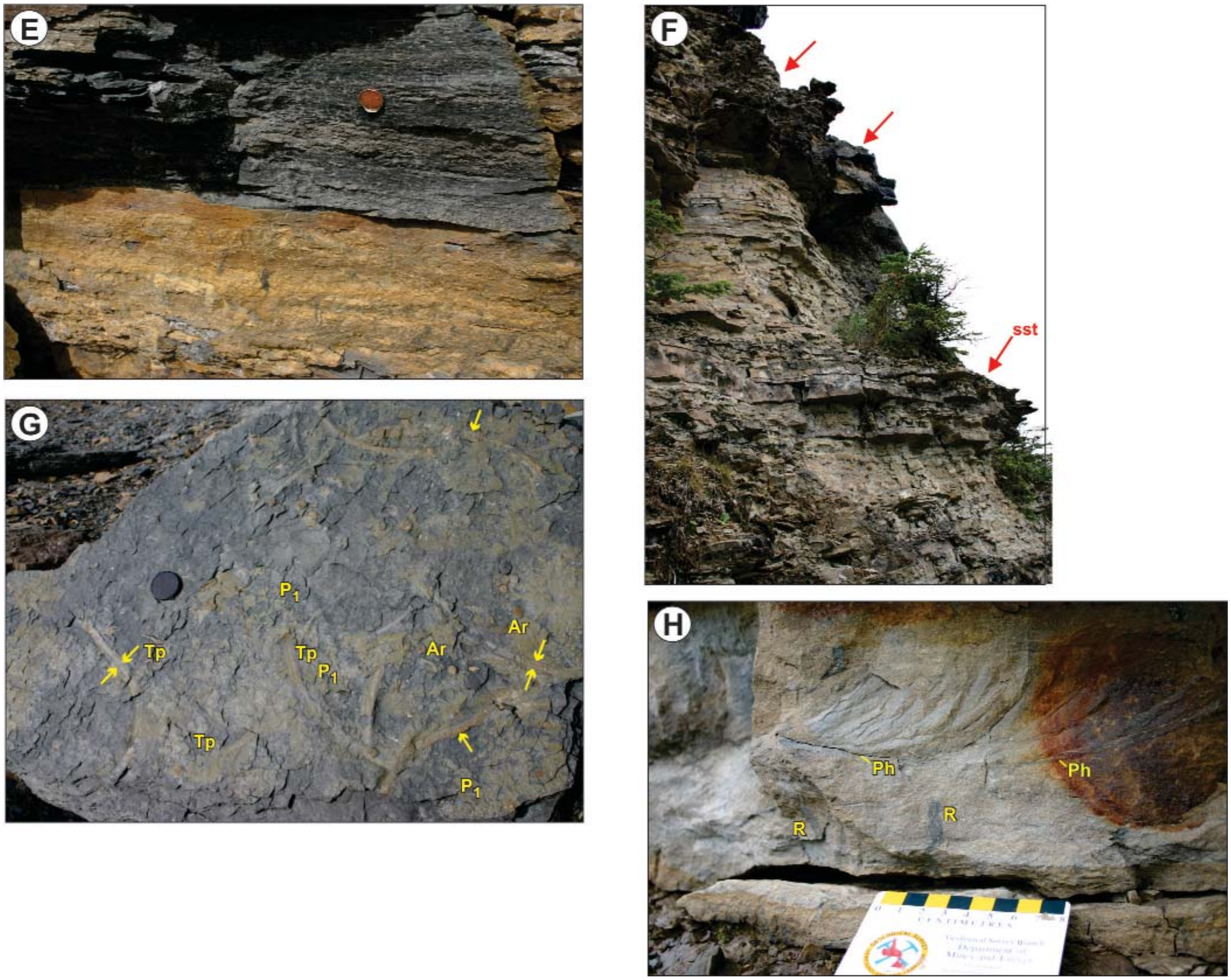


**Plate 3.** *Middle shale, GNP. A) Nodular limestone in mudrock, Mount St. Margaret (MSM) (lens cap 5.5 cm); B) Dark-grey shale, MSM quarry. Measuring stick is 1.5 m long; C) Southern quarry face at MSM displaying the sharp contact of bedded bioturbated siltstones above shale. Beds of sandstone cluster at top of cliff (arrow); D) Shale overlain sharply by bioturbated siltstone, upper Middle shale, R432-1 quarry (measuring stick in 10 cm intervals); E) Intense horizontal and vertical bioturbation in silty mudrock from upper quarry at MSM (coin 19 mm); F) Thin-bedded sandstone, siltstone and shale at top of Middle shale, MSM quarry. Siliciclastics are overlain by carbonate rudstone at base of Upper limestone (arrows). HCS sandstone (sst) (compare to Plate 2I). Cliff about 4.5 m thick below middle arrow; G) Curved horizontal burrows, some with meniscate fill (arrow), others with elevated margins (double arrow).* Arenicolites *(Ar),* Planolites *(Pl), possible* Treptichnus *(Tp), fallen block, MSM quarry; H)* Phycodes *(Ph) feeding burrow and mud-lined* Rossellia *burrow (R) in very fine sandstone–siltstone at R432-1 quarry.*

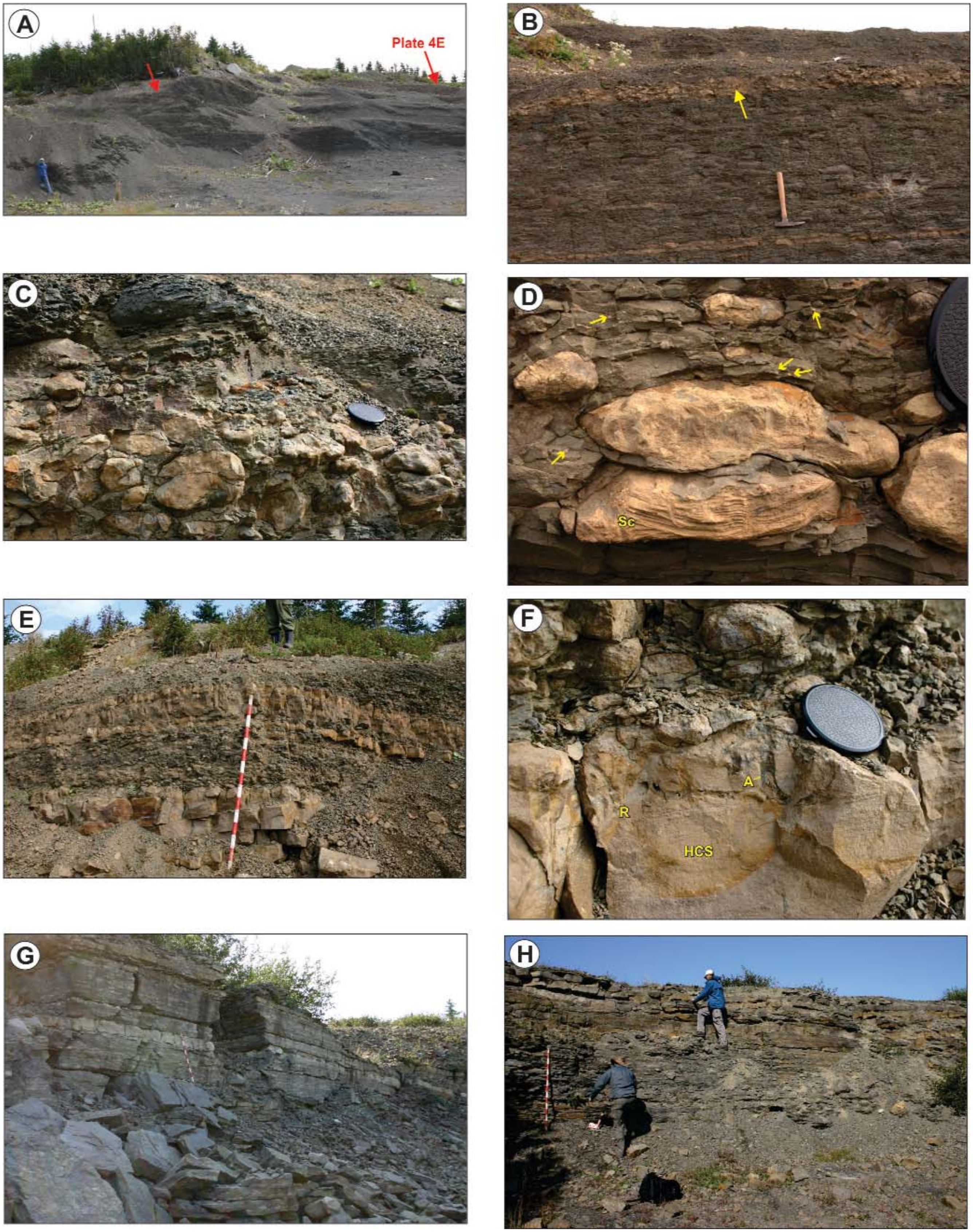


**Plate 4.** *Caption on page 19.*

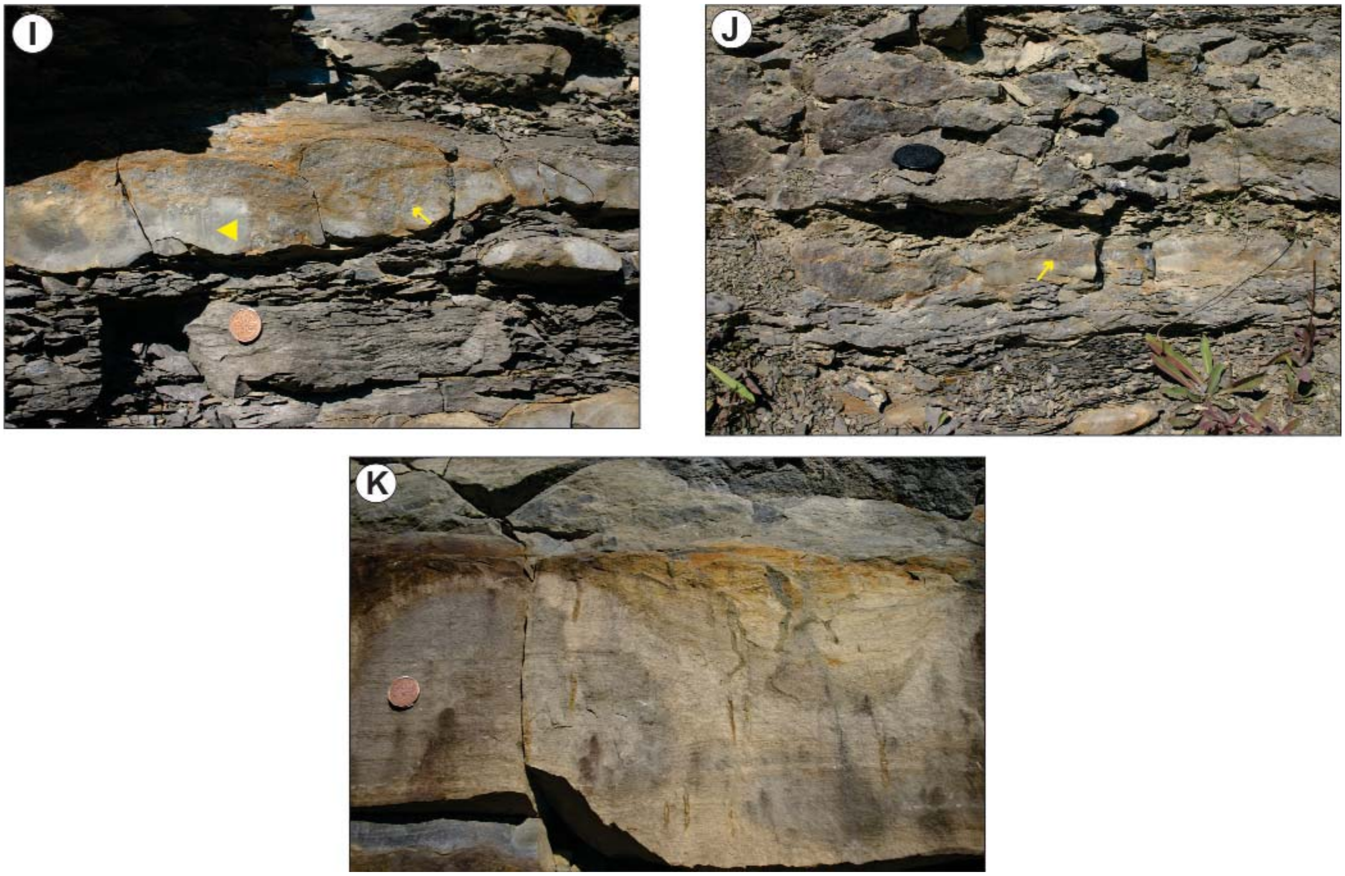


**Plate 4.** *Middle shale, BER and R432. A) Shale quarry at BER-12. Folded lumpy calcareous siltstone bed (left arrow); B) Mudrock intercalated with thin calcareous siltstone and pebbly mudstone of calcareous nodules and lumps (arrow). Hammer 33 cm long; C) Pebbly mudstone of irregular, featureless calcareous siltstone nodular lumps? set in the mudstone matrix. Note disoriented lumps and vague upward grading to mudstone. Lens cap 5.5 cm; D) Scattered pea-sized nodules (arrows) and large nodules that display lamination, scour, and burrows in featureless mudrock. Lens cap 5.5 cm; E) Thick HCS sandstone that is overlain by mudrock rich in calcareous nodules beneath beds of bioturbated calcareous siltstone–sandstone (top of quarry BER-12). Measuring stick 1.5 m long; F) Close up of HCS sandstone top burrowed by* Arenicolites *(A) and* Rossellia *(R). Lens cap 5.5 cm.; G) Silty mudstone rich in calcareous nodules bounds a bed of HCS laminated, calcareous very fine sandstone. Middle shale, roadside quarry (R432-8) just west of Hatters Pond Fault. Measuring stick 1.5 m long; H) Silty mudstone rich in calcareous nodules overlain by beds of sandstone and limestone, quarry R432-9, just west of Hatters Pond Fault. Measuring stick 1.5 m long; I and J) Close up of limestone beds at quarry R432-9 displaying basal lime mudstone below nodular skeletal packstone. Note possible vertical borings (dart) and scour base to packstone (arrows). The limestone and the enclosing nodule-rich mudrock resemble lithologies exposed in Gros Morne National Park (Knight, 2013); K) Mud-filled and mud-lined sand-filled vertical burrows (*Skolithos*?) some of which widen to funnels (perhaps* Rossellia*) penetrating a scour-based sandstone and underlying laminated sandstone (R432-9). The scour has a ripple or hummocky form. Coin 19 mm.*

of chaotic bedding and disoriented yellow-weathering calcareous lumps. Undeformed bedding, below and above the chaotic interval, and the lack of crushed rock and polished or slickensided surfaces suggests that the deformation may be synsedimentary. Mostly featureless, some lumps show lamination, crosslamination, *Skolithos* and *Arenicolites* burrows, and small-scale synsedimentary faults (Plate 4C, D). Phosphatic brachiopods, the calcareous brachiopod *Obolella*, trilobite debris, and rare *Salterella* are present in the quarry section; pyrite also occurs.

Above the deformed interval, the quarry succession is characterized by decimetre thick beds of mudstone and abundant calcareous nodules intercalated with fine sandstone and siltstone that display HCS lamination (Plate 4E). The burrows *Arenicolites*, mud-lined *Skolithos* and *Phycodes* penetrate the sandstones.

The same green-grey nodular mudrock host to sandstone and limestone interbeds occurs in three roadside quarries along Route 432 just west of the Hatters Pond Fault (sections

R432-8, 9 and 10, Figure 4; Plate 4G–K). The laminated sandstone is burrowed by lined *Skolithos* and *Rossellia* (Plate 4K). Also present in this area are limestone beds, 10 to 30 cm thick, consisting of lime mudstone (<10 cm) overlain by stylonodular skeletal packstone (Plate 4I, J). Borings and/or scours mark the top of the lime mudstone that also has a nodular aspect; the packstone yields the trilobites *Bonnia*, *Bristolia* and *Elliptocephala*, phosphatic paterinid brachiopods, and *Salterella*. The lithofacies in this area are very similar to those found in the Forteau succession in Gros Morne National Park (Knight, 2013).

The most southeasterly succession on the GNP occurs at Blue Mountain and the Long Range outliers. There, it is similar to that at MSM beginning with 11 m of bioturbated grey siltstone, shale and bioturbated, grey nodular limestone. The overlying grey and dark grey shale, 40 m thick, hosts limestone nodules and trilobites and is succeeded by an upper 18 m of interbedded laminated and crosslaminated, calcareous siltstone, minor shale and some dark grey skeletal, *Salterella*-rich, limestone (Knight, 1985a, b, unpublished data, 2012). Intraclastic–skeletal grainstone, 6 m thick, occurs in the siltstone near the top of the member.

## UPPER LIMESTONE

The Upper limestone, incomplete in southern Labrador (about 30 m remains), is about 75 m thick in drillcore DH-NF-1A at Savage Cove, GNP (Figure 2). It is about 70 m thick at Blue Mountain (Knight, 1985a, b) and approximately 82 m thick at Frenchmans Brook, HSJ (Dunbar and Lovering *in* Schuchert and Dunbar, 1934, pages 21 to 23).

The basal contact is both locally erosional and conformable. The former occurs at the base of a widely mapped carbonate rudite that defines the base of an archeocyathid biostromal complex and the latter occurs where a thick succession of lime grainstone overlies fine-grained siliciclastics and carbonates of the Middle shale. The erosional surface crosscuts fine-grained siliciclastics and carbonates of the Middle shale from Pointe Amour to Fox Cove in southern Labrador and at drillcore DH-NF-1B and MSM quarry on the GNP (Plates 2I and 3F). The contact is conformable near Diablo Bay and west of Forteau in southern Labrador and also widely on the GNP west of the Long Range Mountains (section R432-2, Figure 7; Plate 6B. The upper contact of the member with the Hawke Bay Formation is placed at the base of the first white quartz arenite above

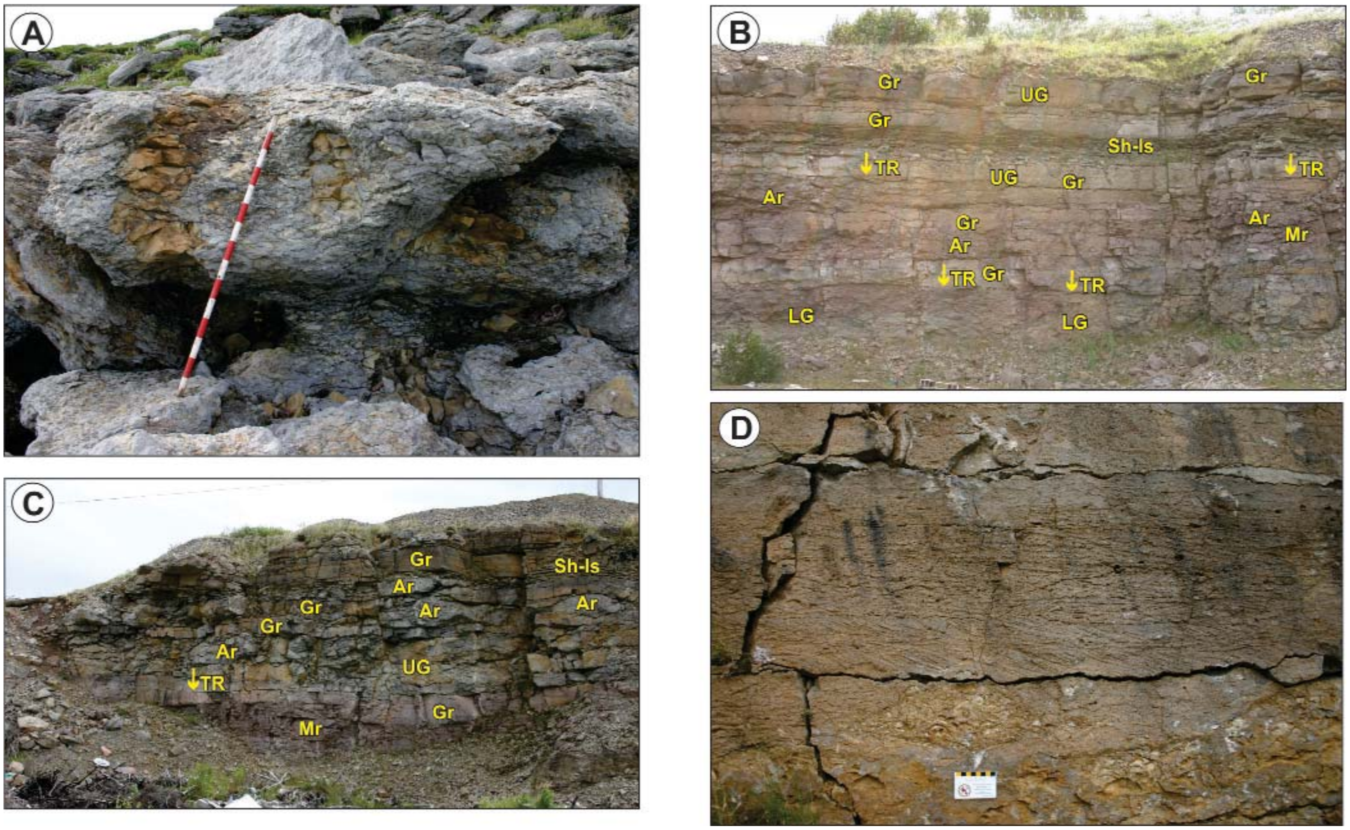


**Plate 5.** *Caption on page 21.*

the last carbonate unit in the succession; the latter is a dolostone unit in the subsurface near Savage Cove (drillcore DH-NF-1B, Figure 2) and the ‘button algae’ bed near Hawkes Bay (Schuchert and Dunbar, 1934). The base of the quartzite is generally sharp and conformable upon a unit of interbedded shale, siltstone and flaggy sandstone that overlies both the dolostone and the ‘button algae’ bed.

## Lithostratigraphy

The Upper limestone in drillcore at Savage Cove, GNP comprises a lower interval of archeocyathid buildups and grainstone (both skeletal and oolitic), and an upper interval consisting of a heterolithic succession of shale, siltstone, sandstone and limestone (Figure 2). The lower interval extends from southern Labrador across strike for 60 km as far as the Torrent River–Ten Mile Lake fault system on the GNP (Figures 1 and 4). Southeast of this, archeocyathid buildups are absent and oolitic grainstone overlies the Middle shale. This study and that of Hughes (1979) indicate that the archeocyathid buildups locally pass laterally into oolitic limestone in Labrador and on the GNP (Figures 6 and 7) implying that the two facies may have co-existed as the shelf prograded and before the buildups were smothered by oolite deposits. Nonetheless, it is unclear, from the available data, whether there is a significant thickness of oolitic limestone beyond the limits of the reef trend although the succession at Blue Mountain (*see* below) does, in part, appear to support this.

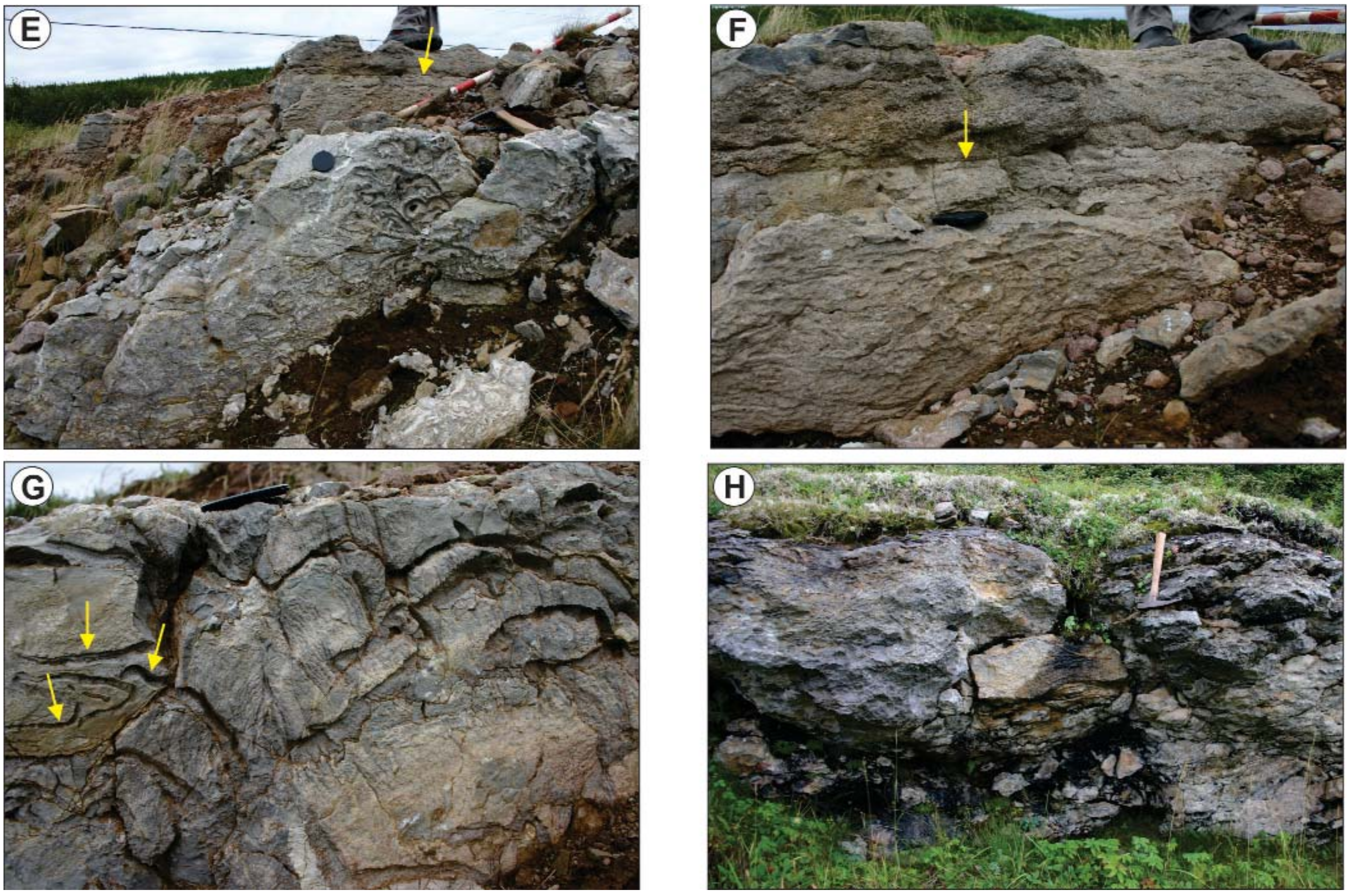


**Plate 5.** *Upper limestone, Labrador. A) Large, yellow-weathering, dolostone masses in a grey rubbly, stylolitic limestone at the point at Fox Cove. The dolostone is mostly massive and cuts limestone but locally displays fine lamination and encases limestone. Measuring stick 1.5 m; B) Upper limestone showing stratified biostromal complex at inner southwest wall of upper L’Anse-au-Loup quarry. The lower grey rubbly unit (LG) is overlain by middle red unit (MR) and the upper grey unit (UG). TR–truncation surface, Gr–grainstone, Md–archeocyathid mound, Sh-ls–shale-thin bedded limestone; C) Archeocyathid mounds encased by stratified limestone of southwest wall near entrance to same quarry. Symbols as in Plate 5A; D) Crossbedded, skeletal grainstone associated with small and large archeocyathid mounds, east wall of quarry; E) A grey archeocyathid mound with inverted bowl* Retilamina *overlain by grainstone (*see *Plate 5F), upper grey interval, roadcut by quarry; F)* Salterella *grainstone sharply truncating (arrow) an oolitic grainstone that rests upon a lower skeletal grainstone. Same locality as 5E. Divisions on stick, 10 cm; G) Microbial boundstone mound associated with* Retilamina *(arrow) near entrance to quarry; H) Boundstone mound adjacent to rubbly limestone, and laminated dolostone high in biostrom sequence at Fox Cove. Hammer 33 cm.*

The upper heterolithic interval, so far unknown in Labrador, is mapped east of Ten Mile Lake on Route 463 and is exposed in scattered outcrops inland of Hawkes Bay along the BER resource road system (Figures 8 and 9). Of particular interest is quartz arenite in the upper parts of the interval, including evidence that oolitic limestone grades upward and laterally into quartz arenite. The Labrador Group outliers atop the western edge of the Proterozoic Long Range Mountain spine and at Blue Mountain comprise two oolitic limestone intervals separated by shale and calcareous bioturbated, fine-grained, siliciclastic rocks. The lower oolitic limestone may be the distal link to the lower interval whereas the calcareous siliciclastics and upper oolitic limestone may correspond to the upper interval.

### *Lower Archeocyathid–Grainstone Interval*

The Upper limestone in southern Labrador hosts the upper archeocyathid biostrome complex of James and Kobluk (1978; *see* also Hughes, 1979) that is, in part, coeval with but also overlain by carbonate sand shoals predominately of oolite (Hughes, 1979). The biostrome–shoal association can be traced for at least 35 to 40 km southeast to northwest GNP, where it appears to give way to a northeast-trending tract, about 20 km wide, of archeocyathid bioherms and channel-bound inter-reef grainstone overlain by oolitic grainstone.

The following description summarizes observations of Hughes (1979) and this field study in southern Labrador (*see* Figure 6). The distribution of the archeocyathid complex and the oolitic grainstone facies above the Middle shale suggest that the archeocyathid complex extended from west of Pointe Amour more than 10 km northeast to L'Anse-au-Loup and passing laterally into the grainstone facies both east and west (*see* also Debrenne and James, 1981). Hughes (1979) documented the two facies juxtaposed north of Blanc Sablon and concluded that the carbonate sand shoals formed at salients flanking deeper water recesses that hosted the biostrome complex. The distribution of the biostrome in a southwest–northeast transect in southern Labrador (Figure 6) suggests that the complex may reside within an erosional recess that was later overlain by the carbonate shoal complex.

#### *Archeocyathid Complex, Southern Labrador*

Hughes (1979) used the generic term moundstone to describe the general structure of the archeocyathid complex rather than specific terms of reef construction such as framestone, bindstone and bafflestone (Embry and Klovan, 1971; James, 1978). He concluded that the buildups were at best broad, low-relief bodies associated with other lithofacies and recognized 5 ascending subdivisions within the interval, namely: dolomite mound, red mound, nodular mound, oolitic bioherm and grey mound. Each subdivision consists of two or more lithofacies, moundstone and skeletal grainstone being the dominant facies; he also described bioherms, thrombolitic and stromatolitic boundstone, dolostone, shale and siltstone. In this discussion, only three divisions are used: lower grey, middle red and upper grey.

Only three archeocyathans, *Metaldetes profundus*, *Archaeocyathus atlanticus*, and *Retilamina amourensis*, occur in the archeocyathid buildups of the Upper limestone in southern Labrador and GNP (Debrenne and James, 1981). Although *Metaldetes* and *Archaeocyathus* cones and sticks occur throughout the complex, sticks dominate the lower, and cones, the upper parts of the complex (Hughes, 1979). The cnidarian *Labyrinthus soraufi* (Kobluk, 1979) occurs in the mounds. Abundance of the skeletal mound builders varies widely, and is sparse in the dolomite and nodular mound divisions where the facies are grey, distinctly rubbly in texture (*this study*) and rich in quartz silt (Hughes, 1979). Thin sheets and inverted bowls of *Retilamina* characterize the middle red and uppermost grey mounds commonly encrusted with the microbial algae *Epiphyton*, *Girvanella* and *Renalcis*, and by cnidaria. It is noteworthy that *Retilamina* and microbial encrusters are virtually absent from the lower grey subdivisions (Hughes, 1979). The latter he described as grey and green moundstone having a mudstone and packstone matrix, host to rare to locally common, upright archeocyathids, cnidaria skeletons, some inarticulate brachiopods, trilobite debris, common detrital silt, small lenses of skeletal grainstone, and large pods of dolostone; a profusion of stylolites characterizes the nodular mound. He also described skeletal grainstone lenses and sheets many metres in length and black shale and siltstone drapes in the facies at Fox Cove but neither were recognized in this study.

The character of the lower grey interval (dolomite and nodular mound divisions), is, at best, cryptic and not easily defined (*this study*). The massive, chaotic, and rubble-like beds consist of centimetre to decimetre-size, generally angular, limestone rubble set in a fine-grained, argillaceous and dolomitic, green-grey matrix (Plates 2I and 5A). The rubble consists of skeletal and peloidal grainstone, lime mudstone and clustered and scattered archeocyathid debris; discrete archeocyathan mounds occur rarely. A basal scour with local relief of 30 cm or more traced over tens of metres marks the base of the rudite at Fox Cove and may be present in the cliff face at Pointe Amour.

The lower grey, matrix-supported rudstone is at least 3 m thick at Fox Cove and L'Anse-au-Loup quarry where its base is covered. In the quarry, it is truncated by a prominent planar surface with broad swales, and is overlain by 80 cm of grainstone below the red interval (Plate 5B, C). The latter, a mix of broad sheets and small isolated red mounds associated with grainstone and red mudstone, is itself truncated by a higher erosion surface, again overlain by a thick grainstone sheet. Other planar truncation surfaces occur in the upper grey interval and include a scour high in the section at Pointe Amour roadside cliff. The generally flat scour has several skeletal grainstone-filled basin-shaped depressions up to 20 cm deep that may be gutter or pot casts; it is succeeded by oolitic grainstone in which are scattered mounds.

Hughes (1979) described the red mound facies as stylolitic and rubbly in aspect characterized by diverse skeletal content, displays of upright, narrow cone and stick archeocyathids, *Retilamina* sheets and inverted bowls set in mudstone to infrequent packstone. Cnidaria, calcareous algae, brachiopods and uncommon trilobites were also catalogued. At L'Anse-au-Loup quarry, broad sheets and decimetre to metre-wide, lenticular to wedge-shaped mound bodies are encased by grainstone that dominates the interval. The two facies appear to offlap locally like prograding accretionary wedges (Plate 5B, C). *Retilamina* and upright stick and cup-shaped archeocyaths and clusters of toppled sticks make up the broad sheet-like body enclosed in red mudstone; scour-based lenses of skeletal grainstone locally interdigitate in the mound. Crossbedded grainstone overlain by crudely stratified grainstone is associated with mounds on the east wall of the quarry (Plate 5D).

Above the higher truncation surface, the upper grey limestone consists of decimetre- to metre-sized mounds encased mostly by bedded grainstone and an interbed of thinly stratified, shaly, fine-grained limestone overlain by grainstone (Plate 5C, E, F). Hughes (1979) described the mounds as structureless, with scarce to locally common, laminar, stick and cone archeocyaths scattered in upright and dislodged position in a quartz silt-rich (up to 30%) mudstone matrix. He also described wedge, tabular and channeled skeletal grainstone, and rare ripple laminated calcareous siltstone containing abundant trace fossils. The metre-size mounds (*this study*) range from vaguely oblate to bun-shaped to hillocky (defined as bioherms by Hughes, 1979). Although locally rubbly, they often consist of large, robust archeocyathids, including *Retilamina*, encrusted with dark grey *Renalcis* and *Girvanella*, and associated with dolomitic lime mudstone matrix; archeocyathid sticks and narrow cones of *Metaldetes* also occur as do dolostone and prismatic and pink rimming calcite that partially occlude open spaces. Stromatolitic and thrombolitic boundstone mounds occur with the archeocyathid mounds near the top of the section at L'Anse-au-Loup (Plate 5G) and in the undergrowth inland of Pointe Amour and Fox Cove (Plate 5H). Hughes (1979) described domal and digitate stromatolite mounds, the latter of laterally linked mounds of *Girvanella* and growth forms of SH-V stromatolite.

The archeocyathid mounds in the upper grey interval are both surrounded and interstratified with horizontal to gently inclined, crudely stratified grainstone that range from very coarse and granular to well-sorted, medium and coarse grained (*this study*). The skeletal grainstone consists of echinoderm debris, phosphatic brachiopods, trilobites, hyolithids and scattered archaeocyathid fragments particularly near to mounds (Hughes, 1979). Upwards, oolitic grainstone, interbedded with *Salterella*-rich grainstone, is associated with isolated and clustered, hillocky archeocyathid mounds (*see* also Hughes, 1979). The oolitic grainstone is locally rich in *Salterella* and oncolites. Horizontal to inclined planar scours overlain by skeletal grainstone erode the oolitic beds locally (Plate 5F). Thin dolostone lenses and flaser are present in some grainstone beds that are also locally cut by narrow carbonate breccias. Similar mound and grainstone association in the upper parts of the biostrome interval occur at Fox Cove and Pointe Amour, where they are locally associated with microbial mounds (*this study*).

Discrete, decimetre-size bodies of fine-grained dolostone that appear to postdate earlier sedimentary fabrics are widespread in the grey rubbly facies, especially at Fox Cove. Hughes (1979) described them as irregular pods, part of the lithological mix of the moundstone. However, the yellow to greenish weathering, green-grey dolostone bodies, 10s of centimetres in size, contrast sharply with the host rudstone and appear to occupy cavern-like open space characterized by smooth but uneven walls and ceilings (Plate 5A). The dolostone is generally structureless but may display crude stratification and lamination. Hughes (1979) described bioturbation in one dolostone pod but this was not observed in the present study.

### *Oolitic Grainstone Association, Southern Labrador*

The oolitic grainstone facies association overlying and lateral to the mound association was described, north of L'Anse au Clair and Forteau, near the Osprey Reef (Hughes, 1979; Debrenne and James, 1981). Hughes (1979) recognized several facies: skeletal grainstone, oolitic grainstone, mixed oolitic grainstone, mixed peloidal packstone, mixed oncolitic grainstone, intraclast grainstone and dolostone–dolomitic siltstone.

Poorly to moderately sorted, fine to granular skeletal grainstone consists of broken, abraded and whole *Salterella*, trilobite, hyolithid, brachiopod, *Girvanella*, ooids, peloids, quartz silt and encrusted grains. The generally structureless grainstone is mottled by dolostone burrows and locally displays small crossbeds and thin skeletal coquinas (*this study*). The oolitic grainstone in the Forteau and Diablo Bay areas comprise fine to coarse grained, concentric to radial-concentric ooids in medium to thick beds that are often extensively dolomitized (*this study*). Scour-based, skeletal (commonly *Salterella*) grainstone overlain abruptly by oolitic grainstone is common. Small to medium scale, planar and trough crossbeds, some with reactivation surfaces, occur, some sets thickening upward below low-angle crossbeds; bimodal crossbeds occur. Structureless, mixed oolitic grainstone of medium- to coarse-grained ooids and 20 to 60% peloids and skeletal grains is closely associated with structureless peloidal packstone (Hughes, 1979). Poorly sorted mixed oncolitic grainstone consist of pebble-size *Girvanella* oncoliths, ooids, peloids, skeletal fragments, composite grains and quartz silt. Poorly sorted intraclastic grainstone includes pebble-size algal intraclasts and skeletal grains encrusted by *Girvanella*; sparry calcite cements open space along with some geopetal microspar (Hughes, *op. cit.*). Dolomite- and lime mudstone-filled burrows are common throughout. The dolostone–dolomitic siltstone facies is generally planar laminated with rare crosslamination and minor bioturbation.

Roadside and quarry sections, northeast of the L'Anse-au-Loup mound complex to Diablo Bay and west of Forteau, indicate that the transition into the basal Upper limestone comprises cycles, 80 to 205 cm thick, of shale or shaly siltstone rich in limestone nodules and bioturbation, bioturbated dolomitic lime mudstone/wackestone and uneven stylo-nodular grain-dominated carbonate. The cycles become grainier and limestone dominated upwards, the packstone, grainstone and pebbly intraclastic floatstone abruptly overlying burrowed limestone. Near Forteau, *Salterella* grainstone, host to floating archaeocyathid clasts, is succeeded by oncolitic skeletal grainstone. Beds, 77 cm thick of unstratified, bioturbated, *Salterella*–oolite packstone and irregular mudstone patches, capped by well-sorted, crossbedded oolitic grainstone also occur, as do inversely graded mud-matrix packstone below oolitic packstone. Concentric-laminated ovoid oncolites, oncolites with multiple, overlapping growth layers (*see* also Hughes, 1979), oncolites encrusted by 5 cm wide and high, inclined, columnar stromatolite and algal-encrusted platy intraclasts of *Salterella* grainstone and peloidal packstone are suspended in both packstone and grainstone. Dolostone–mudstone lenses occur in some beds. Burrows replaced by dolostone and lined by ooids are common. Of biostratigraphic interest is the presence of *Olenellus crassimarginatus* Walcott, 1910 in grainstone below and in the base of the Upper limestone, west of Forteau and near Pointe Amour.

### *Upper Limestone, Great Northern Peninsula*

On the GNP, the Upper limestone, 75 m thick (Straits shore, drillcore DH-NF-1B, Figure 2), comprises 6 m of archaeocyathid moundstone overlain by a grainstone-dominated interval, 19 m thick. The latter consists of oolitic, skeletal (*Salterella*) and mixed grainstone, host to scattered archeocyathids and oncoliths and intercalated with microbial mounds and bioturbated and ribbon-bedded fine-grained limestone. The upper interval, 50 m thick, comprises carbonate–siliciclastic sequences of shale, nodular and thin-bedded lime mudstone that have skeletal lenses, skeletal and oolitic–oncolitic grainstone, siltstone, fine- to coarse-grained sandstone, quartz arenite and dolostone.

Matrix-supported carbonate rudite marks the base of the lower interval at MSM and drillcore DH-NF-1B beneath archeocyathid biohermal reefs and grainstone-filled channels at MSM (Figures 2, 4 and 7). The bioherms also occur at East Castor Pond and along Route 463 (Plate 6), and are traced south to Hawkes Bay (Schuchert and Dunbar, 1934; Knight, 1991; *see* below). Reef buildups are absent locally near Ten Mile Lake (Knight and Boyce, 2015; section R432-2, Figures 4 and 7; Plate 6B), oolitic grainstone instead marking the base of the member as it does at Blue Mountain and Labrador Group western Long Range outliers (Knight, 1985a, b, 1991). *Olenellus crassimarginatus* is associated with the Middle shale–Upper limestone, contact interval at section R432-2.

Outcrops at the eastern end of Route 432 (Figures 4 and 8) and BER forest-resource road (Figures 5 and 9) mostly be-

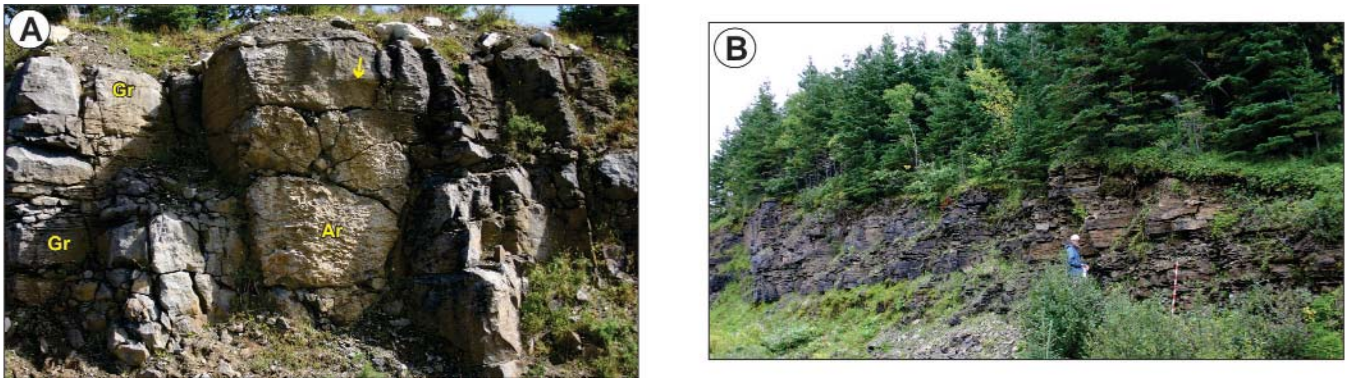


**Plate 6.** *Upper limestone, GNP: A) Archeocyathid bioherm (Ar; ~5 m high) and grainstone (Gr) at R432-3 east of Ten Mile Lake (TML). Truncation surface (arrow) erodes top of bioherm and is overlain by a crossbedded, oolitic grainstone; B) A thick oolitic limestone marking the base of the Upper limestone at R432-2 roadcut near TML. Measuring stick 1.5 m.*

long to the upper interval of Upper limestone, the BER succession lying between the Torrent River Fault and the southern end of the HSJ, its top hugging the eastern shoreline of Hawkes Bay south of Torrent River. The interval also occurs as far southeast as Blue Mountain and the Long Range outliers but except for its lowest strata is poorly exposed, not easily accessible and consequently only described in the broadest terms and not well understood.

### *Archeocyathid Bioherms*

Archeocyathid bioherms, 6.4 to 10 m thick, occur in the subsurface at Savage Cove (drillcore DH-NF-1B, Figure 2) and outcrop southwest, for 70 km, from section R432-3 near Ten Mile Lake to Long Steady on Torrent River (Figures 4 and 5; Schuchert and Dunbar, 1934; Knight, 1991; Knight and Boyce, 2015a); no reef facies has been found east of this northeast-trending tract. The last appearance of archeocyathid detritus in the core at Savage Cove occurs 12 to 13 m above the main archeocyathid interval suggesting that the reef complex remained a prominent feature of the Forteau shelf as it accreted.

Like Labrador, the archeocyathid-bearing succession in drillcore DH-NF-1B includes grey and red intervals and rubble beds, potential mounds and grainstone that, in ascending order, include 1.98 m of grey, 0.70 m of red, 0.70 m grey, 2.56 m of red and 0.28 m of grey. Grey limestone rubble having vague layering, thin-bedded lime mudstone, skeletal grainstone (each with scattered archeocyathid debris) and an archeocyathid mound mark the lower grey layer. The 80 cm mound consists of archeocyathid bowls, sticks and sheets that support *Renalcis*-like, pendant microbial bushes and encrusting laminar cements; green calcareous mudstone infills open space. Thin-bedded, stylolitic lime mudstone and shale and a fenestral, spicule rich-archeocyathid layer forms the top of the interval.

Red shale/mudstone intercalated with archeocyathid debris and sheet and stick archeocyathids occur below the middle grey archeocyathid layer that is draped by grey, sponge spicule-bearing shale. Large *Metaldetes* cups, some with grainstone-filled macroborings (*Trypanites*?) occur. The upper red layer comprises beds of archeocyathids with encrusting fabrics interbedded with mudstone, grainstone, lime mudstone and archeocyathid-bearing rudstone. A sharp truncation surface overlain by grainstone occurs 53 cm from the top. Overlying grey, stylolitic, archeocyathid-bearing, carbonate rubble is also truncated by a sharp surface.

The succession at MSM begins with 3.5 m of massive, unstructured, dolostone-supported carbonate rubble succeeded by 120 cm of skeletal grainstone and small, isolated archeocyathid mounds. It culminates in several metres of grey and red archeocyathid biohermal reefs overlain by oolitic grainstone. The bioherms, up to 14 m wide, are separated by inter-reef zones of approximately equal dimension consisting of skeletal and oolitic grainstone. Grey bioherms are constructed of archeocyathid sticks and cones, while the red buildups are associated with red mudstone, scattered bioclasts, and calcite cements. Associated fauna include paterinid brachiopods and the bivalve *Stenothecoides*.

Grey archeocyathid bioherms, 6 m wide and high, separated by inter-reef grainstone channels outcrop east of Ten Mile Lake (section R432-3, Figure 7; Plate 6) and near ECP. The steep, essentially parallel-margined bioherms, that trend roughly east to west, rest upon a few metres of interbedded shale and calcareous siltstone. A thin layer of ripple cross-laminated dolostone mid way through the bioherms and channel grainstone suggest that the reefs grew roughly in sync with their channel fills. The reef framework of densely packed to open clusters of archeocyathid sheets, cups, sticks and branching bushes shelter attached dark-grey, bush-like *Epiphyton* and *Renalcis* in irregular open spaces. Fossiliferous grainy limestone, and grey and red structureless, fine-grained limestone and laminated dolostone occlude remaining reef space.

The channel grainstone ranges from skeletal to intraclastic–skeletal to oolitic. Erosional surfaces are frequent. Archeocyathid intraclasts and tabular rip-up clasts of fine-grained limestone up to 15 cm long occur in intraclastic–skeletal grainstone and rare oncolites in the medium- to fine-grained oolite grainstone. Grainstones are trough crossbedded, their bimodal paleocurrents dominantly westward directed. Both bioherm and channel grainstone are truncated (Plate 6A) beneath a 1.5 m thick bed of bimodally crossbedded, skeletal–intraclastic–oolitic grainstone that lacks reefal debris; it likely marks the base of the oolite interval in the area.

At Frenchmans Brook, HSJ, two archeocyathid intervals (Dunbar and Lovering *in* Schuchert and Dunbar, 1934) include a lower archeocyathid reef, 1 m thick, in a 6–7 m unit of shale and nodular shaly limestone immediately above a thick interval of shale (Middle shale). The upper reef, up to 2 m thick, occurs in 3 m of thin-bedded and crossbedded sandy limestone that overlies 1 m of massive crystalline limestone. A rudstone consisting of reef debris in a silty, skeletal wackestone–packstone matrix occurs southwest of Frenchmans Brook (Knight, 1991). The most southerly archeocyathid bioherm is exposed at Long Steady, Torrent River. It consists of upward-expanding pedestal-shaped reefs of *Metaldetes profundus*, *Retilamina* and calcareous algae; at least 2 m high, the pedestals coelesce in the upper metre (Knight, 1991). They overlie fine-grained sandstone associated with current-bedded, archeocyathid-bearing, skeletal grainstone.

### *Grainstone-dominated Interval*

This subsurface interval at Savage Cove includes strata, 19 m thick, above the archeocyathid bioherms and below the lowest unit of siltstone and sandstone in the core. Its presence at MSM is incomplete and it likely correlates with Bed 8 of Dunbar and Lovering's section at Frenchmans Brook, HSJ, described as 22 m of "thin bedded arenaceous limestone with shale partings" (*see* Schuchert and Dunbar, 1934, Figure 3).

The succession in drillcore DH-NF-1B is characterized by skeletal grainstone, oolitic grainstone, probable microbial boundstone, bioturbated limestone, nodular shaly lime mudstone, thin-bedded dolomitic ribbon limestone and shale. Some oolitic grainstone and shaly lime mudstone beds host archeocyathid debris. The succession consists of cycles, 0.33 to 3.3 m thick, of fine carbonate (or shale) and grainstone. Based on cycles that feature gradual interleaving of grainy beds with fine-grained carbonate below thick grainstone, it is likely that the cycles generally coarsen upwards. Dark grey to black shale beds are found mostly low in the interval where they are characterized by nodules and stringer of fine-grained limestone, scattered crinoid ossicles and thin-shelled skeletal remains. Lined *Paleophycus* burrows in the fine carbonate are filled by fine carbonate mud.

The grainstone, like in southern Labrador, includes skeletal, skeletal–intraclastic, oolitic and skeletal–oolitic types that range up to 3 m in thickness and dominate some cycles. Oncolites are scattered in both skeletal and oolitic beds and archeocyathid debris in oolitic grainstone marks the middle of the interval. Skeletal–oolitic grainstone rich in *Salterella* dominates some cycles in which burrowed grainstone having lined burrows alternates with unburrowed grainstone. In other cycles, skeletal grainstone, low in the cycle, is replaced upwards by oolitic grainstone and vice versa.

Beds of dark-grey, lime mudstone displaying structureless and laminoid fabrics are interpreted as microbial mounds. Rare layers of laminated stromatolite also occur; archeocyathids are associated in some beds.

Thick grainstone overlies the Middle shale at section R432-2 on Route 432, and at BER road system, Blue Mountain and the outliers along the western edge of the Long Range crystalline massif (Knight, 1991, unpublished data, 2012; *this study*). Scattered archeocyathid clasts in *Salterella*-rich grainstone of bedded heterolithic strata at sections BER-8 and BER-15 suggests that these correlate with the lower archeocyathid reef-grainstone interval (*see* also below). Sections BER-10, BER-11 and BER-12, (Figures 8 and 9) indicate that the base of the Upper limestone consists of thick oolitic and oncolitic grainstone host to floating pebbles of massive and laminated calcareous siltstone, shale and laminated skeletal grainstone. An irregular basal scour with some very coarse grainstone-filled gutter casts marks the contact; glauconite is also common.

At Blue Mountain and the Long Range outliers, medium to thick-bedded, oolitic grainstone, 11 m thick, is linked to the grainstone-dominated interval. Stylo-thin-bedded and locally crossbedded skeletal grainstone rich in *Salterella* and trilobite debris (*Elliptocephala*) marks the base of the member below locally dolomitized, dark blue-grey, medium to coarse-grained oolitic grainstone. The limestone has scours, crossbeds and layers of crosslamination. Upwards it is interbedded with thin-bedded, bioturbated and laminated dolomitic limestone. *Salterella* grainstone and intraclastic skeletal grainstone also occur locally, their discoidal intraclasts, dominantly of oolitic grainstone; pebbles can reach 10 by 2 cm in size; oncolites also occur. Dolostone replaces burrows and forms laminated and crosslaminated lenses in the oolite locally.

### *Upper Heterolithic Interval*

The upper heterolithic interval, 50 m thick, spans the 1st clastic unit to the top of the formation in drillcore DH-NF-1B (Figure 2). It comprises 8 subdivisions: namely lower siltstone–sandstone, lower carbonate, middle siltstone–sandstone, middle carbonate, upper siltstone–sandstone, upper carbonate, dolostone, and cyclic shale to sandstone.

#### *Siltstone–Sandstone*

Three coarsening-upward (CU) intervals of siltstone and sandstone, 245, 285 and 228 cm thick, respectively, plus a siltstone bed, 53 cm thick in the upper carbonate, form this facies. The lower siltstone–sandstone, conformable upon underlying grainstone, consists of 70 cm of undulose to planar laminated siltstone and some horizontal burrows as well as layers of echinoderm debris below laminated and crosslaminated, grey, very-fine-grained sandstone; some lamination is gently inclined. *Skolithos* occurs low in the sandstone. Its brecciated, irregular top contains *Salterella* from the lower carbonate.

The middle siliciclastic unit begins with laminated black shale (45 cm) that grades upward through 63 cm of shaly siltstone to grey very-fine-grained calcareous sandstone; thin-bedded, silty limestone marks the top of the unit. Unidentified fossils including possible sponge spicules characterize the shale and siltstone; lamination gives way upwards to crosslamination in the sandstone.

The upper unit that includes limestone interbeds rests erosively upon black nodular lime mudstone of the middle carbonate. Basal, dark-grey to grey, fine- to medium-grained sandstone, 115 cm thick, is increasingly quartz rich and bio-

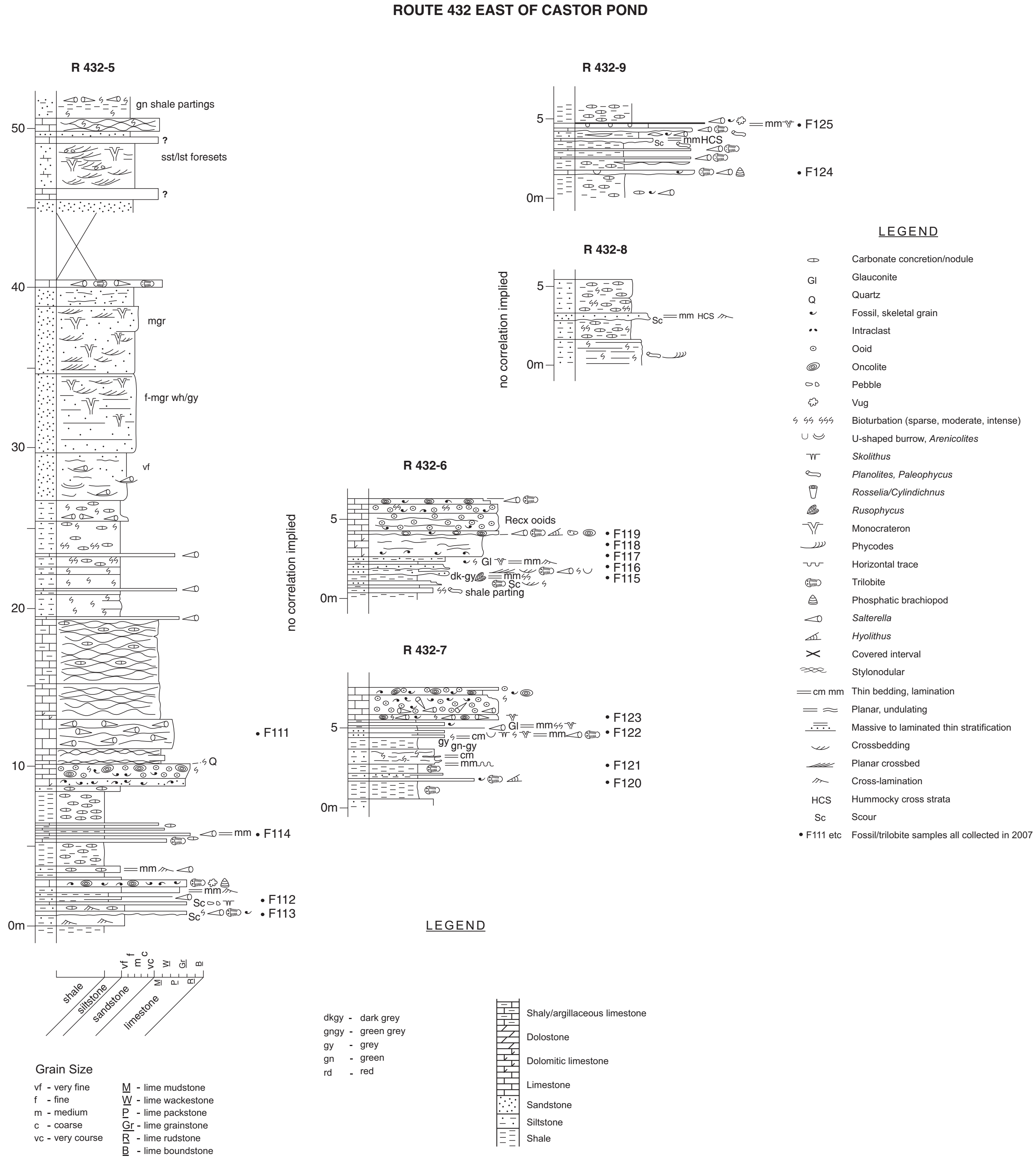


**Figure 8.** *Graphic logs of short sections (R432-5* etc.*) measured along Route 432 east of Castor Pond fault (*see *Figure 4). The sections are mostly in the Upper limestone. R432-5 is a heterolithic carbonate-siliciclastic section that occurs close to the top of the formation. Sections R432-6 and 7 likely underlie R432-5. R432-8 underlies R432-9 and may be more distal deposits of the Forteau shelf.*

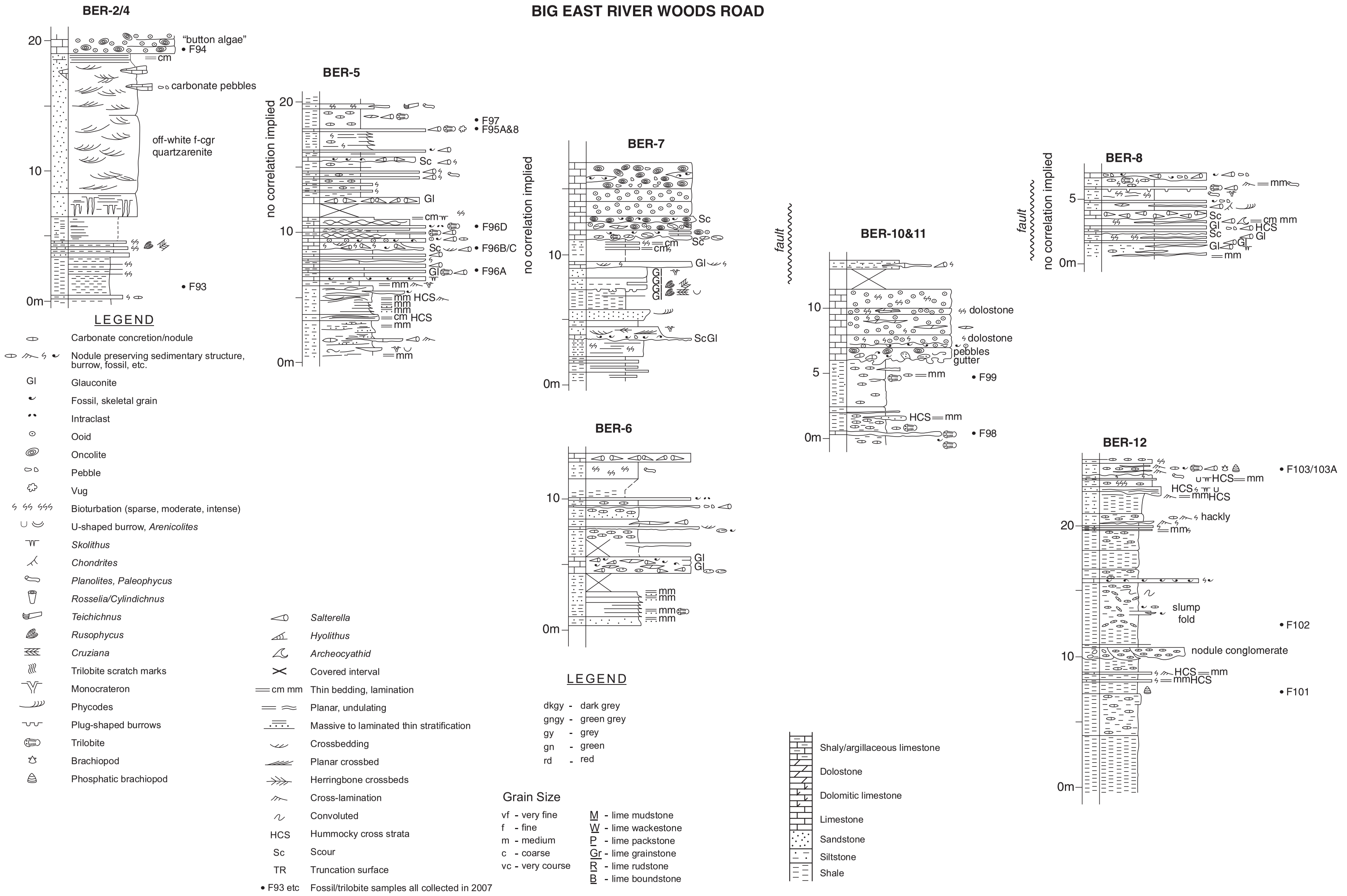


**Figure 9.** *Graphic logs of short sections (*e.g., *BER-2/4) measured in the Forteau Formation along Big East River woods road northeast of Hawkes Bay (*see *Figure 5). Sections BER-6 and 12 are part of the Middle shale; BER-10-11 may define the contact of the Middle shale and Upper limestone. BER-2/4, Ber-5, 7 and 8 are part of the Upper limestone. BER-2/4 overlies the oolitic sandstone outcropping at the salmon ladder on Torrent River (SL, Figure 5).*

turbated upwards. Black, *Chondrites*-burrowed, echinoderm-bearing lime mudstone–wackestone, 33 cm thick intervenes below bioturbated, slightly calcareous, light-grey, very-fine-grained quartz sandstone that hosts a thin nodular lime mudstone and grades into the upper carbonate.

### *Carbonate Intervals*

The lower carbonate, 3.9 m thick, rests with possible discontinuity on the lower siliciclastic unit. It comprises two CU sequences, each about 1.7 m thick, of shale and fine-grained limestone capped by grainstone. The lower fine-grained strata include black shale, shaly ribbon lime mudstone, stylonodular lime mudstone, and bioturbated lime wackestone/mudstone host to scattered echinoderms, *Salterella* and *Chondrites*. Scour-based, inversely graded, skeletal packstone and grainstone, 45 cm thick, caps the lower sequence whereas only a few centimetres of crosslaminated, fine-grained grainstone caps the second.

The middle carbonate unit, 16.6 m thick, is dominated by fine-grained carbonate with cyclicity at best cryptic in the absence of definitive contacts. Black shale, and carbonate mudrocks, 20 to 45 cm thick, capped by skeletal and oolitic grainstone, low in the unit, however resemble CU cycles. A 13 cm bed of mudstone–wackestone in the grainstone may be microbial because it displays a clotted fabric and patches of calcite spar. Most of the unit, however, consists of lime mudstone–skeletal packstone couplets that range from 63 to 200 cm thick. The dark grey, stylonodular to bioturbated, locally shaly lime mudstone, wackestone and some laminated, dolomitic ribbon limestone hosts echinoderms alone or with *Salterella* and trilobites. Lime mudstone-filled lined burrows are common. The packstone and grainstone intercalate as thin layers and lenses in the fine-grained limestone and also occur as beds 15 to 25 cm thick. They are dominated by echinoderm debris with lesser *Salterella*, trilobites, calcareous brachiopods, hyolithids and oncolites.

The upper carbonate, 13.3 m thick, returns to alternating fine grained and grainy carbonate cycles ranging from 48 to 300 cm in thickness, the thickest cycles at the base and top of the unit. The basal cycle comprises 87 cm of stylobedded to bioturbated, skeletal wackestone overlain by 214 cm of fine-grained oolitic grainstone containing scattered fossils and oncoliths below a thin skeletal-rich grainstone cap. The wackestone contains scattered *Salterella*, echinoderms and unidentified fossils; bioturbation increases upwards. Above this cycle, black, pyritiferous, nodular lime mudstone and mudstone/shale, 5 to 36 cm thick intercalate with thin grainstone (5 to 12 cm) below thicker beds of grainstone; the mudstones are unbioturbated and unfossiliferous but for echinoderm-bearing packstone lenses. The grainstone includes skeletal–oncolitic grainstone, intraclastic grainstone hosting intraclasts of lime mudstone, and oolitic grainstone containing fossils and oncolites. Fossiliferous, nodular lime mudstone and dark mudstone with limestone nodules includes a bed of bioturbated, laminated siltstone at the top of the unit below dolostone.

### *Dolostone*

The dolostone is 1.53 m thick in drillcore DH-NF-1B, at least 4 m thick in drillcore DH-NF-2 and 9.1 m thick in the Yankee Point drillhole (Ham *et al., in* Bostock *et al.*, 1983). This suggests it is a prominent, subsurface marker below the south shore, Strait of Belle Isle. The finely crystalline dolostone has ghosts of fossils, oncolites and oolites as well as dolomite spar-filled vugs in drillcore DH-NF-1B. A fenestral fabric is preserved in drillcore DH-NF-2.

The dolostone is not present near Hawkes Bay, but may correlate there with the ‘button algae’ bed of Schuchert and Dunbar (1934), as both appear to underlie the shale–sandstone unit that marks the formation top in both areas.

### *Shale to Sandstone*

This unit, 7 to 10 m thick, is essentially the lower part of a coarsening-upward sequence that includes the basal quartz arenite of the Hawke Bay Formation (Ham *et al. in* Bostock *et al.*, 1983; drillcore DH-NF-1B, Figure 2, *this study*). Intercalated black shale and thin-bedded mudstone, 4.5 m thick, is succeeded by 3.64 m of interbedded siltstone, very fine sandstone and mudstone. The lower mudrock displays lamination, good fissility and is fossiliferous. The overlying thin-bedded siltstone and very fine sandstone is laminated, crosslaminated and convoluted locally; trace fossils and rare synaeresis cracks occur. The upper 1.78 m of the unit consists of laminated to massive, very fine to medium-grained sandstone intercalated with beds of black shale and laminated siltstone; bioturbation is common. At Frenchmans Brook, HSJ, Dunbar and Lovering (*see* Schuchert and Dunbar, 1934) described 14 m of *Salterella*- and *Olenellus*-bearing shale and thin limestone.

The unit exposed in the southwest corner of Hawkes Bay is rusty-weathering, grey calcareous sandstone interbedded with grey shale containing olenellid trilobite debris (Knight, 1991). Thin-bedded, flaggy clean sandstone replete with shale partings and thin beds is intensively bioturbated and locally ripple marked. Trace fossils include *Skolithos*, *Arenicolites*, *Teichichnus*, *Chondrites*, simple burrows and criss-crossing, straight and meandering, molluscan(?) feeding traces of *Climactichnites*/*Plagiogmus*/Psammichnites affinity (*cf.* to Kowalski, 1978; McIlroy and Heys, 1997; Getty and Hagadorn, 2008; Seilacher and Hagadorn, 2010) (Plate 7A, B). Brachiopods, trilobite debris and glauconite occur in the sandstones as do some bioturbated, thin limestone.

***Upper Limestone, Route 432 and Big East River Road***

Scattered sections assigned to the heterolithic interval occur along Route 432 east of the Castor Pond Fault (sections R432–5, 6 and 7, Figures 4 and 8) and the forest resource road, north of Hawkes Bay and the Torrent River Fault (sections BER-1 to BER-4, BER-5 and BER-8, Figures 5 and 9). Also, sections BER-7 and BER-11 may belong to the same interval or place lower in the Upper limestone. Exposed in a faulted and openly folded succession that lacks definitive biostratigraphic support makes the placement of sections stratigraphically at best speculative, in spite of geographic positioning, structural context and attempted correlation with the Forteau section in drillcore DH-NF-1B.

The succession in these areas comprises an array of facies including shale, shale with limestone nodules, interbedded shale and siltstone, bedded and bioturbated siltstone, lenticular to thin and thick bedded, laminated and crossbedded sandstone, rich in trace fossils and often glauconitic, and fine-grained to grain-dominated skeletal, oolitic, oncolitic and sandy limestone (Plates 8 and 9). Some intervals are dominated by carbonate, and sequences close to the top of the formation include thick quartz arenites (sections R432-5, BER-1 to BER-4, Figures 8 and 9). Common depositional motifs occur in several sections but the lack of confident faunal links precludes correlation as a common depositional cycle.

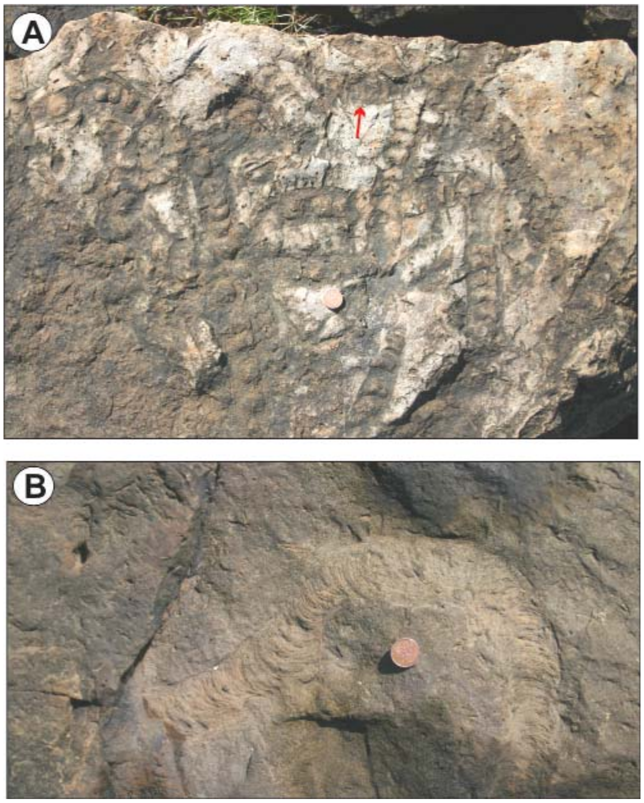


**Plate 7.** *Molluscan? trace fossil, Hawkes Bay. A) Crosscutting and meandering* Plagiogmus *traces on a quartz sandstone flagstone, South shore of Hawkes Bay. Note backfill locally exposed within burrow (arrow) similar to* Climatichnites*. Coin 19 mm; B) Curved and intersecting backfilled burrows on a quartz sandstone flagstone. South shore of Hawkes Bay. Coin 19 mm.*

Metre-scale sequences of intercalated shale, burrowed to laminated and crosslaminated siltstone and sandstone and fine-grained and skeletal limestone (packstone and grainstone composed of *Salterella* and trilobite debris) are common. *Rossellia* burrows in siltstone and *Skolithos*, *Arenicolites*, *Paleophycus*, *Monocraterion*, *Monomorphichnus*, *Cruziana* and *Rusophycus* in sandstone are common (Plate 9A-F). Many skeletal grainstone and sandstone beds are glauconitic particularly in the BER area. Beds of oolitic grainstone host to scattered pebbles, oncolites and skeletal material, largely *Salterella*, intercalate locally (section R432-6 and 7, Figure 8; section BER-7, Figure 9). Similar sandstone exposed along Squid Cove Resource Road near Castor River preserves trace fossil assemblages dominated by trilobite traces *Cruziana*, *Rusophycus* and *Monomorphichnus* up to 5 cm wide and 12 cm long and various robust (8 cm long by 2 cm wide) to small tubular to nodulose horizontal burrows such as *Arenicolites*, *Paleophycus*, *Phycodes*, possibly *Neonereites*, *Skolithos* and *Teichnichnus* amongst others (*cf.* Fillion and Pickerill, 1990, Pickerill and Peel, 1990 and Mangano *et al.*, 2002). The close association of large trilobite traces and burrows (on the base of the beds) perhaps reflects a predational relationship (Jensen, 1990; Fortey and Owens, 1999). Some slabbed samples show obliquely dipping centimetre-wide zones of turbated sandstone between the top and base of *Rusphycus*-bearing sandstone that may support such predatory behaviour.

Section BER-5 (Figure 9) is characterized by a succession of shale and siltstone interbedded with *Salterella*-rich grainstone to packstone, overlain by fine-grained ribbon bedded, limestone and dolostone, which, in turn, is overlain by pebbly, skeletal grainstone (Plate 8A–D); helcionellid molluscs occur in the limestones. The planar thin beds of finely laminated limestone and dolostone (ribbon limestone) are locally truncated by a steeply inclined surface, interpreted as a slump scar (Plate 8B). The grainstone (Plate 8C), of densely packed, skeletal grains, displays thin stratification including grainstone that have thin dolostone caps, and dolostone that have basal concentrations of *Salterella* but little limestone. Convex-upward curvature to some thin beds may support HCS. Intraclastic skeletal grainstone containing floating, centimetre-size, angular to irregularly shaped rounded dolostone

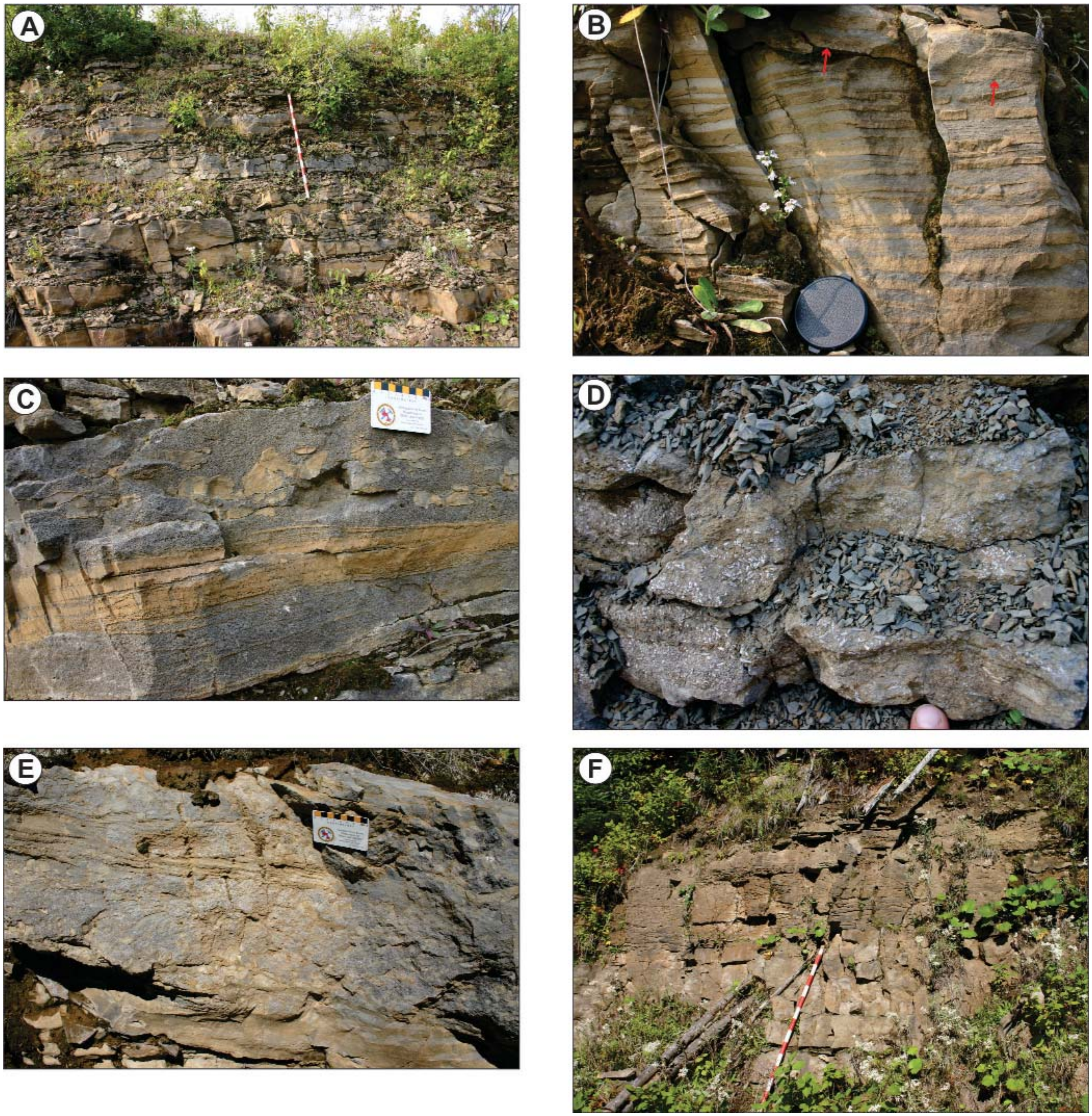


**Plate 8.** *Upper limestone, GNP. A) Thinly bedded, fine-grained, dolomitic and silty limestone giving way upward to bedded skeletal grainstone, some host to dolostone intraclasts (BER-5). Measuring stick 1.5 m; B) Laminated, thin-bedded (ribbon) limestone and dolostone. Note the inclined erosion surface (arrow), possibly a slump scar (BER-5). Lens cap 5.5 cm; C) Skeletal grainstone intercalated with thin-bedded dolostone; small crossbeds occur in the lower grainstone, irregular dolostone intraclasts are suspended in the upper grainstone (BER-5); D) Dolomitic,* Salterella *limestone (BER-5). A basal packstone cedes upward to irregular patches of* Salterella*. Finger 2 cm wide; E) Intraclastic floatstone intercalated with thin-bedded dolomitic lime mudstone (BER-8). The fine-grained intraclasts are suspended in a skeletal grainstone matrix; F) Crossbedded oolitic grainstone overlying bioturbated calcareous siltstone. A bioturbated, thin-bedded fine grained limestone caps the grainstone (BER 7). Measuring stick 1.5 m.*

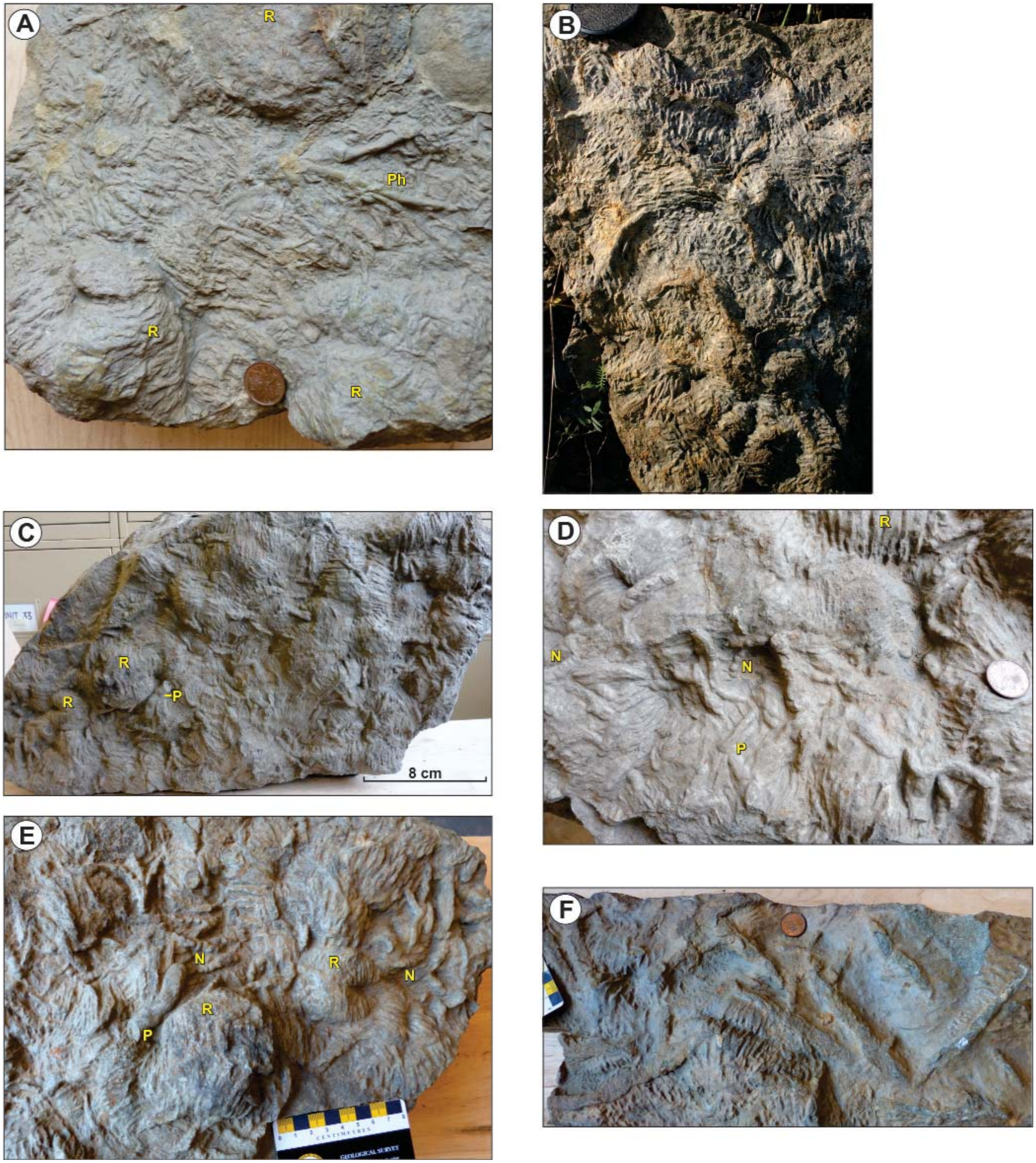


**Plate 9.** *Trilobite traces. A)* Rusophycus *(R), other arthropod markings and horizontal tubular feeding traces including a branching* Phycodes *(Ph) on the base of a sandstone bed at BER 7. Coin 19 mm; B) Abundant* Monomorphichnus *associated with horizontal burrows, base of sandstone bed at R432-6. Lens cap 5.5 cm; C) A large block of grey sandstone, its base host to abundant* Rusophycus *(R) and* Monomorphichnus *traces associated with numerous nodulose/beaded, tortuous, branching and horizontal burrows. P -* Paleophycus*; N - ?*Neonereites*; Squid Cove Resource road near Castor River; D and E) close ups of the block in 9C. Coin 19 mm; F) Arthropod trace fossils associated with large possible* Arenicolites *burrows, base of sandstone slab. Squid Cove Road. Coin 19 mm.*

intraclasts overlies the thin-bedded carbonate. At section BER-8, the succession, mostly of skeletal (*Salterella*) grainstone interbedded with bioturbated siltstone, includes scour-based, intraclastic floatstone intercalated with thin-bedded dolomitic limestone (Plate 8F). Archeocyathid clasts in one grainstone suggest the section may occur low in the Upper limestone.

In contrast, section BER-7 has sequences 3 to 4 m thick of interbedded shale, bioturbated siltstone overlain by metre-thick bimodally crossbedded, glauconitic, skeletal grainstone grading up into sandy limestone containing small quartz pebbles (Plate 8F), as well as cycles completed by metre-thick beds of grey, glauconitic, quartzose sandstone capped by grainstone. A thick, scour-based unit of oolitic grainstone and carbonate pebbles and fossil debris at the base and oncolites at the top marks the sections' top.

*Heterolithic Association with Quartz Arenite*

Thick, quartz arenite occurs near the top of the formation in two areas (section R432-5, Figure 8, and sections BER-2 to BER-4, Figure 9). The succession at section R432-5 is broadly similar, lithologically, to the middle carbonate and the upper siliciclastic in drillcore DH-NF-1B. However, the sections at BER-2 to BER-4 are characterized by a CU shale to quartz arenite succession that sits above a lower quartz arenite, and is capped by limestone similar to the 'button algae' bed. No correlation of the quartz arenites is possible.

The well-exposed sequence at section R432-5 (Figure 8) is 50-m thick, dips moderately to the southeast, and consists of two parts, a lower part of fine-grained siliciclastic and carbonate (Plate 10A) and an upper part of siltstone overlain by crossbedded quartz arenite and limestone interbeds (Plate 10B). The lower part begins with intercalated shale, siltstone, packstone and grainstone not unlike other sections described in the area (*see* above). Crosslaminated siltstone host to calcareous nodules intercalates with skeletal packstone that grades up into wackestone and siltstone and have normal graded beds of intraclastic–skeletal grainstone. Intraclasts of laminated, crosslaminated and burrowed calcareous siltstone range from small and rounded to large tapered and platy clasts, up to 12 x 2 cm in size. The beds have erosional bases. Most fossils are *Salterella* and trilobites but one bed includes helcionelloid and stenothecoid molluscs. The trilobites include *Bonnia parvula* and *B. senecta*.

The overlying dark grey shale, 5.5 m thick, is host to scattered fossil debris and layers of closely spaced flattish lime mudstone nodules that gradually increase in concentration upward. Although mostly structureless, some nodules display lamination, crosslamination and burrows. A cluster of

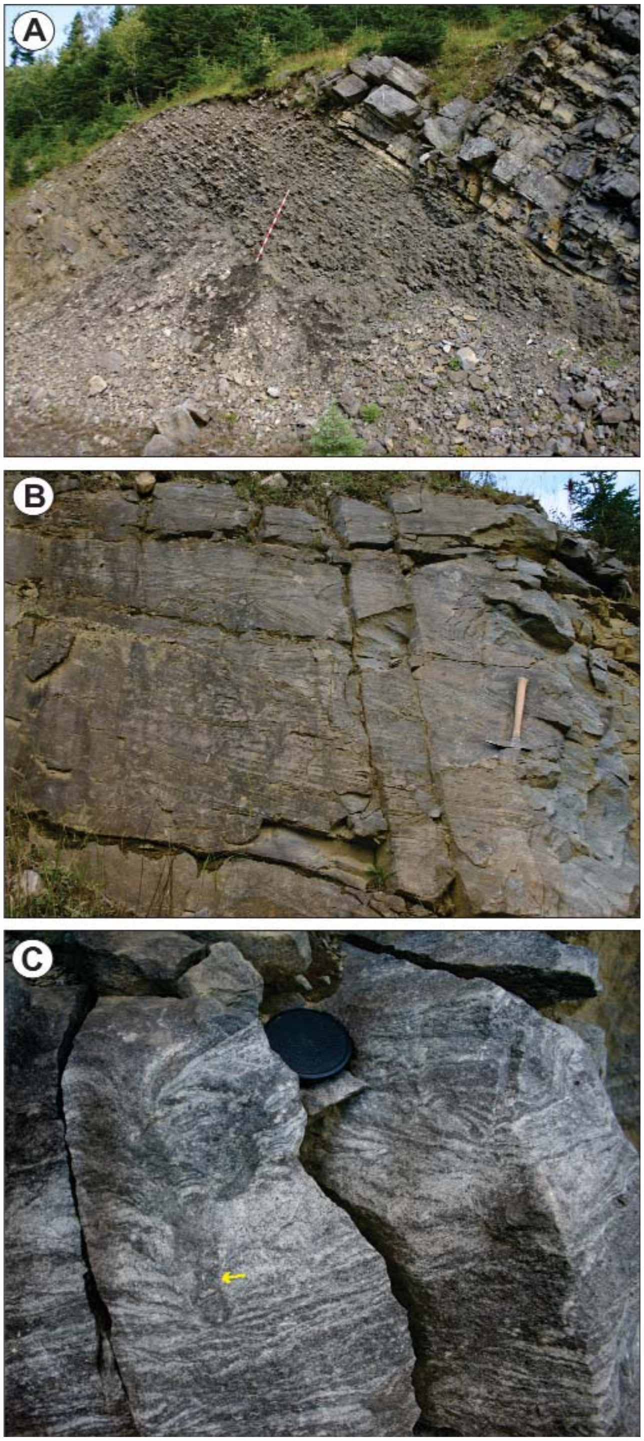


**Plate 10.** *Section R432-5. A) The lower part of section R432-5 showing skeletal rich limestone overlain by shale with numerous lime mudstone nodules succeeded by skeletal oolitic oncolitic grainstone and bedded stylonodular lime mudstone and wackestone. Measuring stick 1.5 m; B) Swaley cross strata overlain by crossbedded and planar stratified, calcareous quartzose sandstone, top of section R432-5. Hammer 33 cm; C)* Monocraterion *burrows (arrow) in calcareous quartzose sandstone. Lens cap 5.5 cm.*

grainstone and packstone beds and lenses in the middle of the interval are comparable to those below the shale.

The nodular shale is abruptly overlain by grainstone, 1.37 m thick, of dolomitic, planar thin bedded, very fine grained, intraclastic skeletal grainstone overlain by oolitic grainstone rich in skeletal grains and oncolites. Ooid-lined tubular burrows are lime mud filled. A bed of *Salterella*-trilobite packstone–wackestone having sandstone-filled burrows, marks the base of an overlying 10 m thick nodular, fine-grained limestone that becomes more dolomitic and argillaceous upwards. *Salterella*, hyolithids and trilobites, including *Bonnia* sp. nov. are scattered in the limestone and include clusters of oriented *Salterella* cones, (oriented 060° and 150°).

Overlying yellow-weathering, bioturbated calcareous siltstone, 4.25 m thick, is host to scattered limestone nodules, *Salterella*, lined burrows and *Salterella* grainstone interbeds near the base. The siltstone grades up *via* 3 m of brown-weathering, apparently massive, very-fine-grained sandstone containing calcareous *Salterella* patches, into 10 to 20 m of buff-weathering, off-white, well-sorted, fine- to medium-grained quartz arenite containing scattered rounded coarse quartz grains. Largely unstratified in the lower half, the upper half consists of large-scale, bimodal crossbeds overlying a middle 75 cm of low-angle, swaley to inclined planar thin bedding and lamination (Plate 10B). Large, vertical funnel-shaped *Monocraterion* burrows are common (Plate 10C). Some foresets are calcareous and skeletal-rich limestone layers host to *Salterella* and the trilobite *Elliptocephala logani* sclerites intercalate in the top of the quartz arenite.

At least two pulses of quartz arenite mark the upper part of the formation along Torrent River (salmon ladder and section BER-1) and the outer part of BER resource road (sections BER-2 to BER-4). Sections BER-2 to BER-4 overlie a prominent crossbedded, oolitic quartz arenite–quartzose oolitic grainstone that can be followed from the salmon ladder on the Torrent River (*see* Plate 8, Knight, 1991) for several kilometres along the resource road before plunging below section BER-2. At the salmon ladder, crossbedded, white, fine- to medium-grained, well-sorted quartz arenite and brown-weathered quartz sand-rich oolitic grainstone form compositional foresets in large-scale trough and planar crossbeds, that climb over previously truncated sets draped by laminated bottomsets (Knight, 1991). Reactivation surfaces and symmetrical ripple marks with peaked crests also occur. Crossbeds predominantly go to the southwest but some verge northeast including a large planar crossbed (paleoflow 015°).

Shale (section BER-2, Figure 9), at least 7 m thick, overlies the oolitic quartz arenite and hosts olenellid trilobites, in particular *Fritzolenellus lapworthi*, which is also present in shales and limestone in a quarry near Hawkes Bay, below the ‘button algae’ limestone (Boyce, 2006). Interbeds of bioturbated siltstone and very fine-grained sandstone that carry basal trilobite traces and tubular burrows (*Palaeophycus* and *Helminthopsis*) occur below the upper quartz arenite. The latter, which is 8 to 10 m thick, coarsens upwards from an uneven, thinly stratified, very fine- to fine-grained sandstone, rich in carbonaceous-lined *Skolithos*-like burrows to trough crossbedded calcareous quartz arenite that coarsens upwards to coarse grained. The latter is host to well-rounded quartz sand and 15 cm layers of granular sandstone, scattered fossil debris and chip-like dolomite and limestone intraclasts. Planar laminated layers (bottomsets), between thick sets of planar crossbeds, bimodal and graded foresets and lenses of sandy limestone occur towards the top of the unit. The quartz arenite is overlain by thick oncolitic–oolitic limestone, likely the button algae bed of Schuchert and Dunbar (1934).

### *Blue Mountain and Long Range Outliers*

The Upper limestone at Blue Mountain and the Labrador Group outliers on the western edge of the Long Range Inlier, although not well documented, includes a middle interval of shale and calcareous bioturbated, fine-grained siliciclastics 23 m thick, an upper oolitic limestone and shale 23 m thick, and an upper interval of uncertain thickness of shale and sandstone (Knight, 1985a, b, 1986, 1991). Further work is needed to understand the succession in this area.

## BIOSTRATIGRAPHY

The Forteau Formation of southern Labrador and GNP is well known as a sequence deposited during the late Early Cambrian *Bonnia–Olenellus* Zone (James *et al.*, 1989b). It hosts a typical, composite macrofauna of archeocyathans, lingulid, paterinid and obolellid brachiopods, hyoliths[1], molluscs, salterellids and trilobites, amongst other less well known taxa, *i.e.*, echinoderms, chancelloriids and mobergellans (*see* Appendix 1 and 2).

Archeocyathans were first discovered “on the eastern point of Forteau Bay” in “red and white limestone” by Bayfield (1845, page 457), who identified them as *Cyathophyllum*, a coral genus (Rowland, 2001). The first actual systematic study of the Forteau archeocyathans and other associated fossils, however, was that of Billings (1861), who described the material from “Anse au Loup” (northern Pointe Amour). Systematic work on these archeocyathans culminated more than a century later in the work of Debrenne and James (1981). Rowland (2001), in a detailed historical review of phylogenetic interpretations, further concluded that the Class Archaeocyatha belongs within the Phylum Porifera, *i.e.*, the sponges.

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[1] Hyoliths were recently assigned to lophophorates by Moysiuk *et al.* (2017).

Brachiopods and other small shelly faunas, although listed and/or illustrated over 150 years ago by Billings (1861), Logan *et al.* (1863) and Murray (1864, *in* Murray and Howley, 1881), are only now actively being processed and re-evaluated. Preliminary results reveal a rich brachiopod fauna including a number of taxa that are widespread along the eastern margin of Laurentia (*i.e.*, *Obolella*, *Botsfordia*, *Hadrotreta*, *Micromitra*, *Paterina* (Plate 11) as well as other forms (Skovsted *et al.*, *in press*). In addition, associated small shelly fossils (SSF) include bradoriid arthropods, echinoderm ossicles, helcionellid molluscs, hyolithid and orthothecid hyoliths and problematic fossils such as *Salterella*, *Discinella*, *Hyolithellus* and *Chancelloria* (Plate 12). The greatest diversity of brachiopods and SSF is found in the Middle shale, in particular associated with the archeocyathid reefs of southern Labrador and in limestone nodules in the lower part of the Middle shale at MSM. Characteristic fossils such as the brachiopods *Botsfordia* and *Hadrotreta* as well as bradoriid arthropods and *Discinella* are restricted to the lower 30 m of the formation in Labrador and the Devils Cove member in the GNP. The Upper limestone interval, both in Labrador and the GNP, yields a brachiopod and SSF fauna of much lower diversity being dominated by the brachiopod *Paterina* and the cone-shaped problematicum *Salterella*; rare hyolithid hyoliths and helcionellid and stenothecoid molluscs also occur.

## STRATIGRAPHIC DISTRIBUTION OF THE TRILOBITES

The following discussion examines the trilobites collected during this study (Plates 13 to 16) and their biostratigraphic implications. The fauna is dominated by Olenelloidea (Olenel-

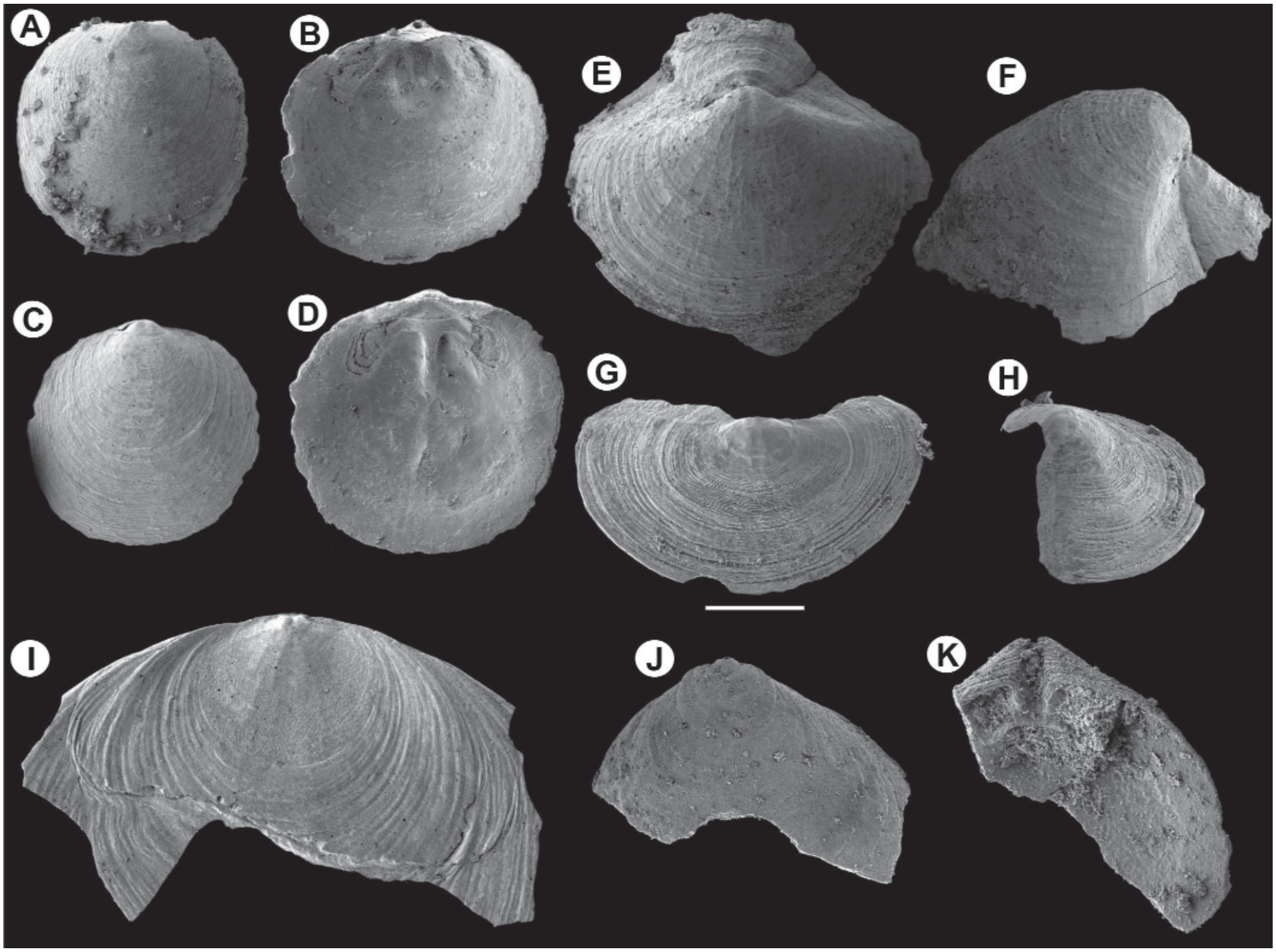

**Plate 11.** *Brachiopods from the Forteau Formation. A-D)* Hadrotreta taconica, *Middle shale at Fox Cove, Labrador; A) Ventral valve exterior; B) Ventral valve interior; C) Dorsal valve exterior; D) Dorsal valve interior; E-F)* Micromitra *sp., Upper limestone at section R432-5, western Newfoundland; E) Ventral valve exterior; F) Lateral view; G-H)* Paterina *sp., Upper Limestone in the upper quarry (LLQ3) at L'Anse Au Loup, Labrador; G) Ventral valve exterior; H) Oblique lateral view; I)* Botsfordia caelata, *Devils Cove member at MSM, western Newfoundland, dorsal valve exterior; J-K)* Obolella *sp., Devils Cove member at East Castor Pond, western Newfoundland; J) Ventral valve exterior; K) Ventral valve interior. Scale bar equals 500 µm.*

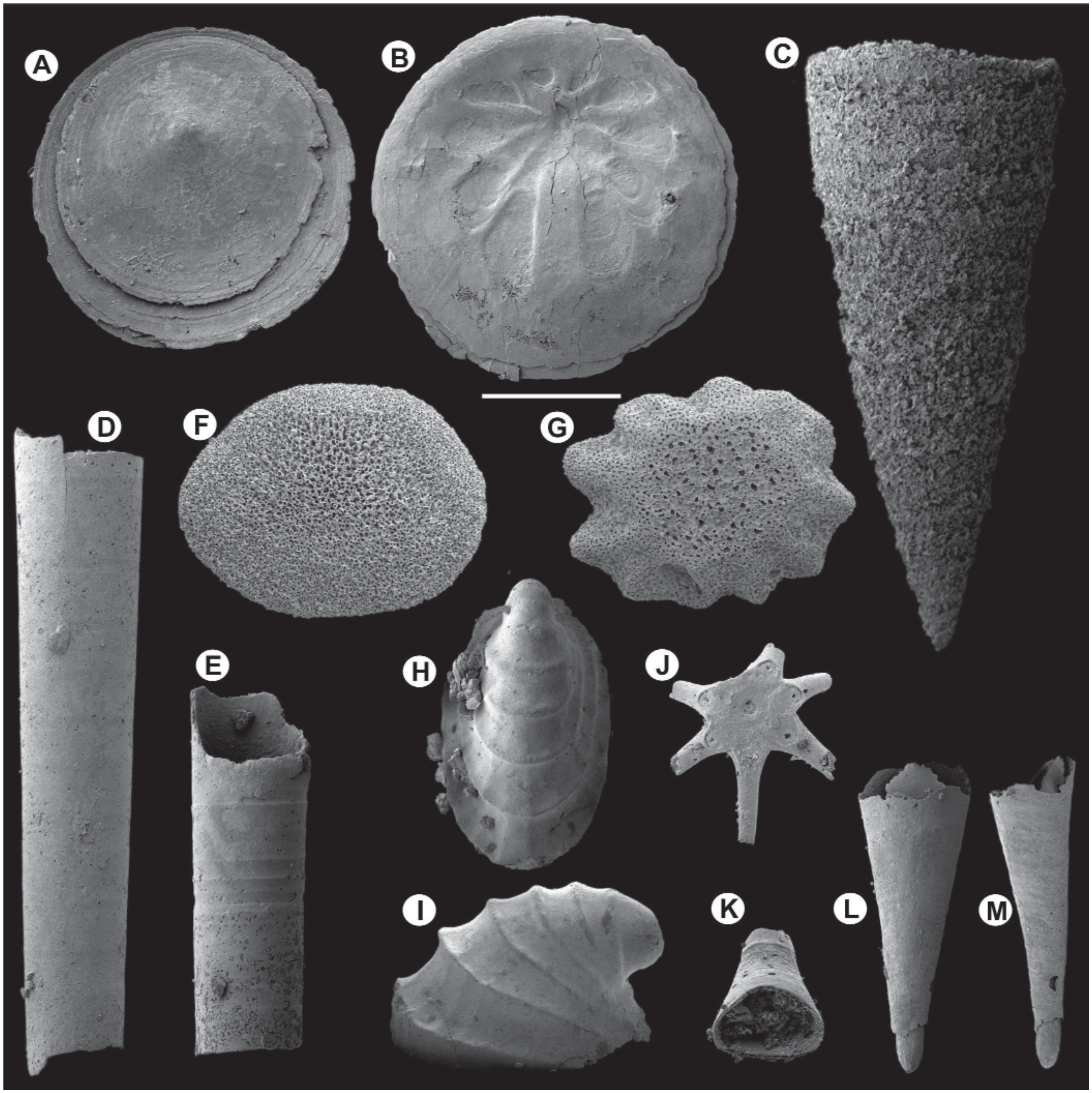

**Plate 12.** *Small shelly fossils from the Middle shale, Forteau Formation at Fox Cove, southern Labrador. A-B)* Discinella micans*; A) External view; B) Internal view with muscle scars; C)* Salterella *sp., lateral view; D-E)* Hyolithellus micans*, tube fragments with effaced ornament in lateral view; F-G) Echinoderm ossicles; H-I), Helcionellid mollusk, internal mold; H) Apical view; I) Lateral view; J) Chancelloriid sclerite with single central ray and seven lateral rays (ray at upper left broken away) viewed from basal plate; K-M) Hyolithid hyolith; K) Apertural view; L) Dorsal view; M) Lateral view. Scale bar equals 500 µm*

lidae, "Laudoniidae", "Wanneriidae"), Corynexochiida, and less common Ptychopariida. The Olenellidae (Plate 14) are represented by *Olenellus crassimarginatus* Walcott, 1910, *O. thompsoni* (Hall, 1859), *O. transitans* (Walcott, 1910), *Mesonacis bonnensis* (Resser and Howell, 1938) and *M. fremonti* (Walcott, 1910); the "Laudoniidae" (Plate 14) include *Bristolia mohavensis* (Crickmay *in* Hazzard and Crickmay, 1933) and *Fritzolenellus lapworthi* (Peach and Horne, 1892); and the "Wanneriidae" (Plate 15) include *Elliptocephala logani* (Walcott, 1910) and *Wanneria walcottana* (Wanner, 1901). The

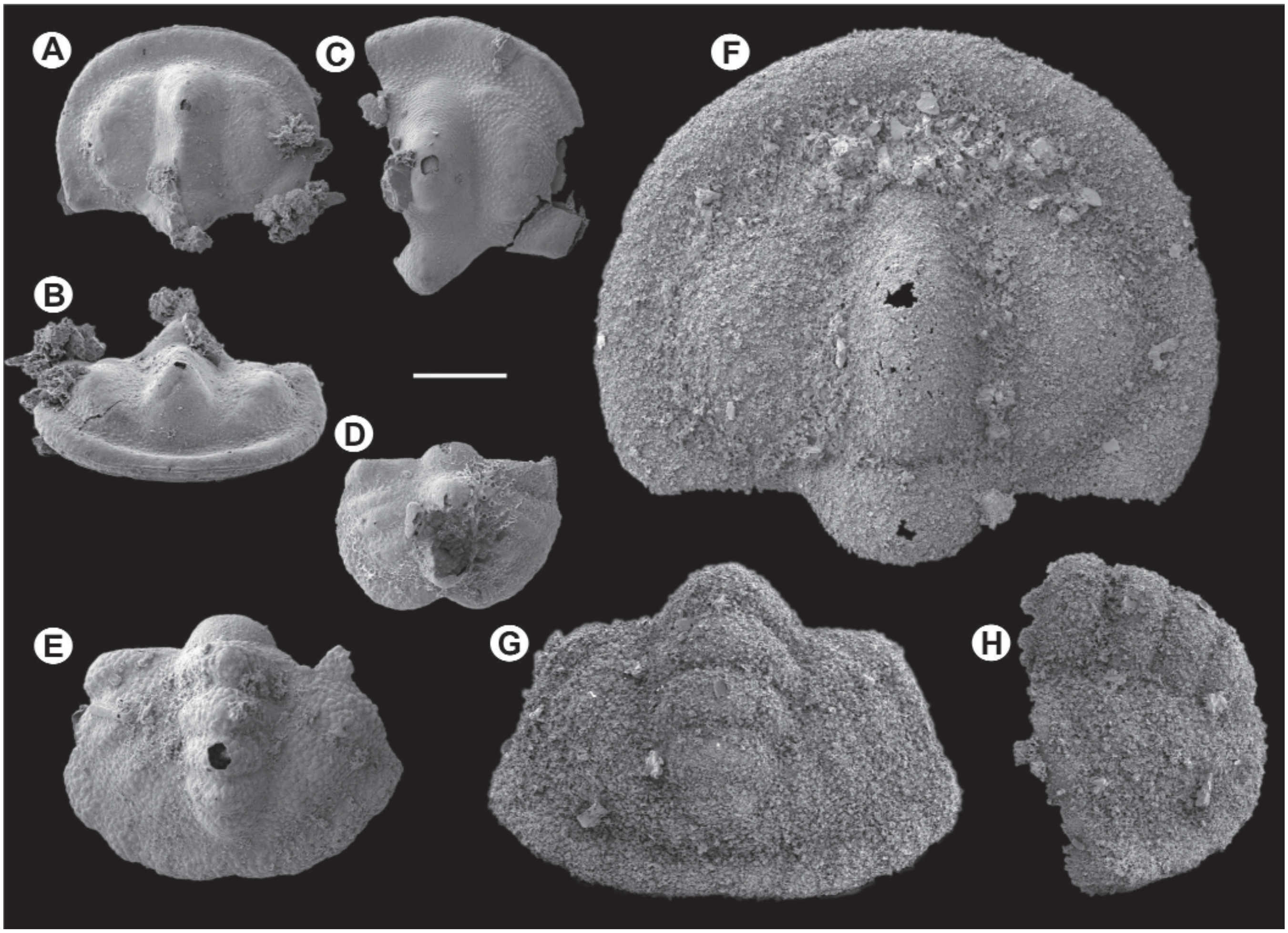

**Plate 13.** *Trilobites of the Forteau Formation: Acid isolated specimens of* Calodiscus lobatus *from the Forteau Formation. Specimens A-E from the skeletal rich limestone of the Middle shale at Fox Cove, southern Labrador. Specimens F-H from limestone nodules in lower part of Middle shale at Mt St Margaret, western Newfoundland. A-B) Phosphatized juvenile cephalon; A) Dorsal view; B) Oblique anterior view; C) Phosphatized juvenile cephalon in dorsal view; D) Phosphatized juvenile pygidium in dorsal view; E) Phosphatized juvenile pygidium in dorsal view; F) Silicified adult cephalon in dorsal view; G-H) Silicified adult pygidium; G) Oblique posterodorsal view; H) Lateral view. Scale bar equals 200 µm.*

Corynexochiida (Plate 14) are represented by *Bonnia parvula* (Billings, 1861), *B. senecta* (Billings, 1861), *Bonnia* sp. nov. and *Bonnia* sp. undet.. Finally, the Ptychopariida include "*Antagmus*" sp. undet., the eodiscid *Calodiscus lobatus* (Hall, 1847) (Plate 15), *Labradoria misera* (Billings, 1861) (Plate 16), and some as yet undetermined taxa.

In his report for 1864, Murray (*in* Murray and Howley, 1881, pages 10-11) reported *Olenellus vermontanus* (Hall) – *Mesonacis vermontana* (Hall, 1859) of modern usage – from blue limestone of the "Potsdam Group", on the north side of the entrance to Long Arm (presumably inner Chimney Arm) in Canada Bay. This identification has yet to be corroborated.

*Elliptocephala logani* (Walcott, 1910) is the only olenelloid species to range throughout the Forteau Formation in both Labrador and the GNP, where it typically occurs in grainy limestones often accompanied by one or more species of the corynexochid *Bonnia*.

*Olenellus thompsoni* (Hall, 1859) is reported from the Devils Cove and Middle shale units in Labrador from 4.57 to 24.38 m above the base of the Forteau Formation (Walcott *in* Schuchert and Dunbar, 1934; *see* Appendix 1). On the GNP, it was recovered from shale float from the lower half of the Middle shale at section R432-1 quarry and from shale float underling an oolitic limestone at section R432-7. This may suggest *O. thompsoni* also occurs in shale units within the Upper limestone (*see* below) but equally section R432-7, which is entirely isolated from other nearby outcrops, may mark the contact of the Middle shale and the Upper limestone.

*Olenellus transitans* (Walcott, 1910) occurs in the Middle shale and Upper limestone throughout the study area. In Labrador, it has been recovered from the thick shale at the base of the lower quarry at L'Anse-au-Loup (section K07-LLQ-1/2, Figure 3). On the GNP, it dominates the lower Middle shale at both MSM and section R432-1 quarries and has also been recovered from uppermost Middle shale just below the Upper limestone at both sections BER-10 and R432-2. It

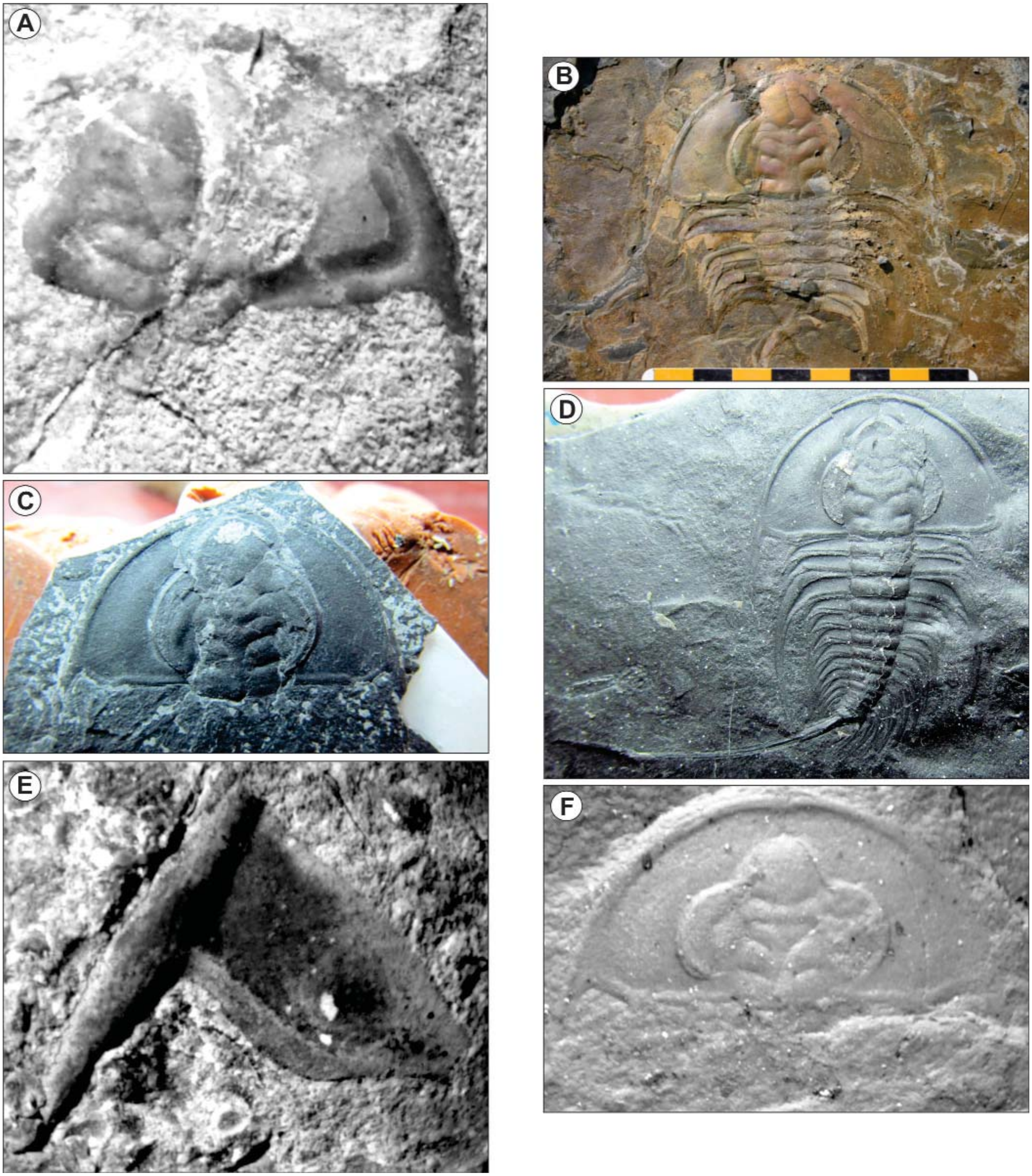

**Plate 14.** *Caption on page 39.*

ranges into the Upper limestone at MSM, and elsewhere on the GNP (sections BER-5 and R432-5). It is also found in the most easterly outcrops (R432-10 quarry) where the facies compare more closely with those in Gros Morne (Knight, 2013). The many complete dorsal shields and an abundance of juvenile forms low in the Middle shale suggest a quiet deeper water setting for the lower Middle shale.

*Olenellus crassimarginatus* Walcott, 1910 appears to principally occur in grainy limestone that straddles the boundary of the Middle shale and the Upper limestone. In Labrador, it is recovered from skeletal grainstone in the uppermost Middle shale and very basal Upper limestone at Pointe Amour roadside cliff section (K07-R2) and at section K-08-F5 west of Forteau. On the GNP, it also occurs in the base of the Upper limestone at section R432-2. However, it is also present at section R432-7, a short isolated section that cannot be firmly placed as basal Upper limestone suggesting that the species may range higher in the Upper limestone.

*Fritzolenellus lapworthi* (Peach and Horne, 1892) occurs in the uppermost part of the upper heterolithic interval of the Upper limestone on the GNP. It is found just below the 'button algae' in a roadside quarry just at the beginning of the road to the Torrent River salmon ladder near Hawkes Bay (Boyce, 2006); it is also present at section BER-2.

*Bristolia mohavensis* (Crickmay *in* Hazzard and Crickmay, 1933) and *Wanneria walcottana* (Wanner, 1901) were recovered from loose material at section R432-9 quarry, where the facies include dark grey, nodular fine and grainy limestone beds that are more similar to those in Gros Morne National Park (Knight, 2013) than those seen in Labrador or the western side of the GNP. It is noteworthy that *B. mohavensis* also occurs in similar lithofacies in a shoreline section in Canada Bay. There, the rocks were placed in the lower Hawke Bay Formation (Knight and Boyce, 1987) but are presently being re-evaluated as uppermost Forteau Formation (I. Knight and D. Boyce, unpublished data, 2017). *B. mohavensis* (Crickmay *in* Hazzard and Crickmay, 1933), *W. walcottana* (Wanner, 1901), and *Fritzolenellus lapworthi* (Peach and Horne, 1892) are not found in Labrador, the former two perhaps reflecting a lack of suitable lithofacies, but all because the uppermost part of the member was removed by glacial erosion in Labrador.

*Mesonacis bonnensis*[2] (Resser and Howell, 1938) and *Mesonacis fremonti* (Walcott, 1910) are both present on the south shore of Hawkes Bay. There, they occur in the unit of shale and sandstone that immediately overlies the 'button algae' and sits below the basal quartz arenite of the Hawke Bay Formation, *i.e.*, the uppermost Forteau Formation (Knight, 1977, 1991; Stouge and Boyce, 1983). *M. fremonti* also occurs in a unit of shale at Otter Brook, 30 m above the base of the Hawke Bay Formation (Knight, 1977, 1991; Stouge and Boyce, 1983). Neither *M. bonnensis* (Resser and Howell, 1938) nor *M. fremonti* (Walcott, 1910) have been found in Labrador likely because the top of the Forteau Formation was eroded away.

*Bonnia parvula* was originally reported in Labrador from 12.19 to 19.81 m above the base of the formation (Walcott *in* Schuchert and Dunbar, 1934; Appendix 1), *i.e.*, from lower biohermal and shelf facies interval of the Middle shale. During this study, it was recovered from the Middle shale and Upper limestone at sections K07-R2, K08-F3 and K08-F5. On the GNP, *B. parvula* has not been found in the Middle shale but is common in limestone beds high in the Upper limestone at sections BER-5, R432-2, R432-5 and R432-6.

*Bonnia senecta* was originally reported in Labrador from 12.19 to 24.38 m above the base of the formation (Walcott *in* Schuchert and Dunbar, 1934; Appendix 1), *i.e.*, from the lower biohermal and shelf facies interval of the Middle shale. During this study, it was also found in the uppermost Middle shale, in skeletal packstone and grainstone interbeds within a few metres of the base of the Upper limestone at the Pointe Amour roadside cliff and at section K08-F3 section west of the town of Forteau. On the GNP, *B. senecta* was only recovered from the upper heterolithic interval of the Upper limestone at section BER-5. There, it occurs together with *B. parvula* in the lowest limestone beds of the section below the shale containing limestone nodules (Figure 9). *Bonnia* sp. nov. (Boyce and Knight, unpublished data, 2017) occurs 2 m above the base of a thick limestone that overlies the shale in the same section where it was recovered from float. It has not

**Plate 14.** *Trilobites of the Forteau Formation. A)* Olenellus crassimarginatus *Walcott, 1910. Incomplete cephalon with detached glabella, 10 mm wide, Middle shale or Upper limestone, block on beach at Pointe Amour, Labrador; B)* Olenellus thompsoni *(Hall, 1859). Cephalon and partial thorax, 60 mm long, Middle shale, float, section R432-1 quarry, GNP; C)* Olenellus thompsoni *(Hall, 1859). Cephalon , 34 mm wide, Middle shale, float, section R432-10 quarry, GNP; D)* Olenellus transitans *(Walcott, 1910). Latex cast of complete dorsal shield, 22 mm cephalic width Middle shale, float, section R432-1 quarry, GNP; E)* Bristolia mohavensis *(Crickmay* in *Hazzard and Crickmay, 1933). Fragmentary left cephalic sclerite, 11 mm wide, possibly Upper limestone, section R432-9 quarry, GNP; F)* Fritzolenellus lapworthi *(Peach and Horne, 1892). Latex cast of complete cephalon, 15 mm wide, Upper limestone, quarry at the western end of the road to the Torrent River Fish Ladder, Hawkes Bay, GNP.*

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[2] Stouge and Boyce (1983, Plate 8, Figure 4) illustrated this as *O. brevoculus* Resser and Howell. However, Lieberman (1999) synonymized *Olenellus brevoculus* Resser and Howell, 1938 and *O. terranovicus* Resser and Howell, 1938 with *Mesonacis bonnensis* (Resser and Howell, 1938).

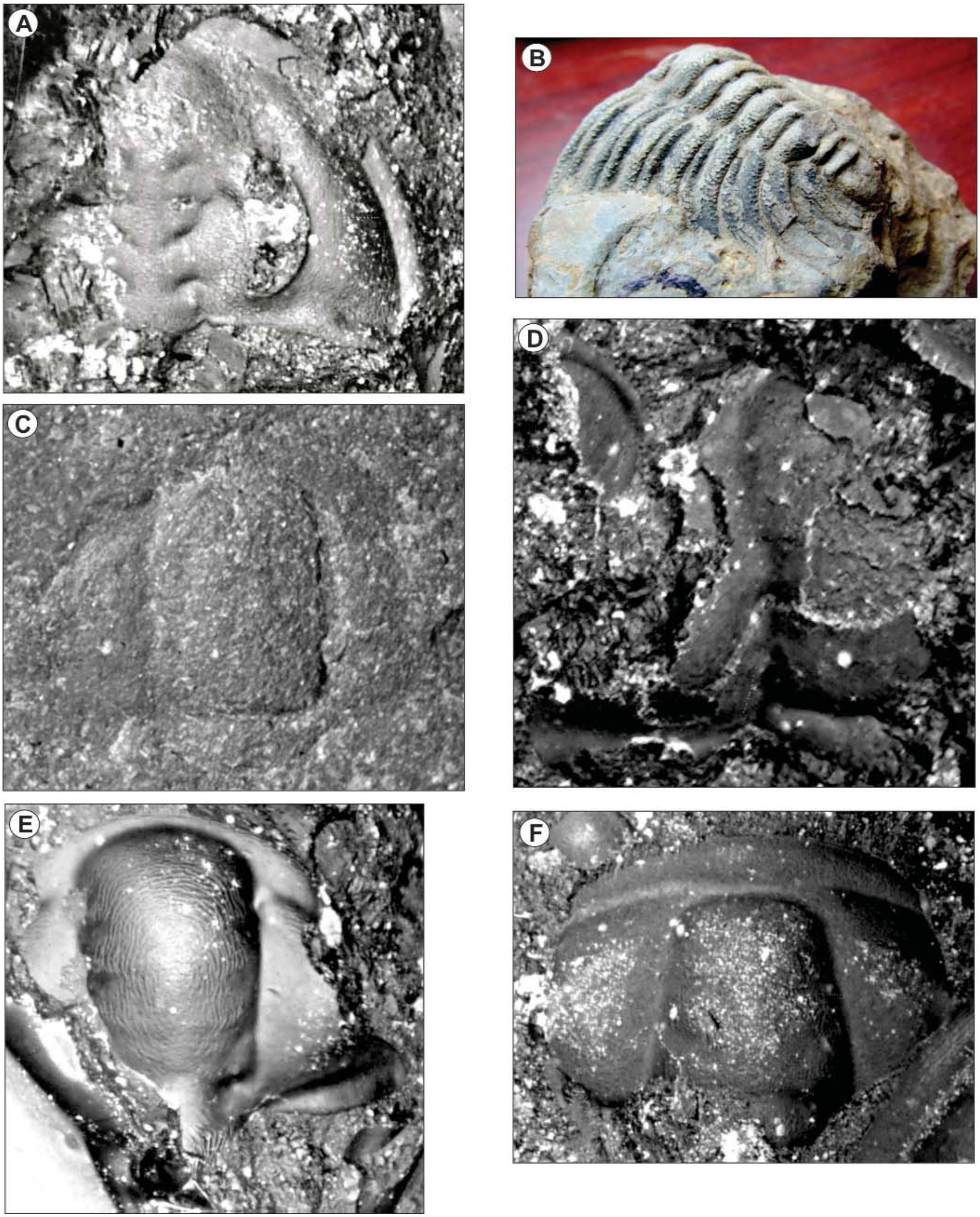

**Plate 15.** *Caption on page 41.*

been found in Labrador, likely because the relevant part of the member was eroded away during Pleistocene glaciations.

"*Antagmus*" sp. undet., (Plate 15F) so far, has only been found in Labrador, where it ranges from the lower part of the Middle Shale at Fox Cove (*see* also James and Kobluk, 1978) to the basal Upper limestone member (K08-F5). In Labrador, *Calodiscus lobatus* (Plate 13) ranges from the Devils Cove member, through the Middle shale and into the lowermost Upper limestone. On the GNP, *C. lobatus* is reported from the Devils Cove member on the eastern shore of Cloud Pond, Canada Bay (Betz, 1939; Palmer, 1969); it was recovered from the Middle shale at MSM (Plate 13) and has been found at section R432-10 where the facies are characteristic of a distal setting. *Labradoria misera* (Billings, 1861; Plate 16) is restricted to Labrador, to the basal 20 m of the formation where Walcott (*in* Schuchert and Dunbar, 1934) reported it from 12.19 to 19.81 m above the base of the formation, *i.e.*, within the lower part of the Middle shale. It was also obtained from grainy carbonates of the Devils Cove member in Section K08-FC2, east of Fox Cove (Figure 6).

In summary, *Labradoria misera* is restricted to the Devils Cove member and the lower Middle shale; "*Antagmus*" sp. undet., *Bonnia parvula*, *B. senecta*, *Olenellus crassimarginatus*, and *O. transitans* range between the Middle shale and Upper limestone; in particular *O. crassimarginatus* is most common in grainstone beds that straddle the contact of the two members; *Bonnia* sp. nov., *Fritzolenellus lapworthi*, *Mesonacis bonnensis*, and *M. fremonti* are restricted to upper heterolithic interval of the Upper limestone, whereas *Calodiscus lobatus*, *Elliptocephala logani*, and *Olenellus thompsoni* range throughout the formation. *Bristolia mohavensis* and *Wanneria walcottana* are restricted to the most easterly outcrops of the Forteau Formation on the GNP where the lithofacies are mudrock, nodular limestone and beds of sandstone characteristic of more distal facies of the formation seen in Gros Morne (Knight, 2013). The presence of *B. mohavensis* in Canada Bay from strata close to the top of the formation or base of the Hawke Bay Formation suggests this species likely occurs high in the formation equivalent of the Upper limestone. The absence of uppermost Upper limestone trilobite species in Labrador compared to Newfoundland is probably because that interval was removed by glacial erosion.

## BIOFACIES CONSIDERATIONS

Of the olenelloids, *Fritzolenellus lapworthi*, *Olenellus thompsoni*, *O. transitans*, *Mesonacis bonnensis* and *M. fremonti* mostly occur in shale and mudrock facies within the Forteau Formation, although *O. transitans* also occurs in limestone interbeds and nodules. *Bristolia mohavensis*, *Olenellus crassimarginatus* and *Wanneria walcottana* currently are known mostly from nodular limestone, but *Elliptocephala logani* appears to exclusively occur in grainy limestone, where it is typically represented by comminuted, reticulate fragmentary sclerites. *Olenellus crassimarginatus* however appears to mark the Middle shale–Upper limestone contact restricted to skeletal grainstone deposited at, or just below, the base of the Upper limestone. This suggests that it may have flourished in the transition from open-shelf settings to a carbonate sand-shoal complex.

The corynexochids comprise various species of *Bonnia*. Except for one occurrence of *Bonnia parvula* (2007F068, K07-FC1) in a bedded open-shelf facies near the base of the Middle shale at Fox Cove, Labrador, the *Bonnia* species characteristically occur as disarticulated sclerites in grainy *Elliptocephala*-bearing limestone. The ptychopariids, "*Antagmus*" sp. undet. and *Labradoria misera*, are also restricted to limestone. *Calodiscus lobatus* also occurs in limestone recovered from sections on the inner part of the Forteau shelf in southern Labrador and northwest GNP. It has also been recovered from more easterly sections on the GNP where the lithofacies suggest a more distal shelf setting like that in Gros Morne National Park (Knight, 2013) where it has also been recovered during sample processing for SSF.

## CORRELATION WITH THE STANDARD EARLY CAMBRIAN ZONATIONS OF LAURENTIA

The trilobite faunas of the Forteau Formation have long been recognized as correlative with the *Bonnia–Olenellus* zone of Rasetti (1951) and Fritz (1972b) (North, 1971; James and Kobluk, 1978; Debrenne and James, 1981; James *et al.*, 1989b). However, the relative age of the formation can be refined further by comparing its trilobite fauna with those in western Canada and the Great Basin, USA. Fritz (1972b) was the first to describe the Early Cambrian trilobite faunas of the 706 m thick Sekwi Formation in the Mackenzie Mountains,

**Plate 15.** *Trilobites of the Forteau Formation. A)* Elliptocephala logani *(Walcott, 1910). Latex cast of incomplete cephalon, 5 mm long, middle of Upper limestone, section R432-6; B)* Elliptocephala logani *(Walcott, 1910). Oblique view of partial thorax and incomplete pygidium, 45 mm long, Middle shale, MSM quarry, GNP; C)* Bonnia parvula *(Billings, 1861). Nearly complete cranidium, 6 mm long, Middle shale, Fox Cove, Labrador; D)* Bonnia senecta *(Billings, 1861). Latex cast of incomplete cranidium, 5 mm long, uppermost Middle shale, Pointe Amour cliff section, Labrador; E)* Bonnia *sp. nov. Latex cast of incomplete, highly ornamented, spinose cranidium, 5 mm long, uppermost Upper limestone, float, section R432-5, GNP; F) "*Antagmus*" sp. undet. Latex cast of incomplete cranidium, 4 mm long, basal Upper limestone, K08-F5, Labrador.*

**Plate 16.** Labradoria misera *(Billings, 1861). Fragmentary cranidium, 3 mm long, Devils Cove member, K08-FC2, east of Fox Cove, Labrador.*

Northwest Territories, Canada, and to propose three, new biostratigraphic zones namely *Fallotaspis*, *Nevadella* and *Bonnia–Olenellus* Zones[3] (Table 1). He extended the zones to other Cambrian sequences in British Columbia (Fritz, 1972a) and the Yukon Territory (Fritz, 1991), whereby they temporarily became the *de facto* standard for the Early Cambrian of Laurentia. Later work by Palmer (1998) in the Great Basin, western USA, assigned Early Cambrian rocks of the *Bonnia–Olenellus* zone to the Dyeran Stage that he subdivided into a lower "*Olenellus*" and an upper *Olenellus* Zone. Together with the Montezuman (includes *Fallotaspis* and *Nevadella* zones), the Dyeran was placed in the Waucoban Series (Table 1). Division of the older Montezuman and older strata in the Great Basin by Hollingsworth (2007) has no relevance to the Forteau Formation whereas work in the upper third of the *Bonnia–Olenellus* Zone of the southern Great Basin by Webster (2011) led to the erection of six new trilobite zones namely the *Arcuolenellus arcuatus*, *Bristolia mohavensis*, *Bristolia insolens*, *Peachella iddingsi*, *Bolbolenellus euryparia*, and *Nephrolenellus multinodus* zones (*see* also Hollingsworth, 2011; Table 1).

Of particular importance to the correlation of the Forteau Formation with the Dyeran *Bonnia–Olenellus* Zone are the trilobites *Elliptocephala logani* (Walcott, 1910), *Bristolia mohavensis* (Crickmay *in* Hazzard and Crickmay, 1933), *Mesonacis fremonti* (Walcott, 1910) and *Bonnia columbensis* Resser, 1936, the latter known from the lower Hawke Bay Formation in western Newfoundland.

*Elliptocephala logani* (Walcott, 1910) is the only trilobite common to both the Sekwi Formation and the Forteau Formation. Whilst it ranges throughout the Forteau Formation, it is only present in the middle third (146.74 to 236.54 m interval) of the 346 m thick *Bonnia–Olenellus* Zone of the Sekwi Formation (*see* Fritz, 1972b, Figure 3). This strongly indicates that the Forteau is principally medial *Bonnia–Olenellus* Zone age.

*Bristolia mohavensis*, originally described from the Latham Shale of the eastern Mojave Desert in California (Hazzard and Crickmay, 1933; Riccio, 1952; Mount, 1976, 1980) is the nominate species of the *Bristolia mohavensis* Zone of Upper Dyeran Depositional Sequence I in the Great Basin (Webster, 2011). This taxon is present in the Forteau Formation in nodular, fine-grained to skeletal (*Salterella*-rich) packstone–grainstone, encased in nodule-rich mudstone at section R432-9 35 km east of Ten Mile Lake suggesting its shelf setting is relatively distal. Its stratigraphic location is uncertain, although its presence with *Salterella* and other olenelloids suggest that it likely resides quite high in the formation. The species also occurs at Weymouth Cove, Canada Bay (Knight and Boyce, 1987, unpublished data, 2017) associated with *Bonnia columbensis* Resser, 1936 in a unit of shale, rich in lenses, thin beds and nodules of fine-grained limestone as well as lesser skeletal grainstone. *Bonnia columbensis* occurs just below the disconformable 'top' of the *Bonnia–Olenellus* Zone in the Sekwi Formation (Fritz, 1972b, Figure 3). Whether the Weymouth Cove rocks are uppermost Forteau Formation or lowest lower Hawke Bay Formation is not yet resolved. However, the combined evidence of the two collections of *B. mohavensis* in lithologically similar rocks and the presence of *B. columbensis*, suggests the top of the Forteau Formation resides somewhere between the base of the *B. mohavensis* zone and the top of the *Bonnia–Olenellus* Zone.

*Mesonacis fremonti* is a widespread taxon (Lieberman, 1999), its type locality being at Prospect Mountain in Nevada (Walcott, 1910). It occurs in the *Bristolia* Biozone of the Latham Shale and in lower Chambless Limestone at Marble and Providence mountains of the Mojave Desert, California (Walcott, 1910; Resser, 1928; Riccio, 1952; Mount, 1976, 1980), in the *Bristolia* and *Nephrolenellus multinodus*[4] zonules of the *Olenellus* Zone in the Carrara Formation of the southern Great Basin (Palmer and Halley, 1979), and in the *Bristolia* Zonule of the Delamar Member, Pioche Formation in Nevada (Webster, 2007). Webster (2011) shows *M. fremonti* ranging from the middle of the *Arcuolenellus arcuatus* Biozone to the top of the *Nephrolenellus multinodus* Biozones, effectively the uppermost third of the *Bonnia–Olenellus* Zone.

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[3] The *Bonnia–Olenellus* Zone was first used by Rasetti (1951). Suggestions for its total abandonment (Palmer, 1998; Hollingsworth, 2011; Webster, 2011) Boyce regards as premature, because of the apparent scarcity of *Bonnia* species in the Great Basin sequences.

[4] Previously *Olenellus multinodus*.

**Table 1.** Late Early Cambrian Laurentian trilobite zones, stages and series showing the approximate range of the Forteau Formation, based on collections in southern Labrador and GNP. Based on studies of Fritz (1972b), Palmer (1998) and Hollingsworth (2011)

|  | Global Series and Stages |  | Series (Palmer 1998) | Stages (Palmer 1998) | Trilobite Zones Sekwi Formation (Fritz 1972b) | Trilobite Zones Great Basin, USA (Hollingsworth, 2011; Webster, 2007, 2011) | Newfoundland Stratigraphy |
|---|---|---|---|---|---|---|---|
| 510 Ma | ? Series 2 | ? Stage 4 | Waucoban | Dyeran | *Bonnia-Olenellus* | *Nephrolenellus multinodus*<br>*Bolbolenellus euryparia*<br>*Peachella iddingsi*<br>*Bristolia insolens*<br>*Bristolia mohavensis*<br>*Arcuolenellus arcuatus* | Hawke Bay Formation |
|  |  |  |  |  |  | Not Zoned | ? Forteau Formation |
|  |  |  |  |  |  |  | ? Bradore Formation |
| 517 Ma |  | Stage 3 |  | Montezuman | *Nevadella* | *Nevadella eucharis*<br>*Nevadia addyensis*<br>*Avefallotaspis maria*<br>*Grandinasus patulus*<br>*Esmeraldina rowei* |  |
|  |  |  |  |  | *Fallotaspis* | *Fallotaspis* |  |
|  |  |  | Begadean | No stages designated |  | *Fritzaspis* |  |
| 521 Ma | ? | ? Stage 2 |  |  | No Trilobites | No Trilobites |  |

## OTHER CORRELATIONS

The Forteau Formation shares several trilobites in common with other shallow-water Early Cambrian stratigraphic units along the Appalachian Laurentian margin from Greenland to Pennsylvania. This includes *Bonnia parvula*, *B. senecta*, *Calodiscus lobatus*, *Elliptocephala logani*, *Fritzolenellus lapworthi*, *Olenellus crassimarginatus*, *O. thompsoni* and *Wanneria walcottana*.

Speyer (1983) reported mutually exclusive occurrences of *Bonnia parvula* and *Olenellus thompsoni* in the Monkton Formation of northwestern Vermont.

*Calodiscus lobatus* is a cosmopolitan trilobite known widely along the Laurentian margin but also has been reported from Avalonian rocks in eastern Newfoundland (Fletcher, 2006) and from west Gondwana, Baltica and Siberia (Ahlberg, 1984; Hinz, 1987; Geyer, 1988; Ahlberg and Bergström, 1993; Blaker and Peel, 1997, Geyer and Landing, 1995; Ahlberg *et al.*, 2007; Cederstrom *et al.*, 2009). Known from Canada Bay (Betz, 1939; Palmer, 1969) and Gros Morne (Skovsted and Peel, 2007, *this study*), it also occurs in the Taconic *Elliptocephala asaphoides* fauna of New York and Vermont states (Lochman, 1956; Rasetti, 1967). Besides *C. lobatus*, the Forteau Formation fauna and the *E. asaphoides* fauna of the U.S. Taconic region also share the following species: *Discinella micans* (Billings, 1871a)[5], *Hyolithes communis* (Billings, 1871a), *Kutorgina cingulata* (Billings, 1861), *Obolella crassa* (Hall, 1847) and *Salterella pulchella* (Billings, 1861). Theokritoff (1982) concluded that the *Elliptocephala asaphoides* fauna was indicative of the lower part of the *Bonnia–Olenellus* Zone, based on the presence of *Discinella*. However, the above species all occur within the range of *Elliptocephala logani*, which indicates a direct correlation with the middle part of the *Bonnia–Olenellus Zone* (*see* above). This is a view shared by McMenamin *et al.* (2000) following studies of archeocyathid-bearing shelf strata farther south in Virginia and Alabama that includes some of the fauna recognized in the Devils Cove member in Gros Morne and the Forteau Formation in southern Labrador. *C. lobatus* is also known in North Greenland where it occurs in co-eval strata of the Aftenstjernesø and Kap Troedsson formations, Bronlund Fjord Group, (Blaker and Peel, 1997) and is correlated with the middle of the *Olenellus* Zone. In North-East Greenland, *C. lobatus* and *Discinella* occur in the Bastion Formation and have been correlated with the median *Bonnia–Olenellus* Zone (Skovsted, 2006).

*Elliptocephala logani* occurs in the Ella Island Formation on Ella Ø, North-East Greenland (Poulsen, (1932). Poulsen originally described it as *Wanneri nathorsti* n. sp., but Fritz (1972b, 1991) later synonymized it with *Wanneria logani* (now *E. logani*).

*Fritzolenellus lapworthi*, part of the trilobite fauna from near the top of the heterolithic interval of the Upper limestone (*see* above) below the 'button algae' bed (Boyce, 2006) was originally described from the Fucoid beds of the lower An-t-Sron Formation of northwest Scotland (Peach and Horne, 1892; Peach, 1894; Cowie and McNamara, 1978). It is also known from the Bastion Formation of North-East Greenland (Stein, 2008).

In the Forteau Formation, whereas *Olenellus crassimarginatus* occurs in exclusively shallow-water shelf limestone deposited at the fringing edge of a prograding carbonate sand shoal complex, *O.transitans* and *O. thompsoni* mostly occur in deep-water shale. *Olenellus crassimarginatus* and *O. transitans*, however, are restricted to basinal facies within the Parker Formation of Vermont (Webster and Landing, 2016) and the Kinzers Formation of Pennsylvania (Walcott, 1910; Resser and Howell, 1938; Whittington, 1989; Lieberman, 1998, 1999; Webster and Landing, 2016) where they are also associated with *O. thompsoni* (Webster and Landing, 2016). However, *O. thompsoni* also occurs in shelf facies rocks of the Monkton Formation in Vermont, indicating it ranges from deep off-shelf to shallow-shelf settings (Webster and Landing, 2016). A probable cephalon of *O. crassimarginatus* was documented from "limestone of the Slakli series, in Sørkapp Land, Spitsbergen (Major and Winsnes, 1955). Although Webster and Landing (2016) regarded *O. crassimarginatus* as being restricted to basinal facies, its occurrence in shallow-water limestone in Spitsbergen, southeastern Labrador and western Newfoundland, strongly suggests it ranges into shallow-shelf settings as well.

*Wanneria walcottana* (Wanner, 1901), the type species of the monotypic genus *Wanneria*, is also present in the Kinzers Formation (Lieberman, 1999). In western Newfoundland, *W. walcottana* was found in loose material in section R432-9 and *in situ* in the post-Deer Arm limestone succession in Gros Morne (Knight, 2013). This suggests it is exclusively linked to distal, mud-dominated deeper water parts of Newfoundland's Forteau shelf.

# INTERPRETATION OF THE FORTEAU FORMATION IN SOUTHERN LABRADOR AND NORTHWEST GREAT NORTHERN PENINSULA

The Forteau Formation in southern Labrador and the western side of the GNP, north of Blue Mountain, preserves

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[5] Formerly identified as the operculum of *Hyolithellus micans* (Billings, 1871).

a succession that bridges the later stages of a fully marine transgressive system tract (TST) and a high-stand system tract (HST). The post-rift megasequence, deposited on a ramp shelf (James *et al.*, 1989b) reflects late Early Cambrian sea-level rise that drowned Newfoundland's Laurentian margin in response to margin subsidence and eustatic sea-level rise in the middle Dyeran *Bonnia–Olenellus* zone. The transgression resulted in a mud-dominated, eastward deepening shelf to basin succession preserved in the lower third of the formation. Likely slowing sea-level rise and the increasing input of fine but gradually coarsening sediment forced offlap and the clastic shelf to prograde in the early stages of regression before giving way to a highstand carbonate shelf 60 m thick. The carbonate shelf, deposited in an inner ramp setting (*cf.* Burchette *et al.*, 1990) prograded to reach its oceanward limit close to the western edge of the GNP's Long Range Massif, after which accretion of the succession was likely accommodated by a fine balance of sea-level rise, subsidence and sedimentation rate. A fine-grained succession of mixed clastics and skeletal rich carbonates of subtidal aspect, typical of a mid-ramp setting, dominate much of the Forteau Formation east of the inner ramp where they persisted into the later stages of the formation. Isolated and singular units of shallow-water limestone in more easterly successions, such as Canada Bay and towards the top of the Upper limestone at Blue Mountain, suggest that tongues of shallow-shelf facies extend into more distal and nominally deeper water, mid- to outer-ramp settings during the end of the Forteau; at the same time, clastic sedimentation was beginning to dominate the inner part of the shelf. Quartz-rich clastic sediments intercalated with the carbonates in the final stage of the highstand shelf herald a low-stand, storm-dominated clastic shelf preserved in the overlying Hawke Bay Formation.

The TST began with a storm-dominated clastic strandline of arkosic, micaceous and quartzose sandstone (Bradore Formation; Hiscott *et al.*, 1984; Knight, 1991; Long and Yip, 2009) that was drowned as Forteau seas rose over Newfoundland's Laurentian margin. With cutoff of the coarse clastics, an open-marine shelf evolved in the lower Forteau Formation. It comprises a thin carbonate, the Devils Cove member and the lower 25 m or so of the Middle shale that includes shallow, nearshore muddy shelf and archeocyathid reefs in Labrador, and a deeper water mud-dominated basin to the east on the GNP. The succession culminated at the maximum flooding surface (MFS) about 20 to 30 m above the base of the formation.

The high-stand system tract (HST) commenced in the upper half of the Middle shale, host to a fine-grained coarsening upward succession that began with mudrock and passed upward into extensively bioturbated siltstone, punctuated by event beds that include fine-grained sandstone and skeletal carbonate. The latter anticipates the oceanward advancing carbonate shelf preserved in the Upper limestone. The shelf began as an archeocyathid–carbonate shoal complex that extends from Labrador, southeast to the western edge of the Long Range Mountains. The Upper limestone cannot be traced convincingly east of this part of the GNP, the more easterly, deeper water succession consisting of mostly limestone-nodule hosting, fine-grained clastics intercalated with beds of fine-grained and skeletal limestone and only a rare tongue of shallow-water carbonate in Canada Bay, White Bay and Gros Morne (Knight, 1987, 2013; Kerr and Knight, 2004). This perhaps suggests that the shelf steepened at this transition implying a distally steepened ramp (*see* Read, 1985; Sarg, 1988; Burchette *et al.*, 1990; Williams *et al.*, 2011). Irrespective, the regressive part of the Forteau succession appears to preserve a high- to moderate-energy, shallow-water inner ramp dominated by grainstone facies, particulary oolitic limestone that was up to 75 km wide. It ceded to a mid to outer ramp of deeper water lithofacies to the east, southeast and south, the succession typified by thin-bedded, fine clastics and lesser, mostly nodular, skeletal-rich carbonates (Knight, 2013). The outer ramp succession is twice the thickness of the inner ramp succession and likely exceeds 130 km in width, the succession being significantly shortened by Appalachian thrusting (Knight, 1987, 2013).

Intercalated siliciclastic units, high in the Upper limestone in northwest GNP prelude the demise of the high-stand carbonate shelf late in the *Bonnia–Olenellus* zone, when it was smothered by CU clastic sequences of the Hawke Bay Formation (the Lower to Middle Cambrian Hawke Bay Event of Palmer and James, 1980). Coeval shallow-water carbonates were forced outboard to a narrow mixed belt of carbonates and clastics preserved in parautochthonous rocks along the east of the Long Range Inlier from Canada Bay in the north, to Coney Arm, White Bay, in the south (Knight, 1987; Knight and Boyce, 1987; Kerr and Knight, 2004). This restricted geographic distribution reflects perhaps the depositional influence of the Newfoundland Promontory during the Hawke Bay Event.

## THE TRANSGRESSIVE SYSTEM TRACT (TST)

The TST in the inboard belt of the Forteau Formation is more complex than specifically implied above. The basal Devils Cove member, the most extensive regional, possibly chronostratigraphic marker throughout western Newfoundland, rests sharply upon the underlying Bradore Formation. In many places, the switch from Bradore clastic to Devils Cove carbonate sedimentation is gradational where beds and ribbons of Bradore sandstone intercalate in the base of the carbonate (*see* also Knight, 2013). This suggests that the marker may be diachronous above the Bradore Formation, although no convincing biostratigraphic evidence supports this, and it is likely that the transgression was relatively rapid, reflecting the low-gradient shelf.

A subtle change from south to northwest occurs in the basal carbonate member that is widely dolomitized in more northerly outcrops. Sandy dolostone overlain by stylonodular fine-grained carbonate at Blue Mountain suggests an upward deepening trend in the most southerly part of the inboard belt. Farther north, near MSM and into southern Labrador, the member is essentially a grainy and skeletal-rich carbonate with interbeds locally of Bradore-type sandstone and grainstone rich in quartz sand.

Archeocyathid reefs occur in the Devils Cove member northwest of the south coast of the Strait of Belle Isle (drillcore DH-NF-1B *etc.*, Savage Cove). The small mounds atop the last clastics of the Bradore Formation east of Fox Cove suggest the colonization here was rapid. The geographic distribution of the reefs suggests they thrived as scattered and isolated patch? reefs surrounded by grainy carbonate in a manner similar to the patch reefs scattered upon the later muddy Forteau shelf in southern Labrador (lower Middle shale; James and Kobluk, 1978; Debrenne and James, 1981). Isolated archeocyathid clasts in skeletal grainy carbonate, in areas such as MSM and East Castor Pond, either suggest debris swept from the reefs to the northwest or attempts to colonize the seabed were unsuccessful. Because the archeocyaths in the study area have not been identified, no correlation with those in the member in Gros Morne (James and Debrenne, 1980a) is possible.

Above the Devils Cove member, the Forteau succession (lower Middle shale) indicates a clear divide between that in southern Labrador and that in the northwest GNP, north of Blue Mountain. On the GNP, the shale-dominated succession has interbeds of fossiliferous, nodular, fine-grained limestone rich in *Salterella*, brachiopods and trilobites but lacks archeocyathids. In contrast, southern Labrador is famous for its archeocyathid patch reefs that thrived in grouped clusters, on an otherwise shallow, open, muddy shelf (James and Kobluk, 1978; Debrenne and James, 1981). The latter, a succession of siliciclastic mud, bioturbated calcareous siltstone and fine-grained carbonate, marks much of the TST. James and Kobluk (1978; *see* also Debrenne and James, 1981) argued for a somewhat quiet shelf above fair weather base, the abundance of microbial algae in the reef framework indicating growth within the photic zone of the shallow sea.

The largest patch reefs are upward-expanding stacked bioherms, the open archeocyathid-calcareous algal framework supporting a thriving ecosystem of microbial algae, sponges, sessile and mobile organism, all contemporaneous with precipitation of marine cements (James and Kobluk, 1978; Kobluk and James, 1979; Debrenne and James, 1981; Pruss *et al.*, 2012). The irregular to roughly circular to oval bioherms surrounded by coarse- and fine-grained sediment had modest, metre-high synoptic relief above the seabed (James and Kobluk, 1978). Organisms that thrived on, or around the reefs, principally echinoderms and trilobites, supplied the flanking skeletal grainstone (James and Kobluk, 1978; Kobluk and James, 1979; Debrenne and James, 1981; Pruss *et al.*, 2012).

The restricted distribution of reef-flanking, wedge-like grainstone banked up against the reefs suggests that they were fashioned by local wave and current action intrinsic to the reef itself. Nonetheless, small-scale mudstone to grainstone sequences locally within the reefal buildup suggest that reef growth perhaps also responded to the same extrinsic dynamics that controlled cyclicity of the open-shelf facies. The repetitive, essentially coarsening- to cleaning-upward nature of the open-shelf facies cycles implies depositional cycles that may have responded to small-scale, 5th order sea-level fluctuations and/or to climatic events that generated and transported fine-grained sediment across the Forteau shelf. The shale to siltstone cycles, rarely greater than 1 m thick, imply repeated progradation of fine clastic sediment across the shelf, the laminated and crosslaminated siltstone perhaps linked to punctuated climatically controlled fluvial discharge of distant river systems. During fair weather, siltstones were extensively bioturbated and deposition of limestone reflected cleaning water conditions. Shale likely implies interpluvial fair weather sedimentation.

The archeocyathid reef–open shelf association of southern Labrador did not extend across the Strait of Belle Isle to Savage Cove, 12 km away from the classic reef buildups; archeocyathid reefs and detritus are absent there, and open-shelf sedimentation is confined to a few metres at the base of the Middle shale (drillcore DH-NF-1B). At MSM, 40 km farther to the south, the succession is dominated by dark shale suggesting the shelf deepened southeastward. The shale, host to numerous disarticulated and complete, mature and juvenile olenellid trilobites, dominates the lower Middle shale as far south as Blue Mountain and nearby Labrador Group Long Range outliers. Common pyrite suggests anoxic seabed conditions generally and the importance of intact olenellid carapaces supports generally quiet bottom conditions below storm wave base.

Carbonate rocks in the shale-dominated succession of the Middle shale are restricted to horizons of limestone nodules and nodular to lumpy, coarsely bioturbated skeletal limestone beds. The latter, a mix of comminuted and disoriented broken shells of brachiopods, hyolithids, salterellids and trilobites amongst others, are interpreted as storm deposits, transported from a shallow-shelf setting into deeper water, where they were subsequently bioturbated by an opportunistic infauna.

The range of sedimentary structures and fossils preserved in early burial limestone nodules but not noted in the host shale indicates that the muddy seafloor was nonetheless a fairly dynamic setting below storm wave base. Whereas massive nodules may suggest mud transported as gravity-driven bottom flows across the low-gradient shelf floor, laminated nodules likely reflect pelagic settling. Nonetheless, crosslamination in some nodules, and burrows in others, indicate that the seafloor was influenced by bottom currents and that oxygen was sufficient to support bottom dwelling and infaunal organisms. *Elliptocephala logani* in a nodule (Plate 12B) contrasts to the flattened olenellids of the host shale, as it displays significant body shape and ornamentation. A large hyolithid in another nodule suggests these lophophorates inhabited the muddy seafloor but were otherwise obliterated by compaction and early diagenesis.

## MAXIMUM FLOODING SURFACE (MFS) AND HIGH-STAND SYSTEM TRACT (HST)

The MFS in the Middle shale is projected to lie about 20 to 30 m above the base of the formation on the GNP in a dark-grey shale interval largely devoid of carbonate nodules. It is correlated with a thick grey-green shale, host to complete olenellid trilobites, in southern Labrador (L'Anse-au-Loup lower quarry, shaly raised bench inland of Fox Cove). Upwards in southern Labrador, shale is interbedded with discrete limestone beds and burrowed, laminated and crosslaminated siltstone and sheet-like and lenticular, fine-grained sandstone having inclined to hummocky lamination. This suggests a shelf shallowing above storm wave base. The silts and fine sands were likely supplied by flood-related fluvial input, bioturbated during fair weather and periodically reworked by storms.

Limestone interbeds scattered through the shale succession compositionally depend on their proximity to the contact with the Upper limestone. Limestone beds low in the shale are generally thinner, skeletal and peloidal grainstone, packstone and wackestone. Siltstone rip-up intraclasts and internal structure imply that they were deposited during storms; trace fossils (*Cruziana* assemblage) suggest an opportunistic infaunal community followed their deposition. Limestone interbeds close to the contact with the Upper limestone range from skeletal grainstone (many *Salterella*-rich) to oncolitic–oolitic grainstone. This suggests that carbonate sand was likely swept from prograding carbonate sand shoals that characterize the Upper limestone; scattered archeocyathid detritus indicates buildups on the encroaching carbonate shelf.

The southern Labrador succession likely reached to the south shore of the Strait of Belle Isle (drillcore DH-NF-1B), and passed southeast into a succession of shale and burrowed siltstone giving way upwards, into intensely bioturbated calcareous siltstone and very fine sandstone seen from MSM, north around the Long Range Inlier and south to Blue Mountain; the ichnofauna is typical of a *Cruziana* trace assemblage. Remnant depositional structures in the burrowed siltstone–sandstone support deposition by waning bottom currents below storm wave base. The extensive distribution of this 20 m thick bioturbated interval may imply a possible local depocentre on the shelf, perhaps linked to fluvial input. Lenses and beds of *Skolithos*-bearing quartz-rich HCS sandstone near the top of the member indicate the shelf accreted above storm wave base, the sands bioturbated by a limited fauna of opportunistic burrowers.

Slumping affected a nodular shale interval in the thick shale exposed in the BER area (*see* section BER-12, Figure 9). The slump fold, chaotic bedding, small-slide surfaces and matrix-supported nodule conglomerate suggest not only that the basin was unstable for a time, but that shallow burial calcareous nodules and lumps were exposed to erosion on the seabed. Storms reworked the basin floor mud to leave conglomeratic lags of nodules. Evidence for similar slumping and seafloor dynamics is not seen elsewhere in the GNP region so the exact cause of the instability is uncertain. However, the shale quarry lies adjacent to the Torrent River Fault, part of a broad zone of basement-linked faults that includes the Ten Mile Lake Fault and the faults along the western margin of the Long Range Massif. This may imply that movement on the fault zone influenced local collapse of the basin slope and that a hinge zone of shelf to basin steepening occurred in this area. It is noteworthy that the fault zone also appears to coincide roughly with the southeastern limit of archeocyathid buildups in the area (*see* below).

## HIGHSTAND CARBONATE SHELF

The Upper limestone preserves a highstand carbonate shelf in southern Labrador and northwest GNP. It began with a broad belt of archeocyathid buildups associated with carbonate sand complexes that, in time, smothered the buildups. Together they support a broad, prograding, high-energy shallow shelf in which the archeocyathid buildups advance no farther southeast than a southwest-trending tract, just east of Ten Mile Lake to Hawkes Bay. The eastern edge of the buildup and sand complex essentially coincides with the merged northeast trace of the Torrent River and Castor Pond faults perhaps reinforcing the importance of this fault zone to the evolution of the Forteau shelf (*see* above).

### The Upper Archeocyathid Biostrome in Labrador

The archeocyathid interval in southern Labrador was designated as a biostrome complex by Hughes (1979) and Debrenne and James (1981), with the former proposing that the buildups thrived in deeper water recesses adjacent to shallower water salients, the site of carbonate sand shoals. The 5-part stratigraphy of the archeocyathid complex suggested to Hughes (1979) a broad tract of small 'moundstone' buildups associated with a range of grainstone lithofacies, the grey and red mounds and associated facies interleaving on a broad scale (*see* Figure 29, Hughes, 1979). Matrix-supported, lime rudstone rather than archeocyathid mounds forms the lower grey interval of the complex (*this study*), small red archeocyathid buildups associated with grainstone and red mudstone characterize the middle and isolated mounds associated with thrombolitic and stromatolitic mounds and oolitic and skeletal grainstone the upper grey interval (Hughes, 1979; *this study*).

The poorly sorted, rubbly, grey, conglomeratic limestone at the base of the succession is here interpreted as broken and dislodged, angular fragments of many limestone lithologies including archeocyaths set in an argillaceous, dolomitic matrix rather than biostromal as interpreted by Hughes (1979). Its crosscutting erosional base at Fox Cove, the chaotic, fragmentary, polymictic nature of the facies, its dolostone matrix, the lack of any demonstrable reef mounds, lack of laminar archeocyaths that are important in the red and upper biohermal mounds, and its high silt and sponge spicule content all suggest an alternative interpretation should be sought for this widespread facies. The basal scour, the chaotic rubbly fabric, and intercalation of rubble beds and grainstone in off-lapping wedge-like deposits associated with major truncation surfaces at L'Anse-au-Loup could suggest that the facies is reef talus. Alternatively, in the absence of reef buildups, the matrix-supported chaotic rubble mapped over tens of kilometres in southern Labrador may preserve an extensive rubble terrace or bench perhaps formed by *in-situ* death and disintegration, of poorly framed and cemented skeletal buildups and associated facies.

The middle red interval of the biostrome suggested to Hughes (1979) a well-oxygenated, tidal setting to explain its colour. The presence of bimodal crossbedded grainstone enclosing small to large archeocyathid mounds support a high-energy tidal setting for the red biostrome in the L'Anse-au-Loup area. However, red mudstone trapped amongst mounds of bush-like and dislodged stick-archeocyaths suggests that flood-driven fluvial and/or wind-blown fine terrigenous clastic detritus derived from a coeval non-marine coastal plain to landward (*i.e.*, to the northwest) inundated the peritidal buildup. The truncation surfaces that bound the red interval imply that significant erosional events planated the complex, the storm generated marine erosion perhaps reflecting sea-level low-stand at this time. The upper grey interval overlying the upper truncation surface, harbours distinctive small mound-like archeocyathid bioherms surrounded by skeletal and oolitic grainstone and associated with thrombolitic and stromatolitic boundstone mounds. This suggests the upper grey interval as seen at L'Anse-au-Loup also evolved close to sea level in a generally dynamic setting.

The laterally extensive Pointe Amour to L'Anse-au-Loup biostrome complex is outflanked to the southwest and northeast by thick oolitic grainstone. The regional relationships in southern Labrador (Figure 6) also show the oolitic shoal facies overlying the biostrome in the Pointe Amour to L'Anse-au-Loup area as well as conformably overlying bedded shelf-facies rocks beyond the buildup. The localization of buildups suggested to Hughes (1979) that the biostrome was related to a recess along the Forteau shelf in southern Labrador, and that the oolitic shoals formed at salients flanking the buildups; he gave no reason for these physical features. Nonetheless, the presence of a scour with visible relief below the lower rubbly grey interval suggests that the recess may have been an erosional embayment, centred on the area of Fox Cove. However, a truncation surface with grainstone-filled gutter casts marking the top of the biostrome at Pointe Amour below oolitic limestone with microbial boundstone mounds, may suggest that the oolitic shoal complex rather than being co-eval with the biostrome largely postdates it. It is noteworthy that the only evidence of a contemporaneous oolitic complex at L'Anse-au-Loup occurs at the top of the upper grey interval. Ooids were not observed in any of the earlier biostrome facies at Pointe Amour, Fox Cove or L'Anse-au-Loup. They are also not recorded by Hughes (1979) even though he proposed buildups such as those near the Osprey Reef (*see* Debrenne and James, 1981) lay directly adjacent to the oolitic shoals. Since the grainstone facies of the biostrome displayed at L'Anse-au-Loup indicate that the biostrome was likely fashioned in a high-energy tidal setting with frequent erosion and shifting grainstone bodies, it seems reasonable that co-eval oolite shoals, if they were present, would have been fashioned by the same dynamic, and that ooids would have been swept into the biostromal recess from an adjacent salient. The geological relationships outlined above and the paucity of ooids in the biostrome complex seems to argue that the biostrome and the oolite shoal are not therefore penecontemporaneous. If this is a correct interpretation of the local southern Labrador relationships, it is suggested that the biostrome essentially thrived in an erosional recess on the Forteau shelf during the early stages of progradation of the carbonate highstand shelf. This perhaps could indicate an episode of falling sea level and shelf incision or fault-related local subsidence affecting the Forteau shelf at this time.

The origin of dolostone-filled cavities in the grey rubble beds is not understood. Hughes (1979) proposed that they were integral to the biostrome but this seems unlikely because the structures cut the grey rubble facies and have a range of fabrics, some of which compare to geopetal stratification. Hence, they are considered to be post-burial structures formed in lithified carbonate. Taken alone, they could imply that the southern Labrador succession was affected by meteoric groundwaters, the cavities later infiltrated by dolomite mud.

Whether the dolostone bodies formed essentially coincident with the formation of the grey rubble is not known, but if this was the case, then it suggests that the rubble may have formed during local sea-level fall and subaerial exposure.

## The Inner Ramp, GNP

The stratigraphic succession in the northwest of the GNP shows archeocyathid bioherms underlie the oolitic grainstone facies in both, the subsurface at Savage Cove and in outcrops farther east. Grey matrix dolostone-supported limestone rubble is also present locally in northwest GNP, interbedded in the base of the archeocyathid interval at Savage Cove (drillcore DH-NF-1B) and marking the base of the section at MSM. Steep-sided bioherms flanked by crossbedded inter-reef grainstone above the basal carbonate rubble in this area suggest the latter could be forereef talus. However, the grey bioherm at section R432-3, east of Ten Mile Lake rests directly upon bedded-shelf facies indicating that the rubble unit is localized. Scattered archeocyathid debris in the oolitic grainstone complex (drillcore DH-NF-1B, Figure 2) suggests that bioherms likely continued to thrive locally within the shoal complex or at its leading edge. The thick oolitic and skeletal grainstone in which archeocyathid detritus is scattered, abruptly overlies the reef complex at Savage Cove (drillcore DH-NF-1B) and east of Ten Mile Lake; an erosional relationship that occurs is also present atop the archeocyathid complex at Pointe Amour, Labrador.

Traced for up to 80 km along strike, from Torrent River to Ten Mile Lake, yet absent from Forteau rocks to the southeast suggests that the biohermal reef-carbonate sand-shoal association forms a north-northeast trending tract defining the seaward margin of the prograding Forteau inner ramp. Regional stratigraphic relationships suggest that the reefs lay oceanward of the shoal complex (Hughes, 1979; *this study*) and that the reef tract-shoal complex essentially was an offlapping, diachronous couple to the easternmost known extent of the reef tract.

## The Carbonate Shoal Complex

Hughes (1979) proposed a collage of subenvironments within the carbonate sand complex depending on the composition and mix of allochems. Consequently, he proposed that the complex ranged from high-energy oolite shoals to mixed oolite and skeletal grainstone and packstone deposited in moderate- to low-energy setting in the lee of the shoal. Oncolitic oolitic grainstone is assigned to relatively deeper channelways, whilst intraclastic pebble-bearing grainstone hosting clasts of lithified carbonate are viewed as storm-deposits stranded high upon the shoal. Laminated and crosslaminated dolostone formed in intertidal to supratidal parts of the sand shoal.

Coarsening-upward cycles of mudrock, burrowed siltstone or dolomitic wackestone and packstone capped by skeletal and oolitic grainstone recognized near Forteau and Diablo Bay (*this study*) suggest shoaling facies were deposited oceanward of the shoal margin. Modern analogues of oolite carbonate sand shoals, such as those of the Bahama Banks, suggest that the carbonate shoal complex developed in shallow subtidal to emergent, high-energy settings close to the shelf edge (Ball, 1967; Rankey *et al.*, 2006). The presence of thrombolite mounds associated with grainstone in drillcore DH-NF-1B and in Labrador is compatible with this.

Recent studies of the Bahaman oolitic sand shoals indicate that they are characterized by a complex of linear, curved to parabolic carbonate sand ridges that host a range of bedforms (Rankey *et al.*, 2006; Rankey and Reeder, 2011; Harris *et al.*, 2011). Well- to moderately sorted, coarser grained oolitic sands mark ridge crests and flanks respectively in the outer part of the shoals, where the complex is largely influenced by the strongest current velocities of the flood tides. This is facilitated by channels between bedrock islands or by the self-organizing channel-ridge shoal structure along which tidal currents funnel onto the bank top. Currents lose energy as they partition and spread out across inner areas of the shoal. Consequently, finer grained, less well-sorted sands consisting of mixed allochems, lie in deeper flanking parts of the ridges, in channels as well as bars in more distal parts of the shoal. Ebb currents locally also influence the shoal ridges but generally they appear to be less important in shaping the shoal complex because seawater can escape off a bank through a range of options overall reducing current velocity. Wind-driven currents (trade winds and weather system driven) are generally not sufficient to move any but the finer sand in the complex.

How much of this recent insight can be applied to the oolitic and mixed carbonate sands of the Forteau shoal complex is debatable as no systematic studies have occurred; tidal ranges were likely small on the inner ramp and the Forteau shoal complex formed on the inner part of a wide, low-gradient ramp shelf rather than at the edge of a rimmed platform as in the Bahamas. Nonetheless, the work of Hughes (1979) suggests that a range of subenvironments are necessary to account for the many grain-dominated lithofacies in the Forteau carbonate shoal implying that the morphology of the shoal was complex. On a local scale, crossbedding in carbonate sand at L'Anse-au-Loup, and in grainstone-filled channels between bioherms at MSM and section R432-3, suggest that the bioherms may have effectively funnelled and intensified current velocities in the channels during flood tides, the crossbeds dominantly suggesting cratonward paleoflow. Where bioherms are not present it seems likely that the shoals intrinsically were self-organizing.

Beyond the eastern edge of the reef tract, carbonate sands appear to thin within the upper Forteau. Athough it occurs above the Middle shale at Blue Mountain and adjacent Cambrian outliers, oolitic limestones of the carbonate sand facies are confined to the base and the top of the Upper limestone, subordinate to thick intervals of fine grained, shelf clastics. Thick beds of grainstone also appear to thin and are less prominent in the area east of MSM and ECP and at the southeast end of the HSJ along the BER resource road; only a single, metre-thick unit of oncolitic oolitic grainstone occurs near the top of the formation in Canada Bay (Knight, 1987; Knight and Boyce, 1987). This suggests that the oolite shoal did not substantially outflank the reef tract in an oceanward direction and implies that the break from inner high-energy shallow ramp shelf to lower energy, deeper water, mid to outer ramp shelf was maintained near the western edge of the Long Range Inlier likely throughout the member. Grainy limestone is dominantly skeletal rather than oolitic, the thin beds and sheets rich in macrofossils, supporting a mid-ramp setting; glauconite is also common. Deeper water facies in the most eastern part of the area approaching the Hatters Pond Fault comprise nodular mudrocks and subordinate nodular carbonates that have affinities to facies described in Gros Morne (Knight, 2013). Nonetheless, isolated units of oolitic grainstone like those noted south of the HSJ and in Canada Bay suggests that grainstone tongues periodically reached more distal parts of the ramp at times of sea level fall. The upper oolitic limestone at Blue Mountain may perhaps link to the oolitic grainstone at Canada Bay.

### The Heterolithic Interval, Uppermost Forteau Formation: Evidence of Sea-level Rise and Later Advance of the Clastic Sediment at the Northwestern Landward Margin of the Ramp

Thick limestone intervals in association with siltstone to sandstone intervals in the uppermost 40 m of the formation in sections DH-NF-1B, R432-5 to 7 and BER-2 to BER-4 suggest that the later stages of the Forteau shelf preserve a series of shallowing-upward parasequences that become increasingly dominated by clastic input as the deposition of the Forteau Formation came to a close. The succession in section DH-NF-1B is thought to reflect its more northwesterly inshore position on the inner ramp. Thick limestone in carbonate parasequences includes a range of smaller scale fine to grainy limestone cycles and although oncolitic, fine oolitic grainstone does occur, it is generally subordinate and rarely thick. It seems reasonable that rising sea level brought these finer carbonates inboard to the inner ramp leading to deposition of shaly and thin bedded, fine carbonate and shale, the latter often black and pyritic suggesting low oxygenated bottom conditions developed in the early phase of the flooding. However, bioturbated limestone and skeletal limestone higher in the limestone intervals suggest that improving bottom conditions fostered a typical Forteau fauna dominated by echinoderms, *Salterella* and trilobites amongst others that suggest the limestone were fully marine subtidal deposits, perhaps comparable to mid-ramp facies (Burchette *et al.*, 1990). Beds of oolitic limestone in the uppermost limestone interval of the Savage Cove succession, likely indicate that oolitic shoals were also locally important, even though the limestone intervals are intercalated with fine clastic sands indicating their inshore setting overall.

Thin-bedded to sheet-like skeletal limestone and glauconitic sheet sandstone in mudrock in sections in the area of Route 432 east of TML and along the BER resource road, favour a dominantly mid ramp setting in this broad area. Oolitic grainstone bodies, some with bimodal cross strata, locally suggest this area likely lay close to the seaward margin of the inner ramp and that carbonate shoals built into the tidal zone. However, the most striking aspect of the late Forteau succession in this area is the presence of thick quartz sand bodies that occur close to the top of the formation.

The 50 m thick-carbonate-siliciclastic sequence at section R432-5 provides the best example of the mixing of carbonate and siliciclastic sand deposition, and suggests a significant episode of sea-level rise that influenced carbonate sedimentation at a late stage in accretion of the Forteau shelf. It supports a fluctuating shelf dynamic of marine flooding, rejuvenation of the carbonate factory and abrupt termination of carbonate sedimentation by coarsening- and cleaning-upward siliciclastic marine sedimentation perhaps suggesting forced regression. The association of oolite in the sandstone at Hawkes Bay and BER (salmon ladder sandstone) and foresets of carbonate in quartz arenite in the Ten Mile Lake area (R463-5), suggest that the lateral transition from carbonate to clastic dominated settings was also fairly abrupt as the shelf and its carbonate factory was increasingly overwhelmed by a shoreline of clastic sediment. Consequently, the uppermost cycles of the formation are dominantly clastic sediment where thick crossbedded, clean quartz arenite prograde over offshore deeper water shale and siltstone in CU sequences as seen near Hawkes Bay (sections BER-2 to BER-4). The 'button algae' bed of Schuchert and Dunbar (1934) sandwiched between the CU siliciclastics at Hawkes Bay likely was deposited when short-lived rising seas flooded the landward edge of the shelf. The likely correlation of the 'button algae' at Hawkes Bay with the dolostone in the subsurface at Savage Cove (drillcore DH-NF-1B and others cores) suggest that the carbonates may have been restricted geographically and subjected to early diagenesis.

The crossbedded quartz arenites, characterized by swaley cross strata below migrating large-scale megaripples, sand waves, and tabular sand bars atop CU sequences of shale to sandstone support shelf to shoreface, to tidal sand bodies and barrier complexes. The repeated metre-scale, prograding cycles indicate the importance of a 4th or 5th order sea-level fluctuation affecting the late Forteau shelf. *Monocraterion* burrows in quartz arenite near Ten Mile Lake and the presence of *Climatichnites–Plagiogmus–Psammichnites* trackways in flaggy sandstone more typical of an intertidal sand flat setting at Hawkes Bay suggest that the clastic shoreline was favourable ecologically for early molluscs (trackways) and anemone dwelling burrows. The molluscan trackways in *Bonnia–Olenellus* Zone, Early Cambrian sandstone, makes them some of the oldest known along the Laurentian margin. Similar CU sequences, some with shale overlain by flaggy sandstone capped by fossiliferous oolitic and oncolitic grainstone rather than quartz arenite, are characterized by intense arthropod activity. The multiple trace types preserved as hyporelief on sandstone bases suggest arthropods gathered in large numbers on peritidal sand flats (*see* Mangano *et al.*, 2014). The presence of large arthropod traces together with burrows of marine annelids(?) provides good evidence of predatory in-sediment pursuit of prey by the arthropods.

The importance of thick, CU quartz sand bodies in the Hawke Bay to Ten Mile Lake area does not appear to be replicated in the Savage Cove area where the sandstones are fine grained. Also interestingly, the ‘button algae’ bed sandwiched between clastics at Hawkes Bay appears to correlate with the dolostone at Savage Cove sitting atop a thick carbonate interval that is not well developed at Hawkes Bay. The dolostone has locally developed fenestrae and replaces an oolitic and oncolitic grainstone perhaps suggesting emergence of the carbonate shelf with accompanying dolomitization.

## IMPLICATIONS OF THE FORTEAU TRILOBITE FAUNAS

The trilobite fauna in the formation suggests that much of it was deposited within the middle part of the *Bonnia–Olenellus* Zone, Dyeran Stage (Table 1) a conclusion previously drawn by Fritz (1972b) and Skovsted and Peel (2007). This is supported by *Elliptocephala logani* that occurs in the middle third of the zone in western Canada (Fritz, 1972b), and which in southern Labrador and western Newfoundland ranges from the basal Devils Cove member into the lower part of the Upper limestone. The presence of the cosmopolitan trilobite *Calodiscus lobatus* in the lowest part of the transgressive sequence allows a correlation with the transition of *E. asaphoides–Acimetopus bilobatus* faunas of Lower Cambrian Taconic shale of New York State (Theokritoff, 1982) and with the late *Callavia* zone of the Cambrian of the Avalon Peninsula (Fletcher, 2006). Although this suggests deposition of the base of the formation may have begun lower in the *Bonnia–Olenellus* Zone, the overall fauna in the Forteau Formation does not support this and this may have implications for Taconic strata in New York State. Several olenellid species in the formation allow a ready correlation with shelf and basin rocks of the Kinzer Formation in Pennsylvania and the Parker and Monkton formations in Taconic rocks of New York State and Vermont. Of these species, *Olenellus crassimarginatus* found in deepwater settings of the Parker Shale and the Kinzer Formation of Pennsylvania (Liebermann, 1999; Webster and Landing, 2016), occurs in skeletal grainstone of a thin stratal interval that straddles the Middle shale–Upper limestone contact in both southern Labrador and GNP. This suggests *O. crassimarginatus* also thrived in the transition between deep offshore settings and carbonate shoals.

Trilobites indicate that the *Bonnia–Olenellus* Zone persists into the overlying Hawke Bay Formation throughout western Newfoundland. Recent work on the successions in the GNP, Canada Bay and Gros Morne, have found that *Bonnia columbensis*, *Bristolia mohavensis*, and *Mesonacis fremonti* straddle the top of the formation into the base of the Hawke Bay Formation. *B. mohavensis* is present in the uppermost Forteau Formation (and perhaps lowermost Hawke Bay Formation) at, and northwest of, Canada Bay. *Bonnia columbensis*, which occurs in the lower Hawke Bay Formation in Canada Bay, is known from the very top of the *Bonnia–Olenellus* Zone in the Sekwi Formation of British Columbia (Fritz, 1972b). *Mesonacis fremonti* (Walcott, 1910), which occurs in the uppermost beds of the Forteau Formation as well as in a shale 10 m or so above the base of the Hawke Bay Formation at Hawkes Bay, ranges from the middle of the *Arcuolenellus arcuatus* Biozone to the top of the *Nephrolenellus multinodus* Biozone, effectively the uppermost third of the *Bonnia–Olenellus* Zone and Dyeran Stage (Webster, 2011). This suggests that the top of the formation likely occurs later than the *B. mohavensis* Biozone but before the end of the *Bonnia–Olenellus* Zone.

*Fritzolenellus lapworthi* occurring near the very top of the Forteau Formation below the basal beds of the Hawke Bay Formation may provide a potential correlation with the *F. lapworthi*-bearing An-t-Sron Formation of northwest Scotland. The Scottish formation comprises the Fucoid beds and the Salterella Grit that, in past studies, were correlated respectively with the Forteau and Hawke Bay formations of the Labrador Group in Newfoundland and Labrador (Swett and Smit, 1972a, b). The Scottish strata are noteworthy for their relative thinness (about 25 m in total, Johnstone and Mykura, 1989) compared to the 270 m succession of the combined Forteau and Hawke Bay formations in western Newfoundland. However, the two members of the An-t-Sron Formation readily compare in thickness and general lithology with the CU shale to sandstone sequences that occur near the top of the Forteau Formation and straddle the Forteau and Hawke Bay contact in western Newfoundland. Any of these CU cycles might correlate with the Scottish rocks (*see* also Davies *et al.*, 2009).

The succession in the upper Labrador Group is generally believed to reflect a prograding succession, part of a late highstand systems tract, *i.e.*, falling stage system tract and regressive low stand that can be traced along the Appalachian margin as the Hawke Bay Event (Palmer and James, 1980; James *et al.*, 1989b; Knight *et al.*, 1995; Landing, 2007; Webster and Landing, 2015). In Scotlnd, the Fucoid beds have been linked to maximum flooding and the Salterella Grit tentatively correlated with Hawke Bay Event (McKie, 1990, 1993). Recent work on the succession in Scotland by Davies *et al.* (2009) suggests that the Salterella Grit is a response to short-lived sea-level fall during overall margin transgression. In addition, isotope-based studies of Faggetter *et al.* (2016) indicate that the Salterella Grit is marked by a strong negative δC excursion that has been linked to the global Redlichiid-Olenellid Extinction Carbon Isotope Excursion (ROECE) toward the end of the *Bonnia–Olenellus* Zone. Because olenellids continue to occur after the event, it confirms that both Scottish and Newfoundland strata, which host *F.lapworthi* and were both deposited towards the end of the *Bonnia–Olenellus* Zone, may be correlative, and that this trilobite could be used for further study of global events.

In western Newfoundland, the low-stand event, dominated by quartz rich siliciclastic rocks, can be proven to outlast the very latest *Bonnia–Olenellus* Zone and persist into the Middle Cambrian (known from rocks in Canada Bay and Gros Morne; Knight and Boyce, 1987; Knight, 2013, unpublished data, 2012). Faunas equivalent to the Delameran *Eokochaspis nodosa*, *Amecephalus arrojoensis*, *Poliella denticulata*, *Mexicella mexicana* and *Glossopleura walcotti* zones and the Topazan *Ehmaniella* Zone are all present in the mixed carbonate–clastic rocks of Canada Bay to White Bay and Goose Arm (Knight and Boyce, 1987; unpublished data, 2017). Trilobites of the *Glossopleura walcotti* Zone are also recovered from the fully siliciclastic succession of the upper part of the Hawke Bay Formation on Port au Port Peninsula (Knight and Boyce, 2015b). The establishment of a highstand carbonate shelf in Newfoundland was to wait for regional transgression in the late Middle Cambrian Topazan *Ehmaniella* Zone, long after sea-level rise had favoured a carbonate shelf in the latest part of the *Bonnia–Olenellus* Zone in both northwest Scotland (McKie, 1993; Rushton and Molyneux, 2011; Raine and Smith., 2012) and North-East Greenland (Stouge *et al.*, 2012).

However, based on isotopic studies, Faggetter *et al.* (2016) have proposed that the contact of the Salterella Grit (*Bonnia–Olenellus* Zone) and base of the Ghrudaidh Formation (Middle Cambrian), Durness Group, marks the sequence boundary between Sauk sequences I and II in Scotland. In western Newfoundland, this sequence boundary likely occurs within the *Glossopleura* Zone, well within the Hawke Bay Formation based on the succession in Canada Bay (Knight and Boyce, 1987; unpublished data, 2017) and Port au Port Peninsula (Knight and Boyce, 2015b; unpublished data, 2017; compare to Figure 14, Bond *et al.*, 1989). Apart from several thin oolite-dominated carbonates in the mixed terrigenous– carbonate succession of Canada Bay and Goose Arm, the transition from the late Sauk I Dyeran *Bonnia–Olenellus* Zone to upper Delameran *Glossopleura walcotti*–Topazan-*Ehmaniella* Zone (early Sauk II) sedimentation in the Hawke Bay succession is dominated by quartz arenites throughout the western Newfoundland shelf. The first significant lithological change, regionally in western Newfoundland, occurs at the base of the Port au Port Group (Topazan *Ehmaniella* Zone) when significant sea-level rise lead to the earliest Grand Cycle of the group (Chow and James, 1987; Cowan and James, 1993). The cycle commenced with shale of the Middle Cambrian March Point Formation that abruptly overlies Hawke Bay Formation quartz sandstone. The shale grades up into March Point Formation limestone and then dolostone of the Petit Jardin Formation. This flooding event is regarded as the beginning of the Newfoundland portion of the Great American Carbonate Bank (Lavoie *et al.*, 2012) but visibly postdates the likely sequence boundary in Newfoundland. It is noteworthy that the March Point Formation carbonates in the northwest of the GNP are predominantly bioturbated, dark grey, crystalline dolostone, lithologically very similar to the dolostone that makes up the Ghrudaidh Formation at the base of Sauk II in Scotland (I. Knight, unpublished data, 1990; Wright and Knight, 1995). This indicates that a significantly different margin dynamic controlled sedimentation along the Scotland–Greenland (Caledonian) Laurentian margin compared to that controlling sedimentation along the Newfoundland Reentrant and Promontory of the Appalachian–Newfoundland margin (I. Knight and W. Boyce, unpublished data, 2017) a geological dilemma explored briefly by James *et al.* (1989b) who suggested that important cratonic uplift may have occurred in the foreland to the Newfoundland margin and influenced the clastic-rich Hawke Bay Formation sedimentation.

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# APPENDIX 1

## Fauna Previously Identified from the Forteau Formation

**Southeastern Labrador**

| Range above base of formation | |
|---|---|
| 0 to 40 ft /0 to 12.19 m | *Spirocyathus atlanticus* (Billings, 1861) |
| 0 to 80 ft /0 to 24.38 m | *Archaeocyathus profundus* Billings, 1861 |
| 15 to 80 ft /4.57 to 24.38 m | *Kutorgina cingulata* (Billings, 1861) |
| 15 to 80 ft /4.57 to 24.38 m | *Micromitra bella* (Billings,1872)[1] |
| 15 to 80 ft /4.57 to 24.38 m | *Nisusia* (Jamesella) oriens Walcott, 1924 |
| 15 to 80 ft /4.57 to 24.38 m | *Olenellus thompsoni* (Hall, 1859) |
| 20 to 65 ft /6.10 to 19.81 m | *Obolella chromatica* Billings,1861 |
| 20 to 65 ft /6.10 to 19.81 m | *Salterella obtusa* Billings, 1861 |
| 20 to 65 ft /6.10 to 19.81 m | *Salterella pulchella* Billings, 1861 |
| 20 to 65 ft /6.10 to 19.81 m | *Salterella rugosa* Billings, 1861 |
| 25 to 30 ft /7.62 to 9.14 m | *Discinella* sp. undet. |
| 25 to 30 ft /7.62 to 9.14 m | *Stenotheca* sp. undet. |
| 25 to 65 ft /7.62 to 19.81 m | *Hyolithes communis* Billings, 1871a |
| 25 to 65 ft /7.62 to 19.81 m | *Stenothecoides elongata* (Walcott, 1884)[2] |
| 25 to 80 ft /7.62 to 24.38 m | *Elliptocephala logani* (Walcott, 1910)[3] |
| 25 to 80 ft /7.62 to 24.38 m | *Hyolithellus micans* Billings, 1871b |
| 40 to 65 ft /12.19 to 19.81 m | *Bonnia senecta* (Billings, 1861)[4] |
| 40 to 65 ft /12.19 to 19.81 m | *Labradoria misera* (Billings, 1861)[5] |
| 40 to 80 ft /12.19 to 24.38 m | *Bonnia parvula* (Billings, 1861)[6] |
| 40 to 80 ft /12.19 to 24.38 m | *Micromitra (Paterina) labradorica* (Billings, 1861) |
| 50 to 65 ft /15.24 to 19.81 m | *Hyolithes billingsi* Walcott, 1886 |
| 50 to 65 ft /15.24 to 19.81 m | *Protopharetra* sp. undet. |
| 50 to 80 ft /15.24 to 24.38 m | *Obolella crassa* (Hall, 1847) |

Identified by C.D. Walcott in 1910 as listed in Schuchert and Dunbar (1934, pages 19-20).

**Canada Bay**

*Callavia bröggeri* (Walcott)?
*Eodiscus*, species undetermined, probably new
*Helcionella rugosa* (Hall)
*Hyolithes impar* Ford
*Hyolithes princeps* Billings

Collected from boulders of Devils Cove member on the eastern shore of Cloud Pond. Identified by B.F. Howell in Betz (1939, page 14). The material[7] subsequently was restudied by Palmer (1969, pages 141-142), who re-identified the *Eodiscus* as *Calodiscus lobatus* (Hall, 1847) and the "*Callavia bröggeri* (Walcott)?" as *Wanneria*.

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[1] *Micromitra (Paterina) bella* (Billings,1872)
[2] *Helcionella elongata* Walcott, 1884
[3] *Olenellus logani Walcott, 1910*
[4] *Corynexochus senectus (Billings, 1861)*
[5] *Conocephalites miser Billings, 1861*
[6] *Corynexochus (Bonnia) parvulus (Billings, 1861)*
[7] Princeton University Collection 49972, apparently now lost

# APPENDIX 2

## Study Area Since 1976

Arthropoda—Trilobita
  *Bonnia parvula* (Billings, 1861)
  *Bonnia senecta* (Billings, 1861)
  *Bonnia* sp. nov.
  *Bonnia* sp. undet.
  *Bristolia mohavensis* (Crickmay *in* Hazzard and Crickmay, 1933)
  *Elliptocephala logani* (Walcott, 1910)
  *Fritzolenellus lapworthi* (Peach and Horne, 1892)
  gen. et sp(p). undet. – fragments
  *Labradoria misera* (Billings, 1861)
  olenellid gen. et sp. undet.
  *Olenellus crassimarginatus* Walcott, 1910
  *Olenellus* sp(p). undet.
  *Olenellus thompsoni* (Hall, 1859)
  *Olenellus transitans* (Walcott, 1910)
  ptychopariid gen. et spp. undet.
  *Wanneria walcottana* (Wanner, 1901)
Brachiopoda—Articulata
  gen. et. sp. undet.
Brachiopoda—Inarticulata
  acrotretid gen. et sp. undet.
  gen. et. sp(p). undet.
  *Kutorgina cingulata* (Billings, 1861)
  *Lingulella* sp undet.
  ?*Paterina* sp. undet.
  paterinid gen. et. sp(p). undet.
Hemichordata—Pterobranchia or Porifera
  Gen. et sp(p). undet. – microscopic, phosphatic? fragments, spicules/otherwise?
Ichnofauna
  gen. et spp. undet.
Incertae Sedis
  *Salterella rugosa* Billings, 1861
  *Salterella* sp. undet.
Lophophorata—Hyolitha
  gen. et sp(p). undet.
  *Hyolithes* sp. undet. – tiny form
Mollusca—Helcionelloida
  *Helcionella* sp. undet. – “low” cap
  *Latouchella* sp. undet. – “high” cap
Mollusca?—Mobergellidae
  *Discinella micans* (Billings, 1871a)
Porifera—Archeocyatha
  gen. et sp. undet.