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THE FORTEAU FORMATION, LABRADOR GROUP, IN GROS MORNE NATIONAL PARK: A PRELIMINARY REASSESSMENT OF ITS STRATIGRAPHY AND LITHOFACIES

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ABSTRACT

The Forteau Formation in Gros Morne National Park is a heterolithic succession, approximately 230 m thick, of fine-grained mudrocks, thin-bedded (ribbon) siltstones and sandstones, and fossiliferous, nodular limestone. It was deposited during the Dyeran stage of Sauk I, as part of an outer-shelf-facies belt in western Newfoundland. It is divided into three members, the Devils Cove Member and two informal members, the Mackenzie Mill member and the Big Hill member. Two limestone marker beds, including the Deer Arm limestone, occur in the Mackenzie Mill member. The formation is conformably overlain by the Hawke Bay Formation.

Deposition of muds, following rapid Dyeran transgression, in a deep outer-shelf setting largely below wave base, characterizes much of the formation. The sandier rocks of the upper Mackenzie Mill member and overlying Big Hill member, however, suggest that the formation shallows upward, when the shelf was increasingly influenced by storms. Trace fossils increase in quantity in the upper Mackenzie Mill member as it becomes sandier; the ichnofauna Rosselia *dominates throughout the member.*

Limestone in the Mackenzie Mill member is minor, dominantly nodular and fossiliferous, and shows a virtual absence of shallow-water indicators. The formation likely hides three subsequences, the first includes the succession below and including the Deer Arm limestone, the second terminates at an upper limestone interval, and the third includes rocks of the Big Hill member and the overlying Hawke Bay Formation.

INTRODUCTION

The Forteau Formation is a succession of Early Cambrian shale, siltstone, sandstone and carbonate and is the middle unit of the Labrador Group, which is the lowest stratigraphic unit of the lower Paleozoic shelf of western Newfoundland. The group is named for the succession best known along the southern shore of Labrador, even though it is incomplete (Schuchert and Dunbar, 1934); the Forteau Formation was named for the community at Forteau Bay. On the Great Northern Peninsula, northwestern Newfoundland, the Labrador Group is known from drillholes and a collage of incomplete sections that preserve an inboard assortment of shallow-water shelf facies deposited during the Early Cambrian sea-level rise, and following sea-level fall, through the late Early Cambrian and Middle Cambrian (James *et al*., 1989). Sandstones of the Bradore Formation mark the basal deposits of Early Cambrian transgression, and sandstone and shale of the Hawke Bay Formation are well known as the culminating deposits of late Early to Middle Cambrian regression (Palmer and James, 1979). Mixed clastic and carbonate rocks of the Forteau Formation that lie between these two bounding formations were deposited in the Dyeran stage of Sauk I sequence of Sloss (1963).

Southeastward and southward in western Newfoundland, the Labrador Group succession reflects a more outboard shelf setting from Canada Bay in the north (Knight and Saltman, 1980; Knight, 1987; Knight and Boyce, 1987), south through Coney Arm, southern White Bay (Kerr and Knight, 2004), to the hinterland thrusts of the Goose Arm and Blue Pond thrust stacks (Knight and Boyce, 1991; Knight, 1993, 2004, 2007, 2010) and southwest to the Phillips Brook and North Brook anticlines near Stephenville (Knight, 1994; Knight and Boyce, 2000). Also part of this outboard succession is the Penguin Cove Formation, which has been mapped in the leading foreland thrusts of the Goose Arm and Blue Pond thrust stacks and is coeval with the Hawke Bay Formation (Knight and Boyce, 1991; Knight, 1993, 2007, 2010) (*see* Figure 1 for regional context).

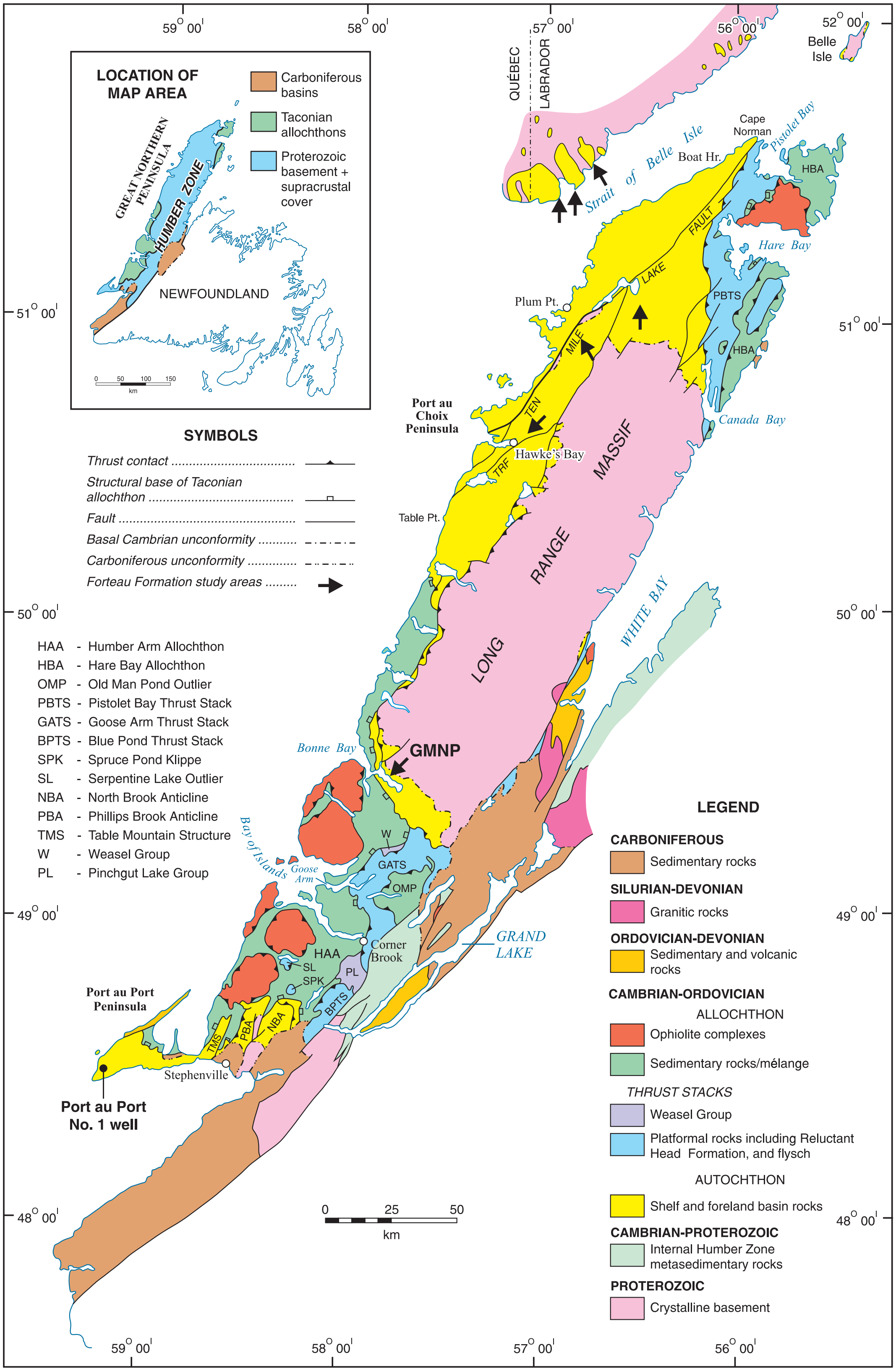


Figure 1. *Geology map of western Newfoundland showing the primary geological terranes. Arrows locate the various study areas where Forteau Formation was studied. GMNP - Gros Morne National Park.*

A significant part of this outboard belt is preserved in Gros Morne National Park (GMNP) where, although mapped at 1: 50 000 scale by Williams *et al*. (1984) and Williams (1985) and included on a 1: 250 000 map by Williams and Cawood (1989), it remains largely unstudied, and is understood in only the most general terms (Schuchert and Dunbar, 1934; James and Stevens, 1982; James *et al*., 1988). Sections measured along the northern arms of Bonne Bay by Richardson in the 19th century and documented by Schuchert and Dunbar (1934) are unfortunately unhelpful because they are difficult to place geographically, and rock units are misidentified. This study is an attempt to flesh out the stratigraphy and facies of the Labrador Group in the area. In this publication, the stratigraphy of the Forteau Formation is described and defined for the GMNP.

This stratigraphic study is part of an ongoing small-shell fossils study of the Forteau Formation by C. Skovsted, of the Swedish Museum of Natural History (Skovsted, 2003; Skovsted *et al.*, 2004; Skovsted and Peel, 2007; Skovsted *et al.*, 2010) (*see* Figure 1 for study areas). The collaboration began in 2007 with a brief reconnaissance of several outcrops along Route 430, adjacent to East Arm and Deer Arm (shown on the latest topographic maps as Eastern Arm) of Bonne Bay, from which limestone samples were collected; no stratigraphic context for these samples was available at the time, providing the impetus for this study.

The present work is based on detailed sectioning of many roadside outcrops along Route 430 beginning at Deer Arm, just south of the Matty Mitchell Trail (GM-2, Figure 2), and continuing southeast for 20 km to the well-known unconformity outcrop on the highway at Southeast Hills (GM-1, Figure 2). All outcrops along this stretch of the highway were examined, and structural measurements recorded to supplement stratigraphic placing of the measured sections that were logged using a graduated measuring stick. Limestone beds and nodules were systematically collected for further small-shell fossil studies; macrofossils, principally trilobites, were also collected wherever found, in both siliciclastic and carbonate rocks.

The stratigraphy of the Forteau Formation in GMNP, described here, introduces new, informal stratigraphic nomenclature at the member level, incorporating the framework established during mapping of the area by Williams *et al.* (1984) and Williams (1985). They included an unnamed unit of "black calcareous shale and buff-weathering (also described on the same map as rusty-weathering) grey-green calcareous sandstone and quartzite" at the top of the Forteau Formation immediately below the Hawke Bay Formation. However, thick units of similar lithofacies intercalate with thick quartz-arenite units in the Hawke Bay Formation in GMNP, and elsewhere in western Newfoundland. The lithofacies compares to the overall lithological character of the Penguin Cove Formation and to ribbon sandstone and shale (with minor limestone) included in the lower siliciclastic member of the Hawke Bay Formation in Canada Bay (Knight, 1987; Knight and Boyce, 1987). Such stratigraphic and lithological complexity suggests that the stratigraphic relationships, at the transition of Forteau to Hawke Bay formations, will require further revision as a result of ongoing studies into the Labrador Group and coeval units of western Newfoundland. Its place in the context of the wider regional paleogeographic setting of the outboard facies belt in western Newfoundland is ongoing.

GEOLOGICAL SETTING OF THE GROS MORNE AREA

Gros Morne National Park, a rugged landscape of mountainous and coastal beauty, is a UNESCO world heritage site because of the classic Appalachian geology of the area. The far-travelled Humber Arm Allochthon, of deep-water rift and off-shelf rocks of the Humber Arm Supergroup, overlain by a dissected slab of lower Paleozoic, ocean-floor ophiolite, dominates much of the western edge of the park. East of the allochthon, lies deformed parautochthonous sedimentary rocks of the ancient lower Paleozoic shelf of Laurentia, and a mountainous massif of uplifted Proterozoic basement rocks of the Long Range Mountains. The terrain was assembled and deformed during Taconian (Late Ordovician) to Acadian (Middle Devonian) orogenesis.

The Labrador Group in GMNP forms a narrow, southeast-trending, southwest-dipping succession sandwiched between Grenvillian crystalline basement of the Long Range Mountains and the fjord waters of Deer Arm, East Arm and Southeast Arm (Figure 3). The terrain lies in the hanging wall of a major thrust that strikes north, from the head of Deer Arm to Bakers Brook Pond and beyond (Williams, 1985). In this area, the Long Range Massif and its Labrador Group cover are juxtaposed above younger elements of the lower Paleozoic shelf sequence west and north of Deer Arm. Although the thrust is not projected beneath the ocean (Williams *et al*., 1984), it likely continues under the fjord southeast to the head of Southeast Arm. This is implied by complex, and presently poorly understood, structural relationships of Labrador and Port au Port groups at the head of Southeast Arm and by recent mapping near Angle Pond, 12 km inland of Southeast Arm. The latter shows that the Long Range basement complex, with only thin Labrador Group cover locally, is carried upon a significant, low-angle mylonite zone above Paleozoic shelf sediments (Knight, 2010). This implies that an undefined thrust is probably present in the intervening area.

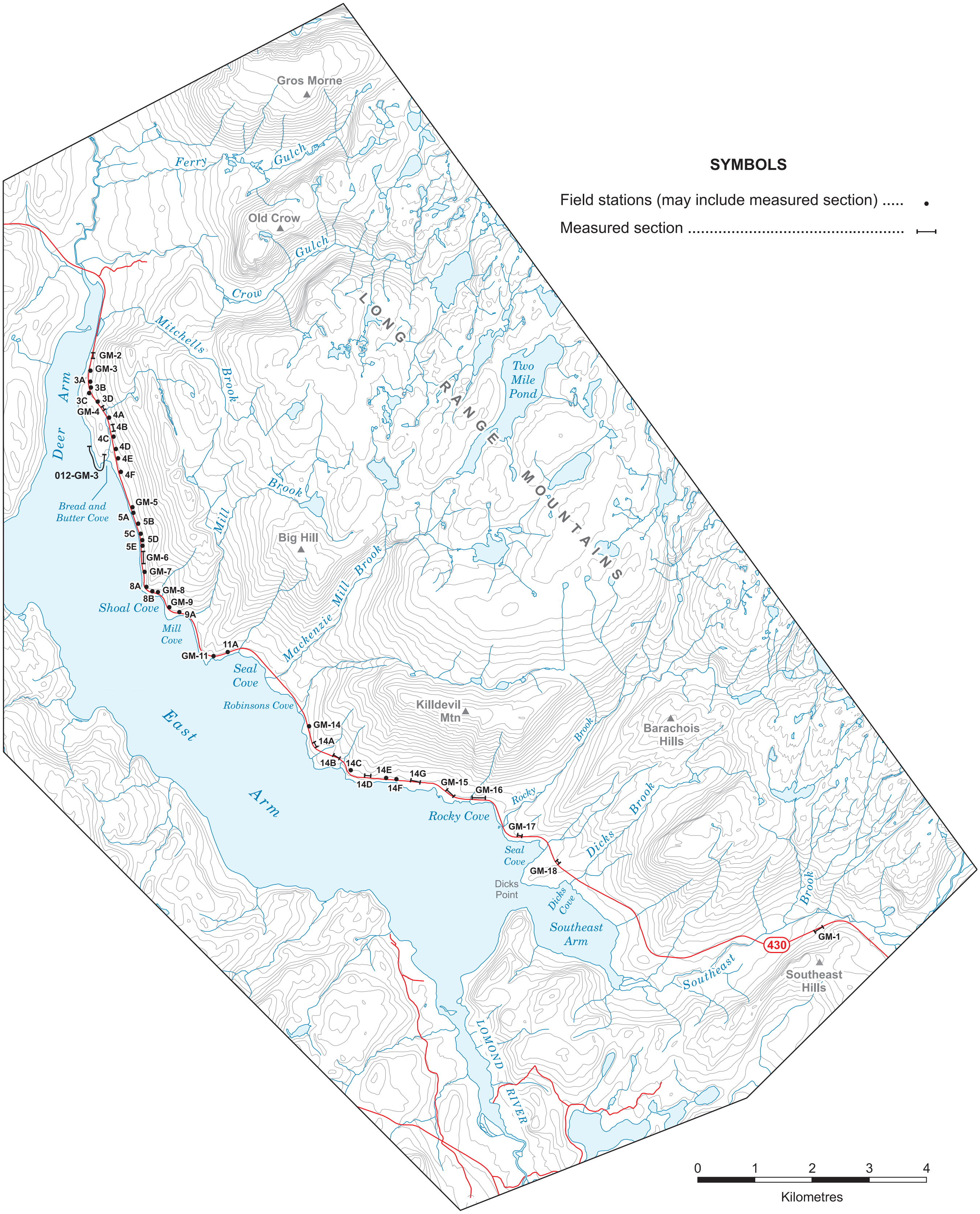


Figure 2. *Map showing location of field stations and sections of Forteau Formation in GMNP.*

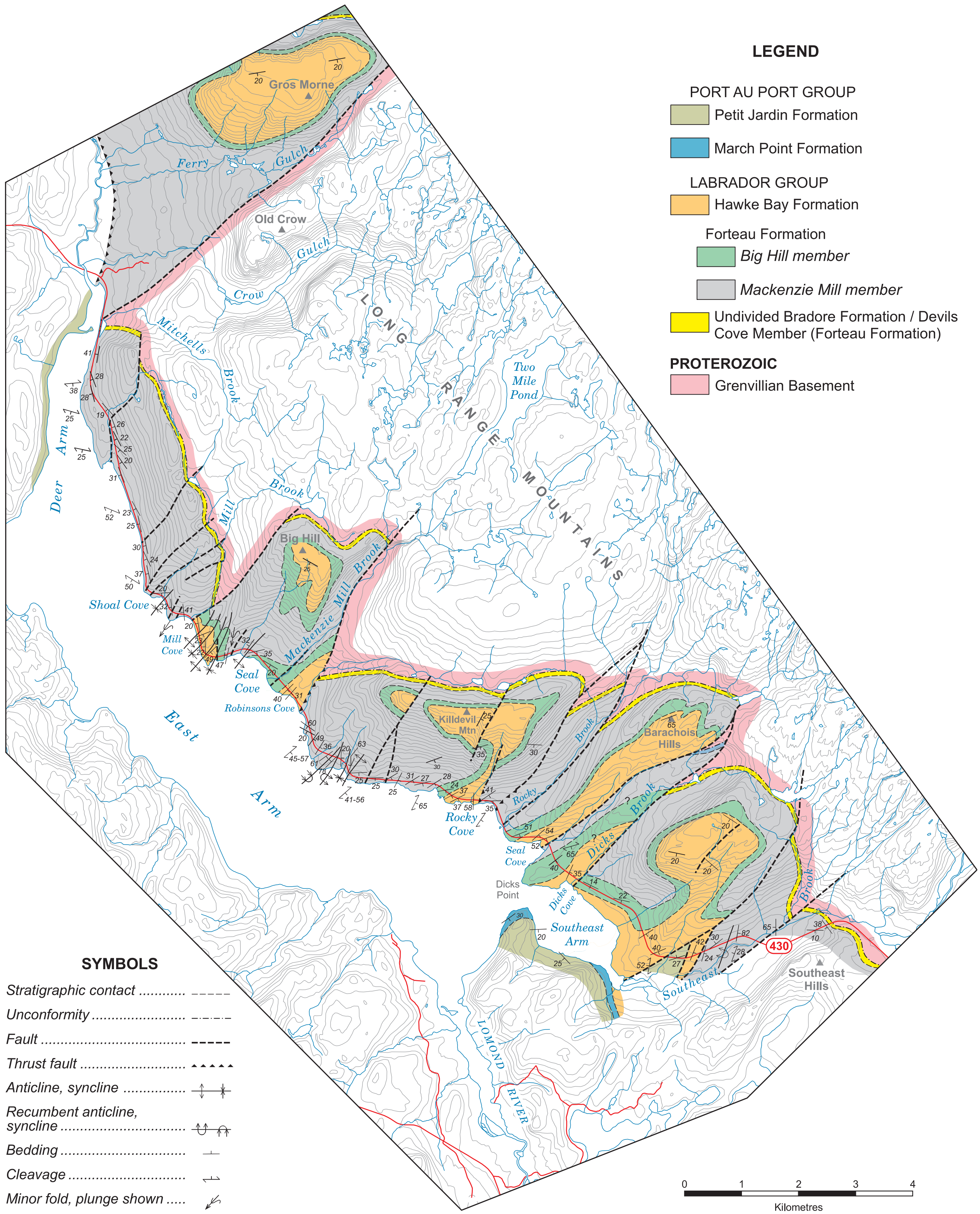


Figure 3. *Geological map of the Labrador Group in GMNP based in part on mapping of Williams* et al. *(1984) and Williams (1985) and field mapping in 2011.*

The sedimentary rocks of the Labrador Group are folded and faulted throughout the area (Figure 3). The fine-grained rocks display a well-developed slaty cleavage that mostly trends west to southwest and dips to the south and southeast at low to steep angles. Intersection of cleavage with bedding indicates that fold structures plunge to the south-southwest to southwest at low angles (averaging about 20°). Asymmetrical northwest- to west-verging folds occur at outcrop scale. A later crenulation lineation is carried on the cleavage locally. Transposition of bedding into the plane of the cleavage locally affects thinly interstratified siltstone, sandstone and shale and nodular to lumpy limestone in the Forteau Formation. Northeast-striking reverse faults and thrust faults that mostly verge to the northwest, are common, in the various sections, along the road; some normal strike slip and lag faults were also noted. Most of the folds are spatially linked to faults, and this pattern parodies the structural relationships associated with the major faults that cut the Labrador Group and basement in the area and are expressed by strong topographic erosional incision.

STRATIGRAPHY OF THE FORTEAU FORMATION

CONSTRAINTS AND METHODS

Compilation of the stratigraphy of the Forteau Formation is hindered by the broken nature of the succession reflecting covered intervals and deformation and displacement of the succession by folds and faults. However, combining mapping and logging of sections along Route 430, the succession is compiled with some degree of certainty. The basal 60 m of the Labrador Group, including the basal unconformity, the Bradore Formation and the lowest beds of the Forteau Formation, were logged in the Route 430 roadcut on the long highway decline below Southeast Hills (GM-1, Figures 2, 4A, 5 and Plate 1A). Williams *et al.* (1984) called the Bradore Formation in GMNP, the Badweather formation. This distinctive, thin unit of the Bradore Formation mapped in Canada Bay at the top of the formation and extensively above basement elsewhere throughout the outer facies belt, will be referred here informally as the Badweather Pond member. The oldest strata measured in the Forteau Formation along Deer Arm, more than 20 km away to the northwest appears to be at least 50 to 60 m above the base of the group (Figures 4B, 5 and Plate 1B), suggesting that stratigraphic overlap of the two sections is unlikely although possible.

A limestone marker, informally named the Deer Arm member by James and Stevens (1982), and here referred to as the Deer Arm limestone (DAL; Figure 4B, C and Plate 1C, D) together with some other limestone units higher in the succession (Plate 1E, F and Figure 4C), form markers that allow correlation of the sections in the Forteau Formation at Deer Arm and East Arm (Figure 4C). James *et al*. (1988) show an uninterrupted but generalized measured section, 215 m thick, through the formation on the vertiginous north face of Gros Morne. There, the Deer Arm limestone lies about 110 m above the base of the Forteau Formation and about 95 m below the first thick unit of quartz arenite that marks the base of the Hawke Bay Formation (Figure 5). The upper 95 m is presumed here to include the upper unit of the Forteau Formation of Williams *et al*. (1984). James *et al*.'s (1988) thickness for the Forteau Formation, anchored by the limestone marker, is used here to constrain construction of the Forteau Formation succession. This is particularly important above the limestone marker, because the succession is repeated in many roadcut outcrops adjacent to East and Southeast Arm and easy, straightforward correlation is hindered by the deformation and by surmized subtle lateral facies and sequence changes.

Some of the numerous limestone beds within these sections are correlated to constrain the Forteau Formation close to the thickness in Gros Morne. However, it is not always obvious that the limestone beds are correlative, or, that to constrain the formation by correlating to the Gros Morne section of James *et al*. (1988) is the only viable stratigraphic option? By ignoring the thickness constraints, and correlating limestone beds between sections in the Bonne Bay area, the formation in Bonne Bay would be thicker than that at Gros Morne, the thickness being enlarged by inclusion of the upper unit of the Forteau Formation mapped by Williams *et al*. (1984). The thickness of the redefined formation in Gros Morne is therefore likely to range up to 230 m and may be thicker.

Elsewhere in western Newfoundland, the thickness of the Forteau Formation is known from a drillhole at Flowers Cove on the Northern Peninsula (inboard facies belt) to be only 114 m thick (*see* Bostock *et al*., 1983 for drillhole log). About 310 m is assigned to the Forteau Formation in the Garden Hill drillhole on western Port au Port Peninsula (interpreted from the down-hole electric log; Hunt Oil Canada, 1996). The log suggests a distinctive marker of limestone, sandstone and shale 90 m above the base (likely equivalent of the Deer Arm limestone) and an interval of thinly stratified siliciclastic rocks in the upper 50 m of the formation. The lack of thick, continuous limestone in the formation in the well suggests it is likely part of the outer facies belt.

STRATIGRAPHY

The Forteau Formation in GMNP rests conformably upon the Bradore Formation, and is conformably overlain by the Hawke Bay Formation. It comprises the basal Devils

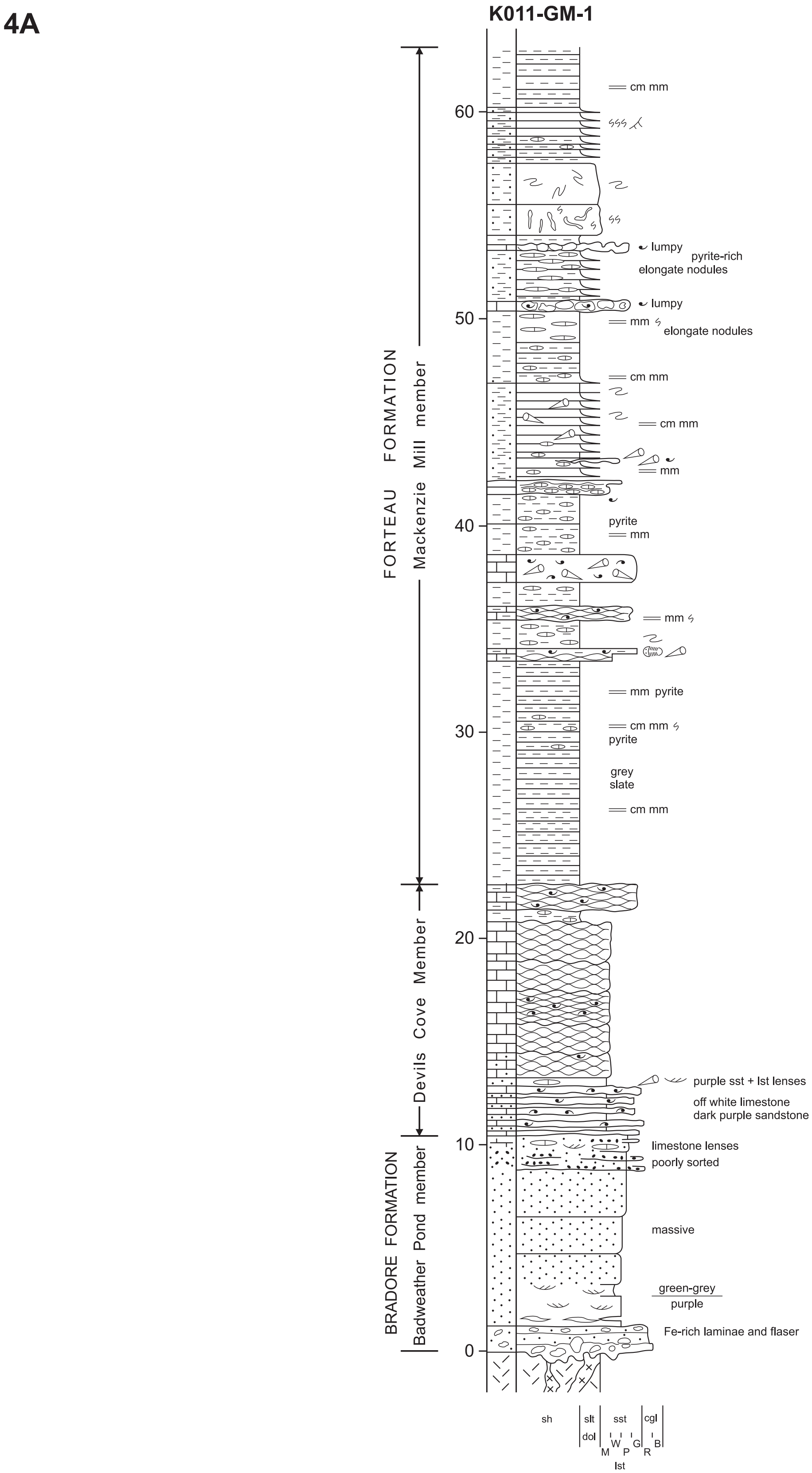


Figure 4. *Graphic logs of stratigraphic sections measured through the Forteau Formation in GMNP. Sections correspond to field stations on Figure 2.*

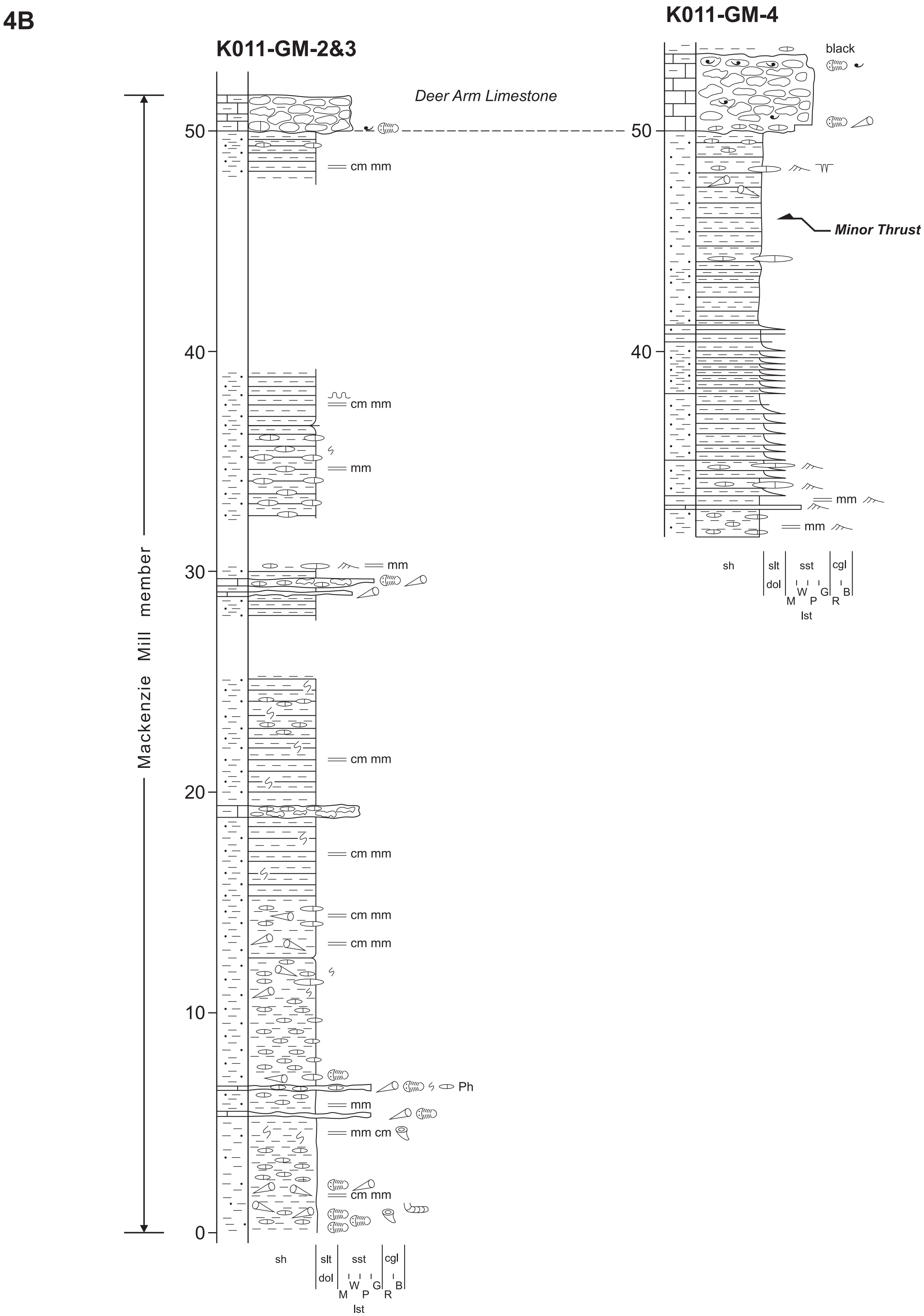
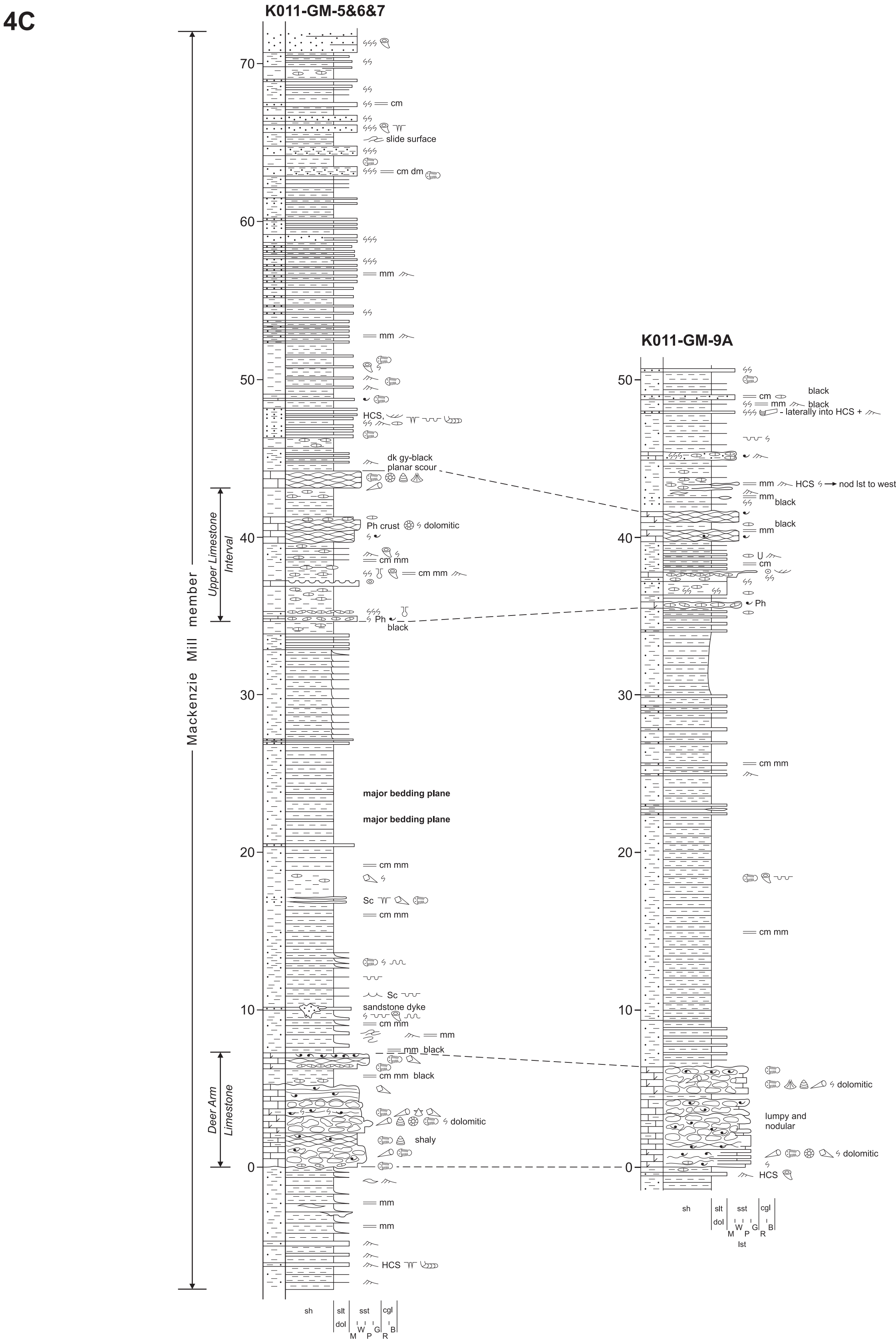


Figure 4. *Continued.*



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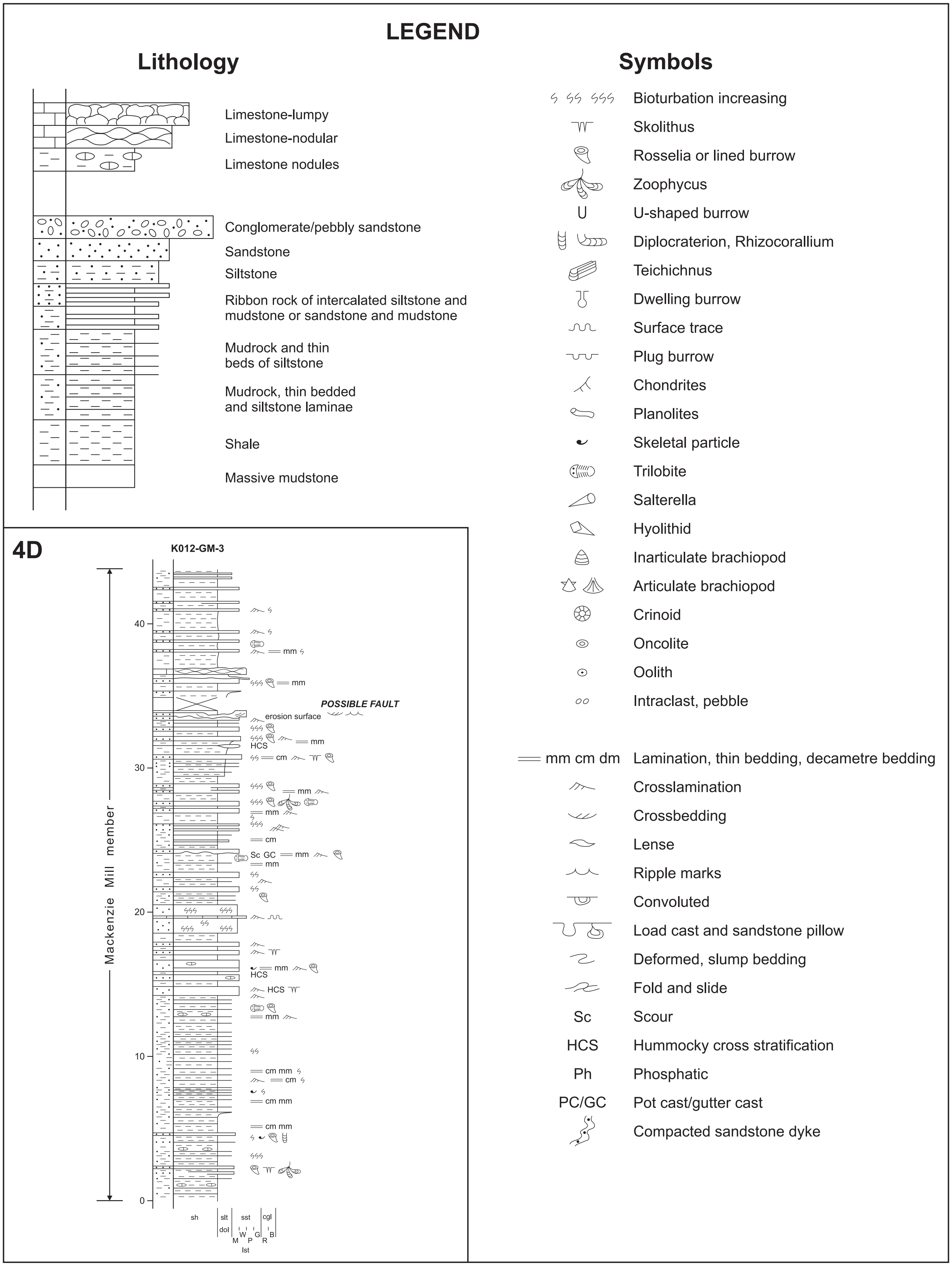
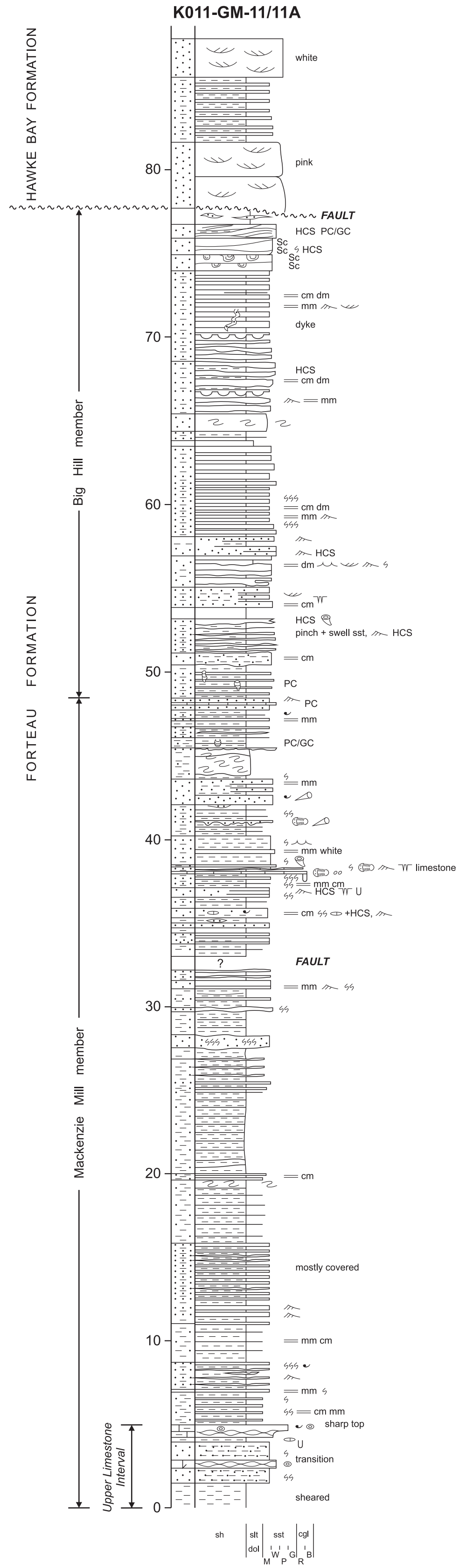


Figure 4. *Continued.*

4E



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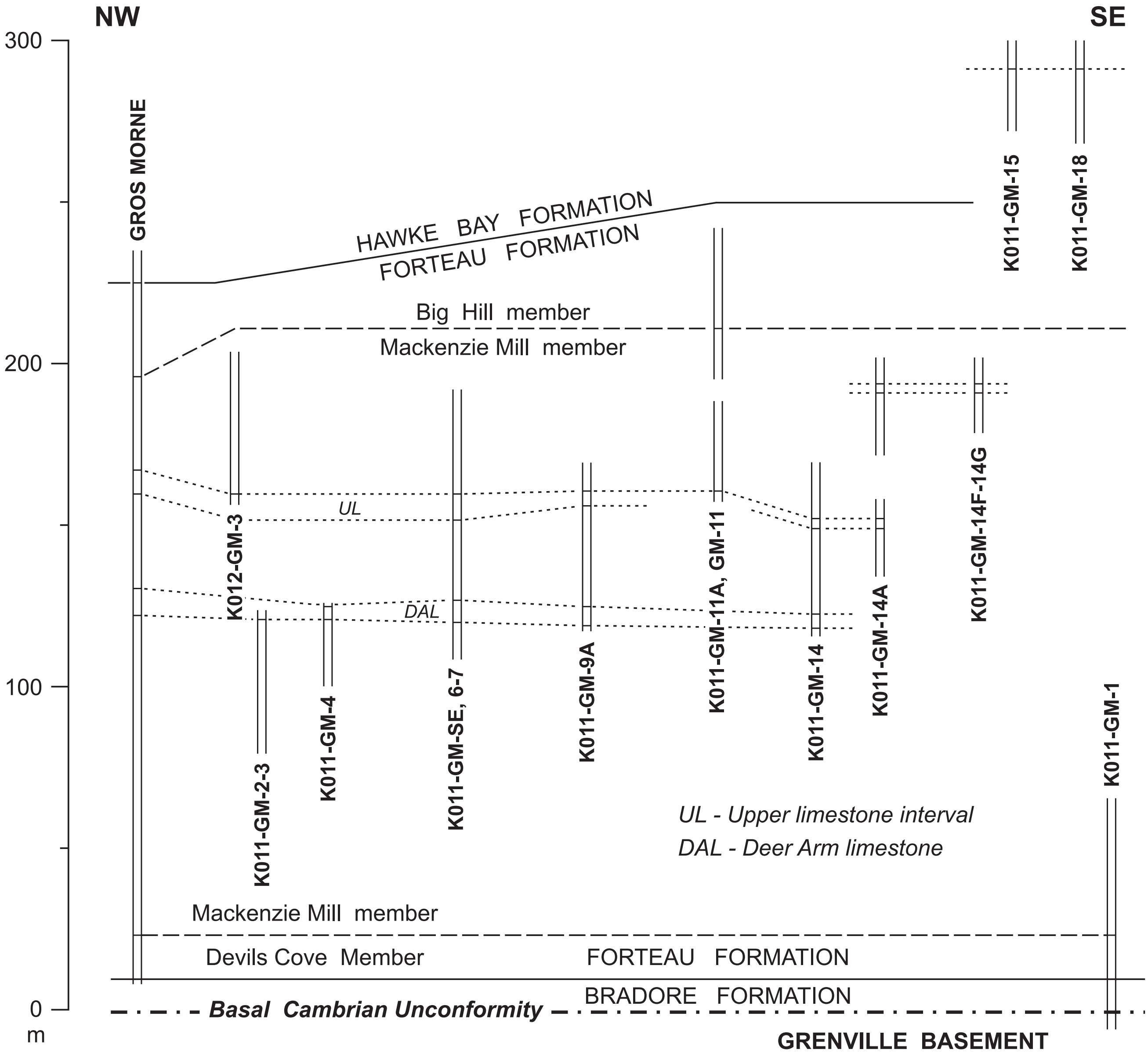

Figure 5. *Relative stratigraphic position of various sections through the Forteau Formation in GMNP discussed and illustrated in this study. Section at Gros Morne is based on that illustrated by James* et al. *(1988).*

Cove Member, a middle unit of shale and mudstone (now slate and herein called mudrock), ribbon-bedded siltstone and fine-grained sandstone, thicker sandstone beds, and nodular to fossiliferous limestone that is here informally named the Mackenzie Mill member, and an overlying heterolithic, somewhat coarser grained unit of ribbon-bedded, siliciclastic rock, here informally called the Big Hill member[1]. The lithofacies of the Big Hill member also form significant parts of the Hawke Bay Formation suggesting a gradational, and possible diachronous transition between the two units.

Devils Cove Member

The Devils Cove Member, lying conformably upon the Badweather Pond member (BWP) of the Bradore Formation sandstone (Plate 1A), is 12.3 m of pink, off-white, greenish-white to grey, impure limestone that is exposed in the Route

[1] Neither name is listed in the Lexicon of Canadian Geological Names seen online at Canadian Geoscience Knowledge Network

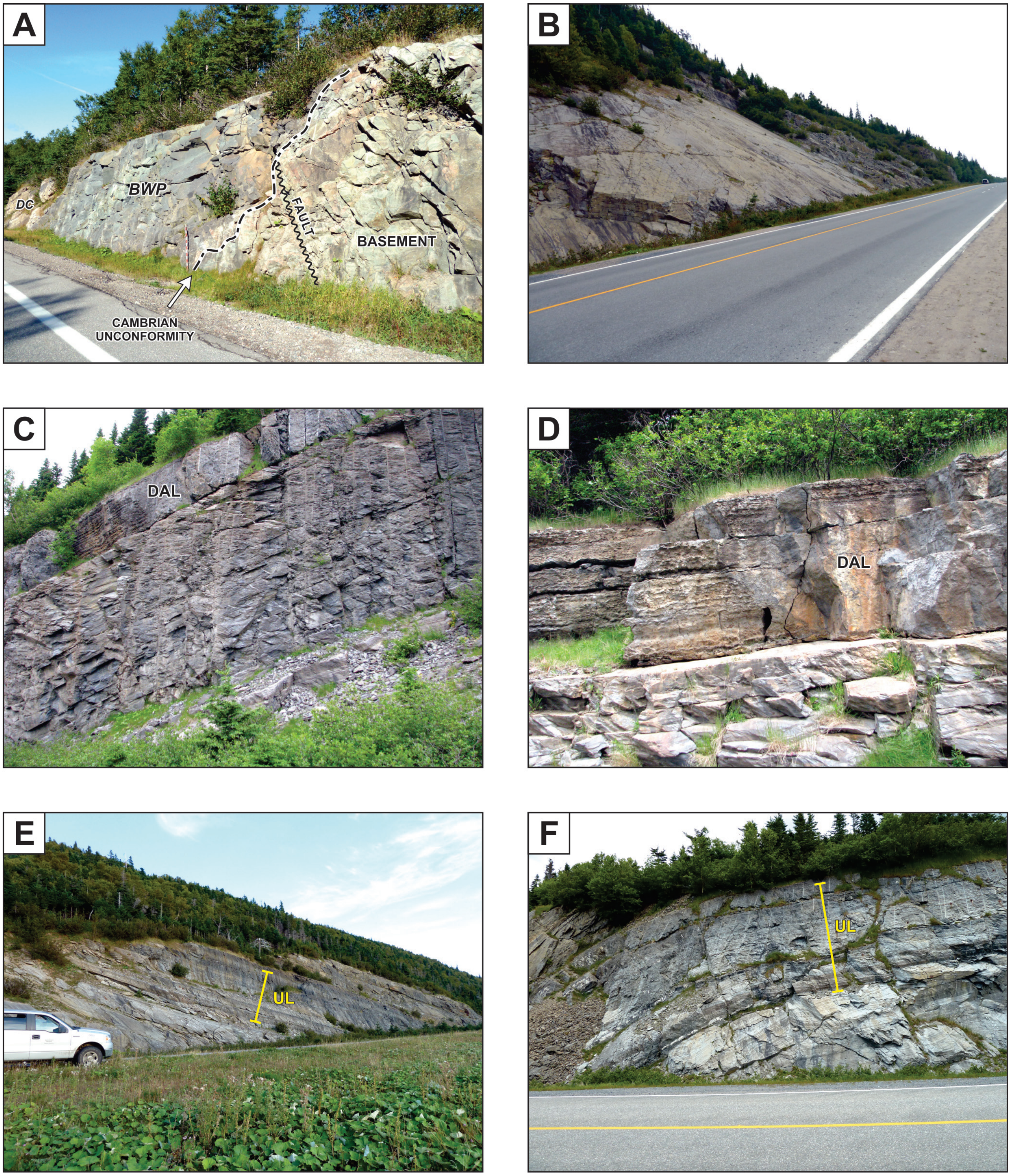

Plate 1. *A) Grenvillian basement overlain by basal Labrador Group at section GM-1, Southeast Hills; BWP- Badweather Pond member, DC- Devils Cove Member. Measuring stick 1.5 m long; B) Lower mudrock interval, Mackenzie Mill member, Section GM-2, Route 430, Deer Arm; C) Deer Arm limestone (DAL) overlying the lower mudrock interval, quarry section GM-4, Route 430; D) Deer Arm limestone, section GM-5, East Arm; E) Upper mudrock interval, upper limestone interval (UL) and upper heterolithic interval, Mackenzie Mill member, Route 430, East Arm; F) Upper limestone interval (UL) at section 011-GM-9A, Route 430.*

430 roadcut near Southeast Hills (Figure 4A); it has been mapped at the base of the formation, regionally, throughout western Newfoundland. An off-white, stratified (5 to 10 cm) skeletal, locally nodular, grainstone and packstone interstratified with 1 cm, dark-grey to purple, very fine-grained sandstone of BWP affinity marks the first 2.2 m of the member. It is gradationally overlain by 40 cm (north side of the road) to 60 cm (south side) of dark-brown to purplish, fine-grained, possibly crossbedded, sandstone (Plate 2), and lenses of skeletal packstone–grainstone that include cone-shaped, phosphatic micro-clasts. Impure, stratified to nodular, skeletal-rich, lime mudstone–wackestone, and purplish siltstone to very fine sandstone partings dominates the overlying 7.9 m of the member. The limestone becomes grey toward the top, where it is overlain by a 60-cm green-grey shale with limestone nodules, capped by a bed of nodular, skeletal limestone-coquina, composed of centimetre-size, thin-shelled skeletal debris. The unit is abruptly overlain by the Mackenzie Mill member.

Trilobites, *Salterella* and archeocyathids, the latter identified as the solitary regularis species A. occur in the member in GMNP (James and Debrenne, 1980; James and Stevens, 1982; James *et al*., 1988).

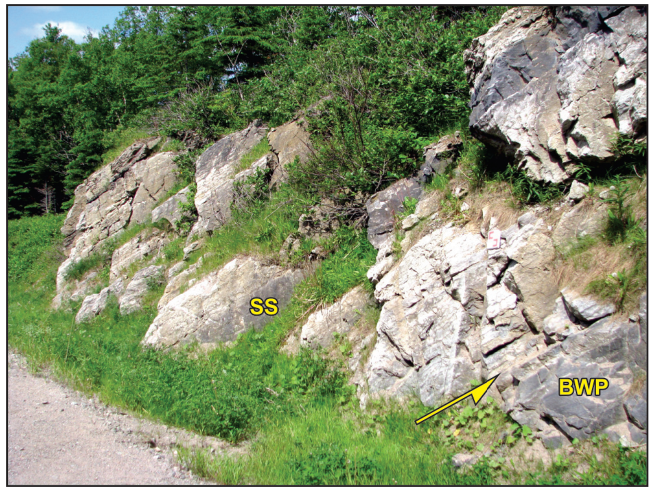

Plate 2. *Pink to grey, nodular limestone intercalated with beds of sandstone (ss) conformably overlying (at arrow) Badweather Pond member (BWP), Bradore Formation, section GM-1. Notebook 17.5 cm long.*

Mackenzie Mill Member

Lithostratigraphy

The Mackenzie Mill member consists of calcareous mudrock, black and dark grey shale and mudstone, here termed mudrock[2], calcareous ribbon-bedded siltstone and sandstone, current-bedded and bioturbated sandstone and nodular to lumpy, fine-grained to skeletal-rich limestone. Based on the measured sections in this study, the member is at least 190 m thick, and perhaps as much as 210 m thick. The succession is divided at about 95 to 100 m by the prominent dark-grey fossiliferous limestone marker, the Deer Arm limestone (DAL), as illustrated in the section measured on the north face of Gros Morne by James *et al*. (1988). The upper contact with the Big Hill member is placed at the top of an uppermost unit of khaki mudrock that occurs just above the last, thin limestone logged at section GM-11 (Figure 4E). The contact is also exposed at sections GM-14C and -14 D.

Based on the sections logged and the mapping of the numerous outcrops along Route 430 (Figures 2 and 4), the succession in the Mackenzie Mill member consists of intervals of thin-bedded, fine-grained, sometimes calcareous siliciclastic rocks (predominantly mudrock), each several tens of metres thick, separated by limestone-bearing intervals that rarely exceed 10 m in thickness and include the DAL marker. The siliciclastic rocks, although remaining dominantly fine grained, progressively coarsen above the marker with the presence of ribbon siltstones and sandstones forming important parts of the fine-grained clastic intervals. Accompanying this sand enrichment is greater intensity of bioturbation.

The succession is compiled as follows from the base upward:

1. A lower interval of mudrock, about 95 m thick, which is host to numerous lime mudstone nodules (Plates 1B, 1C, and 3) for about 80 m, and is intercalated with a number of limestone beds in the lower half of the interval. The dark-grey to grey mudrock is generally thinly stratified and finely laminated, rarely bioturbated and hosts scattered to concentrated skeletal remains (mostly *Salterella* and trilobites), as well as complete, large olenellid trilobites.

2. The Deer Arm limestone (Plates 1C,1D, and 4) comprises 3.5 to 9 m of crudely stratified, nodular to lumpy, fine-grained to fossiliferous, dark-grey, locally shaly and dolomitic limestone intercalated with some black shale and limestone conglomerate. The limestone is rich in *Salterella* and dorypygid and olenellid trilobites but also hosts scat-

[2] The term mudrock is used to lump together the cleaved and indurated, argillaceous sedimentary rocks of the formation. Although no petrographic study of the mudrocks has occurred, it is believed the original protolith is likely a mix of mudstone and silty mudstone.

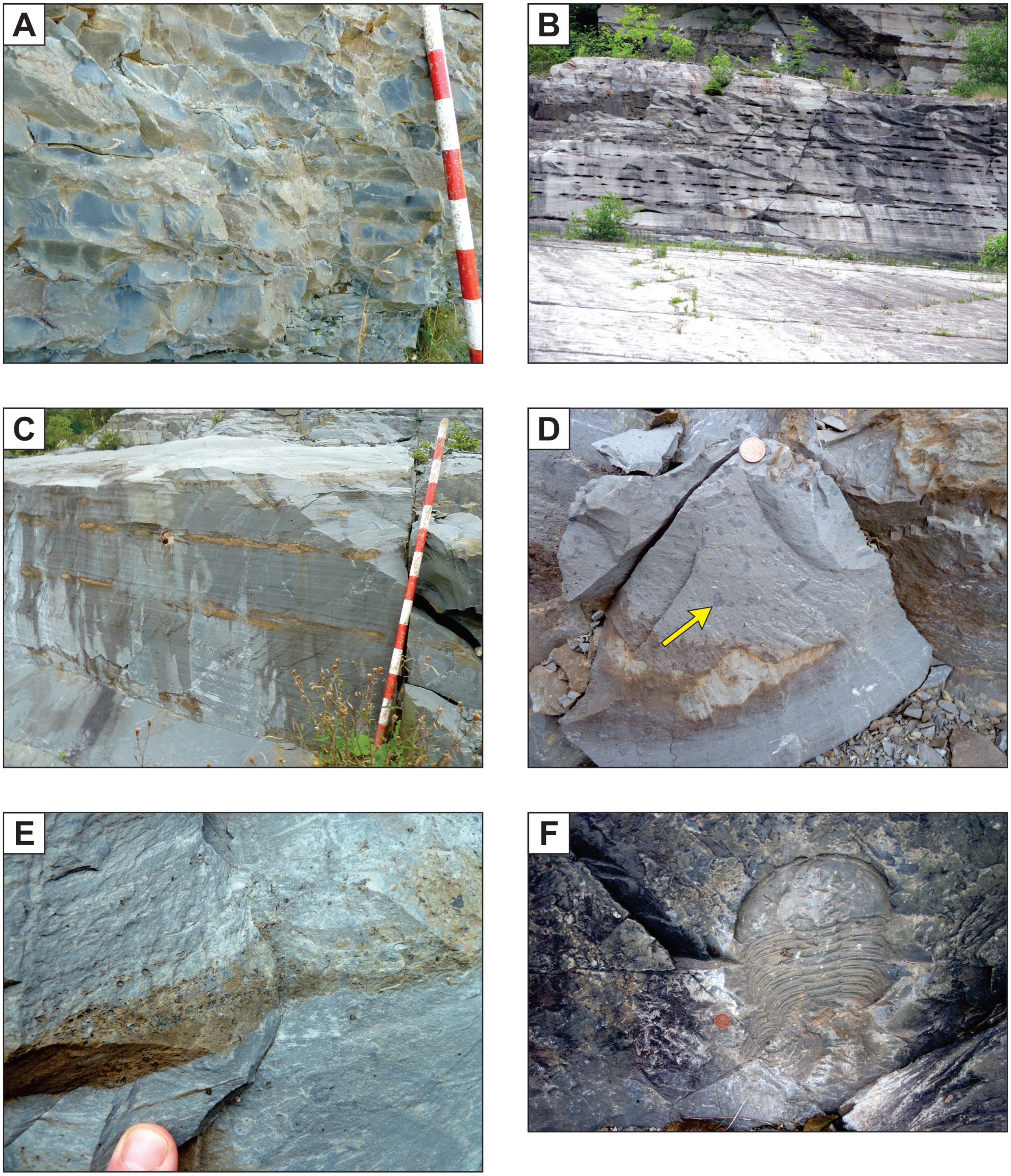

Plate 3. *Lower mudrock interval, Mackenzie Mill member. A) Lime mudstone nodules within mudstone low in the member at GM-1 section. Scale divisions 10 cm; B) Spaced bedding-parallel, recessively weathering, carbonate nodule in thin-bedded mudrock, section GM-2. Outcrop about 3 m thick; C) Planar thin-bedded mudrock with carbonate nodules, section GM-2. Measuring stick 1.5 m long; D) Dark, concentrically laminated burrow mottles (arrow) in mudrock, section GM-2. Coin 1.75 cm diameter; E) A calcareous bed rich in* Salterella *that is also scattered in bounding mudstones, section GM-2; F)* Wanneria logani *(Walcott, 1910) on a bedding plane, section GM-2. Coin 1.75 cm diameter.*

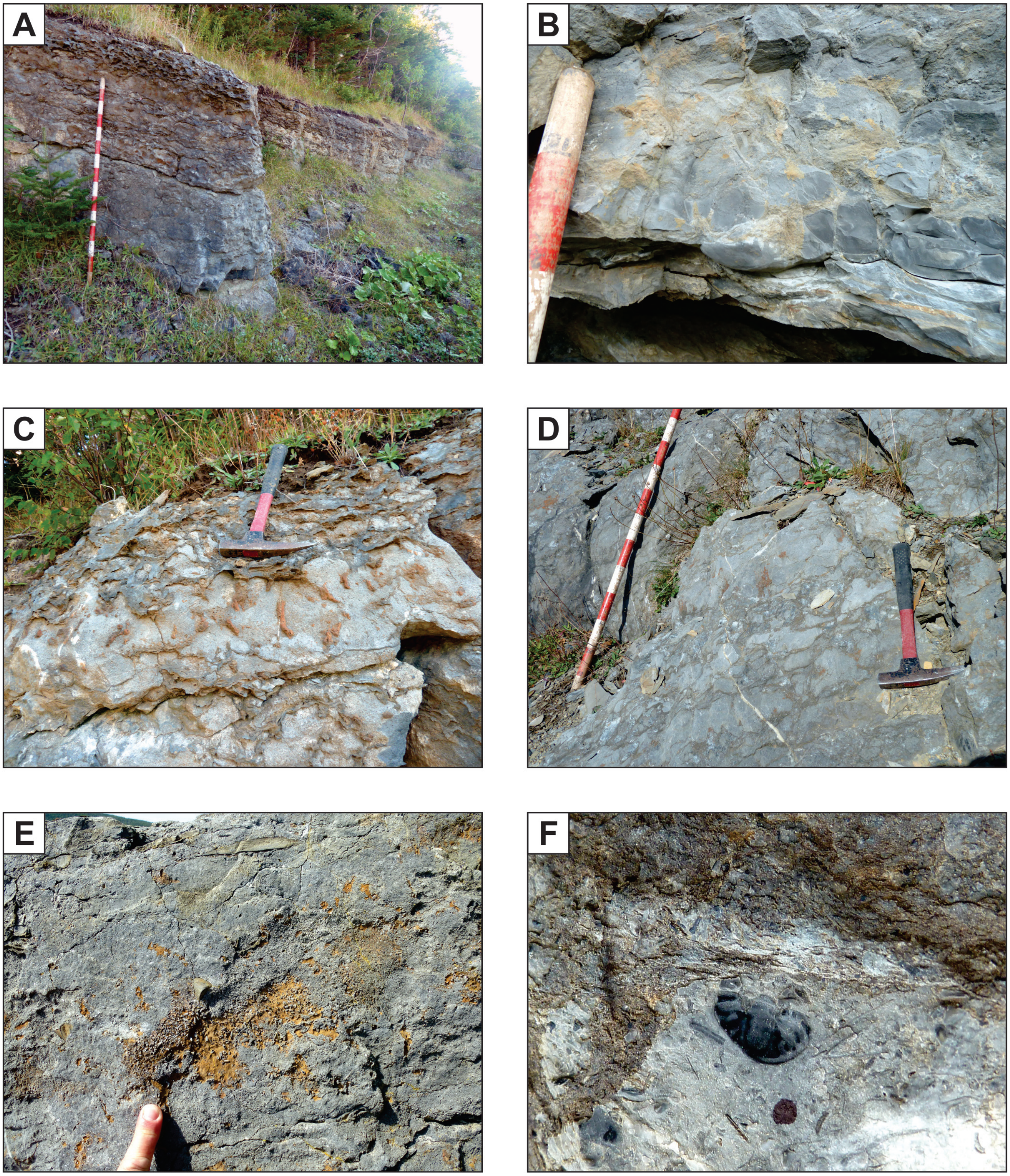

Plate 4. *Caption on opposite page.*

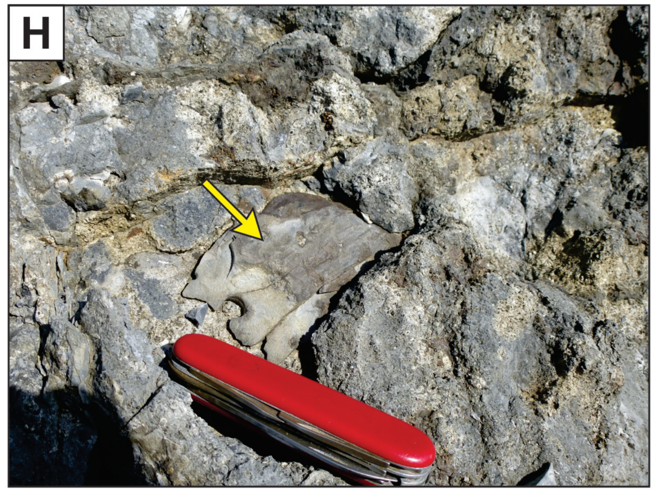

Plate 4. (opposite page, 4A-F) *The Deer Arm limestone (DAL): A) Stratified, shaly nodular limestone intercalated with clean, bioturbated dolomitic limestone, section 5D. Measuring stick 1.5 m long; B) Lime mudstone nodules in the base of the DAL overlying thin-bedded mudrocks, section GM-9. Scale divisions 10 cm; C) Dolomitic burrows in a skeletal packstone bed near top of the DAL, section GM-5C. Hammer 25 cm long; D) A conglomerate of angular limestone clasts in the middle of the DAL, section GM-9. Measuring stick 1.5 m long; E)* Salterella *packstone enclosing irregular patches of dolostone; F) Skeletal packstone enclosing a pygidia of* Bonnia senecta *(Billings, 1861), 1 cm wide, GM-4; G) Knobbly and rubbly top of the DAL at section GM-9; note the mud infiltrating between the limestone rubble; trilobites in overlying shale. Hammer head 14 cm across; H) A discoid limestone intraclast (arrow) in the top of the DAL at Bread and Butter Cove. Knife 9 cm long.*

tered brachiopods and minor hyolithids and molluscs; most small shelly faunas described in the formation to date come from this unit (Skovsted, 2003; Skovsted *et al.*, 2004; Skovsted and Peel, 2007). The DAL thins as it is traced southeast through the area.

3. An upper mudrock interval (Plates 1E and 5), 22 to 29 m thick, that generally lacks lime mudstone nodules, but is intercalated with irregular diagenetic calcareous lenses that preserve current structures near the base, and some ribbon siltstone and rare beds of sandstone. A thin black shale and scattered limestone nodules directly overlies the DAL and a few slump beds of re-sedimented mudrock and sandstone dykes also occur. Bioturbation is more common in the upper mudrock interval than in the lower mudrock interval. Trilobites are common in this interval but *Salterella* appears to be absent.

4. An upper limestone interval (Plates 1E, 1F, and 6), 2.5 to 11 m thick that consists of intercalated, nodular and phosphatic sandy dolostone, dark-grey, fossiliferous nodular limestone, grey and dark-grey shale hosting limestone nodules, and beds of intensely bioturbated siltstone and sandstone. Four distinct carbonate beds occur in this interval, the lower two beds associated with bioturbated siltstone and sandstone and the upper two beds intercalated with black to dark-grey shale, and commonly occurring limestone nodules. Traced to the southeast, the interval thins and loses at least one of its carbonate layers.

5. An uppermost heterolithic interval, at least 45 to perhaps 70 m thick, of ribbon-bedded sandstone and shale, intercalated with lesser mudrock, beds of bioturbated sandstone, crossbedded sandstone, rare quartz-rich sandstone, and several thin, dark-grey fossiliferous limestone beds and some dark-grey nodular limestone (Figure 4D, E and Plate 7). Black shale and siltstone lenses, laminae and thin beds, fossil debris along the fissility, and scattered lime mudstone nodules and pyrite mark the base of the interval. A dark-grey massive silty mudstone, 60 cm thick, occurs near the top of the interval. Disarticulated to complete olenellid trilobites are common in the mudrock and diffuse patches of skeletal debris were also noted in the sandier rocks. The interval, which coarsens upward and at the same time bioturbation increases, is dominated by decimeter- to metre-scale, coarsening-upward cycles of mudrock, ribbon-bedded siltstone and bioturbated sandstone. Incised erosional surfaces associated with crossbedded sandstone and fossiliferous sandstone occur close to the top of the interval. Centimetre-thick fossiliferous limestone beds and a few beds of nodular fossiliferous limestone also occur distributed throughout the interval. A few pot casts and a slump breccia occur in khaki mudrock, just below the top of the member.

Siliciclastic Rocks

Light-grey, silvery-grey to grey, cleaved, well-lithified and variably calcareous mudrock, which commonly weathers khaki, dominates the Mackenzie Mill member below and

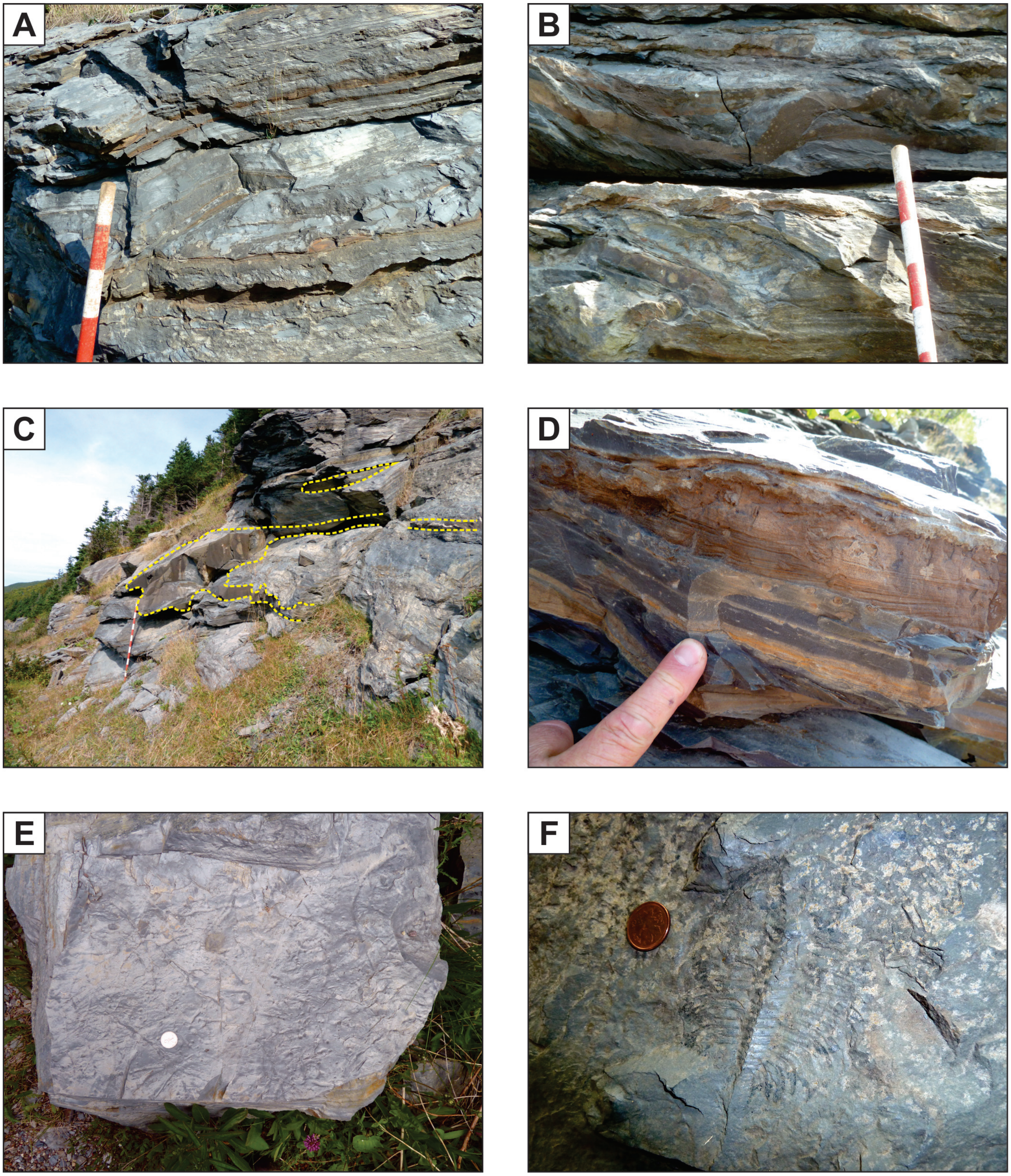

Plate 5. *The middle mudrock interval: A) Thin-bedded, silty mudstone with rusty calcareous beds near base of interval, section GM-6. Scale divisions 10 cm; B) Buckled ribbon bedding, section GM-6. Scale divisions 10 cm; C) Massive sandstone intruding mudrock (dashed outline); it has a domed top and sills that project into beds, section GM-6. Measuring stick 1.5 m long; D) Burrowed HCS in a brown-weathering calcareous siltstone; E) Bioturbation preserved on upturned block, section GM-6. Coin 2.5 cm diameter; F)* Wanneria walcottana *(Wanner, 1901) from middle of the interval, section GM-6. Coin 1.75 cm diameter.*

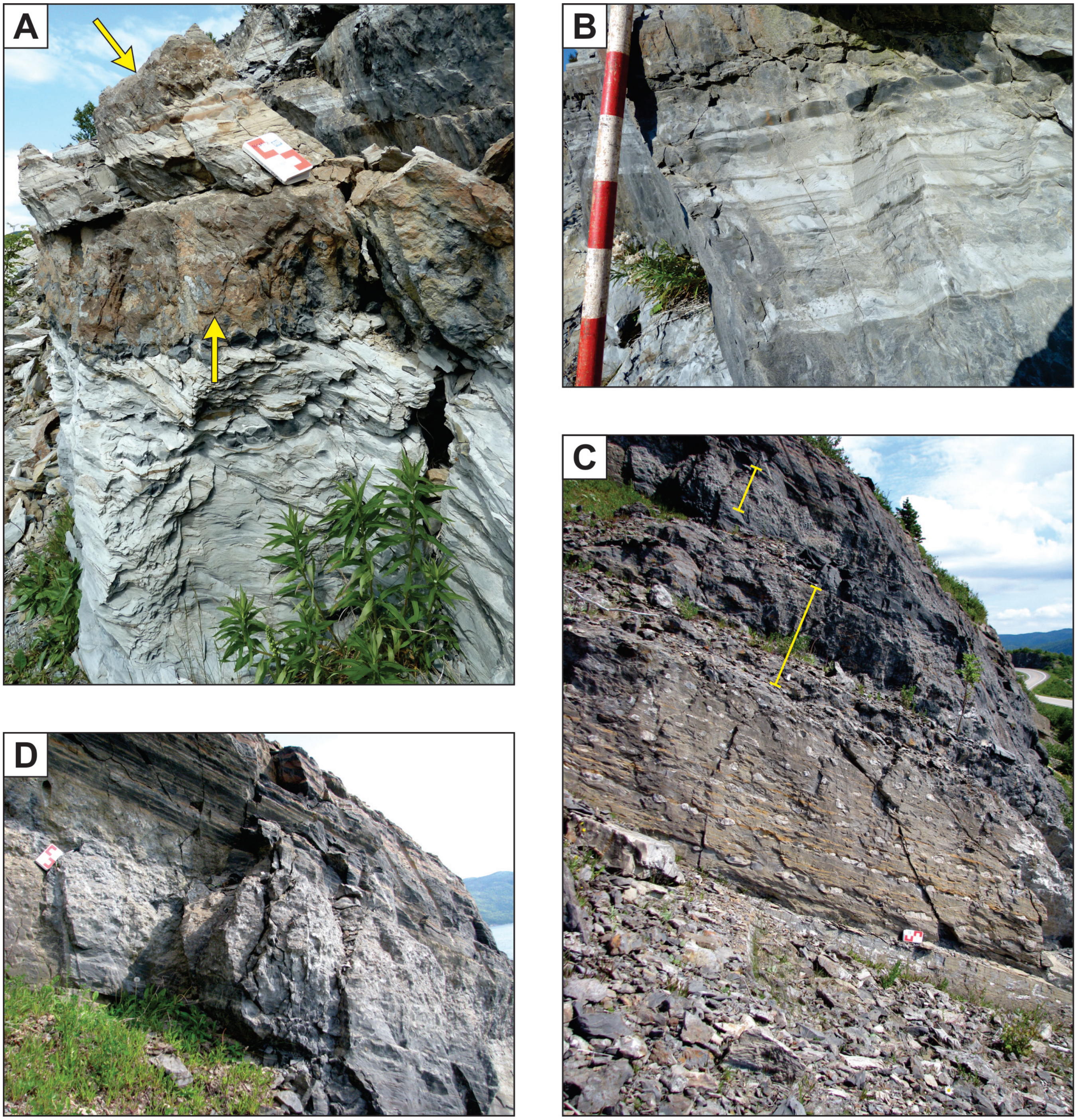

Plate 6. *The upper limestone interval, Section GM-6, Route 430. A) Two dolomitic carbonate beds (arrows) at the base of the interval, overlie thin-bedded grey mudstone and intercalate with khaki-coloured thin-bedded siltstone and mudstone. Notebook 17.5 cm long; B) Bioturbation in the thin-bedded khaki mudrock of Plate 6A. Scale divisions 10 cm; C) Black shale with limestone nodules overlain by two dark-grey nodular limestone beds (yellow bars) separated by shale. Notebook 17.5 cm long; D) Sharp planar surface above the uppermost nodular dark-grey limestone* at *GM-6. The surface is overlain by dark-grey to black shale. Notebook 17.5 cm long.*

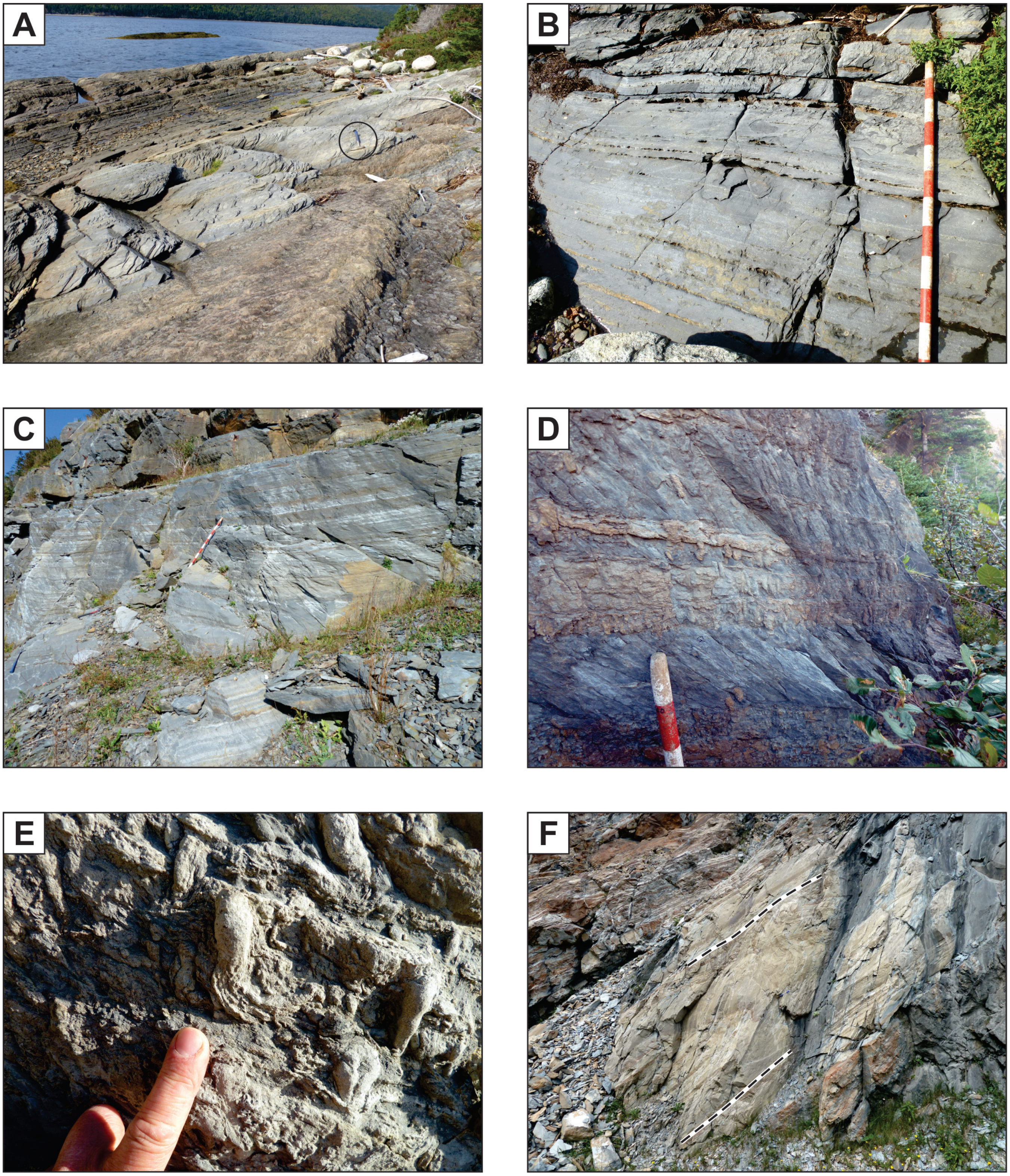

Plate 7. *Caption on opposite page.*

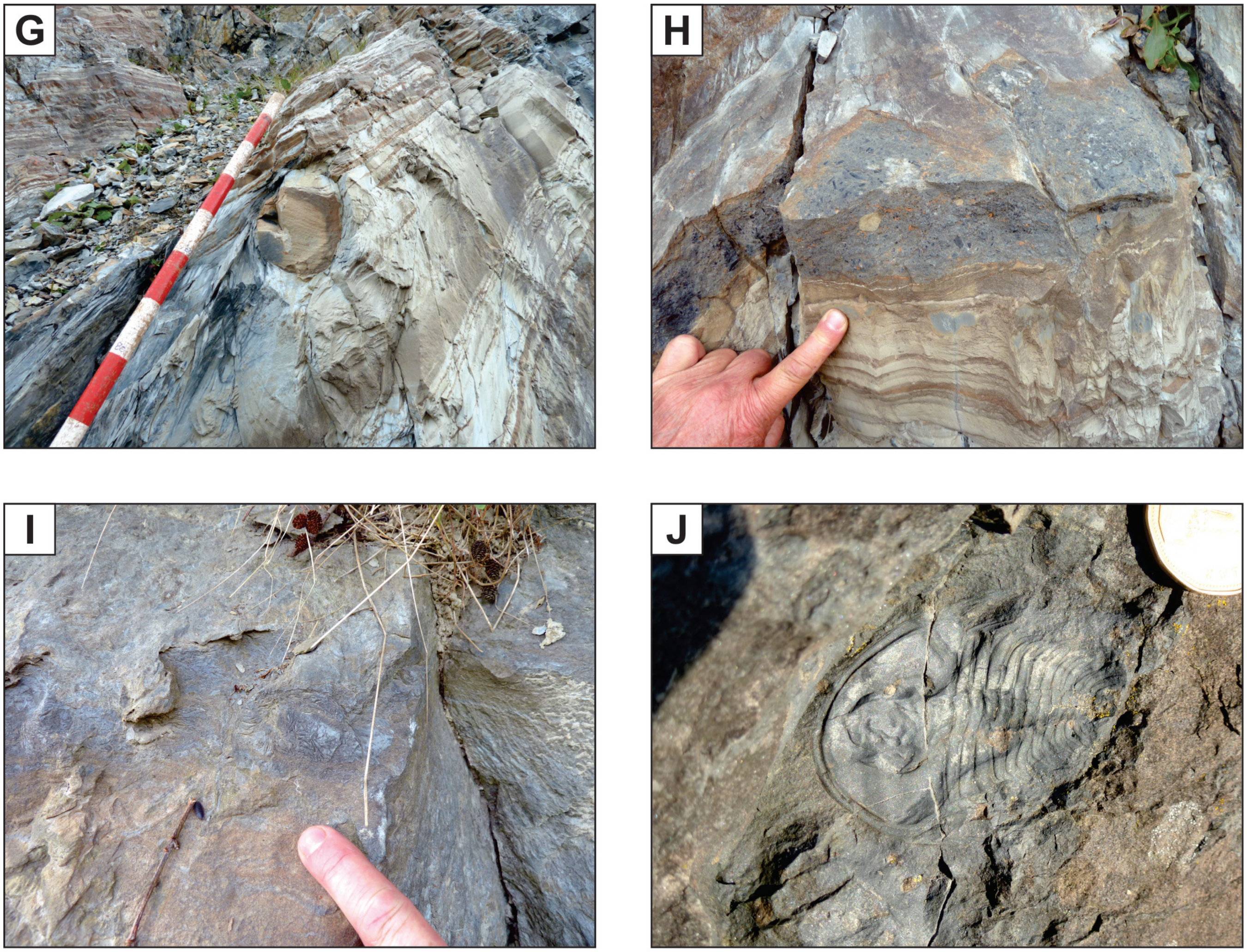

Plate 7. (opposite page, 7A-F) *The upper heterolithic interval. A) Well-stratified shoreline section through the interval at Bread and Butter Cove point. Hammer 32 cm long; B) The dark-grey shale with thin ribbons of siltstone at base of the interval at Bread and Butter Cove. Measuring stick 1.5 m long; C) Rhythmic alternation of mudstone and siltstone at GM-7, Route 430. Measuring stick 1.5 m long; D) Interbedded mudstone and strongly bioturbated beds of ribbon sandstone, GM-7. Scale divisions 10 cm; E)* Rosselia socialis *burrows GM-7, Route 430; F) Deformed thin-bedded mudrock (contacts shown), 1.5 m thick, near the top of the interval at GM-11, Route 430; G) An inclined pot cast in mudrock near the top of the interval at section GM-11. Scale divisions 10 cm; H) A fossiliferous and pebbly, scour-based limestone in thin-bedded siliciclastics at section GM-11; I) Bed of trilobite-rich limestone in the middle of a bioturbated sandstone at section GM-14F, Route 430; J)* Olenellus crassimarginatus *(Walcott, 1910) section Bread and Butter Cove point. Coin 2.6 cm diameter; K)* Olenellus roddyi *Resser and Howell, 1938, lower part of the interval, section GM-9, Route 430. Coin 1.75 cm diameter.*

above the Deer Arm limestone. The thin-bedded mudrock (Plates 3B, C and 5A) usually consists of sharp planar bases overlain by mm-thick laminae (very rarely micro-crosslaminated) to thin beds of siltstone gradationally below structureless to laminated mudrock. Pyrite occurs as nodules and locally replaces burrows and skeletal material. In the heterolithic interval, the facies also intercalates in decimetre- to metre-thick coarsening-upward sequences with ribbon siltstone and/or sandstone and bioturbated sandstone. Trilobites, often as complete carapaces (Plates 3F, 5F, 7J and K), but more frequently as scattered sclerites, adorn mudrock-facies bedding planes throughout the member. Millimetre-size *Salterella* cones are scattered, apparently randomly, in some beds of mudstones in the lower mudrock interval and are also clustered along some beds where they are partly cemented by carbonate (Plate 3E).

Although bioturbation is uncommon (Plate 3D) in the lower mudrock intervals, (BI ranging from 0 to 2; *cf.* Bann *et al*., 2004; MacEachern *et al*., 2010) it affects the middle mudrock interval more widely (Plate 5E) (BI from 0 to 4). Burrows include simple, vertical to randomly oriented mud-filled, often compacted tubes (possibly *Chondrites*), vertical to subvertical, concentrically laminated filled tubes of *Rosselia* affinity, scattered structureless, mud- or very fine sandstone-filled plug burrows (*Bergaueria* ?), vertical mm-size cylindrical cross-sections scattered on bedding planes, and faint, unstructured, bedding-parallel tubular traces (*Planolites*?). Millimetre-size mottles mark some mudstone layers higher in the member, some of which are commonly rich in comminuted skeletal debris.

Dark-grey to grey, lime mudstone nodules (Plate 3A, B and C) are ubiquitous in the lower 80 m of the member but they decline in frequency just below the DAL and are insignificant, although locally present in the facies, above the limestone marker. The flat, oval to irregular, internally structureless nodules are generally spaced in layers, up to 25 cm apart, in the lower interval, and present an almost ribbon-limestone-like aspect locally in the member at Southeast Hills; some nodules there display lamination, however.

Irregular yellow- or brown-weathering, dolomite-rimmed limestone nodules with diffuse gradational contact are common in the mudrocks immediately straddling the DAL. Lamination, crosslamination and burrows (including *Skolithus*, *Rosselia*, and *Diplocrateria*) characterize these irregular nodules that are mostly no more than a few centimetres thick, and about 10 to 15 cm long; their vague lenticular shape and spacing is locally reminiscent of starved ripple marks. The largest nodules of this kind are up to 10 cm thick and can be traced for up to a metre. They preserve HCS, current ripple crosslamination and sparse, but always present, burrows (Plate 5B), and at least one has a basal scour overlain by a lag of *Salterella* below burrowed crosslamination. Because of these characteristics, it is reasonable to suggest that the irregular nodules replace current deposited fine-grained siliclastics and are likely related to brown- to yellow-brown-weathering, calcareous ribbon siltstone and very-fine- to fine-grained sandstone that intercalate within the mudrock immediately below and above the DAL and again just below the upper limestone interval.

Thin-bedded siltstone and fine-grained sandstone intercalated with dark mudstone (ribbon bedded) however, is the dominant lithofacies (Plate 7A and C) above the upper limestone interval where it succeeds a bed of black to dark-grey shale, a few metres thick (Plates 6D and 7B). The ribbon-bedded facies marks the middle of decametre and metre-scale coarsening-upward sequences (CUS) that begin with khaki-weathering mudrock having tapering lenses and laminae of siltstone, and are topped by ribbon-bedded or bioturbated sandstone (Plate 7D). Tops of some CUS are eroded and the incised surfaces overlain by mudstone. The ribbon beds may be structureless, or exhibit undulose lamination and crosslamination. Hummocky cross-stratified and current crosslaminated sandstone occur in thicker beds that are host to a few vertical burrows of *Skolithus* and *Rosselia*-type as well as rare, centimetre-wide vertical burrows with convex-upward spreite. In the transition into the overlying bioturbated sandstone that tops a CUS, burrows rework the top of some ribbon sandstones and random networks of sand-filled exichnial tubes penetrate intercalated dark-grey, finely laminated mudstones. The bioturbated bed at the top of the CUS comprises clustered ribbon sandstone alternating with mudstone partings and thin beds, largely bioturbated (BI of 4 to 5; *cf.* Bann *et al*., 2004; MacEachern *et al*., 2010) by predominantly vertical tubular funnels and rarely spindles of *Rosselia socialis* (Plate 7E); looped sand-filled tubes (*Planolites*?) and sand-filled bow-shaped tubes (perhaps *Catenarichnus* (*cf.* Bradshaw *et al.*, 2002), *Arenicolites* or inarticulate brachiopod escape burrows (*see* Zonneveld *et al*., 2007) also occur in the bioturbated sandstone beds.

Distinct beds, 10 to 80 cm, but locally up to 170 cm, thick, of very-fine- to fine-grained, bedded, grey sandstone, also occur in the upper heterolithic interval toward the top of the member in more southernly sections (GM-11, 14A and 14G). Intercalated with the ribbon facies and also associated with limestone beds, the thick sandstones that locally host fine shell debris are intensely bioturbated by *Skolithus*, *Arenicolites*, *Diplocrateria*, *Rosselia*, possibly *Rhizocorallium* and *Phycodes*, and rarely *Teichichnites*. Two thick beds of intensely burrowed, calcareous siltstone in the lower mudrock interval, 8 m below the top of the Southeast Hills section may fit within this facies (Figure 4A). Where bioturbation is absent, the sandstones are 1) laminated, well-sorted, white quartzose sandstone, 2) scour-based massive sandstone overlain by lamination, or 3) ripple-crosslaminated sandstone overlain by small crossbeds and/or hummocky cross-stratification that may pass laterally into climbing crosslamination. Burrows penetrate tops of the beds and load casts decorate some bases.

An irregular, downcutting erosion surface that excavated a very large depression by incising into a thick bed of ripple-marked and crossbedded sandstone occurs high in the shoreline section, north of Bread and Butter Cove (Figure 4D). The irregular surface was first draped by a thin dark-grey shale, then partially offlapped by a tabular crossbedded sandstone, 25 cm thick, that imitates the shape of the scour and ends abruptly after a short distance into the depression. Small ripple marks ornament the avalanche foreset face below a later shale drape. This suggests that sand-carrying bottom currents were starved of sufficient sand to infill the erosional basin. A rusty-weathering, fossiliferous sandstone, rich in trilobite debris and hyolithids, rests on a basal scour with deeply incised scallops (likely gutter casts) at the top of the member at section GM-11 on Route 430. The 20-cm-thick bed is, in turn, truncated by a flat scour; associated khaki mudrocks host some pot casts (Plate 7G).

Paleocurrents can rarely be measured in any section. Apparent direction of crosslamination in cross-sections of sandstone beds is both to the east and west. Paleoflow defined by some ripple-mark crosslamination and crossbeds in the upper part of the member, however, is consistently toward the northwest (290°).

Evidence of soft-sediment deformation, is generally limited. However, several slump deposits, up to 150 cm thick, associated with both mudrock and ribbon-bedded facies, occur as single beds locally in several parts of the member. In general, the slump beds (Plate 7F) rest sharply upon thin-bedded mudrock facies and are, in turn, overlain sharply and conformably, by mudrocks or thin-bedded ribbon sandstone. Internally they show decimetre-size rafts of mudrock, some folded, others imbricated as slabs set in a mud matrix. In addition, small-scale slide surfaces associated with east-verging rucking of a few beds of ribbon siltstones (Plate 5C) occur 2 m above the DAL at Southeast Arm (K011-GM-6). In the same interval, a few metres of mudrock is intruded by a large, compacted dyke of structureless sandstone, up to 25 cm wide (Plate 5D); sandstone sills inject metres into the host.

Limestones

Limestone in the Mackenzie Mill member is commonly dark grey, is rarely found in beds more than tens of centimetres to a few metres thick, is mostly fine grained and fossiliferous, and dominantly displays a nodular to lumpy fabric. Limestone occurs throughout but forms only 1% of the member.

Below the DAL, several limestone beds occur in association with limestone-nodule-rich mudrock in the basal 22 m (Figure 4A), but limestone is rare higher in the sub-DAL succession (Figure 4B). The DAL, about 100 m above the base, and the upper limestone interval, 22 to 29 m higher (Figure 4C), are important markers that have been logged at sections GM-3, 4 through 6, 8, 9, 9A, 11 and 14, a distance of about 8 km. Thin fossiliferous limestones and some nodular limestone in the upper heterolithic interval have been traced a similar distance from Bread and Butter Cove to GM-11A, GM-14A, 14C, 14 D, 14F and G. Several beds of limestone exposed in sections along Route 430, however, prove difficult to place stratigraphically.

Limestone of the Lower Mudrock Interval

The dark-grey, nodular limestone beds, 20 to 140 cm thick at Southeast Hills range from lime mudstone at the base, some showing lamination and burrows, to skeletal-rich wackestone, packstone and grainstone at the top of the beds, all set in an argillaceous matrix. Trilobites and *Salterella* are the common fossils. In the upper 50 m below the DAL, a few irregular beds of skeletal packstones, 10 to 30 cm thick, are dominated by *Salterella* and trilobite fragments and enclose lime mudstone nodules in the base of beds. Rare inclined lined burrows in the packstones may be pebble-size intraclasts eroded from *Rosselia* burrows.

Deer Arm Limestone

This dark-grey, shaly and dolomitic, nodular to lumpy, fossiliferous limestone ranges from 3.6 to 8.2 m in thickness, and thins to the southeast. Bounded by thin black shale, the limestone marker, which can vary in thickness and stratigraphy even within a few hundreds metres, locally consists of two limestone beds separated by an interbed of nodular black shale, 35 to 100 cm thick about 4.25 to 5 m above the base. The most easterly exposure of the limestone (section GM-14) consists of 3.6 m of interbedded limestone and shale.

The crudely stratified, limestone marker (Plates 1D and 4A) consistently ranges from lime mudstone to skeletal wackestone and packstone; granular limestone composed of amorphous grains and scattered skeletal grains also occurs[3]. Nodular lime mudstone is common at the base of the unit

[3] No petrology has been done to date

(Plate 4B), but upward skeletal lime wackestone and packstone are dominant although lime mudstone is still present. The lumpy to nodular fabric mostly has a shale matrix (Plate 4A and 4C); it intercalates with beds of clean limestone (Figure 4C). Dolomitized coarse bioturbation (*Thalassinoides*) occurs near the top of the unit at GM-4 to 6 (Plate 4C). In general, the marker is shalier at GM-4 to 6 than at GM-9/9A. Locally, the contact between lime mudstone–wackstone (below) and packstone (above) layers is deformed by load and flame structures. An unusual bed of limestone conglomerate in the middle of the marker at GM-9 (Plate 4D) suggests the limestone was locally reworked by storms or moved *en masse* by gravity. The centimetre-size angular clasts of the different rock types, some shaped like the lumpy fabric, are supported in a fine-grained lime matrix.

The lime wackestone and packstone is commonly rich in skeletal debris that can range from concentrated patches of *Salterella*, trilobite-rich wackestone to mixed trilobite-*Salterella* packstone (Plate 4E and 4F). Other less-common skeletal elements include inarticulate brachiopods, hyolithids? and molluscs.

The limestone marker is characterized by a sharp but locally irregular base; a recessive-weathering thin black shale below is locally cut out along strike. Lime mudstone nodules occur in the immediately underlying mudrocks and in the base of the marker (Plate 4B), where their random orientation implies that they may have been reworked into the limestone. The top of the limestone ranges from sharp and relatively featureless in some sections, to irregular and lumpy (Plate 4G) in others. At the latter, the local relief of 5 to 10 cm is blanketed by the overlying shale that is host to abundant, bedding-parallel, trilobite debris. A dark rim encrusts irregular lime mudstone lumps locally in and at the top of the bed. At Bread and Butter Cove, the top of the unit is host to discoidal pebbles (Plate 4H), some displaying burrow pits and others fine lamination. Intriguing irregular patches of yellow-weathering, fine dolostone encasing floating *Salterella* occur below the top of the unit; the patches having indistinct margins that suggest geopetal dolostone infilling possible cavities in the limestone (Plate 4E).

Upper Limestone Interval

This interval, best seen at GM-6 (Figure 4C; Plate 1E), is 9.5 m thick and consists of four carbonate beds, 70, 30, 165 and 100 cm thick respectively, interbedded with khaki-weathering mudrock and burrowed sandstones (lower 2 beds) and dark-grey shale (upper two beds). The interval is traced with certainty to GM-9A (Figure 4C; Plate 1F), 1 km to the southeast where the four beds form an interval 6 m thick and to GM-14, 5 km farther southeast, where the interval is only 1.5 m thick and comprises just two limestone beds.

The lowest carbonate in the marker at GM-6 consists of two beds of nodular carbonate, 40 and 15 cm thick, separated by burrowed, fine siliciclastics, 35 cm thick (Plate 6A). Sandy dolostone, rich in sand-sized phosphatic debris, numerous, disorganized, floating lime mudstone nodules, and robust burrows characterizes the lower bed. It grades up over 20 cm into bioturbated sandstone that hosts scattered phosphate sand grains and is overlain by 15 cm of thinly stratified, bioturbated siltstone and shale (Plate 6B). The upper nodular carbonate consists of tightly packed lime mudstone nodules enclosed in a dolomitic matrix with scattered phosphatic sand. It, in turn, is overlain by intensely bioturbated rusty-weathering siltstone. *Diplocrateria*, *Skolithus*, *Arenicolites* and centimetre-wide lined burrows occur in the sandy beds; dwelling burrows consisting of vertical tubes connecting downward to triangular/balalaika- and flask-shaped, sand-filled chambers also occur.

The second carbonate bed at GM-6 consists of 30 cm of black, pyritiferous, massive, unfossiliferous, fine-grained limestone with an irregular lumpy top locally rich in 2 to 5 mm structureless oncolites. At GM-9A the carbonate bed consists of 60 cm of nodular to lumpy, lime mudstone gradationally above nodule-bearing siltstone; it is capped by 5 cm of crossbedded, oolitic grainstone. The siliciclastic mudrock to ribbon rock facies that occur below, between and immediately above the lower two carbonates, is rich in lime mudstone nodules; beds of intensely bioturbated siltstone occur at GM-9A.

Dark-grey shale, rich in lime mudstone nodules, some of which display internal shrinkage cracks cemented by calcite spar, occur below the upper two limestone beds (Plate 6C). The third and fourth limestone beds in the upper limestone marker are both dark-grey, nodular, fossiliferous limestones with a dolomitic matrix (Plate 6C and D). At GM-6, the third limestone, 165 cm thick, consists of 85 cm of bioturbated, fine-grained limestone with small scattered fossils overlain by crudely stratified (10–15 cm), bioturbated, wackestone–-packstone, the burrows replaced by dolostone. The upper stylonodular dolomitic lime wackestone, 100 cm thick, hosts trilobites, crinoids, possibly rare molluscs and a cm-long phosphatic horn. The dark-grey to black shale, separate the two limestones (Plate 6C). The nodules also occur in the base of the fourth limestone, which is overlain by black shale that rests upon a sharp planar (?erosive) contact (Plate 6D).

At GM-9A, the two upper limestones, each 75 cm thick, are separated by 45 cm of black shale that displays very fine lamination and contains lime mudstone nodules up to 10 cm in diameter. It is likely only the third and fourth limestone can be traced to GM-14.

At each locality, the upper limestone interval is overlain by black shale intercalated with mm- to cm-thick, current-bedded siltstone and very fine-grained sandstone that host trilobite and other? thin-shelled skeletal debris. At GM-9A, however, the current-bedded ribbon siltstones become rich in limestone nodules as they are traced laterally over a few metres to then pass into bioturbated and fossiliferous nodular limestone. Limestone nodules and nodular limestone beds occur within the overlying black shale at GM-14.

Limestone of the Upper Heterolithic Interval

Although less precisely located or defined in the member, single and clustered limestone beds occur in the upper heterolithic interval. Nodular to lumpy limestone beds that range from skeletal wackestone to packstone and mostly having a shale matrix, occur in the interval at the Bread and Butter Cove section. Comminuted fossil debris is commonly broken plates of trilobites but also includes a few inarticulate brachiopods. Other limestone beds in the same section, show ripple crosslamination.

A cluster of thin, fossiliferous, dark-grey limestone beds, 2 to 10 cm thick, occur over 58 cm within 12 m of the top of the member at GM-11 where they are intercalated in the khaki mudrock facies and in thick, generally bioturbated, sandstone. The beds are irregular in thickness because of scour bases and irregular tops and are locally discontinuous. The skeletal packstone comprises olenellid trilobite and hyolithid debris and one bed also hosts centimetre-size limestone pebbles (Plate 7H). Similar thin fossiliferous limestone beds occur at GM-14A, 14C, 14 D and 14F and G (Plate 7I).

Big Hill Member

Introduction

The Big Hill member is a succession of rusty- to dark-brown-weathering, very-fine- to fine-grained sandstone intercalated with dark-grey mudstone and siltstone. Thin intervals of khaki-weathering mudrock and ribbon-bedded siltstone like that in the Mackenzie Mill member also occur low in the unit; a rare bed of structureless mudstone and internally deformed muddy sandstone also occurs. The member lies conformably upon the Mackenzie Mill member and is, in turn, overlain sharply by the Hawke Bay Formation, the top of the member placed at the base of the first, decametre-thick, white or pink quartz-arenite (*see* Gros Morne section of James *et al*., 1988, page 89).

Because no complete section through the member occurs in GMNP and the selection of its upper contact is presently speculative (*see* below), its true thickness is unknown. The section, illustrated by James *et al.* (1988) at Gros Morne, shows an upper unit of siltstone, 30 m thick, which may be the Big Hill member; Williams *et al.* (1984) suggested 20 m for the unit. Twenty-nine metres of strata was logged at section GM-11 where the member lies conformably upon the Mackenzie Mill member but the top of the section and hence the member is faulted against the overlying Hawke Bay Formation (Plate 8A). A number of wedge-shaped, hummocky beds of whitish-weathering quartzose sandstone in the member, adjacent to the faulted contact however, suggest an imminent transition into the younger formation and that the member may be only a few metres thicker in this section. The conformable base is placed at the first bed of dark-brown-weathering, ribbon-bedded sandstone intercalated on a centimetre-scale with dark-grey to black mudstone; the base is also present at GM-14C and 14D.

However, because the upper contact of the member is defined as the base of the first thick quartz-arenite bed, it is possible the top of the formation is exposed at sections GM-15, 17 and 18 farther to the east. Twenty five metres of fine-grained siliciclastic sediments underlie the first Hawke Bay Formation quartz-arenite unit at GM-15, 40 m at GM-17 and 35 m at GM-18. However, by including the strata from these sections, the member (and hence the formation) would increase in thickness by as much as 30 m or more. The rock types seen in section GM-11 would have to be replaced upward by, genetically similar, but petrographically and visually distinct, strata. The latter include intercalated, dark-grey, massive mudstone, dark-grey, micaceous, thin-bedded, fine-grained sandstone and mudstone, and thicker, mostly grey, sandstone beds below the first quartz arenite. This appears to argue against their inclusion in the member (*see* Figure 5). A single trilobite head in GM-18, not dissimilar to *Pagetides* (W.D. Boyce, personal communication, 2013), a species known to occur well within the Hawke Bay Formation at Canada Bay (Knight and Boyce, 1987) also supports the inclusions of these sections in the Hawke Bay Formation.

In addition, the general character of the Hawke Bay Formation in GMNP consists of many intervals, a few metres to tens of metres thick (the thickest measured to date at 40 m thick), of dark-grey mudstone and dark-grey, micaceous sandstone (like those at GM-15, 17 and 18) alternating with equally thick units of quartz arenite. This sequence architecture can easily accommodate the thick units of mudstone and sandstone logged at the three sections within the Hawke Bay Formation proper.

These arguments, combined with the modest thicknesses indicated by the work of James *et al.* (1988) and Williams *et al.* (1984), suggest that the upper stratigraphic contact of

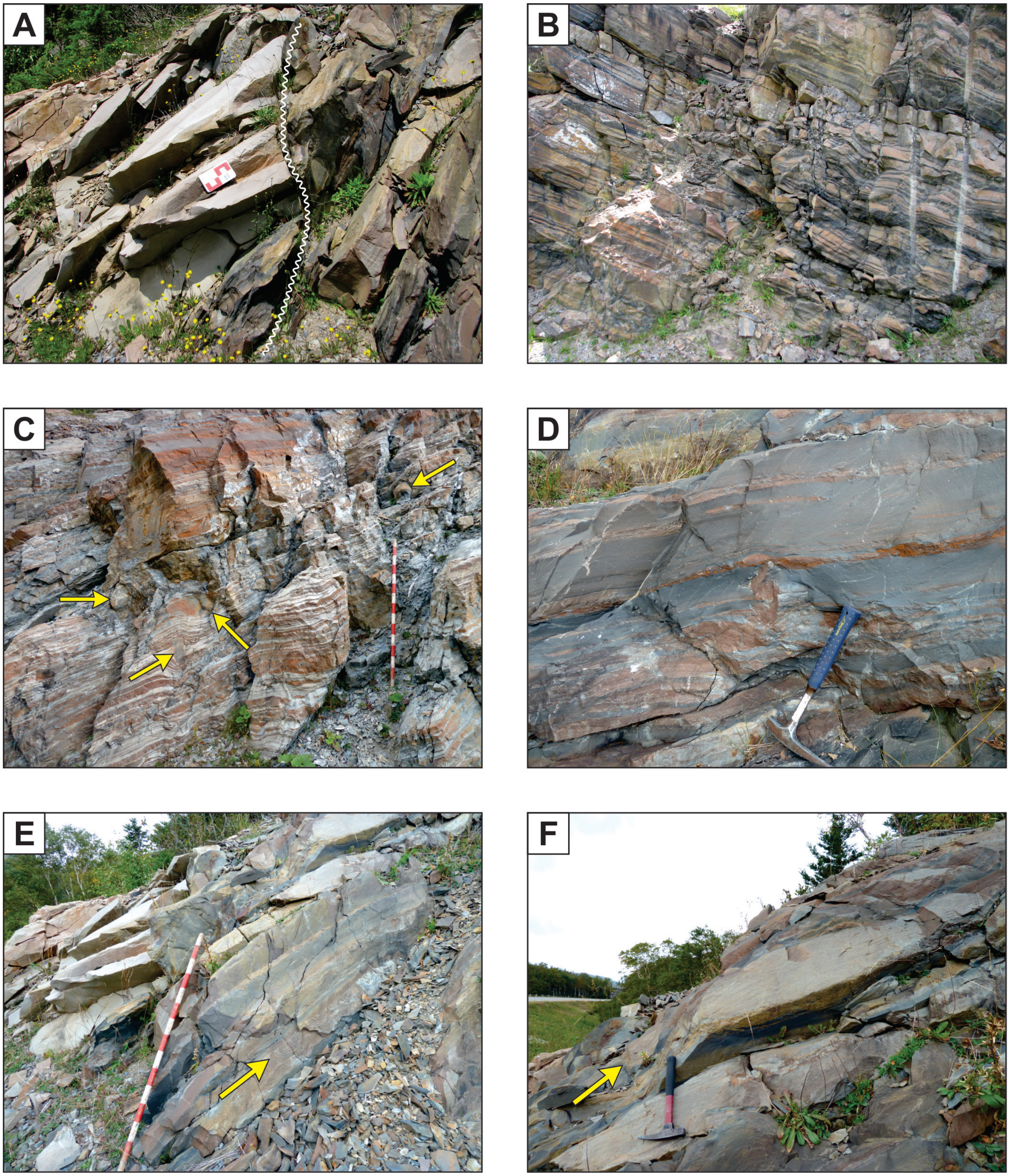

Plate 8. *The Big Hill member, section GM-11, Route 430. A) Brown-weathering sandstone beds of the member in fault contact (line) with Hawke Bay Formation quartz arenite. Notebook 17.5 cm across; B) Intercalated thin-bedded (ribbon-bedded) brown-weathering sandstone and dark-grey mudstone characteristic of the member. Section about 3 m thick; C) Pot and gutter casts (arrows). Measuring stick 1.5 m long; D) Compacted sandstone dyke cutting a dark-grey mudstone bed. Hammer 32 cm long; E) Convoluted laminated sandstone load balls (arrow) truncated by a scour near the top of the section. Whitish weathering, HCS sandstone occur above. Hawke Bay Formation sandstone in upper left. Measuring stick 1.5 m long; F) Wedge-shaped sandstone beds with hummocky cross-stratification near the top of the section; a gutter cast is indicated by arrow. Hammer 25 cm long.*

the member is not exposed along Route 430 unless further work proves the absence of a thick Hawke Bay Formation quartz arenite below the sections at GM-15, 17 and 18.

Lithology

The member exposed at GM-11 (Figure 4E) is dominated by intercalated dark-brown to rusty-weathering, centimetre-thick ribbon-bedded to sheeted sandstone and black to purplish-grey mudstones (Plate 8B and 8C). A few beds of khaki-weathering mudrock, dark-grey massive mudstone and thick sandstone are intercalated in the succession. No repetitive facies motif has been distinguished in this part of the succession. In addition, no limestone is present, no fossils have been found and pyrite is quite common.

Although sedimentary structures are obscure in many ribbon sandstone beds, others display a wide range of features. The ribbon bedding (1 to 10 cm thick) characteristically pinches and swells, some perhaps reflecting shallow gutter scours as they abruptly terminate at smooth, rounded, vertical contacts suggesting shallow erosion of mudstone before deposition of the sandstone. Some ribbon beds clearly have sharp bases and grade *via* a laminated transition into overlying mudstone; other beds have sharp bases and tops. Less common are small sets of HCS consisting of gently curved and inclined lamination at low angle to the base of the bed and separated by similar scours from adjoining sets within the beds; crosslamination locally occurs and some bedding planes have low-amplitude ripple marks. Bioturbation is virtually absent. Compacted, centimetre- to millimetre-wide sandstone dykes sporadically cut the facies (Plate 8D).

Gutter and pot casts are common in the ribbon sandstone especially just above the base of the member (Plate 8C). These structures, seen in both cross-section and in 3-D, are present in khaki mudrock and ribbon-bedded sandstone facies. The pot casts, which are either isolated or in clusters, are smooth and sharp-sided, goblet-shaped to flat-bottomed cylindrical pots up to 15–20 cm in diameter and at least 15 cm deep. At least two of the pots are steeply inclined to bedding at an angle of 45°[4]; sandstone fills the pot casts.

Cross-sections of narrow (8-cm-wide), sand-filled trowel-shaped bodies up to 20 cm deep, and larger broad saucepan-shaped to irregular, scoop-shaped, scour-bounded sandstone bodies in the ribbon-sheeted sandstone facies are interpreted as gutter casts. The gutter casts, which have a general, southeast alignment, include vertical to steeply inclined, to recessively curved margins undercutting the host sediment; they can be 90 cm wide and 30 cm deep. Scours, flat, curved to inclined lamination, crosslamination, and bioturbation mark the gutter fill; a thin, sparsely burrowed mudstone layer occurs halfway through one gutter cast infill. Compaction around the gutter casts including downward penetration through underlying bedding suggests that the gutter cast sand-fill was firmer than the ribbon-bedded host; compaction of at least 60% occurred.

Although sporadic at first, brown-weathering sheet sandstone, 10 to 30 cm thick, increase in number up through the lower part of the member. With sharp planar to erosive bases and sharp tops, the beds notably display undulating to hummocky lamination suggesting HCS and can be capped by thin crosslamination. High in the section, one sandstone sheet supports a layer of symmetrically convoluted, laminated sandstone load balls before they were planed off by later scour-based sandstone (Plate 8E). Lined funnel burrows (*Rosselia*?) were noted in one bed at GM-11. A single, very fine-grained, essentially massive, muddy sandstone bed, 85 cm thick in the upper part of the section, displays a vague internal soupy texture that suggests it has suffered dewatering or was re-sedimented. A few units of centimetre- to decimetre-thick khaki-mudrock like those in the underlying Mackenzie Mill member occur near the base of the member. Bioturbation is best seen in these khaki- mudrocks.

Several, thick, wedge-shaped to hummocky, white-weathering, quartz-rich sandstone beds interbedded with massive mudstone, however, occur at the top of the section (Plate 8E and 8F). Large-scale hummocky cross-stratification occurs in the sandstone beds. They are associated with deeply incised (up to 30 cm deep) gutter casts. Rare vertical burrows penetrate the sandstones.

DISCUSSION

The sedimentary rocks of the Forteau Formation in western Newfoundland, are understood within the context of a long-term sequence of transgression and regression, in response to late Early Cambrian sea-level rise and fall across the Newfoundland margin of Laurentia The sequence also involves the underlying Bradore and overlying Hawke Bay formations. Deposited during the late stages of Sauk I, the sequence is the first to accumulate along Newfoundland's lower Paleozoic passive margin. Faunas indicate that the Forteau Formation is contained within the Dyeran *Bonnia-Olenellus* zone of the Sauk I sequence (James *et al*., 1988; Skovsted and Peel, 2007). The formation regionally consists of two distinctive facies belts, an inboard facies belt in southern Labrador and northwest Newfoundland, and an

[4] Some part of this angular discordance may reflect rotation of the pots into the plane of the cleavage cutting the succession.

outer facies belt, preserved throughout much of the outer Humber (tectonostratigraphic) Zone of western Newfoundland; it includes GMNP.

In the inboard facies belt of the Laurentian shelf, preserved on the Great Northern Peninsula and southern Labrador, the Forteau Formation succession is demarcated by a tripartite stratigraphy. A basal limestone (Devils Cove Member) and middle dark-grey shale was laid down when rising Early Cambrian sea-level flooded the previously storm-dominated clastic shoreline of the Bradore Formation (Hiscott *et al.*, 1984; Long and Yip, 2009). The transgression reached its maximum during deposition of the middle shale unit. Subsequent regressive shelf progradation saw deposition of fine-grained, bedded, extensively burrowed, siliciclastic mudstone, siltstone and fine sandstone across the inboard facies belt. These rocks were succeeded by a thick, upper interval of shale, sandstone and limestone, that includes archeocyathid reefs (James and Kobluk, 1978; Debrenne and James, 1981), crossbedded oolitic, oncolitic and skeletal grainstone (Knight, 1991), and some thick units of sandstone (James *et al*., 1988; Knight, 1991), the product of a shallow, high-energy, likely warm water shelf (James and Kobuk, 1978; Debrenne and James, 1981). In all, the Forteau Formation in this region is 114 m thick and the inner facies belt likely ranged from 50 to 70 km in width; its lateral extent is unknown but it is postulated that it extends southwest, hugging the northern geographical edge of lower Paleozoic sedimentary rocks beneath the Gulf of St. Lawrence.

The GMNP succession is part of a deeper water, outer-shelf facies belt that extends from Canada Bay in the northeast, to Phillips Brook and North Brook anticlines, and the Port au Port No 1 well in the southwest of western Newfoundland (*see* Figure 1). The outer-facies belt is at least 80 to 120 km wide and extends from the northeast to the southwest for up to 300 km. The thicker outer-shelf succession in GMNP is dominated by a 230-m-thick, thin-bedded heterolithic succession of mudrock and ribbon clastics and minor limestone. Although obscured beneath the leading thrust panels of the various thrust stacks in western Newfoundland (*see* Figure 1), the outer-shelf facies belt shales out to the southeast, the distal part of the basin, characterized by dark-grey to black shale, now metamorphosed to polydeformed slate and phyllite as mapped in hinterland slices of the thrust stacks. This overall south to southeastward deepening of the basin fits well with a ramp shelf, defined for the Sauk I sequence in western Newfoundland by James *et al.* (1988).

However, the succession in GMNP is very different from that of the inner-facies belt of southern Labrador and northwest Newfoundland. Except for the Devils Cove Member, which is a reliable, basal limestone marker throughout the region, the rest of the succession in GMNP contrasts sharply with the inner-facies belt. First, the succession in Bonne Bay is twice as thick as the formation 200 km to the northwest suggesting a major depo-centre in this area. Second, the succession consists almost exclusively of fine-grained siliciclastics and the carbonates that are present are generally thin beds that lack any convincing evidence of shallow-water carbonate deposition in contrast to the upper part of the formation in the northwest Newfoundland.

DEVILS COVE MEMBER

The Devils Cove Member limestone (DCL) overlies gradationally the Badweather Pond member, Bradore Formation, a thin purple to grey quartz arenite (12-m thick) that blankets Grenvillian basement throughout the region, underlain by the outer-shelf facies belt. The only exception occurs at Canada Bay where the sandstone member is disconformable upon lower Bradore Formation (Knight, 1987). The sea-level rise and marine flooding of the Canadian craton dampened the supply of coarse terrigenous sediment to the Newfoundland shelf led to the widespread deposition of the DCL. This regional carbonate marker in GMNP, as elsewhere in western Newfoundland, is a shallow-water, skeletal-rich carbonate sand and gravel, that is likely both gradational and diachronous from southeast to northwest across the ancient shelf. In GMNP, grainy skeletal carbonate intercalated with purple sandstones and siltstones in the base of the member is overlain by a mostly argillaceous, fine-grained nodular carbonate; beds of shale and grainy carbonate mark the top of the member before the carbonate is abruptly succeeded by mudrocks of the Mackenzie Mill member.

SILICICLASTIC ROCKS OF THE MACKENZIE MILL AND BIG HILL MEMBERS

Based on the Southeast Hills section, the sharp contact of the lower mudrock interval with the DCL suggests, that deepening of the shelf, coupled with input of abundant mud terminated carbonate productivity, and established a mud-dominated shelf. Nonetheless, intercalated skeletal-rich nodular limestone in the first 30 m of the Mackenzie Mill member suggests carbonate productivity was intermittently possible at this stage in the transgression, perhaps whenever mud was cut off or reduced, or sediment was diverted to bypass the basin.

Much of the Mackenzie Mill member is dominated by mudrock. The upper part of the lower mudrock interval and the upper mudrock interval in sections at Deer Arm and East Arm, support a deep, outer-shelf setting below storm-wave base, coupled with high influx of siliciclastic mud. The importance of planar-thin stratification and lamination throughout both intervals supports prolonged periods of quiet deposition from suspension, perhaps aided by aggregation of fines (*see* Plint, 2010). Metre-thick units of thin-bedded mudrock typified by sharp-based siltstone laminae that grade up into mudstone suggest repetitive movement of sediment across the shelf floor. The domination of siliciclastic muds in the succession supports a steady supply of river-sourced mud, perhaps similar to the Atlantic margin of South America. Mud and silt are known to be carried offshore across the shelf to deeper water in buoyant hypocynal plumes, across-shelf diastrophic flows and gravity-driven turbid muddy flows. Mud that accumulated nearshore was likely re-sedimented into deeper water by storms, by combined storm and gravity induced downslope transport and by slope instability (Kuehl *et al.*, 1996; Nittrouer *et al.,* 1996; Wright *et al.,*2001, 2002).

The limestone nodules in these laminated mudrocks imply early shallow-carbonate diagenesis beneath the seabed and confirm quiet suspension sedimentation, as do the presence of complete trilobite exoskeletons preserved on bedding planes. Storms and waves mobilized fine calcareous mud from the shallower inboard shelf to the outer-facies belt to supply the carbonate in the mudrock. The nodules likely formed at the base of a sulphate reduction zone in the shallow subsurface, where carbonate precipitation is encouraged by high alkalinity (MacQuaker and Gawthorpe, 1993; Wignall, 1994). The regular spacing of nodule horizons in the mudrock succession suggests that the suitable conditions repeatedly occurred beneath the seafloor as it accreted. The preservation of undulose lamination, crosslamination, and even vertical tubular burrows in some carbonate concretions higher in the thin-bedded mudrock facies of the lower mudrock interval, indicate that sedimentation on the outer-shelf seafloor was more dynamic than one supplied by suspension alone. This suggests that bottom currents were important and were perhaps enhanced by strong storms that facilitated movement of fine sediment including aggregate grains (Schieber *et al.*, 2007) at considerably deeper depths on the shelf – perhaps a reflection of western Newfoundland's Atlantic type paleomargin.

Bioturbation throughout the lower mudrock interval is generally sparse but seems to increase in abundance upward below the DAL. The low BI values in the interval may reflect anoxia (suggested by presence of pyrite), low nutrient potential or the unsuitability of the seafloor substrate, *e.g.*, soft, fluid-rich, seafloor substrate or perhaps even the monotony of the sediment type (MacEachern *et al.*, 2010; Plint, 2010). Of the burrows noted in the mudrocks and in carbonate concretions, small sediment-filled tubes such as *Chondrites* and *Planolites* and uncommon and widely spaced sediment-lined burrows of the *Rosselia–Asterosoma* association, suggest a limited infauna of deposit feeders (Pemberton *et al*., 2001). The macrofauna is also limited to whole and disarticulated olenellid trilobite debris and scattered but locally common *Salterella* cones that lie along mudstone bedding.

The mudrock intervals subtly shift in their lithological composition in the strata bounding the DAL, implying shallowing of the seafloor. The scattered interbeds of ribbon rock and the thicker beds of calcareous siltstone that occur within the mudrock succession just beneath and above the DAL display undulose to planar lamination, crosslamination and in some instances, small HCS. This implies accretion of the shelf into the zone of storm influence; opportunistic colonizers, especially *Rosselia*, burrowed the storm deposits.

The upper mudrock interval, immediately above the DAL, consists of thin-bedded mudrock intercalated with calcareous siltstones and fine sandstones that exhibit HCS and crosslamination. They also exhibit some slump deposits, local soft sediment slides as well as a thick body of massive sandstone that intrudes the mudstone. This seems to imply a deepening of the seafloor as well as seabed instability, the latter reflecting high local sedimentation rates and/or perhaps basin tectonism. Above this lower interval, the mudrock is monotonous thinly stratified, silty mudstone that suggests quiet suspension sedimentation in which whole trilobites were often preserved. *Salterella,* however, is absent from the mudstone interval. Approaching the overlying upper limestone interval, however, the khaki-weathering grey mudrock shows increased bioturbation, implying perhaps low sedimentation rates and/or improving bottom conditions that supported an in-sediment burrowing fauna. Bioturbation is most intense in the khaki mudstone, siltstone and fine sandstone intercalated with the two lowest limestones of the upper limestone interval.

Dark-grey to black, pyritic and nodule-rich shales intercalated with nodular dark-grey limestone dominate much of the upper limestone interval and the base of the overlying upper heterolithic interval. The dark pyritic shale supports a more distal or sheltered setting on the shelf. Quiet, suspension sedimentation, low sedimentation rates and high organic productivity likely occurred at this juncture in the succession discouraging a bottom fauna, but facilitating the early precipitation of carbonate nodules beneath the seafloor

Above these strata, the succession in the rest of the upper heterolithic interval is dominated by repetitive, decimetre- to metre-thick CUS dominated by mudrock, and ribbon siltstone and sandstone that are bioturbated with increasing frequency higher in the unit; the interval is conformably replaced upward by the sandier ribbon rocks of the Big Hill member. The ribbon sandstone was likely deposited by frequent turbid sandy flows. The increasing volume of sand points to river source point discharging sand onto the shelf that was both shallowing and prograding. The repetitive CUS possibly preserve sandy lobes that prograded across the shelf, adjacent to the river mouths. Slump deposits in the succession suggest local slope instability due to high sedimentation rates. Hummocky cross-stratification (HCS) in thicker sandstone beds possibly suggest hummocky megaripples (Li and Amos, 1999) and implies both the strong influence of storms and the shelf above storm-wave base. This is supported by the presence of inclined pot casts that suggest storm-induced helical scour (Myrow, 1992) and by the scour-based, pebbly skeletal limestone, some with the geometry of gutter casts, that suggest storms reworked and then concentrated fossil debris in the gutters as the storms waned. The large scour-based depression in the upper part of the heterolithic interval indicates impressive erosion of the seafloor but insufficient sediment to fill the depression even during subsequent multiple events. This may imply that sediment bypass was important during these events.

Opportunistic burrowers colonized the HCS sandstones and also the ribbon sandstone that forms the top of the CUS. This bioturbation may completely mix the ribbon sandstone and intercalcated thin mudstone implying that some sand lobes were abandoned. *Rosselia socialis*, a spindle-shaped, concentrically laminated domicile fill that sits above a funnel-shaped tube and was made by terebelloid polychaetes (Nara, 1995) is the dominant ichnofauna in the upper heterolithic succession; the trace is probably indicative of a lower shoreface position in the marine shelf profile (*cf*., Pemberton *et al*., 2001). Although most commonly seen as funnels or tubes, locally the spindle dwelling trace is abundant in sandstone layers. The dominance of the funnel–tube association likely reflects the frequent influence of storm erosion (*i.e.*, above storm-wave base) whereas the preservation of the spindles implies either deposition below storm-wave base, reduced storm intensity or prolonged fair-weather conditions (Nara, 1995, 1997; *see* also Campbell *et al*., 2006). Scours, which erode the top of a CUS and are overlain by mudstone, show the importance of erosive storm events on the Newfoundland shelf.

The influence of storm events in the sandier ribbon beds and thick sandstones of the Big Hill member is supported by erosion-based sandstones, HCS, pot and gutter casts and the apparent paucity of bioturbation in this unit except in beds of the khaki-mudrock. The pot and gutter casts in the lower part of the member likely formed during strong storm-generated offshore unidirectional flow (Myrow, 1992; Amos *et al.*, 2003). The gutter casts generally trend northwest–southeast. The member is likely to pass gradationally upward into the Hawke Bay Formation.

CARBONATE ROCKS OF THE MACKENZIE MILL MEMBER

Limestone of the Mackenzie Mill member is characteristically nodular, dark grey, and fossil-rich of which the Deer Arm limestone is the most prominent example midway through the unit. The nodular fabric, the importance of lime mudstone to skeletal packstone as the dominant textural classes, the absence of current structures, and the virtual absence of shallow-water allochems, such as ooids, oncolites and archeocyathans (essential components of inboard-facies belt carbonates), suggest that the unit's limestones were deposited on the outer shelf in quiet subtidal settings. The DAL appears to be bounded by mudrock that shows the presence of structures that imply some shallowing of the shelf. It is probable that limestone deposition was encouraged when the seafloor was no longer overwhelmed by clastic sedimentation. This implies, perhaps, that river-sourced sediment bypassed the GMNP area along canyons, and might support sea-level fall. Alternatively, climatic change may have led to the sharp reduction of terrigenous sediment influx and perhaps reduction in storm frequency and ferocity. Black shale bounding the limestone suggests a quiet depositional setting. The upward gradation from lime mudstone to packstone in the limestone suggests that once carbonate mud production was established, calcareous shelled organisms, especially *Salterella* and trilobites, proliferated across the seafloor to form a broad carbonate bank; shale partings, matrix to nodules and thin interbeds beds show that terrigenous mud stifled carbonate productivity periodically.

Several features of the DAL are enigmatic. The locally crosscutting base with the incorporation of lime mudstone nodules, similar to those believed to have formed in the shallow subsurface in underlying mudrocks, the local deformation of lime mudstone/packstone contacts in the bed, a body of limestone conglomerate derived from the bed itself, and the rubbly irregular top infiltrated by the overlying trilobite-rich shale, suggest that the limestone may have been unstable and locally moved *en masse* over its muddy substrate on the low-inclined shelf slope. At Bread and Butter Cove, pebbles occur in the rubble at the top of the limestone; irregular, cavity-like structures filled by dolostone and *Salterella* occur in *Salterella* packstone just below the top. These features could perhaps have formed when gravity-movement disorganized the bed. Alternatively, they may suggest exposure of the limestone, although this does not seem likely based on the overall depositional setting well into the basin. Nonetheless, it is possible that the sea-level fall may have influenced the deposition of the limestone, and led to its top being exposed long enough to be disrupted, pebbles formed, and shallow subsurface dissolution create cavities that were infiltrated by dolomite mud.

The other dark-grey nodular limestone beds, which occur in the upper limestone interval and are scattered in the upper heterolithic interval of the Mackenzie Mill member, are likely to support deposition in subtidal settings when terrigenous sediment was at a minimum. The upper two beds of the upper limestone interval, intercalated with carbonate nodule-rich dark shale, were deposited in quiet, organic-rich settings. Beds of nodular limestone in the upper heterolithic interval are generally associated with bioturbated sandstones at the top of CUS. Although some of these beds may be diagenetic, it is likely most formed in abandoned areas of the shelf, where seawater and bottom conditions were suitable for local carbonate production. Skeletal-rich, scour-based limestones in the top of the upper heterolithic interval suggest the limestone and skeletal debris were not immune from reworking by storms.

The lower carbonate beds of the upper limestone interval are interpreted to be re-sedimented beds associated with beds of bioturbated, siliciclastic mud- and ribbon-rock. Chaotically distributed limestone nodules in a dolomitic matrix, rich in phosphatic sand grains and robust burrows, which penetrate both nodules and matrix, characterize the lowest carbonate bed, and suggest it has a complex depositional history. The mixing of disorganized limestone nodules, phosphate sand, and dolostone suggests that the bed was redeposited by gravity movement, the sandy, phosphatic dolostone, enclosing carbonate nodules during the late stages of movement; the deposit was later colonized by opportunistic burrowers. Ooliths and oncolites noted at the top of the second limestone of the same interval may also have been transported to a deeper setting rather than reflecting shallow water.

Looking at the Forteau Formation overall, the alternation of mudrock intervals with limestone intervals suggest three sub-sequences may comprise the formation in GMNP. The first consists of the Devils Cove Member and the lower mudrock interval and the Deer Arm limestone of the Mackenzie Mill member. The second includes the upper mudrock interval and the lower half of the upper limestone interval of the Mackenzie Mill member, and the third consists of the shale-dominated upper dark-grey limestone of the upper limestone interval, the upper heterolithic interval of the Mackenzie Mill member and the sandy ribbon rocks of the Big Hill member; it would also likely include the first quartz-arenite unit of the overlying Hawke Bay Formation. The sub-sequences may reflect the interplay of margin subsidence, fluctuating rates of sea-level rise, variable supply of sediment to the shelf that might involve shifting loci of deposition on the shelf related to major shifts of source points along the margin, and changes of climate. It has already been argued that the limestone in the Mackenzie Mill member may reflect climatic changes that reduced sediment input from rivers. Slowing sea-level rise coupled with high sediment input could control shallowing of the shelf.

Sub-sequence 1 includes rocks deposited during sea-level rise across the Laurentian margin and culminates with the deposition of the Deer Arm limestone. Evidence that the shelf had shallowed and was effected by storms, before and after the limestone was deposited, supports the possibility of relative sea-level fall at this time. This suggests that the deposition of the DAL may coincide with a period of lowered sea level and the cut-off of clastic input to the shelf as a result of sediment bypass.

However, the succession above the DAL does not so easily lend itself to subdivision into two sub-sequences. Siliciclastic rocks in the second sub-sequence appear to deepen, possibly associated with some shelf instability. The shelf appears to be deepest during the deposition of monotonous thin-bedded mudrock hosting complete trilobites in the middle of the interval, above which ribbon-bedded siltstone and sandstone and increasing amounts of bioturbation suggest shelf shallowing. The re-sedimented carbonate beds occurred at the peak of this shallowing. However, there is no clear sense that this is a correct interpretation and it seems equally probable that the succession above the DAL reflects shifting depositional dynamics on the shelf as outlined above. Dark-grey nodular limestone associated with dark shale immediately above the bioturbated clastics and re-sedimented carbonate beds likely responded to cut-off of clastics and an opportunity for carbonate production to occur. Above this upper limestone interval, the succession clearly coarsens and shallows upward, reflecting the dynamics of a prograding shelf-shoreline sequence supplied by abundant and increasingly coarse clastic sediment.

CONCLUSIONS

1. The Forteau Formation in GMNP consists of three members, Devils Cove Member overlain by two informal members, the Mackenzie Mill and Big Hill members. Two limestone markers, including the Deer Arm limestone, in the Mackenzie Mill member allow correlation of the succession throughout the park.

2. The thick dominantly siliciclastic Forteau Formation was laid down in an outer-shelf facies belt. The succession was deposited below storm-wave base throughout much of the formation. Only the upper part of the Mackenzie Mill and the overlying Big Hill member were deposited above storm-wave base and shows clear evidence of a storm-dominated margin.

3. The succession reflects deposition during the Dyeran stage of the Sauk 1 sequence following transgressive flood-

ing of the Newfoundland lower Paleozoic margin and later regressional progradation of the shoreline accompanied to relative sea-level fall.

4. Limestone in the formation was deposited subtidally on the shelf distant from a shoreline. The limestone units may reflect episodes of shelf shallowing but more likely formed in response to cut off to the shelf of siliciclastic input associated with climatic or bypass events.

5. Proliferation of *Salterella* and other shelly macrofossils reach a peak at the Deer Arm limestone. *Salterella* is absent above this unit.

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