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Stratigraphy of the upper Nelson Head, Aok, Grassy Bay, and Boot Inlet formations in the Brock Inlier, Northwest Territories (NTS 97-A, D)

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Introduction

This report is a product of the "Mackenzie-Shield to Selwyn Geo-transect" project within the Geological Survey of Canada's Geomapping for Energy and Minerals (GEM-2) program. It updates the lithostratigraphy of parts of the late Meso- to mid-Neoproterozoic Shaler Supergroup in the Brock Inlier, a structural uplift located east of Darnley Bay, Northwest Territories (Figure 1; Rainbird et al., 1994). Measured strata are mainly exposed along the Hornaday River and its tributaries and include the upper Rae Group (upper Nelson Head and Aok formations) and the lower Reynolds Point Group (Grassy Bay and Boot Inlet formations). Stratigraphic sections of underlying Nelson Head and Mikkelsen Islands formations strata, well exposed to the north, along the Brock River, are described in detail by Rainbird et al. (2015), and Ielpi and Rainbird (2016). The primary focus of this report is on the Boot Inlet Formation, for which a detailed facies analysis is presented (see also Greenman, 2017).

Geologic Background

The Amundsen Basin, located in northwestern Canada (Figure 1), comprises ~4 km of evaporite, carbonate and fluvio- deltaic siliciclastic rocks of the Shaler Supergroup (Figure 2), interpreted to represent deposition within an embayment of a much larger epeiric sea within the supercontinent

Rodinia (Evans, 2009; Rainbird et al., 1996; Young 1981). Remnants of the Amundsen Basin are exposed in several large structural inliers on the northern mainland and western Arctic Islands, of which the Brock Inlier is one (Figure 1).

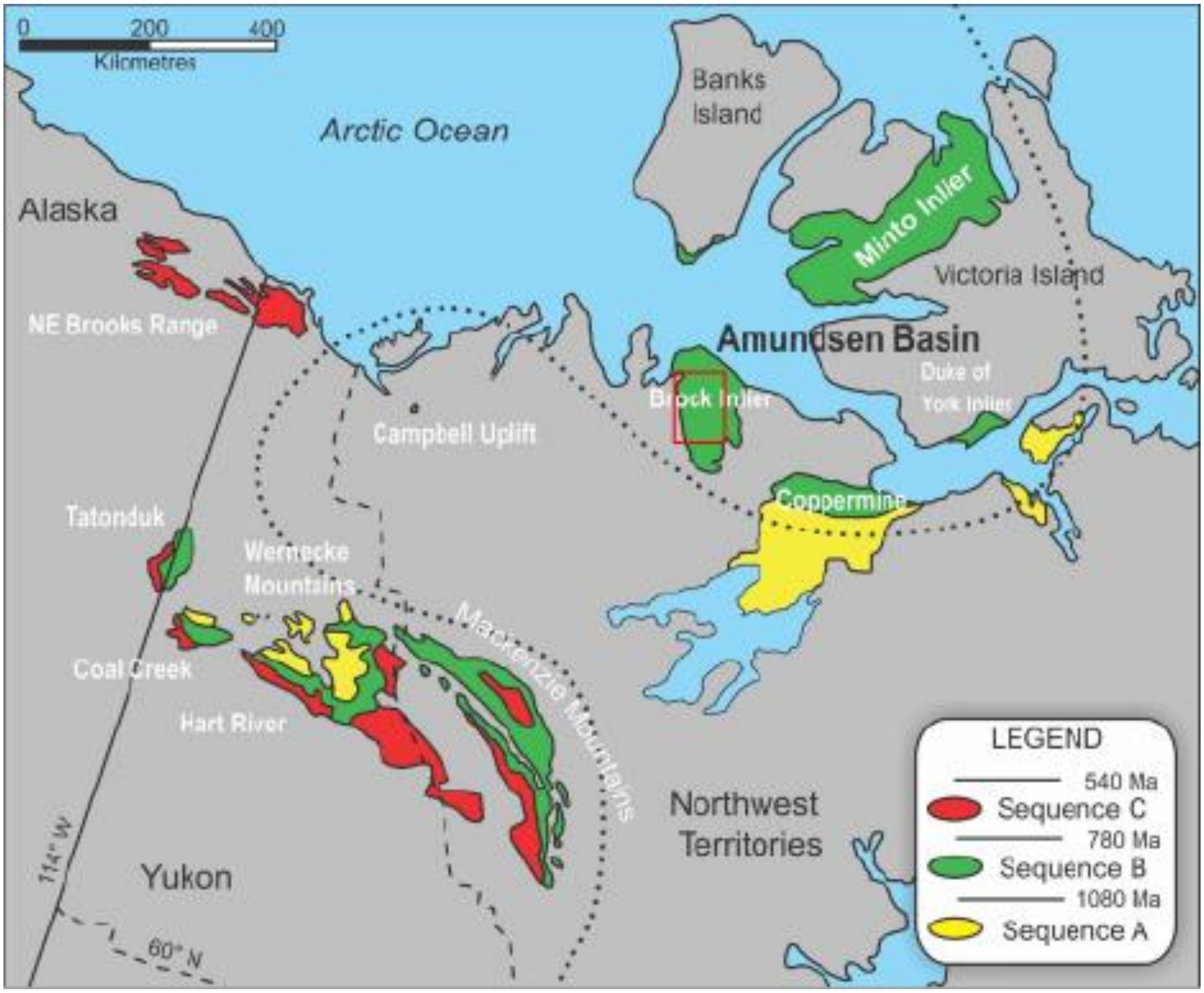

Figure 1: Amundsen Basin inliers and location of age-equivalent strata in the Mackenzie Mountains, northwestern Canada after Young et al. (1979). Dotted line represents hypothetical former margin of the Amundsen-Mackenzie basin (after Young et al., 1981). Red box outlines the approximate location of Figure 3.

The Boot Inlet Formation, exposed in the Brock and Minto inliers, is interpreted to be correlative with the Silverberry and Stone Knife formations in the Mackenzie Mountains Supergroup exposed in the Mackenzie Mountains approximately 400 km to the southwest of the Brock Inlier (Rainbird et al., 1996; Turner and Long, 2012; Young, 1977; Figure 1). Correlations based on chemo-, litho, and sequence stratigraphy have been proposed between Victoria Island and the Mackenzie Mountains (Long et al., 2008). The Boot Inlet Formation is interpreted to have been deposited on a storm-dominated carbonate ramp in a shallow marine setting during a period of transgression and prolific reef growth that interrupted deposition of fluvial-deltaic sediments represented by the underlying and overlying Grassy Bay and Fort Collinson formations, respectively (Morin and Rainbird, 1993; Narbonne et al., 2000; Young, 1981; Figure 2).

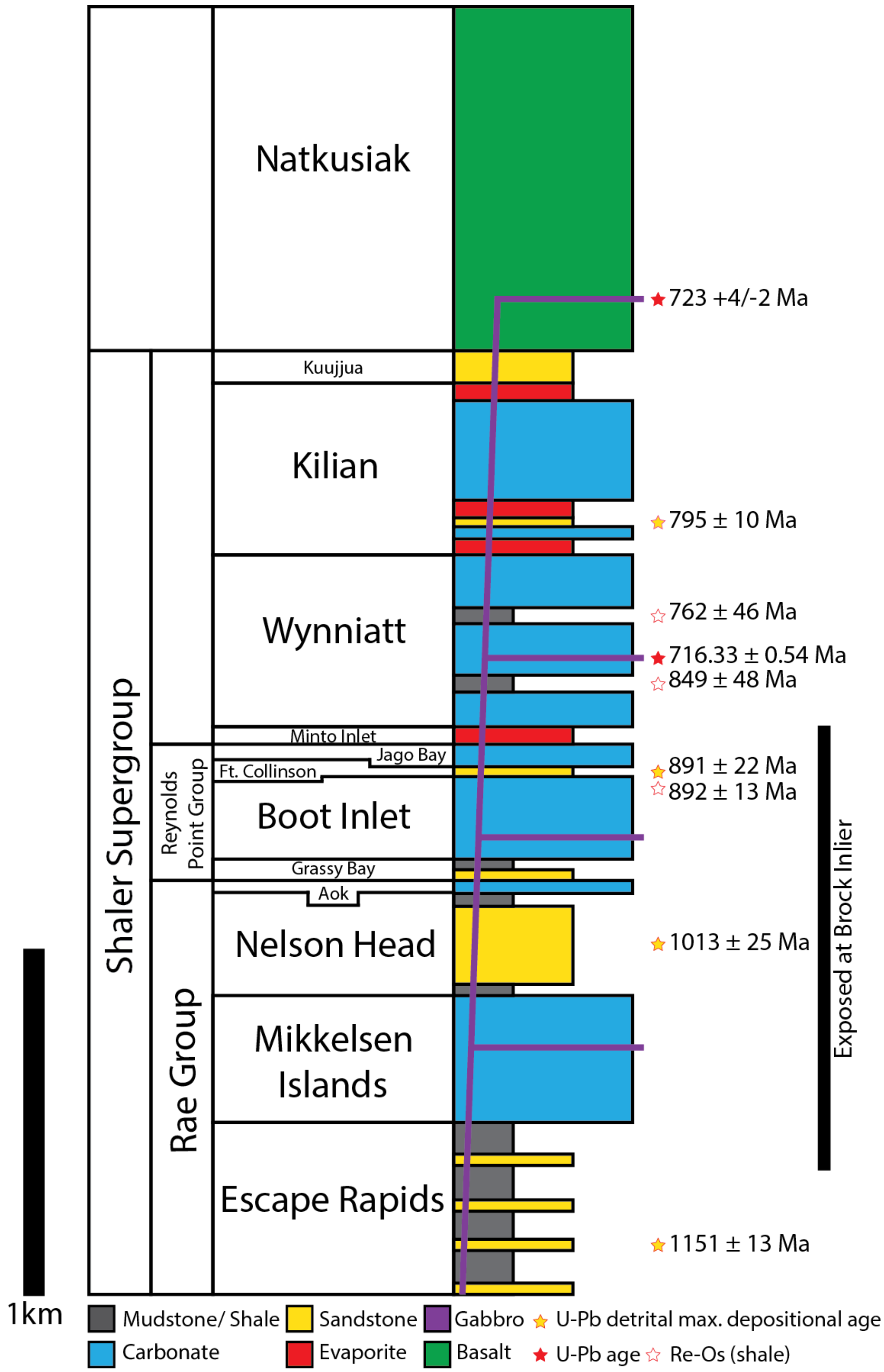

Figure 2: Generalized stratigraphy of Shaler Supergroup, after Thomson et al., (2014) and Rainbird et al., (1994). Note the vertical black line showing the exposed portion in the Brock Inlier. Age constraints from Rayner and Rainbird (2013), van Acken et al. (2012), and Heaman et al. (1992).

Previous Work

The Shaler Group was originally described by Thorsteinsson and Tozer (1962) on Victoria Island (Minto Inlier), and mapping of the Brock Inlier, which included descriptions of the Shaler Group, was undertaken by Balkwill and Yorath (1970), and Cook and Aitken (1969). The Reynolds Point Formation was described by Young (1974, 1977), but was later elevated to Group status when the Shaler Group was elevated to supergroup status by Rainbird et al. (1994). The lithostratigraphic assemblages described in the Minto Inlier are the rhythmitic, stromatolitic and oolitic facies associations with an observed overall shallowing of facies assemblages interpreted to represent four stages of progradation (Morin and Rainbird, 1993). A detailed description of well-exposed stromatolite reefs from the Boot Inlet Formation on Victoria Island is given by Narbonne et al. (2000). Chemostratigraphy ($\boldsymbol{\delta}^{13}$C and $\boldsymbol{\delta}^{18}$O isotopes) of the stratigraphic section between the Aok and Wynniatt formations from the Minto Inlier was described by Jones et al. (2010), and Thomson et al., (2015a). Lithostratigraphic correlations between the Shaler and Mackenzie Mountains supergroups and the Wernecke Mountains were proposed by Young (1982, 1977), Aitken et al., (1978a, 1978b), and Young et al. (1979). The "orange-weathering stromatolite biostrome", which characterizes the Aok Formation in the Shaler Supergroup of Amundsen Basin, and the McClure Formation in the Mackenzie Mountains Supergroup of the Mackenzie Mountains, represents an important marker bed in the regional lithostratigraphic framework (Jefferson and Young, 1989; Turner and Long, 2012). Chemostratigraphic and sequence stratigraphic frameworks have been proposed that build upon this foundation (Jones et al., 2010; Long et al., 2008; Macdonald et al., 2012; Thomson et al., 2015a; Thomson et al., 2015b).

The uplifted region known as the Brock Inlier contains a large plateau (Brock Uplands), in places rising to 800 m above sea level (Balkwill and Yorath, 1970; Jones et al., 1992). Sedimentary rocks in the Brock Inlier are essentially flat lying and unmetamorphosed. The Brock Uplands mainly exposes late Meso- Neoproterozoic rocks of the Shaler Supergroup via recent incision by the Hornaday, Brock and Roscoe river canyons. Exposure of Proterozoic strata decreases east of Hornaday Lake as glacial deposits become thicker, although there are well exposed outcrops along the Amundsen Gulf coast. Proterozoic rocks are surrounded by younger strata belonging to the Cambrian to Ordovician aged Mount Clark, Mount Cap, Saline River and Franklin Mountain formations. The Mount Clark Formation often disconformably overlies Proterozoic exposures (Figure 3; see also Bouchard and Turner, 2017; Rainbird et al., 2016). Overlying these deposits are poorly consolidated Cretaceous sediments (Rainbird et al., 2016).

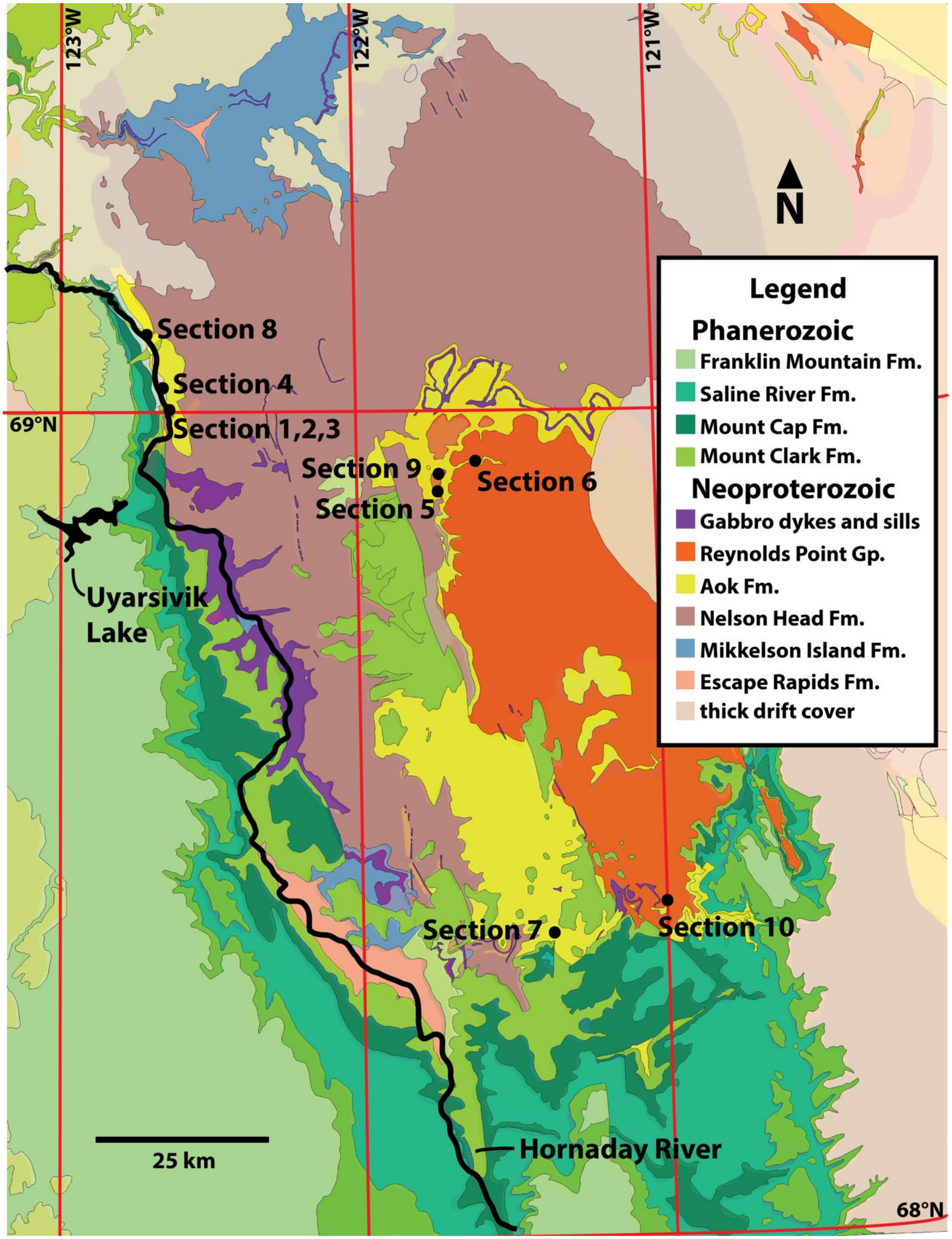

Figure 3: Brock Inlier field area with locations of measured sections. Formation data after Okulitch, (2000). Graphic logs and coordinates of stratigraphic sections in Appendix.

Lithostratigraphy

Upper Nelson Head Formation

Description

The Nelson Head Formation has an overall thickness of approximately 460 m in the Brock Inlier. The lower part of the formation, including the basal contact with the Mikkelsen Islands Formation, is exposed in a spectacular canyon along the lower reaches of the Brock River where its sedimentary architecture was described in detail by Ielpi and Rainbird (2016). The upper part of the Nelson Head Formation is generally not well exposed, except at one location along the Hornaday River (Section 1-see Appendix; Figure 4). Section 1 exposes the uppermost 60 m of the Nelson Head Formation and its conformable contact with the overlying Aok Formation (Figures 4, 5). The base of this section consists of fine-medium grained, tabular plane-bedded and tabular trough cross-bedded sandstones, some of which display evidence for tidal influence (Figure 5a-c). Overall grain size decreases gradually upsection as interbeds of shale increase relative to sandstone. Wavy-lenticular-bedded sandstone, combined-flow ripples and siltstone with mud drapes also become common as quartz-sand content decreases (Figure 5d). The top of the formation weathers recessively and is dominated by laminated siltstone punctuated by cross-laminated sandstone interlayers that form gutters with soft-sediment loading features (Figure 5e). Interlayers of dolostone are observed near the top of the section and become more frequent until the abrupt, conformable contact with thick dolostones of the Aok Formation (Figure 5f).

Figure 4: Conformable contact between the Nelson Head and Aok formations along the Hornaday River at Section 1 (Figure 3, for location; Section 1, for stratigraphic log). Section is approximately 100 metres thick.

Interpretation

The Nelson Head Formation is interpreted to represent the deposition of a moderate sinuosity fluvial braidplain flowing to the northwest (Ielpi and Rainbird, 2016; Rainbird et al., 1994; Jones et al., 1992). The upper 60 m, studied at Section 1, records a period of transgression to marine conditions via a prograding marine delta. The basal planar and trough cross-bedded sandstones represent deposition on a relatively high-energy delta front bar or upper shoreface. Gradual sand starvation with the emergence of shale interbeds above this indicates water deepening and deposition on the middle to lower shoreface. Sand-filled gutters, HCS and combined-flow ripples mean that storms were the main mechanism for delivering coarse siliciclastic detritus to the basin (see Plint, 2010). The presence of dolostone interbeds near the top suggest the revival of the carbonate factory in marine conditions not choked by siliciclastic influx.

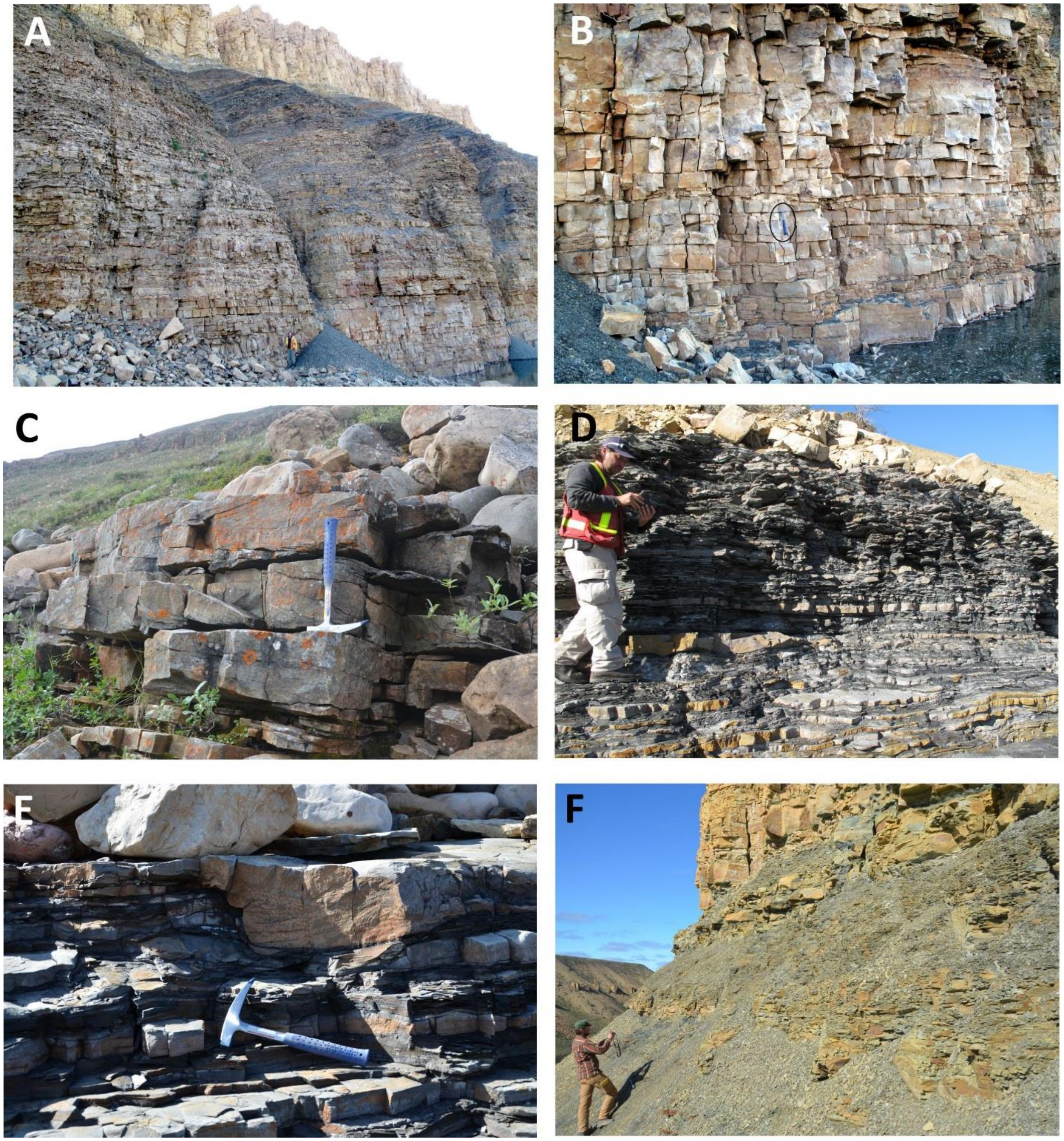

Figure 5: Upper Nelson Head Formation at section 1 (Figures 3 and 4). A: Base of section, person for scale. B: Close-up of mainly tabular-bedded, fine-medium grained quartz arenite at base of section. Hammer (circled), for scale. C: Cross-bedded quartz arenite with exhumed foresets showing opposed sense of transport. D: Interbedded wavy- to lenticular-bedded sandstone and dark, parallel-laminated siltstone. E: Sandstone gutter loaded into underlying

laminated siltstone. F: Recessive siltstones with sandstone (below) and dolostone (above) interbeds, just below contact with thick, orange-weathering dolostone (Aok Formation). Hammer in figures B, C and E is about 40 cm long.

<u>Aok Formation</u>

Description

This distinct orange-weathering stromatolite unit has been a useful stratigraphic marker for regional correlations across northwestern Canada, being represented in the Mackenzie Mountains by the Maclure Formation (Turner and Long, 2012), and by the Aok Formation in the Shaler Supergroup (Jefferson and Young (1989). A detailed report of the reefal and stromatolite morphology is given by Jefferson and Young (1989). In the Brock Inlier, it outcrops along the Hornaday River north of Uyarsivik Lake and to the east on the Brock Uplands west of Hornaday Lake (Figure 3). Three measured stratigraphic sections through the Aok Formation comprise a composite section containing its lower and upper contacts with the Nelson Head and Grassy Bay formations, respectively (Figure 6, sections 1, 2, 5). The abrupt lower contact with the Nelson Head Formation is visible at Section 1 (Figures 4, 5f). The Aok Formation comprises two stromatolite biostromes (composed of Inzeria; e.g. Jefferson and Young, 1989; Walter, 1972; Figure 7) that were measured at approximately 16 m and 5 m thick, respectively, separated by very recessive shale (approximately 12 m thick at Section 2-see Appendix; Figure 6). The contact with the Grassy Bay Formation is poorly exposed at Section 5.

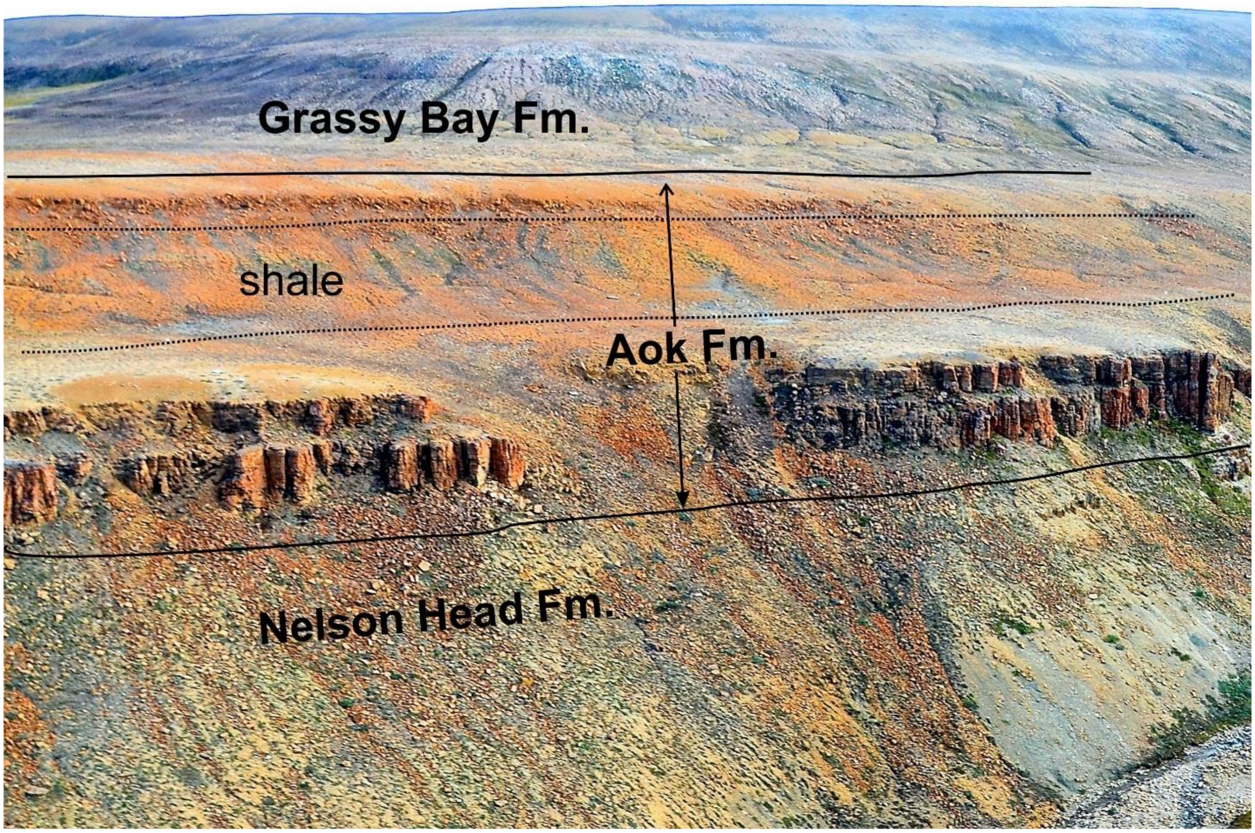

Figure 6: Typical exposure of the Aok Formation (approximately 70m thick) along tributary east of the Hornaday River, comprising two, orange-weathering stromatolite biostromes separated by recessive shale marked by the dashed lines.

Figure 7: Distinctly orange-weathering, digitate stromatolitic dolostone characterizing the lower biostrome of the Aok Formation. Pencil, for scale, is about 12 cm long.

Interpretation

Deposition of thick stromatolite biostromes indicates that the depositional environment was tectonically stable and that changes in sea-level generally were matched by sedimentation rates. The exception to this is represented by the recessive shale bounded by the two biostromes, that suggests a drowning period when stromatolite growth was outpaced by sea-level rise. The return of stromatolite growth offers evidence of a drop in sea level that continued well into the development of the overlying Grassy Bay Formation.

Grassy Bay Formation

Description

The Grassy Bay Formation is very poorly developed and not well exposed in the Brock Inlier, relative to the Minto Inlier, where its type section occurs (Rainbird et al., 1994). It mainly outcrops on the Brock Uplands between the Uyarsivik and Hornaday lakes (Figure 3) and has a total thickness of approximately 70 m in the Brock Inlier (Section 5) with the best exposure outcropping at Section 9 (Figures 8, 9). Most of the formation weathers recessively and is mainly observed as loose blocks near the top of the formation. In the upper part of Section 9 it comprises 10 m of variegated, red/green, laminated siltstone and lenticular bedded, fine-grained quartz arenite (Figure 9). Upsection, toward the contact with the Boot Inlet Formation, hummocky cross-stratification is observed within loose, frost-tilted blocks composed of fine-grained sandstone. The contact of the Grassy Bay Formation with the overlying Boot Inlet Formation is described below.

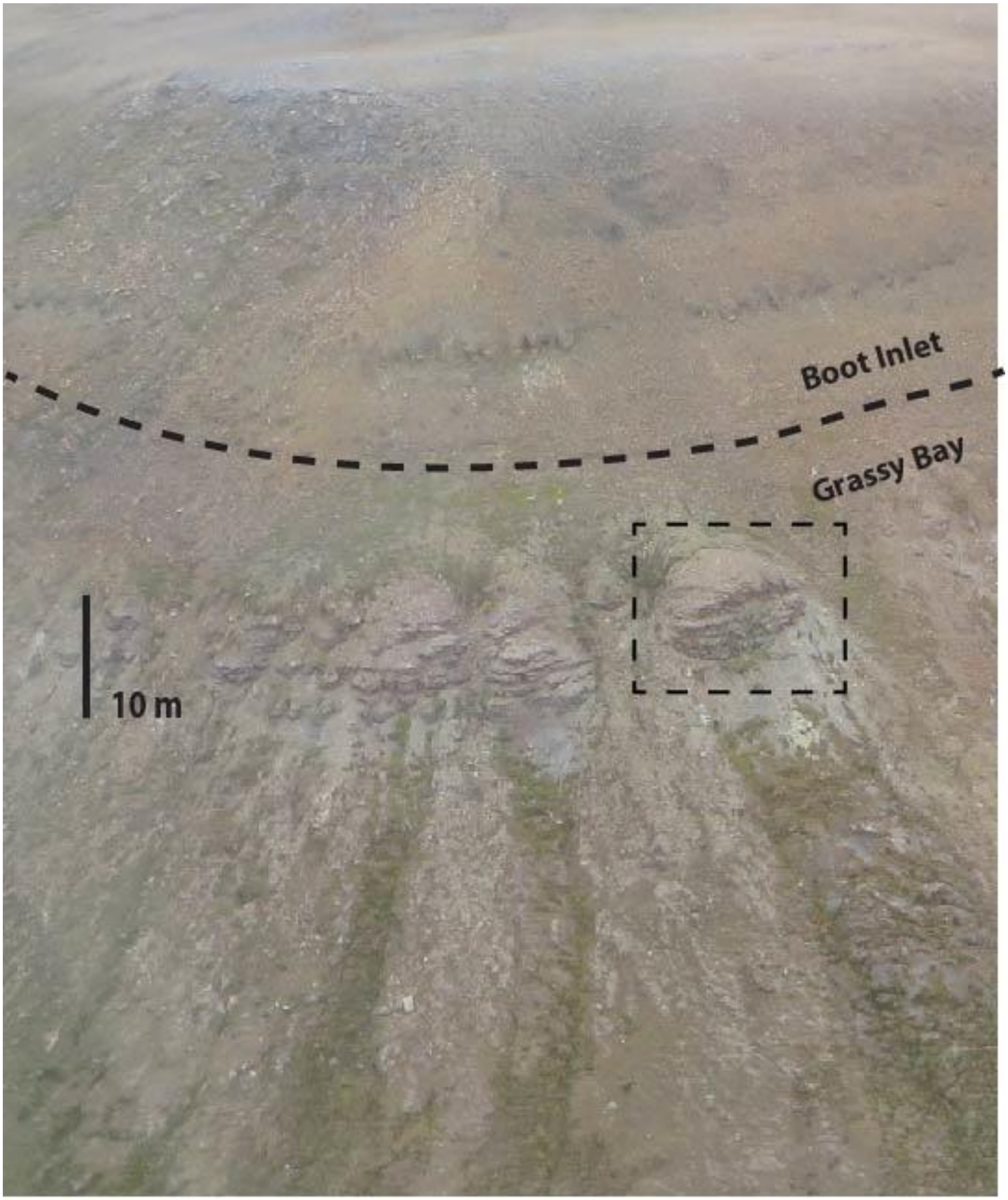

Figure 8: Exposure of the Grassy Bay and overlying Boot Inlet formations, referred to as stratigraphic Section 9. Dashed rectangle indicates location of outcrop in Figure 9.

Figure 9: Outcrop of Grassy Bay Formation. Jacob's staff is 1.5 m tall.

Interpretation

The poor quality of exposure makes it difficult to contribute a comprehensive interpretation of the depositional environment of the Grassy Bay Formation as compared to the type area in the Minto Inlier, where it has been interpreted to represent a prograding delta overlain by fluvial deposits that then experienced transgression and storm reworking (Rainbird et al., 1994; Morin and Rainbird, 1993; Rainbird, 1992; Young and Long, 1977). Exposures at Section 9 and elsewhere give the impression of upward coarsening, supporting the prograding delta interpretation; but cross-bedded sandstones with unidirectional paleocurrents, indicative of fluvial deposition, are absent from the Brock Inlier. Wavy-lenticular-bedded sandstones in the upper part of the section indicate reworking of terrigenous detritus by tidal currents in relatively shallow water. Evidence of storm reworking is supported by the presence of hummocky cross-stratification just below the contact with the Boot Inlet Formation.

Boot Inlet Formation

The Boot Inlet Formation is well exposed in the Brock Inlier, and eight of the ten stratigraphic sections in this report contain portions of it. It is predominantly located along the Hornaday River (north of Uyarsivik Lake) and along the Roscoe and Little Hornaday rivers and their respective tributaries (Figure 3). Exposures are also observable along the Amundsen Gulf coast, north of Hornaday Lake. The following text is divided into part 1, which describes the lithofacies and facies associations; and part 2, which describes the stratigraphy.

Lithofacies descriptions

The Boot Inlet Formation is subdivided into eight distinct lithofacies summarized in Table 1, using the Dunham classification system (Dunham, 1962), supplemented with the term “calcisiltite” denoting mechanically transported allochems between ~5 - 62.5 µm after Kay (1951).

Table 1: Facies descriptions of the Boot Inlet Formation

Facies	Lithology	Sedimentary Structures	Additional Features	Depositional Environment
1. Stromatolite biostrome	Dolostone	Large domal to tabular morphology tens of meters thick, thickly bedded	Laminations with high Fe oxide/organic content interbedded with fine crystalline dolomite (<62um)	Mid-ramp, above storm wave base
2. Stromatolite bioherm	Dolostone	Domal features approximately 2 m across, laterally discontinuous	Medium-coarse dolomite crystals	Inner-ramp, shallow water above fair-weather wave base.
3. Intraclastic grainstone/rudstone	Limestone-dolostone	Framework supported stromatoclasts	Framework supported. Crystal size of cements differs from that of allochems when recrystallized to dolostone	Inner-, mid-ramp, in close association with stromatolites
4. Ooid grainstone	Limestone-dolostone	Elongate intraclasts present, often cross-bedded. Stylolitized, locally compacted. Herring-bone cross-stratified near top of Boot Inlet Formation	Chert replacement some allochems are ghosts.	Inner-ramp, high-energy environment
5. Laminated mudstone with molar-tooth structure	Limestone-dolostone	Mudstone with molar-tooth structures (MTS) disrupting laminations. MTS are lighter colour than host, brecciated into elongate molar-tooth intraclasts (>2mm) that form interbeds.	Nodular pyrite	Inner- to mid-ramp, above storm wave base; low-energy environment aside from intermittent storm activity
6. hummocky cross-stratified calci/dolo-siltite	Limestone-dolostone	Hummocky cross-stratified (HCS) to planar cross-stratified silt-sized carbonate grains	Rare, thin detrital quartz horizons,	Mid-ramp, between fair-weather wave base, shallower than facies 5.
7. Dolo/lime mudstone	Limestone-dolostone	Laminations that have pinch-and-swell structures, organic rich.	Laminations with horizons rich in organic/Fe oxide content	Outer-ramp; below storm wave base
8. Shale	Mudrock, claystone	Laminations		Outer-ramp; below storm wave base. Deposition of terrestrial wash-load

Stromatolite biostrome (facies 1)

Description. Two thick stromatolite biostromes (sections 7 and 8) represent a laterally extensive reef structure that is correlatable throughout the Brock Inlier. Bedding is laterally extensive and tabular with thicknesses ranging from 0.3-2 m. At Section 7, biostromes have an uninterrupted thickness of approximately 85 m (Figure 10a). Stromatolite bioherms underlie and grade into thick, tabular biostromes. Stems are unbranching and resemble the morphology of *Baicalia* to *Jurusania* (Narbonne et al., 2000; Walter, 1972; Figure 10b, c). All observed biostromes in the Brock Inlier have been recrystallized to crystalline dolomite. Petrography reveals that laminations are steeply convex and typically are accentuated by organic matter or Fe-oxides. Minute amounts of detrital quartz (modal percentage < 5) are trapped within stromatolite laminations, but are more commonly observed above them. Horizontal stylolites following microbial laminations, or in the underlying beds, are common.

Figure 10: Facies 1 and 2 (stromatolite biostromes and bioherms). A: Sheets of tabular stromatolite biostromes; person for scale. B: Thickly bedded stromatolite biostrome, hammer for scale. C: Cross section view of stromatolites with morphology similar to *Jurusania,* (Walter, 1972). D: Top view of stromatolite (*Baicalia)*. Pencil, for scale, in figures C and D is about 12 cm long. E, F: Stromatolite bioherms, hammer and field book, for scale, are about 40 and 20 cm tall, respectively.

Interpretation. Stromatolite biostromes are interpreted to have been deposited as low amplitude sheets just below fair-weather wave base during periods of platform stability allowing complex regional biogenic structures to develop. When stromatolites grew above fair-weather wave base, constant wave agitation eroded their tops, supplying clasts (stromatoclasts) to the ramp.

The initial growth by isolated bioherms (Figure 10e) overlain by continuous stromatolite sheets (biostromes) is similar to what is described from the Boot Inlet Formation in the Minto Inlier by Narbonne et al. (2000). Their work likens the transition from mounds to sheets to “catch-up” reefs as described by Neumann and MacIntyre (1985). The low-amplitude domal morphology (~5 m synoptic relief) overlain by tabular sheets of columnar stromatolites observed at Section 8 (Appendix), resembles the shallowing-upward stromatolite cycles described from the Bitter Springs Formation in Australia by Southgate (1989), but in the Amundsen Basin this shallowing-upward pattern occurs on a much larger scale. These previous interpretations suggest that the change in morphology of microbial communities preserved in these stromatolites represent shallowing. Topographic relief of the largest complexes, in the Minto Inlier, was interpreted by Narbonne et al. (2000) to be no greater than 3-5 m in the Minto Inlier and this is supported in the Brock Inlier where the synoptic relief is no more than 5 m. Collectively, this implies that, while these reefs were regionally extensive and thick, they likely did not form restrictive barriers.

Stromatolite bioherms (facies 2)

Description. Bioherms are ~1-3 m in diameter, outcropping as resistant, rounded mounds with ~0.3-1 m synoptic relief, composed of columnar stromatolites. They are observed at the base of Section 3 (Appendix), the middle of sections 7 and 8 and the top of sections 4 and 10 (figures 10e, f). Individual stromatolites resemble *Tungussia* as described by Walter (1972), while areas between bioherms are infilled with grainstone/rudstone facies composed of stromatoclasts (Figure 11b), and ooids.

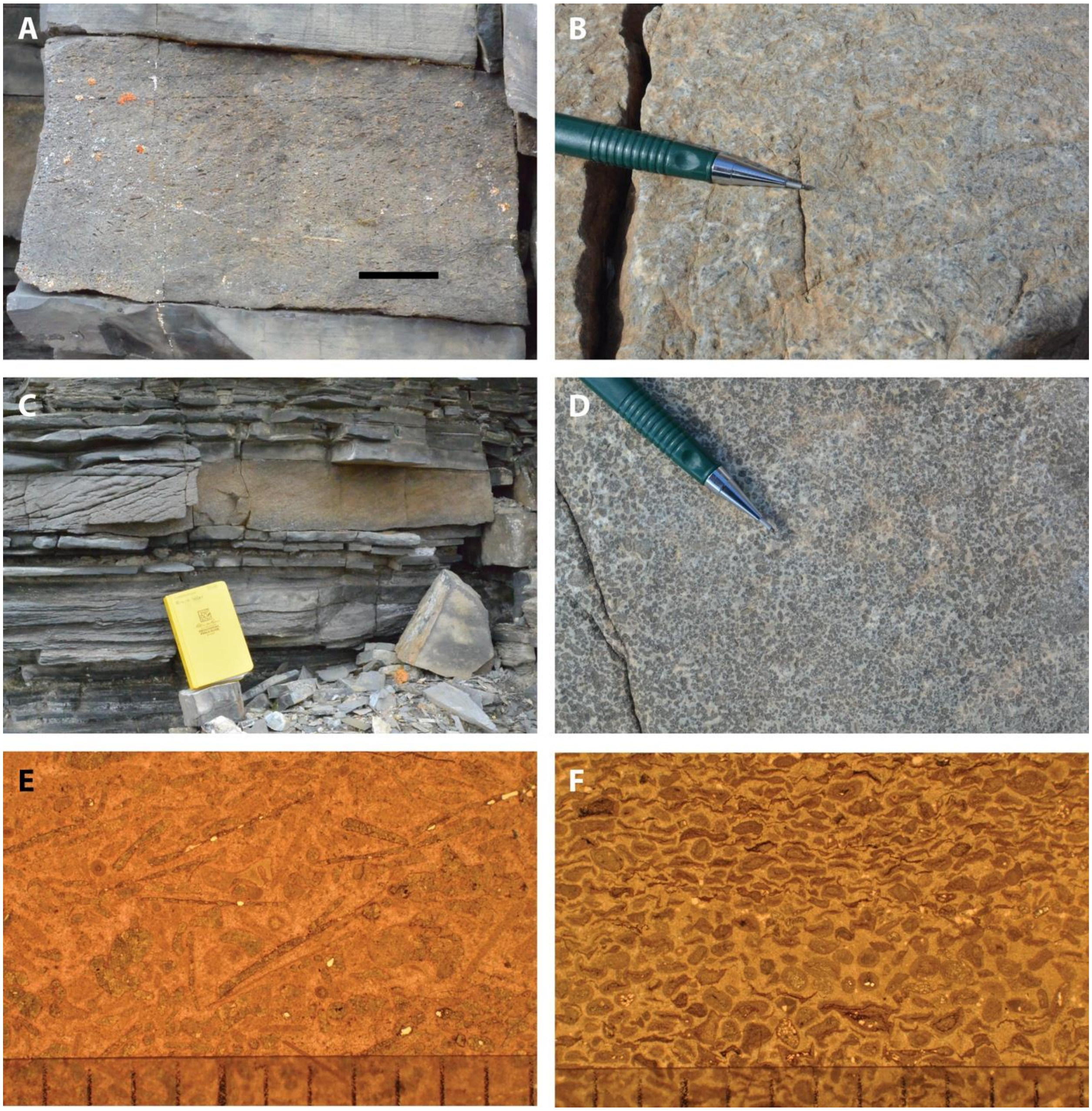

Figure 11: Facies 3 and 4 (Intraclast grainstone/rudstone and ooid grainstone). A: Intraclast grainstone, scale bar is 4 cm. B: Plan view exposure of intraclast rudstone facies with visible stromatoclasts. C, D: Cross section and plan view exposures of ooid grainstone facies. Pencil, for scale in figures B and D is about 12 cm long and field book is about 20 cm tall in figure C. E: Thin-section photo of intraclast rudstone. F: Ooid grainstone showing

"elephant parade" fabric (Scholle and Ulmer-Scholle, 2003). Scale divisions in E and F are 1 mm.

Interpretation. Bioherms are interpreted to have formed in a shallow, inner-ramp depositional environment. They are observed to be overlain by deeper water facies, and two responses to sea-level rise are observed. At the base of Section 3, infill by normally graded sediments overlain by clays suggests the bioherms were drowned, too quickly for stromatolite growth to continue. The lack of karsting indicates that bioherms were never subaerially exposed, or only briefly, if they were. Bioherms at sections 7 and 8 are overlain by biostromes (facies 1) likely representing a rise in sea-level, but a gradual one that facilitated the growth of biostromes. Facies overlying bioherms in the Brock Inlier are interpreted to reflect different rates of sea-level rise.

Intraclast rudstone (facies 3)

Description. Intraclast rudstone facies, best observed at the base of Section 3, is characterized by medium- to thickly bedded, commonly dune cross-stratified ooidic stromatoclast rudstone (Figure 11a, b, e). Allochems are randomly oriented and framework-supported. Isopachous cements are commonly visible where rocks have not been dolomitized; remaining voids are filled with equant, blocky calcite cement. Intraclast rudstone facies is most commonly associated with facies 2.

Interpretation. This poorly sorted facies contains the largest allochems observed in the Boot Inlet Formation, and is dominated by clasts interpreted to be shed from stromatolites. Above fair-weather wave base (FWWB), bioherms would be subject to constant wave agitation as would biostromes, if they aggraded to this zone, resulting in the shedding of stromatoclasts. The fragility of grains, paired with the lack of a consistent orientation suggests that stromatoclasts mixed with ooids during storms but later reworking was minimal. Deposition of intraclast rudstone facies would have occurred very close to stromatolites, mostly in inner-ramp to the uppermost mid-ramp depositional environments.

Ooid grainstone (facies 4)

Description. Ooid grainstone facies, composed of ~1 mm ooids, is best observed at sections 3, 4 and 5 (figures 11c, d, f). Rare stromatoclasts, detrital quartz, and aggregates of small ooids are present. Beds vary in thickness between approximately 5 and 30 cm and generally are cross-stratified (Figure 11c). Certain horizons display “elephant parade” fabric (Figure 11f) as described by Scholle and Ulmer-Scholle (2003). In Section 5, ooids are rarely replaced by mimetic chert.

Interpretation. Ooid grainstone facies would have been deposited in an inner-ramp setting above the FWWB. The formation of ooids relies on tides or wave agitation, in warm seawater highly saturated with calcium carbonate (Flugel, 2004). Rare remineralization of ooids to chert preserves their concentric laminations (Section 5), as does early mimetic dolomitization (Section 9-see Appendix). Silicification, if occurring during early diagenesis, may imply that a range of fluid compositions persisted (Manning-Berg and Kah, 2017). Ooid grainstone facies is less common in the Brock Inlier than in the Minto Inlier (cf. Morin and Rainbird, 1993), and does not form thick beds, potentially due to unfavourable seawater chemistry for the precipitation of concentric laminations, or a lack of strong tidal currents or wave-energy.

Molar-tooth mudstone (facies 5)

Description. Molar-tooth mudstone facies is very common in the Boot Inlet Formation in the Brock Inlier and is observed at sections 3, 4, 6, 7, 8, and 10. This facies consists of small ptygmatically folded, light-coloured molar-tooth structures (MTS) hosted in laminated lime- or dolomudstone composed of rounded grains (4-15 μm in diameter; Figure 12f) with rare framboidal pyrite. MTS are filled with coarse, white calcite spar or fine (4-15 μm) rounded grains of calcite and are commonly recrystallized to crystalline dolomite. Laminated mudstone layers are interbedded with 5-50 cm thick massive to cross-bedded rudstone beds with erosive basal contacts, composed of elongate, poorly sorted, MTS clasts (Figure 12a). Grain size in the host rock of molar-tooth mudstone does not vary greatly; laminations are visible due to the presence of dark interstitial organic material along laminations. Molar-tooth mudstone facies is observed in close association with or is interbedded with thin shaley units (Figure 12c), as well as stromatolitic bioherms and biostromes.

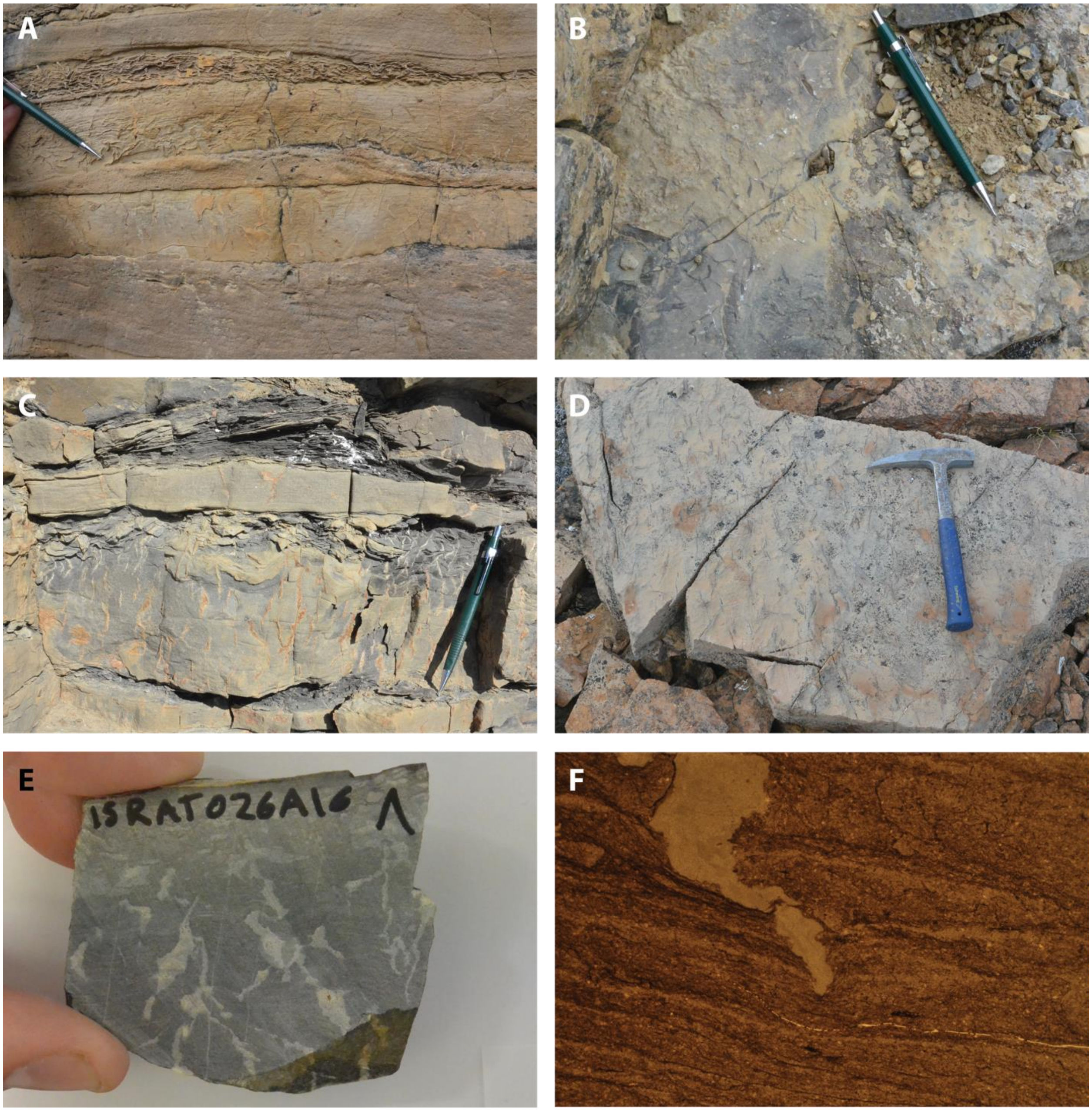

Figure 12: Facies 5 (molar-tooth mudstone). A: Molar-tooth mudstone interbedded with cross-bedded molar-tooth clast rudstone. B, D: Plan view exposure of molar-tooth structure. C: Molar-tooth mudstone facies overlain by shaley interval. Pencil, for scale, in figures A, B and C is approximately 12 cm long and hammer in figure D is approximately 40 cm long. E: Hand sample showing ptygmatically folded molar-tooth structure, width of sample is approximately 8 cm. F: Thin section photo of molar-tooth structure, field of view is about 2 cm.

Interpretation. Molar-tooth structure is an enigmatic feature and its origin has been debated for over a century. A detailed review on their occurrence as well as their temporal and paleoenvironmental significance is given by James et al. (1998). Possible interpretations include seismically induced fluid escape structures (Pratt, 1999) or biogenically induced gas-expansion cracks (Furniss et al., 1998). The Boot Inlet Formation was deposited within a very stable intracratonic basin and given that there are no other structures representing seismic activity, the latter hypothesis is favoured, although minor seismic activity could have acted as a catalyst for their formation. MTS does not appear to form when the host rock's grain size exceeds approximately 15 µm.

The presence of MTS-clast rudstone interbeds with erosive contacts suggest molar-tooth mudstone facies must have formed above storm wave base. Given their close association with shallow-water deposits (facies 2, 3, and 4) and facies deposited below SWB the depositional environment of molar-tooth mudstone facies appears to range from SWB to FWWB. MTS is interpreted to have lithified prior to lithification of the host muds, as they are preserved as clasts in rudstone interbeds.

Hummocky cross-stratified calci/dolosiltite (facies 6)

Description. This facies is common at sections 3, 4, 5 and 9 and is composed of limestone, or mimetic and fabric destructive dolomite, expressing ripple, dune and hummocky cross-stratification (HCS), (Figure 13a, b, c). Weathered, dolomitized surfaces have an orange cast and primary structures are difficult to discern. Well-preserved specimens that are composed of calcite or that have been recrystallized by fabric-retentive dolomite show rounding of small, silt- to sandsized grains. MTS is distinctly absent from this facies. Siltite locally contains small ooids (<1mm) at Section 9, forming wackestone and packstone fabrics (Figure 13f).

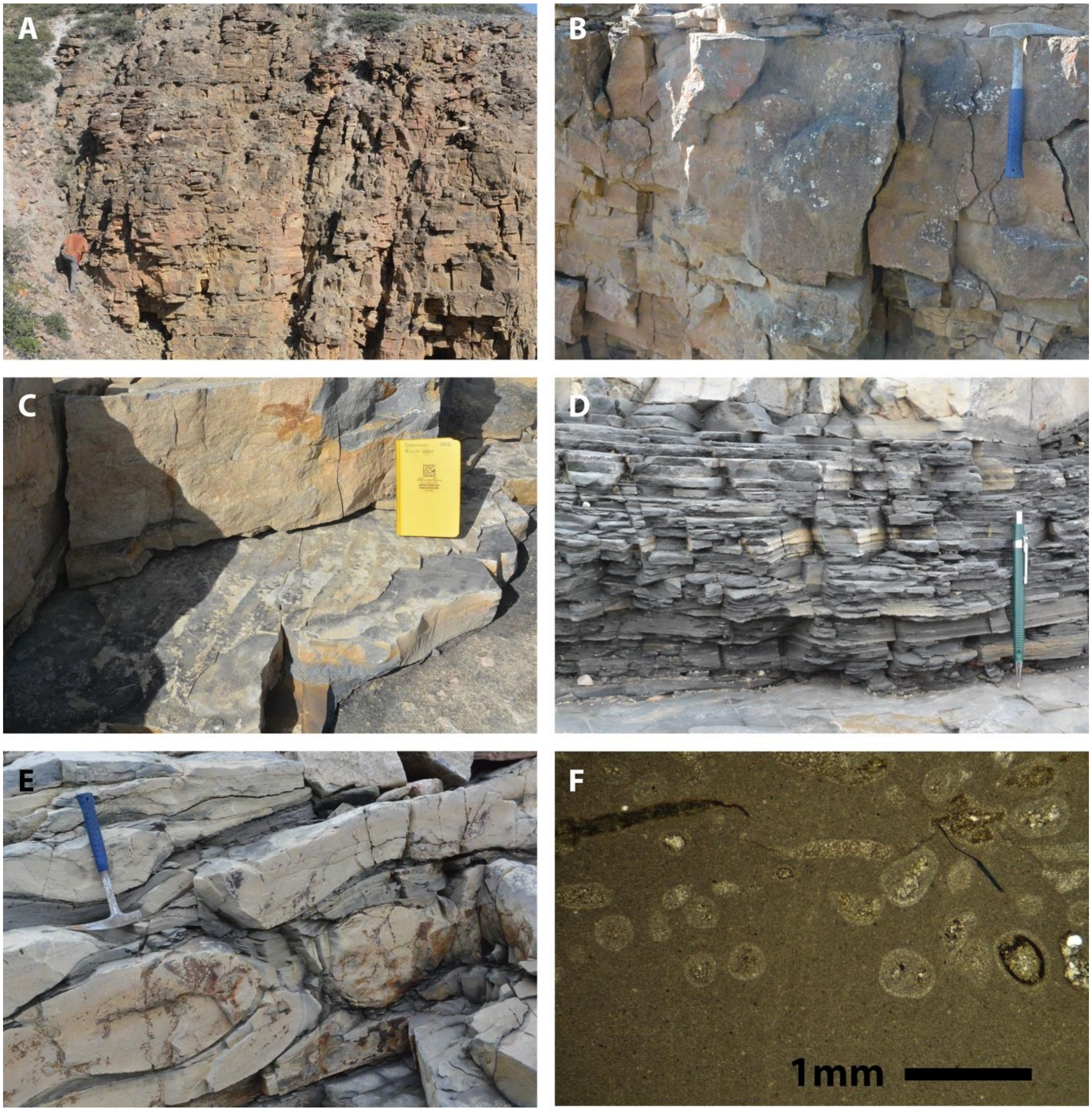

Figure 13: Facies 6, 7 and 8 (Hummocky cross-stratified calci/dolosiltite and laminated mudstone facies interbedded with shale. A: Outcrop of facies 6, person for scale. B: Thickly bedded doloarenite, hammer, for scale, is about 40 cm long. C: Plan view exposure of dolosiltite with rippled tops. D: Laminated dolomudstone interbedded with shale. Pencil, for scale, is about 12 cm long. E: Dolomudstone, expressing pinch-and-swell structures,

interbedded with shale. Hammer, for scale, is approximately 40 cm long. F: Ooid wackestone in thin section.

Interpretation. Facies comprising predominantly hummocky cross-stratified siltite suggests a depositional environment influenced by storm activity. MTS is absent, the formation of which is interpreted to be inhibited by larger grain size. Allochems are interpreted to have been sourced from stromatolites and mixed with silt-sized material, including ooids that were deposited on the upper-mid to inner-ramp.

Laminated mudstone (facies 7)

Description. Facies 7 is uncommon in the Boot Inlet Formation but it is best observed at the base of Section 4 (Appendix), where it is approximately 5 m thick (Figure 13d). It is composed laminated carbonate mudstone (grain size <5 um), that lack MTS and wave-generated structures. Colour variation between laminations is observed to be caused by organic matter in the matrix, rather than a change in grain size. Primary fabrics have been erased by the growth of fine, crystalline dolomite. Pinch-and-swell structures (Figure 13e) occur in this facies and are observed near the bases of sections 3 and 4.

Interpretation. Laminated mudstone facies would have been deposited on the outer ramp below storm wave base, in the lowest-energy depositional environment of the Boot Inlet Formation. This is supported by the fine grain size and the lack of any wave generated structures.

Shale (facies 8)

Description: This facies is rare in the Boot Inlet Formation and is characterized thin interbeds, best exposed at the base of sections 3 and 4. Green, friable claystones, observed at Section 3, are also included in this facies. Shale facies is commonly associated with laminated mudstone (facies 7), and rarely with molar-tooth mudstone (facies 5). Shale facies weathers very recessively.

Interpretation: Shale facies occur as thin, compressed layers between facies 7 and in close association with molar-tooth mudstone facies. It is interpreted to represent fine, terrigenous, wash-load sediment that was transported offshore, eventually settling in the low-energy, outer-ramp environment through suspension fallout below SWB.

Lithofacies associations

The geographic setting of the Shaler Supergroup is interpreted to be an embayment of a larger intracontinental sea within the supercontinent, Rodinia (Figure 1; Young, 1981). Facies assemblages reflect deposition around the periphery of the embayment, the area constantly was affected by tides, storms and wind-generated waves comprising the inner-ramp (facies association 1); areas where water was calm, aside from periodic storm activity (facies association 2), and the outer-ramp position (facies association 3), that was not influenced by these processes (Figure 14).

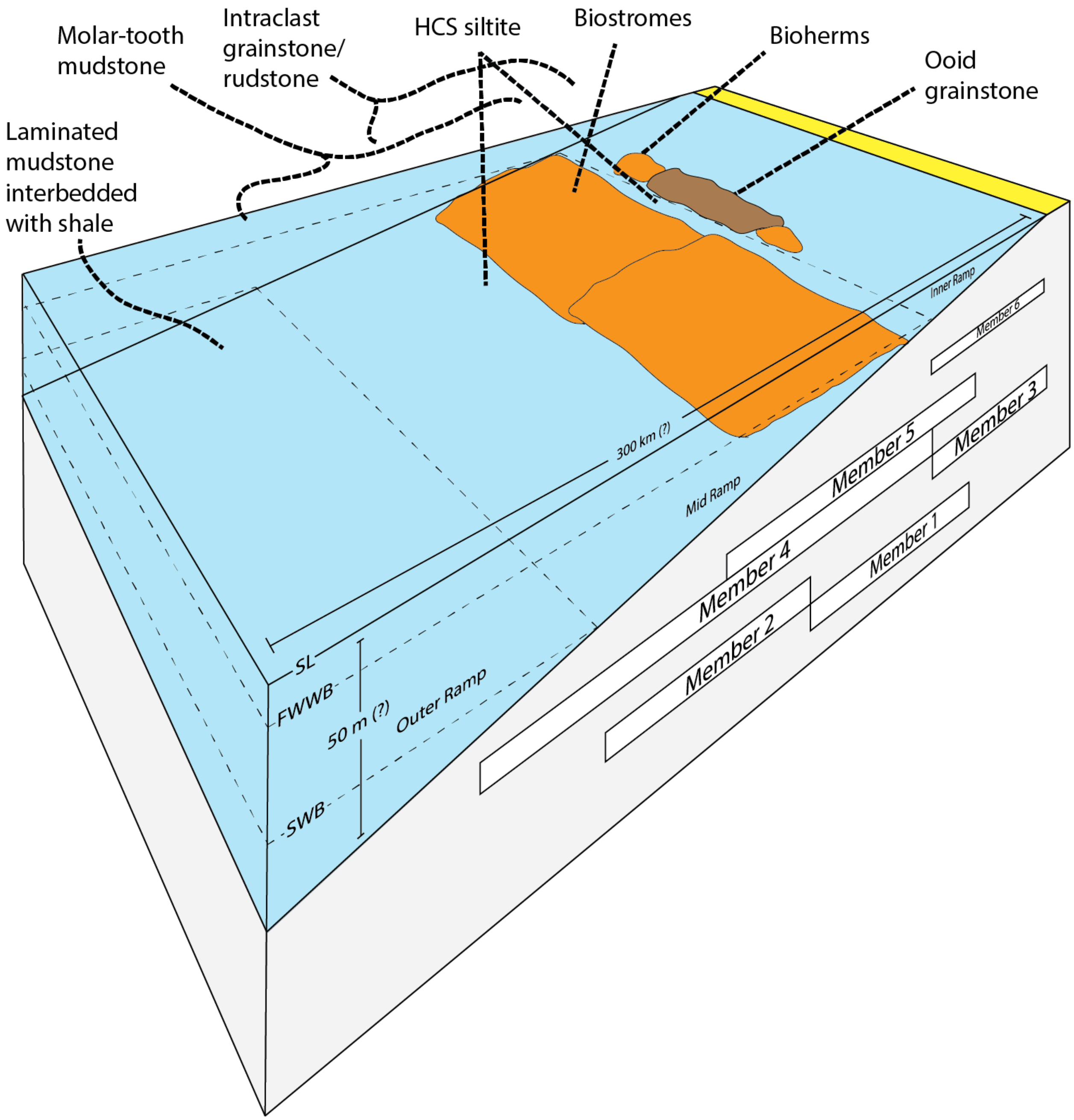

Figure 14: 3D depositional model of the Boot Inlet Formation.

Facies association 1: Inner-ramp

The inner-ramp would have been subject to constant wave agitation and represents the area located between upper shoreface and fair-weather wave base (Burchette and Wright, 1992). Stromatoclasts (facies 3) and ooids (facies 4), comprise the dominant allochem types. Early-cemented substrates or topographic highs would have been colonized by stromatolite bioherms, which shed stromatoclasts during storm-surges. Some of these clasts would have lithified quickly, forming facies 3, whereas many were broken down into sand- and silt-sized carbonate clasts and transported to the mid-ramp. Bioherms may have caused local restriction, although channelized sediments between them are observed, suggesting that water flowed freely between environments (Figure 15). The inner-ramp is also interpreted as entirely subtidal, as there is no evidence of subaerial exposure, such as desiccation cracks or evaporites.

Figure 15: Facies association 1: inner-ramp. Stromatolite bioherms (orange outline) surrounded by inter-reef channels (yellow). Hammer, for scale, is approximately 40 cm long.

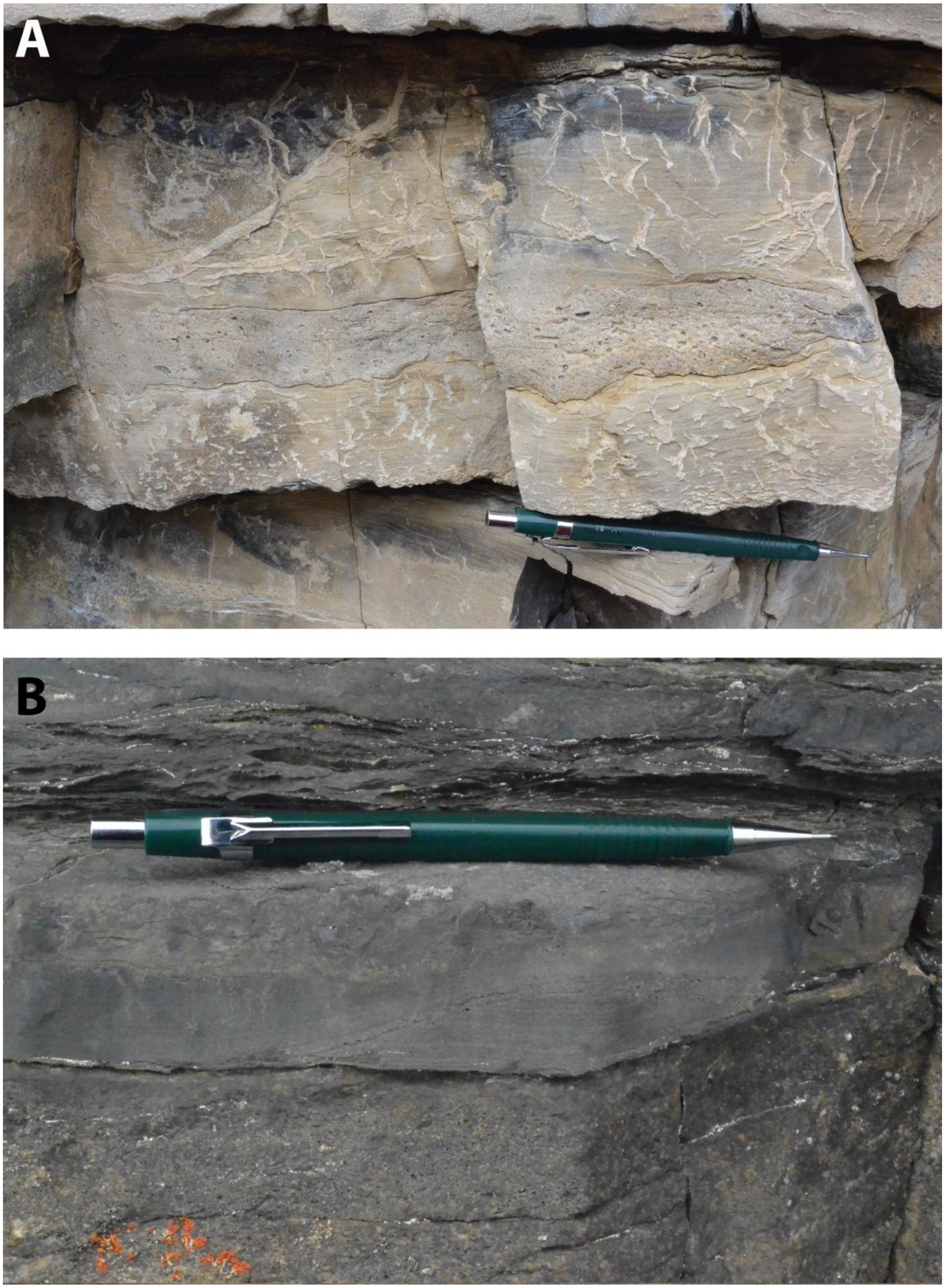

Figure 16: Facies association 2: mid-ramp. A: Molar-tooth mudstone interbedded with molar-tooth clast rudstone. B: HCS calcisiltite overlying ooid grainstone. Pencil, for scale, is about 12 cm long.

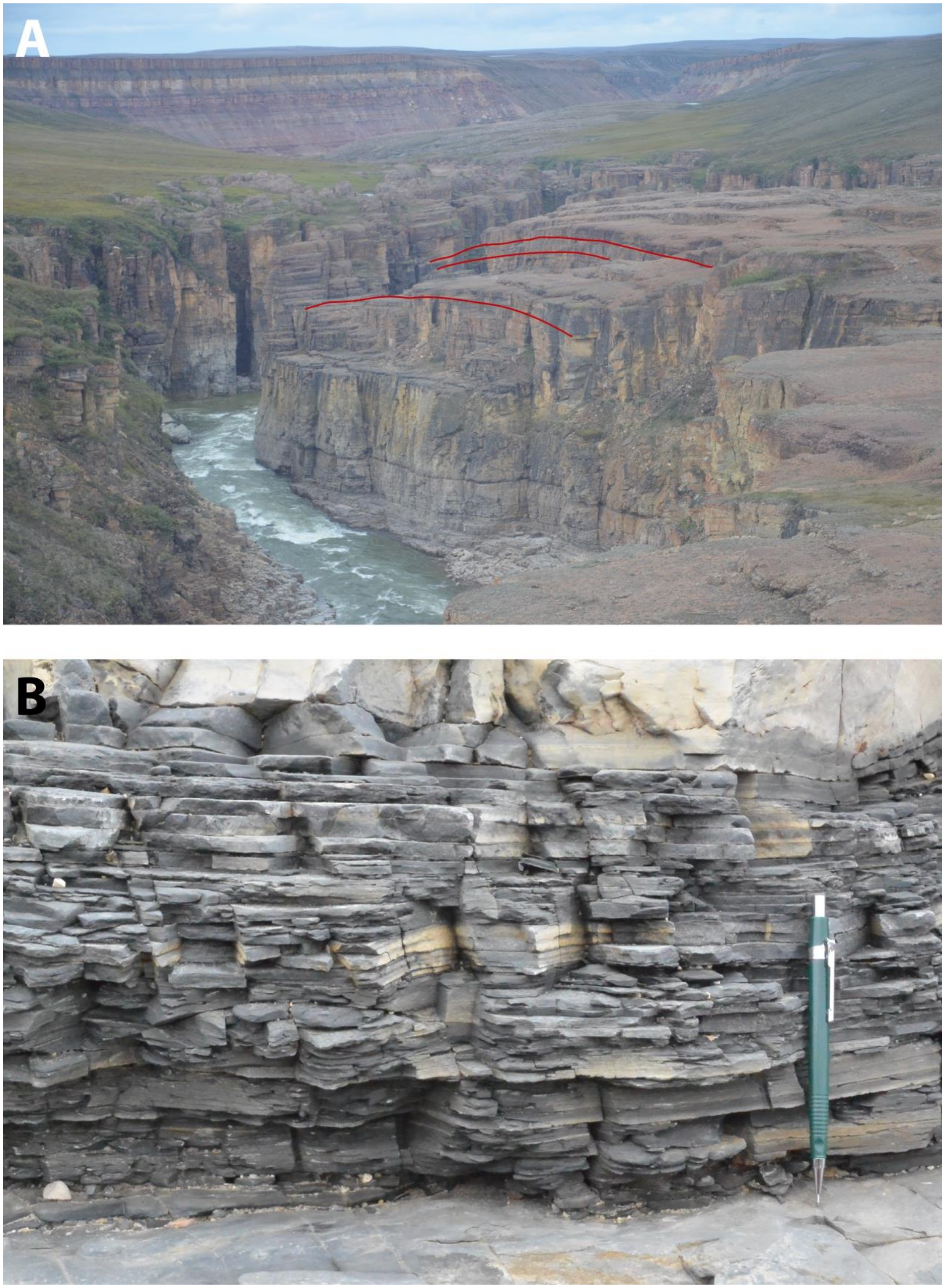

Figure 17: Facies associations 2 and 3 (mid- and outer-ramp). A: Large, low-amplitude stromatolite biostrome; height of broad domes is approximately 5 m. B: thinly laminated dolomudstone interbedded with shale. Pencil, for scale, is about 12 cm long.

Facies association 2: Mid-ramp

Molar-tooth mudstone (facies 5; Figure 16a), and hummocky cross-stratified calcisiltite (facies 6; Figure 16b) and stromatolite biostromes (facies 1: Figure 17a), comprise facies association 2 (Figure 14). The mid-ramp facies association would have been reworked by storms and swells and represents the area on the ramp between fair-weather wave base and storm wave base (Burchette and Wright, 1992).

The stromatolitic portion of the mid-ramp facies association is observed at sections 7 and 8 and is composed of facies 1 representing large, regionally extensive biostromes (Figure 17a). They are observed stratigraphically above stromatolite bioherms, and are interpreted to represent table reefs as described by Narbonne et al. (2000). Their position on the ramp is constrained to below fair-weather wave base as it is interpreted that constant wave agitation would erode the microbial films of biostromes. Given the great thickness (~90 m) and lateral extent of the biostromes, they must represent long periods of relatively calm water and platform stability. These reefs show great affinity to the "type 4" stromatolite boundstone facies reported in the platformal assemblage of the Little Dal Group from northwestern Canada, interpreted to have formed in quiet water conditions along the mid-ramp (Batten et al., 2004). The increased turbidity and unconsolidated substrates resulting from mud suspended in the water column may have also had detrimental effects on the nucleation and growth of stromatolites, which implies that they were most prolific during periods of decreased carbonate production (Sherman et al., 2000). Periods of platform stability would have facilitated the formation of complex microbial structures for long periods of time and constant wave agitation would have planed their tops when they aggraded above fair-weather wave base (Southgate, 1989). During relative sea-level rise, the morphology *Jurusania* became dominant. Once stromatolite biostromes were established on the ramp, they kept pace with sea-level rise.

The distal portion of the mid-ramp facies association (Figure 14) is composed of facies 5 (molar-tooth mudstone facies) and facies 6 (hummocky cross-stratified calcisiltite facies). HCS calci-dolo-siltite grades offshore into molar-tooth mudstone facies. Molar-tooth mudstone facies is observed in association with outer-ramp deposits (facies association 3) suggesting that they were deposited close to storm wave base. During storms, semi-consolidated carbonate mud containing MTS were reworked into molar-tooth clast rudstone interbeds. Mid-ramp deposits are interpreted to have been sourced from stromatolites, being mechanically transported during storm activity and reworked into facies 5 and 6.

Facies association 3: Outer-ramp

Facies association 3 is composed of facies 7 and 8 and is characterized by very fine grain sizes, thin, parallel laminations and no wave or molar-tooth structures (Figure 17b), implying low rates of sedimentation, below storm wave base. It is not volumetrically abundant but occurs above facies association 1 (at the base of Section 3) and facies association 2 (at the base of Section 4), the latter occurrence representing part of an overall rapid shallowing from outer- to mid- to inner-ramp deposits. The lack of wave structures in facies association 3 implies a very quiet-water depositional environment, below storm wave base, representing the deepest water depositional environment recorded by strata of the Boot Inlet Formation in the Brock Inlier (Figure 14).

Lithostratigraphic members of the Boot Inlet Formation

The Boot Inlet Formation can be subdivided into six distinct, informal stratigraphic members that are easily recognizable in the Brock Inlier (Table 2). The Boot Inlet Formation is mainly exposed in cliff sections along the Hornaday, Little Hornaday and Roscoe rivers and at coastal cliff sections along the Amundsen Gulf; plan view exposures are very limited. Thick tabular-bedded stromatolitic dolostone of the *second stromatolite member* is prominent throughout the inlier, acting as a useful stratigraphic marker. The stratigraphic record of the Boot Inlet Formation in the Brock Inlier is summarized into an approximately 400-metre-thick composite section with small gaps of estimated thicknesses (Figure 18). The lower contact with the Grassy Bay Formation is gradational, although it is recessive. The upper contact with the Fort Collinson Formation was not observed; instead, the upper part of the formation is disconformably overlain by the Cambrian Mount Clark Formation.

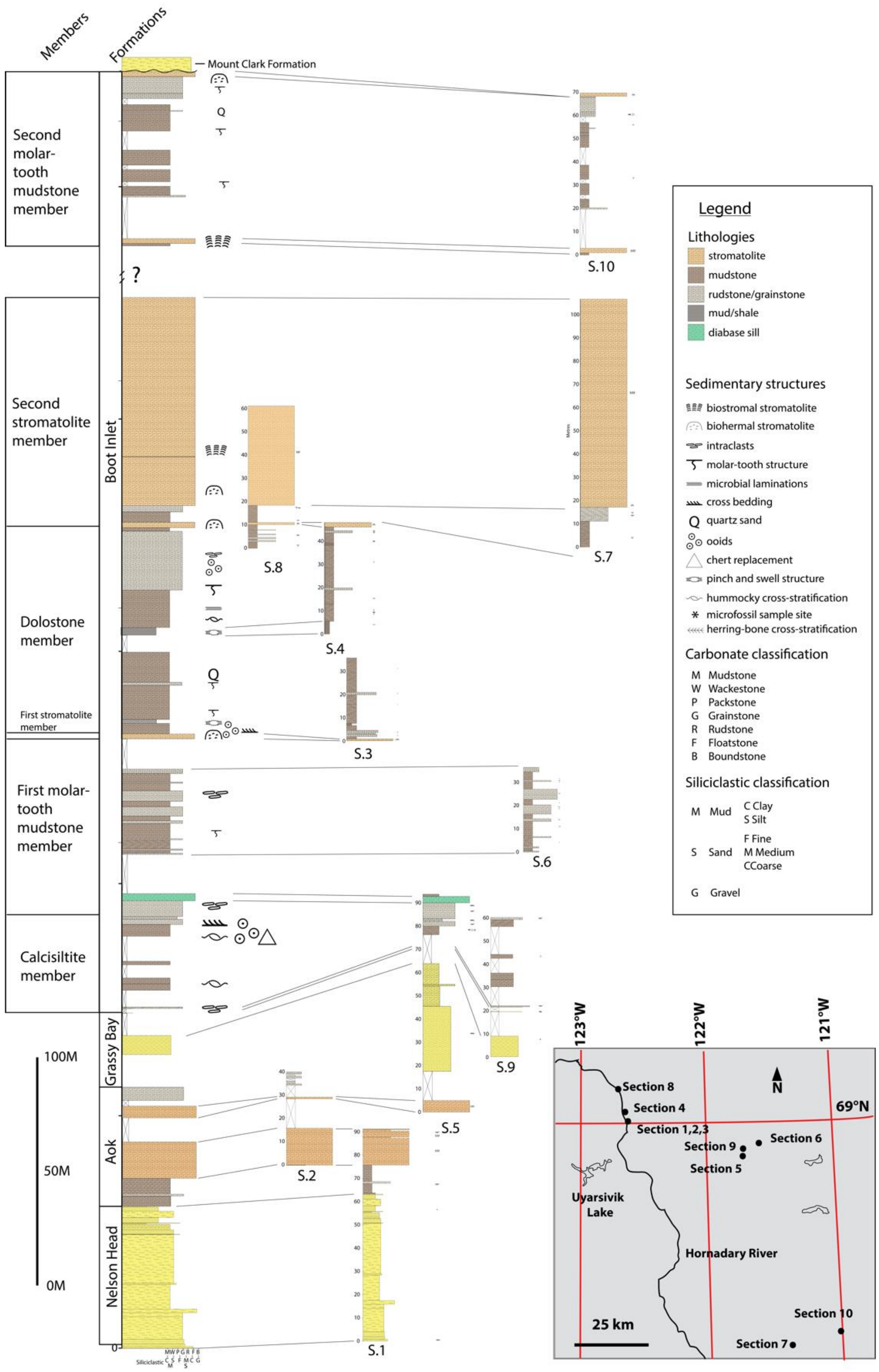

Figure 18: Correlation of measured sections in the Brock Inlier.

Table 2: Summary of informal stratigraphic members of the Boot Inlet Formation in the Brock Inlier. Members are presented in ascending stratigraphic order. See Figure 18 for composite stratigraphic section.

Member	Lithology	Basal Contact	Thickness
Second molar-tooth mudstone member	Biohermal stromatolites at base and top. Lime/dolomudstone with abundant molar-tooth structure is dominant. Herring-bone cross-stratification and detrital quartz content increase upwards	Not exposed	~70 m at section 10
Second stromatolite member	Basal part of unit is composed of stromatolite bioherms that are overlain by molar-tooth mudstone facies. Thickly bedded stromatolite biostromes comprise the upper 70 m	Conformable, gradational	~90 m at section 7
Dolostone member	Predominantly orange, fabric-destructive dolostone. Basal interval characterized by greenish claystones. 5 metres of thinly laminated dolomudstone containing pinch-and-swell structures is observed about 25 metres from the base. Overall upward decrease in shale interbeds. Microbialites, and grainstone facies become more abundant near the top	Sharp, most likely representing a drowning unconformity	~80 m at section 3 and 4
First stromatolite member	Bioherms with inter-reef channels composed of grainstone. Beds of intraclast rudstone, ooid grainstone with abundant cross-stratification	Not exposed	≤5 m at section 3
First molar-tooth mudstone member	Molar-tooth mudstone interbedded with intraclast rudstone/ grainstone facies. Thickly bedded intraclast rudstone at base	Gradational	~40 m at section 6
Calcisiltite member	Hummocky cross-stratified calcisiltite. Basal interval contains quartz silt/arenite interbeds; ooid packstone/grainstone facies interbedded near the top	Erosional contact with Grassy Bay Formation	~40 m at section 9

Description

The *calcisiltite member* is an approximately 40 m thick, recessively weathering unit, that is best exposed at Section 9, where it gradationally overlies the Grassy Bay Formation. Its basal interval is a dolomudstone-intraclast conglomerate that is also observed in the Minto Inlier (Morin and Rainbird, 1993; Young and Long, 1977). In the Brock Inlier, dolomudstone intraclasts are faintly laminated. This conglomerate is overlain by calcisiltite and dolosiltite (facies 6), interbedded with hummocky cross-stratified, fine grained quartz arenite. Upsection, quartz sand content diminishes and ooid wackestone and grainstone interbeds (facies 4) become more abundant. This transition is observed at Section 5 (Appendix), where the *calcisiltite member* is erosionally overlain by molar-tooth-clast rudstone beds characterizing the *first molar-tooth mudstone member*.

The *first molar-tooth mudstone member* was observed at sections 5 and 6, and has an inferred thickness of approximately 70 m in the Brock Inlier, although it is not fully exposed (Figure 18). The base of the *first molar-tooth mudstone member* is exposed at Section 5, where it capped by a diabase sill. Using the sill as a stratigraphic marker, it can be followed towards Section 6 (Appendix), and used to infer that there is a stratigraphic gap between the sill and overlying strata at Section 6 interpreted to be less than 20 m. Section 6 is approximately 40 m thick and comprises molar-tooth lime mudstone cyclically interbedded with molar-tooth-clast rudstone (facies 5).

The *first stromatolite member* is exposed at the base of Section 3, along the Hornaday River (Figure 15a), but its contact with the underlying *first molar-tooth mudstone member* is not exposed. The *first stromatolite member*, a thin unit of approximately 5 m, is composed of laterally linked metre-scale bioherms composed of resistant stromatolites resembling *Baicalia*. Bioherms are surrounded by ooid grainstone facies with symmetrical wave-rippled tops, and stromatoloclast rudstone facies. These facies are preserved as tabular beds and inter-reef channels. The *first stromatolite member* is abruptly overlain by the *dolostone member*.

The *dolostone member* is approximately 70 m thick, with the lower portion being exposed at Section 3, and the upper portion at Section 4. This member is characterized by orange-weathering fabric-destructive dolostone with irregular bedding thicknesses, and MTS is locally evident on fresh surfaces. Its basal interval consists of thinly laminated green claystone interbedded with shale, with abundant pinch-and-swell structures (Figure 13e). The base of Section 4 begins with 5 m of rhythmically laminated dolomudstone facies with pinch-and-swell structures (facies 7). This is overlain by interbedded hummocky cross-stratified calcisiltite (facies 6), molar-tooth mudstone (facies 5), microbialites and ooid grainstone (facies 4), characteristic of the inner- and mid-ramp facies associations. The top of the *dolostone member* is abruptly overlain by the *second stromatolite member*.

The *second stromatolite member* is a resistant, well-exposed unit that serves as a prominent stratigraphic marker in the Brock Inlier. It was measured at sections 7 and 8 but is present throughout the inlier (Figure 10a, 17a). At Section 8, 2 m of stromatolite bioherms (facies 2) are overlain by 5 m of molar-tooth mudstone facies (facies 5), with abundant small-scale cross-bedding in the molar-tooth clast rudstone interbeds. These are, in turn, overlain by a thick (at least 85 m at Section 7 (Appendix), domal to tabular-bedded, stromatolitic reef complex (facies 1). Reefal morphology shifts upsection from metre-scale bioherms (facies 2) to larger low amplitude domal structures with widths exceeding 500 m (Figure 17a) into flat, tabular biostromes (Figure 10a). Bioherms and domal reefs are composed of stromatolites with the morphology of *Baicalia*, that grade upwards into tabular biostromes containing stromatolites with the morphology of *Jurusania* (Walter, 1972; Figure 10c). Tabular-bedded biostromes cap the top of sections 7 and 8. There is a vertical gap of approximately 100 m between the *second stromatolite member* in Section 7 and the overlying *second molar-tooth mudstone member* at Section 10 (Appendix). This unobserved portion of the succession is roughly correlative with the second ooid and fourth rhythmite submembers from the Minto Inlier as described by Morin and Rainbird (1993).

The *second molar-tooth mudstone member* is only exposed at Section 10, where it is approximately 70 m thick, weathers recessively, and is disconformably overlain by the Mount Clark Formation. The contact with the underlying member is not exposed and the basal interval is composed of dolomudstone, overlain by approximately 3 m of poorly preserved stromatolite bioherms (facies 2). An 18 m covered interval separates these stromatolites from an overlying unit of interbedded molar-tooth lime- and dolomudstone. Detrital quartz sand content increases upsection within the dominantly carbonate facies as herring-bone cross-stratified ooid grainstone becomes more abundant near the top of this member. The last exposed portion of the *second molar-tooth mudstone member* is composed of 2 m of stromatolite bioherms.

Interpretation

The conglomerate at the base of the *calcisiltite member* is interpreted as a transgressive lag on the basis that it is regionally extensive, separates fluvial-deltaic siliciclastic deposits (Grassy Bay Formation) from carbonate rocks representing a deeper-water, mid-ramp depositional environment

(Boot Inlet Formation), and contains intraclasts derived from a deeper-water, outer-ramp setting. The succession from the Grassy Bay Formation to the top of the *first molar-tooth mudstone member* marks a shift to a fully marine carbonate ramp. The *calcisiltite member* reflects an abrupt decrease in siliciclastic sediment influx relative to carbonate sedimentation. The *first molar-tooth mudstone member* represents quiet-water deposition along the mid-ramp with frequent storm reworking as indicated by the accumulation of molar-tooth clast rudstone.

The *first stromatolite member* represents shallow water, relatively high-energy deposition based on the presence of abundant ooids, stromatolite bioherms and inter-reef channels characteristic of facies association 1. The transition from the *first molar-tooth mudstone member* is not exposed but it is interpreted as a progradation of the carbonate platform as molar-tooth mudstone facies aggraded toward sea-level, and facies stacking patterns display a shift from mid- to inner-ramp.

The transition from the *first stromatolite member* to the *dolostone member* is interpreted to represent a rapid sea-level rise that drowned stromatolite growth analogous to “give-up” reefs described by Neumann and MacIntyre (1985). The lower half of the *dolostone member* (exposed at Section 3), is composed predominantly of facies 5, 6, 7 and 8 representing mid- to outer-ramp deposition. At Section 4, planar and trough cross-bedding, as well as HCS in rudstone, become common upsection, as does detrital quartz and the occurrence of microbial laminites. An upward transition from facies association 3 to 2 to 1 through Section 4 represents an overall shallowing as the carbonate platform gradually prograded, eventually facilitating the development of inner-ramp stromatolite bioherms (facies 2) that mark the base of the *second stromatolite member*.

The *second stromatolite member* is laterally extensive across the Brock Inlier and represents the most prolific period of reef growth in the Boot Inlet Formation. Stepped table reefs that are observed at sections 7 and 8 resemble those which occur near the transition from inner- to mid-ramp from the Boot Inlet Formation in northeastern Minto Inlier (Narbonne et al., 2000). The change in reef morphology resembles stacking patterns observed in the Loves Creek Member of the Bitter Springs Formation in the Amadeus Basin of central Australia, where they are interpreted to represent upward shallowing (Southgate, 1989). Collectively, the shift from metre-scale bioherms (facies association 1), to molar-tooth mudstone facies to broad biostromes (facies association 2), is interpreted to represent an initial rise in sea-level and shift to a mid-ramp depositional environment during a period of platform stability capable of supporting a large, laterally extensive stromatolite reef complex. Subsequently, the shift from broad domal biostromes to tabular ones is interpreted to represent more rapid sea-level rise resulting in a “catch-up” reef as described by Neumann and Macintyre (1985).

There is a missing interval in the succession between the *second stromatolite member* and *second molar-tooth mudstone member*, inferred to be less than 100 m, that is represented in the Minto Inlier by ooid grainstone and rhythmite facies (Morin and Rainbird, 1992). Above this interval, increased quartz content, herring-bone cross-bedding and stromatolite bioherms comprise the *second molar-tooth mudstone member* and suggest shallow-water, higher-energy deposition characteristic of facies association 1. Herring-bone cross-bedded ooid grainstone facies are observed near the top of section 10 and resemble the third ooid submember in the Minto Inlier (Morin and Rainbird, 1993), likely indicating that Section 10 is very close to the upper contact with the Fort Collinson Formation, typified by herring-bone cross-bedded quartz arenite in the

Minto Inlier (Rainbird et al., 1994). The Fort Collinson Formation is not recognized in the Brock Inlier.

Lithostratigraphy of the Boot Inlet Formation reveals an initial, gradual progradation of the carbonate platform as siliciclastic input from the Grassy Bay Formation diminished during an overall sea-level rise. Facies association stacking patterns indicate that the platform then underwent four, upward-shallowing episodes that are correlatable to the four phases of progradation recorded in the Minto Inlier (Morin and Rainbird, 1993). The platform aggraded towards sea level in the fourth upward-shallowing cycle, siliciclastic input began to increase, resulting in deposition of the Fort Collinson Formation in the area now represented by the Minto Inlier.

Summary

Detailed lithostratigraphic studies of the Shaler Supergroup in the Brock Inlier contribute to the overall Neoproterozoic stratigraphic framework of northwestern Canada. Stratigraphic units reported here have previously been described in the Minto Inlier (Narbonne et al., 2000; Morin and Rainbird, 1993), and interpretations from the Brock Inlier generally agree with them, aside from some minor differences. The most apparent difference is the poor development of the Grassy Bay and Fort Collinson formations in the Brock Inlier relative to the type areas in Minto Inlier. This can be explained simply by a lack of terrigenous influx to that part of the Amundsen basin represented by the Brock Inlier. Notably, the Boot Inlet Formation, the primary focus of this work, contains thick stromatolitic biostromes that act as a marker bed within the Brock Inlier but are not easily correlatable with those of the Minto Inlier, suggesting that stromatolites were diachronous, possibly only forming in areas where growth conditions were favourable. Another sedimentological difference within the Boot Inlet Formation is the lack of abundant high-energy ooid grainstone facies in the Brock Inlier, which form one of the 3 dominant lithofacies associations in the Minto Inlier. Collectively, the Brock Inlier deposits, representing deposition within the Amundsen Basin, contain the same stratigraphic units and as the Minto Inlier, with minor lithological and facies variations being attributable to local variations in basin paleogeography.

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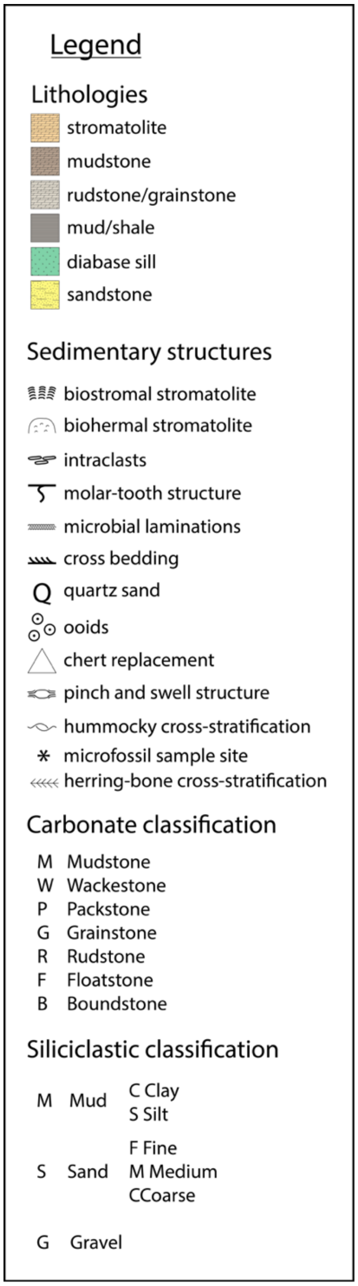
Appendix

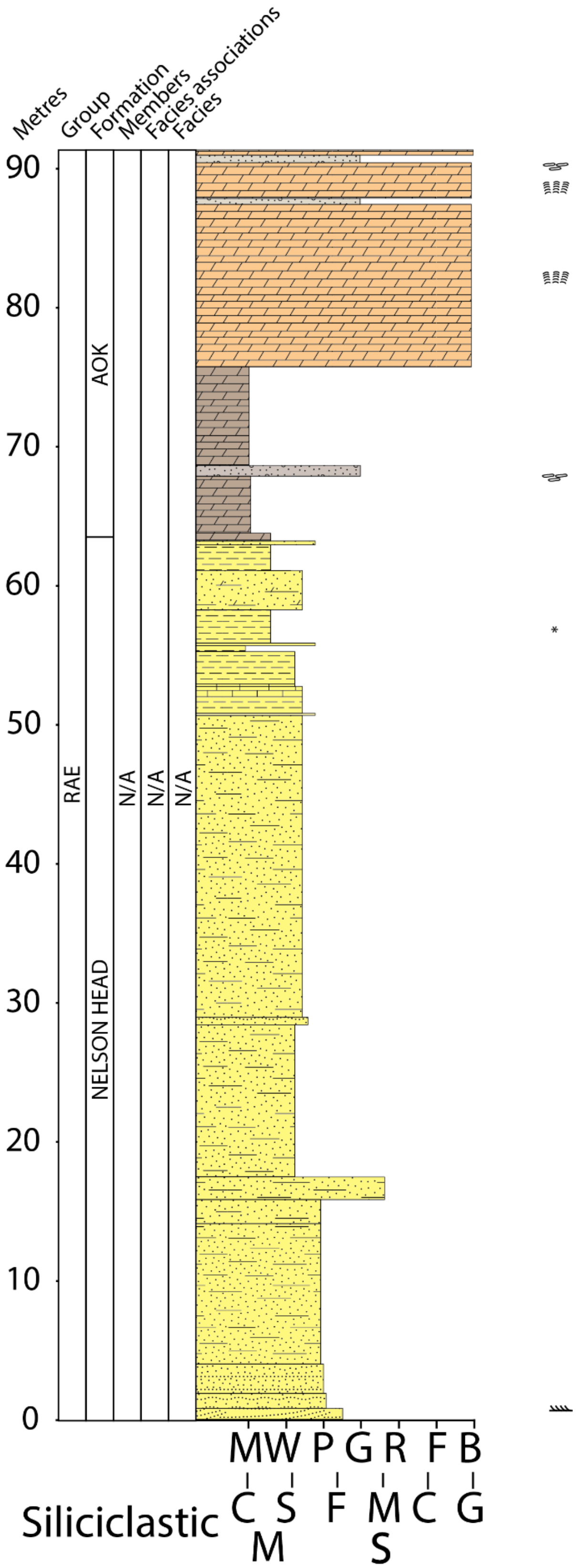
GPS coordinates of stratigraphic sections (NAD83)

Section	GSC* ID number	Latitude	Longitude	Formations measured
1	15RAT02	69°0'18.80"N	122°39'47.05"W	Aok Nelson Head
2	15RAT028	69°0'22.12"N	122°40'14.13"W	Aok
3	15RAT026	69°00'53.88"N	122°40'14.69"W	Boot Inlet
4	15RAT027	69°01'56.84"N	122°41'15.94"W	Boot Inlet
5	15RAT012	68°54'11.00"N	121°44'20.20"W	Boot Inlet Grassy Bay Aok
6	15RAT013	68°56'40"N	121°3'34"W	Boot Inlet
7	15RAT017	68°21'50.5"8N	121°20'58.57"W	Boot Inlet
8	15RAT019	69°05'52.99"N	122°44'54.48"W	Boot Inlet
9	15RAT021	68°55'41.92"N	121°44'14.20"W	Boot Inlet Grassy Bay
10	15RAT024	68°24'08.72"N	120°58'07.07"W	Boot Inlet

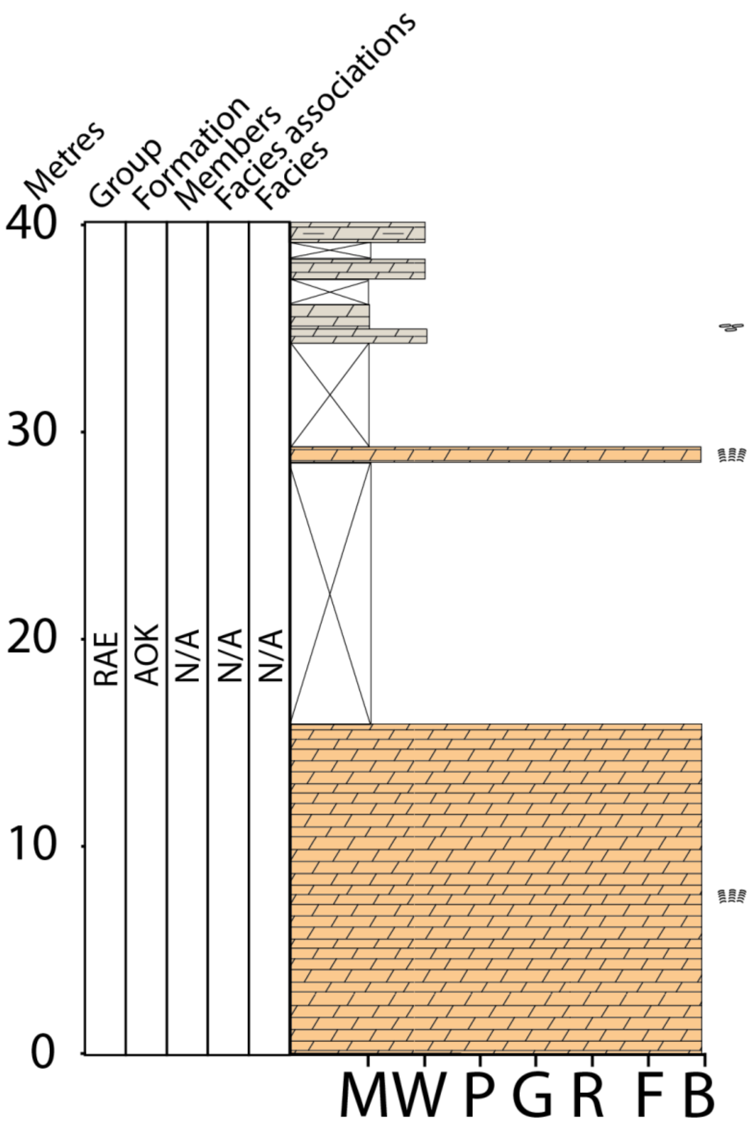
*Geological Survey of Canada



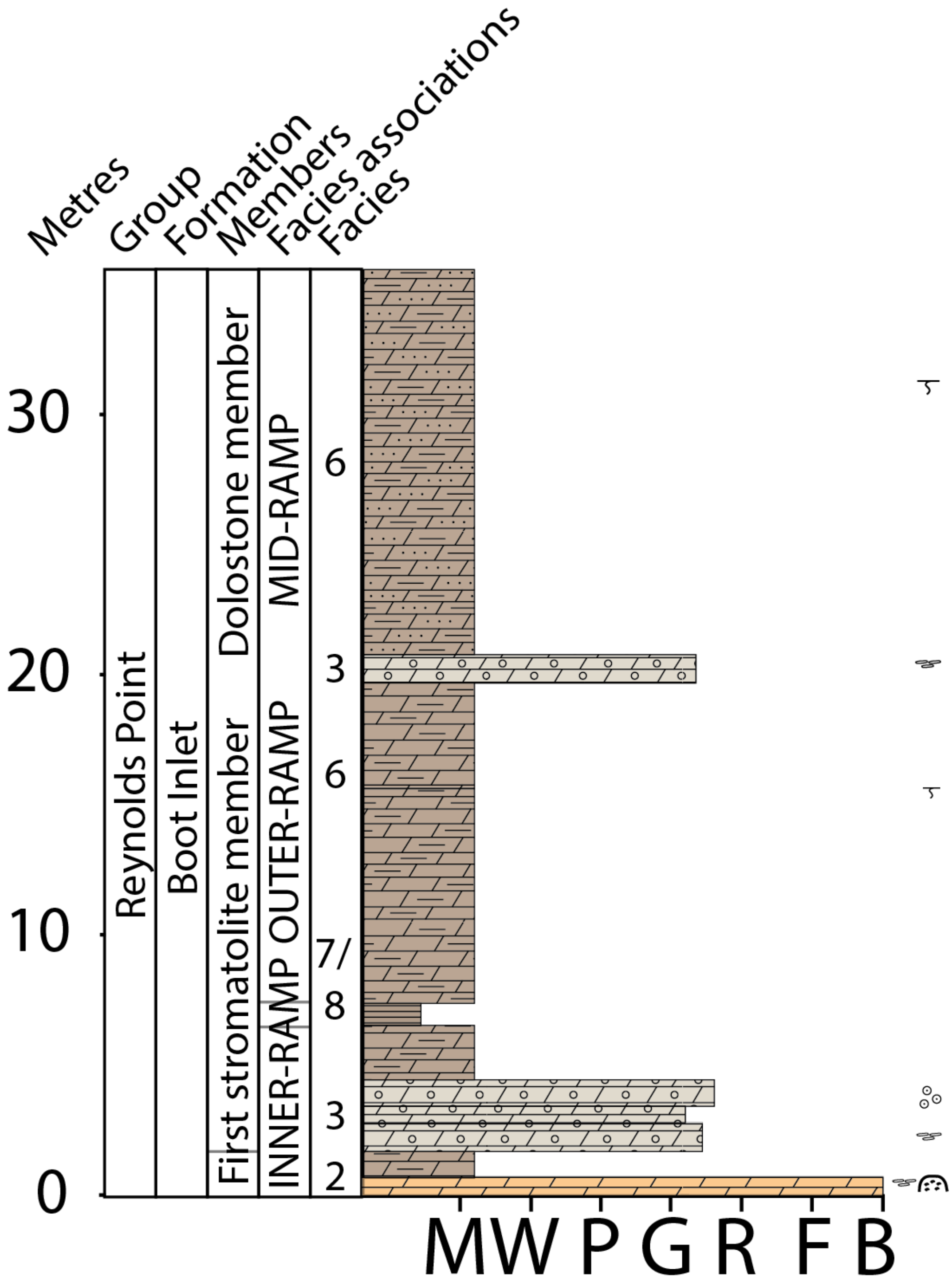
Legend for stratigraphic sections



Stratigraphic Section 1



Stratigraphic Section 2



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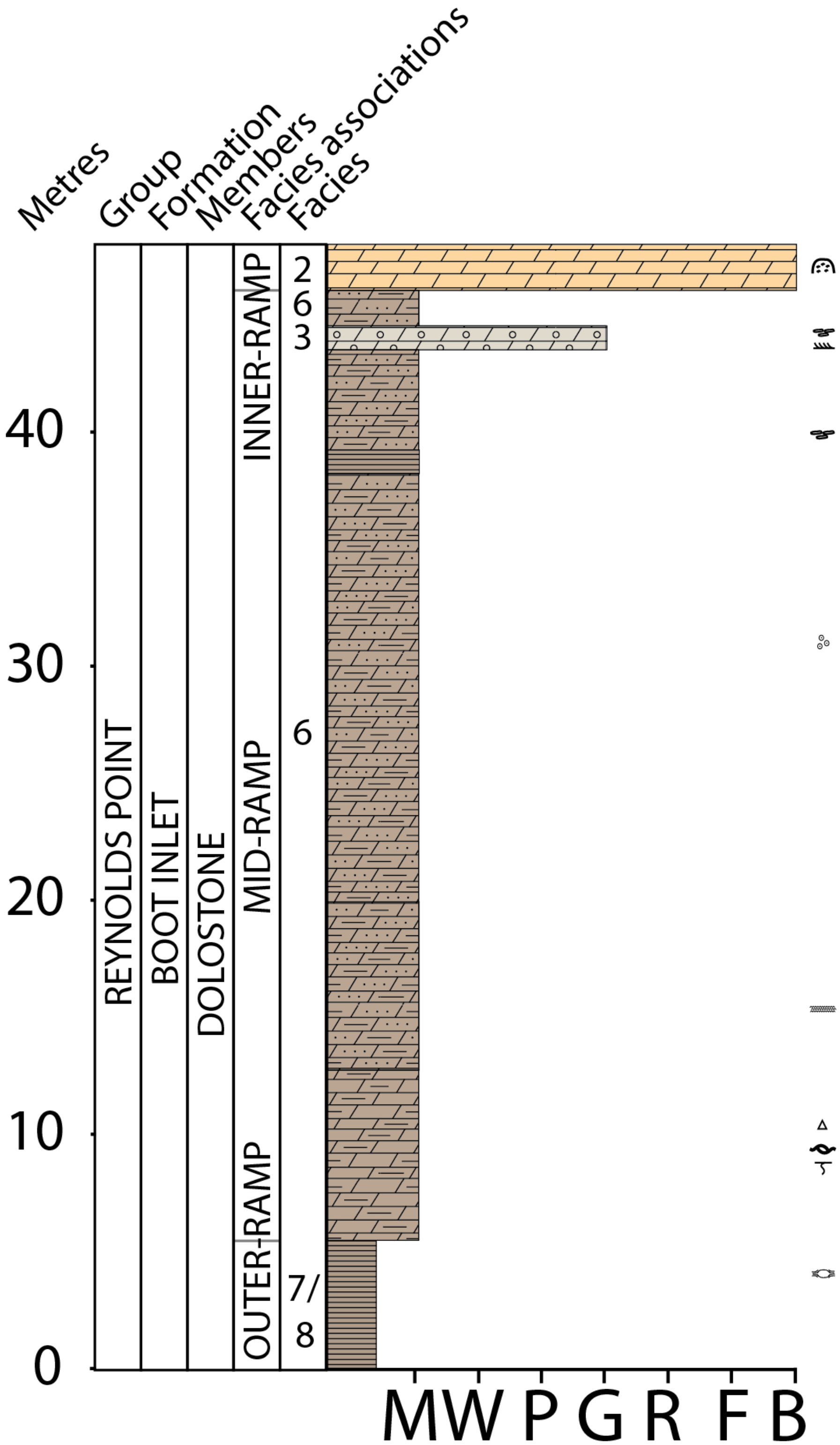
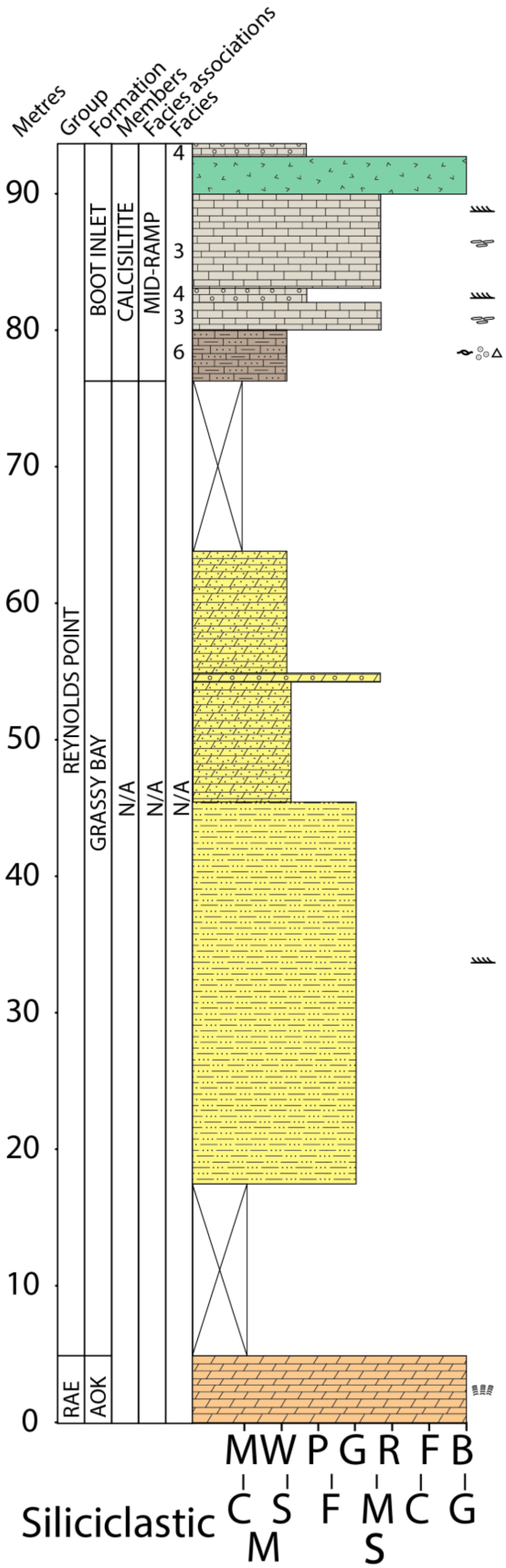


Stratigraphic Section 4



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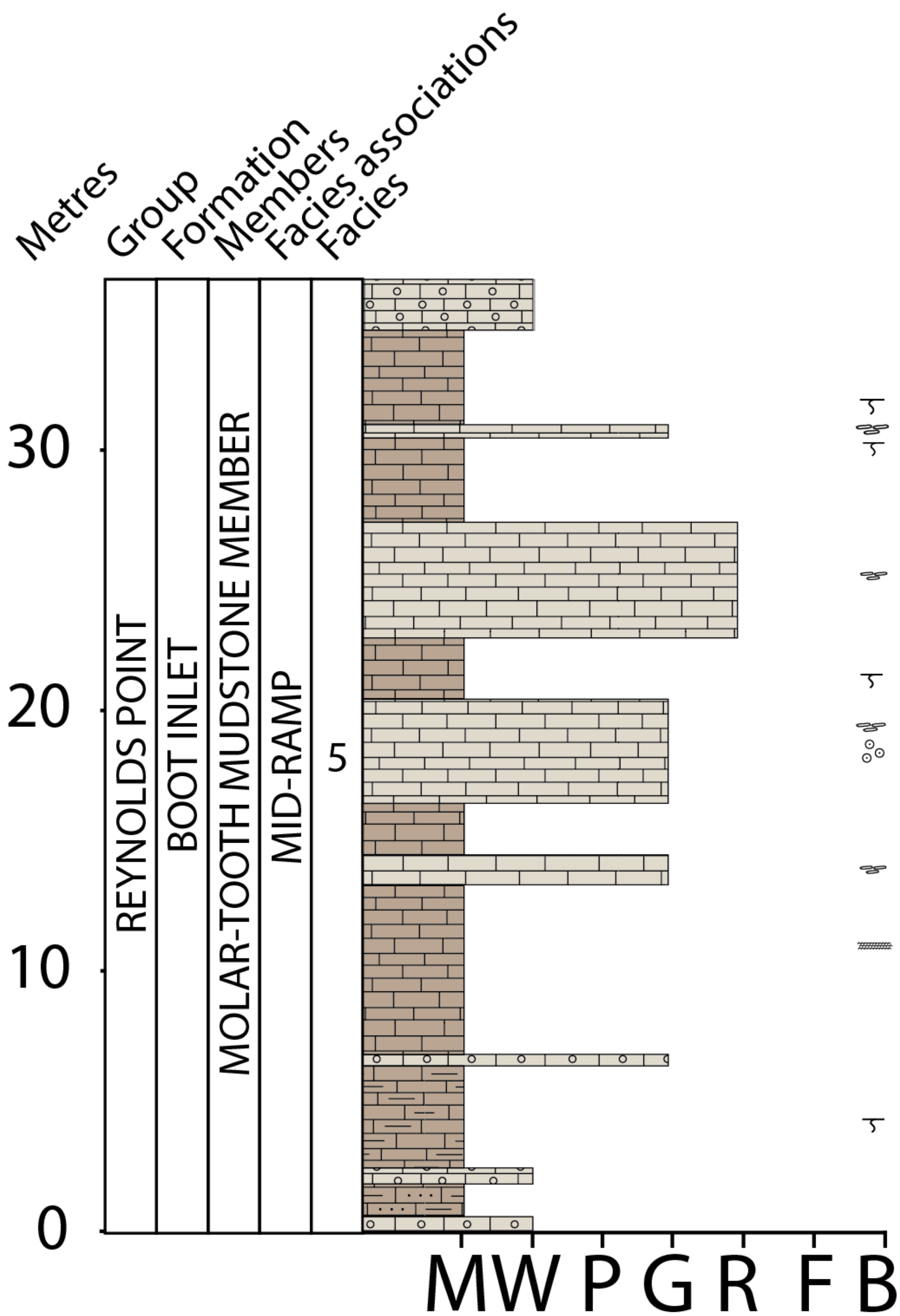

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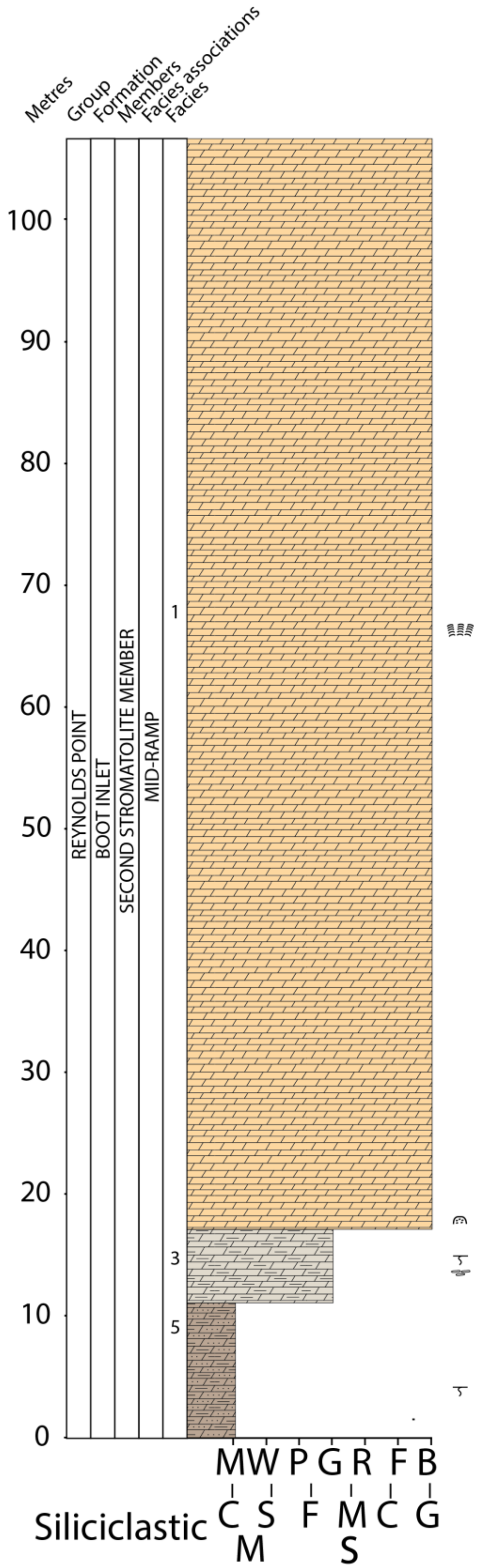

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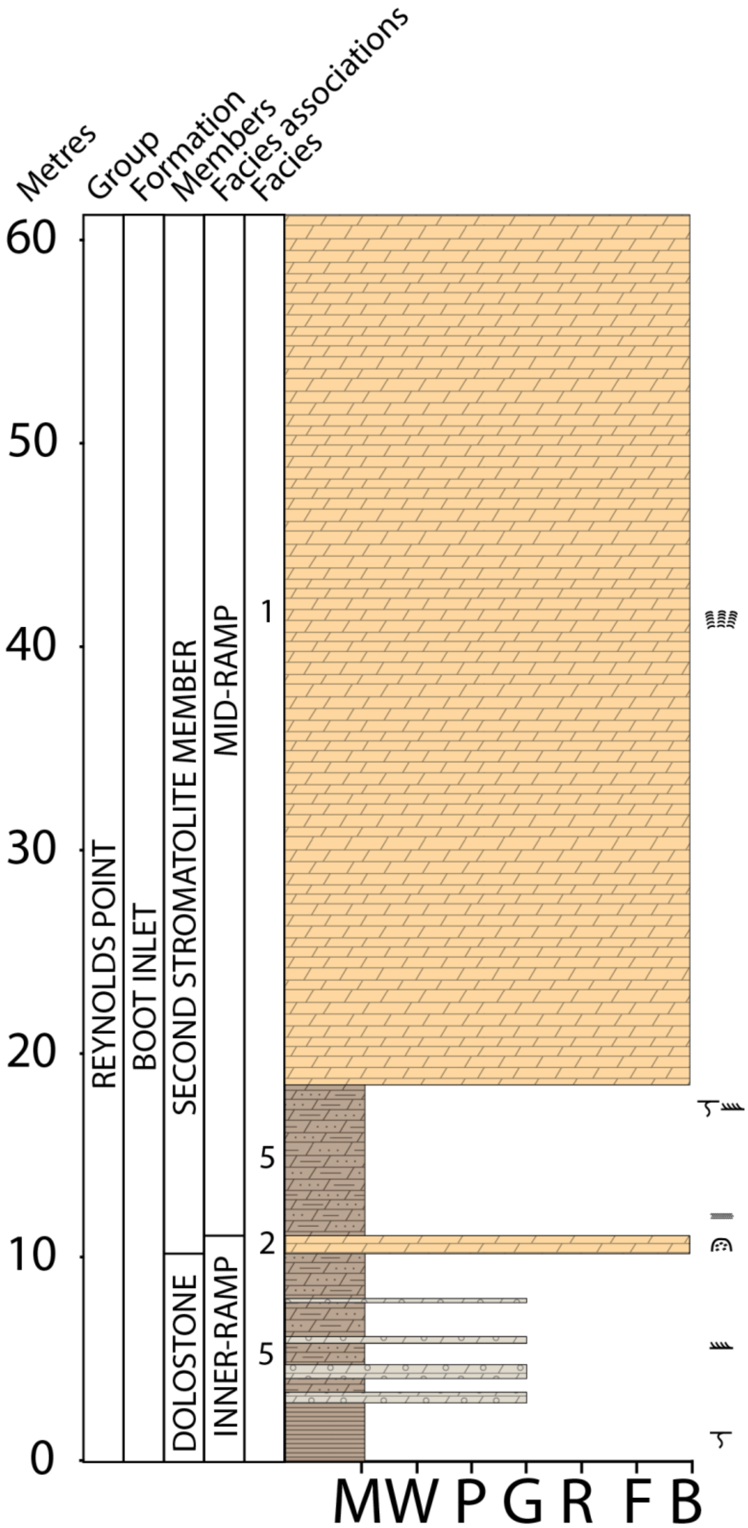

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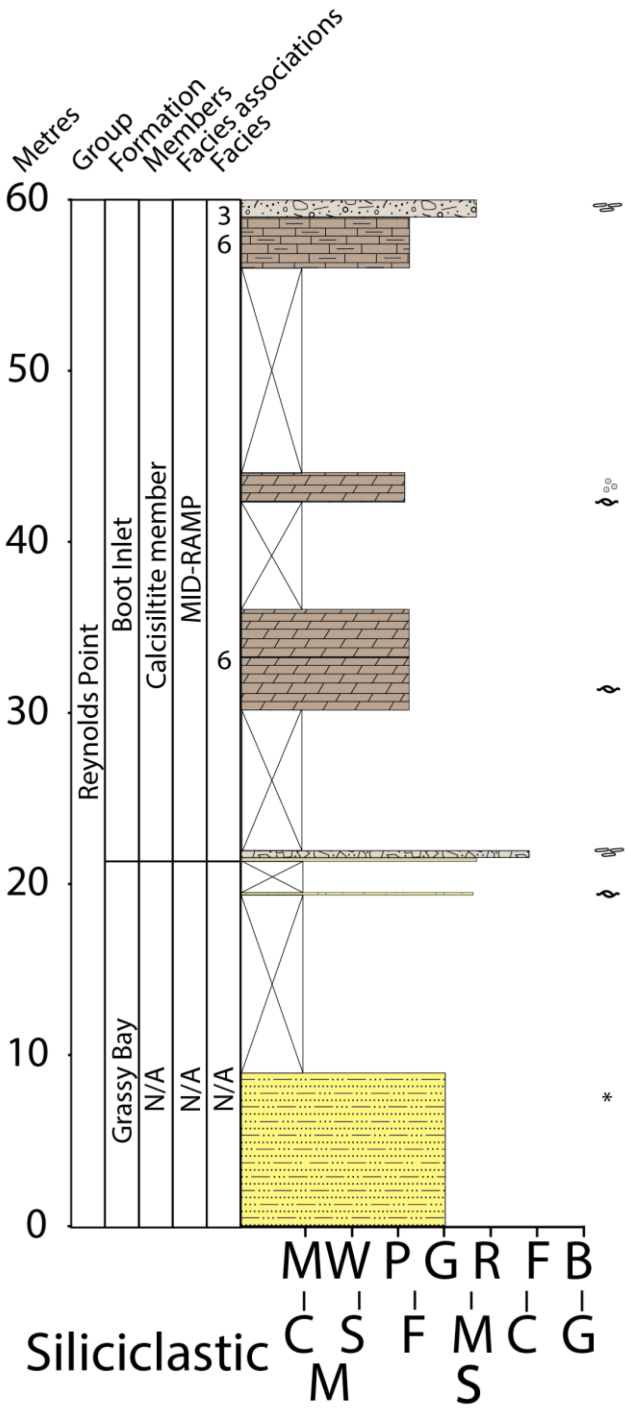

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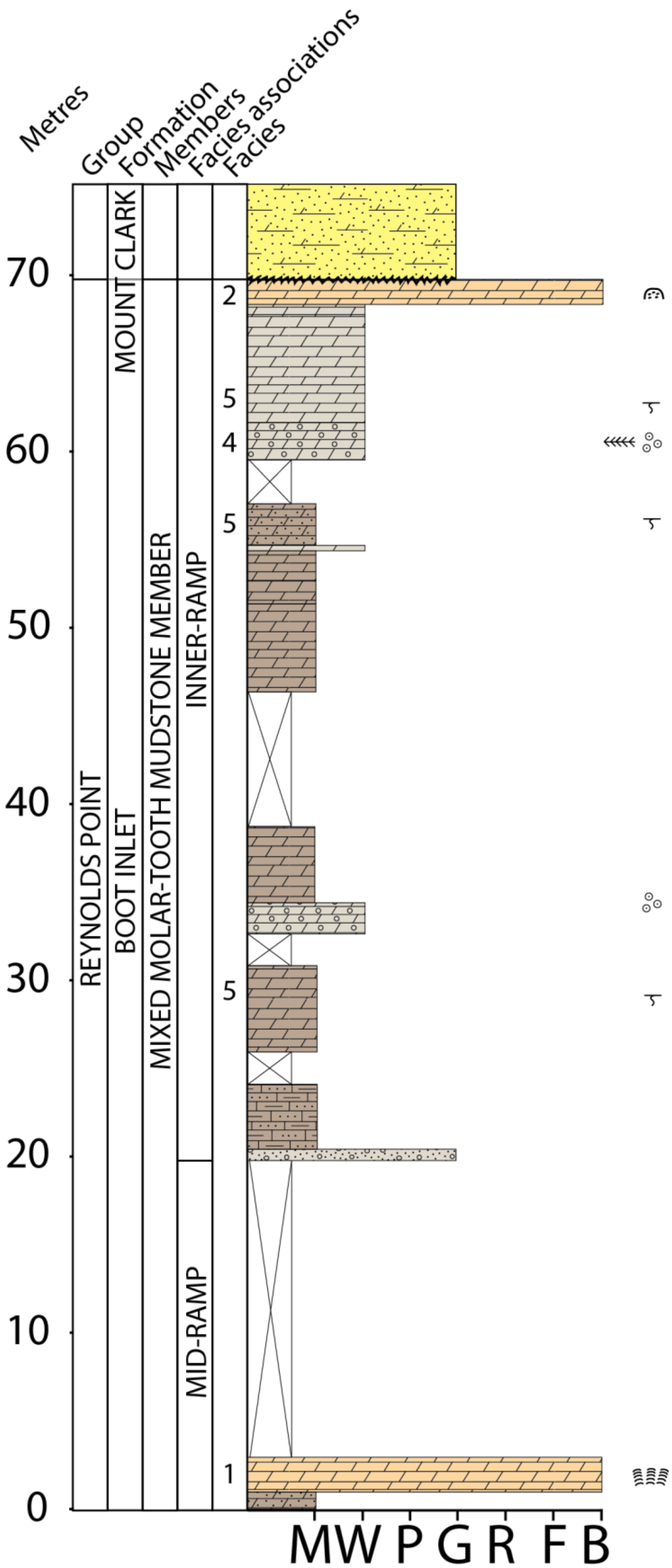

Stratigraphic Section 10