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Abstract

Two stratigraphic sections were measured through Late Triassic - Early Jurassic aged strata in the Blue Mountains map area (NTS 340-B/11) on Ellesmere Island and the Depot Point map area (NTS 049-G/7) on Axel Heiberg Island. These sections are subdivided in terms of established member and formation names based on previous mapping along the north-eastern margin of the Sverdrup Basin. The lowermost strata in the Heiberg Formation, the Romulus Member (510-575 m thick), is a coarsening-upward succession of mudstone to fine-grained sandstone from a prodelta to delta plain environment. The overlying Fosheim Member (317-425 m) is a coal-bearing and sandstone-rich interval from a mixed alluvial-marine environment, such as a delta plain. It is overlain by the Remus Member (100-112 m); a sandstone-rich unit representative of shallow marine deposits. The Heiberg Formation at Depot Point is of similar thickness (1009 m) to the Blue Mountains (1035 m) and may represent a marginally more distal basinal setting with a thinner Fosheim Member but a slightly thicker Romulus and Remus members.

Introduction

The Sverdrup Basin is located in the northwestern Canadian Arctic Islands (Fig. 1). The Sverdrup Basin originated in the Carboniferous as a rift basin where up to 5000 m of Upper Paleozoic strata accumulated in a shelf to deep-basin setting (Balkwill, 1978), underwent significant subsidence in the Triassic followed by Early Jurassic-Early Cretaceous rifting resulting in the opening of the Amerasia Basin (e.g. Hadlari et al., 2016). The Heiberg Formation (Fig. 2) in the central and eastern part of the basin is subdivided into three members: Romulus, Fosheim and Remus (Fig. 2; Embry, 1983a), which are stratigraphically equivalent to the Heiberg Group in the western part of the basin (Embry, 1983b). The Heiberg Group consists of five formations: the deltaic Skybattle Formation, overlain by marine mudstone of the Grosvenor Island, then coarsening-upward into the sandstone-rich Maclean Strait Formation which is subsequently overlain by marine shale of the Lougheed Island Formation and ultimately capped by the sandstone-dominant King Christian Formation (Fig. 2).

There were two predominant sediment sources for the basin during the Triassic (e.g. Embry, 2009; Midwinter et al., 2016); one from the southern and eastern margins of the basin, and another derived from the northwestern margin. The tectonic setting of the Sverdrup Basin in the Triassic was long considered tectonically quiescent (e.g. Embry and Beauchamp, 2008); however, observations of volcanic ash beds and nearly syn-depositional detrital zircon ages through the Permian to late Triassic indicate local volcanism near the northwestern margin of the basin (Midwinter et al., 2016; Hadlari et al., 2018; Alonso-Torres et al., 2018).

Regional Tectono-Stratigraphic Context

The Heiberg Formation records the transition from the pre-rift stage to the syn-rift stage as shallow marine sandstones prograded across the Sverdrup Basin, and multiple unconformities within the formation indicate a basin-filled state. The rift onset unconformity is likely within the Fosheim Member, estimated to be 200-190 Ma in age (Hadlari et al., 2016). Detrital zircon geochronology (Midwinter et al., 2016) indicates that the King Christian Formation (coeval with the Fosheim and Remus members) had a different sediment source due to the onset of rifting to the north of the Sverdrup Basin. This period marked the initial extension of the proto-Amerasia Basin, which is proposed to have developed as a retroarc system driven by slab rollback where sediment transport from Arctic Alaska Chukotka Microplate (AACM) to the Sverdrup Basin was interrupted by intervening extensional basins. This key transition occurred within the sedimentary succession of the Heiberg Formation which makes the stratigraphic sections in the proximal Blue Mountains and slightly more distal Depot Point vital to better understand the timing and duration of the extension with its location near both the northern and eastern margins of the Sverdrup Basin.

Study Sections and Methods

A section spanning the entire Heiberg Formation occurs on the north-eastern margin of the Sverdrup Basin in the Blue Mountains, northern Ellesmere Island (80°38'42.20"N, 85°39'38.38"W; Fig. 3A). The measured section started in the Late Triassic Barrow Formation and ended in the Early Jurassic Jameson Bay Formation with lithological and sedimentological observations made for the approximately 1,200 m thick section. This area was previously mapped at a regional scale in Thorsteinsson (1971a).

The measured section at Depot Point, Axel Heiberg Island (79°27'10.75"N, 85°32'22.46"W; Fig. 3B) started in the Barrow Formation and ended in unsubdivided Jurassic strata with a thickness of approximately 1,140m. The Depot Point section has a lower level of detail than the Blue Mountains section. This area was previously mapped at a regional scale in Thorsteinsson (1971b). The type section for the Heiberg Formation is at Buchanan Lake, Axel Heiberg Island (Souther, 1963), approximately 40 km to the west of the Depot Point section. The type section was not subdivided into members, but measured 1,600 m which included 200 m of mafic sills.

Measured Sections

Blue Mountains

The Blue Mountains measured section with geological descriptions is illustrated in Figure 4.

Romulus Member

The lowest member of the Heiberg Formation, the Romulus Member, is underlain by the very thin bedded, sandy mudstone of the Barrow Formation. The contact between the Barrow Formation and Romulus Member is defined by the first notable sandstone bed. The member consists of mudstone, siltstone, and very fine- to fine grained sandstone with a measured thickness of 510 m.

A typical cycle within the member is a coarsening-upward succession of about 20 to 30 m (Fig. 5). The base is interbedded mudstone with very well sorted, very-fine to fine-grained sandstone. The mudstone is often very thin to thin bedded and fissile. Mudstone becomes less common with sandstone becoming more predominant towards the upper member with cm-scale coarsening-upward cycles (Fig. 5B) within the larger coarsening-upward cycle. When interbedded with mudstone, contacts are often parallel to wavy (Fig. 5C) and have wavy or lenticular laminations. Sandstone units that are medium to thick bedded typically have low-angle trough (Fig. 5D) to planar cross-bedding or cross-lamination. This is subsequently overlain by mudstone to siltstone or very-fine grained, thin bedded sandstone.

There are large covered intervals which are interpreted to represent recessive finer-grained facies. The uppermost exposed outcrop is a 6 m thick medium-grained sandstone that grades into coarse-grained medium bedded sandstone. Rare wood fragments are observed. The uppermost observed bed before a thick recessive, covered interval is a thin bed of very-coarse grained sand with extra-formational chert pebbles (Fig. 5E) and an exposed bedding plane with symmetrical, irregular linguoid ripples (Fig. 5F).

Fosheim Member

The middle member of the Heiberg Formation consisted of mudstone, very fine- to medium-grained sandstone with a measured thickness of 425 m. The contact between the Romulus and Fosheim members is the base of the first carbonaceous sandstone. The sandstone is typically quartzose, weathers white to light yellow, is medium-grained and medium to thick bedded with trough cross-bedding. Both fining and coarsening upward cycles occur in this member; however, fining-upward cycles are less common than the general coarsening-upward cycles (Fig. 6).

A typical sedimentary cycle in the Fosheim Member has carbonaceous silty shale, often highly carbonaceous mudstone with occasional coal beds, at the base. The mudstone is often fissile, very thin to thin bedded, and planar. The interbedded sandstone has wavy or lenticular laminations and may locally exhibit flaser bedding. The succession then coarsens to a very fine-grained to fine-grained sandstone. The sandstone is often trough cross-stratified with carbonaceous laminations and rare wood fragments (Fig. 6B) or planar and parallel bedded. Symmetrical, slightly sinuous ripples are occasionally observed (Fig. 6C) along with possible synaeresis or mud cracks (Fig. 6D). The sandstone beds are sparsely bioturbated with vertical and horizontal burrows.

Well-defined trace fossils were observed in the upper 100 m of the member. The *Diplocraterion* burrows, observed both in cross-section (Fig. 6E) and on the bedding surface (Fig. 6F) have spreiten which are approximately 1 cm wide and ranging from 3 to 10 cm depth.

Remus Member

The contact between the Remus and Fosheim members is placed at the top of the highest carbonaceous shale and siltstone bed above which sandstone is nearly continuous for the remainder of the Heiberg Formation. The measured thickness of the uppermost member of the Heiberg Formation is 100 m.

The Remus Member was typically comprised of white, quartzose, fine- to medium-grained sandstone either planar or trough cross-stratified (Fig. 7), and forms distinctive cliffs along the section (Fig. 7B). Outcrop appears massive in part due to intense bioturbation in the lower part of the member (Fig. 7C). There are rare, thin intervals of ironstone beds with brachiopod and bivalve fragments (Fig. 7D).

At the top of the member is fine-grained, thin-bedded rooted sandstone 4 to 6 m in thickness (Fig. 7E) with hematized sandstone 1-3 m in thickness (Fig. 7F). The hematized red sandstone is highly indurated. The contact of the Remus Member with the overlying Jameson Bay Formation is placed at the top of the uppermost red sandstone bed.

Depot Point

The Blue Mountains measured section with geological descriptions is illustrated in Figure 8.

Romulus Member

The Romulus Member at Depot Point measured 575 m in thickness. The typical observations of the Romulus Member are coarsening-upward cycles ranging from 5 to 15 m. Sandstone is predominantly planar and parallel bedded and thin-bedded with occasional ripple cross-lamination. At the top of the coarsening-upward cycles are fine-grained, medium-bedded sandstone with low-angle to locally sigmoidal cross-stratification with erosional scours and rare bivalve fragments. Towards the top of the Romulus Member is a thin conglomerate bed with chert pebbles above bioturbated sandstone with mud rip-up clasts. The top of the unit is a predominantly covered interval and subcrop of bioturbated sandstone with *Skolithos*. The contact with the Fosheim Member is placed at the base of the first quartzose sandstone (578 m, Fig. 8) below an interpreted transgressive coal seam.

Fosheim Member

The Fosheim Member measured 317 m in thickness. The Fosheim Member weathers more white to light yellow than the Romulus Member, which can be seen on satellite imagery (Fig. 3B). This interval has 5 – 10 m fining-upward cycles. The sandstone is typically very well-sorted, medium- to thick-bedded, quartzose sandstone with tabular, planar and trough cross-bedding with cross-sets ranging from 5 to 20 cm. The sandstone also has weak to intense bioturbation. Trace fossils observed includes *Skolithos* and *Diplocriterion*, with up to 5 cm wide spreiten. Additionally, thin ironstone beds are observed with plant fragments. The occasional bedding surface has symmetrical ripples with preserved carbonaceous laminations within the cross-stratification. Highly carbonaceous or thin coal intervals are present. The contact with the Remus Member is placed where carbonaceous materials are no longer observed.

Remus Member

The Remus Member was measured at 112 m. The typical sandstone is quartzose, poorly consolidated, thin- to thick-bedded sandstone with ripple cross-laminations to trough cross-bedding. The sandstone also has weak to intense bioturbation. The uppermost Remus Member is very-fine grained sandstone with thin paleosol beds interbedded with dark grey to black mudstone. Paleosol beds may be evidence of an unconformity.

Early to Middle Jurassic Strata

Above the Remus Member is a mix of covered interval, mudstone and sandstone that could include the mudstone-rich Jameson Bay, McConnell Island and Ringnes formations. Overlying the fine-grained interval is likely the sandstone-rich Awingak Formation.

Depositional Environments

Observations of ripple cross-lamination and interbedded sandstone and mudstone from the Romulus Member are consistent with previous studies which have interpreted the Romulus Member to represent a prodelta to delta front environment (Embry, 1982; Embry 1983a). At Blue Mountains the conglomerate bed near the top of the member may represent a transgressive lag deposit. The irregular linguoid ripples below the conglomerate layer observed in the Blue Mountains are indicative of increasing velocity and/or decreasing depth.

Previous studies have interpreted the Fosheim Member to represent a delta plain environment (Embry, 1982; Embry 1983a) which is consistent with observation from the measured sections with abundant cross-bedding, coal and carbonaceous intervals, trace fossils, tidal ripples, and synaeresis and/or mud cracks.

Lastly, the Remus Member has been interpreted by previous studies to represent near shore deposits of a deltaic environment (Embry 1983a). The observations of abundant bioturbation, fossil fragments, lack of channel successions and rooted beds are more consistent with a shallow marine shoreface system.

Correlation

The thickness and lithology of the Upper Triassic-Lower Jurassic Heiberg Formation/Group changes from the basin margin to basin centre. Along the northwestern margin, on Ellef Ringnes Island, the Heiberg Group is approximately 950 to 700 m, thinning to the south of the island (Hadlari et al., 2018; Fig. 9). Within the Heiberg Group, the mudstone-rich formations of Grosvenor Island and Lougheed Island thin towards the southeast. Along the southeastern margin, the Heiberg Formation ranges between 140 to 160 m (Fig. 9).

The measured sections are compared to a well where the Heiberg Group/Formation is of similar thickness, near the basin centre (Fig. 10). The Upper Triassic Romulus Member represents the first major progradation into the basin as the rate that accommodation space was generated decreased. The Fosheim Member is the thickest member along the north-eastern margin. Identified from palynological studies (Embry and Suneby, 1994), the Grosvenor Island Member contains the Triassic-Jurassic boundary. This basin centre mudstone is correlative with thin marine mudstone in the lower Fosheim Member (Suneby and Hills, 1988). At Depot Point, there is a thin marine mudstone near the base of the member which is interpreted to be the thin marginal representation of the Grosvenor Island Formation; therefore, the Triassic-Jurassic boundary is interpreted to be within the mudstone at some point between 588-607 m (Fig. 10). Additional evidence for this mudstone being correlative to the Grosvenor Island Formation is the presence of ironstone rubble. In the southwestern margin of the Sverdrup Basin, ironstone was observed within the Grosvenor Island Formation, indicative of a starved shelf (Embry and Johannessen, 1993). Due to lack of quality outcrop exposure, the location of the Triassic-Jurassic boundary was not approximated at the Blue Mountains section. The Remus Member has a similar thickness along the northern-eastern and eastern margin, and basin centre (Fig. 10).

In terms of tectonostratigraphy, the filling of the basin with shallow marine sandstones marks the end of the pre-rift phase of the Sverdrup Basin (Hadlari et al., 2016). The stage is marked by northern sediment input into the basin as indicated by detrital zircon data (e.g. Midwinter et al., 2016). During the transition to the syn-rift phase, sediment from the northern source no longer reached the Sverdrup Basin as indicated by detrital zircon data in the King Christian Formation; therefore the provenance change occurred below the King Christian Formation (equivalent to the Remus Member) and above the Romulus Member (which is equivalent to the Skybattle Formation; Fig. 2), which places the onset of rifting between ca. 210-190 Ma. The onset of rifting by the Early Jurassic is further supported by the presence of upper Heiberg Group strata at the base of half-grabens on Prince Patrick Island (Harrison and Brent, 2005).

The marine deposition of mudstone at the base of the Jameson Bay Formation, above the Heiberg Formation, represents a transgression and the creation of new accommodation space in the basin and the start of the syn-rift succession. The syn-rift phase persisted until the breakup unconformity near the base of the Lower Cretaceous Isachsen Formation, ca. 135-130 Ma (Hadlari et al., 2016) which predates the onset of the High Arctic Large Igneous Province (ca. 125-75 Ma), with three major pulses at ca. 124–120, ca. 100–92 and ca. 84–78 Ma (Dockman et al., 2018 and references therein).

Conclusion

The Upper Triassic to Lower Jurassic Heiberg Formation outcrops along the north-eastern and eastern margins of the Sverdrup Basin provide great exposure to study the stratigraphy during a significant tectonic change within the basin. During the deposition of the Heiberg Formation, rifting to the north of the Sverdrup Basin resulted in the genesis of the proto-Amerasia Basin and the formation of extensional basins in the intervening areas that interrupted sediment transport to the basin from the northern source area.

The widespread distribution of the Late Triassic Romulus Member, comprised of prodelta to delta plain deposits, indicates that the basin was filled prior to rifting. The Fosheim Member marks the transition from a pre-rift to syn-rift tectonic setting and the deposition of predominantly delta plain sediment. Deposition of the Remus Member commenced with a shift from deltaic to near-shore sedimentation as a basin-wide transgression occurred, and the transport of sediment from the north of the Sverdrup Basin had ceased.

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Figures

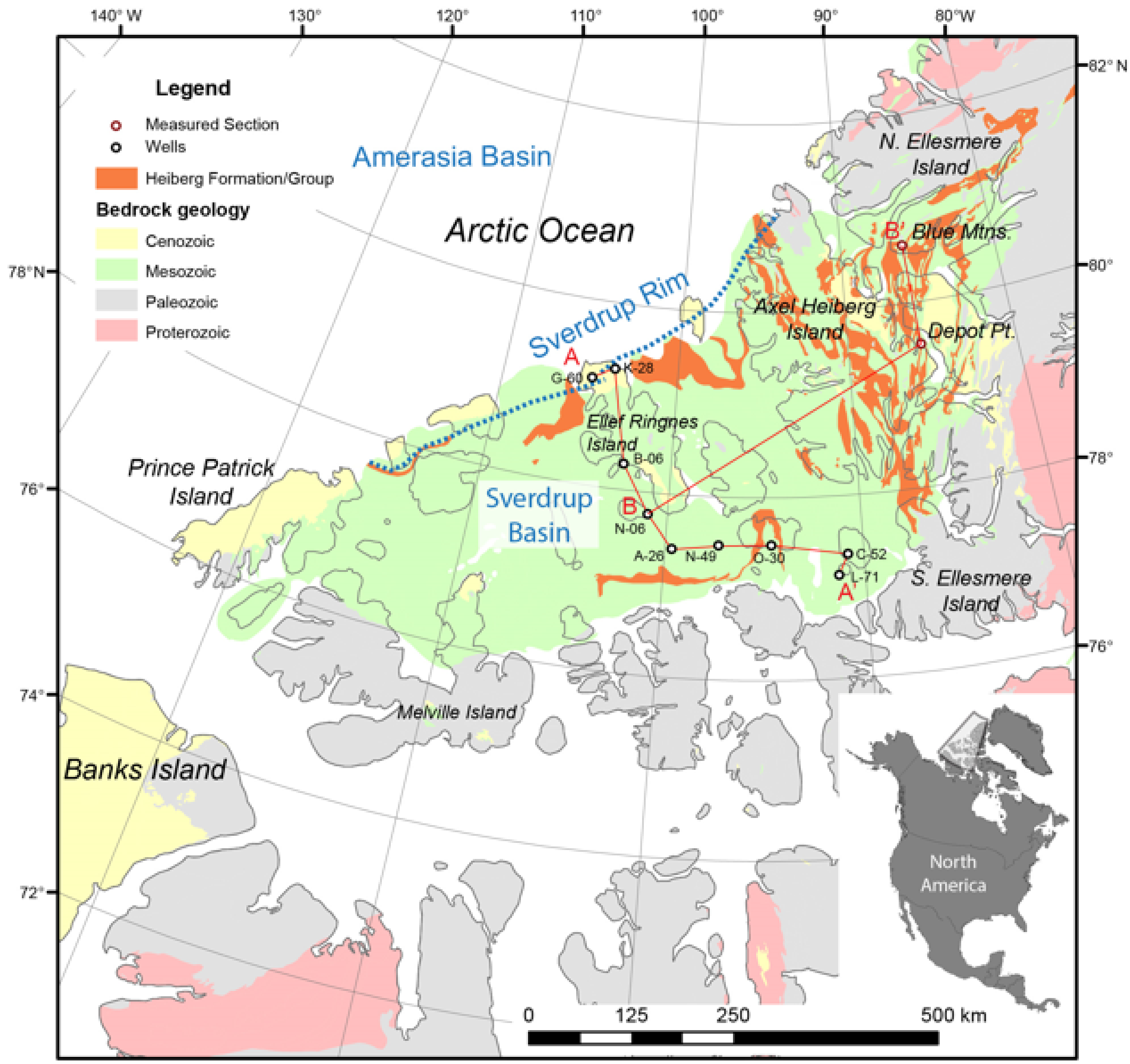

Figure 1: Map of the Sverdrup Basin showing the location of the measured sections (Fig. 4 and 8), cross-sections (Fig. 10 and 11) and Late Triassic to Early Jurassic Heiberg Formation/Group strata. Surface and sea bottom bedrock geology is from Okulitch (1991).

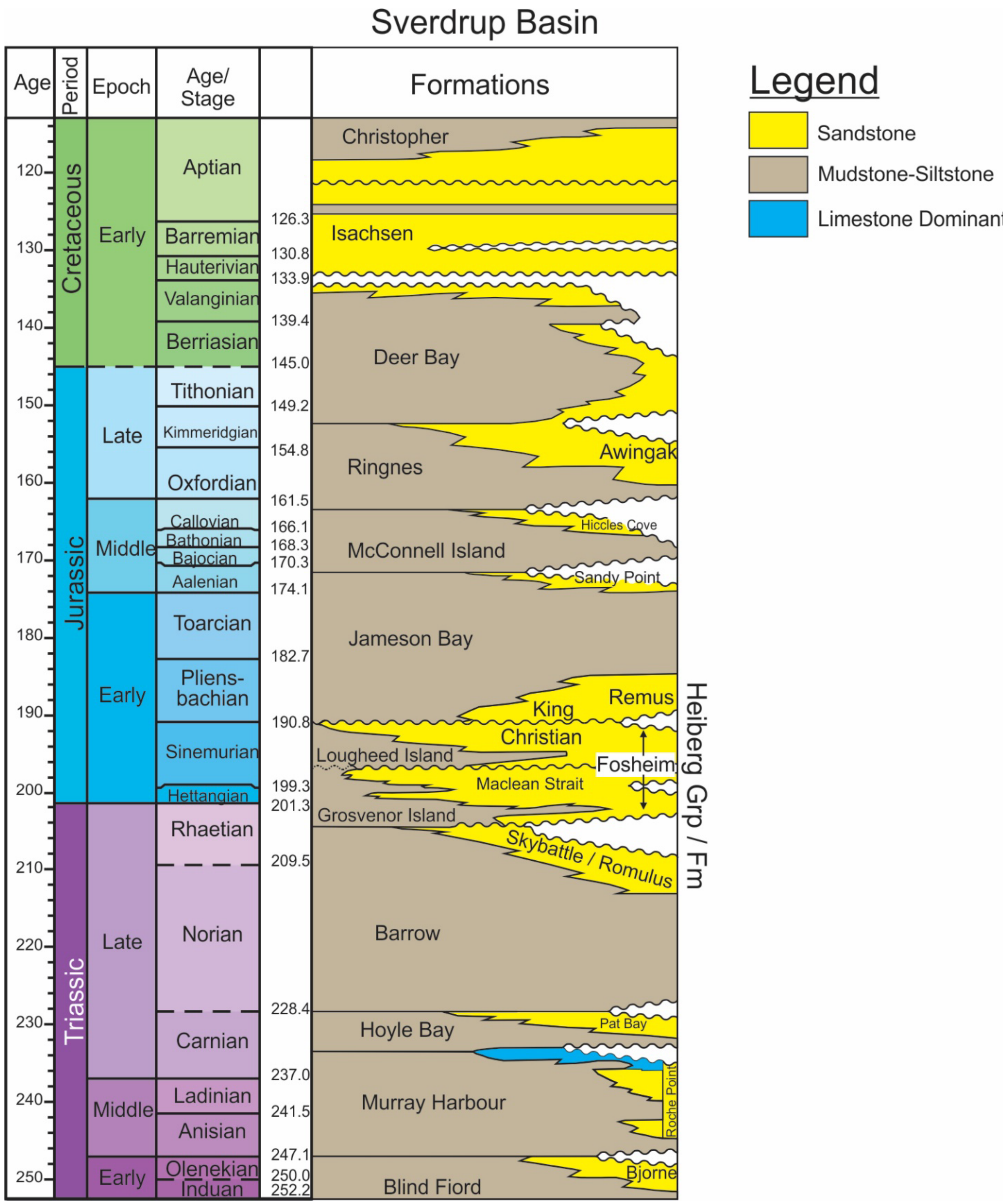

Figure 2: Triassic to Early Cretaceous stratigraphic chart of the Sverdrup Basin (Embry and Beauchamp, 2008; Hadlari et al., 2016)

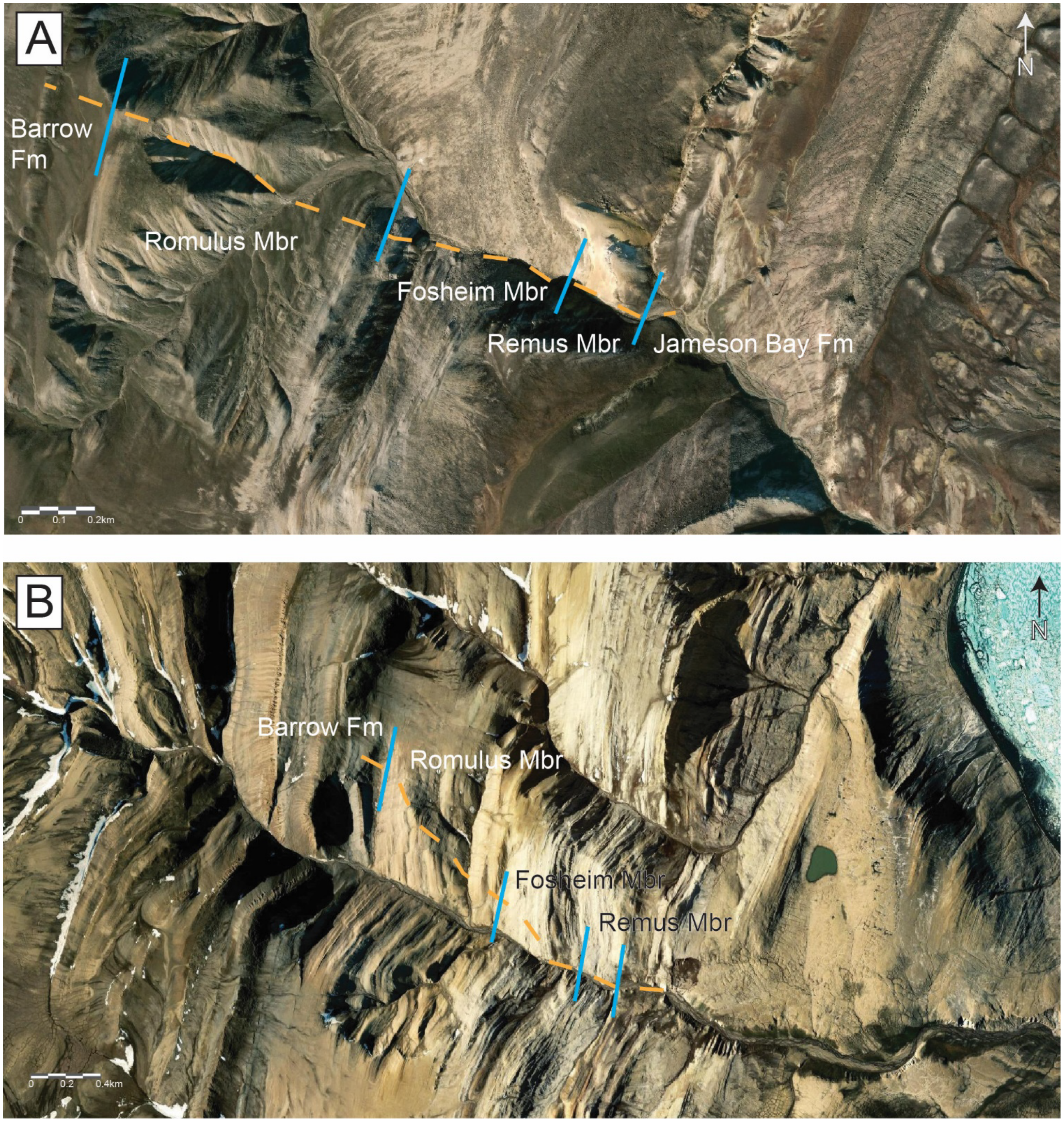

Figure 3: Satellite imagery of the Blue Mountains (A) and Depot Point (B) measured section. Satellite imagery sourced from ESRI https://www.arcgis.com/home/webmap/viewer.html. See Figure 1 for approximate locations of measured sections within the Sverdrup Basin.

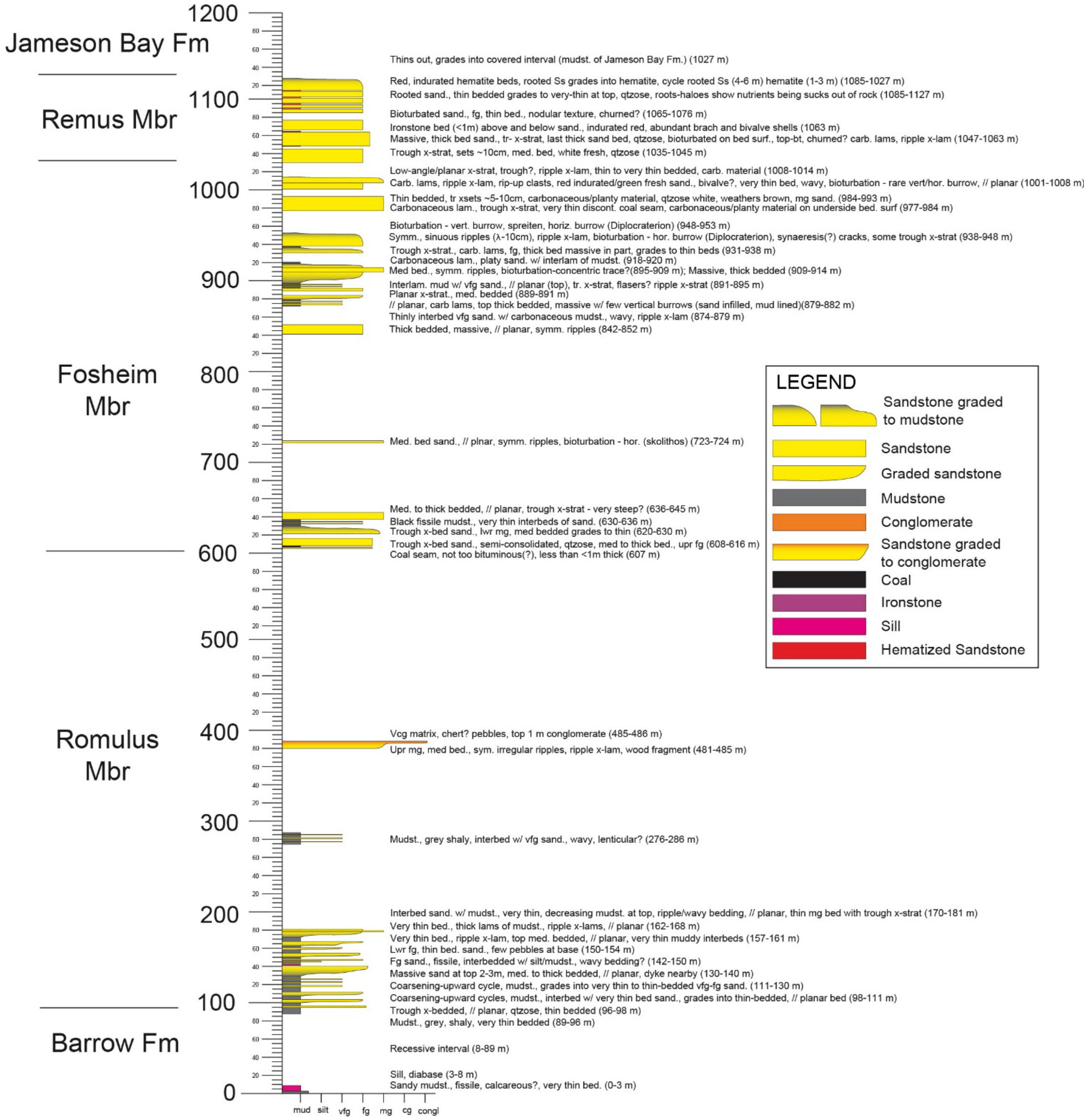

Figure 4: Stratigraphic section measured at Blue Mountains with geological descriptions for specific meterage.

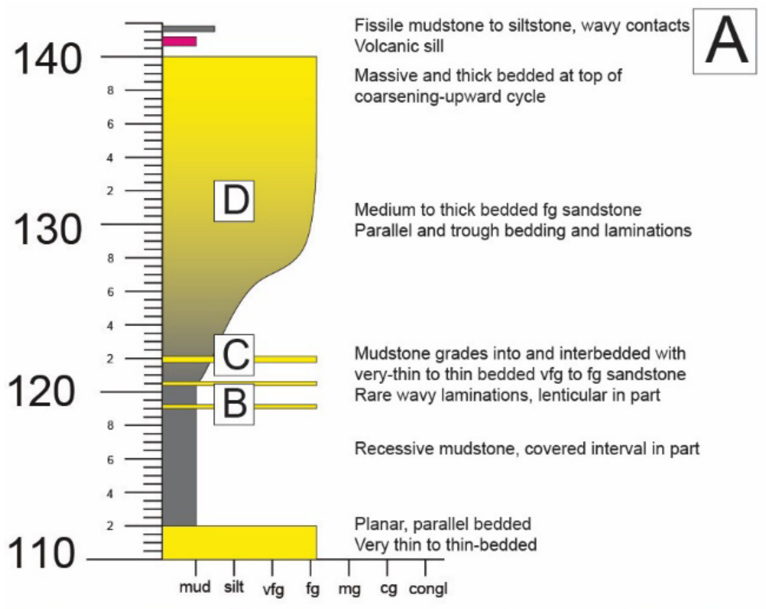

Figure 5: Detailed section from the Romulus Member. Letters correspond to sedimentary features. B: coarsening-upward cycles; C: wavy bedding contact; D: low-angle trough cross-bedding; E: conglomerate bed; F: irregular linguoid ripples on bedding surface, arrow indicates flow direction. Refer to Figure 4 for legend.

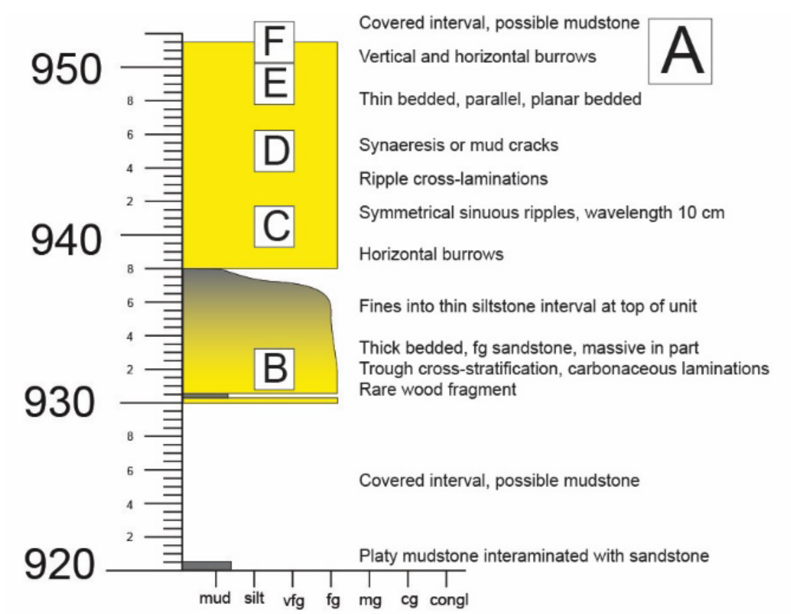

Figure 6: Detailed section from the Fosheim Member. Letters correspond to sedimentary features. B: trough cross-laminations, inset displays coal/carbonaceous material within the laminations; C: symmetrical ripples on bedding surface; D: synaeresis or mud cracks on bedding surface; E: U-Shaped burrow with spreiten, interpreted as *Diplocraterion*; F: *Diplocraterion* on bedding surface. Refer to Figure 4 for legend.

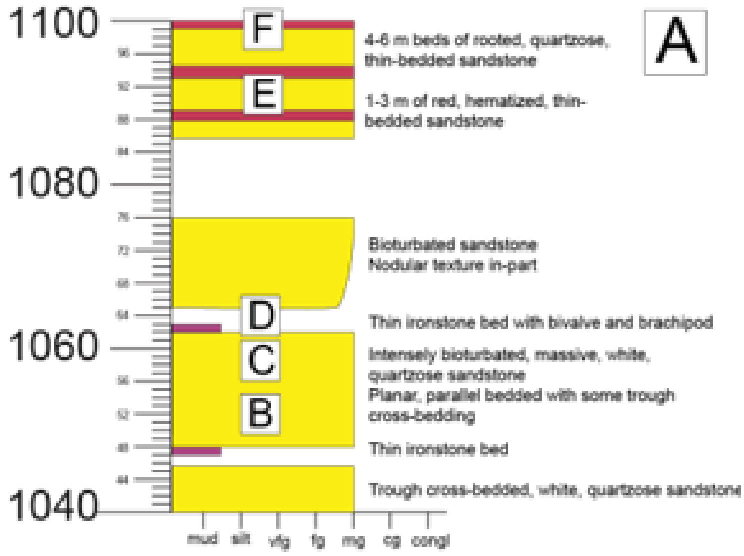

Figure 7: Detailed section from the Remus Member. Letters correspond to sedimentary features. B: quartzose sandstone with ironstone in outcrop from 1048 to 1062 m; C: intense bioturbation; D: bivalve fragments within ironstone; E: rooted sandstone; F: hematitized sandstone above rooted sandstone. Refer to Figure 4 for legend.

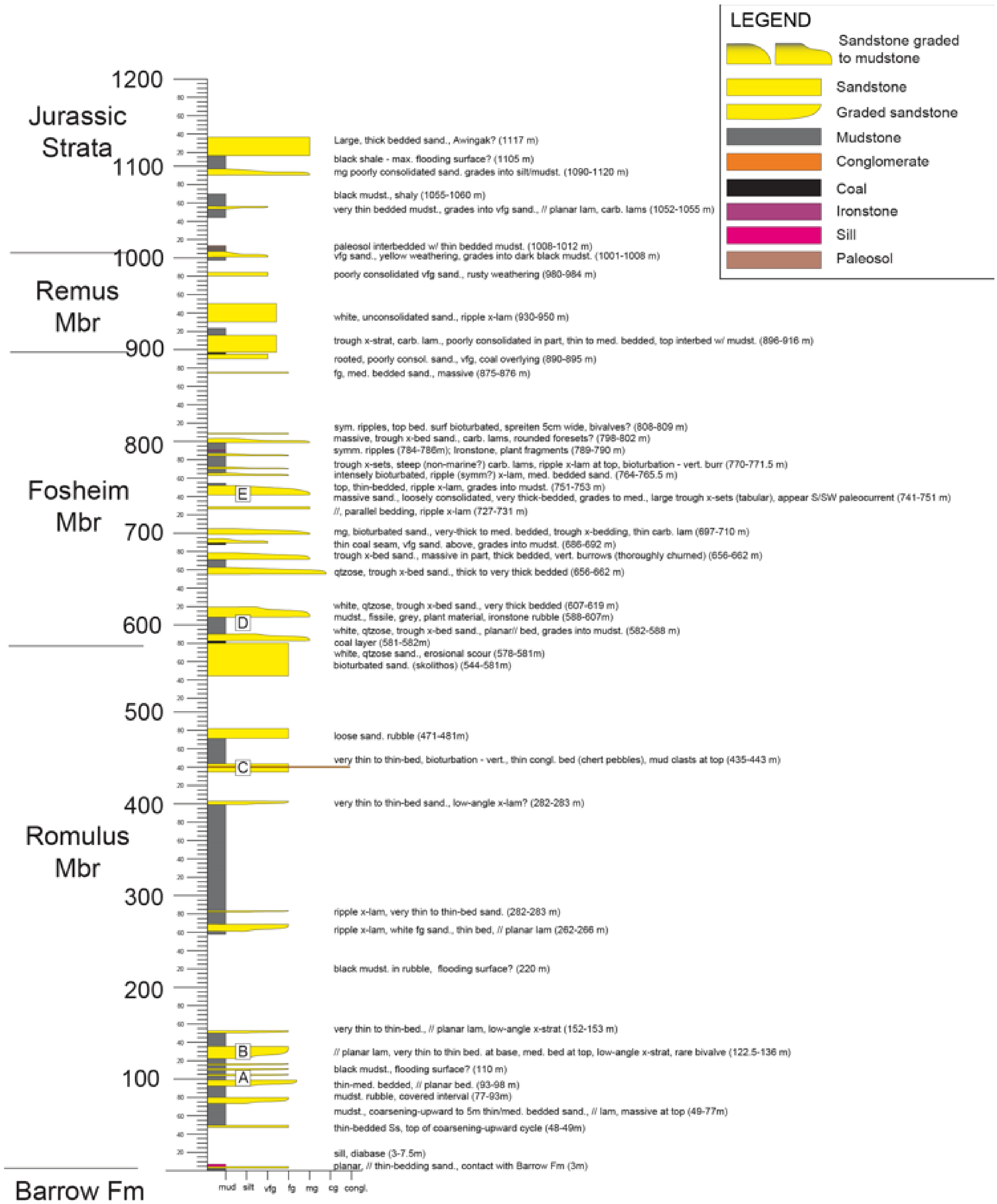

Figure 8: Stratigraphic section measured at Depot Point with geological descriptions for specific meterage. Boxes A-E indicate photo locations for Figure 9.

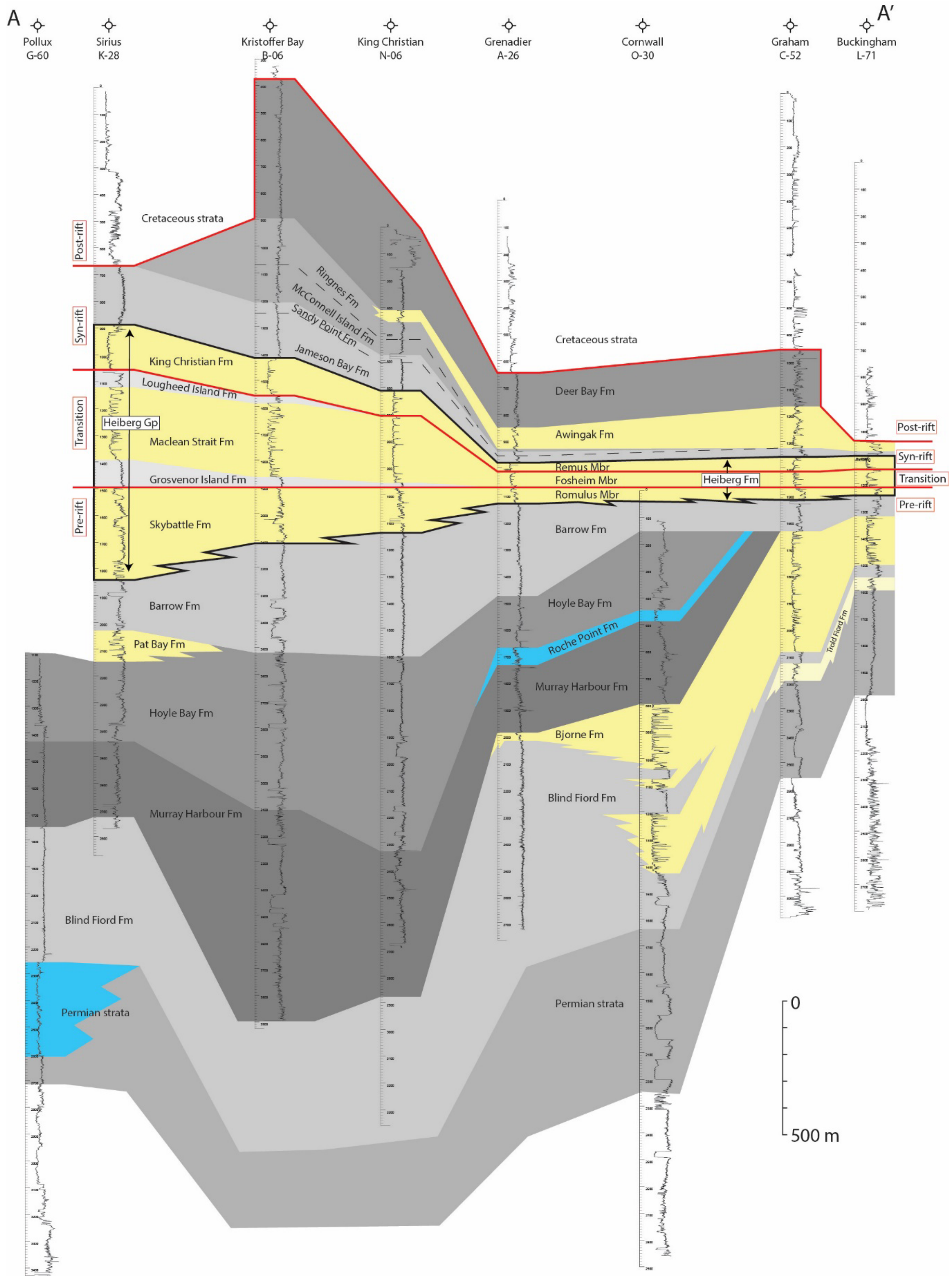

Figure 9: Transverse stratigraphic cross-section of the Sverdrup Basin centred on Ellef Ringnes Island. Location of cross-section shown in Figure 1. Gamma logs are shown for each well. Horizontal dimension not to scale. Stratigraphic framework is from Embry (1983b, 1991, 1993) and Dewing and Embry (2007). The rifting stages are modified from Hadlari et al. (2016). Modified from Hadlari et al. (2018).

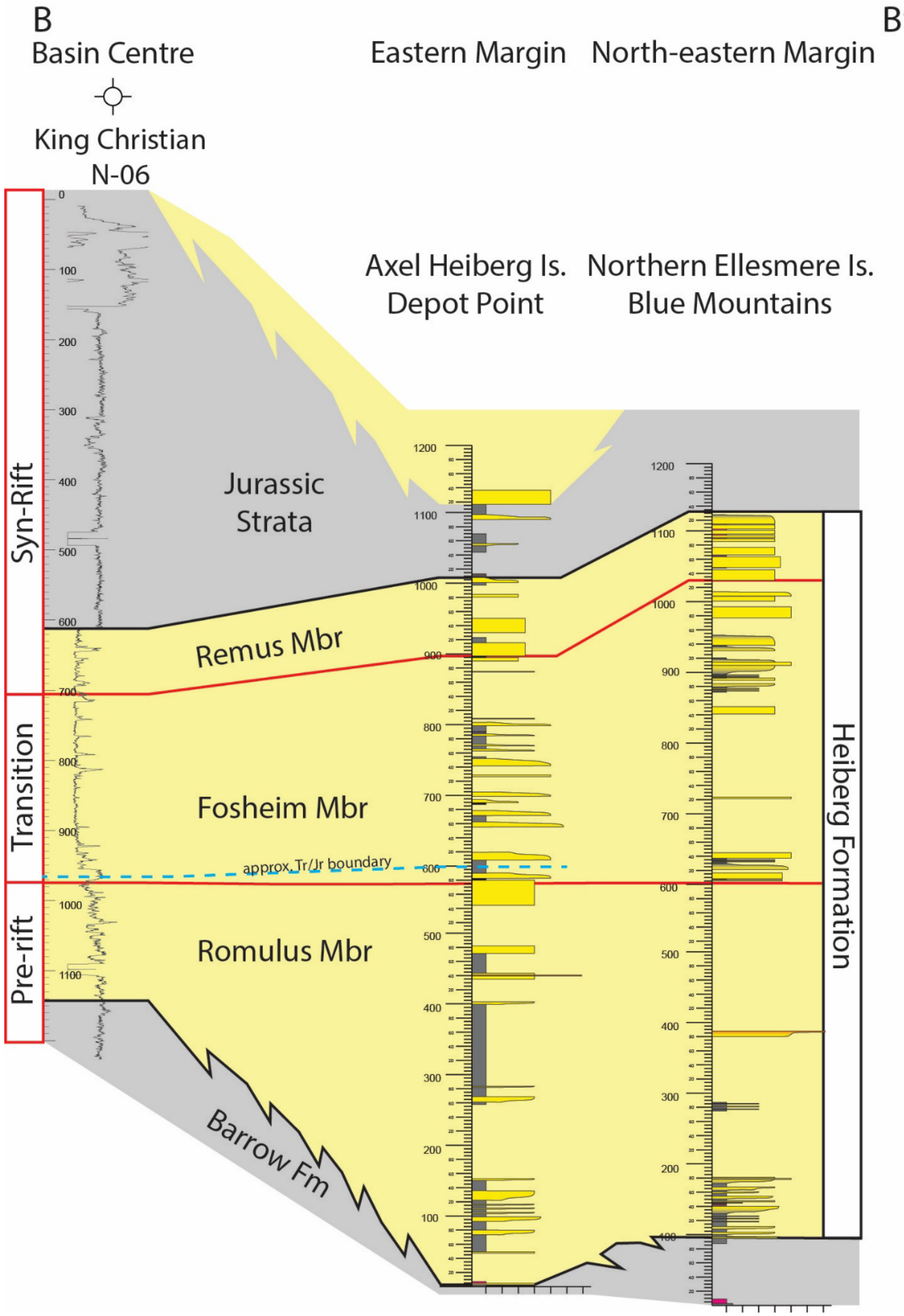

Figure 10: Stratigraphic cross-section of the Sverdrup Basin from the basin centre, south of Ellef Ringnes Island to the north-eastern basin margin, at Blue Mountains. Approximate location of Triassic-Jurassic boundary based on Suneby and Hills (1988) and Embry and Suneby (1994). Location of cross-section shown in Figure 1. Horizontal dimension is not to scale. Stratigraphic framework is from Embry (1983b, 1991, 1993) and Dewing and Embry (2007). The rifting stages are modified from Hadlari et al. (2016).