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Tonian deltaic and storm-influenced marine sedimentation on the edge of Laurentia: The Veteranen Group of northeastern Spitsbergen, Svalbard

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ABSTRACT

The Hecla Hoek succession of northeastern Svalbard, Norway, is an ~7 km thick Tonian–Ordovician sedimentary succession that overlies Stenian–Tonian felsic igneous and metasedimentary rocks. The carbonate-dominated upper Tonian–Ediacaran (ca. 820–600 Ma) Akademikerbreen and Polarisbreen groups have yielded important insights into Earth's Neoproterozoic climate, environment, and biological evolution. However, the underlying siliciclastic-dominated lower Tonian (ca. 950–820 Ma) Veteranen Group has garnered little attention despite the fact that it is remarkably well-preserved and hosts diverse microfossil assemblages. Here, we present the first detailed sedimentological analysis of the Veteranen Group from a continuous ~4.4 km thick stratigraphic section at Faksevågen, Ny Friesland, Spitsbergen. Integrated facies analysis, sequence stratigraphy, and carbonate $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ chemostratigraphy elucidate the early depositional history of the Hecla Hoek basin and provide fundamental paleoenvironmental constraints for future investigations of this succession as an archive of Tonian Earth History. The Veteranen Group records a long-lived deltaic and storm-influenced marine sedimentary system that reveals dynamics of Precambrian clastic sedimentation prior to the evolution of land plants. Five asymmetric transgressive-regressive (T-R) sequences within the Veteranen Group thin upwards, providing support for the hypothesis that the contact with the Akademikerbreen Group represents a rift-to-drift transition. This complex record of Tonian deltaic and storm-influenced marine sedimentation along the Laurentian margin strengthens correlation between the Veteranen Group and coeval strata from East Greenland and sets the stage to better understand the Proterozoic tectonic evolution of the North Atlantic–circum-Arctic region following the Grenville orogeny.

1. Introduction

The Hecla Hoek "succession" (also referred to as "series," or "complex") is an informal designation for a low-grade and well-exposed ~6 km thick Neoproterozoic–Ordovician sedimentary succession in the northeastern Svalbard archipelago of Norway (Fig. 1). These strata are recognized worldwide for yielding key insights into Neoproterozoic paleontology (e.g., Knoll et al., 1991; Butterfield et al., 1994; Mus et al., 2020; Riedman et al., 2021), paleoclimate (Harland et al., 1993; Bao et al., 2009; Hoffman et al., 2012), and global biogeochemistry (e.g., Knoll et al., 1986; Halverson et al., 2005; Wörndle et al., 2019). Yet, these diverse insights are all from the middle Tonian–Ediacaran Akademikerbreen and Polarisbreen groups (middle and upper Hecla Hoek succession, respectively), whereas the underlying ~4.5 km thick lower Tonian Veteranen Group has garnered relatively little attention. For example, a regional investigation of stratigraphic correlatives to the lower Veteranen Group (Sandelin et al., 2001) is the only study to examine these strata since their early map-scale descriptions (Harland et al., 1966; Flood et al., 1969). Although abundant and well-preserved microfossils, including likely early eukaryotic life, have also been recovered from the Veteranen Group (Knoll, 1982; Knoll and Swett, 1985), they have been presented with reconnaissance-level sedimentological and stratigraphic context. In fact, no detailed sedimentological, geochemical, or geochronological data exist from the Veteranen Group.

Similarities between the age, stratigraphy, detrital zircon U—Pb geochronology, and basement geology of the Neoproterozoic Hecla Hoek succession in northeastern Svalbard and the Eleonore Bay Supergroup and

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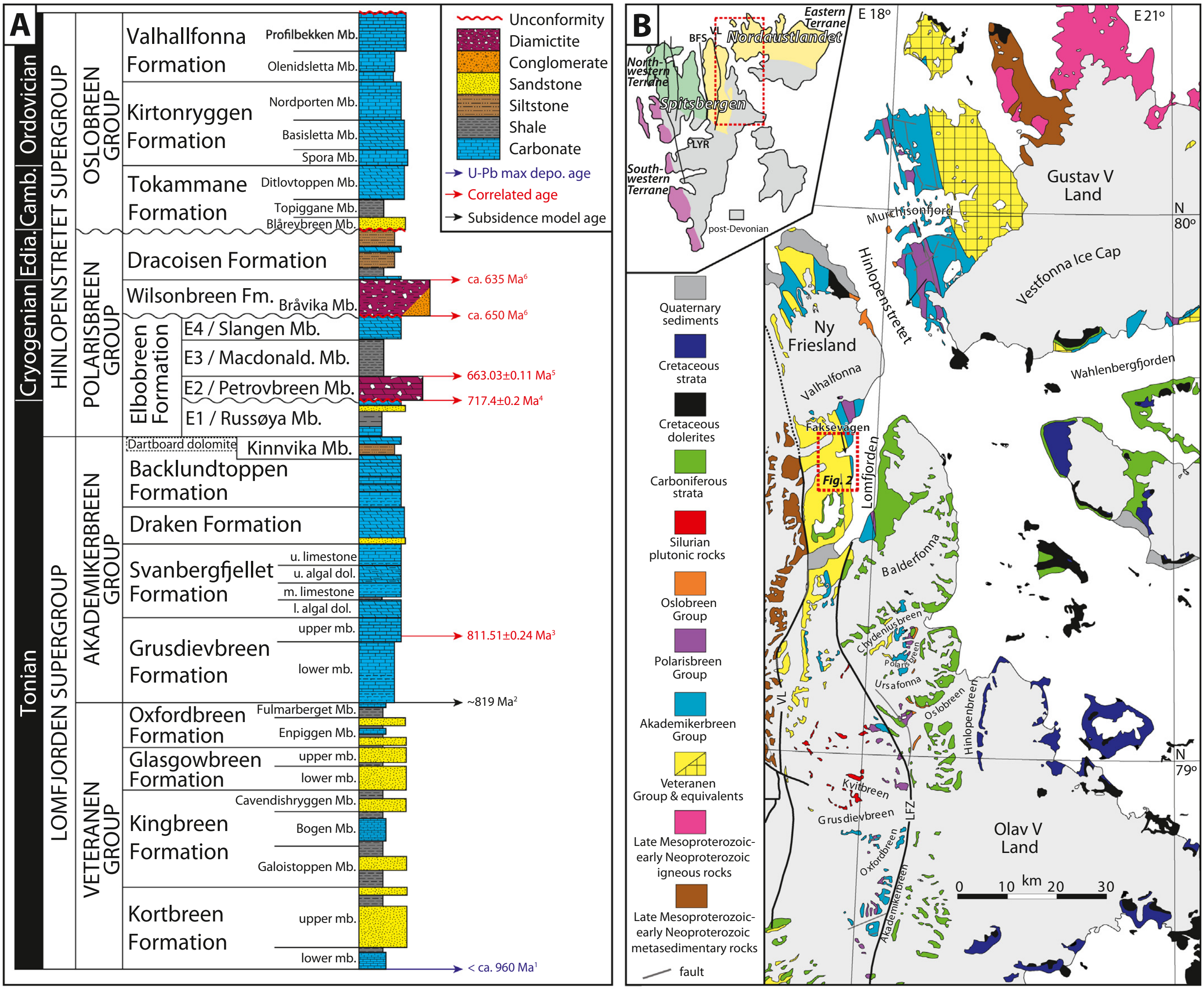
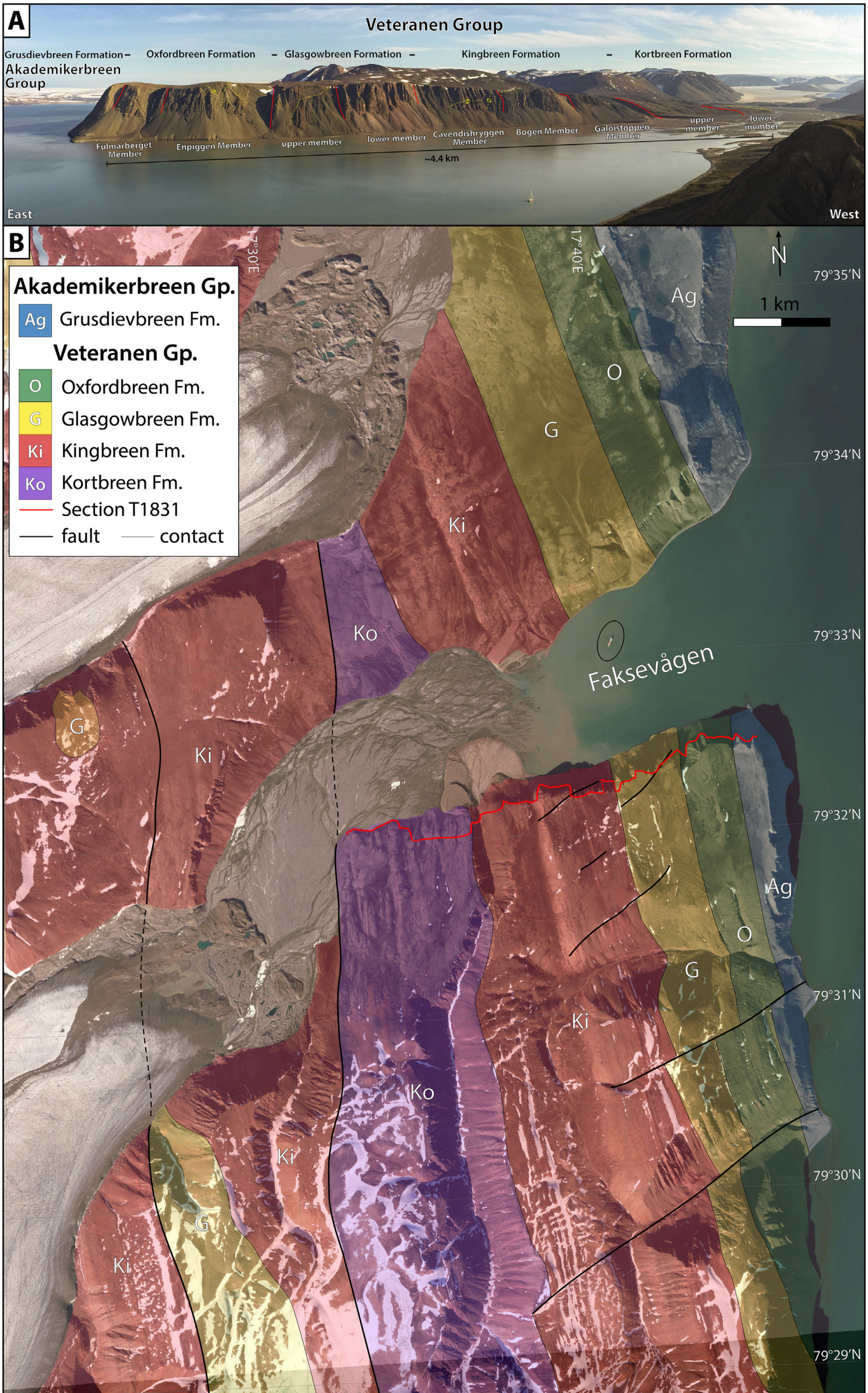


Fig. 1. A. Schematic lithostratigraphy of the Tonian–Ordovician Hecla Hoek succession of northeastern Svalbard, Norway modified from Halverson et al. (2018a). Stratigraphic thicknesses are not to scale. Edia.—Ediacaran; Camb.—Cambrian; Depo.—depositional; Mb.—Member; Fm.—Formation; u.—upper; l.—lower; m.—middle. Age constraints are color-coded based on methodology and are from the following sources: 1—Johansson et al. (2005); 2—Halverson et al. (2018b); 3—Cohen et al. (2017); 4—Macdonald et al. (2018); 5—Cox et al. (2018); 6—Hoffman et al. (2017) and references therein. B. Geological map of northeastern Spitsbergen and western Nordaustlandet modified from Halverson et al. (2018a). The red box indicates the study location at Faksevågen shown in Fig. 2b. VL—Veteranen Line; LFZ—Lomfjorden fault zone. Inset Map: Simplified terrane map of the Svalbard archipelago showing the three pre-Devonian basement provinces (green—Northwestern; pink—Southwestern; yellow—Eastern). The black box indicates the area shown on the larger map. BFZ—Billefjorden fault zone; VL—Veteranen Line; LYR—Longyearbyen. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Tillite Group in East Greenland suggest they originated from a unified basin that was segmented and displaced during the Silurian–Devonian Caledonian orogeny (Knoll et al., 1986; Fairchild and Hambrey, 1995; Harland, 1997; Gee and Teben'kov, 2004; Johansson et al., 2005; Sønderholm et al., 2008; Lorenz et al., 2012; Bazarnik et al., 2019). Despite these similarities, there are key differences between these age-equivalent successions, such as their relationships to underlying Tonian magmatic rocks and contrasts in thicknesses, which are crucial for evaluating tectonic models for the greater North Atlantic region (e.g., McClelland et al., 2019). Thus, a detailed reconstruction of the depositional history of the Veteranen Group is necessary to shed light on the tectonic setting of this and other poorly understood Tonian sedimentary basins that originated along the periphery of northeastern Laurentia (e.g., Nystuen et al., 2008). Here, we provide the first detailed stratigraphic and sedimentological analysis of the Veteranen Group from a remarkably well-preserved ~4.5 km thick section in northeastern Spitsbergen (Fig. 2). This study provides critical environmental context for understanding the Hecla Hoek succession as an extraordinary archive of Neoproterozoic geobiology and geochemistry and for shedding light on Tonian sedimentary basin formation along the edge or Laurentia.

Fig. 2. A. Subvertical outcrop of the Veteranen and lowermost Akademikerbreen groups along the southern coast of Faksevågen where stratigraphic section T1831 was measured and logged. The photograph is looking south and stratigraphic up is to the left. Contacts are traced in red, and faults are marked with yellow dashed lines. Fault kinematics are shown with yellow arrows where they could be resolved. B. Annotated airphoto and geological map of the study location at Faksevågen, northeastern Spitsbergen showing the main geological relationships. Note ~100 m long ship anchored in Faksevågen for scale (circled). Gp.—Group; Fm.—Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


A
Veteranen Group
Grusdievbreen Formation
Akademikerbreen Group
Oxfordbreen Formation
Glasgowbreen Formation
Kingbreen Formation
Kortbreen Formation
Fulmarberget Member
Enpiggen Member
upper member
lower member
Cavendishryggen Member
Bogen Member
Galoistoppen Member
upper member
lower member
~4.4 km
East
West
B
Akademikerbreen Gp.
Ag Grusdievbreen Fm.
Veteranen Gp.
O Oxfordbreen Fm.
G Glasgowbreen Fm.
Ki Kingbreen Fm.
Ko Kortbreen Fm.
Section T1831
fault
contact
17°30'E
17°40'E
N
1 km
79°35'N
79°34'N
79°33'N
79°32'N
79°31'N
79°30'N
79°29'N
Faksevågen
Ag
O
G
Ki
Ko

2. Geological background

Svalbard consists of three pre-Devonian basement domains—the Southwestern, Northwestern, and Eastern basement provinces—that are generally separated by significant north–south-trending strike-slip fault zones (Fig. 1 inset) (Harland, 1997; Gee and Teben'kov, 2004; Wala et al., 2021). These basement provinces were likely juxtaposed during the Silurian–Devonian Caledonian orogeny and later blanketed by Devonian–Paleogene overlap assemblages (Piepjohn, 2000). The Eastern basement province is itself subdivided into the West Ny Friesland (northeastern Spitsbergen) and Nordaustlandet terranes (comprising Nordaustlandet and eastern Ny Friesland) (Gee et al., 1995; Harland, 1997). The boundary between these terranes is represented by the Veteranen Line (also known as the Eolussletta shear zone) (Lyberis and Manby, 1999; von Gosen et al., 2019), which is a broad (up to 3 km) subvertical and polydeformed sinistral strike slip fault zone with unknown displacement. Both terranes are considered to have Laurentian tectonic affinities (Gee et al., 1995; Bazarnik et al., 2019 and references therein), but the Neoproterozoic–Ordovician Hecla Hoek succession is only preserved in the Nordaustlandet terrane (Fig. 1).

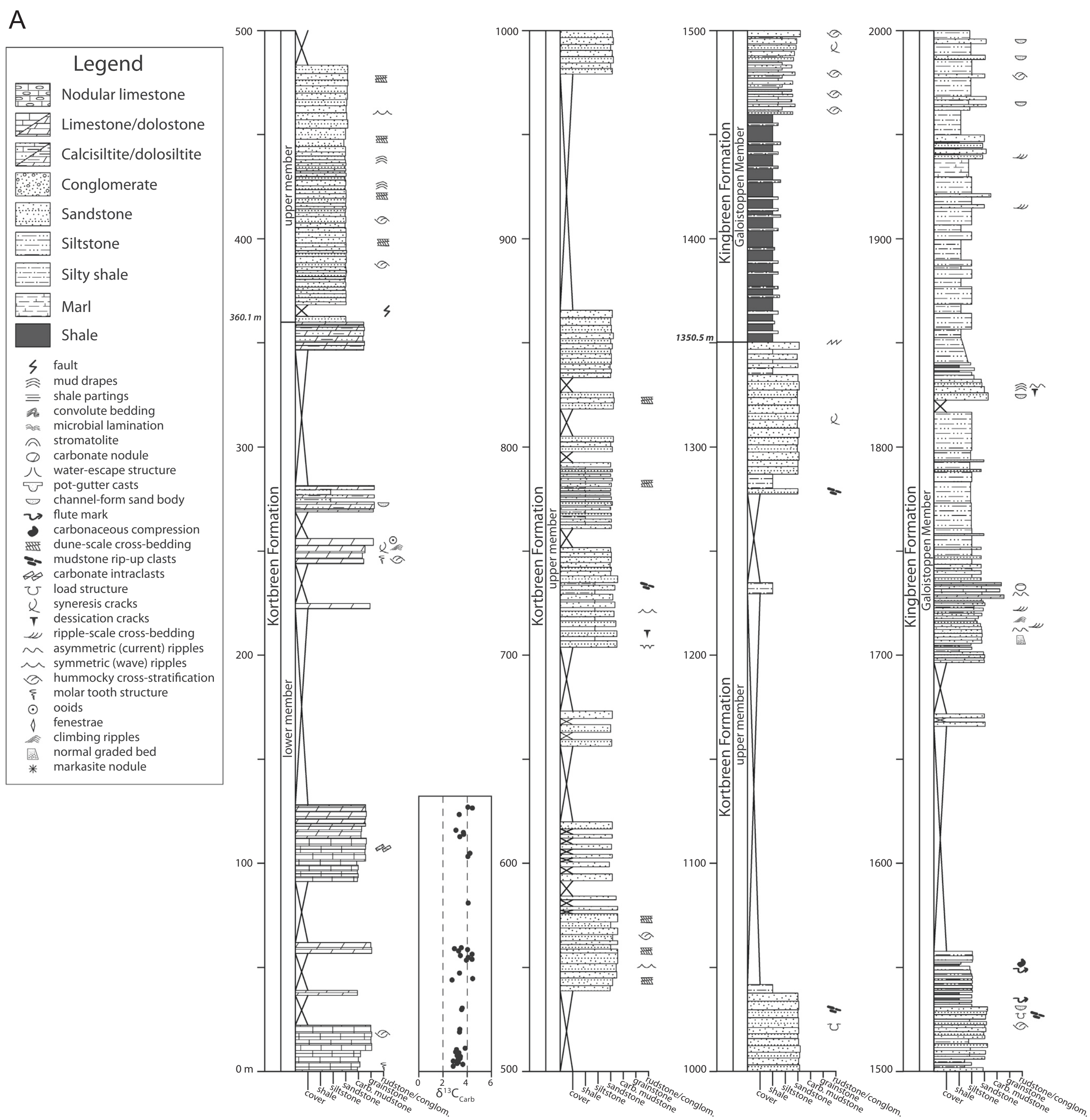


Fig. 3. Detailed stratigraphic section (T1831) of the Veteranen Group and lowermost Akademikerbreen Group at Faksevågen plotted against $\delta^{13}C_{carb}$ from carbonate-dominated intervals (Table S1). Stratigraphic heights are cumulative from the base of the section.

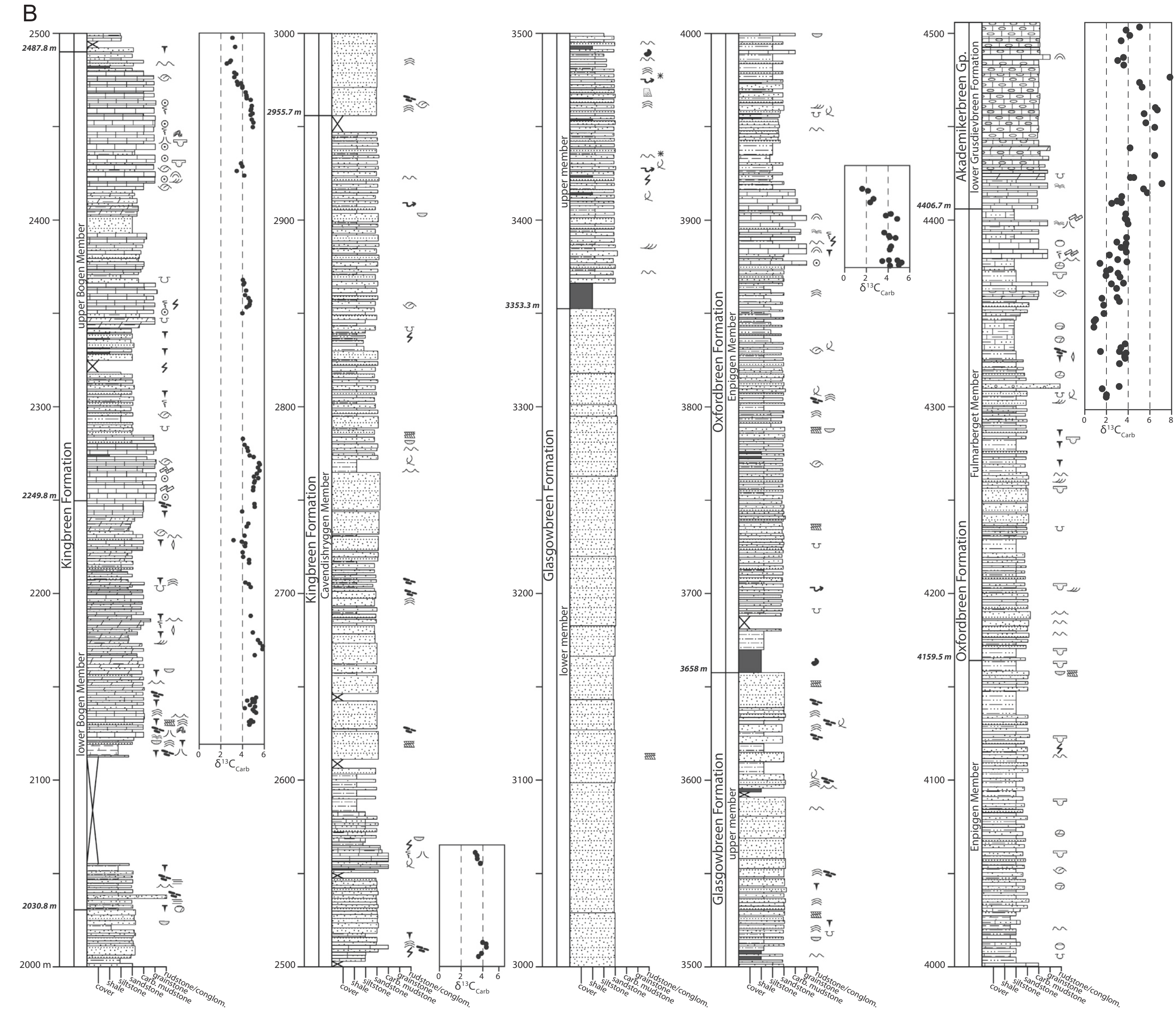


Fig. 3 (*continued*).

The Hecla Hoek succession has historically been defined to include different metasedimentary and igneous units along with the overlying sedimentary successions (Harland and Wilson, 1956; Harland et al., 1966). Here we follow the more restricted definition that only includes the Neoproterozoic–Ordovician sedimentary succession (Halverson et al., 2018a). Although a different nomenclature has been used for correlative strata on either side of Hinlopenstretet (Fig. 1), the lower to middle Hecla Hoek succession consists of correlative Tonian strata in Ny Friesland and Nordaustlandet (Harland et al., 1966; Flood et al., 1969; Fairchild and Hambrey, 1995; Sandelin et al., 2001; Halverson et al., 2005). In Ny Friesland, the Veteranen and Akademikerbreen groups comprise the Lomfjorden Supergroup. Correlative strata in Nordaustlandet includes the Galtedalen, Franklinsundet, Celsiusberget, and Roaldtoppen groups, which together comprise the Murchisonfjorden Supergroup (Fig. 1). These strata are all unconformably overlain by the Hinlopenstretet Supergroup, which includes the Cryogenian–Ediacaran Polarisbreen Group and Cambrian–Ordovician Oslobreen Group; these latter groups are separated by an erosional unconformity (Fig. 1).

The contact between the lower Hecla Hoek succession and underlying Stenian–Tonian basement units is only exposed in north-central Nordaustlandet, where the ~300 m thick Galtedalen Group rests unconformably atop both metasedimentary units of the ca. 1050 Ma Brennevinsfjorden Group and ca. 960–940 Ma felsic volcanics of the Kapp Hansteen Group and its intrusive equivalents (Kontaktberget granite and Lapponiafjellet augen gneiss) (Gee et al., 1995; Gee and Teben'kov, 1996; Johansson et al., 2000, 2005). Presently, the Galtedalen Group is thought to either be correlative with, or to conformably underlie the basal units of the lower Hecla Hoek succession (Sandelin et al., 2001). Together, these relationships broadly constrain the maximum depositional age of the Veteranen Group to <940 Ma.

The Veteranen Group comprises ~4.4 km of mixed carbonate and siliciclastic strata in Ny Friesland, which can be divided into four formations (in ascending stratigraphic order): the Kortbreen, Kingbreen, Glasgowbreen, and Oxfordbreen formations (Fig. 1) (Harland et al., 1966). The upper contact of the Veteranen Group with the overlying carbonate-dominated Akademikerbreen Group is transitional and marked by a gradual increase in carbonate content (Harland and Butterfield, 1997; Halverson et al., 2018a). Lower Akademikerbreen Group carbonate units of the Grusdievbreen and Svanbergfjellet formations preserve the globally synchronous Bitter Springs carbon isotope anomaly (Halverson et al., 2007), which commenced at ca. 810 Ma (Macdonald et al., 2010; Swanson-Hysell et al., 2015; Cohen et al., 2017) and provides a minimum depositional age for the Veteranen Group.

3. Methods and materials

3.1. Fieldwork and sample collection

The Veteranen Group crops out on the south side of Faksevågen in Ny Friesland, northeastern Spitsbergen (Fig. 2). There, ~4.4 km of subvertical strata of the Veteranen Group were measured, logged, and sampled as a single stratigraphic section (T1831) (Fig. 3). This section begins with low-lying outcrops of the lower Kortbreen Formation just west of an unnamed north–south-striking fault, and continues to the east, connecting the best exposed and most accessible exposures along talus slopes and on the top or bottom of the large cliffs south of Faksevågen (Fig. 2). The general inaccessibility of many of the thick sandstone-dominated stratigraphic intervals prevented the collection of detailed paleocurrent data. Strata were correlated across small faults (<100 m of displacement), whose stratigraphic positions are indicated on the measured section (Fig. 3). All heights are expressed as the cumulative stratigraphic height from the base of section T1831.

3.2. Carbonate carbon and oxygen isotope geochemistry

We present 243 new stable carbonate carbon and oxygen isotopic analyses of carbonate samples collected from stratigraphic section T1831 (Figs. 2, 3). Hand samples (~100–500 g) were collected from carbonate-dominated intervals at ~0.5–4.0 m resolution throughout the Veteranen Group. All isotopic data are reported in delta notation ($\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$) as per mil (‰) deviations relative to the Vienna Pee Dee Belemnite (VPDB) standard (Table S1, Fig. 12 Inset). Samples were first cut perpendicular to bedding and micro-dilled (~2–10 mg of powder) parallel to lamination to avoid secondary veins, cements, and any siliciclastic components. Isotopic compositions were analyzed via a continuous flow Thermo Scientific™ Delta Plus XL isotope ratio mass spectrometer (IRMS) coupled with a Gasbench II inlet device at Dartmouth College. Purified phosphoric acid (H_3PO_4) was added to approximately 0.1 mg of powder from each sample in 12 ml glass vials at 70 °C. The evolved CO_2 from this reaction was analyzed against an in-house reference gas. Sample data were then calibrated to the VPDB scale using three international standards (NBS-18: $\delta^{13}C_{carb} = -5.01$‰, $\delta^{18}O_{carb} = -23.2$; NBS-19: $\delta^{13}C_{carb} = +1.95$‰, $\delta^{18}O_{carb} - 2.20$‰; CM: $\delta^{13}C_{carb} = 1.85$‰, $\delta^{18}O_{carb} - 2.22$‰) and an in-house standard (Callison Lake Dolostone [CLD] $\delta^{13}C_{carb} = 2.36$‰, $\delta^{18}O_{carb} = -3.57$). Total analytical uncertainty is better than ±0.2‰ (1σ) for $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$, which was calculated from repeat standard analyses.

4. Stratigraphy and sedimentology

4.1. Kortbreen Formation

4.1.1. Lower member description

The Kortbreen Formation is divided into two informal members (Fig. 3). The lower Kortbreen Formation is the lowest unit of the Veteranen Group exposed at Faksevågen, where it is in fault contact with stratigraphically higher units of the Veteranen Group to the west (Fig. 2) and is exposed in patchy, steeply dipping outcrops just above a braided gravel plain west of Faksevågen (Fig. 3). This 360.1 m thick unit is predominantly composed of light gray to black, wavy-bedded limestone with minor shale and siltstone interbeds (Fig. 4A, B, C). Carbonate facies include thin- to medium-bedded lime mudstone and grainstone with molar tooth structures (MTS), small- to medium-scale hummocky cross-stratification (HCS), syneresis cracks, sigmoidal trough cross-stratification, and minor intraclast conglomerate. Less common facies include buff-weathering, crudely stratified and recrystallized dolostone with spar-filled vugs and rare oolitic dolograinstone with silty to sandy laminae (<1 cm thick) (Fig. 3).

4.1.2. Lower member interpretation

Sedimentary structures in the lower Kortbreen Formation, such as HCS, syneresis cracks, and MTS, indicate these strata record open marine, storm-influenced carbonate deposition above storm wave base (SWB) in a middle to inner shelf environment. HCS requires powerful waves, and the wavelengths between large HCS crests (>100 cm) scale to the orbital diameter of the waves that created them (Yang et al., 2006). Thus, the fetch necessary to produce the observed HCS wavelength (maximum = ~100 cm) from the lower Kortbreen Formation requires a body of water with at least ~10–50 km of fetch (e.g., Myrow et al., 2008). This storm influenced middle to inner shelf setting is supported by the presence of rare intraclast conglomerate (e.g, Myrow et al., 2004) and the input of terrigenous siliciclastic material within the carbonate facies.

4.1.3. Upper member description

The contact between the lower and upper Kortbreen Formation is marked by the abrupt transition from carbonate to siliciclastic facies (Fig. 3). The 990.4 m thick upper Kortbreen Formation is primarily composed of poorly exposed white to brick red, medium- to thick-bedded, and moderately to well-sorted quartz arenite, which is exposed just above a gravel plain west of Faksevågen. Sandstone strata between ~360–700 m in section T1831 contain abundant ~10–70 cm thick (herein referred to as dune-scale) sigmoidal to tabular cross-stratification (Fig. 4D) and rare HCS, as well as symmetric wave ripples (straight-crested and bifurcated; Fig. 4E) and ~ 50 cm thick normal-graded beds. There is little to no interbedded shale or siltstone in this unit, except for a poorly exposed interval between ~700–800 m. The base of this finer-grained interval (~705 m) contains abundant polygonal sand-filled structures, herein identified as mudcracks, and floating siltstone and shale rip-up clasts within sandstone beds. Sandstone facies in the upper part of this interval (at ~760 m) transition to predominantly red and white, dune-scale trough and tabular cross-bedded quartz arenite, although much of the remaining upper member is covered. The generally poor exposure and lack of three-dimensional outcrop exposures prevented our ability to accurately measure paleocurrents in this member.

4.1.4. Upper member interpretation

Sandstone facies in the upper Kortbreen Formation are dominated by dune-scale trough and tabular cross-stratification, wave ripples, and minor HCS (Figs. 3, 4D, E), which along with a near absence of shale, provide evidence for shallow marine deposition almost entirely above fair-weather wave base (FWWB), likely within shoreface and foreshore environments. Given the lack of paleocurrent data and the general poor exposure of this unit, some of these coarser-grained strata may include terrestrially influenced sedimentation, such as within sandy fluvial to coastal plain environments, but the common occurrence of symmetrical wave ripples and HCS suggest they were short-lived.

The presence of unambiguous mudcracks in the upper Kortbreen Formation (Fig. 3) requires episodic subaerial exposure and may reflect deposition within a periodically exposed muddy shoreline system (e.g., intertidal zone of a tidally influenced shoreline). The remainder of the measured section from ~700–800 m contains few diagnostic sedimentary structures, although the interbedded sandstone and shale between ~760–790 m may reflect deposition between FWWB and SWB.

4.2. Kingbreen Formation

4.2.1. Galoistoppen Member description

Laminated silty shale at the base of the 680.3 m thick Galoistoppen Member of the Kingbreen Formation rests sharply on medium- to

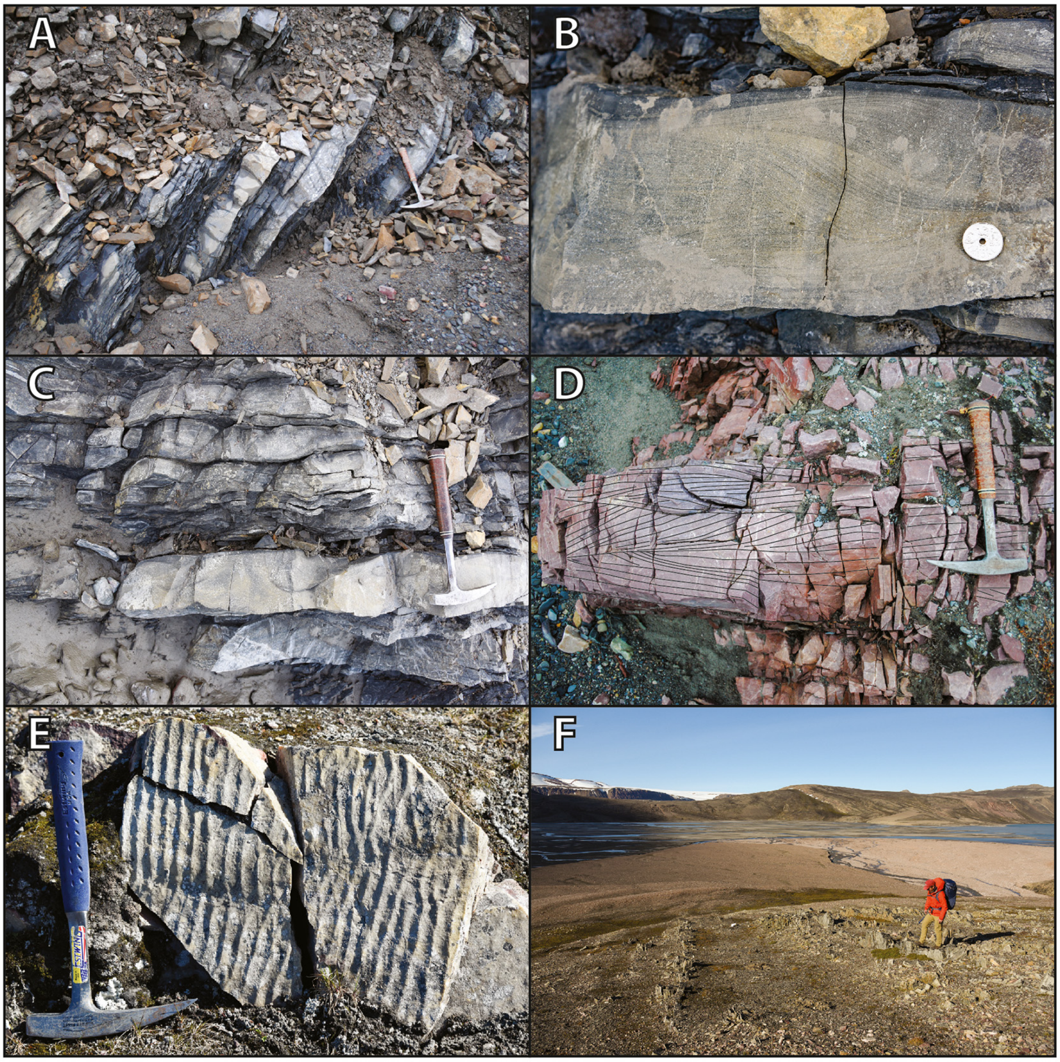


Fig. 4. Photographs of the Kortbreen Formation from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Rock hammer is 33 cm long, and coin is ~2.1 cm in diameter. A. Interbedded, wavy, carbonaceous lime grainstone and mudstone from the basal Kortbreen Formation. Stratigraphic up is to the left. B. Sigmoidal, stoss-preservational cross-lamination at 245 m in the lower member of the Kortbreen Formation. *C. Medium*-bedded, hummocky cross-stratified grainstone with black shale drapes at 245.5 m in the lower member of the Kortbreen Formation. D. Dune-scale, trough cross-bedded quartz arenite in the upper member of the Kortbreen Formation at ~400 m, annotated to highlight cross-stratification. E. Small, two-dimensional wave ripples with bifurcations in float near 704 m in the upper member of the Kortbreen Formation. F. Poorly exposed, subvertical "tombstone topography" outcrop of the upper Kortbreen Formation ~1230 m. Stratigraphic up is to the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thick-bedded quartz arenite and minor shale of the uppermost 10 m of the Kortbreen Formation (~1340–1350 m) (Fig. 3). Between ~1460 and1532 m, the Galoistoppen Member transitions to medium-bedded and fine- to medium-grained, green micaceous lithic arenite with abundant starved ripples and small-scale HCS with minor syneresis cracks, load structures, and thin normal-graded beds. These normal-graded beds occasionally also preserve distinct assemblages of sedimentary structures consistent with Bouma A-B-C-E or A-C-E subdivisions (Bouma, 1962). The sandstone is interbedded with minor (~10%) very-thin- to thin-bedded siltstone and green silty shale (Fig. 5B). At 1532 m, this facies transitions (Figs. 3, 5A) entirely to gray-green silty shale and thin-bedded gray sandy siltstone with tool marks, flute casts, and rare carbonaceous compressions.

Above a largely covered interval between 1558 and 1697.3 m is ~25 m of thin-bedded, planar-laminated, dark gray-green, fine- to medium-grained, sublitharenite and quartz arenite with siltstone and thin shale interbeds. The siltstone and sandstone contain <5 cm thick (herein referred to as ripple-scale) trough cross-bedding, climbing ripple lamination, thin normal-graded beds, and rare flute marks (Fig. 5C, D, E). Between 1724.3 and 1735.6 m, the sandstone grades upwards into sandy grainstone and ribbon-bedded lime mudstone. Carbonate content abruptly diminishes and gives way to uniform green siltstone with minor thin quartz arenite beds until a distinctive 2.9 m thick and ~ 15 m wide white quartz arenite lens-shaped marker bed at 1823.8 m (Fig. 5F). Above this white quartz arenite is an ~3 m thick wavy-bedded green and brown sublitharenite with symmetrical ripples, mud drapes, and abundant mudcracks. The remainder of the member is composed of fissile, red and green siltstone and silty shale (Fig. 5G) with thin tabular sandstone beds and lensoidal bodies (Fig. 5H), minor marl and calcisiltite, and one dolomitic rudstone bed at 1939.5–1939.9 m. From 2006 m to the contact with the overlying Bogen Member there is an increase in the proportion of sandstone facies with HCS and dune-scale trough cross-bedding.

4.2.2. Galoistoppen Member interpretation

The sharp transition from coarser-grained sandstone facies at the top of the upper Kortbreen Formation to laminated silty shale at the base of the Galoistoppen Member most likely represents a prominent flooding surface into a deeper-water outer shelf to upper slope setting below SWB (Fig. 3). Overlying medium- to thin-bedded sandstone

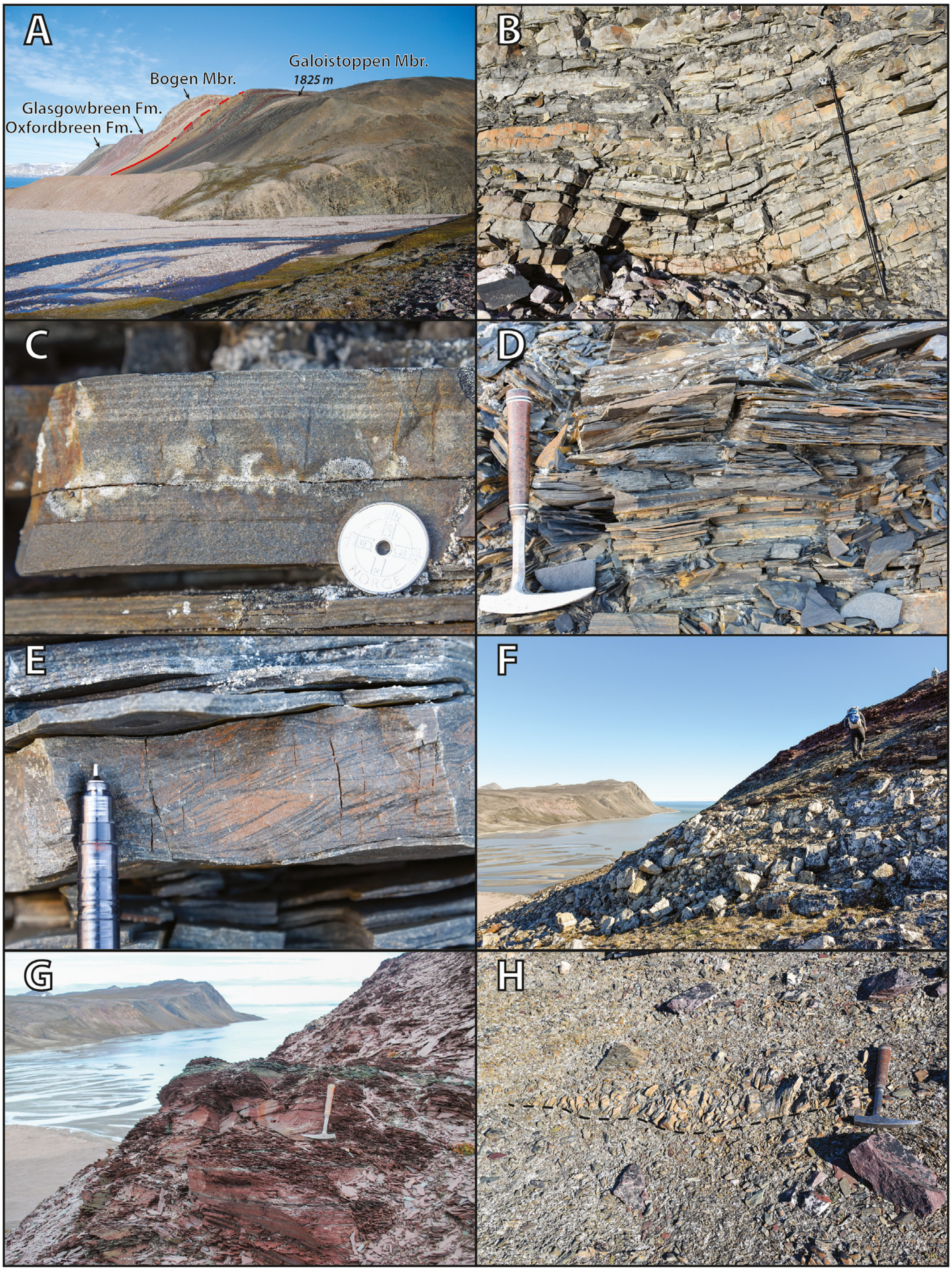


Fig. 5. Photographs of the Galoistoppen Member of the Kingbreen Formation from section T1831. Stratigraphic up direction is toward the top of each photo. Jacob's staff is 160 cm tall, rock hammer is 33 cm long, coin is ~2.1 cm in diameter, and pencil is 0.8 cm wide. A. Outcrop photograph of the Galoistoppen Member starting at ~1520 m, with the lower Bogen Member and Glasgowbreen Formation visible in the background (the upper Bogen and Cavendishryggen members are obscured). The red dashed line marks the Galoistoppen–Bogen contact. B. Medium- and wavy-bedded lithic arenite with thin silty shale and siltstone drapes at 1528 m. C. Planar-laminated, medium-grained lithic arenite transitioning upward into normally-graded, thick laminations at 1703 m. D. Planar-laminated, thin-bedded siltstone and very fine-grained sandstone at 1709 m. E. Ripple-scale cross-laminated lithic arenite at 1713.8 m. F. Channelized white quartz arenite marker bed at 1823.8 m. G. Variegated and laminated silty shale and siltstone at ~1895 m. H. Scour-fill sandstone body at 1985 m (traced by black dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with abundant HCS from ~1460–1530 m, as well as thin siltstone and shale interbeds with syneresis cracks (Fig. 5B), were likely deposited during an episode of shoaling above SWB, but shale and siltstone with tool and flute marks from ~1530–1560 m again indicate deposition below SWB. A similar setting below SWB is recorded in the overlying planar-laminated and dolomite-cemented sandstone and siltstone facies with minor sandy grainstone and ribbon-bedded lime mudstone beds between ~1560 and 1820 m (Figs. 3, 5D, E). These predominantly fine-grained strata of the Galoistoppen Member all likely record a combination of hypopycnal sediment plume and rare turbidity current deposits delivered to the distal outer shelf or upper continental slope from a fluvial deltaic point source along the basin margin.

The distinctive white quartz arenite channelized marker bed at 1823.8 m is overlain by interbedded sandstone and shale with symmetrical ripples, mud drapes, and mudcracks (Fig. 5F), which are consistent with a much shallower (possibly intertidal) setting. This abrupt change in the upper Galoistoppen Member likely reflects a marine regression. This is supported by the increased proportion of coarser-grained trough cross-stratified sandstone facies starting at ~2000 m, which reflects shoaling above FWWB through the contact with the Bogen Member at 2030.8 m.

4.2.3. Bogen Member description

Here, we designate informal "upper" and "lower" subdivisions of the 457 m thick Bogen Member with a distinct facies transition between the two units (Fig. 3). The lower Bogen Member consists of interbedded dark red and green lithic arenite, siltstone, and red silty shale with mudcracks, minor subrounded shale intraclast horizons, and rare raindrop prints (Fig. 6A, B, C). Starting at 2120.6 m, planar to lenticular thin to

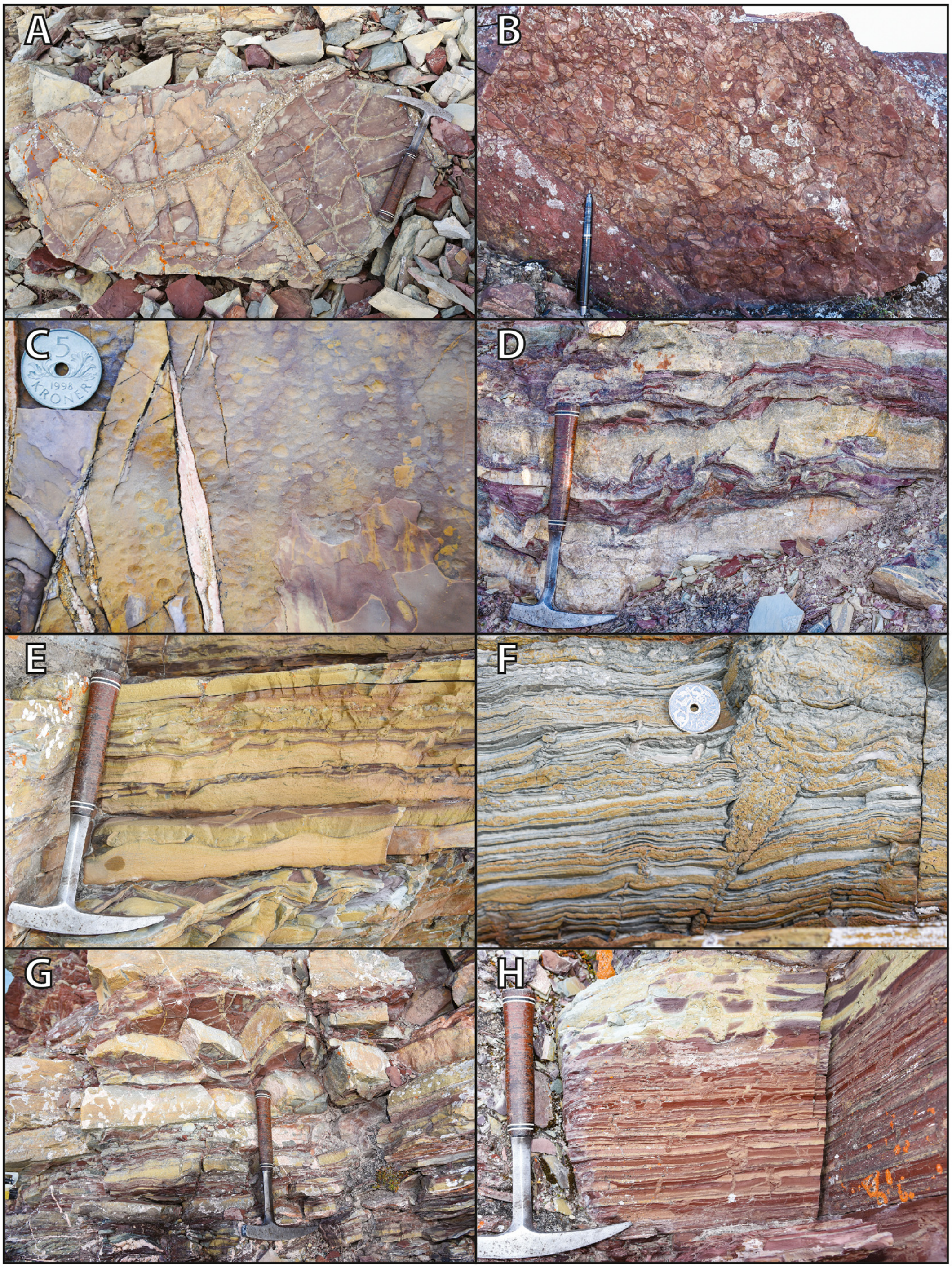


Fig. 6. Photographs of the lower portion of the Bogen Member (middle Kingbreen Formation) from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Rock hammer is 33 cm long, pencil is 14 cm long, and coin is ~2.1 cm in diameter. A. Multiple generations of mudcracks in red and green silty shale and medium-grained quartz arenite in float at the base of the Bogen Member at ~2031 m. B. Lower bedding plane view of sub-rounded lime mudstone intraclasts at ~2039 m. C. Upper bedding plane view of raindrop prints in float at ~2115 m. D. Wavy bedded white quartz arenite with red calcareous shale interbeds that transition laterally to rip-up clasts at 2120.8 m. E. Current ripples and parallel lamination in fine-grained sandstone and grainstone with fenestrae, mudcracks, intraclasts, and calcareous red shale drapes at 2127.4 m. F. Abundant molar tooth structures and mudcracks of various sizes in lime mudstone at 2131.5 m. G. Thickening-upward beds of quartz arenite to sublitharenite with mudcracked calcareous red shale interbeds at 2140 m. H. Molar tooth structures in red calcareous shale and buff dolomitic siltstone at 2244 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

medium beds of quartz arenite are interbedded with mudcracked calcareous red shale and calcisiltite with calcite microspar filled vugs. The carbonate content of the calcareous red shale facies increases until 2123.6 m, above which there are also thin beds of pale green and red carbonate mudstone with abundant water escape structures and intraclasts (Fig. 6D). Facies between 2123.6 and 2249.8 m comprise interbedded thin- to medium-bedded pale green and red lime carbonate mudstone, fine- to coarse-grained quartz arenite, and parallel-laminated to ribbon-bedded buff dolograinstone and dolosiltite. Water escape structures, microspar-filled MTS, and mudcracks are common in the carbonate facies (Fig. 6E, F, H), and the sandstones are often tabular to lenticular with both symmetrical and asymmetrical ripples (Fig. 6E, G). Many sandstone beds are carbonate-cemented and grade vertically into lime mudstone intervals that contain floating sand grains and microbial fenestrae or birds eye textures. Shale or mudstone intervals are commonly mudcracked (Fig. 6G) and contain intervals of subrounded rip-up clasts (Fig. 6D).

A massive black-weathering oolitic grainstone bed at 2249.8 m marks the transition to the upper Bogen Member (Fig. 7A, B). These strata predominantly consist of two alternating facies associations. The first outcrops from 2250–2285, 2343–2366, and 2416–2480 m and comprises HCS and trough-cross bedded oolitic and intraclast grainstone with floating coarse-grained quartz sand grains (Fig. 7C, E), organic-rich lime mudstone with MTS, green and gray planar-laminated calcisiltite/dolosiltite with pot and gutter casts (Fig. 7D), lime mudstone with water-escape structures (Fig. 7F), and very thin-bedded lime mudstone–shale couplets (Fig. 7E). In many cases, these facies are packaged into thickening- and coarsening-upward cycles, which at 2423.9 m culminates with <30 cm tall domal to columnar stromatolites. The second facies association is siliciclastic-dominated and consists of medium- to thick-bedded, tabular, carbonate-cemented quartz arenite with HCS, symmetrical ripples, load structures, thin interbeds of gray calcisiltite and silty shale with mudcracks, and rare soft-sediment deformation (Fig. 7G). Starting at 2480.8 m, the Bogen Member records the appearance of thin beds of brick red to white poorly-sorted quartz arenite that is transitional with the overlying Cavendishryggen Member of the Kingbreen Formation at 2487.8 m.

4.2.4. Bogen Member interpretation

The mixed siliciclastic–carbonate facies of the Bogen Member mostly display evidence for subtidal to peritidal sedimentation in a marginal marine setting. Abundant mudcracks, water escape structures, and well preserved raindrop imprints within these strata support episodic subaerial exposure, while intervals of lens-shaped medium to coarse-grained and cross-bedded sandstone reflect subaqueous scouring and deposition within possible tidal channels or tidal deltas. The facies transition between the lower and upper Bogen member at ~2250 m (Figs. 3, 7A, B) coincides with some facies that may reflect slightly deeper subtidal sedimentation, such as the appearance of oolitic grainstone or MTS lime mudstone, but much of the upper Bogen Member was deposited in a similar setting. The upper Bogen Member also preserves evidence for storm-influenced sedimentation, such as HCS and pot and gutter casts—the latter of which were generated by scouring and rapid infilling during storms in nearshore settings (Myrow, 1992). The carbonate grainstone beds with scoured bases, and which exhibit a vertical progression from parallel lamination to HCS (e.g., Fig. 7E), are storm-generated event beds (i.e., tempestites) deposited between FWWB and SWB (Myrow and Southard, 1991, 1996; Gibson et al., 2013). Finally, alternations between shallow-water carbonate- and siliciclastic-dominated facies were likely controlled by variation in the flux of terrestrially derived sand along a low-gradient sandy to muddy shoreline.

4.2.5. Cavendishryggen Member description

The basal Cavendishryggen Member is marked by ~5 m of mudcracked red, poorly-sorted sublitharenite, which is overlain by interbedded thin- to thick-bedded, medium- to coarse-grained quartz arenite to sublitharenite and shale. These facies transition at 2548 m to laminated black lime mudstone with water escape structures and syneresis cracks, which are interbedded with dolosiltite with thin sandstone lenses and eventually red and gray silty shale with rare thin- to medium-bedded sandstone. At 2555 m, this facies grades into tabular, thick- to medium-bedded, green and red, ripple cross-laminated quartz arenite and shale. Between 2603.4 and 2611.3 m, these facies exhibit thickening-upwards cycles composed of 10–50 cm thick beds of quartz arenite and 10–30 cm thick shale interbeds (Fig. 8C).

Above 2611.3 m, the Cavendishryggen Member is composed of an ~150 m thick interval of predominantly amalgamated, thick- to very-thick-bedded, brick red, white, and maroon quartz arenite with dune-scale tabular to trough cross-bedding and minor red shale drapes and intraclasts. Also present are ~1–5 m thick recessive intervals of thin to medium interbeds of quartz arenite (Fig. 8D) and siltstone. Symmetrical rippled sandstone at the top of this interval is in sharp contact (at 2765 m) with laminated silty shale above. The shale coarsens upwards over 7 m to medium-bedded and medium-grained quartz arenite with asymmetric ripples and shale interbeds with syneresis cracks (Fig. 8E). The remainder of the Cavendishryggen Member consists of coarsening- and thickening-upwards cycles of dark silty shale and quartz arenite; although in some cases, there are fining- and thinning-upwards cycles. These coarsening-upward deposits typically consist of interbedded sandstone and siltstone or silty shale, but there are also some ~2–6 m thick intervals of massive to crudely bedded (50–150 cm thick) amalgamated and tabular medium- to coarse-grained quartz arenite, as well as lens-shaped beds up to ~80 cm across and ~ 20 cm thick. Sedimentary structures in these strata include asymmetric ripples, load structures, HCS, and tool marks. The shale and siltstone are darker gray to black above 2860 m (Fig. 8F), and a number of 3–6 m thick, broadly channelized sandstone beds are present between ~2890 and~2900 m. The Cavendishryggen Member is 467.9 m thick.

4.2.6. Cavendishryggen Member interpretation

Mudcracked red shale at the base of the Cavendishryggen Member rests on an exposure surface that marks the contact with the Bogen Member at 2487.8 m (Figs. 3, 8A, B). The overlying thin-bedded mixed carbonate-siliciclastic facies with mudcracks and intraclast horizons in the lower ~60 m of the member (Fig. 8B) likely represent nearshore deposits similar to those envisioned for the underlying Bogen Member. The Cavendishryggen Member then records a prominent transition up-section into siliciclastic-dominated strata, which may reflect the return of a clastic point-source or marine transgression. Although distinctive channel-fill deposits in the lower Cavendishryggen Member are not well preserved, the ~3–5 m thick coarsening- and thickening-upward cycles that vary from mudcracked silty shale to amalgamated cross-bedded sandstone may reflect tidal channel or tidal delta migration within a tidally influenced delta plain or delta front setting.

The coarsening- and thickening-upward succession from ~2585–2600 m is dominated by a thick interval of amalgamated, thick- to very-thick-bedded sandstone with dune-scale trough and tabular cross-bedding (Figs. 3, 8A, C) with minor red shale/siltstone drapes and rip-up clasts (Fig. 8D). These strata likely represent a transition from subaerial shoreline deposition to subtidal sedimentation between FWWB and SWB. We interpret the abrupt transition at ~2765 m into laminated silty shale (Fig. 3) as a deepening trend into outer shelf facies, reflecting marine transgression. This is supported by the presence of tabular sandstone and shale interbeds with syneresis cracks, symmetric ripples, load structures, and HCS in the interval from 2765 m to the top of the Cavendishryggen Member at ~2950 m, which were similarly deposited between FWWB and SWB (Fig. 8E). The transition from more organic-rich shale above 2860 m, to coarsening- and thickening-upwards cycles with broadly channelized sandstone facies above ~2890 m, suggests a gradational transition back into nearshore, tidally influenced delta plain or delta front depositional environments just below the contact with the Glasgowbreen Formation at 2955.7 m (8F).

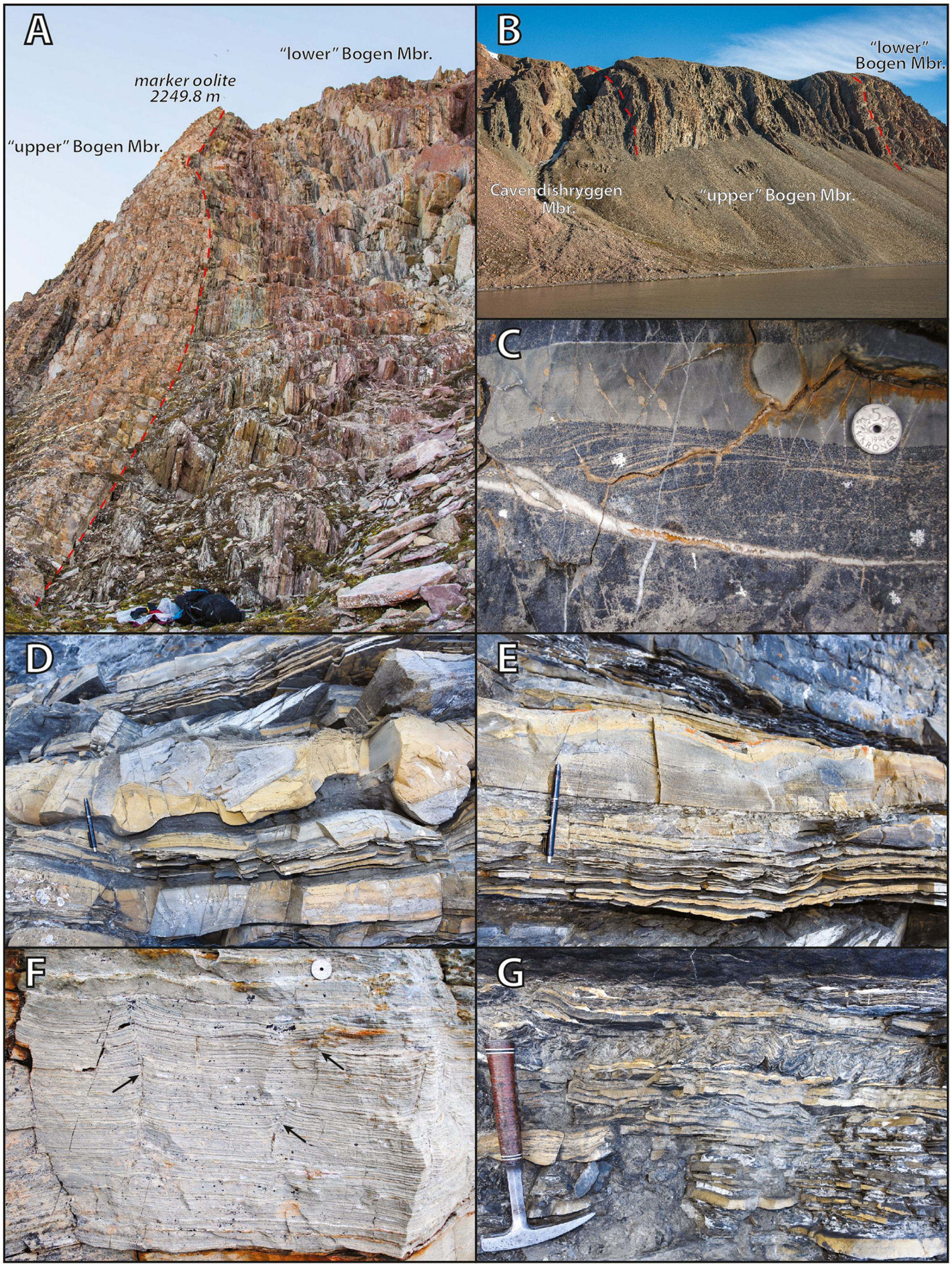


Fig. 7. Photographs of the upper portion of the Bogen Member (middle Kingbreen Formation) from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Rock hammer is 33 cm long, pencil is 14 cm long, and coin is ~2.1 cm in diameter. A. Outcrop view of an oolitic grainstone bed at 2249.8 m (base is traced in red dashed line) that marks the transition from the red, tidally-influenced carbonate–siliciclastic facies of the lower Bogen Member to the gray, storm-dominated carbonate facies and minor sandstone of the upper Bogen Member. Stratigraphic up is to the left. B. Outcrop view of well-bedded carbonate-dominated facies of the upper Bogen Member (contacts traced by red dashed line). C. Sigmoidal cross-stratification in dark gray, oolitic grainstone grading upwards into fine-grained grainstone at 2420 m. D. Gutter-casts of variably dolomitized calcareous siltstone cutting down into laminated silty to sandy shale at 2430 m. E. Interbedded oolitic grainstone and black shale overlain by sharp-based oolite bed that grades upwards from parallel lamination into hummocky cross-stratification at 2432 m. F. Laminated lime mudstone with thin, subvertical fluid escape structures shown with black arrows at 2438.3 m. G. Thin-bedded lime mudstone and black shale interbeds with *syn*-depositional convolute bedding at 2441 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Glasgowbreen Formation

4.3.1. Lower member description

The 397.6 m thick lower Glasgowbreen Formation consists almost entirely of amalgamated, tabular, white, red, and maroon, medium- to thick-bedded quartz arenite (Figs. 3, 9). The sandstone is dominantly fine- to medium-grained and moderate to well-sorted. This highly uniform facies forms very steep walls and talus cones (Fig. 9A), making much of the lower Glasgowbreen Formation inaccessible. This interval was measured across the top of glacially peneplaned plateau, and thus fewer details were observed for this unit, including the collection of paleocurrent data. Most observed beds in this unit are parallel-

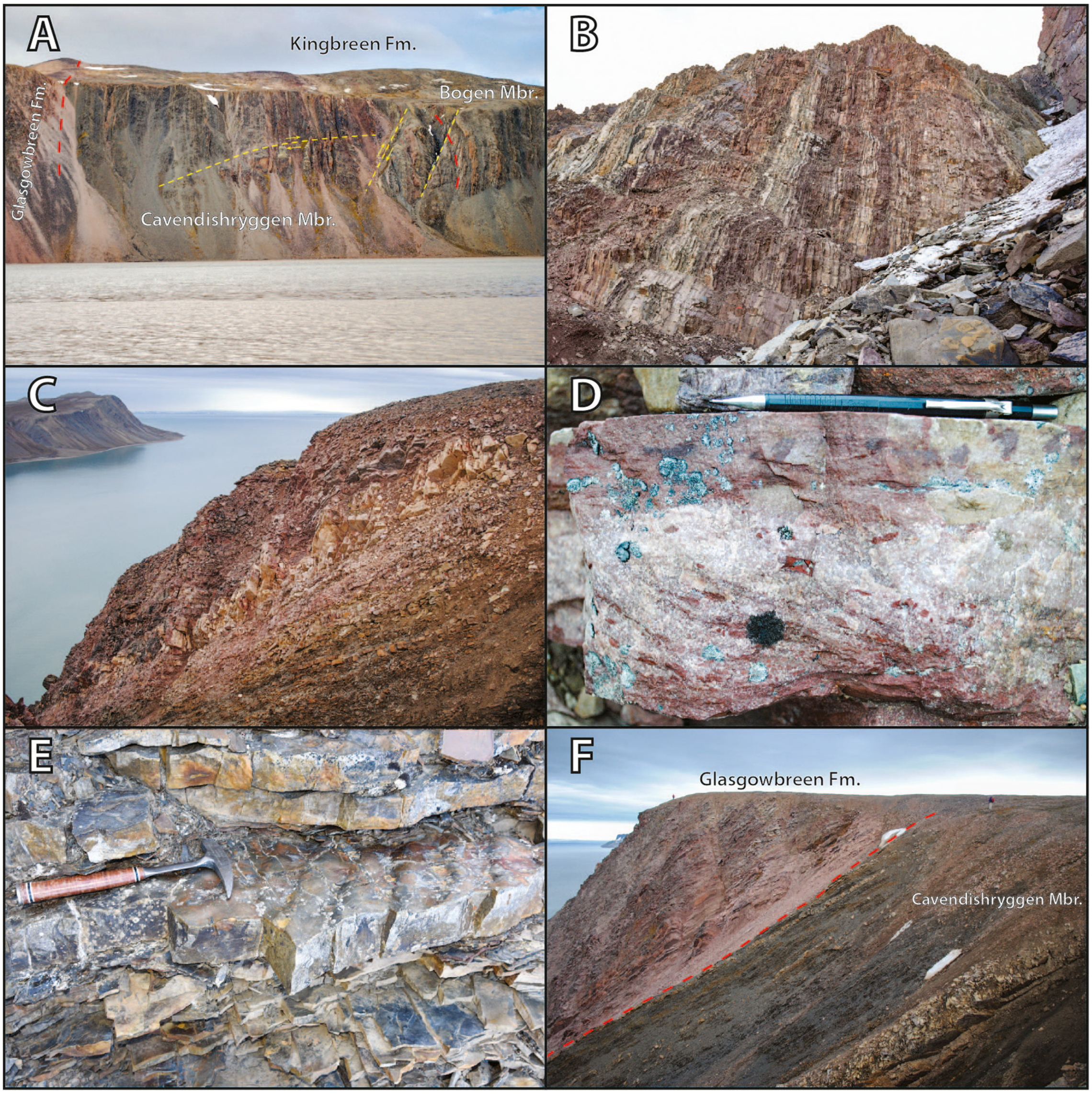


Fig. 8. Photographs of the Cavendishryggen Member of the Kingbreen Formation from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Rock hammer is 33 cm long and pencil is 14 cm long. A. Annotated outcrop photograph of the Cavendishryggen Member showing contacts (red dashed lines) with the underlying Bogen Member (right) and overlying Glasgowbreen Formation (left). Faults are marked by yellow dashed lines with yellow arrows showing kinematics. Stratigraphic up is to the left. B. Tabular, thin-bedded sandstone between ~2508–2525 m in the lowermost Cavendishryggen Member. Stratigraphic up is to the left, and beds are ~20–70 cm thick. C. Outcrop view of coarsening- and thickening-upward transition into amalgamated quartz arenite near ~2600 m in the lower Cavendishryggen Member. D. Cross-bedded, fine- to medium-grained quartz arenite with red shale intraclasts at 2626.5 m. E. Upper bedding plane view of symmetric ripples in medium-grained quartz arenite with mud-cracked black silty shale interbeds at 2772 m. F. Transition starting near ~2900 m from fine-grained strata of the uppermost Cavendishryggen Member of the Kingbreen Formation to the amalgamated quartz arenite beds of the overlying Glasgowbreen Formation at 2955.7 m. The contact between these units is marked by the red dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

laminated, but some proportion contain dune-scale trough and tabular cross-bedding. In the lower 20 m, sandstone beds also contain shale drapes, shale intraclasts, and minor HCS. In the upper ~30 m, there is a prominent thickening-upward succession leading to the contact with the upper Glasgowbreen Formation at 3353.3 (Fig. 9B).

4.3.2. Lower member interpretation

The thick interval of cross-bedded quartz arenite in the lower member of the Glasgowbreen Formation (Fig. 9A, B) shows minimal variation, although the presence of HCS indicates deposition likely started within FWWB, perhaps in a shoreface setting. The remarkably uniform tabular nature of the overlying sandstone strata and their consistent grain size is inconsistent with traditional channelized or braided fluvial sedimentary environments. However, these types of deposits may reflect pre-vegetated sheet-braided fluvial deposits (e.g., Dalrymple et al., 1985; Eriksson et al., 1998; Dott, 2003; Turner and Long, 2008). For example, the rare shale drapes and intraclasts intervals could represent overbank deposits adjacent the main thread of the braided fluvial system. Further, the intimate association between plane-lamination and cross-stratification, as observed in the lower Glasgowbreen Formation, has been interpreted to result from highly variable discharge regimes within a braidplain that prevented meandering (Sønderholm and Tirsgaard, 1998). However, it also remains possible these strata simply reflect a very thick accumulation of shoreface to foreshore deposits, a scenario that would most likely require rapid sedimentation rates (see Discussion). Given our lack of paleocurrent data, the depositional setting of these strata remains ambiguous beyond reflecting a broad marginal marine to marine-influenced terrestrial setting.

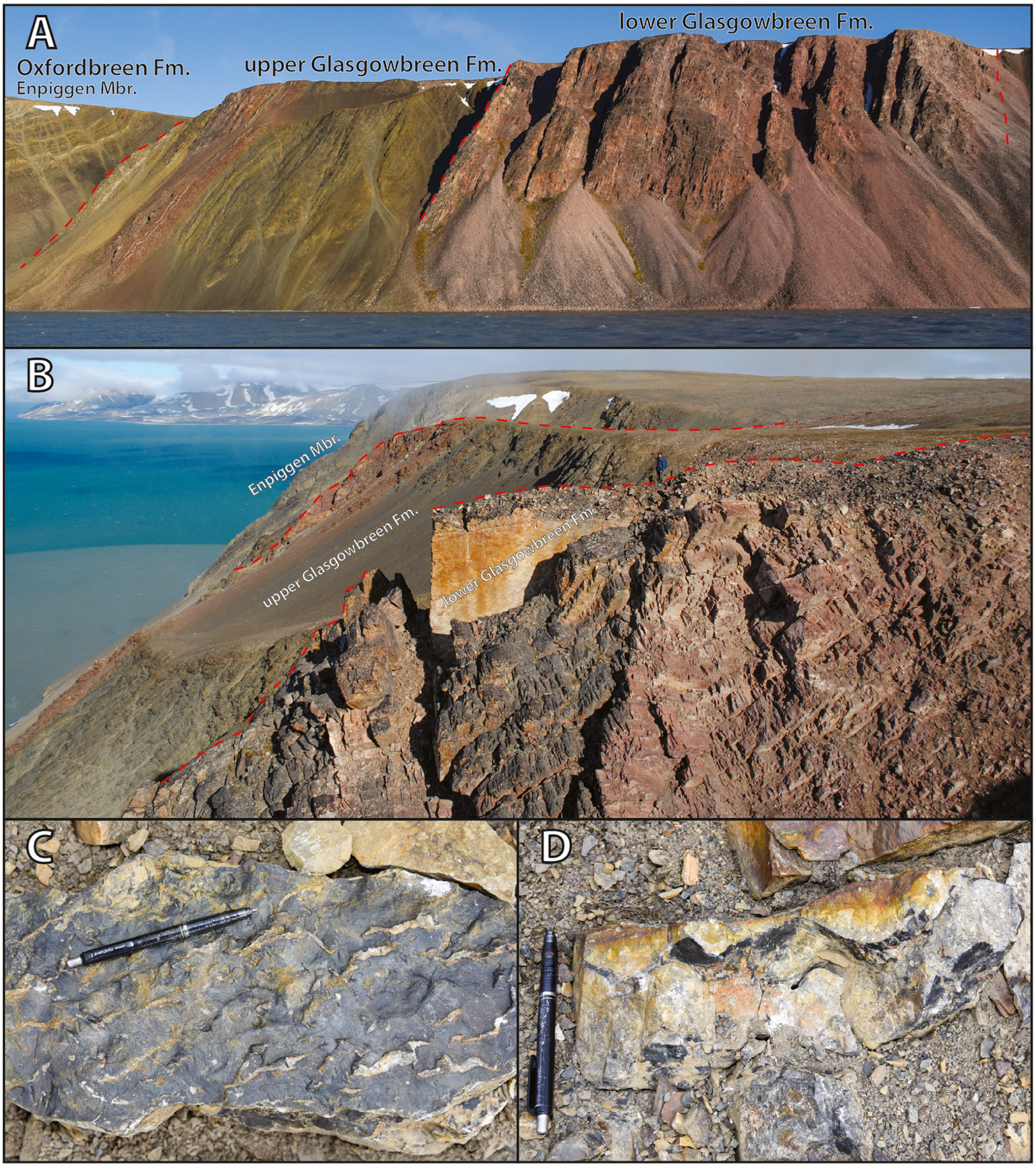


Fig. 9. Photographs of the Glasgowbreen Formation from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Pencil is 14 cm long. A. Outcrop view of the of the Glasgowbreen Formation and overlying Enpiggen Member of the Oxfordbreen Formation. Contacts are marked by red dashed lines. Stratigraphic up is to the left. B. Thick- to medium-bedded, amalgamated quartz arenite beds at the top of the lower Glasgowbreen Formation in the foreground, with the upper Glasgowbreen Formation and Enpiggen Member of the Oxfordbreen Formation in the background. Contacts are marked by red dashed lines. C. Bedding plane view of syneresis cracks filled with medium- to coarse-grained quartz arenite within black shale in float near ~3595 m of the upper Glasgowbreen Formation. D. Black shale drapes over symmetric ripples at ~3599 m of the upper Glasgowbreen Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3.3. Upper member description

The base of the 304.7 m thick upper Glasgowbreen Formation is marked by a recessive, 13.5 m thick dark brown and gray shale interval that rests sharply on the underlying sandstone strata of the lower member (Figs. 3, 9). Above this basal shale and up to 3520 m, there are thin to medium interbeds of fine- to medium-grained quartz arenite and siltstone with minor shale. Syneresis cracks and asymmetric ripples are ubiquitous in these strata, and flute marks, tool marks, and normal-graded beds are also present. This facies fines upwards between 3481 and 3487 m to predominantly organic-rich silty shale with rare carbonaceous compressions, very thin sandstone interbeds, and m-scale lens-shaped sandstone horizons up to 3520 m.

At 3520 m, there is a ~ 25 m thick interval dominated by ~3–4 m thick cycles of massive, fine-grained, poorly-sorted, red lithic arenite with shale intraclasts, sandy red shale interbeds with mudcracks, and dune-scale trough cross-bedded white quartz arenite. These strata are overlain by ~70 m of amalgamated, thick- to very-thick-bedded, medium- to coarse-grained, pale quartz arenite with minor red shale drapes and shale intraclasts, as well as red muddy lithic arenite, siltstone, and silty shale. At 3595.2 m, these coarse-grained strata are overlain by black shale that grades upwards into medium-bedded quartz arenite with abundant syneresis cracks, symmetric and asymmetric ripples, and black shale drapes and intraclasts (Fig. 9C, D). Between 3595.2 and 3637.5 m, there are ~2–10 m thick intervals of white, amalgamated quartz arenite, laminated silty shale with very thin rippled siltstone beds, silty shale with thin- to very-thin-bedded quartz arenite, and medium-bedded, muddy green lithic arenite and sublitharenite with shale intraclasts, shale partings, and syneresis cracks. The remainder of the upper Glasgowbreen Formation to the contact with the Enpiggen Member of the Oxfordbreen Formation (3658 m) contains thin- to medium-bedded quartz arenite that thicken upwards to ~20 m thick, amalgamated quartz arenite with dune-scale tabular cross-bedding and minor shale partings and intraclasts.

4.3.4. Upper member interpretation

The abrupt transition from sandstone to shale at the contact between the upper and lower Glasgowbreen Formation (Figs. 3, 9A) marks a significant flooding surface that records a shift from nearshore and/or possibly fluvial deposits to a distal offshore environment. The fine-grained interval between ~3370 and 3510 m comprised of rippled sandstone beds with various sole marks may represent hyperpycnal flow or turbidite deposits that were deposited in a prodelta setting. The upward increase in sandstone with subaerial exposure indicators starting at ~3510 m reflects a return to shallower water marine or delta plain environments. The overlying massive to dune-scale cross-bedded sandstone and red shale interbeds with mudcracks, channel-fills, and asymmetrical ripples (Fig. 9C, D) record similar shallow-water sedimentation in marginal marine to fluvial-deltaic environments through the reminder of the upper Glasgowbreen Formation, similar to those represented by the middle Cavendishryggen Member of the Kingbreen Formation.

4.4. Oxfordbreen Formation

4.4.1. Enpiggen Member description

The base of the 501.5 m thick Enpiggen Member of the Oxfordbreen Formation is comprised of a dark gray shale with carbonaceous compressions (3658–3688.7 m) that grades upwards into silty shale with very thin-bedded laminated quartz arenite (Figs. 3, 10A, B). These strata grade upwards into an interval with thin to medium interbeds of laminated organic-rich silty shale and very fine-grained glauconite(?)-rich dark gray, green, and brown quartz arenite. The latter coarsens and thickens upwards to ~3785 m and contains load structures, flute marks, and abundant HCS (Fig. 10C). At 3784.4 m there are two distinctive, laterally extensive white quartz arenite marker beds (Fig. 10A) that contain amalgamated, tabular, dune-scale cross-bed sets (~10–30 cm thick each) and are separated by 1.4 m of sandy green siltstone. Over the next ~100 m (3789.8–3876 m), there are cycles composed of the following: (1) ~0.5–1 m thick, white and green, medium-grained quartz arenite beds; (2) ~1–3 m thick intervals of white-weathering silty shale and thin lenticular sandstone; and (3) ~1–2 m thick intervals of gray siltstone and very-thin- to thin-bedded, gray, brown, and purple, fine-grained quartz arenite with small-scale HCS (Fig. 10E), asymmetrical ripples, mud drapes, shale intraclasts, and syneresis cracks.

A 2.2 m thick bed of massive black oolitic lime grainstone at 3876 m marks a transition to carbonate-dominated facies. Over the following ~40 m, cycles similar to the interval below (3789.8–3876 m) continue, but with the addition of ~2–3 m thick units of medium-bedded, gray oolitic grainstone with siltstone and shale interbeds. Between 3876 and 3917 m the oolitic grainstones are locally replaced by biohermal stromatolitic boundstone composed of broad domal (~20–50 cm across; ~10–20 cm synoptic relief) and small, irregular, branching columnar (~5–10 cm across; ~5–10 cm synoptic relief) stromatolites and planar microbialite (Fig. 10D). Above 3917 m, the upper Enpiggen Member is comprised of ~35 m of green siltstone interbedded with gray, wavy-laminated marl and thin rippled sandstone beds and then ~110 m of interbedded green and purple, laminated siltstone and shale, medium- to thick-bedded fine-grained quartz arenite, and dark gray grainstone that is gradational with carbonate-cemented sandstone and siltstone. This upper interval contains load structures, asymmetric ripples, and abundant sandstone with pot and gutter casts (Fig. 10F). Carbonate nodules, HCS, and dune-scale cross-bedded and lenticular quartz arenite beds are also present. The first occurrence of red siltstone at 4159.5 m marks the contact with the overlying Fulmarberget Member.

4.4.2. Enpiggen Member interpretation

The sharp contact at the base of the Enpiggen Member (Figs. 3, 10A, B) represents another major flooding surface to below SWB in a middle to outer shelf setting. Above 3688.7 m, these distal deposits record shoaling through interbedded silty shale and glauconitic sandstone with load structures, flute marks, and HCS (Fig. 10C) to a depth between FWWB and SWB. The two white quartz arenite marker beds with tabular, dune-scale cross-bedding at 3784.4 and 3786.9 m (Fig. 10A) may record shoaling into the shoreface, although this is unlikely given the immediate return to similar facies above which record deposition between FWWB and SWB on a storm-influenced shelf.

The shift at 3876 m to mixed carbonate–siliciclastic facies of the Enpiggen Member, as well as the coarsening- and thickening-upwards parasequences with mudcracks (Fig. 3) and stromatolites (Fig. 10D) record similar subtidal to peritidal environments as those recorded in the upper Bogen Member (middle Kingbreen Formation). Similarly, carbonate precipitation was sustained in shallow water environments when it was not overwhelmed by the high influx of terrigenous sediment, such as in an interdistributary bay or lagoonal setting. Shallow water tidally influenced carbonate facies also indicate that the flux of siliciclastic sediment to the basin, which had persisted since deposition of the Cavendishryggen Member (upper Kingbreen Formation), may have waned at this time. Above 3917 m, the interbedded sandstone and siltstone with abundant pot and gutter casts (Fig. 10F), HCS, minor channel-fill sandstone bodies, and dune-scale cross-bedding again suggest episodic tempestite deposition between FWWB and SWB along a storm-dominated shelf.

4.4.3. Fulmarberget Member description

The base of the 257.2 m thick Fulmarberget Member at 4159.5 m is marked by a ~ 5 m thick, red laminated siltstone horizon (Figs. 2, 3). The lower ~70 m of the member is dominated by green and purple siltstone and fine- to medium-grained, thin- to medium-bedded, quartz arenite with abundant pot and gutter casts, and both symmetrical and asymmetrical ripples. This interval also hosts some thick- to very-thick-bedded, massive and tabular to trough dune-scale cross-bedded white quartz arenite with siltstone drapes and occasional shale intraclasts. Above 4230.5 m, the member is mostly medium-bedded sandstone with lenticular geometries (~5 × 30 cm) and abundant load structures interbedded with silty shale. Thick- to very-thick, massive, white quartz arenite with large (~1 m diameter) ball-and-pillow load structures are also present.

From 4267.8–4312.4 m, the Fulmarberget Member consists of interbeds of thin, wavy-bedded and laminated sandy siltstone to medium-bedded sublitharenite and red to gray silty shale with abundant mudcracks (Fig. 11A). Over the following ~80 m, this facies alternates with medium beds of quartz arenite with pale green siltstone interbeds in 0.3–2 m thick packages. Mudcracks and syneresis cracks are ubiquitous in the silty shale and siltstone, and there are abundant gutter casts, and load structures, as well. Above 4289 m, there is a gradual increase in carbonate content, and at 4312.4 m there is a distinct ~50 cm thick, tabular intraclast cobble to boulder conglomerate horizon with elongate, subrounded to subangular lime mudstone to calcisiltite intraclasts up to ~50 cm across (Fig. 11B).

Above this conglomerate marker bed is a mudcracked siltstone interval (Fig. 11C) interbedded with poorly sorted lithic arenite with siltstone intraclasts and mixed carbonate-siliciclastic facies similar to those of the upper Enpiggen Member. These include: (1) green calcareous siltstone and very fine-grained sandstone with large (up to 50 cm diameter) carbonate nodules, HCS, load structures, and gutter casts (Fig. 11D); (2) ribbon-bedded lime mudstone with irregular dolomite nodules; (3) flakestone, or intraclast packstone, composed mostly of

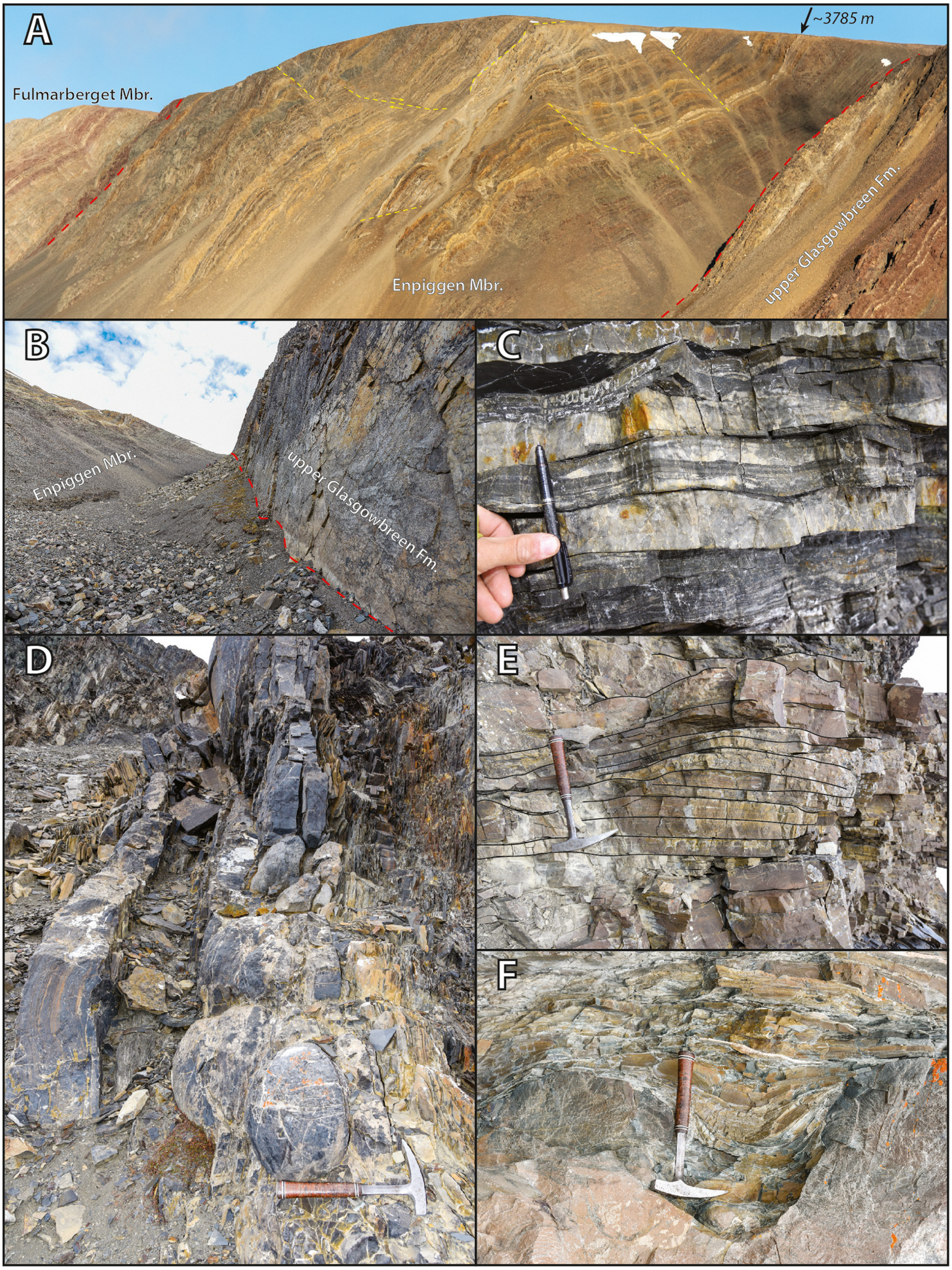


Fig. 10. Photographs of the Enpiggen Member of the Oxfordbreen Formation from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Rock hammer is 33 cm long and pencil is 14 cm long. A. Outcrop view of the contact between the Enpiggen Member and overlying Fulmarberget Member of the Oxfordbreen Formation. The white quartz arenite marker bed at ~3785 m is marked with an arrow. Stratigraphic up is to the left. Contacts are marked by red dashed lines and faults by yellow dashed lines. B. Sharp, subvertical flooding surface overlain by recessive black shale and siltstone at the base of the Enpiggen Member at 3658 m. Stratigraphic up is to the left. C. Wavy interbeds of quartz arenite and carbonaceous black shale and siltstone at 3698 m. D. Gently and moderately convex domal stromatolitic and microbial boundstone at ~3900 m. Stratigraphic up is to the left. E. Hummocky cross-stratified quartz arenite at 3831 m with bedding planes traced in black. F. Gutter cast filled with shale and carbonate concretions at 4257.5 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stromatolitic intraclasts (Fig. 11E); and (4) fine-grained gray grainstone with syneresis cracks and symmetric ripples (Fig. 11F). Above ~4380 m, medium beds of fine-grained grainstone and nodular and ribbon-bedded lime mudstone become increasingly abundant until the contact with the overlying Grusdievbreen Formation of the Akademikerbreen Group at 4406.7 m (Fig. 11G). Just below this contact, at 4397.5 m, is a microbial-laminated boundstone interval with a discontinuous intraclast conglomerate horizon and water escape structures.

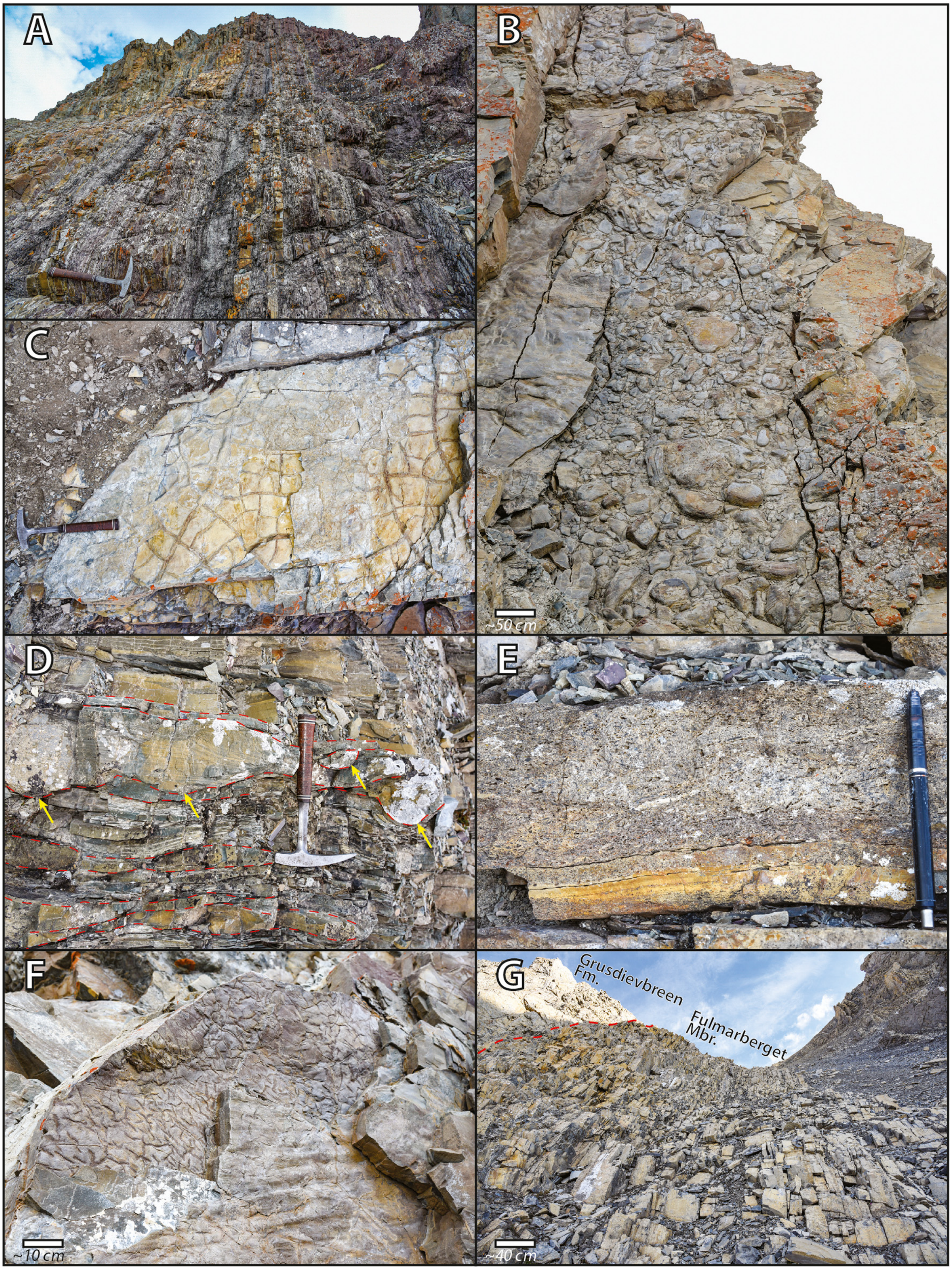


Fig. 11. Photographs of the Fulmarberget Member of the Oxfordbreen Formation from section T1831. Stratigraphic up direction is toward the top of the photo unless otherwise specified. Rock hammer is 33 cm long and pencil is 14 cm long. A. Thin-bedded, brown lithic and quartz arenite interbedded with mud-cracked red siltstone at 4284 m. Stratigraphic up is to the left. B. Upper bedding plane view of intraclast cobble to boulder conglomerate horizon composed of subrounded to subangular carbonate clasts up to ~50 cm across at 4312.3 m C. Upper bedding plane view of mudcracks in yellow-weathering siltstone and quartz arenite at 4331 m. D. Low-angle cross-stratification (traced by dashed red lines), multiple generations of gutter casts, and carbonate nodules in calcareous siltstone at 4351 m. Yellow arrows point to erosional basal geometries of gutter casts. E. Carbonate "flakestone" or intraclast packstone composed of stromatolitic intraclasts at 4380 m. F. Upper bedding plane view of syneresis cracks and symmetric wave ripples in light-gray grainstone at 4381 m. G. Gradational transition from well-bedded lime mudstone and grainstone with thin siltstone and silty marl interbeds of the Fulmarberget Member to nodular lime mudstone beds of the lowermost Grusdievbreen Formation (basal Akademikerbreen Group; contact marked by red dashed line) between ~4400–4406 m. Stratigraphic up is to the left. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Section T1831 (Figs. 2, 3) continues into the lower Grusdievbreen Formation through another ~100 m of tabular to wavy, well-bedded to massive, dark gray lime mudstone with dolostone nodules and smaller proportions of microbial-laminated and stromatolitic boundstone and marl interbeds, which are characteristic of the basal Grusdievbreen Formation (Halverson et al., 2007).

4.4.4. Fulmarberget Member interpretation

The sandstone–siltstone interbeds of the lower ~70 m of the Fulmarberget Member, with features such as pot and gutter casts and symmetrical ripples (Figs. 3, 10A), are consistent with deposition in a storm-dominated middle to inner shelf setting. The overlying mudcracked interval between 4267.8 and 4312.3 m (Fig. 11A) indicates shoaling into an episodically subaerially exposed subtidal to intertidal setting. Except for the intraclast boulder conglomerate, facies of the upper Fulmarberget Member are similar to those throughout the lower–middle Fulmarberget Member that are interpreted to record deposition in shallow marine to marginal marine settings.

The ~50 cm thick intraclast boulder conglomerate horizon at 4312.3 m (Fig. 11B) is interpreted as a tempestite that formed when early cemented carbonate facies were ripped-up and redeposited locally during an exceptionally large storm (hurricane) or tsunami. The interbedded carbonate and siliciclastic facies with abundant carbonate nodules from ~4330–4380 m reflect a gradational transition toward a carbonate-dominated depositional setting. Syneresis cracks and wave ripples (Fig. 11F) provide evidence that much of this interval was deposited in shallow water. Combined with HCS, load structures, gutter casts (Fig. 11D), and stromatolitic intraclasts (Fig. 11E), this interval most likely represents a storm-dominated inner ramp setting. Gradation of these carbonate-dominated facies above ~4380 m with the overlying lower Grusdievbreen Formation at 4406.7 m (Figs. 3, 11G) supports the progressive development of a carbonate ramp.

5. Carbonate carbon and oxygen isotope chemostratigraphy

The $\delta^{13}C_{carb}$ compositions of samples from carbonate-dominated stratigraphic intervals of section T1831 vary between +0.9‰ and + 7.9‰; $\delta^{18}O_{carb}$ values range between −19.1‰ and −3.8‰ (Table S1, Figs. 3, 12). Carbon isotope ($\delta^{13}C_{carb}$) values of carbonate-dominated intervals of the Veteranen Group span from +0.9‰ to +6.2‰, and values in the lower Grusdievbreen Formation values span from +2.5‰ to +7.9‰. Oxygen isotope ($\delta^{18}O_{carb}$) values span from −19.1‰ to −3.9‰ in the Veteranen Group and −19.1‰ -to −4.6‰ in the lower Grusdievbreen Formation. There is no discernable covariation between $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ values when all data are plotted (Fig. 12 inset).

In the lower Kortbreen Formation (~0–280 m), $\delta^{13}C_{carb}$ values fall between +2.8‰ and + 4.5‰ with no clear stratigraphic trend. Carbonate $\delta^{13}C_{carb}$ values in the Bogen–lower Cavendishryggen members of the Kingbreen Formation (~2120–2560 m) vary between +2.5‰ and + 6.2‰ with multiple small-scale positive and negative perturbations. A thin carbonate-dominated interval in the Enpiggen Member of the Oxfordbreen Formation (~3845–3935 m) shows a $\delta^{13}C_{carb}$ trend decreasing from +5.3‰ to +1.7‰. Finally, carbonate facies in the upper Fulmarberget Member of the Oxfordbreen Formation between ~4300–4406.7 m show a small negative $\delta^{13}C_{carb}$ excursion down to +0.9‰ at 4350 m, then a broad increase in $\delta^{13}C_{carb}$ to +4.0‰ just before the contact with the lower Grusdievbreen Formation of the Akademikerbreen Group at 4406.7 m. Carbonate $\delta^{13}C_{carb}$ compositions increase through the lower Grusdievbreen Formation and remain elevated between ~+4‰ and +8‰, before falling to between ~+3‰ and +5‰ by the top of the measured section at 4500 m. Similar trends have previously been observed in the lower Grusdievbreen Formation (Halverson et al., 2005, 2007, 2018a).

6. Discussion

6.1. Depositional environments and sequence stratigraphy

Depositional environments of the Veteranen Group at Faksevågen, Spitsbergen include an array of marine to nearshore and possibly terrestrial sedimentary settings. Although there are no major identifiable internal unconformities in the Veteranen Group, the abundant subaerial exposure surfaces and presence of terrestrial facies suggest that many depositional hiatuses exist throughout the succession. Facies analysis reveals five transgressive-regressive (T-R) sequences (Fig. 12) that each represent a full cycle of change in accommodation space and/or sediment supply. This approach aims to broadly define the large-scale tectono-stratigraphic transitions within the Veteranen Group. Within each sequence, the maximum flooding surface (MFS) separates the transgressive phase from the regressive phase, which is a composite of the highstand, falling-stage, and lowstand systems tracts (sensu Catuneanu et al., 2009). Most T-R sequences are asymmetric, in which the transgressive facies are substantially thinner than the regressive facies.

Carbonate facies of the lower Kortbreen Formation indicate deposition on a storm-influenced middle to inner shelf environment (Figs. 3, 4). Bedforms indicative of deposition within a body of water sufficiently expansive to generate large waves (i.e., HCS) suggest the Hecla Hoek basin was likely marine at the time. The lower member of the Kortbreen Formation therefore records the transgressive phase of TR-1 (Fig. 12). Since the base of the section is truncated, the lowest part of TR-1 is missing. The MFS of TR-1 is likely within the covered interval near the top of the lower Kortbreen Formation. Sandstone facies of the upper Kortbreen Formation record a progressive shoaling-upwards pattern into storm-influence and subtidal to intertidal shallow marine depositional environments, and possibly into fluvial environments (Figs. 3, 4). This shoaling-upwards trend represents the prolonged regressive phase of TR-1 (Fig. 12).

The base of the Galoistoppen Member of the Kingbreen Formation represents a sequence boundary, representing a major flooding surface that marks the transition into the transgressive phase of TR-2 (Fig. 12). The MFS sits near the top of the ~110 m thick basal shale, which records a transition to deeper-water hemipelagic sedimentation punctuated with thin-bedded turbidites within an outer shelf to continental slope environment (Figs. 3, 5). The turbidites most likely originated from hyperpycnal flows, which often originate from dense, flood-generated fluvial sediment dispersions at delta mouths (Mulder et al., 2003). The channel-form quartz arenite body at 1823.8 m marks the regressive phase of TR-2 (Fig. 12) that ultimately resulted in shallow-water deposition along a tidally influenced shoreline through the remainder of the Galoistoppen Member.

Mixed carbonate–siliciclastic facies with subaerial exposure surfaces in the lower Bogen Member demonstrate persistent shallow-water deposition through the middle Kingbreen Formation (Figs. 3, 6). While it is possible that the poorly exposed, 60 m thick interval near the base of the Bogen Member conceals deeper water facies, evaporites were mapped near this stratigraphic horizon in other locations (Dallmann, 2015). Therefore, this interval likely contains similar fine-grained peritidal deposits as directly above and below. The 200 m thick interval of consistent intertidal to subtidal facies in the lower Bogen Member requires that subsidence, sedimentation rates, and relative sea-level change reached a quasi-equilibrium during the regressive portion of TR-2 (Fig. 12).

The upper Bogen Member (Figs. 3, 7) preserves abundant evidence for storm-influenced sedimentation within an evolving mixed carbonate-siliciclastic system. The lateral gradation between oolitic grainstone with floating sand grains and sandstone with floating ooids represents mixing of terrigenous and carbonate sedimentation along a marine shoreline, perhaps within a protected interdistributary bay of a larger fluvial-deltaic system. The few intervals of tabular sandstone in the upper Bogen Member are interpreted to result from lateral deltaic

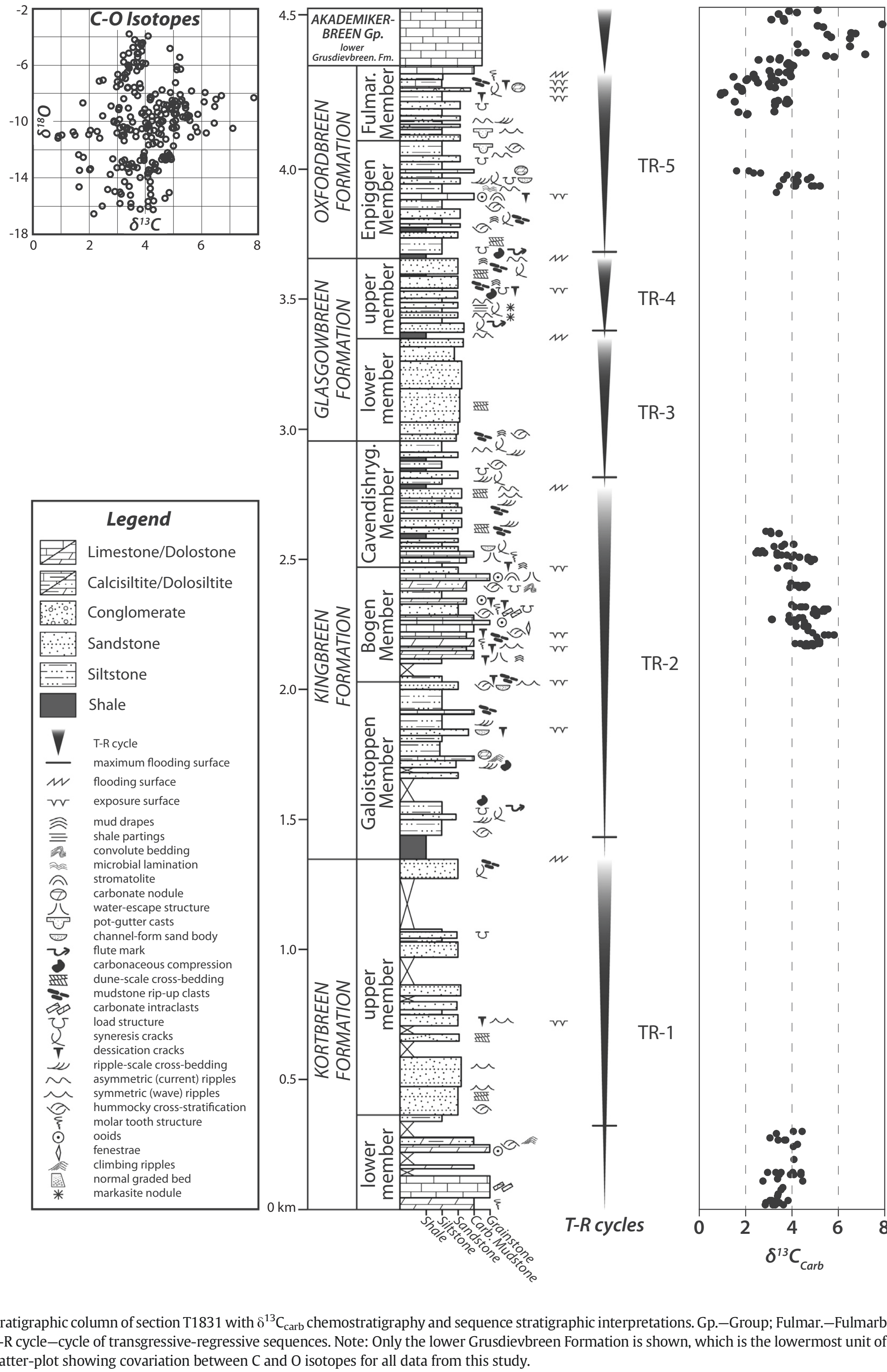


Fig. 12. Simplified stratigraphic column of section T1831 with $\delta^{13}C_{carb}$ chemostratigraphy and sequence stratigraphic interpretations. Gp.—Group; Fulmar.—Fulmarberget; Cavendishryg.—Cavendishryggen; T-R cycle—cycle of transgressive-regressive sequences. Note: Only the lower Grusdievbreen Formation is shown, which is the lowermost unit of the Akademikerbreen Formation. Inset: Scatter-plot showing covariation between C and O isotopes for all data from this study.

progradation, revealing an interplay between carbonate production and siliciclastic sediment supply.

The mudcracked surface at the base of the Cavendishryggen Member occurs at the transition from carbonate-dominated to siliciclastic-dominated facies reflects a subaerial exposure surface (Figs. 3, 12). Above this, the Cavendishryggen Member consists of sandstone-dominated shoreline and nearshore marine facies, possibly due the to migration of a clastic point source. For example, the ~150 m thick interval of amalgamated and thick-bedded sandstone at ~2600 m are consistent with tidal channel or tidal delta migration within a tidally influenced delta front and possibly delta plain. A transition to fine-grained outer shelf siliciclastic facies at ~2765 m in the upper

Cavendishryggen Member represents a flooding surface at the base of TR-3 (Fig. 12). The uppermost Cavendishryggen Member contains coarsening- and thickening-upwards cycles (similar to the interval above ~2600 m) that require a transition back to marginal marine to nearshore, tidally influenced delta plain or delta front settings. This marks the beginning of the regressive phase of the thinner TR-3 sequence (Fig. 12).

The lower Glasgowbreen Formation consists of a thin interval of definitive sandy shoreline facies and then ~600 m of amalgamated quartz arenite facies interpreted here to reflect shoreface to strandline or sandy braidplain to braided fluvial sedimentation (Figs. 3, 9). These deposits, along with the upper Cavendishryggen Member strata mentioned above, comprise the regressive phase of TR-3 (Fig. 12). The contact between the lower and upper Glasgowbreen Formation marks another major flooding surface at the base of TR-4 (Figs. 9A, 12). The 13.5 m thick shale at the base of the upper Glasgowbreen was deposited in a distal, possibly outer shelf environment and comprises the transgressive phase and contain the MFS of TR-4. These offshore facies transition upwards through the middle portion of the upper Glasgowbreen Formation into fine-grained turbidites and hemipelagic shales deposited in a prodelta or upper slope setting. These potential prodelta facies form the regressive portion of TR-4 and eventually give way to marginal marine and fluvial-deltaic facies of the upper Glasgowbreen Formation (Fig. 12).

The Glasgowbreen–Oxfordbreen contact represents a major flooding surface and the beginning of TR-5 (Fig. 12), and distal shale facies at the base of the Enpiggen Member contain the MFS (Fig. 3B, 10B). These distal facies shoal upwards into shallow-water storm-dominated shelf facies and form part of the prolonged regressive phase of TR-5. Mixed carbonate–siliciclastic parasequences and storm-dominated facies of the Enpiggen Member reflect tempestite deposition between FWWB and SWB along a storm-dominated middle or inner shelf. Similar facies continue through the lower Fulmarberget Member and transition upwards into a variety of nearshore marine to potential delta plain deposits (Figs. 3, 11). The upper Fulmarberget Member records a progressive shift to carbonate-dominated sedimentation, where storm-dominated inner carbonate facies reflect the final establishment of a carbonate ramp that ultimately grade into deeper-water middle shelf carbonate facies of the Grusdievbreen Formation (Akademikerbreen Group). The shoaling upward trend to inner shelf and possibly distal fluvial deposits through the upper Enpiggen Member and the majority of the Fulmarberget Member represent the regressive phase of TR-5.

The Oxfordbreen–Grusdievbreen (Veteranen-Akademikerbreen) contact was previously defined as the first carbonate beds with HCS above laminated siltstone facies of the Fulmarberget Member (Wilson, 1961). However, the transition from siliciclastic- to carbonate-dominated facies is gradational over ~50 m. Thus, we propose that the contact be defined as the transition to carbonate beds with little to no interbedded marl or shale partings, which is directly above the stratigraphically highest shallow-water carbonate facies (i.e., microbial limestone with water escape structures and intraclast conglomerate; Figs. 11A). This contact is more easily recognizable on a map-scale and corresponds to another major sequence boundary.

6.2. Comparison with Precambrian sandstone-dominated depositional systems

Anomalously thick (>75 m) intervals of amalgamated tabular beds of medium- to coarse-grained quartz-rich sandstone that predominantly lack interbedded conglomerate and/or fine-grained lithologies occur in the upper Kortbreen Formation, the Cavendishryggen Member of the Kingbreen Formation, and lower Glasgowbreen Formation (Figs. 3, 8, 9). These strata share many similarities with shallow marine (i.e., shoreface to foreshore) facies and may indeed reflect long-lived periods of shoreline sedimentation in the Veteranen Group. However, for marine deposition to occur within such a narrow range of water depths (~0–20 m), it would require a near steady-state between accommodation space and sediment supply. Since these two variables are independent, the persistence of such an equilibrium during deposition of hundreds of meters of strata (as observed here) is challenging to reconcile.

Here, we suggest these tabular beds may also represent marginal marine to terrestrial sedimentation within braided fluvial-deltaic systems. These include distal fluvial deposits from within a delta or coastal plain, mouth bar deposits from a delta front, and/or non-deltaic foreshore to shoreface deposits. Thick, fluvial sheet-sand facies that lack interbedded shale remain anomalous because they require large-scale channel belts, only seen in modern glacial outwash plains (Davies et al., 2011). However, similar facies are also present in other Precambrian–lower Paleozoic stratigraphic successions worldwide and have been attributed to several different processes (Dalrymple et al., 1985; Fedo and Prave, 1991; McCormick and Grotzinger, 1993; Macnaughton et al., 1997; Eriksson et al., 1998; Dott, 2003; Turner and Long, 2008). For example, it has been suggested that before the evolution of land plants, which provide critical stability to modern channel banks, tabular “sheet-sand”-dominated sandstone facies were deposited by unconfined fluvial depositional processes (Rainbird, 1992; Long, 2011; Went and McMahon, 2018). Enhanced eolian winnowing on pre-vegetated landscapes has also been proposed to explain the occurrence of thick, mature sandstone-dominated successions with little to no shale (Dalrymple et al., 1985).

Reappraisal of many of these successions has revealed diverse morphometric elements in Precambrian fluvial systems (i.e., large channel-forms and stable floodplains) that are similar in morphology to modern rivers (Ielpi and Rainbird, 2015, 2016; Ielpi et al., 2018b; Ganti et al., 2019). Specifically, remote-sensing investigations utilizing greater along-strike evaluation of Precambrian fluvial deposits has revealed that channels are common and have largely retained similar aspect ratios throughout much of Earth history (Ielpi and Ghinassi, 2015; Ielpi and Rainbird, 2016; Ghinassi and Ielpi, 2018; Ielpi et al., 2018b). Thus, rapidly migrating and amalgamating braided river channels can also produce what appear to be tabular, sheet-sand facies because their channel geometries are difficult to observe in outcrop using traditional field methods (Miall, 1985; Ielpi and Rainbird, 2015; Ielpi et al., 2018a). This is potentially the case for the thick sandstone facies of the Veteranen Group, but the absence of detailed measured sections and paleocurrent data in our current examination (due to the inaccessibility of the outcrops at Faksevågen) precludes definitive confirmation of this hypothesis.

6.3. Chemostratigraphy

The predominantly positive $\delta^{13}C_{carb}$ values recorded in the Veteranen Group (+0.9‰ to +6.2‰) are also similar to those reported in other ca. 950–800 Ma stratigraphic successions globally (Figs. 3, 12) (e.g., Kuznetsov et al., 2006; Jones et al., 2010; Thomson et al., 2015; Turner and Bekker, 2015; Greenman et al., 2020; Zhou et al., 2020; Zhang et al., 2021). The most pronounced $\delta^{13}C_{carb}$ excursion occurs in the middle Enpiggen Member of the Oxfordbreen Group, where values decline from +5.3‰ to +1.7‰. At the Oxfordbreen–Grusdievbreen contact, $\delta^{13}C_{carb}$ values rise from between +3‰ and +4‰ up to between +7‰ and +8‰, consistent with previously published data (Halverson et al., 2005, 2007, 2018a). This transition to $\delta^{13}C_{carb}$ > +4‰ at the top of T1831 helps to constrain the stratigraphic position of this contact. Variations in the $\delta^{13}C_{carb}$ composition throughout the Veteranen Group may reflect perturbations in the global carbon cycle. Although it is difficult to correlate these $\delta^{13}C_{carb}$ patterns directly to other successions due to the general lack of age constraints within the Veteranen Group, they bear resemblance to data from lower Tonian successions in North China and Canada (e.g., Greenman et al., 2020; Zhou et al., 2020; Zhang et al., 2021). This further illustrates that the Tonian carbon isotope record represents a transition between the minimal variability of the Mesoproterozoic Era and immense variability of the Neoproterozoic Era; however, the origin of this trend remains unsettled.

The highly depleted $\delta^{18}O_{carb}$ compositions (Table S1) of the Veteranen Group are broadly consistent with other records from Precambrian carbonate units (Shields-Zhou and Veizer, 2002), although the source of such depleted values is debated (Veizer et al., 1999; Jaffrés et al., 2007). Data for the entire Veteranen Group do not display $\delta^{13}C_{carb}$–$\delta^{18}O_{carb}$ correlation (Fig. 12 inset), but when data from each carbonate-dominated interval is plotted separately, there is a weak positive covariation between $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ values in the Bogen and lower Cavendishryggen members ($R^2 = 0.42$; Table S1). Such correlation is commonly associated with diagenetic alteration, but other mechanisms, such as evaporative concentration in restricted bodies of water, can also produce such trends (e.g., Talbot, 1994; Drummond et al., 1995). Considering the coherent secular structure in the data (Figs. 3, 12), we suggest $\delta^{13}C_{carb}$ experienced minimal diagenetic alteration, whereas the highly depleted $\delta^{18}O_{carb}$ values may reflect some degree of alteration to the O component.

6.4. Basin evolution and implications for the Tonian evolution of the North Atlantic

The Veteranen Group records cyclical decameter-scale siliciclastic-dominated packages of deltaic to storm-influenced shelf sedimentation leading up to establishment of the stable carbonate platform of the overlying Akademikerbreen Group. Transgressive–regressive cycles thin upwards substantially through the Veteranen Group (Fig. 12). Assuming these sequences were governed largely by allogenic processes driven by regional extension (Maloof et al., 2006; Halverson et al., 2018a), this trend implies a decrease in subsidence rates through time. Higher subsidence rates during deposition of the Veteranen Group relative to the Akademikerbreen Group is consistent with the Veteranen–Akademikerbreen contact marking the the transition from active rifting to thermal decay at the onset of passive margin sedimentation in the Hecla Hoek basin (Halverson et al., 2018a). The major decline in the delivery of siliciclastic sediment to the basin (assuming no major systems of sediment bypass) coincident with this facies transition at the Veteranen–Akademikerbreen Group contact may represent final marine flooding of continental source regions following a long-term reduction of rift-related relief. Therefore, the transition to carbonate-dominated facies in the Akademikerbreen Group was controlled, to some extent, by the abandonment or marine flooding of the long-lived fluvial-deltaic systems in the basin, either because the fluvial system migrated away from this area of the margin or due to the ultimate erosion of remnant rift-related topography that served as the sediment source.

This general progression is similar to that of age-eqiuvalent Neoproterozoic strata in East Greenland, which are proposed to have originated as along-strike equivalents to the Hecla Hoek succession from within a single, unified basin (Fairchild and Hambrey, 1995; Hartz and Torsvik, 2002; Nystuen et al., 2008). This interpretation is based on stratigraphic similarities between the lower–middle Hecla Hoek succession in the Nordaustlandet terrane of Svalbard and the Eleonore Bay Supergroup and overlying Tillite Group in East Greenland (Swett and Knoll, 1989; Halverson et al., 2004; Hoffman et al., 2012), as well as their geochemistry (Knoll et al., 1986; Derry et al., 1989) and microfossil assemblages (Knoll, 1982). The Akademikerbreen Group and upper Eleonore Bay Supergroup are further suggested to represent remnants of the "East Greenland–Eastern Svalbard" (EGES) carbonate platform, which existed along the Laurentian margin in tropical latitudes (Halverson et al., 2004; Maloof et al., 2006; Sønderholm et al., 2008).

The ~11 km thick Nathorst Land and ~3 km thick Lyell Land groups of the lower Eleonore Bay Supergroup in East Greenland (Sønderholm and Tirsgaard, 1993; Tirsgaard and Sønderholm, 1997; Sønderholm et al., 2008), and the putatively correlative >10 km thick Rivieradal and lower Hagen Fjord groups in North-East Greenland (Sønderholm and Tirsgaard, 1998; Higgins et al., 2001; Smith et al., 2007), sit on Caledonian thrust sheets and each contain >10 km of siliciclastic strata that include fluvial facies. The Veteranen Group only consists of ~4 km of siliciclastic-dominated strata, whereas lower Tonian strata in East and North-East Greenland have been suggested to consist of as much as 16 km of shallow marine to terrestrial siliciclastic strata (Sønderholm and Tirsgaard, 1993). Therefore, if the Veteranen Group and Tonian strata in East and North-East Greenland originated from the same basin, the substantial difference in their thickness must be reconciled. One possibility is that these successions, which both consist of abundant shoreline and marginal marine facies, represent disparate margins of the same basin. This possibility presents specific predictions for the relative deepening directions between each location. Alternately, these successions may reflect along-strike equivalents from the same margin that experienced differential subsidence, perhaps due to transtension associated with rifting.

7. Conclusions

The 4.5 km thick lower Tonian Veteranen Group of northeastern Spitsbergen, Svalbard, Norway, records long-lived deltaic to storm-influenced shelf sedimentation along the edge or Laurentia. The depositional evolution of the Veteranen Group detailed herein provides the foundation for future investigations of the Hecla Hoek succession as an archive of Neoproterozoic geobiology and geochemistry, and the Tonian tectonostratigraphic evolution of the northeastern Laurentian margin. New sedimentological observations, facies analysis, sequence stratigraphy, and carbonate carbon and oxygen isotope data originating from a detailed measured section at Faksevågen, Ny Friesland, support the following conclusions:

- The Veteranen Group consists of five asymmetric transgressive-regressive (T-R) sequences that progressively thin upward. Such a thinning-upward pattern is consistent with basin subsidence diminishing through time, and thus, the Veteranen–Akademikerbreen contact representing the rift-to-drift transition in the Hecla Hoek basin.
- Analysis of thick, sandstone-dominated facies of the Veteranen Group reveal deltaic sedimentary dynamics prior to the evolution of land plants. This record of marginal marine sedimentation also affords a rare glimpse into possibly nutrient-rich environments that may yield critical insights into Tonian geobiology.
- Results from this study broadly support correlation between the Veteranen Group and coeval strata from East Greenland. However, if these successions were deposited within the same basin, they likely originated from disparate margins or along a common margin that underwent differential subsidence.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sedgeo.2021.106011.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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