Vendian – Lower Ordovician stratigraphy of Ella Ø, North-East Greenland: new investigations

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Field work on Ella Ø in summer 2000 formed part of an ongoing research project to investigate the development of the Laurentian margin facing the Iapetus Ocean in the early Palaeozoic (Fig. 1). The extensive study region includes the well-exposed strata extending along the present coastlines of western Newfoundland, Canada, North-West Ireland and North-West Scotland, North-East Greenland and Svalbard. It is hoped to establish both the architectural and chronostratigraphic continuity and variation of these now disparate parts of a once contiguous platform.

Detailed lithostratigraphic studies of the uppermost Neoproterozoic (Vendian) – Lower Palaeozoic succession of North-East Greenland will provide the framework to underpin sedimentological and palaeogeographic interpretations as well as assist with diagenetic and detailed biostratigraphic studies. Geochemical data from isotopic analyses will support these studies. Detailed collection of macrofaunas (including trilobites, brachiopods and gastropods) and microfaunas (conodonts) should improve chronostratigraphic understanding.

The 2000 results suggest that the existing lithostratigraphy will require revision. For example, studies of measured sections show that dolomitisation in much of the Cambrian carbonate succession has overprinted and obscured lithostratigraphic boundaries.

Ella Ø study area

Vendian and Cambro-Ordovician sediments are exposed in a broad N–S-trending belt of the fjord region of North-East Greenland between latitudes 71°38′N and 74°25′N (Fig. 2). On Ella Ø the Vendian Tillite Group overlies

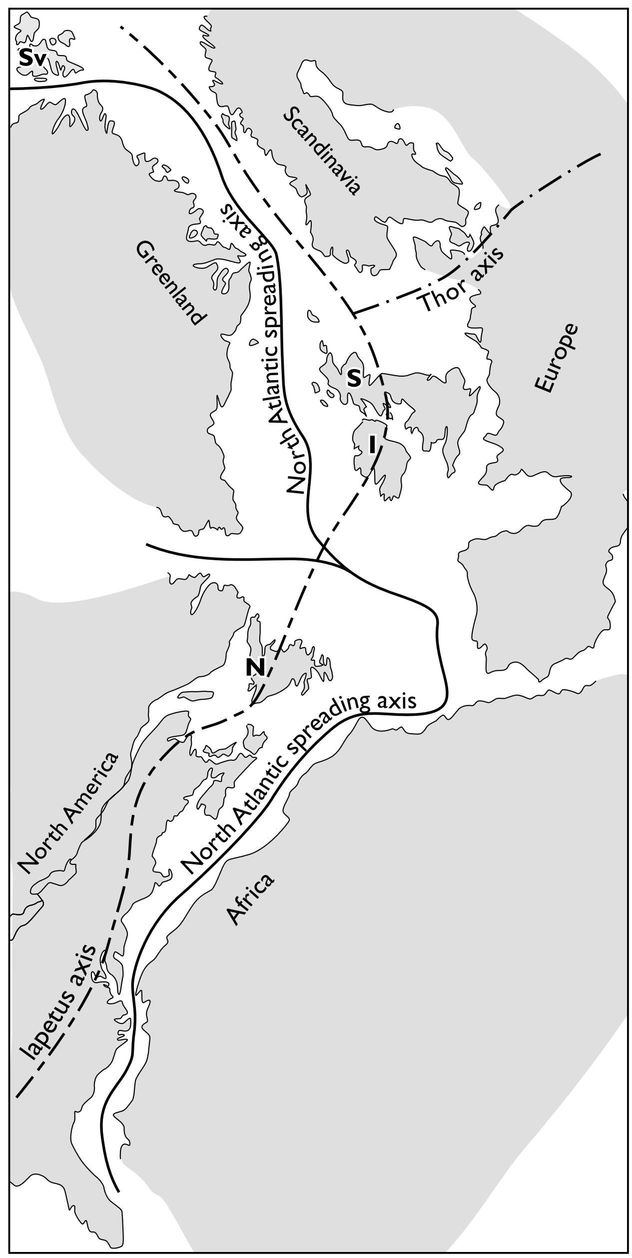

Fig. 1. Spreading axis of the North Atlantic Ocean compared with the position of the Early Palaeozoic Iapetus suture. Svalbard (**Sv**), Western Newfoundland (**N**), North-West Ireland (**I**), North-West Scotland (**S**) and Greenland are on the same side of the Iapetus axis. Modified from Williams (1987) and Berthelsen (1998).

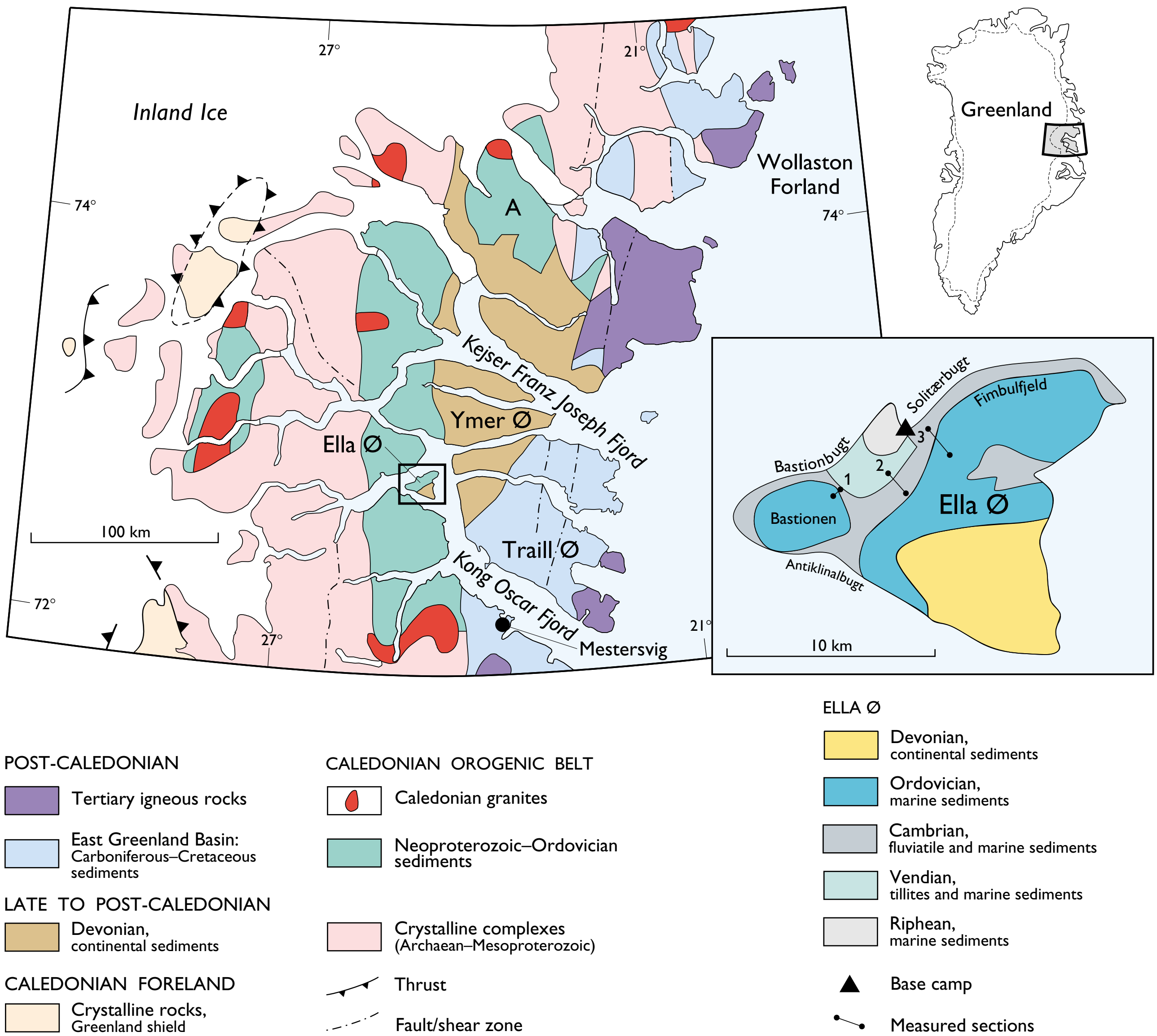

Fig. 2. Locality map of southern North-East Greenland with simplified geology. **A**: Albert Heim Bjerge. The map of Ella Ø shows locations of the base camp (see Fig. 3) and the investigated sections. Geology modified from Poulsen & Rasmussen (1951), Cowie & Adams (1957) and Henriksen (1994).

the Riphean Eleonore Bay Supergroup, while the Cambro-Ordovician succession is unconformably overlain by Devonian rocks. The pre-Devonian sediments are deformed by major Caledonian folds, the Bastion syncline and Kap Oswald anticline of Cowie & Adams (1957), associated with minor thrust and normal faults. A strong ridge-and-valley topography essentially reflects rock lithologies and structure with valleys associated with recessive units or minor low-angle faults. The highest elevation is Bastionen at 1367 m (Figs 2, 5).

Field work was carried out from the scientific station at Solitærbugt established by Lauge Koch in 1931 (Fig. 3), and focused on three sections exposed to the east, south and west (Fig. 2). The field party consisted of the five authors, responsible for stratigraphy, geochemistry, palaeontology and sedimentology. This report provides preliminary results, with field identifications of macrofossils, and documents well-developed microbialites (*sensu* Riding 1991) in the Ordovician sequence.

Vendian

Tillite Group

The Vendian System in North-East Greenland is represented by the 800 m thick Tillite Group (Hambrey & Spencer 1987; Hambrey 1989; Herrington & Fairchild

Fig. 3. The scientific station on Ella Ø used as base camp for the summer 2000 field work (see Fig. 2 for location). The outcrops behind the house are carbonates of the Riphean Eleonore Bay Supergroup, which also make up the mountains in the background.

1989), which overlies disconformably the Eleonore Bay Supergroup (Sønderholm & Tirsgaard 1993; Tirsgaard & Sønderholm 1997). Of the five formations (Fig. 4), the upper Spiral Creek Formation was studied in detail.

Spiral Creek Formation

The Spiral Creek Formation, 25–55 m thick, comprises varicoloured siltstones interbedded with sandstones. The depositional environment is interpreted as evaporitic non-marine (Fairchild 1989; Fairchild & Herrington 1989).

The uppermost member of the formation – 'unit e' of Cowie & Adams (1957) – is known only from Ella Ø, where it is well exposed in section 2 and in Antiklinalbugt (Fig. 2). It comprises 7–14 m of yellow-weathering, fine-grained dolostones associated with black chert developed along bedding surfaces or as irregular lenses. A quartzitic conglomerate with rounded chert clasts occurs at the base, overlying a disconformity. Black dense dolomites are considered indicative of anoxic bottom conditions in a lagoonal setting. No fossils have been recorded, but a latest Proterozoic age can be presumed.

Cambro-Ordovician

The Lower Cambrian shelf succession on Ella Ø starts with dominantly clastic to mixed clastic-carbonates of the Kløftelv, Bastion and Ella Island Formations (Fig. 4). These units, investigated at sections 1 and 2, record part of a transgressive–regressive sequence that also includes part of the overlying Cambrian to Lower Ordovician carbonate succession (Hyolithus Creek, Dolomite Point, Antiklinalbugt, Cape Weber and Narwhale Sound Formations; Fig. 4). Our observations ranged from the Kløftelv Formation to the Antiklinalbugt Formation. The Cape Weber and Narwhale Sound Formations were not studied in detail, while the uppermost unit in the succession (Heimbjerge Formation) is

SYSTEM	GROUP	FORMATION
Ordovician		Heimbjerge Narwhale Sound Cape Weber Antiklinalbugt
Cambrian		Dolomite Point Hyolithus Creek Ella Island Bastion Kløftelv
Vendian	Tillite	Spiral Creek Canyon Storeelv Arena Ulvesø

Fig. 4. Stratigraphic nomenclature of the Vendian – Middle Ordovician sediments of North-East Greenland. **Dashed line** indicates that the exact location of the Cambrian–Ordovician boundary is poorly constrained.

Fig. 5. Bastionen seen from the north; the nearest peaks left of centre are 1200 m above the terrain in the foreground. The dark-grey and yellow sediments at left form the Canyon Formation (**C**), which is overlain by yellow dolostones of the Spiral Creek Formation (**SC**). Reddish-coloured sediments are sandstones of the Kløftelv Formation (**K**), and the dark-green to grey recessive unit is the Bastion Formation (**B**). The succeeding thick-bedded rocks forming the steep cliffs of Bastionen are Cambrian and Lower Ordovician carbonates (**C–O**).

not preserved on Ella Ø. The Cambro-Ordovician sequence is more than 2000 m thick (Cowie & Adams 1957; Smith 1991; Smith & Bjerreskov 1994).

Kløftelv Formation

The Kløftelv Formation was measured in section 2 to be 70–75 m thick, and disconformably overlies 'unit e' of the Spiral Creek Formation. The base of the formation is an erosional surface; an irregularly bedded, pebbly quartz arenite with rounded shale pebbles is succeeded by a vivid-red unit of interbedded shale and cross-bedded and cross-laminated, very fine to fine-grained quartz arenite.

The Kløftelv Formation is dominated by fine- to medium-grained, white to pale-pink and red quartz arenite, arranged in metre to decametre-scale sequences. Wedge-shaped trough cross-beds dominate. Herringbone cross-stratification is common and locally foresets are overturned below scours. Rare sinuous ripple-marks occur. Poor exposures precluded detailed palaeocurrent measurements, but those made suggest polymodal directions dominated by a southward flow, with subordinate flow directions to the north-east.

The formation was probably laid down in a relatively high-energy, near shore to sandy shoreline setting. Trace fossils were noted by Hambrey & Spencer (1987), and an early Cambrian age is considered likely (Vidal 1979, fig. 4; Pickerill & Peel 1990, fig. 1).

Bastion Formation

The Bastion Formation, *c.* 140 m thick, is composed of glauconitic siltstone, shale, minor sandstone and calcareous sandstone. The formation crops out at high altitudes in the steep cliffs at Bastionbugt (Figs 2, 5) where the lower boundary is well exposed, and along the nearly vertical wall of Antiklinalbugt; at Solitærbugt minor exposures are easily accessible. Lower Cambrian fossils are common in the lower and middle parts of the formation (see e.g. Poulsen 1930; Cowie & Adams 1957; Cowie & Spencer 1970; Pickerill & Peel 1990).

Ella Island Formation

This formation is 80 to 100 m thick (Cowie & Adams 1957). In the lower part thin beds of laminated siltstone, commonly with trace fossils, are intercalated with shale at the base of metre-scale sequences, generally capped by a thick unit of medium-bedded calcareous siltstone and silty limestone. A few palaeocurrent measurements indicate south-eastward flow.

The upper part of the formation is made up of thin-bedded lime mudstone in 1–3 m thick sequences; these are intercalated with 20–70 cm thick beds of intraclastic skeletal grainstone, pebbly grainstone and rudstone. Vertical U-shaped or tubular burrows occur. The grainstone beds are rich in locally derived angular platy clasts of limestone (up to 10 cm) and locally dolostone.

Salterella and trilobites such as *Olenellus* and *Wanneria* are common in some beds (Poulsen 1932) indicating the *Bonnia-Olenellus* zone, i.e. late Early Cambrian.

Hyolithus Creek Formation

The dolostones of the Hyolithus Creek Formation are 145 m thick at Fimbulfjeld; at Antiklinalbugt the formation was measured at 210 m by Cowie & Adams (1957).

Patches and beds of pale grey, very fine-grained limestone remain as vestiges in both the mound and laminated facies at the base of the dark dolostones forming the upper 48 m interval of the formation. This limestone-bearing interval appears to correlate with limestones noted by Cowie & Adams (1957) about 100 m above the base of the dolostone at both Antiklinalbugt and in Albert Heim Bjerge suggesting that this may be a useful marker unit.

The dolostones of the Hyolithus Creek Formation are barren of fossils but *Salterella* in the limestone-bearing interval suggests the *Bonnia-Olenellus* Zone.

Boundary between the Ella Island and Hyolithus Creek Formations

From a conformable section in the east limb of the Kap Oswald anticline along the south-facing cliff wall at Antiklinalbugt, Cowie & Adams (1957) described the Ella Island Formation as comprising lower and upper limestone units separated by shale, and the Hyolithus Creek Formation as dark dolomite with minor limestone. Our logging on the same fold limb at sections 2 and 3 (Fig. 2) on the west slopes of Fimbulfjeld indicates that Cowie & Adams' (1957) boundary is a nearly stratiform dolomitisation front. A more natural boundary would be at the base of an underlying package of ribbon limestone and thinly bedded and bioturbated limestone. These rocks are replaced upwards by the dolostones that define the Hyolithus Creek Formation of Cowie & Adams (1957). If parts or all of the upper limestone of Cowie & Adams (1957) are incorporated in the Hyolithus Creek Formation, the revised Ella Island Formation would be no more than 60 m thick on Ella Ø. Further work will be necessary to confirm this.

Dolomite Point Formation

The Dolomite Point Formation is 260 m thick at section 3 on Fimbulfjeld (Fig. 2); Cowie & Adams (1957) recorded 330 m at Antiklinalbugt. It consists of grey microcrystalline dolostones, argillaceous dolostones and pale-grey and green-grey shale intercalated with two decimetre thick intervals of dark-grey sucrosic dolostone.

The base of the formation is at the first continuous interval of light-grey, thin-bedded microcrystalline dolostone above the Hyolithus Creek Formation. The contact is not well exposed at section 3, but appears to be sharp and conformable. The topmost 20 m included by Cowie & Adams (1957) in the Dolomite Point Formation should probably be assigned to the overlying Antiklinalbugt Formation; this interval consists of sucrosic dolostones similar to the basal limestones of the Antiklinalbugt Formation.

Six members are provisionally recognised, and will be described elsewhere. No body fossils are known, but burrow-mottling and thin tubular burrows (possibly *Planolites*) occur sporadically. The formation is younger than the uppermost Lower Cambrian Hyolithus Creek Formation and older than the lowermost Ordovician Antiklinalbugt Formation.

Antiklinalbugt Formation

The Antiklinalbugt Formation was introduced by Peel & Cowie (1979) to replace the Cass Fjord Formation of North-East Greenland as used by Poulsen (1930), Poulsen & Rasmussen (1951) and Cowie & Adams (1957). The Cass Fjord Formation is now restricted to north-western Greenland (Henriksen & Peel 1976) and adjacent Canada (De Freitas & Mayr 1995).

The Antiklinalbugt Formation, 235 m thick, consists of muddy, bioturbated carbonates of peritidal to subtidal aspect, and siltstones to shale interbedded with subtidal limestones. Planar to domal stromatolitic and thrombolite mounds become larger and more complex up-section. The carbonate sediments vary from dolostone to selectively dolomitised limestone to almost pure limestone. Three members are recognised (Cowie & Adams 1957).

The microbial buildups (*sensu* Kennard & James 1986; see Riding 1991) are composed of stromatolitic-thrombolite-?sponges and cryptic microbialites. The mounds range from single colonies to well-defined microbial constructions (Fig. 6), whose development appears to be associated with the progression of the basal lower Ordovician transgression. The succession culminates with prominent and complex thrombolitic-stromatolitic-?sponge microbial mounds (Fig. 7).

The gastropod *Sinuopea whittardi*? Poulsen is the earliest fossil recovered; brachiopods and trilobites occur

Fig. 6. Vertical cross-section of well-developed microbial mounds in the upper part of the lower member of the Ordovician Antiklinalbugt Formation. The mounds, 1.7 m high, are composed of thrombolites, stromatolites and minor lithid sponges, with grainstones between each buildup. The recessive middle member of the formation is seen in the upper part of the photograph. Section 3 on Fimbulfjeld; hammer (centre) is 28 cm long.

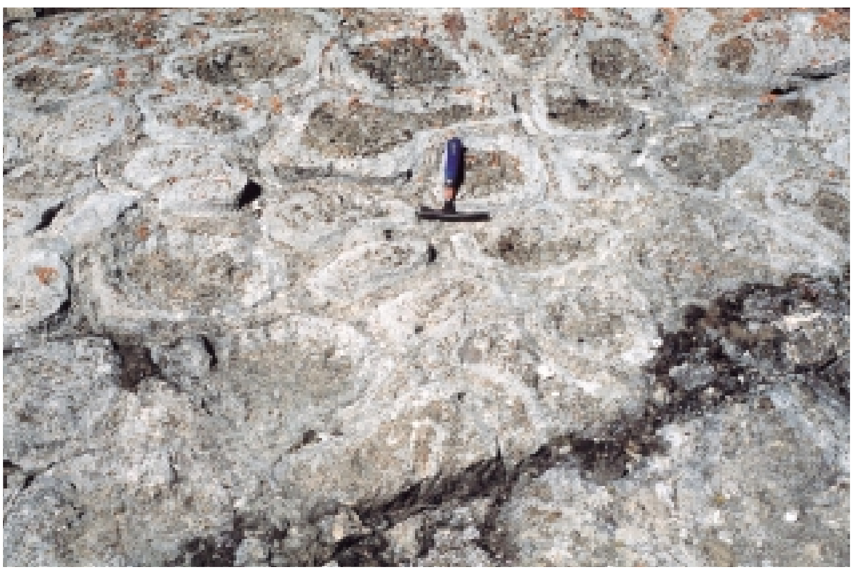

Fig. 7. The upper surface of the microbial mound in Fig. 6, showing the oval to rounded shape of the thrombolites.

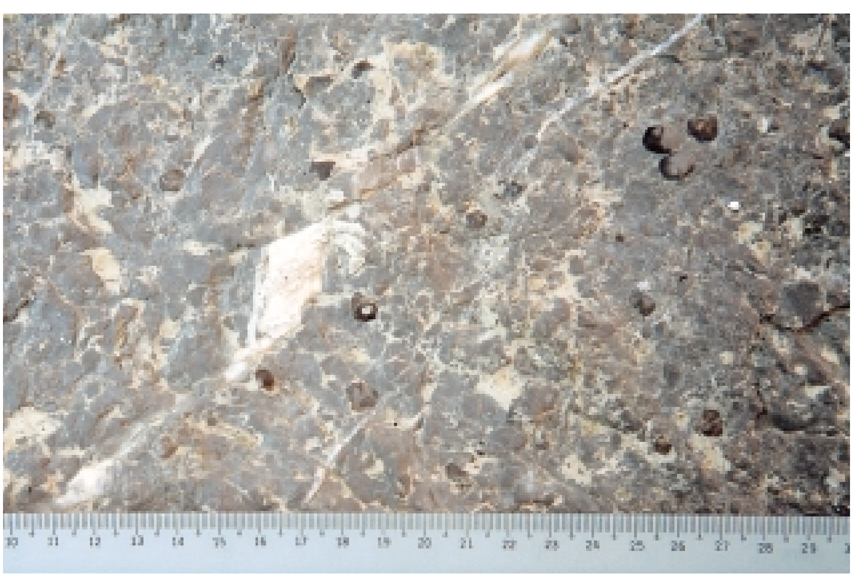

Fig. 8. Clusters of disarticulated shells of a finklenburgiid orthide brachiopod on an upper bedding surface from the middle member of the Antiklinalbugt Formation (section 3).

in the upper part of the lower member. Trilobites and brachiopods, and occasionally orthide brachiopods (Fig. 8), occur in the middle member; Poulsen (1930) reported graptolites.

Hystricurus armatus Poulsen and species of *Symphysurina* dominate the trilobite fauna. The presence of ?*Mannschreekia* sp., *Symphysurina woosteri* Ulrich, *Bellefontia* sp. and *Clelandia* sp. indicate the Antiklinalbugt Formation is Early Canadian (Gasconadian) *Symphysurina* and *Bellefontia-Xenopstegium* zones (Lower Ordovician).

The new fossil collections suggest that the boundary with the overlying Cape Weber Formation is a substantial hiatus; the basal beds of the latter formation contain ?*Cyptendoceras* sp. undet. indicating a Late Canadian (Jeffersonian) age. The lack of Middle Canadian macro-taxa (e.g. *Diaphelasma*, *Bassleroceras*, *Lecanospira* or *Hillyardina*) indicates a condensed sequence or major hiatus, a view in accordance with Poulsen (1930) and Poulsen & Rasmussen (1951), who suggested that much of the Lower Canadian and all of the Middle Canadian are not represented on Ella Ø.

Summary

The 2000 field work allows for the following interpretations.

1. An erosional surface developed at the top of 'unit e' of the Spiral Creek Formation on Ella Ø is overlain by the Kløftelv Formation. Northwards the former formation wedges out and the Kløftelv Formation rests on the Canyon Formation (Hambrey & Spencer 1987; Hambrey *et al.* 1989). This is indicative of a regional hiatus or disconformity at the base of the Kløftelv Formation, which conventionally is taken to be the base of the Cambrian in North-East Greenland.

2. The Lower Cambrian Ella Island and Hyolithus Creek Formations comprise a shallowing-upward sequence of fine-grained siliciclastics and limestones conformably above the shales of the Bastion Formation. The present contact between the Ella Island and Hyolithus Creek Formations is conformable and coincides with a dolomitisation front; the upper limestones of the Ella Island Formation (*sensu* Cowie & Adams 1957) would be better placed in a revised Hyolithus Creek Formation. The successions separated by such a boundary would be predominantly siliciclastic below and carbonate above.

3. The microbialite developments in the Antiklinalbugt Formation are characteristic for the Upper Cambrian to Lower Ordovician interval along the margins of Laurentia (Kennard & James 1986; Knight & James 1988; De Freitas & Mayr 1995). Microbial mounds and buildups similar to those in the Antiklinalbugt Formation are also reported from time-equivalent beds, e.g. the Cape Clay Formation of north-western Greenland (Dawes *et al.* 2000) and Arctic Canada (De Freitas & Mayr 1995).

4. The prominent hiatus recorded between the Antiklinalbugt and Cape Weber Formations corresponds to the Demingian Stage of the Canadian Series. An equivalent but less extensive hiatus is known elsewhere along the Iapetus margin in North America (Boyce 1989; James *et al.* 1989; Boyce & Stouge 1997) and is associated with an important faunal extinction event (Ji & Barnes 1993).

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