Lower–Middle Ordovician stratigraphy of North-East Greenland

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The Upper Proterozoic (Riphean) to Lower Palaeozoic succession in North-East Greenland is exposed in a broad N–S-trending belt in the fjord region between 71°38´ and 74°25´N (Fig. 1). The succession comprises mainly marine sediments accumulated during the later stages of the break-up of the Rodinia supercontinent, the subsequent opening of the Iapetus Ocean and formation of the passive margin along the edge of the Laurentian palaeocontinent.

Investigations of the sedimentary succession were initiated on Ella Ø in the summer of 2000 as part of a project to investigate the development of the Laurentian margin facing the Iapetus Ocean in the Early Palaeozoic, when studies of the uppermost formations of the Riphean Eleonore Bay Supergroup to the Lower Ordovician Antiklinalbugt Formation on Ella Ø were undertaken (Stouge *et al*. 2001). Ella Ø was revisited during the summer of 2001, with the focus on the Ordovician formations. In addition, investigations were undertaken in the Albert Heim Bjerge area where the uppermost part of the Ordovician succession is preserved (Fig. 1).

The scientific station at Solitærbugt on Ella Ø (Fig. 1) was used as the operational base, and helicopter support allowed the establishment of camps on the plateau of Ella Ø and in the Albert Heim Bjerge area.

Ella Ø

Ella Ø preserves exposures of the uppermost part of the Riphean Eleonore Bay Supergroup and the whole of the Vendian Tillite Group, while the Lower Palaeozoic sequence ranges from the Lower Cambrian to the lower Middle Ordovician (Fig. 2; Poulsen 1930; Poulsen & Rasmussen 1951; Cowie & Adams 1957; Hambrey 1989). This succession is unconformably overlain by Devonian continental aeolian and fluviatile clastic rocks.

The main aims of the work on Ella Ø in 2001 were to carry out detailed stratigraphic logging of the upper Lower Ordovician Cape Weber Formation and the lower Middle Ordovician Narwhale Sound Formation, to collect samples for biostratigraphical control throughout the succession in order to constrain the duration of the major hiatus recorded in the Lower Ordovician part of the succession, and to define the lithological boundaries between the recognised units.

Excellent exposures of the Lower to Middle Ordovician strata are found on the 500–900 m high central plateau of Ella Ø (Fig. 1, section 4; Fig. 3) and along the steep cliffs around Antiklinalbugt (Fig. 1, section 5; Fig. 4) which were reached from the base camp using a rubber dinghy.

The overall succession through the stratigraphic interval of the upper Canadian Series (Lower Ordovician) and into the lower Whiterockian (Middle Ordovician) is a conformable, shallowing-upward carbonate succession that begins disconformably above the silty, dolomitic beds forming the top of the Antiklinalbugt Formation (Figs 2, 4).

Cape Weber Formation

The basal contact of the Cape Weber Formation is placed at the top of the dolomitic beds mentioned above. The upper boundary of the Cape Weber Formation is placed at the appearance of the finely laminated, light grey, yellow-weathering dolostone and dolomitic limestone of the overlying Narwhale Sound Formation.

Cowie & Adams (1957) subdivided the Cape Weber Formation on Ella Ø into a lower 'Banded Limestones', the 'Main Limestones' and the upper 'Dolomites and Dolomitic Limestones'. In this study the formation has been measured to be 1140 m thick on Ella Ø, and four informal mappable lithological units are distinguished: units A–D. Unit A and the lower part of Unit B correspond to the 'Banded Limestones', Unit C is equivalent to the 'Main Limestones' and Unit D comprises the upper part of the 'Main Limestones' and the 'Dolomites and Dolomitic Limestones' of Cowie & Adams (1957).

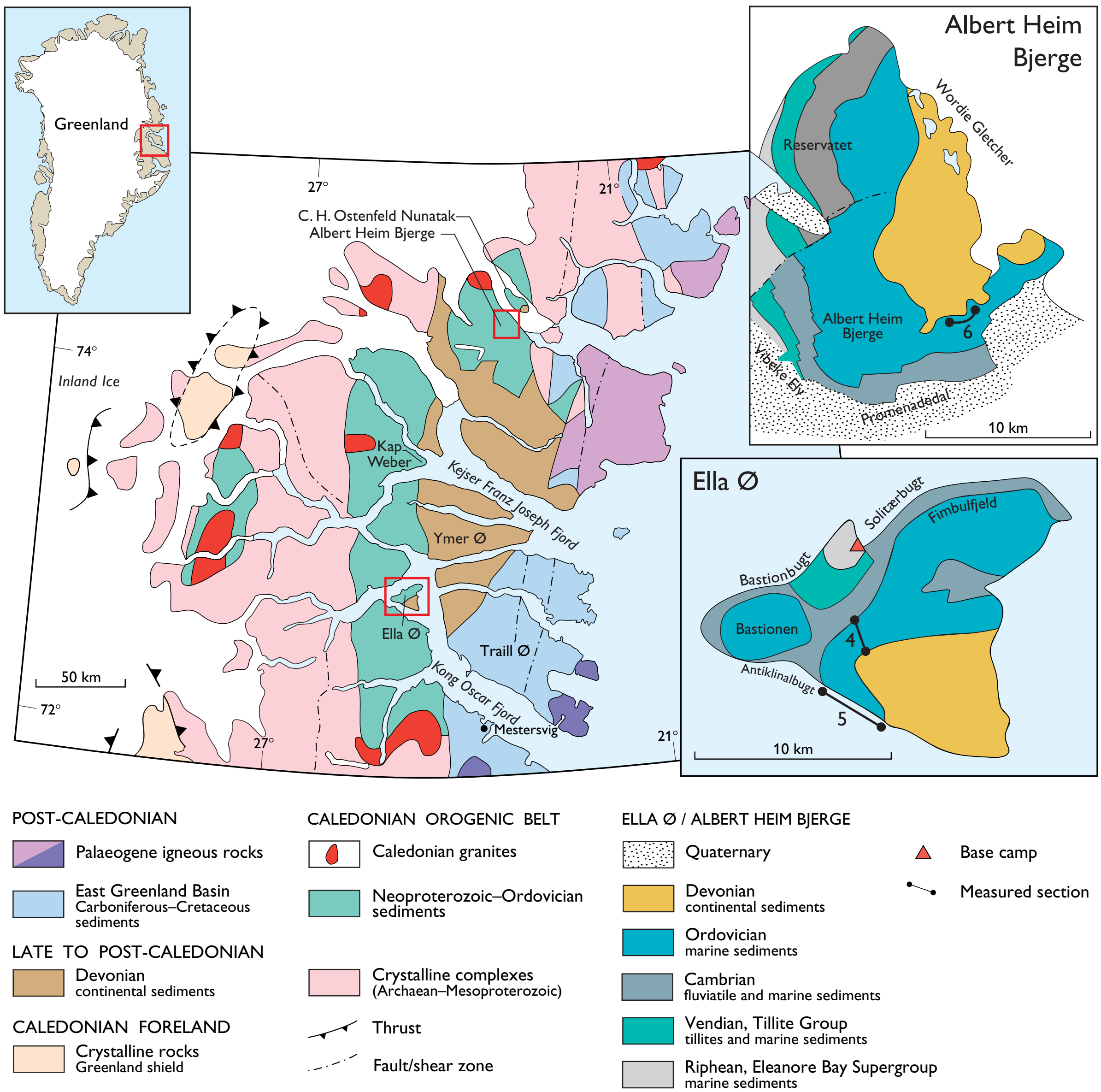

Fig. 1. Locality map of North-East Greenland with simplified geology. The inset maps of Ella Ø and Albert Heim Bjerge show locations of the investigated sections 4, 5 and 6. Geology modified from Cowie & Adams (1957) and Henriksen (1999).

Unit A

Unit A is 100 m thick. The sequence is made up of metre-thick carbonate beds composed of domal to broad, flat stromatolitic and thrombolitic mounds (Fig. 5), laminated lime mudstone and dolostone, intraclastic limestones, minor chert nodules and white-weathering silty interbeds.

The macrofauna recorded from the unit includes trilobites, cephalopods and gastropods. The lower interval is characterised by the trilobite *Peltabellia* sp. whereas the higher part of Unit A is referred to the *Strigigenalis brevicauda* Zone (Boyce 1989; Boyce & Stouge 1997). These two faunal intervals represent the Jeffersonian Stage of the Canadian Series. The sparse conodont fauna (Smith 1991) is included in the comprehensive Fauna D of Ethington & Clark (1971). Smith (1991) had

System	Series		Stage (North America)	Ibex-Utah, USA: Trilobite zones, Ross (1951); Hintze (1953, 1973)	W. Newfoundland: Trilobite zones, Boyce & Stouge (1997)	North-East Greenland: Formations informal units, Albert Heim Bjerge	North-East Greenland: Ella Ø	
Ordovician	Middle	Whiterockian		O – L	(Not zoned)	Heimbjerge	Hiatus	
						Narwhale Sound	Narwhale Sound	
	Lower	Canadian	Cassinian	J		Cape Weber	Cape Weber	Unit D
				I	*Benthamaspis gibberula*			Unit C
				H	*Strigigenalis caudata*			Unit B
			Jeffersonian	G	*Strigigenalis brevicaudata*			Unit A
					('*Peltabellia* sp.')			
			Demingian	E/F	*Randaynia saundersi*	?	Hiatus	
			Gasconadian	B	*Symphysurina*	Antiklinalbugt	Antiklinalbugt	

Fig. 2. The upper Lower to Middle Ordovician stratigraphy of North-East Greenland compared to trilobite zones of Utah, USA and western Newfoundland, Canada.

Fig. 3. Plateau of Ella Ø showing the lower part of section 4 looking north-east. The banded unit to the left is Unit B, which is succeeded by Unit C. Camp (in circle) for scale.

placed the lowermost *c.* 50 m of his Cape Weber Formation within the *Rossodus manitouensis* Zone, which is Tremadoc (Gasconadian–Demingian) in age. However, this packet of carbonate sediments occurs below the extensive disconformity recognised by Stouge *et al.* (2001; Fig. 2), and on lithological criteria these older sediments are better placed within the Antiklinalbugt Formation.

Unit B

Unit B is 250 m thick. The lower part consists of peritidal cycles composed of well-bedded bioturbated and stylonodular limestones, thrombolitic mounds and thinly bedded, laminated dolomitic limestones; ostracodes and trilobites are recorded. The upper part of Unit B is characterised by bedded, bioturbated and peloidal limestones, mounds and abundant brown-weathering chert nodules. The chert nodules are stratabound and richly fossiliferous; coiled and straight cephalopods are common.

The lower part of Unit B belongs to the conodont Fauna D of Ethington & Clark (1971), whereas the upper cherty part of Unit B is included in the *Oepikodus communis* Zone (Smith 1991; Boyce & Stouge 1997). The *Strigigenalis brevicaudata* trilobite zone extends into the lower portion of Unit B, whereas the upper part of the unit is in the *Strigigenalis caudata* Zone.

Unit C

Unit C is 330 m thick and composed of thick-bedded, grey to dark grey peloidal and bioturbated packstone

Fig. 5. Stromatolite and thrombolite mounds from Unit A, Cape Weber Formation, Ella Ø.

Fig. 4. Section 5 in Antiklinalbugt on the southern side of Ella Ø. Devonian clastic rocks at right unconformably overlie the Middle Ordovician Narwhale Sound Formation.
A: Antiklinalbugt Formation
CW: Cape Weber Formation
NS: Narwhale Sound Formation
D: Devonian
T: 1047 m above sea level

to grainstone associated with mounds and closely spaced, stratabound nodular chert. The macrofauna is rich and varied and often silicified. Faunal elements include brachiopods, trilobites, gastropods, cephalopods, crinoids and sessile *insertae sedis*, possibly representative of sponges. The trilobite fauna indicates equivalence with the *S. caudata* Zone or perhaps the *Benthamaspis gibberula* Zone. The conodont fauna is sparse and corresponds to the upper part of the *O. communis* Zone (Smith 1991; Boyce & Stouge 1997).

Unit D

Unit D, about 460 m thick, is composed of grey lime mudstone and peloidal limestone, dark bituminous mudstone and peloidal, thickly bedded, bioturbated carbonates with minor dolomitic horizons containing chert. A characteristic marker bed about 100 m from the top of the unit is composed of thrombolites and stromatolites with grainstone intrabeds. The marker horizon is overlain by medium-bedded wackestone and peloidal lime mudstones and dolomitic bioturbated limestone associated with chert. The macrofauna is highly diverse and rich below the local marker horizon, and cephalopods are common (Fig. 6). The trilobites are assigned to the *Benthamaspis gibberula* Zone, which is coeval with Zones H and I *sensu* Ross (1951) and Hintze (1953, 1973) of the Utah–Nevada sections (Boyce & Stouge 1997). It is possible, however, that Unit D may be as young as Zone J (= *Pseudocybele nasuta* Zone of Fortey & Droser 1996) of the Utah–Nevada successions. The conodont fauna (Stouge 1978; Smith 1991)

Fig. 6. Straight silicified cephalopod from Unit D, Cape Weber Formation, Ella Ø.

is abundant and highly diverse, and is referred to the *Jumodontus gananda – ?Reutterodus andinus* Interval of Ethington & Clark (1981). In the uppermost 100 m of the unit (above the grainstone marker horizon) the conodont fauna is, however, of low diversity and not biostratigraphically distinctive (Smith 1991).

Narwhale Sound Formation

On Ella Ø the Narwhale Sound Formation was only studied in section 4 (Fig. 1); in section 5 many closely spaced and nearly coast-parallel faults disrupt the succession. The sediments comprise sucrosic dolostones with a vuggy texture, and no original sedimentary structures are preserved.

The base of the Narwhale Sound Formation is recorded as a prominent 7 m thick bed of laminated and cross-bedded dolostone and dolomitic bioturbated limestone. The remainder of the 260 m thick succession consists of pale grey to cream grey microcrystalline to sucrosic dolostone, pale grey to grey fine-grained dolomitic limestone and pale grey limestone. Small thrombolitic mounds are present and cross-bedding is common. Individual beds vary in thickness from 5 cm to over 7 m. Throughout the formation beds of brown to black cherts and chert-like silicified dolostones occur. The upper boundary is the Devonian unconformity.

Silicified macrofossils are present. The fauna primarily consists of gastropods, cephalopods and occasional brachiopods, sponges and trilobites.

Conodonts recorded from the upper part of the formation are Middle Ordovician in age (Smith & Bjerreskov 1994), and the Lower to Middle Ordovician boundary is probably within the lower part of the Narwhale Sound Formation (Fig. 2; Stouge 1978; Smith 1991).

Albert Heim Bjerge

The Albert Heim Bjerge are bounded by Wordie Gletscher to the north-east and Reservatet to the north (Fig. 1). The major E–W-trending valley of Promenadedal and the river Vibeke Elv form the southern limit of the study area (Fig. 1). The area is noted for the exposures of the Middle Ordovician Heimbjerge Formation, which is the youngest preserved pre-Caledonian unit in this part of North-East Greenland (Bütler 1940; Cowie & Adams 1957; Frykman 1979). As is the case on Ella Ø, Devonian clastic sediments unconformably overlie the Ordovician rocks.

Investigations in the Albert Heim Bjerge area were focused on the 'Black Limestones' of the Cape Weber Formation and the type area of the Heimbjerge Formation (Fig. 1, section 6; Cowie & Adams 1957).

Cape Weber Formation

Cowie & Adams (1957) subdivided the Cape Weber Formation in the Albert Heim Bjerge into 'Lower Limestones', 'Black Limestones', 'Upper Limestones' and 'Dolomites and Dolomitic Limestones'. The 'Black Limestones' facies has so far only been distinguished in the Albert Heim Bjerge area (Cowie & Adams 1957), where it is 80–100 m thick and consists of black, bituminous wackestone to grainstone with shaly partings, and with chert in the upper part. Fossils are common and trilobites, including a species of the cosmopolitic genus *Carolinites*, have been reported (Cowie & Adams 1957). In 2001 macrofossils were collected from the 'Black Limestones', and samples were collected throughout the unit for conodont studies.

The 'Black Limestones' represent a deep-water marine incursion on the outer margins of the platform of North-East Greenland. On Ella Ø the coeval interval may be either the dark limestones and cherts of the upper part of Unit C, or the dark bituminous limestones of Unit D.

Heimbjerge Formation

The basal 10–15 m of the Heimbjerge Formation are dominated by brown and dark red laminated lime mudstones with birds-eye structures, stromatolites and bioturbated limestones. Above follows *c.* 50 m of laminated, grey brown lime mudstone with intraclast conglomerates overlain by platy carbonate mudstones with thin layers of calcite. A further 10 m are represented by a heterogeneous succession of massive and platy limestones, in places bioturbated, and marked by the development of small stromatoporoid mounds. Thick beds of light grey, bioturbated clean wacke- to grainstones with discontinuous horizons of chert nodules occur throughout the overlying 80 m of section. The highest exposed 50 m comprise a platy limestone facies dominated by the development of stromatoporoid bioherms. The preserved succession of the Heimbjerge Formation is only 300 m at the type locality in Albert Heim Bjerge, but Frykman (1979) recorded more than 1200 m of strata belonging to the formation on C.H. Ostenfeld Nunatak about 25 km to the north (Fig. 1). The Heimbjerge Formation is Whiterockian in age (Middle Ordovician; Smith & Bjerreskov 1994).

Thermal and burial history of the Ella Ø succession

Smith (1991) briefly reported on the conodont alteration indices (CAI; Epstein *et al.* 1977) from the upper Lower to Middle Ordovician rocks of the study area. Low values (CAI 1–1.5) are characteristic for the study area, and higher values (CAI 2) are found in the C.H. Ostenfeld Nunatak succession to the north (Smith 1991). The provisional results of CAI studies on samples collected in 2000 and 2001 are reported below.

The sequential change in colour of conodont elements reflects the progressive and irreversible alteration of organic matter preserved in the conodont elements in response to temperature, usually a consequence of thickness of overburden. The CAI values 1–5 have been experimentally calibrated with temperature ranges and correlated with other indices of organic metamorphism by Epstein *et al.* (1977). Thus, CAI 1 (50–80°C) and CAI 1.5 (50–90°C) are unaltered to nearly unaltered pale-yellow to yellow conodont elements, CAI 2 (60–140°C) are yellow to light brown, whereas CAI 3 (110–200°C) comprises brown altered conodont elements.

CAI determinations from limestones of the Antiklinalbugt Formation on Ella Ø give values of CAI 3 decreasing upwards to CAI 1.5 in the Cape Weber Formation and CAI 1 in the Middle Ordovician Narwhale Sound Formation. In Albert Heim Bjerge, CAI values are about CAI 1 in the Heimbjerge Formation. The CAI values recorded from the Ordovician succession on Ella Ø suggest that increased depth of burial was the major factor for the organic metamorphism and that the subsidence in the study area occurred during the Early Palaeozoic.

A conservative estimate of the overburden responsible for the low CAI values in the Narwhale Sound Formation on Ella Ø and the Heimbjerge Formation in Albert Heim Bjerge is about 1.5 to 1.7 km. Thus, 1–1.5 km of strata of the formerly overlying carbonate sequence has been removed from the area between Albert Heim Bjerge and Ella Ø. It follows that the 1200 m thick sequence of the Heimbjerge Formation reported from C.H. Ostenfeld Nunatak by Frykman (1979) is virtually complete. Overburden estimates are based on the geothermal gradient estimates by Rasmussen & Smith (2001) in the Ordovician carbonates of the northernmost East Greenland Caledonides and the estimates of heat flow by Armstrong *et al.* (1994).

Synthesis

The summer of 2001 was devoted mainly to the Ordovician succession overlying the disconformity separating the Antiklinalbugt Formation and the Cape Weber Formation (Stouge *et al.* 2001). The hiatus corresponds to all of the Demingian Stage and the early part of the Jeffersonian Stage of the Canadian Series (Fig. 2).

Faunal evidence from the Cape Weber Formation shows that the four informal units (A–D) represent most of the Jeffersonian and the Cassinian stages of the upper Canadian Series. The Canadian–Whiterockian Series boundary is apparently conformable and can be placed within the lower part of the Narwhale Sound Formation. The Heimbjerge Formation is Whiterockian in age, and sedimentary sequences younger than Whiterockian have not been recorded from the study area.

The Ordovician strata below the Demingian disconformity have conodonts with CAI values of about 3, suggesting that organic maturity had been reached. The overlying strata of the upper Canadian – lower Whiterockian above the disconformity are organically mature to immature with CAI values 1.5 to 1.

The upper Lower Ordovician – lower Middle Ordovician Cape Weber Formation and Narwhale Sound Formation represent a cycle of sedimentation beginning with subtidal facies and concluding with peritidal facies. There is a change from deposition on a slow subsiding passive margin to a faster subsiding margin characterised by rapid accumulation of carbonates. The cycle concluded with a regression in early Whiterockian time.

The 'Black Limestones' of Albert Heim Bjerge and the coeval strata on Ella Ø possibly mark the global sea-level rise corresponding to the '*evae*' transgression (= zones H–I), which is the highest sea-level stand in the Early Ordovician (Stouge 1982; Barnes 1984; Fortey 1984; Nielsen 1992). This sea-level rise can be traced in coeval shelf and slope deposits along the margins around the Laurentian palaeocontinent (Barnes 1984), and is characterised by the appearance of marginal shelf to slope faunal elements in the shallow-water carbonates on the shelf. A second sea-level rise may also be reflected by the 'Black Limestones' that correspond to Zone J of the upper Canadian Series. In Greenland, this younger sea-level rise has been recorded from the Nunatami Formation in North-West Greenland (i.e. the 'Bifidus' shale of Poulsen 1927) and has also been recognised in western and central North Greenland (Higgins *et al.* 1991). In western Newfoundland the sea-level rise has been identified on the basis of faunal evidence (Boyce *et al.* 2000).

The Heimbjerge Formation comprises a second carbonate depositional cycle characterised by shallow-marine subtidal facies. Carbonate accumulation kept pace with sea-level change. The diverse metazoan fauna (stromatoporoids) suggests that clear water and high-energy environments prevailed.

Acknowledgements

The research project is supported by the Danish Natural Science Research Council (Grant no. 9901696). Helicopter transport was funded by the National Geographic Society, Washington D.C., USA.

The project represents an inter-disciplinary co-operation between GEUS, the Geological Survey Division of the Government of Newfoundland and Labrador, Canada, the Geological Museum, Copenhagen, Denmark and the Holbaek College of Education, Denmark. Logistics for this season were organised by T.I. Hauge Andersson of the Danish Polar Center (DPC). The support of Sebastian Rasmussen (DPC) in the field is greatly appreciated. The Sirius Patrol personnel at Ella Ø are thanked for their help and hospitality.

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