Lower Palaeozoic carbonates in eastern North Greenland, and the demise of the 'Sæfaxi Elv nappe'

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As participants in the three-year 1:500 000 mapping programme in eastern North Greenland initiated in 1993 by the Geological Survey of Greenland (Henriksen, 1995, this report), the principal aim of the authors was to document the stratigraphy and structure of Ordovician and Lower Silurian sediments in a *c.* 5000 km^2 area in southern Kronprins Christian Land and westernmost Lambert Land (Fig. 1), and estimate the palaeogeographical position of Greenland in relation to the areas surrounding the Iapetus Ocean. The area studied lies within the East Greenland Caledonian fold belt, in the parautochthonous boundary zone between far-travelled nappe sheets and undisturbed foreland sediments.

Geological setting

The Lower Palaeozoic sediments of Kronprins Christian Land and Lambert Land were deposited on a subtidal to peritidal carbonate platform which constituted the easternmost part of the Franklinian Basin that extended from the Canadian Arctic islands across North Greenland (Higgins *et al.*, 1991). The stratigraphy erected in Peary Land and western Kronprins Christian Land (Peel, 1985; Higgins *et al.*, 1991; Smith & Bjerreskov, 1994) can, to a significant degree, be applied to the successions farther to the east and south within the study area (Fig. 2), although many of the units differ in detail. Eastern Kronprins Christian Land was affected by the Caledonian orogeny, and the Lower Palaeozoic units of the study area make up the parautochthonous foreland in the footwall of the Vandredalen thrust sheet. The parautochthonous succession, which comprises the Ordovician Wandel Valley, Sjælland Fjelde and Børglum River Formations, the Upper Ordovician to Lower Silurian Turesø Formation, and the Lower Silurian Odins Fjord, Samuelsen Høj and Lauge Koch Land Formations, is disrupted by thrust sheets with generally small displacements. Good stratigraphic control of the superficially similar looking alternating units of peritidal dolostone and subtidal burrow-mottled limestones is essential, and was achieved in the field by detailed sedimentary facies analysis and macrofaunal biostratigraphy. This will be followed up by the biostratigraphic analysis of conodonts to verify field determinations.

The 'Sæfaxi Elv nappe' and the Harefjeld problem

One of the initial field work objectives was to investigate the sediments of the 'Sæfaxi Elv nappe' of Hurst & McKerrow (1981), which was thought to comprise allochthonous deeper water equivalents of the Upper Ordovician – Lower Silurian carbonate platform sediments to the west (Hurst & McKerrow, 1981, 1985; Hurst *et al.*, 1985), and to examine an apparent conflict between these accounts and the earlier work of Fränkl (1954, 1955).

Hurst & McKerrow (1981, 1985) recognised a thrust sheet containing Ordovician – Silurian carbonates thrust over the Proterozoic Fyns Sø Formation, and structurally underlying the Vandredalen thrust sheet containing the 'Rivieradal sandstones'. The carbonates were thought to belong to the Danmarks Fjord Dolomite (abandoned name), which was subsequently assigned to the Lower Ordovician Danmarks Fjord Member of the Wandel Valley Formation by Peel *et al.* (1981) and Smith & Peel (1986). These shallow water carbonates were thought to be overlain by deep water carbonates of probable Silurian age assigned to the Harefjeld Formation by Hurst (1984) (Figs 3, 4A). The apparently marked contrast with known foreland successions, which contain only shallow water Ordovician – Silurian sediments, was explained by a proposed transport distance in excess of 100 km (Hurst & McKerrow, 1981, 1985).

In contrast to this interpretation, Fränkl (1955) had earlier recognised an unconformable, tectonically undisturbed, boundary between the Fyns Sø Formation and the Danmarks Fjord Member with a sandstone above the unconformity and sandstone-filled fissures extending downwards into the Fyns Sø Formation.

The Proterozoic – Palaeozoic boundary was examined at a locality 5 km to the west of Marmorvigen where the Danmarks Fjord Member shows relationships to the Fyns Sø Formation very similar to those described by Fränkl (there is evidence to suggest that it may be the same locality). A 1.8 m thick coarse- to very coarse-grained quartz arenite rests on the unconformity surface with a 10–15 cm imbricated conglomerate at the base. The conglomerate clasts are mainly composed of Fyns Sø Formation litholo-

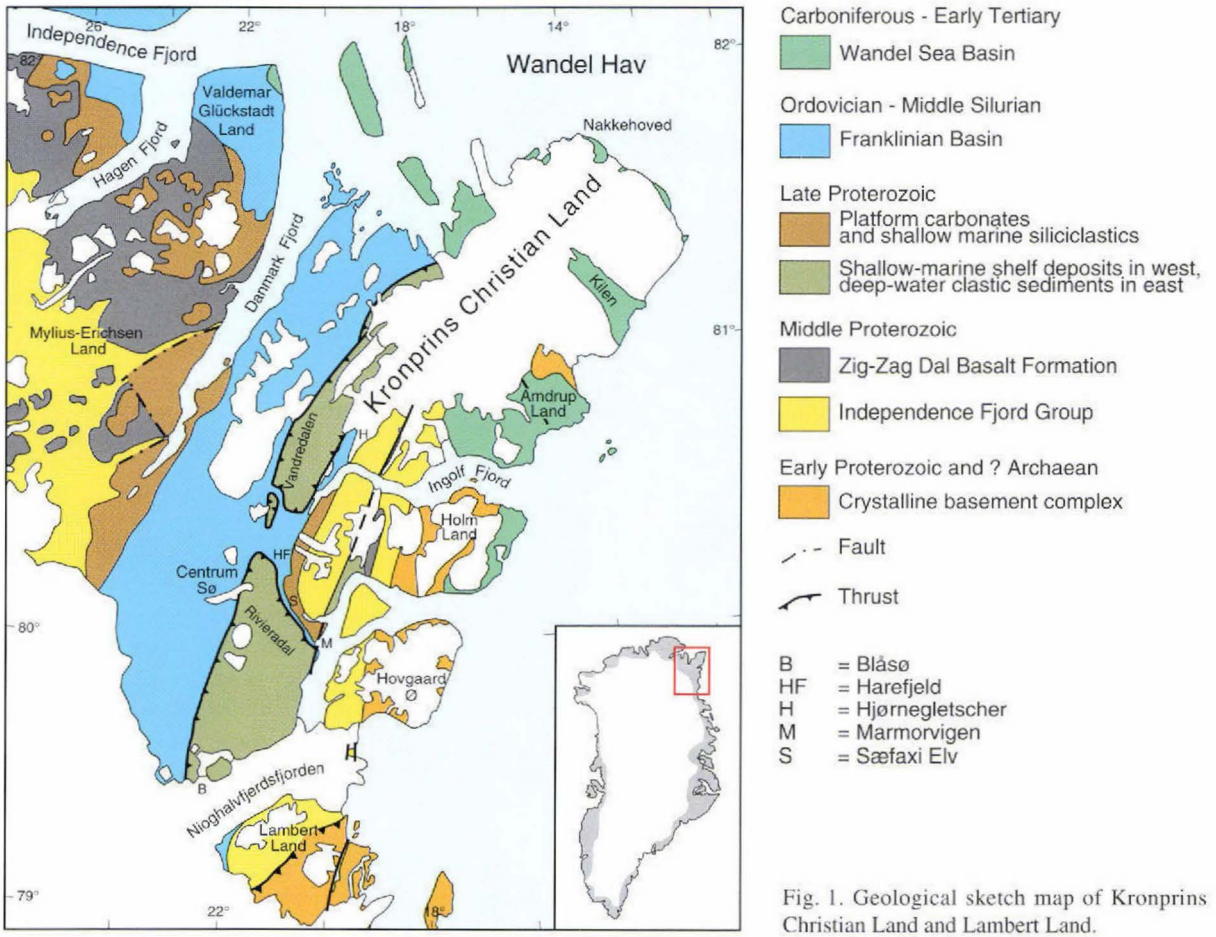

Fig. 1. Geological sketch map of Kronprins Christian Land and Lambert Land.

gies but there are also some coarse-grained quartz arenite clasts. The sandstone passes gradationally upwards into a burrow-mottled dolostone, and the sandstone itself is bioturbated in its upper part. Little relief was seen on the unconformity surface and there is no perceptible angular discordance between the Fyns Sø Formation and the overlying Danmarks Fjord Member. Early Ordovician conodonts have been recovered from samples of the Wandel Valley Formation taken at localities on both Harefjeld and in Sæfaxi Elv.

Beneath the sandstone, vertical to sub-vertical fissures extend down into the Fyns Sø Formation and appear to connect with a network of 1–2 m diameter sub-horizontal tubes up to a maximum of 10 m below the unconformity surface; the latter are interpreted as a fossil cave system. Both fissures and tubes are filled with well-cemented quartz arenites of coarse sand to granule grain sizes. The presence of these fissures connecting with the sandstone at the base of the Danmarks Fjord Member rules out the possibility of a thrust at this boundary.

In summary, there is no evidence for a thrust at the base of the Palaeozoic sequence and as the successions in Sæfaxi Elv and on Harefjeld itself can be unequivocally assigned to the Wandel Valley Formation, it is recommended that the Harefjeld Formation of Hurst (1984) is abandoned. The Sæfaxi Elv nappe does not exist, and the sediments once assigned to it may be regarded as part of an intact footwall sequence underlying the Vandredalen thrust sheet.

Extension of the Early Ordovician overstep

The Lower Ordovician Wandel Valley Formation is the oldest Palaeozoic lithological unit found in Kronprins Christian Land. It comprises three members. The lower member, the Danmarks Fjord Member, includes an up to 10 m thick evaporitic collapse breccia.

East of Vandredalen, the Danmarks Fjord Member is overlain by highly strained burrow-mottled lime mudstones (*c.* 200 m) in which the burrows are considerably stretched (Figs 3, 4A). These have yielded conodonts of late Early Ordovician age and are assigned to the Amdrup Member of the Wandel Valley Formation. This member is in turn overlain by recessive dolostones of peritidal origin (115 m) containing Whiterockian conodonts, together indicative of

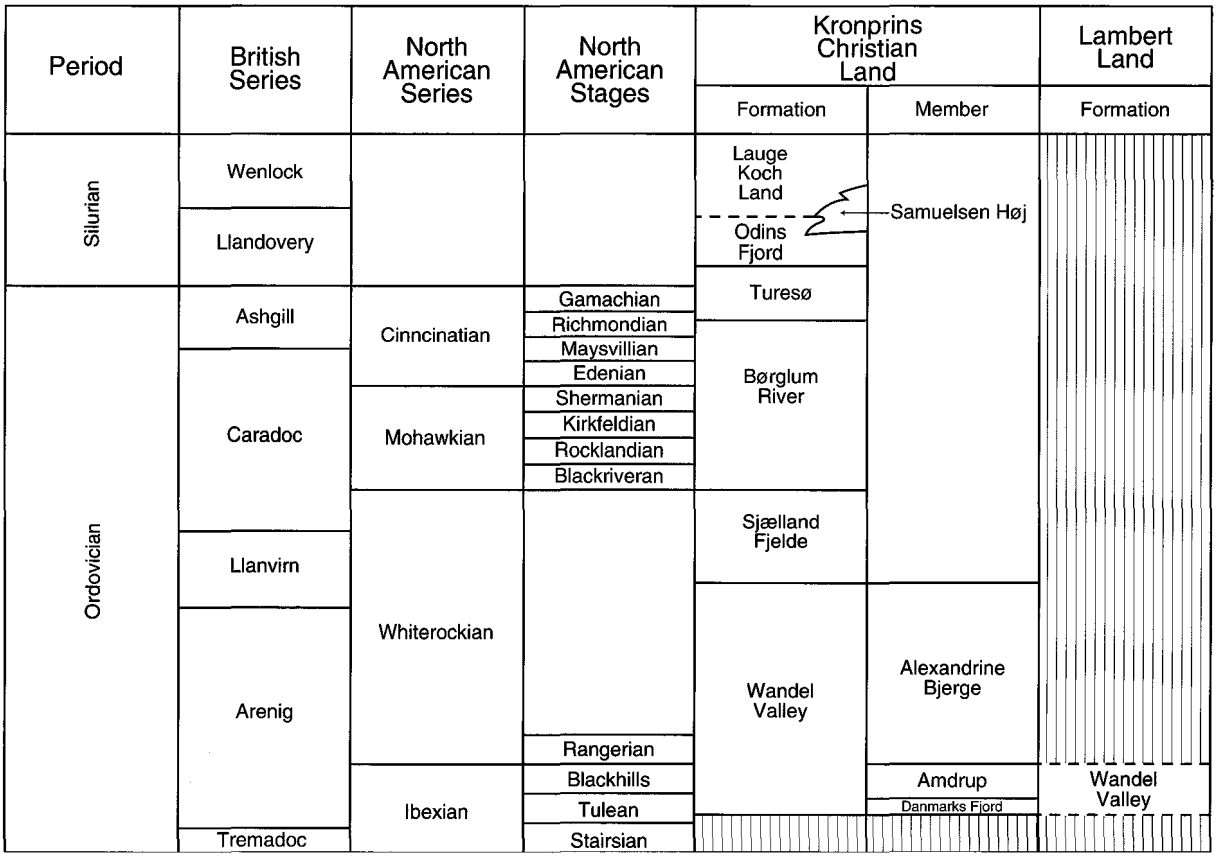

Fig. 2. Lower Palaeozoic stratigraphy of Kronprins Christian Land and Lambert Land.

the Alexandrine Bjerge Member (Fig. 3). In summary, all three members of the Wandel Valley Formation in the Sæfaxi Elv – Harefjeld – Ingolf Fjord area are very similar to their development in the type area around Danmark Fjord on the foreland.

Prior to the current mapping programme, the Wandel Valley Formation was not known to crop out south of Kronprins Christian Land. However, strongly sheared outcrops of carbonates found in westernmost Lambert Land in 1994 were shown to be Palaeozoic in 1995.

Examination of the quartzite–carbonate boundary near the Inland Ice margin demonstrated that the carbonates in question do unconformably overlie Independence Fjord Group quartzites with very slight angular discordance. The basal 25 m of the carbonates constitute a generally pale weathering unit which is made up of current laminated dolostones with scours and some ripple lamination together with darker wavy laminated dolostones with ripples and drapes (Fig. 4B). Some cyclicity is evident, and the top of one cycle contains probable pseudomorphed evaporite nodules. This lower unit is overlain by highly sheared, dark-weathering wavy laminated and burrow-mottled, somewhat dolomitised, carbonates. A rock sample from the lower unit contained a small number of phosphatic, organic fragments of which four have been positively identified as broken, coniform conodont elements indicative of an Ordovician age for the unit. The conodont fragments are black which corresponds to CAI 5 (conodont Colour Alteration Index), suggesting a post-depositional heating of the sediments of 300–480 °C (Rejebian *et al.*, 1987).

Taking into account the lithofacies present, the unconformable relationship with the underlying Independence Fjord Group, and the recovery of fragmentary conodonts, the Lambert Land carbonates are here assigned to the Wandel Valley Formation. Measurements of the strontium-calcium ratio and the manganese content as part of a preliminary chemostratigraphic programme, give further evidence for this interpretation (see below). It is probable that the lower 25 m unit represents the Danmarks Fjord Member and that the upper unit is part of the Amdrup Member. The thickness of the upper unit in Lambert Land is difficult to estimate due to structural complications, but it does not exceed the 200 m seen in the Amdrup Member in Kronprins Christian Land.

Fig. 3. Harefjeld viewed from the south showing steep or cliff-forming burrow-mottled limestones of the Amdrup and Danmarks Fjord Members of the Wandel Valley Formation (WV), which unconformably overlies the Fyns Sø Formation (FS). The recessive pale weathering cap of the hill is the lower part of the Alexandrine Bjerge Member (AB, Wandel Valley Formation).

Chemostratigraphy applied to Lower Palaeozoic carbonates

The biostratigraphical studies associated with the project are mainly based on conodonts, which are the most abundant fossil group throughout the Ordovician and Lower Silurian succession. However, conodonts are rare or absent in coastal marine environmental settings, which means that alternative stratigraphical methods must be considered in these cases.

The potential of chemostratigraphy based on carbonate trace-elements has been known for more than two decades. Hitherto, the studies have been concentrated especially on Mesozoic and Cenozoic sediments such as Cretaceous chalk (Jørgensen, 1975, 1986), and Tertiary pelagic sediments (Renard, 1986). Provisional studies show that chemostratigraphy can add information of the relative age of low-grade metamorphosed, Lower Palaeozoic, peritidal carbonates in eastern North Greenland.

Concentrations of calcium (Ca), magnesium (Mg), strontium (Sr) and manganese (Mn) were determined by a Perkin-Elmer Atomic Absorption Spectrophotometer, and the preparation of sample solution and standards was carried out in accordance with normal procedures for determination of elements in the carbonate fraction of limestone. Subsequently, the Sr/Ca and Mg/Ca ratios, and the Mn ppm content were computed and graphically displayed, following the procedure of Jørgensen (1986). The method has the advantage of being both cheap and quick.

Fifty samples were collected from the Wandel Valley, Sjælland Fjelde, Børglum River, Turesø and Odins Fjord Formations in order to test the method (Fig. 5).

The amount of analysed material is as yet far too small to provide a basis for a chemical zonation scheme, but some apparent trends seem to exist. For example, the burrow-mottled Børglum River and Odins Fjord Formations, which are difficult to distinguish from each other in the field, seem to be separated both on the Sr/Ca ratio and the manganese content. The Sr/Ca ratio is significantly higher within the Børglum River Formation than in the overlying Turesø and Odins Fjord Formations (Fig. 5), and in addition, the manganese content is considerably lower in the latter two formations than in the Børglum River Formation, except for the two lowermost samples of the Turesø Formation. It

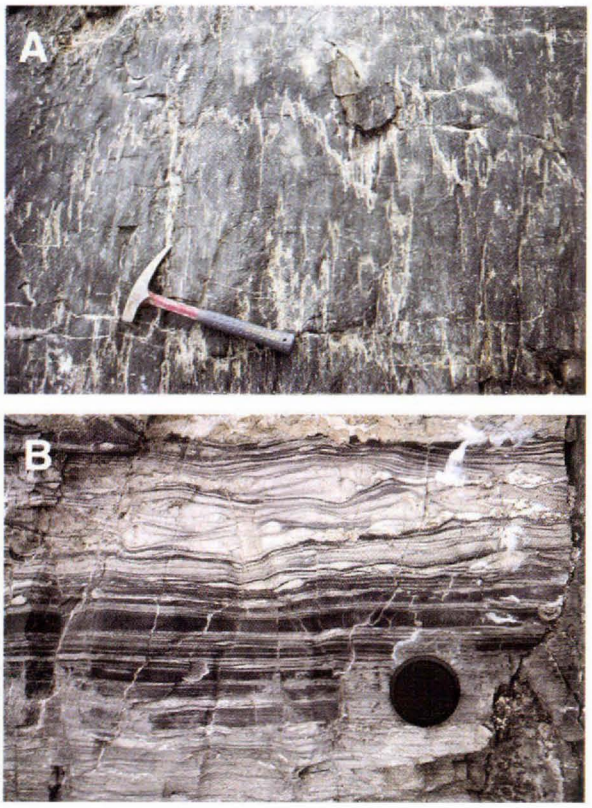

Fig. 4. A: Vertical stylolites in highly strained burrow-mottled facies of the Amdrup Member (Wandel Valley Formation) on Harefjeld. B: Highly strained wavy laminated facies in the basal part of the Wandel Valley Formation (equivalent to the Danmarks Fjord Member) in westernmost Lambert Land. Horizontal, cylindrical, dolomite-filled burrows are seen in cross-section.

is possible that the significant drop in the Sr/Ca ratio and the manganese content in the lower part of the Turesø Formation are related to the significant glacio-eustatic sea-level drop just below the Ordovician – Silurian boundary and the succeeding transgression. Another possibility is that the Sr/Ca ratio changes are influenced by an accelerated hydrothermal activity, which gives an increased Ca concentration in the sea water, finally resulting in a lowering of the Sr/Ca ratio (Renard, 1986).

The manganese content is extremely high in some intervals in the Danmarks Fjord Member and the Alexandrine Bjerge Member (> 200 ppm), a characteristic which seems to be restricted to these two units (Fig. 5).

Four samples from the newly discovered conodont-bearing Ordovician sediments in western Lambert Land were analysed (the 'DF?' and 'AM?' samples in Fig. 5). The DF? sample is characterised by a high manganese value and a medium high Sr/Ca ratio. These values are similar to the values measured from one of the Danmarks Fjord Member samples collected at Danmark Fjord. The succeeding Lambert Land samples ('AM?') show relatively high Sr/Ca ratios and a low manganese content. This pattern is also displayed by the Amdrup Member (AM) and the lowermost part of the Børglum River Formation (BR). Field relations make the Amdrup Member the most likely alternative.

The Mg/Ca ratio is mainly dependent on the dolomite/calcite ratio in the sample, meaning that it has a limited stratigraphical value in this sedimentological setting where alternating dolostone and limestone beds are common. In contrast, the Sr/Ca ratio is not affected significantly by the dolomite/calcite ratio.

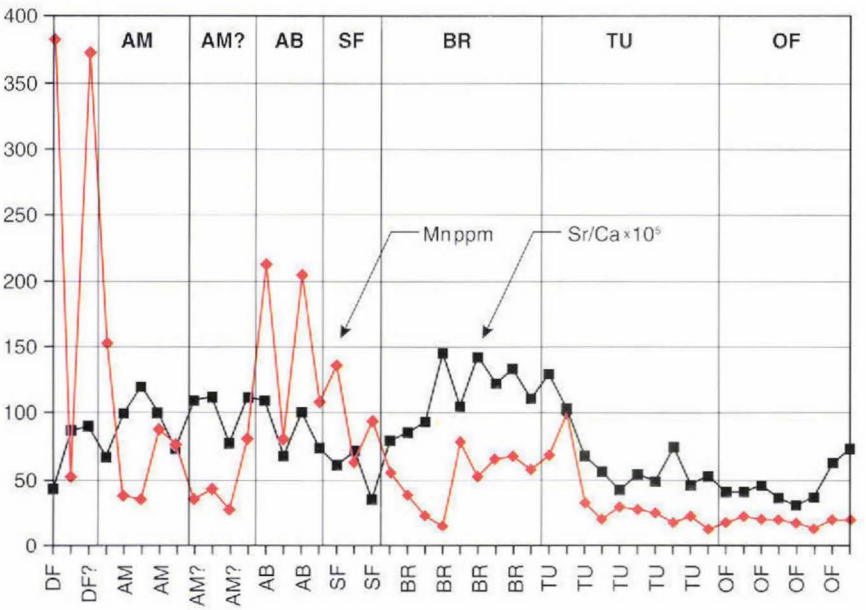

Fig. 5. Evolution of the strontium/calcium ratio and the manganese content in Ordovician and Lower Silurian carbonate samples from eastern North Greenland. DF: Danmarks Fjord Member (Wandel Valley Formation), DF?: probable Danmarks Fjord Member (Lambert Land), AM: Amdrup Member (Wandel Valley Formation), AM?: probable Amdrup Member (Lambert Land), AB: Alexandrine Bjerge Member (Wandel Valley Formation), SF: Sjælland Fjelde Formation, BR: Børglum River Formation, TU: Turesø Formation, OF: Odins Fjord Formation.

In conclusion, it is possible to separate between many, but not all, the studied lithological units based on Sr/Ca and manganese chemostratigraphy. The method can clearly distinguish between the quite similar burrow-mottled, limestone-dominated units, the Middle to Upper Ordovician Børglum River Formation and the Lower Silurian Odins Fjord Formation, as the former unit has a higher Sr/Ca ratio, and commonly also a higher manganese content.

Future work

Detailed sedimentological logging, together with the collection of more than 330 conodont samples through most parts of the investigated Ordovician and Lower Silurian succession, will form the basis for further stratigraphic and basin evolution studies as well as conodont palaeoecological and palaeogeographical analyses. The chemostratigraphic pilot-study suggests it may be possible to establish a chemostratigraphic zonation through the Franklinian Basin carbonate succession in northern Greenland provided a more extensive analysis programme is undertaken.

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