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The geology of the Centrumsø area of Kronprins Christian Land, northeast Greenland, and lithological constraints on speleogenesis

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Abstract: The cave-bearing limestones of Kronprins Christian Land, northeast Greenland, were deposited on the Laurentian craton, on a sector of the margin referred to the Franklinian Basin. A 1.4km succession of Ordovician–Silurian carbonates rests unconformably on Lower Cambrian sandstones and Neoproterozoic sediments, and the carbonate succession is overlain conformably by late Llandovery (Silurian) turbidites that mark the collapse of the continental shelf at the onset of Caledonian tectonics, due to loading by thrust sheets and their erosional products. The cave-bearing limestones form a thin-skinned duplex that sits beneath the Vandredalen thrust sheet, which in turn lies in the footwall of a major fault that bounds exhumed, deep crustal rocks. Despite the thickness of the Lower Palaeozoic succession, most of the caves are concentrated in a thin interval comprising the subtidal–peritidal carbonates of the Odins Fjord Formation and the overlying reef limestones of the Samuelsen Høj Formation (both late Llandovery, Silurian). Caves are found only in the vicinity of the Samuelsen Høj reefs despite extensive exploration of the area as part of the regional mapping programme and the Greenland Caves Project, suggesting a possible genetic link even for those caves developed entirely within the Odins Fjord Formation.

Keywords: Franklinian Basin; Caledonian Orogeny; Silurian; North-East Greenland National Park

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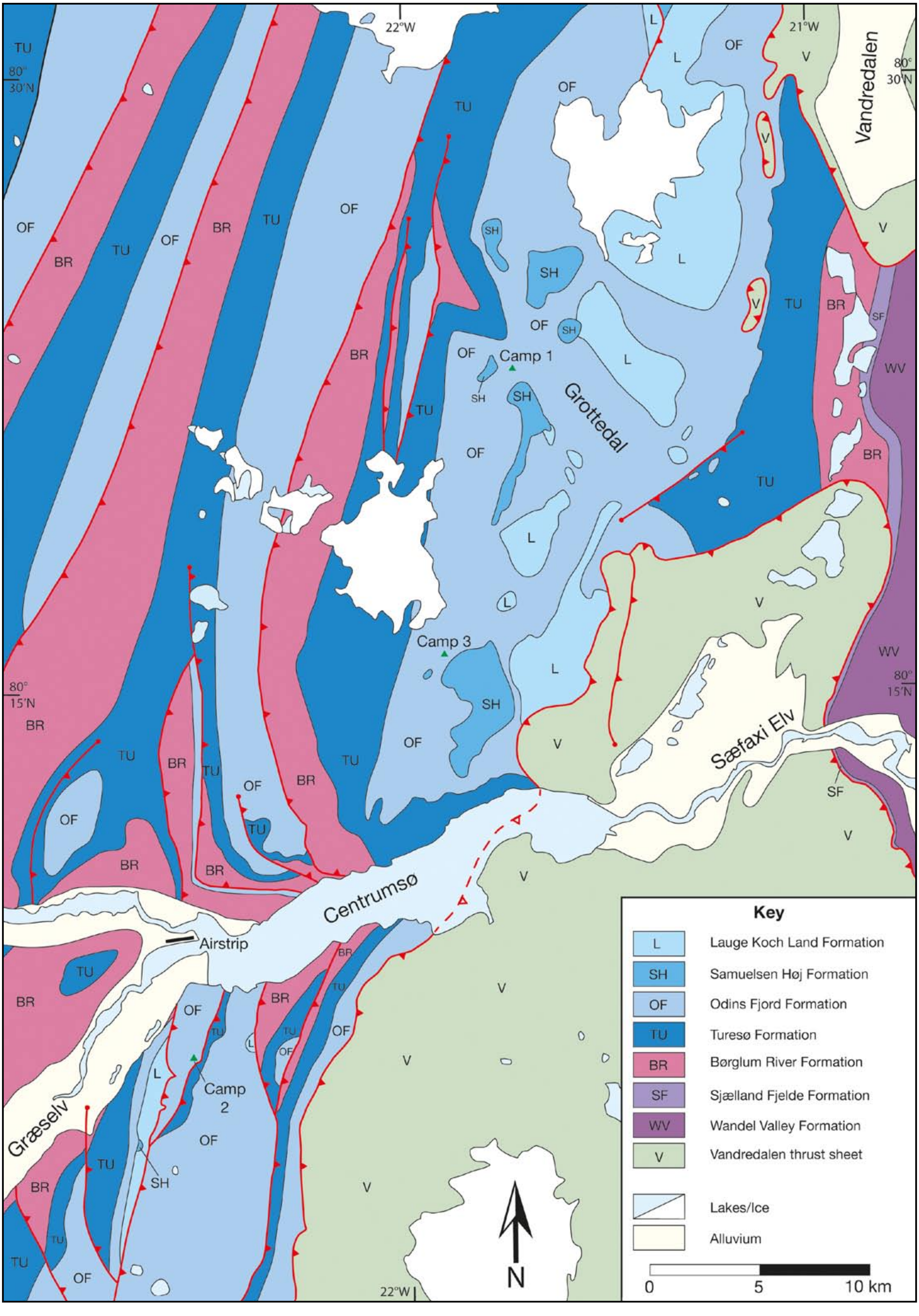
The caves of Kronprins Christian Land (Moseley *et al*., 2020) are developed in Silurian carbonate rocks that were deposited on the northeastern corner of Laurentia, the ancient North American continent comprising modern-day Canada, the USA and Greenland. Kronprins Christian Land lies at a distinctive right-angle bend that constitutes an original Laurentian promontory within the modern coast of Greenland. The east and north coasts of Greenland therefore have contrasting tectonic histories, and Kronprins Christian Land lies at the northernmost extremity of the Caledonian orogen, which extends up the east coast from Scoresby Sund, 1200km to the south (Higgins *et al*., 2008; Moseley, 2020).

The region remains an extremely remote and little-visited land area and was beyond the limit of early ship-based exploration due to summer sea-ice conditions. In consequence, exploration of the geology of Kronprins Christian Land began only in the mid- to late 20th century (Higgins, 2010; Moseley, 2020). Although the first geological investigations of Kronprins Christian Land were undertaken through aerial reconnaissance in 1933 and 1938 (Koch, 1935a, 1935b, 1936, 1940; Dawes, 1991), it was not until 1939 that the first field studies of the region around Centrumsø were carried out as part of the Danish Northeast Greenland Expedition by Eigil Nielsen, who documented the presence of Ordovician and Silurian carbonates (Nielsen, 1941). Systematic geological exploration commenced after the Second World War, led by Lauge Koch, with separate teams exploring the carbonate-dominated terrain from Danmark Fjord to Centrumsø (Adams and Cowie, 1953), and the structurally complex ground from Centrumsø to the coast (Fränkl, 1954, 1955). Adams and Cowie described a single carbonate unit with an estimated thickness of 2.5km, the Centrum Limestone, that spanned the Ordovician–Silurian boundary.

Figure 1 (next page):
Geological map of the Centrumsø and Vandredalen area of Kronprins Christian Land, northeast Greenland, showing the airstrip and the three camp locations used by the Greenland Caves Project in 2019.
The geological mapping was undertaken by the authors as part of the regional mapping programme of Grønlands Geologiske Undersøgelse (now De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS)); Jepsen, 2000; Higgins, 2015) and on the Greenland Caves Project expedition in 2019.
Map colours of Jepsen (2000) and Higgins (2015) are retained for the Lower Palaeozoic units, for ease of reference.
Black linework, stratigraphical boundaries.
Red linework, thrust faults (barbs point down the hanging wall).


22°W
21°W
80° 30'N
80° 15'N
Vandredalen
Grottedal
Camp 1
Camp 3
Camp 2
Sæfaxi Elv
Centrumsø
Airstrip
Græselv
Key
L Lauge Koch Land Formation
SH Samuelsen Høj Formation
OF Odins Fjord Formation
TU Turesø Formation
BR Børglum River Formation
SF Sjælland Fjelde Formation
WV Wandel Valley Formation
V Vandredalen thrust sheet
Lakes/Ice
Alluvium
N
0 5 10 km

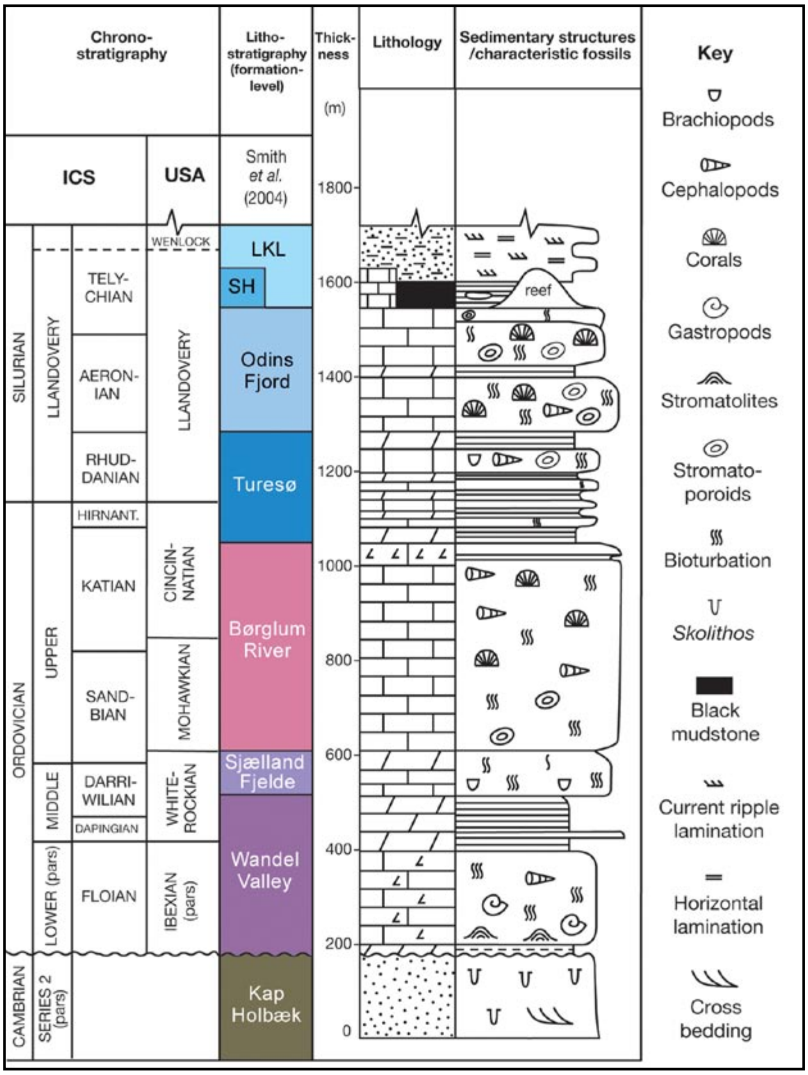


***Figure 2**:*
Composite stratigraphical section of the Lower Palaeozoic succession in Kronprins Christian Land, northeast Greenland, with correlation to International Commission on Stratigraphy (ICS; www.stratigraphy.org*) and Laurentian (USA) chronostratigraphical schemes.*
Unit colours are the same as those in Figure 1.
SH – Samuelsen Høj Formation.

Southern Kronprins Christian Land was the focus of a major topographical and geological mapping programme from 1993–1995 as part of the regional mapping programme of the Grønlands Geologiske Undersøgelse (GGU, now De Nationale Geologiske Undersøgelser for Danmark og Grønland (GEUS)). Geological field-mapping was undertaken on aerial photographs and the newly produced topographical base maps at a scale of 1:100,000, and the geological maps were published at 1:250,000 and 1:500,000 scales (Jepsen, 2000; Higgins, 2015). As part of this programme, the Lower Palaeozoic stratigraphy and its subsequent Caledonian deformation were documented and revised (Rasmussen and Smith, 1996, 2001; Smith *et al.*, 1999; Higgins *et al.*, 2004; Smith *et al.*, 2004; Smith and Rasmussen, 2008) and this was followed up by a University of Copenhagen expedition in 2009 that further documented the carbonate stratigraphy and palaeontology (Rasmussen, 2013; Harper *et al.*, 2014).

The caves of the Centrumsø area, including Grottedal (Moseley, 2020), were first discovered during Operation Groundhog, a US military project to establish ice-free, emergency airstrips in Greenland. Centrumsø was used as a base in 1960 while the 3km rough airstrip was being evaluated; various additional scientific studies were undertaken, including investigations of the geology and geomorphology (Needleman, 1962). The discovery and initial documentation of the Grottedal caves were parts of this project (Davies and Krinsley, 1960). The caves were subsequently visited and documented, with additional exploration during 1983 by a French group (Loubière, 1987), and again as part of the GGU mapping programme in 1994–1995.

Geological context

During the Ordovician and Silurian, the palaeo-equator passed through Arctic Canada and Kronprins Christian Land (Cocks and Torsvik, 2011, figs 13 and 15), leading to a sustained period of carbonate deposition that lasted for 80 million years, from the mid-Cambrian until the early Silurian (Higgins *et al.*, 1991). During this time the Laurentian continental margin in North Greenland, sometimes referred to as the Franklinian Basin, was divided into a carbonate-dominated shelf, with occasional periods of siliciclastic deposition, and a deep-water trough that was located outboard and was correspondingly starved or received siliciclastic input (Higgins *et al.*, 1991). In the eastern part of North Greenland, deposition was terminated by the onset of collision with Baltica at 435Ma, a major orogenic event that created an Alpine/Himalayan-scale mountain belt, the Caledonian orogen (Higgins *et al.*, 2008). A smaller-scale orogenic event, the Ellesmerian orogeny, produced final closure of the Franklinian Basin across the whole of North Greenland during the Devonian (Surlyk, 1991).

For most of its post-Devonian history, Kronprins Christian Land lay on the margins of rifting and ocean-opening in the North Atlantic and Arctic oceans, and the nature of the onshore sediments reflects this history (Stemmerik and Håkansson, 1991; Håkansson *et al.*, 1991). Uplift that began to generate the modern landscape probably commenced during the Miocene, as is evidenced by a regional intra-Miocene seismic unconformity on the northeast Greenland margin at 15–10Ma, which marked the termination of syn-rift deposition in deep-sea basins (Døssing *et al.*, 2016). This unconformity is related to the onset of uplift and massive shelf progradation on this margin and coincides with inner margin uplift in central West Greenland, southern East Greenland and central East Greenland (Døssing *et al.*, 2016).

Ordovician–Silurian stratigraphy and palaeoenvironments of the Centrumsø area

The caves explored in the Centrumsø area in 2015 (Moseley, 2016) and 2019 (Moseley *et al.*, 2020) lie within an interval of Ordovician to Silurian limestones and dolostones that is capped by black mudstones of the Lauge Koch Land Formation (Figs 1 and 2). The oldest unit exposed in Grottedal, the Turesø Formation, is up to 320m thick and spans the Ordovician–Silurian boundary (Smith *et al.*, 2004). The lowest part of the unit comprises prominently banded parasequences in which subtidal, burrow-mottled limestones shallow upwards into peritidal dolostones. These are overlain by a less cyclic, 90m interval of dark grey, burrow-mottled limestones containing an abundant fauna of brachiopods, tabulate corals, cephalopods and stromatoporoids, before passing back into a 130m interval of distinctively striped parasequences (Smith *et al.*, 2004; Smith and Rasmussen, 2008). In Grottedal, the Turesø Formation crops out to the northwest of the caves investigated from Camps 1 and 3, and at the junction of Grottedal with Vandredalen (Fig.1) where the upper Ordovician and Silurian limestones form a footwall ramp beneath the Vandredalen thrust (Higgins *et al.*, 2004; Leslie and Higgins, 2008).

The Turesø Formation is overlain conformably by the Odins Fjord Formation (Fig.2), which marks a change to more-dominantly subtidal deposition within the parasequences following relative sea-level rise; this is the principal cave-bearing unit. Typically, the boundary is marked by a change of weathering colour from grey to golden brown, and the formation

***Figure 3**: Pale-weathering, unbedded reef limestones of the Samuelsen Høj Formation, overlying well-developed, brown-weathering, carbonate parasequences of the Odins Fjord Formation on the southern side of Grottedal, 3km to the southeast of Camp 1. The top of the cliff is 400m above the valley floor. [Photo: Paul Smith.]*

is around 220m thick. It is rather homogeneously developed across the region and comprises highly fossiliferous, well-bedded, dark grey, lime mudstones and wackestones with some packstones; it is typically highly fossiliferous, with burrow-mottling common. Biostromal units are present and are made up of corals, stromatoporoids and skeletal debris. The fauna and lithology suggest that the Odins Fjord Formation was deposited in a subtidal environment, shallowing up into peritidal conditions in some parasequences, but the high organic carbon content and the abundant presence of carbonate mud suggest that deposition was predominantly below fair-weather wave-base.

Locally the Odins Fjord Formation is overlain by patch reefs of the Samuelsen Høj Formation (Figs 2 and 3), which are up to 5km across and 300m thick, though most are far smaller (Hurst, 1984; Smith and Rasmussen, 2008). Technically they are carbonate mud-mounds, composed of massive lime mudstone, with no consistent bedding in the core and no framework. Stromatactis is present in places, and the mounds might have had a microbial origin. Rudstone flanking-beds are commonly present, and crinoid debris is locally abundant. The initiation of reef-growth is well-constrained by conodont biostratigraphy to the *celloni* Biozone (Armstrong, 1990), which corresponds to a mid-Telychian (late Llandovery) age at around 436Ma (Smith and Rasmussen, 2008, fig. 6; Ogg *et al.*, 2016).

Carbonate deposition was terminated abruptly by rapid subsidence of the platform, and the Samuelsen Høj reefs (and where they are absent the limestones of the Odins Fjord Formation) are overlain by clastic sediments and thin interbedded black limestones of the Lauge Koch Land Formation (Fig.2). Conodonts again provide tight biostratigraphical constraint of this major depositional shift as thin black limestones immediately above the boundary record the *celloni–amorphognathoides* biozonal boundary (Armstrong, 1990), corresponding to an age of 435Ma (Ogg *et al.*, 2016) and demonstrating that the period of reef formation was brief (a maximum of 1.1 million years using the timescale of Ogg *et al.*, 2016). The sediments of the Lauge Koch Land Formation that directly overlie the reefs are variably developed across the area. On the west side of Vandredalen, Hurst and Surlyk (1982) recorded quartz conglomerates and sandstone turbidites directly overlying the shallow-water carbonate succession, but black mudstones and limestones are locally developed (Armstrong, 1990) and reach up to 50m thickness south of Centrumsø, close to Camp 2. Here, black, organic-rich siltstones and occasional sandstones are interbedded with distinctive, very dark grey to black, bituminous limestones that contain a fauna of graptolites, cephalopods, and gastropods (Smith *et al.*, 2004). This succession then passes upwards into sandstone turbidites similar to those seen in Vandredalen, with $T_{a\text{–}e}$, $T_{a\text{–}c,e}$ and $T_{b\text{–}e}$ Bouma units reflecting a location close to source and/or on-axis to the main density flows. The presence of channel fills up to 4m thick lends support to this interpretation.

The abrupt change from carbonate- to clastic-dominated sedimentation marks a major shift in the architecture of the Franklinian Basin that is seen as far as Washington Land, 750km to the west (Higgins *et al.*, 1991). It is more than a relative sea-level rise, because the change from a low-gradient carbonate shelf to a depositional setting with turbiditic density flows requires the generation of a slope. It is likely that this was caused by isostatic loading resulting from the onset of Caledonian collision and loading of the shelf and trough by thrust sheets and their erosional products (Hurst *et al.*, 1983; Higgins *et al.*, 1991;

***Figure 4**: A ramp in the Vandredalen thrust (dashed) at the mouth of Sæfaxi Elv, where it meets Hekla Sund, 30km east of Centrumsø. Rift-related sedimentary rocks of the Neoproterozoic Rivieradal Group (R) are emplaced over the folded, pale, sandstones of the Palaeoproterozoic Independence Fjord Group (IF), which is intruded by Mesoproterozoic dolerite sheets (d). Summit of hill is 1400m above sea-level. [Photo: Paul Smith.]*

Figure 5*: Caves on the south side of Grottedal in subtidal–peritidal carbonate parasequences of the Odins Fjord Formation (OF) and the reef limestones of the Samuelsen Høj (SH) Formation, viewed looking southeastwards; the unit boundary is indicated by a dashed line. U-Shaped Cave (GD4 north and south entrances) lies entirely within the Odins Fjord Formation and, for scale, is located around 100m below the formation boundary. In contrast, Crystal Palace Cave (GD19) and Triangle Cave (GD10) are perched on the formation boundary. A small number of caves with limited development are located entirely within the Samuelsen Høj Formation, here exemplified by Multi-level Cave (GD11). [Photography by Robbie Shone, with permission.]*

Surlyk, 1991). The Lauge Koch Land turbidites are the youngest pre-Caledonian sediments present in Kronprins Christian Land, and no further evidence of deposition is preserved until the Carboniferous and Permian rift-related sediments of Amdrup Land and Holm Land, 75km to the east and northeast of Centrumsø on the east coast (Stemmerik and Håkansson, 1991; McClelland *et al*., 2016).

Caledonian deformation

The Caledonian orogen in Kronprins Christian Land comprises a series of N–S oriented structural belts, with deep crustal thrust sheets in the east lying structurally above progressively more thin-skinned structures to the west (Higgins, 2015). From Vandredalen eastwards, Neoproterozoic sedimentary rocks have been transported on a major thrust, the Vandredalen thrust, which can be traced from a steep ramp at Marmorvigen (Fig.4) along a long flat in Lower Ordovician dolostones that is continuously exposed in the south side of Sæfaxi Elv (Fig.1). On the west side of Vandredalen, the thrust cuts upwards again forming another ramp through the Børglum River, Turesø and Odins Fjord formations (Higgins *et al.*, 2004; Leslie and Higgins, 2008, fig.8). The hill tops on the west side of Vandredalen to the north of Grottedal are small klippen of the Vandredalen thrust sheet, which is more completely preserved between the mouth of Grottedal and Centrumsø, and farther to the north and east (Fig.1). Summaries of the tectonic development are provided by Higgins *et al*. (2004), Leslie and Higgins (2008) and Higgins (2015).

The Lower Palaeozoic succession was deformed by the emplacement of the overlying Vandredalen thrust sheet to produce a thin-skinned thrust duplex with individual horses in the order of one kilometre in stratigraphical thickness and up to 8km W–E extent (Fig.1; Higgins *et al.*, 2004, fig.8; Higgins, 2015, fig.15). The caves are developed within these thrust horses composed of folded Ordovician to Silurian rocks that, depending on their position within the horse, have dips varying from horizontal to vertical.

Geological constraints on cave formation

The caves investigated from Camp 1 and Camp 3 lie on the north and south side of Grottedal and in a small canyon system to the north of Centrumsø (Figs 1 and 5). All of these caves lie within the easternmost horse that forms the footwall ramp of the Vandredalen thrust seen on the western side of Vandredalen (see above). The horses seen from here westwards to the limit of thrusting are composed of a triplet of units comprising the Børglum River, Turesø and Odins Fjord formations, indicating that the floor thrust of this duplex is a detachment within the immediately underlying mid-Ordovician carbonates of the Sjælland Fjelde Formation, and this relationship is observed at the junction of Vandredalen with Sæfaxi Elv (Fig.1). Individual horses near Centrumsø may also contain reefs of the Samuelsen Høj Formation and associated turbidites of the Lauge Koch Land Formation, depending upon the erosion level. The easternmost horse does contain all five units, but the erosion is deeper to the west due to an overall eastward dip, and the Samuelsen Høj Formation and then Odins Fjord Formation are progressively absent westwards.

Within the easternmost horse, the dips are horizontal for much of the length of Grottedal, from the junction with Vandredalen as far as Camp 1. To the west of Camp 1 the carbonates are progressively folded as the next thrust is approached, but the caves adjacent to Camp 1 and on the north side of the valley are developed in horizontal limestones (Fig.5), and the same is true of those seen in the canyon adjacent to Camp 3. In contrast, the *Grotte des Quatre* near to Camp 2, to the south of Centrumsø, is developed in a more westerly horse and, furthermore, is situated close to its leading edge where vertical Odins Ford Formation is thrust over gently dipping rocks of the Lauge Koch Land Formation (Fig.1).

In Navarana Fjord, 400km to the northwest, caves have been observed close to the base of the Børglum River Formation, but most caves in the Centrumsø area are developed in the Odins Fjord Formation or at the Samuelsen Høj/Odins Fjord formation boundary, with a few developed within the lowermost Samuelsen Høj Formation. In this region, none have been observed in older stratigraphical units.

Some of the largest passage development occurs in caves located entirely within the well-bedded limestones of the Odins Fjord Formation. Examples of these include U-Shaped Cave (Fig.5), Lemming Cave, Crystal Crawl and Crystal Kingdom on the north and south sides of Grottedal respectively; [Kate's] Cove Cave in the canyon to the north of Centrumsø; and *Grotte des Quatre* to the south of Centrumsø (Moseley *et al*., 2020). U-Shaped Cave, one of the caves originally explored by Davies and Krinsley (1960), sits over 100m below the Samuelsen Høj/Odins Fjord formation boundary and has a distinctive pale dolostone at the top of a parasequence that forms the passage walls. It is likely that the initial anastomoses developed perched on this aquiclude prior to passage enlargement. U-Shaped Cave has passage diameters up to 8m across and must represent the erosional remnant of a significant phreatic system. *Grotte des Quatre* and [Kate's] Cove Cave represent a small number of caves with vadose development, and the former includes a short section of meandering vadose canyon.

A number of the caves develop distinctively at the Samuelsen Høj/Odins Fjord formation boundary, such that the roof is in reef lithofacies and the passage walls and floor in bedded Odins Fjord Formation (see also Barton *et al*., 2020). This context is particularly well observed in Cairn Climb Cave and Crystal Palace Cave (Fig.3), where large phreatic tubes are located at the boundary, but is also seen in Skylight Cave, Triangle Cave and cave 008 on the southern side of Grottedal (Moseley, 2016). It is noteworthy that this group of caves is situated 100m stratigraphically and topographically above some of the phreatic networks developed entirely within the Odins Fjord Formation, such as U-Shaped Cave, raising the question of whether there are multiple phases of speleogenesis in the region.

Despite a lithology of pure limestone with no interleaved dolostones, few caves are present within the patch reefs of the Samuelsen Høj Formation itself, and those that are present are small – examples include Multi-Level Cave (GD11) (Fig.5) and Triplet Arch Cave (GD21–23) near Camp 1. However, it is perhaps significant that although few caves occur within the Samuelsen Høj Formation, all of the caves (with the exception of *Grotte des Quatre*) are in the vicinity of Samuelsen Høj patch reefs, which might suggest a genetic link. This apparent correlation could be an artefact of the search process, but all limestones in the area were investigated within the time available during the 2015 and 2019 expeditions, and the whole 1.4km-thick carbonate succession was examined in detail across an area of around 4,000km^2 during the regional GGU mapping campaign.

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