GEUS Bulletin | Geological Survey of Denmark and Greenland

RESEARCH ARTICLE

The karst and palaeokarst of North and North-East Greenland – physical records of cryptic geological intervals

M. Paul Smith*[1], Gina E. Moseley[2]

[1]Oxford University Museum of Natural History, Oxford, UK; [2]Institute of Geology, University of Innsbruck, Innsbruck, Austria

Abstract

Carbonate rocks of Neoproterozoic to Silurian age are abundantly distributed around the coasts of North and North-East Greenland. Palaeokarst horizons are particularly well developed within the Portfjeld Formation (Ediacaran – earliest Cambrian) and beneath the Buen Formation (Cambrian Series 2), and there are caves within Ordovician limestones infilled by Caledonian molasse of Middle Devonian age. The youngest karst is a series of caves distributed from Hall Land in western North Greenland to Kronprins Christian Land in eastern North Greenland. Caves within Ordovician carbonates in Freuchen Land are currently the northernmost documented karst caves globally. The caves are mainly open phreatic conduits, any fill that is present is unlithified, and cave collapse is limited to minor breakdown associated with frost shattering. These geologically young caves are consistently located up to a few 100 m beneath the distinctive plateau that characterises the topography of the northern coast, and their identical context suggests that they developed in a single phase of speleogenesis. The caves are exposed where the plateau has been incised by outlet glaciers from the Greenland ice sheet. The timing of cave development in North Greenland is constrained by the mid- to late-Miocene (15–5 Ma) uplift of the plateau surface and the onset of fjord-forming glaciation in the latest Pliocene – earliest Pleistocene (*c.* 2.7–2.5 Ma). The evidence suggests that phreatic caves in the southern part of North-East Greenland, on C. H. Ostenfeld Nunatak, are of a broadly similar age. The caves of North and North-East Greenland offer a glimpse of large-scale phreatic drainage systems that developed below an uplifted coastal peneplain during Neogene time. They preserve an important part of the geological history of North and North-East Greenland that is otherwise absent from the physical geological record.

Introduction

Carbonate rocks of Neoproterozoic–Silurian age extend for 1000 km from west to east across North Greenland and then intermittently down the 1300 km length of the N–S-oriented East Greenland Caledonides (Figs 1, 2, 3). The karst developed in these rocks includes both geologically young caves truncated by later glaciation together with regionally extensive palaeokarst horizons developed in rocks of the latest Ediacaran to Ordovician age (Fig. 4), which were generated by a combination of relative sea-level lowstands, periods of subaerial erosion at sequence boundaries, orogenic topography and passive margin uplift.

***Correspondence:** *paul.smith@oum.ox.ac.uk*
Received: 23 Oct 2021
Accepted: 10 Mar 2022
Published: 11 May 2022

Keywords: caves, Cenozoic, karst, Neogene, Miocene, palaeokarst, paleokarst

Abbreviations:
AFTA: Apatite Fission Track Analysis
a.s.l.: above sea level
CAI: colour alteration index
DEM: Digital elevation model
GD: Grottedal (used in alphanumeric scheme of Moseley 2016)
GEUS: Geological Survey of Denmark and Greenland
GGU: Geological Survey of Greenland
ICS: International Commission on Stratigraphy
IUGS: International Union of Geological Science
UPS: Upper Planation Surface
LPS: Lower Planation Surface

Edited by: Jon R. Ineson (GEUS, Denmark)

Reviewed by: Jan Tveranger (NORCE Norwegian Research Centre, Norway), Peter Frykman (GEUS, Denmark)

Funding: See page 21

Competing interests: See page 21

Additional files: See page 21

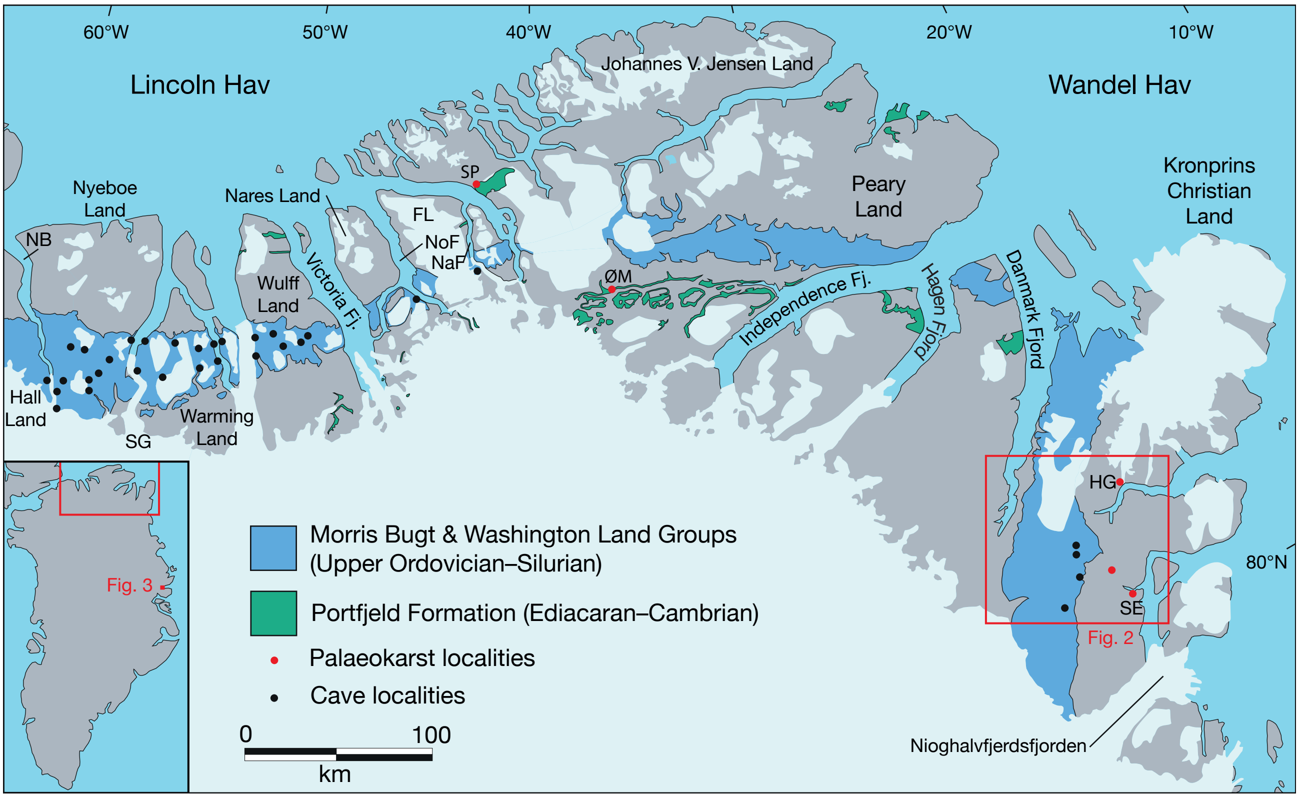


Fig. 1 Map of North Greenland showing the outcrop of Sandbian (Upper Ordovician) to Wenlock (Silurian) shelf limestones. Palaeokarst localities are indicated by a **red dot** and cave localities by a **black dot**; dots may represent more than one instance where localities are closely spaced. For full details of all known caves, see supplementary information. **FL**: Freuchen Land. **HG**: Hjørnegletscher. **NB**: Newman Bugt. **NaF**: Navarana Fjord. **NoF**: Nordenskiöld Fjord. **ØM**: Øvre Midsommersø; **SE**: Sæfaxi Elv. **SP**: Sirius Passet. **SG**: Steensby Gletscher. Linework based on the 1:500 000 GGU and GEUS geological maps (Bengaard & Henriksen 1986; Henriksen 1989; Jepsen 2000).

From the early Cambrian to the Silurian (521–420 Ma), Greenland lay astride the palaeo-equator as part of Laurentia (Mac Niocaill & Smethurst 1994), and North Greenland is one of the few places on the Laurentian margin where an ancient shelf–slope break is preserved with minimal tectonic overprint. The north-east corner of Greenland, where the east and north coast meet, represents an original promontory of the Laurentian continent (Derby *et al.* 2012, fig. 1) and, in consequence, the Cambrian–Silurian successions on these two margins have contrasting stratigraphic frameworks and tectonic histories. The Cambrian–Ordovician succession of the east coast comprises an initial siliciclastic interval of *c.* 200 m thickness overlain by 2.7 km of predominantly subtidal carbonates that span only 60 million years. This succession was once contiguous with equivalent sectors that lay farther to the south on the Laurentian margin, including north-western Scotland and western Newfoundland (Swett & Smit 1972; Swett 1981; Smith & Rasmussen 2008; Raine & Smith 2012). In contrast, the Cambrian–Ordovician on the north coast is stratigraphically thinner, with a substantial hiatus in eastern North Greenland caused by uplift and erosion on the apex of the Laurentian promontory (Peel & Smith 1988; Smith 2000). Depositional continuity and stratigraphic correlation extend westwards across Nares Strait into the coeval sedimentary successions of Nunavut, Canada (Trettin 1991).

An extended period of sea-level lowstands during the Neoproterozoic led to the extensive peneplanation of continental interiors (Peters & Gaines 2012). Late Cambrian to Ordovician sea-level highstands constituted the highest absolute sea levels of the Phanerozoic (Miller *et al.* 2005), which in combination with low relief in Laurentia led to carbonate deposition extending almost continuously for 6500 km from modern New Mexico to Greenland, and the development of a long-lived, non-uniformitarian geological and geomorphological feature – the Great American Carbonate Bank (Derby *et al.* 2012). For the most part, it is the carbonate deposited as part of the Great American Carbonate Bank in which the karst and palaeokarst of Greenland are developed. The aim of this paper is to provide a complete documentation of the palaeokarst and younger caves recorded to date in North and North-East Greenland and to ascertain the timing of their formation, particularly the temporal constraints on the speleogenesis of the younger caves.

The geographical divisions used in this study follow the conventions of the Geological Survey of Denmark and Greenland (GEUS) as outlined by Dawes *et al.* (2016),

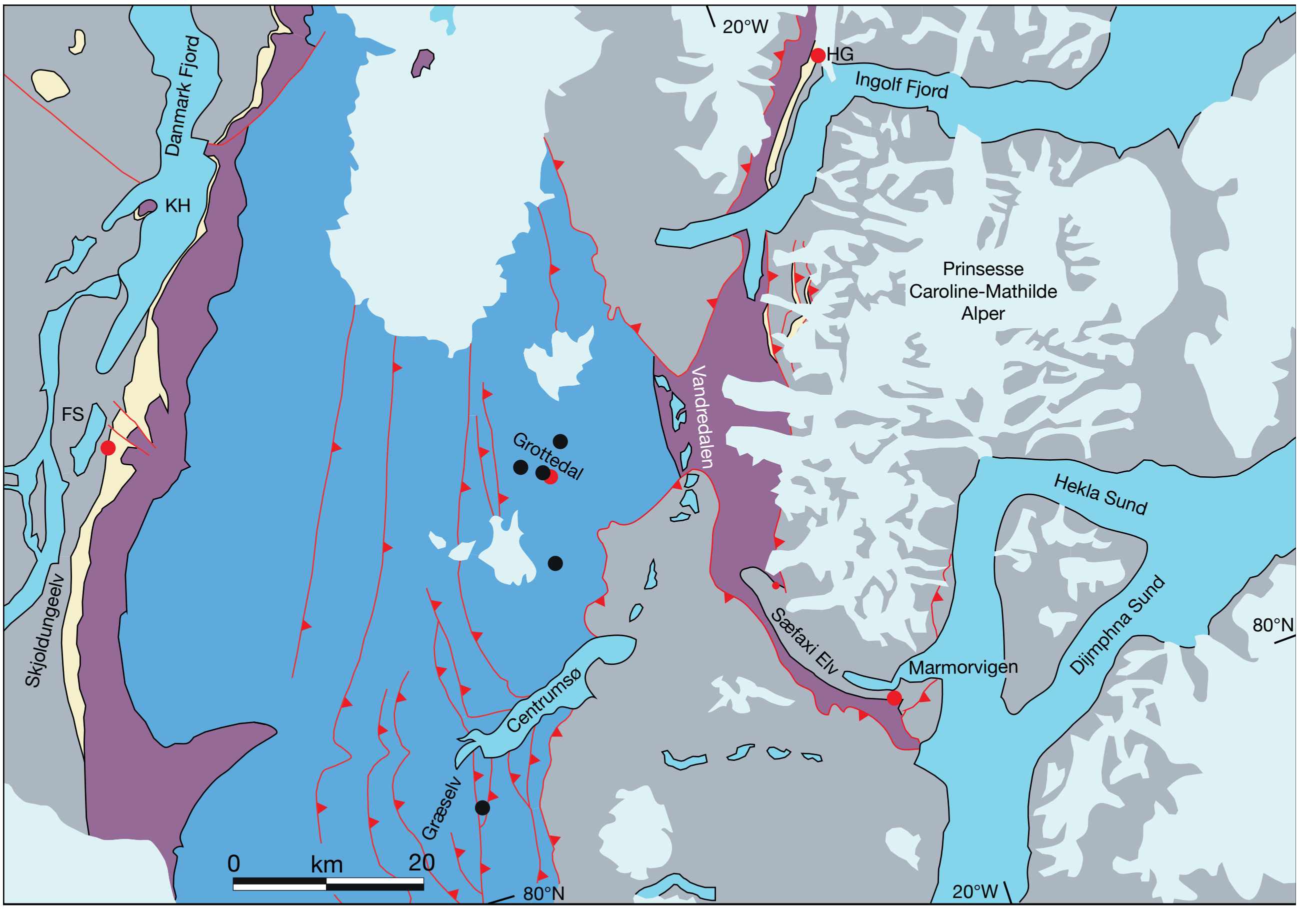


Fig. 2 Geological map of Kronprins Christian Land, North-East Greenland, showing the distribution of Sandbian (Upper Ordovician) to Wenlock (Silurian) shelf limestones in which caves are developed (**black dots**). A regionally extensive palaeokarst horizon is preserved where Cambrian Series 2 quartz arenites of the Kap Holbæk Formation rest on carbonate units such as the Tonian (lower Neoproterozoic) Fyns Sø Formation (**red dots**). **FS**: Fyn Sø. **HG**: Hjørnegletscher. **KH**: Kap Holbæk. Linework based on primary field mapping in 1994, 1995, and 2019, together with the 1:500 000 GEUS geological map (Jepsen 2000).

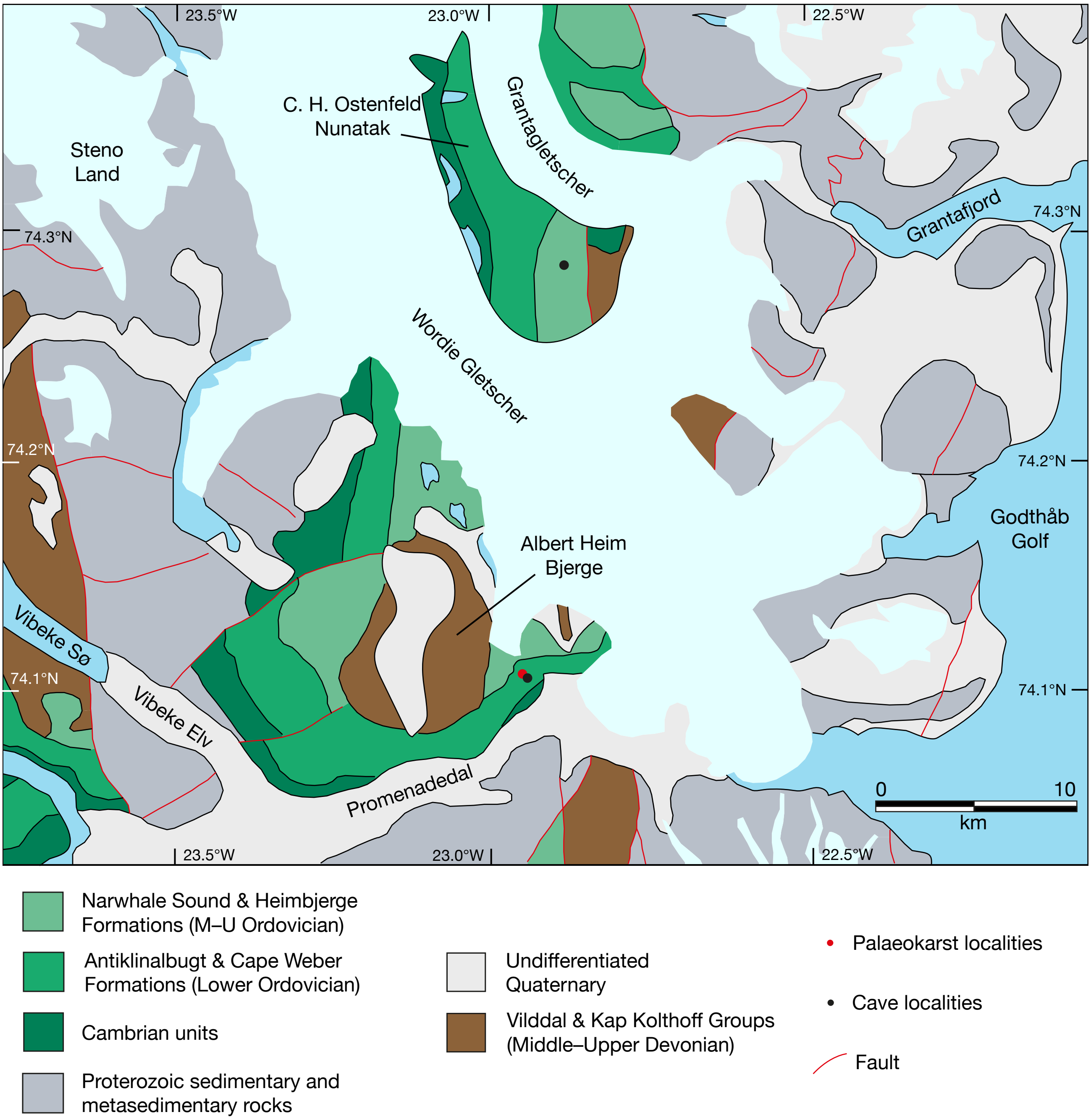
with the boundary between eastern North and North-East Greenland placed at Nioghalvfjerdsfjorden; the boundary between eastern and central North Greenland at Hagen Fjord; and that between central and western North Greenland at Victoria Fjord (Fig. 1).

Palaeokarst in Greenland

Limestones and other carbonate rocks occur commonly in the Neoproterozoic–Silurian shelf succession of the Laurentian margin in North Greenland (Figs 1, 2) and in the Cambrian–Ordovician of the North-East Greenland coast (Fig. 3). This widespread occurrence has provided the potential for the development of karstic horizons at multiple points in the geological history of the area in response to relative changes in sea level. There are three particularly well-developed palaeokarst horizons with regionally extensive distributions.

Intra-Ediacaran palaeokarst

The Portfjeld Formation of North Greenland extends from the inner shelf of the Franklinian Basin, in a southern outcrop belt to the west and east of Øvre Midsommersø (ØM in Fig. 1; 82.23°N, 36.10°W), and a northern outcrop belt along the line of the Cambrian shelf edge, including Sirius Passet (SP in Fig. 1; Higgins *et al.* 1991; Willman *et al.* 2020). The 200–700 m thick formation comprises pale grey dolostones with some marly limestones and sandstones, but the southern outcrop belt contains a major unconformity that separates mid- to late-Ediacaran (<570 Ma) strata from a younger succession that is of the latest Ediacaran or earliest Cambrian age (Fig. 4; Ineson & Peel 2011; Willman *et al.* 2020). The dating of the older unit is confirmed by the presence of the Shuram-Wonoka $\partial^{13}C$ anomaly (570–560 Ma; Willman *et al.* 2020).



[AQ2]

Fig. 3 Geological map of Albert Heim Bjerge and C. H. Ostenfeld Nunatak showing cave (**black dots**) and palaeokarst (**red dot**) localities in limestones of the Cape Weber Formation (Lower Ordovician) and the Heimbjerge Formation (Middle to Upper Ordovician). The Ordovician rocks of this area are unconformably overlain by Middle to Late Devonian molasse deposits of the Vilddal and Kap Kolthoff Groups. Location of the map indicated on Fig. 1. Linework is based on primary field mapping in 1998 and the 1:500 000 GEUS geological map (Escher 2001).

At the western end of Øvre Midsommersø (Fig. 1), Willman *et al.* (2020) also recorded well-developed palaeokarst at the unconformity surface within the Portfjeld Formation. The karst includes extensive intrastratal solution cavities and brecciation that extend for up to 40 m downwards from the subaerial surface represented by the unconformity. Cavities are infilled by sandy breccias and cements.

Sub-Cambrian Series 2 palaeokarst

The most regionally extensive palaeokarst surface is present beneath transgressive siliciclastic shelf sediments of Cambrian Series 2 age, assigned to the Buen Formation from Warming Land to Danmark Fjord and to the Kap Holbæk Formation in Kronprins Christian Land (Figs 1, 2, 4; Smith *et al.* 2004). In the north and west, the Buen Formation overlies carbonates of the Portfjeld Formation,

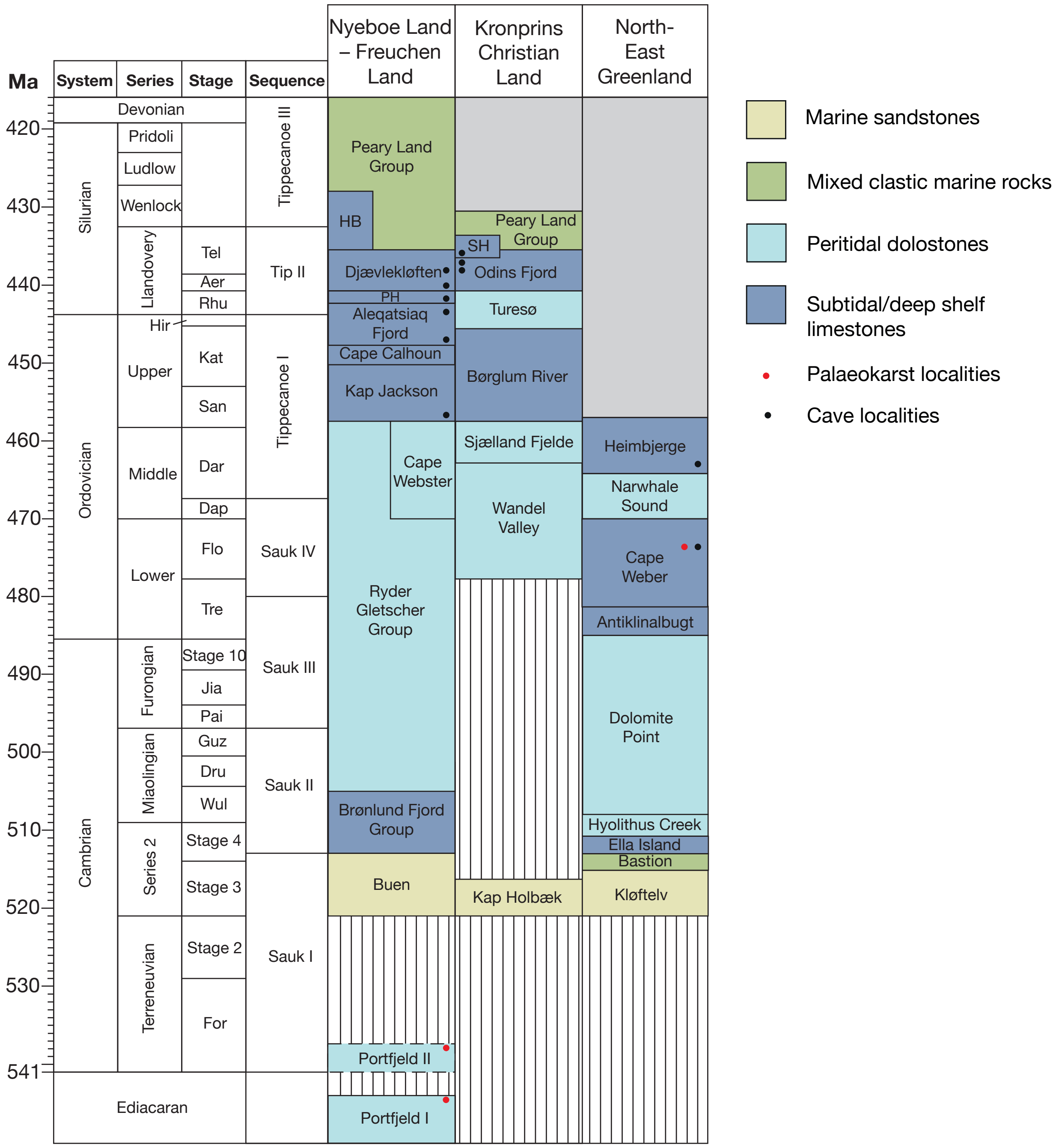


Fig. 4 Correlation chart of Cambrian–Silurian shelf units in central and western North Greenland (Nyeboe Land – Freuchen Land), eastern North Greenland (Kronprins Christian Land) and North-East Greenland (C. H. Ostenfeld Nunatak) showing the stratigraphic distribution of caves and palaeokarst. Stratigraphic units are of formation rank unless otherwise stated. The left-hand columns follow the International Union of Geological Science/International Commission on Stratigraphy (IUGS/ICS) standard (Cohen *et al.* 2013); boundaries of megasequences and supersequences are from Palmer (1981), Golonka & Kiessling (2002) and Smith & Rasmussen (2008). Data for the Greenland sections were compiled from Smith (1985, 1991), Tull (1988), Smith & Bjerreskov (1994), and Huselbee (1998). **For**: Fortunian. **Wul**: Wuliuan. **Dru**: Drumian. **Guz**: Guzhangian. **Pai**: Paibian. **Jia**: Jiangshanian. **Tre**: Tremadocian. **Flo**: Floian. **Dap**: Dapingian. **Dar**: Darriwilian. **San**: Sandbian. **Kat**: Katian. **Hir**: Hirnantian. **Rhu**: Rhuddanian. **Aer**: Aeronian. **Tel**: Telychian. Stratigraphic units: **HB**: Hauge Bjerge Formation. **PH**: Petermann Halvø Formation. **SH**: Samuelsen Høj Formation.

whereas in Kronprins Christian Land, the Kap Holbæk Formation rests on older, Tonian (early Neoproterozoic) carbonates of the Fyns Sø Formation (Fig. 4). In places, the Kap Holbæk Formation is preserved only within palaeokarst cavities of the older unit (Smith *et al.* 1999).

Peary Land – 82.2–82.8°N

A well-preserved karstic surface exhibiting both exo- and endokarst is seen at the top of the Portfjeld Formation at the Sirius Passet Lagerstätte locality adjacent to J.P. Koch Fjord (SP in Fig. 1; 82.79695°N, 42.21585°W), where it is

Fig. 5 Sub-Cambrian palaeokarst developed within the upper 2 m of the Portfjeld Formation (Ediacaran or lowermost Cambrian) at the Sirius Passet Lagerstätte locality, north-western Peary Land (Fig. 1; Harper *et al.* 2019) and infilled with clastic sediments of the Buen Formation (Cambrian, Series 2). **A**: Steeply inclined fissure infilled by millet-seed quartz arenite, margins arrowed, with a fin of dolostone dividing the fissure into two close to the disconformity surface (skyline of block). **B**: Inclined fissure (arrow) and sub-horizontal cavity (above, in shadow) infilled with metamorphosed muddy siltstones. Skyline of foreground is again the unconformity surface. Yellow rule is 1 m.

disconformably overlain by quartz arenites of the basal Buen Formation (Ineson & Peel 2011; Harper *et al.* 2019, fig. 2). The upper part of the Portfjeld carbonates contains vertical and inclined karstic grikes and vadose fissures (kluftkarren) that are 0.1–3 m wide, together with shallow, infilled phreatic tubes immediately beneath the disconformity surface. All of the karstic cavities are infilled with fine- to medium-grained quartz arenites that have millet-seed texture or with black muddy siltstone (Fig. 5). In places a sequential fill of quartz arenites followed by muddy siltstone is observed, and the same depositional sequence is present in the most basal part of the Buen Formation immediately above the disconformity (Harper *et al.* 2019, fig. 2).

The same karstic surface is seen at the Portfjeld–Buen Formation boundary at Øvre Midsommersø (ØM in Fig. 1), 100 km to the south-east of the Sirius Passet Lagerstätte, where the most inboard shelf sediments of this age are seen in North Greenland. At this locality, the palaeokarst is characterised by collapse dolines and other karstic collapse structures containing sandstone infills.

Kronprins Christian Land – 80–81°N

Although the sub-Buen Formation disconformity in Peary Land has well-preserved palaeokarst features and relief, the equivalent surface in Kronprins Christian Land to the south-east (Fig. 1) is notable for containing infilled cave systems of substantial size. In the west, the Buen-equivalent Kap Holbæk Formation rests unconformably on the Fyns Sø Formation of the Hagen Fjord Group (Smith *et al.* 2004) along Danmark Fjord and Skjoldungeelv to the south and in the east along the inner part of Ingolf Fjord and at Marmorvigen in Sæfaxi Elv (SE in Figs 1, 2).

The best-developed sub-Cambrian palaeokarst is at Hjørnegletscher (HG in Figs 1, 2; 80.66891°N, 19.49717°W), which enters Ingolf Fjord from the north. Early Cambrian sandstones of the Kap Holbæk Formation rest unconformably on Tonian (early Neoproterozoic) dolostones of the Fyns Sø Formation, and the succession is strongly deformed by west-vergent folds developed in the footwall of the Vandredalen thrust (Smith *et al.* 1999; Higgins *et al.* 2004). Despite this deformation, a well-preserved, multi-phase palaeokarst system is preserved in the uppermost part of the Fyns Sø Formation (Smith *et al.* 1999). The unconformity surface has two deep channels that are, respectively, 40 m wide by 7 m deep and 30 m wide by 9 m deep (Fig. 6A). One of the channels has a bedding plane-controlled solution cavity that extends beyond the channel margin (Fig. 6A, arrowed). The lowest sediment filling the channel is a moderately sorted, fine- to coarse-grained black sandstone and is overlain by a well sorted, very fine sandstone and in turn by a fine- to medium-grained quartz arenite.

A large number of phreatic conduits are present beneath the unconformity surface, with tubes that range from less than 1 m across up to one that is 15 m wide and at least 5 m high (Figs 6A, B). Some of the conduits are circular in cross-section, but the majority extend laterally along bedding planes. The sedimentary fill and the internal stratigraphy are identical to that of the large channels (Smith *et al.* 1999). The caves extend for only 12 m below the preserved unconformity surface and are perched on an aquiclude of insoluble black siltstones, which probably inhibited their downward development (Smith *et al.* 1999). It is evident from the relative positions of the surface channels and the phreatic tubes that multiple stages of karst development occurred. The first phase was the development of phreatic tubes at an unknown depth beneath the unconformity, as the amount of erosion at the unconformity surface is

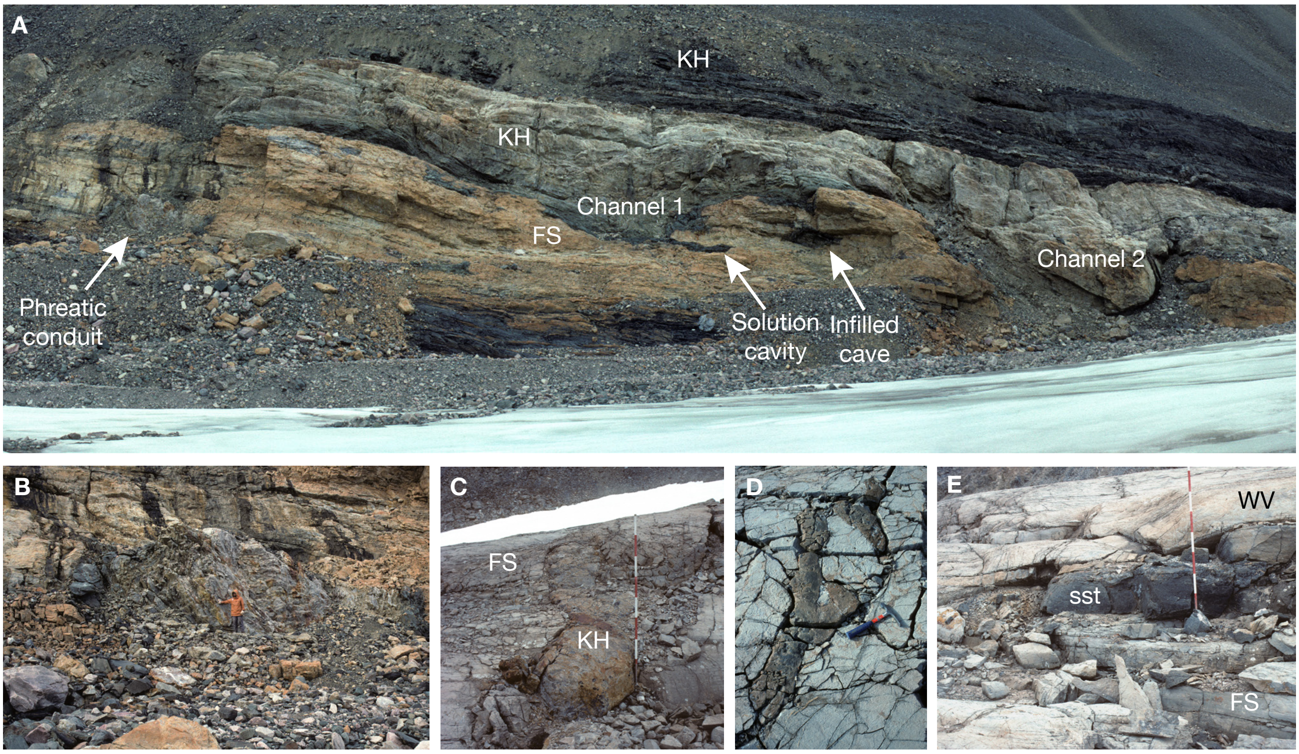


Fig. 6 Sub-Cambrian palaeokarst developed within Tonian (Neoproterozoic) carbonate rocks of the Fyns Sø Formation (**FS**) of Kronprins Christian Land and infilled with quartz arenites of the Kap Holbæk Formation (**KH**; Series 2, Cambrian). **A**: Channel and phreatic tube complex developed in the upper 12 m of the Fyns Sø Formation on the west side of Hjørnegletscher (Figs 1, 2). This is the same conduit as in B, where there is a person for scale. **B**: Close-up of the phreatic conduit seen on the left side of A. **C**: Sub-horizontal phreatic tube with hourglass profile on the south side of Sæfaxi Elv at Marmorvigen (Figs 1, 2), located 10 m below the unconformity surface and infilled with very coarse sand to granule-grade quartz arenite. **D**: Vertical vadose fissure in subhorizontal dolostones and infilled with coarse-grained quartz arenite. **E**: Dark-coloured sandstones (**sst**) overlying the Fyns Sø Formation and in turn overlain by Floian (Lower Ordovician) pale-coloured dolostones of the Wandel Valley Formation (**WV**). Divisions on the survey pole are 20 cm; hammer is 28 cm long.

unconstrained. Following relative base-level fall, incision of the surface channels occurred, and these must have post-dated cave formation as they extend to a greater depth below the unconformity surface than some of the phreatic caves (Fig. 6A). The lateral, bedding plane-controlled solution cavities adjacent to the channels are best interpreted as truncated phreas (sub-water table cave conduit) since they have a similar morphology to the adjacent caves (Fig. 6A, arrowed). The morphology of this phreas may have been modified by Caledonian thrusting associated with the nearby Vandredalen thrust, leading to flattening and an accentuated low profile, but they must originally have been bedding plane-controlled conduits. The final phase of development was infill by the lower Cambrian sediments of the Kap Holbæk Formation. Although there is a substantial age difference between the host Fyns Sø Formation carbonates and the Kap Holbæk Formation infill (>200 million years), the formation of the phreatic tubes and the incision of the channels were probably Cambrian in age, evidenced by the lack of collapse in the caves and the presence of identical sedimentary fills in the caves and channels elsewhere above the unconformity.

In Sæfaxi Elv (Figs 1, 2; 80.08385°N, 20.42261°W), the Tonian dolostones of the Fyns Sø Formation are overlain by a 1 m thick coarse sandstone with imbricated pebbles of dolostone and quartz arenite (Smith *et al.* 1999), and this is in turn overlain by Floian (Lower Ordovician) dolostones of the Wandel Valley Formation (Fig. 6E). Lithologically, this sandstone is best interpreted as the lowest bed of the Ordovician succession. However, sandstone-filled fissures 20–60 cm wide and up to 2 m long (Fig. 6D) extend downwards from the sub-planar unconformity and at a depth of around 10 m connect with a network of subhorizontal phreatic conduits (Smith *et al.* 1999, figs 6, 7). These tubes are circular to elliptical and range in width from a few decimetres up to 3 m. One distinctive example is an hour-glass shaped tube, 1.9 m high and up to 0.8 m wide (Fig. 6C). The fissures and conduits are infilled by a distinctively golden-brown weathering quartz arenite of coarse sand – granule grade, which contrasts with the finer sandstone bed at the base of the Wandel Valley Formation. This lithological contrast and the presence of quartz arenite intraclasts in the boundary sandstone bed suggests that the palaeokarst fill is an older unit, and Fränkl (1955) suggested it was the Kap Holbæk Formation. The similarity to

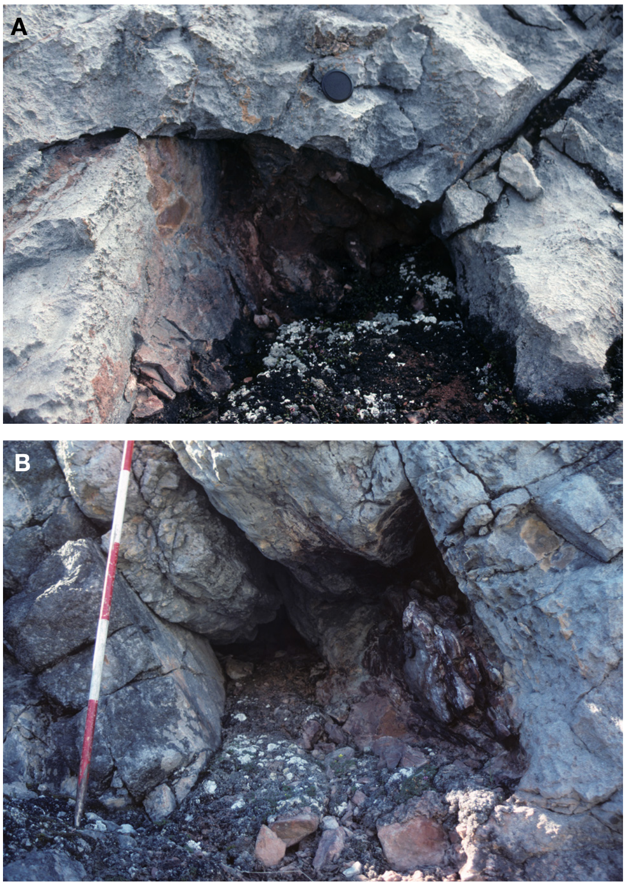


Fig. 7 Examples of quadrate phreatic conduits (**A**, **B**) developed within subtidal limestones of the Cape Weber Formation (Tremadocian–Floian, Lower Ordovician) infilled with Devonian conglomerates of the Vilddal Group (Middle Devonian) that mainly comprise blocks of red-stained Ordovician carbonates in a clastic matrix; the eastern end of Albert Heim Bjerge adjacent to Wordie Gletscher (Fig. 3). Divisions on the survey pole are 20 cm, and lens cap is 7 cm.

the Kap Holbæk Formation and cave infills at Ingolf Fjord, 65 km to the north, strongly supports this correlation. It is noteworthy that the Sæfaxi Elv caves are also developed a very short distance below the unconformity surface, indicating a very shallow vadose zone, which may also be true of the Hjørnegletscher locality, where karst formation was constrained by the aquiclude.

The Sæfaxi Elv and Ingolf Fjord localities both lie in the deformed footwall of the Vandredalen thrust, within the Caledonian thrust belt (Higgins *et al.* 2004), but additional sub-Cambrian palaeokarst localities are present in the foreland to the west, along Danmark Fjord and to the south of it. To the east of Fyn Sø (FS in Fig. 2), the uppermost levels of the Fyns Sø Formation contain fissures and irregular tubes 10–50 cm in diameter infilled with iron-stained, medium- to coarse-grained quartz arenites (Smith *et al.* 1999). The Fyns Sø Formation is here overlain by the Kap Holbæk Formation, and the unconformity surface has a karstic erosion surface with up to 3 m of relief. Farther north along the west side of Danmark Fjord, quartz arenites again infill irregular fissures up to 2 m deep and 0.2 m wide in the uppermost Fyns Sø Formation (Smith *et al.* 1999).

The distribution of sub-Cambrian Series 2 palaeokarst wherever the Buen and Kap Holbæk Formations unconformably overlie carbonate units indicates that this is a major geomorphological surface with exo- and endokarst development of regional extent. That region is bounded by Sirius Passet in the northwest, Øvre Midsommersø in the south-west, north-eastern Peary Land in the north-east and Sæfaxi Elv in the south-east (Fig. 1), equating to a minimum area of over 50 000 km^2.

Hypogene karst in Kronprins Christian Land

Moseley (2016, p. 60) identified one probable example of hypogene karst formed by hot fluids in Grottedal, Kronprins Christian Land, on the basis of its morphology (Fig. 2; 80.37369°N, 21.72854°W). Hypogene Cave (GDX in the alphanumeric scheme of Moseley 2016 where GD refers to Grottedal) comprises a horizontal tube of 30–35 cm diameter that can be traced for around 3 m in limestones of the Odins Fjord Formation (Llandovery, Silurian). Supporting evidence for a high-temperature origin comes from the sequential fill of dense, laminated calcite followed by coarse-grained, euhedral calcite that contrasts markedly with other cave fills in the region. Remaining void is infilled by buff-coloured silt. The conduit is probably of Caledonian origin as this is the only post-depositional event in the Grottedal area likely to have generated sufficiently high temperatures. Rasmussen & Smith (2001) obtained conodonts with a colour alteration index of CAI 4 in Grottedal, corresponding to burial temperatures of 190–300°C (Epstein *et al.* 1977) and in turn indicating a minimum burial depth of 6.8 km beneath the overburden of Caledonian thrust sheets and foreland basin deposits (the latter now removed by erosion; Rasmussen & Smith 2001).

Sub-Devonian palaeokarst – Wordie Gletscher, East Greenland, 75°N

In the North-East Greenland Caledonides, minor palaeokarst features are seen wherever Devonian conglomerates of the post-orogenic molasse (Vilddal Group; Givetian, Middle Devonian) overlie carbonate units within the orogen (Fig. 3). Palaeokarst is best developed in the relatively pure subtidal limestones of the Ordovician Cape Weber and Heimbjerge Formations (Figs 3, 4).

On Albert Heim Bjerge (Fig. 3; 74.1076°N, 22.9273°W) at *c.* 100 m above sea level (a.s.l.), two caves infilled with coarse breccias of the Solstrand Formation (Vilddal Group) were identified during the regional mapping programme in 1998 at the eastern end of Albert Heim Bjerge, adjacent to Wordie Gletscher (Fig. 3). The sub-quadrate phreatic conduits are 40 cm wide (Fig. 7A) and 60 cm wide

(Fig. 7B), respectively. They are developed within subtidal limestones of the Cape Weber Formation (Tremadocian–Floian, Lower Ordovician), around 75 m above the base of the unit, and the infill of Solstrand Formation comprises blocks of red-stained Ordovician carbonates in a finer clastic matrix. The sub-Devonian unconformity surface is deeply erosive into folded Cambrian–Ordovician strata, such that on Albert Heim Bjerge the Devonian overlies Floian Cape Weber Formation and younger carbonates, but on C. H. Ostenfeld Nunatak, 20 km to the north, it rests on Darriwilian limestones of the Heimbjerge Formation (Fig. 4). The unconformity surface is highly irregular at a smaller scale and has a variety of karstic pockets infilled with Devonian sediment. In places, the *c.* 70 m thick Devonian conglomerate overlying the Cape Weber Formation at this locality has such a high proportion of carbonate clasts that it exhibits karstic weathering itself.

The stratigraphic and tectonic context (Higgins *et al.* 2008) constrains phreatic cave formation on Albert Heim Bjerge to the interval between 460 Ma (the youngest pre-orogenic sedimentary unit; Smith & Rasmussen 2008) and 388 Ma (the Givetian infill).

Caves of North and North-East Greenland

The younger caves of Greenland are of Neogene age, in contrast to the older palaeokarst horizons, and lack lithified, pre-Cenozoic fills. They characteristically occur high in fjord walls and other cliffs, where they have been truncated and exposed by glaciation. In North Greenland, they are characteristically located a few tens to hundreds of metres below the distinctive plateau surface that is developed from Hall Land eastwards to Kronprins Christian Land (Figs 1, 8). The caves are predominantly former phreatic conduits, many of which are very large – up to tens of metres in width. There appears to be strong lithological/stratigraphic control over the position and perhaps, in turn, speleogenesis of many of the caves. All of those explored to date are choked by ice or unlithified sediment fill within a few metres or tens of metres (Moseley 2016; Moseley *et al.* 2020). Nevertheless, the caves do have occurrences of speleothems (secondary mineral deposits precipitated in caves) that are beginning to yield important information about Pleistocene climate in North Greenland (Moseley *et al.* 2021). In addition, the geological location and context of the caves in North and North-East Greenland provide an insight into the landscape evolution of these regions, in time intervals that are otherwise unrepresented by a stratigraphic record.

Wordie Gletscher, East Greenland – 74°N

The southernmost documented caves in Greenland without Palaeozoic fill are located in Ordovician carbonates on Albert Heim Bjerge and C. H. Ostenfeld Nunatak

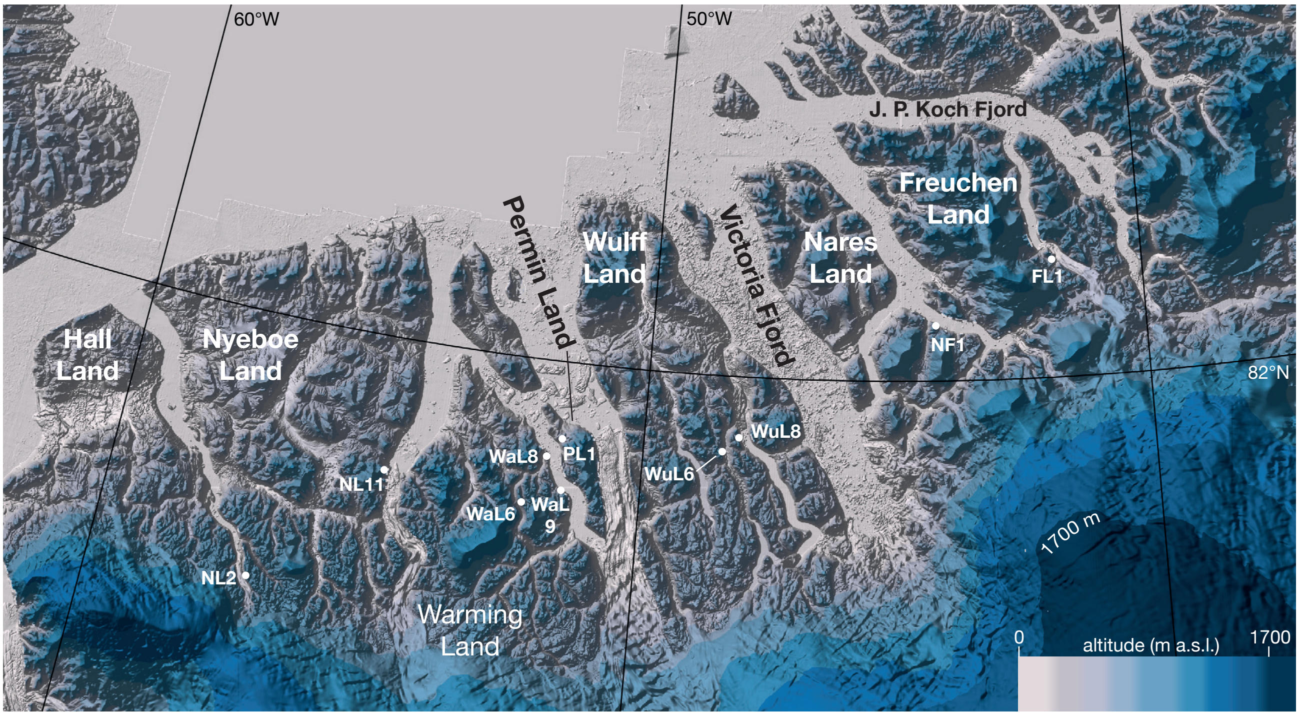


Fig. 8 Digital elevation model (DEM) of central and western North Greenland showing the caves described and figured in the text (data from Arctic DEM, Porter *et al.* 2018). The caves are developed immediately beneath the plateau surface, at an altitude of 800–1000 m, that is seen in the southern parts of the area, from Freuchen Land westwards to Hall Land. The dark blue peaks are ice caps sitting on the plateau surface. Documentation and illustration of other caves discovered during aerial reconnaissance are provided in Supplementary File S1. The colour ramp extends from sea level to 1900 m a.s.l., and the shift to the darkest blue tone is at 1700 m a.s.l.

Fig. 9 A subhorizontal phreatic tube in the Cape Weber Formation at the eastern end of Albert Heim Bjerge adjacent to Wordie Gletscher (Fig. 3). The triangular, flat-based conduit extends for 10 m to an ice choke. Hammer (ringed) is 33 cm long.

(Fig. 3). The age and lithological character of the succession in this area has been documented by Cowie & Adams (1957), Frykman (1979), Hambrey *et al.* (1989), Smith & Bjerreskov (1994) and Smith & Rasmussen (2008). No caves have been recorded to date elsewhere in the outcrop belt of the Cambrian–Ordovician.

Albert Heim Bjerge

A sub-horizontal phreatic tube was observed in steeply dipping, Floian (Lower Ordovician) subtidal limestones of the Cape Weber Formation at the eastern end of Albert Heim Bjerge, adjacent to Wordie Gletscher (Fig. 3; 74.10764°N, 22.92733°W) and close to the palaeokarst documented in section 2.4. The cave is located *c.* 220 m above the base of the Cape Weber Formation at 120 m a.s.l. A triangular, flat-based conduit (Fig. 9) with a maximum width of 120 cm and height of 85 cm extends for 10 m to an ice choke, and there is no draft. The position of the cave, both stratigraphically and topographically, is similar to those that have a red-stained fill, and a similar timing of cave formation cannot be precluded in this instance.

C. H. Ostenfeld Nunatak

Caves are located at the southern end of C. H. Ostenfeld Nunatak (Fig. 3), overlooking Grantagletscher, at an altitude of around 1000 m (74.28727°N, 22.89584°W). Numerous phreatic conduits are erosionally truncated in a cliff of subtidal limestones of the Heimbjerge Formation (Darriwilian–Sandbian; Middle to Upper Ordovician; Smith & Bjerreskov 1994) that dip gently eastwards (Fig. 10). In addition to the large conduits described next, there are several *c.* 0.5 m diameter tubes in the vicinity.

Four main conduits are visible in the cliff (Caves 1–4, Fig. 10). Cave 1 is a 12 m long, ascending phreatic tube (relative to the modern land surface) of around 1 m width (Fig. 10A, B) that ends in a hoar-frost lined chamber that is *c.* 3 m in diameter and 1.5 m high (Fig. 10C). Cave 2 has a blocky breakdown breccia and, beyond a zone of frost shattering, a 0.5 m-wide, square-shaped conduit extends for 10 m to a choke. Cave 3 has a 2 m high by 1 m wide conduit, wider at mid-height with a flat floor (Fig. 10D), and again extends 10 m to an ice choke. Cave 4 was not entered but is clearly seen above Caves 2 and 3 in the cliff. The close spacing suggests that the individual caves may have been part of a single phreatic network prior to erosion. There is no trace of the cemented, coarse, red-stained fill that characterises the Albert Heim Bjerge palaeokarst, and there is no evidence of any fill to these caves other than ice, uncemented silt and breakdown breccias that are also uncemented.

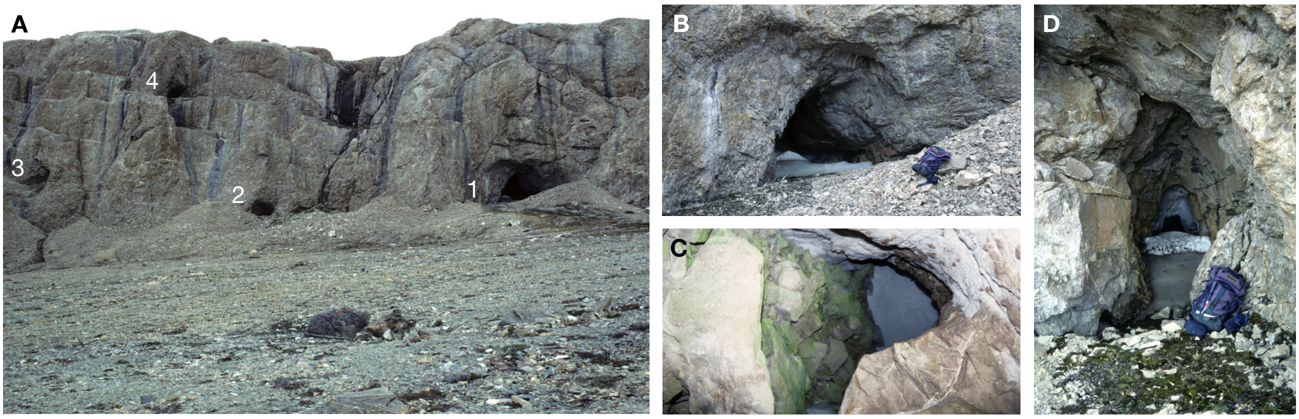


Fig. 10 A complex of erosionally truncated phreatic tubes in subtidal limestones of the Heimbjerge Formation (Darriwilian–Sandbian, Ordovician) at the southern end of C. H. Ostenfeld Nunatak, North-East Greenland (Fig. 3); looking north. **A**: General view of four of the entrances; the part of the cliff containing cave 1 is *c.* 10 m high. **B**: Entrance to Cave 1, which is 1.5 m high. **C**: Conduit in Cave 1, which extends for 12 m before terminating in a 3 m wide × 1.5 m high chamber with an ice choke; maximum conduit height is 2 m. **D**: Entrance and conduit in Cave 3 leading to ice choke. Hammer on rucksack is 33 cm long.

Together with these characteristics, the size and relative morphological complexity of these caves suggests that they are geologically younger than the palaeokarst described in Albert Heim Bjerge.

Kronprins Christian Land

The caves of Kronprins Christian Land are located to the north and south of Centrumsø (Figs 2, 11). They are the best documented in Greenland and have been visited by several expeditions. Caves were first documented in the area by Operation Groundhog, as part of investigations into aircraft landing sites for the US Air Force (Davies & Krinsley 1960). Twelve caves were reported in a large valley they named Grottedal. The caves were next visited by a French caving expedition in 1983 (Loubière 1987) and by GEUS geologists (including the first author) in 1994 and 1995 during the regional mapping programme. Most recently, caves in Grottedal and associated valleys have been extensively documented as part of the Greenland Caves Project in 2015 and 2019 (Moseley 2016; Moseley *et al.* 2020), and for that reason, they are not described in detail here.

Caves in Grottedal and its tributary valleys and one isolated example to the south of Centrumsø (Fig. 2) occur in the limestones of the Odins Fjord Formation (Llandovery, Silurian) particularly in the vicinity of overlying carbonate mud mounds of the Samuelsen Høj Formation (Fig. 4; Smith & Rasmussen 2020). The Odins Fjord Formation comprises grey to golden-brown weathering, highly fossiliferous lime mudstones and wackestones with coral-stromatoporoid biostromes. The mud mounds of the Samuelsen Høj Formation are unbedded with no framework although rudstone flanking beds are commonly developed (Smith & Rasmussen 2020). The initiation of mud mound growth, which defines the formation boundary, commenced in the late Llandovery (Armstrong 1990) at around 436 Ma.

Fig. 11 U-Shaped Cave (Ilusilik Qaarusussuaq, GD4 of Moseley 2016) on the southern side of Grottedal, Kronprins Christian Land, North-East Greenland (Figs 1, 2). Photo: Robbie Shone.

The Grottedal caves are developed at several levels in the sub-horizontal limestones (Moseley *et al.* 2020; Smith & Rasmussen 2020). U-Shaped Cave (Fig. 11; Ilusilik Qaarusussuaq, GD4 of Moseley 2016) was first described by Davies & Krinsley (1960) and is stratigraphically and topographically one of the lowest of the caves at around 100 m below the top of the Odins Fjord Formation. Several caves are distinctively developed at the Odins Fjord – Samuelsen Høj Formation boundary such that the roofs of the caves are in reef lithofacies and the lower part of the conduit in bedded limestones of the lower unit. This is particularly well seen in Cairn Climb Cave (Inussuk Innartooq Qaarusussuaq, GD18) and Crystal Palace Cave (Aligoq Illussaarsuaq Qaarusussuaq, GD19), where large phreatic tubes are present at the boundary. Other examples developed at the boundary are smaller but include Multi-Level Cave (GD11) and Triplet Arch Cave (GD21–23). Detailed descriptions and surveys of these caves are available in Moseley (2016) and Moseley *et al.* (2020).

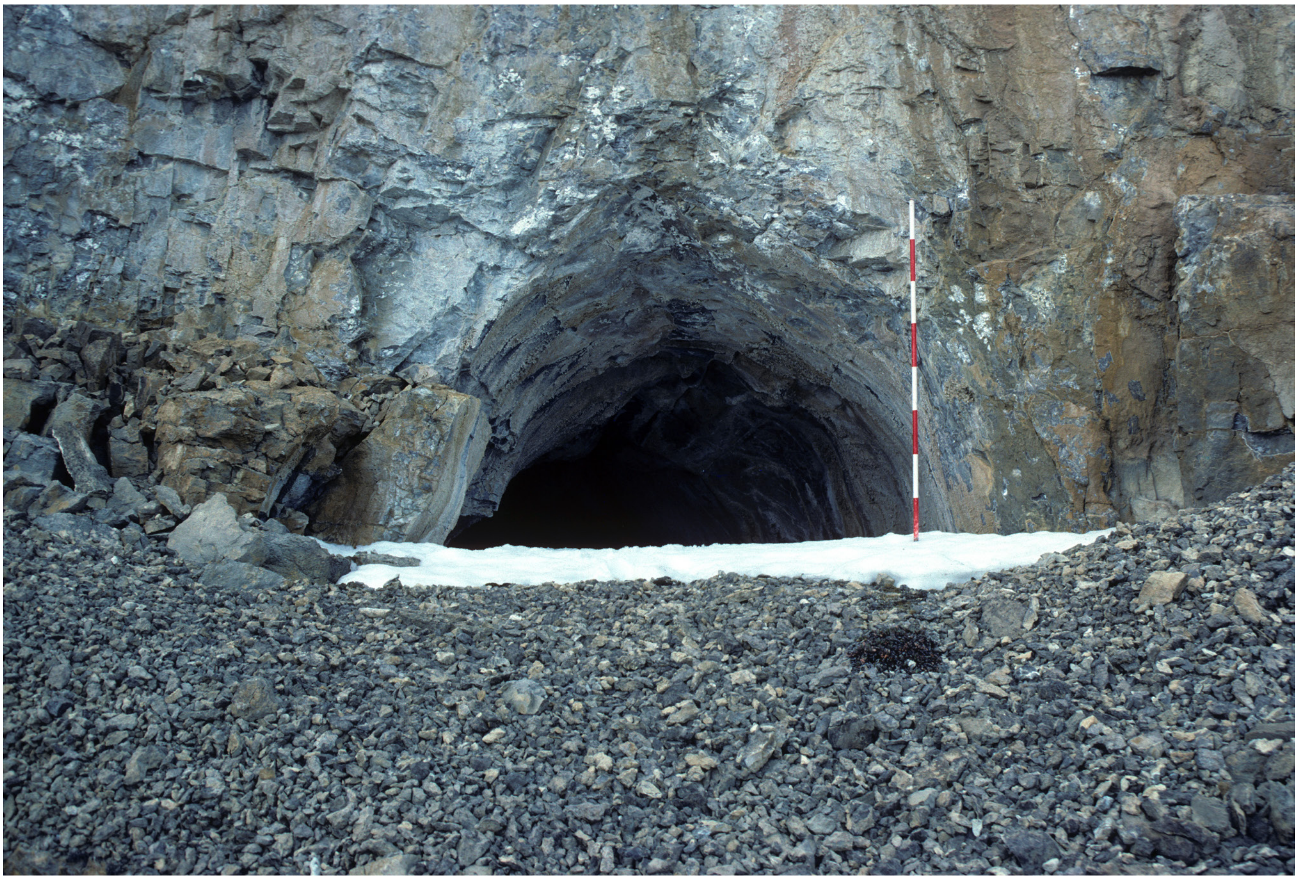


Fig. 12 Phreatic tube in the basal Kap Jackson Formation (Sandbian, Late Ordovician) in south-eastern Freuchen Land, central North Greenland, at the southern end of Navarana Fjord (Figs 1, 8). The cave is one of several at this stratigraphic horizon at the locality and currently represents the most northerly documented cave. All penetrate for 5–7 m before terminating in a silt or ice choke. Divisions on the survey pole are 20 cm.

Most of the conduit development in the Kronprins Christian Land caves comprises sub-horizontal phreatic tubes. Some of these are quite sizeable, and the largest conduit (in U-Shaped Cave) has a width of 8–13 m with a height of up to 10 m, variably filled with unlithified breakdown (Moseley *et al.* 2020, fig. 2–2D). Other phreatic features include anastomoses in the roof of Kodak Cave (GD8), together with phreatic scallops indicating flow inwards from the current entrance, towards the west (Moseley 2016; Moseley *et al.* 2020).

Few of the caves in the region, or in Greenland more generally, have any vadose development. One exception is Grotte des Quatre in a thrust sheet of vertically bedded Odins Fjord Formation to the south of Centrumsø. This is the most geomorphologically complex cave in Greenland with an upper level of phreatic morphology and a lower level that exhibits meandering vadose entrenchment (Moseley *et al.* 2020, fig. 4–4C). A second example is Swirly Cave (Sangujoraartoq Qaarusussuaq) on the southern side of Grottedal (Moseley *et al.* 2020, fig. 10), which has a walking-size vadose canyon that extends downwards from the entrance to two large boulders, beyond which it narrows to a slot. A less well-developed example of vadose development is Cove Cave (Eqik Qaarusussuaq) in a canyon to the south of Grottedal, where a 5 m deep vadose slot is developed in the floor of a linear phreatic conduit (Moseley *et al.* 2020, fig. 13–13E). Finally, Kodak Cave (GD8) contains three vadose wall notches (Moseley 2016).

A 12-cm-thick sample of flowstone was collected from cave GD8 in Grottedal (Moseley 2016; Moseley *et al.* 2021). U-Th dating combined with an orbitally refined age model indicates that speleothem precipitation occurred between *c.* 588 and *c.* 549 ka (Moseley *et al.* 2021), spanning the MIS 15a–14 boundary and indicating a warmer, wetter climate in eastern North Greenland at this time. Speleogenesis must be older than the speleothem deposits, but several lines of evidence indicate that cave formation was much older than this. In particular, all of the explored cave conduits in Kronprins Christian Land are present in vertical rock faces, consistent with the conduits being truncated by glacial erosion, which places older age constraints on the cave formation.

Central and western North Greenland

Caves are abundant in the Ordovician and, particularly, Silurian limestones that extend westwards from J. P. Koch Fjord to Hall Land (Figs 1, 8; Supplementary File S1).

They are developed in topographically consistent positions, high in the vertical walls of the broadly N–S oriented fjords, indicating that cave formation predates incision by the outlet glaciers of the Greenland ice sheet. Most of the exposed conduits are of phreatic origin and are of very large scale, with conduit diameters ranging up to several tens of metres. Details of the geographic and stratigraphic locations of the caves are given in Table 1.

Freuchen Land – 82.5°N

Caves were documented in wackestones and packstones at the base of the Kap Jackson Formation (Fig. 4; early Sandbian, Upper Ordovician) in southern Freuchen Land as part of the regional mapping programme in 1984 (Smith *et al.* 1989). The caves lie on the north side of a small glacier in south-eastern Freuchen Land that flows from the main ice sheet (82.31296°N, 41.83505°W), close to the southern end of Navarana Fjord (FL1 in Fig. 8).

A series of short phreatic tubes lie at the western end of (and 10 m above) the bench that marks the boundary between the Cape Webster and Kap Jackson Formations. The tubes have a maximum length of 5–7 m, and the largest has a width of 2.3 m and a height of 1.6 m (Fig. 12). One tube exhibits phreatic roof domes, and all are choked by either ochre-coloured fine sediment or ice.

These are currently the northernmost documented karst caves globally.

Nordenskiöld Fjord – 82°N

A large entrance of around 30 m width was observed during helicopter reconnaissance in a 700 m high cliff at the southern end of Nordenskiöld Fjord (NF1 in Fig. 8; 82.15836°N, 44.32837°W). The cave lies around 200 m below the cliff-top and is developed within a carbonate mound (m in Fig. 13) immediately above the Djævlekløften – Petermann Halvø Formation boundary (PH in Fig. 4). The mound has pale flanking beds with depositional dips markedly steeper than the inter-mound limestones. Several mounds are visible at this horizon in Nordenskiöld Fjord, and dark grey to black, well-bedded lime mudstones are present between the mounds (Higgins *et al.* 1991). The upper part of the entrance is a large phreatic conduit that extends into the cliff as a dark shadow above a ramp of talus. It is not clear to what extent the entrance has been modified by recent weathering, but a large notch is visible underneath the phreas, consistent with the development of a vadose notch, and is infilled by the talus ramp.

Wulff Land – 81.8°N

WuL8 is a large cave entrance in Wulff Land at the north-western corner of Apollo Sø (Figs 8, 14A, B; 81.84668°N, 48.19241°W; see also Supplementary File S1). The entrance was first noted by Davies & Krinsley

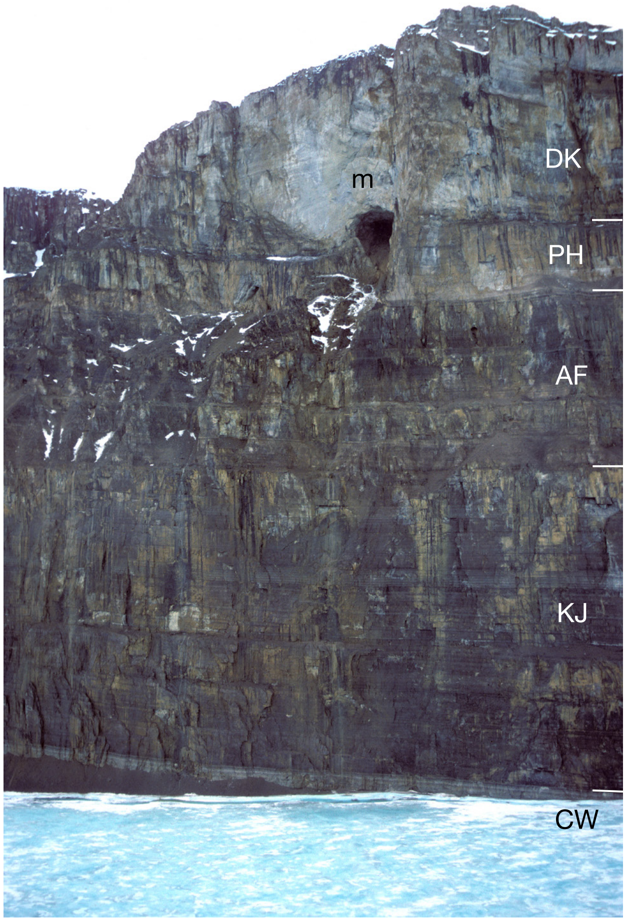


Fig. 13 Large, truncated cave conduit in the 700 m high wall of Nordenskiöld Fjord, central North Greenland (Figs 1, 8), with fine-grained fill weathering out of the entrance; the conduit is around 30 m wide and is located immediately above the Djævlekløften – Petermann Halvø Formation boundary, within a carbonate mound. **AF**: Aleqatsiaq Fjord Formation. **CW**: Cape Webster Formation. **DK**: Djævlekløften Formation. **KJ**: Kap Jackson Formation. **PH**: Petermann Halvø Formation. **m**: carbonate mounds of the Djævlekløften Formation. See Fig. 4 for unit ages.

(1960) around 120 m below the top of the cliff and subsequently examined by helicopter during regional geological mapping in 1984. The cave entrance is approximately 30 m wide (Fig. 14B) and a large talus ramp feeds a steep gulley and alluvial fan at the foot of the slope. The top of the talus ramp is level and the conduit can be seen to continue beyond.

The cave occurs at a significant lithofacies boundary within the Djævlekløften Formation, where a cliff-forming unit principally composed of interbedded dark and light stromatoporoid biostromes with abundant crinoid debris (WG4 of Sønderholm *et al.* 1987) overlies dark grey to black, thinly-bedded lime mudstones with occasional carbonate mounds, one of which occurs at the northern end of the hill (WG3 of Sønderholm *et al.* 1987; see their fig. 5, which is the same cliff).

A very large cave entrance, with associated minor entrances, WuL6 (Fig. 14C) was discovered as part of

Table 1 Geographic and stratigraphic location of caves in central and western North Greenland, together with image resources.

Caves	Latitude, longitude	Altitude	Plateau altitude	Stratigraphic unit	Photo number
Hall Land (HL)					
HL1	81.32145, -57.32228	600	1000	Petermann Halvø Formation	NH-1985-b-032-008
HL2	81.30828, -57.31335	600	1000	Djævlekløften Formation	NH-1985-c-011-004
Nyeboe Land (NL)					
NL1	81.17508, -56.78120	600	900	Aleqatsiaq Fjord Formation	NH-1984-b-025-019
NL2	81.26632, -57.05613	750	900	Djævlekløften Formation	Fig. 15e
NL3	81.33289, -56.91269	600	900	Djævlekløften Formation	NH-1984-c-008-022
NL4	81.53769, -57.13090	500	800	Djævlekløften Formation	NH-1985-b-066-003
NL5	81.51205, -56.67436	600	800	Dj®vlekløften Formation	NH-1985-b-065-027
NL6	81.51033, -55.86095	700	800	Djævlekløften Formation	NH-1985-c-025-017
NL7	81.39275, -55.86233	500	900	Petermann Halvø Formation	NH-1985-c-025-012
NL8	81.36083, -55.97906	600	900	Petermann Halvø Formation	NH-1985-c-009-012
NL9	81.32756, -55.88430	700	900	Petermann Halvø Formation	NH-1985-c-009-010
NL10	81.30028, -55.82104	700	900	Aleqatsiaq Fjord Formation	NH-1985-c-009-009
NL11	81.63091, -54.83647	700	1100	Djævlekløften Formation	Fig. 15d
Warming Land (WaL)					
WaL1	81.64952, -54.37494	600	1000	Djævlekløften Formation	NH-1985-c-001-015
WaL2	81.51402, -54.48893	500	900	Petermann Halvø Formation	NH-1985-b-002-001
WaL3	81.50083, -53.45759	700	900	Petermann Halvø Formation	NH-1985-c-002-003
WaL4	81.70141, -53.32850	600	1000	Djævlekløften Formation	NH-1985-c-001-031
WaL5	81.69487, -52.39740	700	1100	Djævlekløften Formation	NH-1984-c-012-023
WaL6	81.59510, -52.24085	700	900	Aleqatsiaq Fjord Formation	NH-1984-c-012-027
WaL7	81.75259, -51.95520	500	800	Djævlekløften Formation	NH-1985-c-008-019
WaL8	81.73477, -51.83186	600	1000	Petermann Halvø Formation	Fig. 15a
WaL9	81.64486, -51.54484	650	900	Djævlekløften Formation	Fig. 15b, c
Permin Land (PL)					
PL1	81.76106, -51.52399	800	1000	Djævlekløften Formation	NH-1984-c-012-010
Wulff Land (WuL)					
WuL1	81.81245, -50.37283	700	1000	Djævlekløften Formation	NH-1985-c-004-003
Wul2	81.71010, -50.21156	700	1000	Djævlekløften + Petermann Halvø formations	NH-1985-c-004-006
WuL3	81.87180, -49.57921	700	1000	Djævlekløften Formation	NH-1985-c-021-016
WuL4	81.78847, -49.21392	450	1000	Aleqatsiaq Fjord Formation	NH-1985-b-010-027
WuL5	81.84054, -48.61301	700	900	Djævlekløften Formation	NH-1985-c-004-024
WuL6	81.78480, -48.47232	650	900	Aleqatsiaq Fjord Formation	Fig. 14c
WuL7	81.82684, -48.32730	700	900	Djævlekløften Formation	NH-1985-c-004-025
WuL8	81.84386, -48.18393	700	900	Djævlekløften Formation	Fig. 14a, b
Nordenskiold Fjord (NF)					
NF1	82.15836, -44.32837	600	800	Djævlekløften Formation	Fig. 12
Freuchen Land (FL)					
FL1	82.30858, -41.85196	450	800	Kap Jackson Formation	Fig. 13

Further detail of these caves is provided in Supplementary File S1, and for the location of land areas and caves, also see Figs 1 and 8. 'Plateau altitude' refers to the maximum elevation of the land surface (excluding ice) in the vicinity of the cave. Image numbers with the prefix NH-198n- refer to oblique aerial photography of fjord walls obtained during the 1984–1985 regional mapping programme and available on the Greenland Mineral Resources Portal (http://maps.greenmin.gl/geusmap/?mapname=greenland_portal&lang=en).

the regional mapping programme, 8 km to the south-west of WuL8 on the west side of the large un-named valley that lies parallel to Apollo Sø and to the west of it (Fig. 8; 81.78481°N, 48.47232°W), at *c.* 650 m a.s.l. The truncated phreatic tube is trapezoidal in transverse profile with a maximum width of around 20 m and a height of 10 m. Inside, a ramp of debris extends upwards at around 30° but possible open cave could be seen at the top of the ramp. The cave is developed within sub-horizontal, burrow-mottled limestones of the Aleqatsiaq Fjord Formation (Smith *et al.* 1989), which is of mid-Katian to Llandovery (Late Ordovician–Silurian) age (Fig. 4).

Additional entrances were observed on oblique aerial photographs on the opposite side of the valley to WuL6 and around 3 km south-west of WuL8 (Cave WuL7, Supplementary File S1, 81.82684°N, 48.32730°W). At least six entrances are developed along the base of a carbonate mound within the lower Djævlekløften Formation that dips gently north-west. The multiple entrances suggest that a phreatic network has been transected by glacial erosion. This cave development is unlikely to be related in speleogenetic terms to the WuL6 conduits as it is developed at a much higher stratigraphic level, but WuL7 does

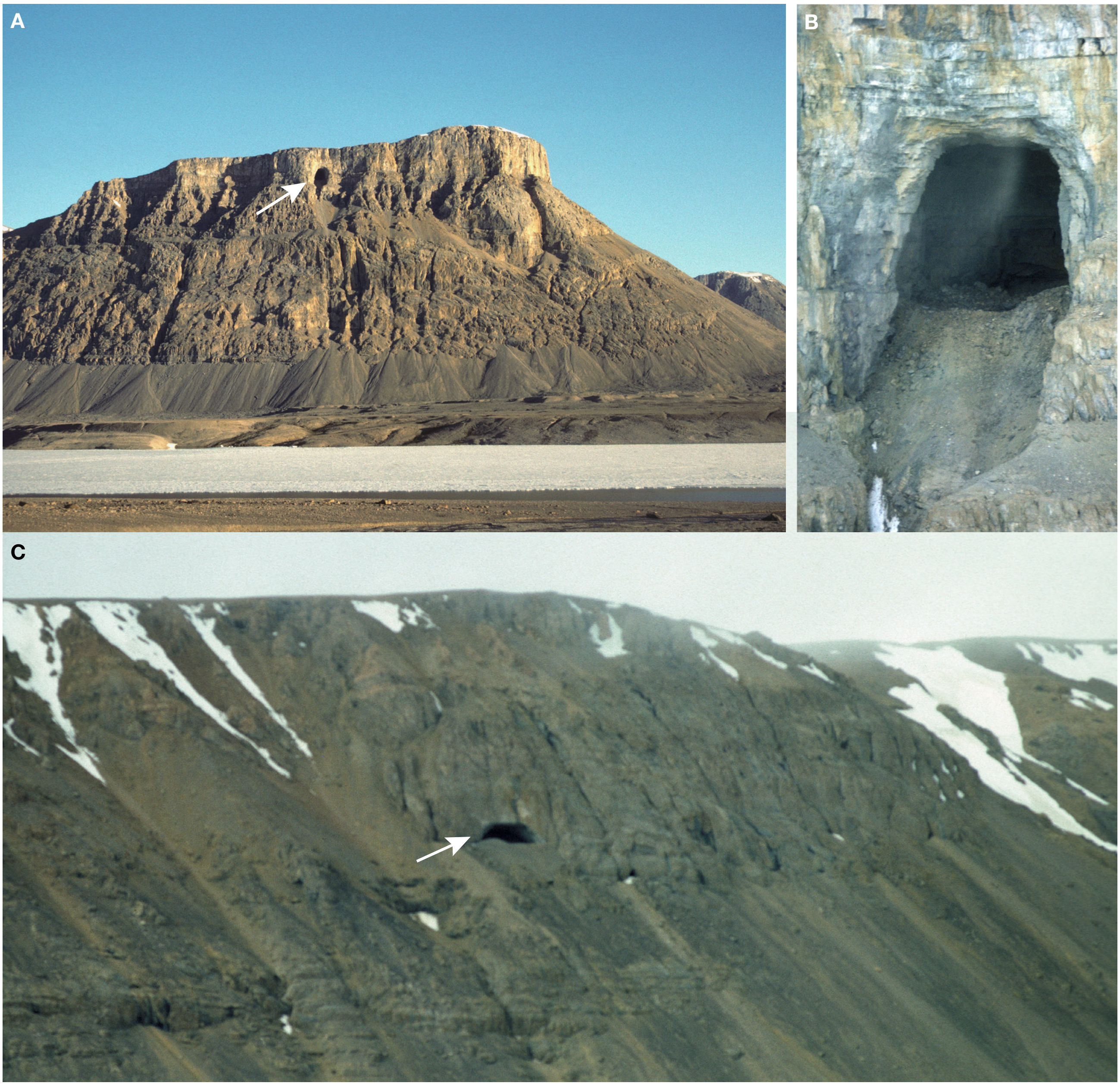


Fig. 14 Cave WuL8, a large cave in the Djævlekløften Formation first noted by Davies & Krinsley (1960) at the north-western end of Apollo Sø, Wulff Land, western North Greenland (Figs 1, 8). **A**: Cave from the east side of Apollo Sø. Cliff is 800 m high from terrace to summit. **B**: Close-up of cave entrance from helicopter; entrance approximately 30 m wide. **C**: The large cave entrance of WuL6 photographed on a helicopter reconnaissance. Located 8 km to the SW of WuL8 at an altitude of *c.* 650 m. The truncated phreatic tube, developed within the Aleqatsiaq Fjord Formation (Fig. 4), is trapezoidal in transverse profile with a maximum width of around 20 m and a height of 10 m.

have a very similar stratigraphic position to WuL8. Other caves observed in Wulff Land during aerial reconnaissance (WuL 1–5; Table 1) are documented in Supplementary File S1.

Warming Land – 81.55–81.75°N

Several entrances are seen in the western wall of the fjord that separates Permin Land from southern Warming Land, in the innermost extension of Hartz Sund (Fig. 8). Cave WaL8 (Figs 8, 15A; 81.73477°N, 51.83186°W) is located *c.* 400 m below the top of an isolated 900 m hill. Stratigraphically, it is developed within the Djævlekløften Formation at a prominent boundary between cliff-forming dark limestones and overlying pale carbonates. The conduit width is *c.* 20 m. Multiple caves are observed in fjord and valley walls across Warming Land (WaL1–8 in Table 1) and Permin Land (PL1 in Table 1) and are described in detail in Supplementary File S1.

A second group of cave entrances (WaL9) is also visible in the fjord wall, 11 km to the south-south-west of the northerly cave (Figs 8, 15B, C; 81.64486°N,

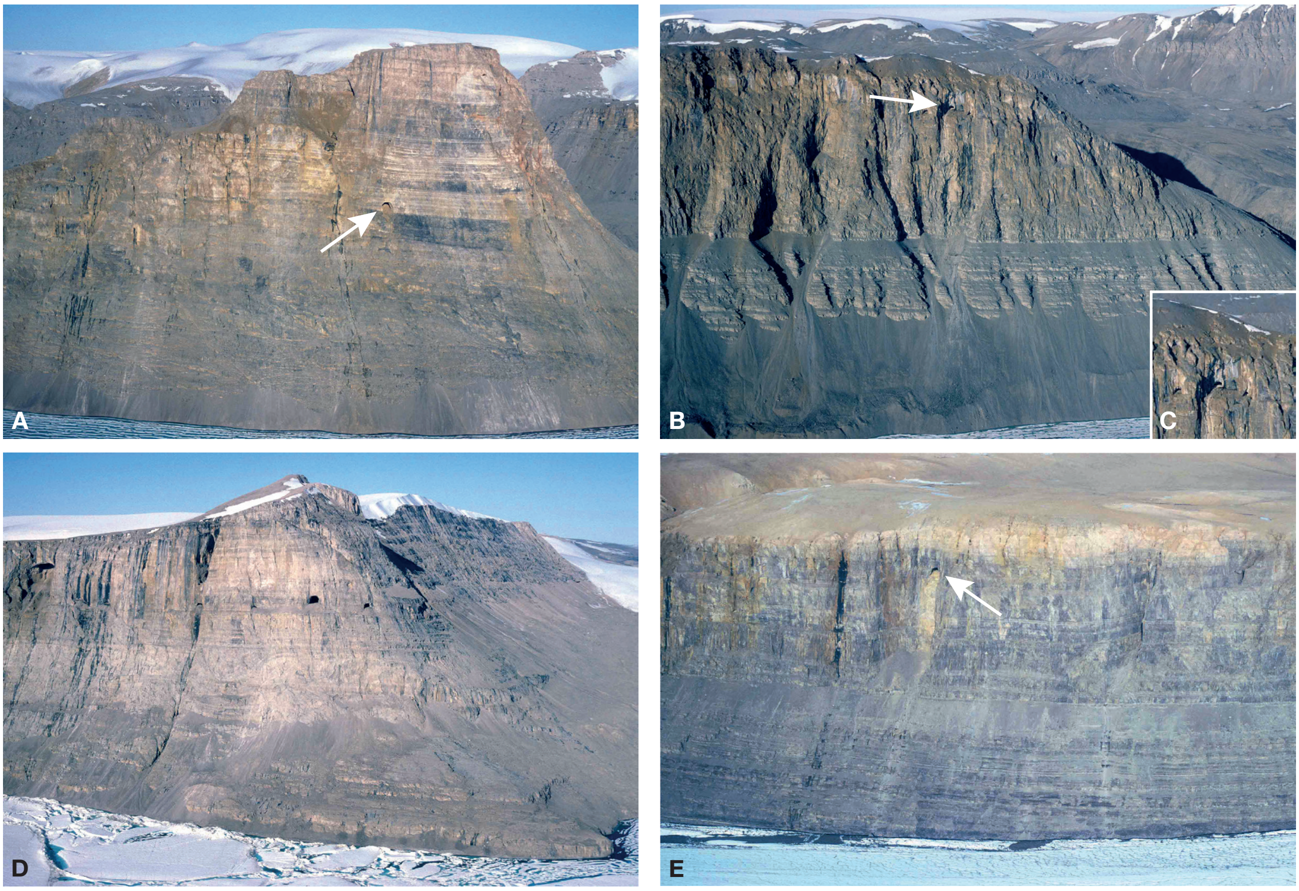


Fig. 15 Caves exposed in fjord walls incised by outlet glaciers from the Greenland ice sheet in Warming Land and Nyeboe Land, North Greenland. **A**: Cave entrance (WaL8) at the base of the Petermann Halvø Formation (Llandovery, Silurian) where it overlies the Aleqatsiaq Fjord Formation in eastern Warming Land (Figs 1, 8). Cliff is 900 m high, and the cave entrance is *c.* 20 m wide. **B**: Multiple cave entrances (arrowed; WaL9) within Djævlekløften Formation, 11 km to SSW of Fig. 14A, where a phreatic network has been transected by glacial erosion. Cliff is 800 m high, and entrances are less than 10 m in diameter. **C**: Enlargement of multiple entrances seen arrowed in B. **D**: Multiple cave entrances (NL11) developed in the Djævlekløften Formation exposed in a cliff in south-eastern Nyeboe Land, western North Greenland (Fig. 1). Cliff is 1100 m high from fjord to summit, and the larger entrance is 30 m wide. **E**: Cave NL2 in south-western Nyeboe Land in cliff bordering the glacier at the head of Newman Bugt. The cave is located in the upper Aleqatsiaq Fjord Formation and the cliff is 650 m high from glacier to plateau edge. The entrance is around 15 m wide, and the wash of fine sediment indicates that there is intermittent water flow through the cave. Photos: Niels Henriksen (**A**, NH-1985-c-008-018; **B, C**, NH-1985-c-008-0115; **D**, NH-1985-c-011-033; **E**, NH-1984-c-008-034).

51.54484°W) and 12 km north of the Geological Survey of Greenland (GGU) base camp in 1984–1985. They occur 150 m below the top of the 800 m cliff that marks the plateau edge and are again located in cliff-forming limestones of the Djævlekløften Formation. The conduit widths are less than 10 m, but the closely spaced cluster of multiple entrances again suggests erosional truncation of a phreatic network.

Cave WaL6 is located within the interior of Warming Land (Fig. 8, 81.59510°N, 52.24085°W; see also Supplementary File S1) and is noteworthy for being one of the few caves in Greenland with active water flow, with a stream emitting from the entrance at an altitude of around 700 m (see Supplementary File S1 for image). A stream appears to sink just back from the cliff edge and emerges from the entrance several tens of metres lower. A second entrance also has a suggestion of vertical development and is located a few tens of metres farther to the south.

Eastern Nyeboe Land – 81.6°N

Caves in the western wall of southern Sankt George Fjord, (NL11 in Figs 8, 15D; Table 1; 81.63091°N, 54.83647°W) were first recorded by Niels Henriksen in 1985 as part of the photo-reconnaissance flights to obtain oblique aerial photography of fjord and valley walls during the regional mapping programme (Fig. 15D). The caves were subsequently photographed during a NASA Operation Icebridge mission (Studinger 2011), and one of those is perhaps the largest cave passage identified in Greenland to date. An entrance of *c.* 30 m width is located within sub-horizontal limestones of the Djævlekløften Formation. It has a talus fan forming the floor, vertical walls and a gently arched roof, creating an overall sub-quadrate conduit cross-section. A second smaller entrance is present 130 m to the north at a similar stratigraphic horizon and may represent the same conduit or system. The caves are located *c.* 360 m below the top of the cliff that rises to 1000 m from sea level. The caves lie directly beneath carbonate mounds of the Hauge Bjerge Formation, but unlike other examples in North Greenland they are at a considerably lower level, around 130 m below the reef mounds, and there is unlikely to be a genetic association.

South-western Nyeboe Land and Hall Land

Multiple cave entrances are present in the west-facing walls that bound the glacier feeding the head of Newman Bugt (NL2 in Figs 8, 15E; Table 1; 81.26632°N, 57.05613°W). The most prominent of these (Fig. 15E) has a 15 m wide entrance located 100 m below the edge of the plateau surface at 900 m. It occurs within the Aleqatsiaq Fjord Formation, just below the boundary with the overlying Petermann Halvø Formation (Fig. 4) and is one of relatively few caves developed within that unit, perhaps because the rubbly weathering nature does not lend itself to stable conduit formation. The cave, and others along this stretch of cliffs, has a conspicuous wash of sediment descending from the entrance, suggesting that water flows out from the cave entrance at least intermittently.

Caves are abundantly developed in the southern, platform areas of Nyeboe Land and Hall Land but to date have only been observed during aerial reconnaissance flights. A summary of caves HL1–2 and NL1–NL11, identified from oblique aerial photography, is available in Supplementary File S1.

Age constraints on cave formation in North and North-East Greenland

Determination of the timing of speleogenesis for the large, open caves exposed in the fjords and cliffs of North-East and North Greenland is dependent on being able to distinguish younger karst features from older palaeokarst. Pre-Cenozoic palaeokarst is extensive across North America and is particularly well developed at the tops of the Sauk megasequence (Middle Ordovician) and the Kaskaskia megasequence (late Mississippian) of Sloss (1963), driven by large-scale changes of relative sea level in carbonate-dominated successions (Palmer & Palmer 1989, 2011). Extensive palaeokarst has also been documented in the Middle Devonian and to a lesser degree Late Devonian of Canada (Ford 1989). These occurrences of endokarst in Palaeozoic rocks across North America are preserved in the geological record by the cavities being infilled with lithified younger sediments that prevent cave collapse. If unfilled cavities undergo deep burial then collapse and mechanical compaction will occur, with a zone of suprastratal deformation extending upwards from the collapse; by the time burial has proceeded to 2–3 km, few cavities are detected by drill-bit drops during drilling (Loucks 2007).

The large cave conduits documented in North and North-East Greenland lack a lithified fill (in distinct contrast to the Palaeozoic palaeokarst), despite being environments with an abundance of calcium carbonate to form cements for any cave sediments. Despite their large size and open character, they also lack large-scale collapse and suprastratal deformation; where collapse occurs, it is localised and probably related to frost-shattering. Together these characteristics indicate that the caves are geologically young, and it is highly unlikely that the caves have been buried to any significant depth or been through multiple burial–uplift cycles.

These geologically young caves, in contrast to the older palaeokarst, consistently occur within the upper few hundred metres beneath the present-day topographic surface, where they are exposed in the fjord walls and other cliffs. Speleogenesis must therefore post-date formation of a terrestrial surface following uplift but predate the earliest fjord-forming glaciation by outlet glaciers from the Greenland ice sheet that overprinted the landscape.

Onset of glaciation in North and North-East Greenland

The earliest evidence for Cenozoic glaciation in Greenland is the presence of ice-rafted debris off the eastern coast of Greenland at 75°N derived, at least intermittently, from glaciation during the late Eocene and early Oligocene (30–38 Ma) that probably corresponded to alpine-style glaciers (Eldrett *et al.* 2007, 2009). During the Cenozoic, northern hemisphere glaciation is unlikely to have been possible prior to the late Eocene (DeConto *et al.* 2008; Bierman *et al.* 2016). Episodic glaciation off the coast of south-eastern Greenland through the Miocene and Pliocene is evidenced by glacial dropstones and ice-rafted debris from 7 Ma (late Miocene; Larsen *et al.* 1994) and quartz sand grains with surface textures characteristic of glacial erosion (Helland & Holmes 1997; see Bierman *et al.* 2016, fig. 5 for summary).

Modelling of the uplift history and glaciation by Solgaard *et al.* (2013) showed an intimate connection between uplift and glaciation by combining geological observations and climate modelling. Solgaard *et al.* (2013) concluded that the low-relief Miocene surface prior to uplift at 10 Ma and 5 Ma (see below) had no ice. A cooling in surface temperature combined with an increase in orographic precipitation after 10 Ma led to ice build-up although evidence suggests that this was confined to localised ice caps in northernmost and south-eastern Greenland. A second period of uplift at 5 Ma enabled ice sheet initiation and relocated the main area of ice sheet nucleation from northernmost Greenland to the south-east, south and south-west. During colder-than-present climatic conditions, ice could flow into the interior of Greenland and form an inland ice sheet although this process was inhibited by a föhn effect (Solgaard *et al.* 2013, fig. 13). Nevertheless, due to climatic deterioration, an expansive and persistent Greenland ice sheet had developed across the interior by *c.* 2.7 Ma (Flesche Kleiven *et al.* 2002; Bierman *et al.* 2016).

The first physical evidence of glaciation preserved in North Greenland is a till that is overlain by nonglacial, marine and deltaic sediments of the Kap København Formation (Funder *et al.* 2001), which are in turn overlain by another till. The difficulty of dating the Kap København Formation has resulted historically in a narrow spread of ages around *c.* 2.4 Ma (Funder *et al.* 2001), but Bennike *et al.* (2010) undertook a detailed re-appraisal of the stratigraphic correlation of Pliocene–Pleistocene units in North and North-East Greenland. The Kap København Formation was separated into two disconformable members, of which the younger one, Member B, was thought to have been deposited just prior to the base of the Olduvai subchron (1.95 Ma). The older Member A, beneath the disconformity, was interpreted as being of terminal Pliocene age (*c.* 2.6 Ma). Funder *et al.* (2001) considered the underlying glacial till to be in conformable contact with the overlying nonglacial sediments and the oldest dateable field evidence for the initiation of glaciation in North Greenland, which could have begun to incise the plateau and transect the caves is therefore *c.* 2.7 Ma.

Independent evidence that the climate remained intermittently warm into the earliest Pleistocene, at temperatures sufficient to support deciduous vegetation in North Greenland, comes from sporadic occurrences of sub-fossil wood across North Greenland, dated at *c.* 3 Ma (Bennike 1998, 2000); the preservation of *Larix* and *Thuja* in Member B of the Kap København Formation (2 Ma) (Funder *et al.* 2001); and a variety of deciduous land plants, including *Larix* and *Betula*, in the Store Koldewey Formation of North-East Greenland (1.95–1.78 Ma; Bennike *et al.* 2010).

Given the paucity of sedimentary evidence for the onset of fjord-forming glaciation in North Greenland, Pedersen *et al.* (2019) took a geophysical approach by examining the flexural isostatic response to erosional unloading around Independence Fjord (Fig. 1), concluding that the fjord systems in this region must have formed by glacial erosion at average rates of *c*. 0.5–1 mm yr^{-1} since around 2.5 Ma. It may therefore be concluded that pre-existing phreatic cave systems were truncated by glacial erosion by the latest Pliocene or earliest Pleistocene and that there is no evidence for active conduit formation or enlargement after that date although speleothem deposition has occurred within open cavities since then (Moseley *et al.* 2021).

Age constraints of cave formation on Albert Heim Bjerge and C. H. Ostenfeld Nunatak

The caves developed in the Cape Weber Formation on Albert Heim Bjerge are short (10 m), at low altitude (100–200 m a.s.l.), and are morphologically simple phreatic tubes similar to the palaeokarst caves infilled with Devonian molasse. Although they could be geologically young features, it cannot be precluded that they are contemporaneous with those caves and erosional pockets nearby that preserve a Devonian fill.

In contrast, the caves developed on C. H. Ostenfeld Nunatak are morphologically more complex, as evidenced by the multiple entrances to what might have been part of a single phreatic endokarst complex and also by the more varied conduit geometries. The presence of open conduits without lithified sedimentary infill or significant collapse strongly suggests that the C. H. Ostenfeld Nunatak caves are geologically young morphological features, in contrast to those filled with Devonian molasse on Albert Heim Bjerge.

The caves on C. H. Ostenfeld Nunatak are located at the southern end of the nunatak at an altitude of 1000 m a.s.l. and are coincident with an observed erosional remnant of a Neogene peneplanation surface, termed the Lower Planation Surface (LPS), that forms the highest ground on the nunatak (Bonow & Japsen 2021, figs 7, 9, supplementary file S2). Given that the caves predate late Pliocene glaciation, they may have been associated with the uplift events that formed successive planation surfaces along the eastern coast of Greenland from at least 68°N to 78°N (Bonow & Japsen 2021). These authors hypothesised that the region was subaerially eroded down to a surface of low topographic relief at a marine base level around the Eocene–Oligocene boundary, which they termed the Upper Planation Surface (UPS). The UPS was subsequently uplifted at *c.* 10 Ma (late Miocene) by around 1 km, leading to incision towards base level and the development of the LPS. Further uplift at *c.* 5 Ma (early Pliocene) then elevated the LPS by a further 1 km above the base level. Given that the caves on C. H. Ostenfeld Nunatak are geologically young, it is possible that they are linked genetically with these Neogene uplift events.

Age constraints of cave formation in North Greenland

The area of the Laurentian shelf in North Greenland in which caves have been recorded, from Kronprins

Christian Land in the east (section 3.2) to Hall Land in the west (section 3.3; Fig. 1), is characterised by a plateau at 800–1000 m, into which fjords with vertical walls are deeply incised by outlet glaciers from the Greenland ice sheet. This plateau surface is highest in the southern parts of Nyeboe Land and Warming Land, reducing in height eastwards into Wulff Land and the area around the head of Victoria Fjord (Fig. 8). It is high again in central Peary Land, at around 1000 m, but mainly at lower altitudes in Kronprins Christian Land. There are two areas of conspicuously higher elevation, one to the north of Peary Land in the mountains of Johannes V. Jensen Land (up to 1850 m a.s.l.) and the second in the Prinsesse Caroline-Mathilde Alper of central Kronprins Christian Land (up to 1742 m a.s.l.; Japsen *et al.* 2021, fig. 19).

The type of landscape analysis that has elucidated the spatial distribution of the UPS and LPS on the eastern and western coasts of Greenland has not yet been extended to North Greenland, but the region does have the characteristics of an elevated passive continental margin *sensu* Green *et al.* (2013, 2018). Apatite Fission Track Analysis (AFTA), together with some vitrinite reflectance data, is, however, available to constrain the Cenozoic uplift history around Independence Fjord and the margins of the Wandel Sea Basin (Japsen *et al.* 2021), between the two main cave-bearing regions of Kronprins Christian Land and western North Greenland (Fig. 1).

The digital elevation model for the Independence Fjord region (Japsen *et al.* 2021, fig. 19) shows that there is a plateau surface on either side of Independence Fjord at around 1000 m a.s.l., and it is this surface that is continuous with the plateau developed at a similar altitude across western North Greenland (Fig. 8). In relation to Cenozoic uplift, the AFTA data identified a short, localised phase of uplift in the mid-Paleocene (60 Ma) associated with inversion and exhumation along major fault zones, and a more regional, but again short lived, cooling/uplift event at the end of the Eocene that led to the almost complete removal of an extensive, kilometer-thick sedimentary cover deposited during Eocene subsidence (Piasecki *et al.* 2018; Japsen *et al.* 2021).

The AFTA data also identified an interval of mid-late Miocene cooling and uplift in the interval from 15–5 Ma that produced the modern plateau topography (Japsen *et al*. 2021), followed by incision. This event is not associated with any known sedimentary record, but Japsen *et al.* (2021) did note that this uplift event does correlate broadly with the events in North-East Greenland that generated the UPS and LPS. On the balance of evidence, Japsen *et al.* (2021) considered it most likely that the North Greenland plateau surface correlates temporally with the initial Miocene (10 Ma) uplift of the UPS farther to the south, rather than the 5 Ma Pliocene event that uplifted the LPS and further elevated the UPS.

The lack of either fill or collapse in the caves developed in North Greenland indicates that they were not part of the Eocene subsidence and basin fill associated with the deposition of the Thyra Ø Formation (Piasecki *et al.* 2018). The oldest that the caves could be is therefore latest Eocene, associated with the latest stages of exhumation that removed the Eocene sedimentary cover identified by Japsen *et al.* (2021). More likely, given their open character, lack of sedimentary fill, and absence of collapse, they are Miocene and broadly associated with the uplift event that generated the plateau. The formation of very large-scale phreatic cave systems must have coincided with a period of relatively wet climate in northernmost Greenland, and Solgaard *et al.* (2013) did note that uplift of the low-relief surface during the Miocene led to an orographic increase in precipitation after 10 Ma.

Speleogenesis persisted no later than the latest Pliocene or earliest Pleistocene when the onset of major glaciation led to the formation of the fjords by valley outlet glaciers emanating from the Greenland ice sheet (Pedersen *et al.* 2019) and the erosional transection of the large-scale phreatic systems.

Conclusions

Spatially extensive Cambrian–Silurian carbonate rocks were deposited on the north-east corner of the Laurentian palaeocontinent as part of the Great American Carbonate Bank (Derby *et al.* 2012), which is today represented by the north and east coasts of Greenland, but which also constituted an original continental promontory during the early Palaeozoic. These carbonates have been prone to the development of karst during times of relative sea-level lowstand. Palaeokarst surfaces are frequently developed at the sequence boundaries with particularly well-developed examples in the Portfjeld Formation (late Ediacaran – Cambrian), beneath the Buen and Kap Holbæk Formations (Cambrian Series 2) of North Greenland and beneath the post-orogenic Devonian cover in southern North-East Greenland. For the most part, this involves the development of morphologically simple karst with grikes (kluftkarren) infilled with sediment, which is often mature quartz sand that has been subject to aeolian reworking. However, in Kronprins Christian Land (Sæfaxi Elv and Hjørnegletscher, Figs 1, 2) the palaeokarst includes infilled cave systems that include a variety of phreatic conduits of probably early Cambrian age, together with penecontemporaneous surface channels that postdate the caves and truncate them. Infilled palaeo-cave systems are also present in the Lower Ordovician Cape Weber Formation on Albert Heim Bjerge (Fig. 6), and in this case, the sediment fills are of Devonian age.

Caves are also widely developed, but for the most part have not previously been documented, in the

Ordovician and Silurian limestones of North-East and East Greenland. In North Greenland, where most of the caves occur, the shelf successions of this age are sub-horizontal and have remained so since deposition. Notably, these caves are similar to each other but contrast markedly with the older palaeokarst. For example, they lack a cemented sedimentary fill and the largest examples are of much larger scale, with conduits measuring tens of metres rather than a few metres or smaller. The only sedimentary fill within them is uncemented mud and silt and localised, uncemented breakdown breccias; many are plugged with ice. They also have a characteristic geomorphological position, located in the steep fjord walls and other glacially eroded cliffs, within a few 100 metres vertically beneath the plateau surface that is developed at elevations of 800–1000 m (Fig. 8). Given these similarities, it is probable that they have a similar speleogenetic history and formed in a single phase of cave development.

In central and western North Greenland, much of this phreas is very large, with individual conduits commonly 20–30 m wide, but where exploration has been more comprehensive, for example in Kronprins Christian Land (Moseley 2016; Moseley *et al.* 2020), abundant smaller caves, still predominantly phreatic, have also been discovered. All caves explored to date end in loose sediment or ice chokes after a few tens of metres. The longest explored cave to date is Cove Cave in Grottedal, Kronprins Christian Land, with a surveyed length of 103 m (Moseley *et al.* 2020). Although short, the caves are significant in containing speleothems, which offer considerable potential for documenting high-latitude Pleistocene palaeoclimate (Moseley *et al.* 2021).

In North Greenland, given that the caves are most commonly exposed in fjord walls and other cliffs, they must predate incision by the outlet glaciers from the Greenland ice sheet that created the fjords and truncated the functional cave systems. The earliest physical evidence for glaciation in North Greenland is a till that conformably underlies marine sediments of the Kap København Formation (Funder *et al.* 2001), which has been dated as the latest Pliocene (Bennike *et al.* 2010). Modelling of early ice sheet growth in North and North-East Greenland is highly responsive to changes in input parameters, and predictions of ice cover vary accordingly (Solgaard *et al.* 2013), but studies of the flexural isostatic response to erosional unloading indicate that fjord formation in North Greenland is likely to have commenced at around 2.5 Ma (Pedersen *et al.* 2019). The available evidence from the geological and geomorphological context thus indicates that the caves of North and North-East Greenland ceased to be active by the latest Pliocene or earliest Pleistocene. The only activity within the caves after that date was the deposition of speleothems during warm, moist intervals (Moseley *et al.* 2021), together with some local breakdown and the accumulation of fine, probably aeolian, sediment.

The maximum age of formation is less well constrained in both North and North-East Greenland. On C. H. Ostenfeld Nunatak, multiple open conduits suggest that a phreatic network has been truncated and passages are up to 3 m in width. Successive uplift episodes at 10 Ma and 5 Ma created distinctive paired planation surfaces at *c.* 1 km and 2 km a.s.l. termed the LPS and UPS, respectively (Japsen *et al.* 2014; Bonow & Japsen 2021). The cave systems observed on C. H. Ostenfeld Nunatak, North-East Greenland (Figs 3, 9), lie directly beneath a glacially eroded remnant of the LPS (Bonow & Japsen 2021, figs 7, 9). The topographical context suggests that the cave formation was possibly associated with the Miocene uplift.

The earliest date for cave formation in North Greenland is also poorly constrained, but the lack of cemented fill and of cave collapse shows that the caves have not been buried deeply within sedimentary basins and nor have they been through multiple cycles of burial–uplift. The clear association with the plateau surface provides a further line of evidence. In North Greenland, there is only a single planation surface, which Japsen *et al.* (2021) ascribed to a Miocene uplift event at 10 Ma (temporally equivalent to the UPS on the east and west Greenland coasts). This event creates the distinctive plateau surface at 800–1000 m from Hall Land in the west to Kronprins Christian Land in the east (Figs 1, 8). The combination of evidence suggests that the initiation of cave formation in North Greenland is unlikely to be pre-Miocene, and that speleogenesis was probably associated with Miocene uplift.

The association of phreatic systems with large conduits and their development beneath a low gradient coastal peneplain may suggest that the cave systems of the Nullarbor Plain in southern Australia (Webb & James 2006; Woodhead *et al.* 2019) offer a partial analogue despite the contrast in climate systems. There, the larger caves that have long flow paths of 100 km or more developed up to 150 m below the low-relief land surface, and the conduit size is directly proportional to the length of the flow path, with deep conduit formation favoured for flow paths with lengths >3 km (Webb & James 2006). The Nullarbor systems are also geologically old, with most of the conduit development having occurred in the Oligocene and only small amounts of speleogenesis since then, during the Pliocene wet period in Australia. The caves of North and North-East Greenland, dissected by later erosion, offer a tantalising glimpse of a large-scale phreatic drainage system that developed beneath the water table and below a coastal peneplain during Neogene time.

The caves of Greenland preserve an important part of the geological history and landscape development of North Greenland that is otherwise absent from the physical geological record. In North Greenland, the youngest pre-glacial sediments that are preserved are the clastic sediments and coals of the Thyra Ø Formation, which is of Paleocene – Middle Eocene age (*c.* 56–41 Ma; Lyck & Stemmerik 2000; Piasecki *et al.* 2018). The caves provide physical evidence of a Cenozoic, probably Miocene, geological history that is otherwise unrecorded, and the study of the loose sediment fills may further elucidate this unrepresented and elusive period in the sedimentary record of North Greenland.

Acknowledgements

The fieldwork for this paper was mainly undertaken as part of the GGU/GEUS regional mapping programme in central North Greenland (1984), Kronprins Christian Land (1994, 1995) and North-East Greenland (1988). Other cave locations have been determined using the oblique aerial photography available in the Greenland Portal (http://maps.greenmin.gl/geusmap/?mapname=greenland_portal&amp). The Polar Geospatial Center, University of Minnesota, is thanked for access to Arctic DEM data, and Lena Friedrich is thanked for assistance with GIS. Work undertaken as part of the Greenland Caves Project (2015, 2019) was funded by the Austrian Science Fund (project no. Y 1162-N37 to Moseley). The Greenland Government is thanked for permission to undertake this fieldwork (KNNO Expedition Permit C-19-32; Scientific Survey Licence VU-00150; Greenland National Museum and Archives 2019/01). We thank the reviewers for detailed and perceptive reviews that significantly improved the manuscript.

Additional information

Funding statement

This work was funded by GEUS (MPS fieldwork 1984–1998), Carlsbergfondet and the Agouron Institute (MPS fieldwork 2009, 2011) and the Austrian Science Fund (Y 1162-N37 to GEM).

Competing interests

The authors declare no competing interests.

Author contributions

MPS: Conceptualisation, Investigation (Equal), Writing – original draft (Lead), Writing – review and editing (Equal).
GEM: Investigation (Equal), Writing – original draft (Supporting), Writing – review and editing (Equal).

Additional files

A supplementary file (S1) is available in the GEUS Bulletin data repository that provides a full record of caves identified in western North Greenland, with additional images of these caves: *https://doi.org/10.22008/FK2/GQGELO*

References

Armstrong, H.A., 1990: Conodonts from the Upper Ordovician–lower Silurian carbonate platform of North Greenland. Bulletin Grønlands Geologiske Undersøgelse **159**, 151 pp. *https://doi.org/10.34194/bullggu.v159.6709*

Bengaard, H.J. & Henriksen, N. 1986: Geological map of Greenland, 1:500 000, Sheet 8, Peary Land. Copenhagen: Geological Survey of Greenland. *https://doi.org/10.22008/FK2/Q7HIDY*

Bennike, O. 1998: Late Cenozoic wood from Washington Land. Geological Survey Bulletin **180**, 155–158. *https://doi.org/10.34194/ggub.v180.5100*

Bennike, O. 2000: Notes on the late Cenozoic history of the Washington Land area, western North Greenland. Geological Survey Bulletin **186**, 29–34. *https://doi.org/10.34194/ggub.v186.5212*

Bennike, O., Knudsen, K.L., Abrahamsen, N., Böcher, J., Cremer, H. & Wagner, B. 2010: Early Pleistocene sediments on Store Koldewey, Northeast Greenland. Boreas **39**, 603–619. *https://doi.org/10.1111/j.1502-3885.2010.00147.x*

Bierman, P.R., Shakun, J.D., Corbett, L.B., Zimmerman, S.R. & Rood, D.H. 2016: A persistent and dynamic East Greenland Ice Sheet over the past 7.5 million years. Nature **540**, 256–260. *https://doi.org/10.1038/nature20147*

Bonow, J.M. & Japsen, P. 2021: Peneplains and tectonics in North-East Greenland after opening of the North-East Atlantic. GEUS Bulletin 45(1), 5297. *https://doi.org/10.34194/geusb.v45.5297*

Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. 2013: The ICS International Chronostratigraphic Chart (updated July 2021). Episodes **36**. 199–204. *http://www.stratigraphy.org/ICSchart/ChronostratChart2021-07.pdf*

Cowie, J.W. & Adams, P.J. 1957: The geology of the Cambro-Ordovician rocks of East Greenland. Meddelelser om Grønland **153**(1), 193 pp.

Davies, W.E. & Krinsley, D.B. 1960: Caves in northern Greenland. National Speleological Society Bulletin **22**, 114–116.

Dawes, P.R., Glendal, E.W. & Holst, J. 2016: A glossary for GEUS publications: Spelling and usage of troublesome words and names made easy. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2016/3**, 74 pp.

DeConto, R., Pollard, D., Wilson, P., Pälike, H., Lear, C.H. & Pagani, M. 2008: Thresholds for Cenozoic bipolar glaciation. Nature **455**, 652–656. *https://doi.org/10.1038/nature07337*

Derby, J.R., Raine, R.J., Smith, M.P. & Runkel, A.C. 2012: Paleogeography of the Great American Carbonate Bank of Laurentia in the earliest Ordovician (early Tremadocian): The Stonehenge transgression. In: Derby, J.R. *et al.* (eds): The Great American Carbonate Bank: The geology and economic resources of the Cambrian–Ordovician Sauk megasequence of Laurentia. AAPG Memoir **98**, 5–13. *https://doi.org/10.1306/13331487m983496*

Eldrett, J.S., Greenwood, D.R., Harding, I.C. & Huber, M. 2009: Increased seasonality through the Eocene to Oligocene transition in northern high latitudes. Nature **459**, 969–973. *https://doi.org/10.1038/nature08069*

Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E. & Roberts, A.P. 2007: Continental ice in Greenland during the Eocene and Oligocene. Nature **446**, 176–179. *https://doi.org/10.1038/nature05591*

Epstein, A.G., Epstein, J.B. & Harris, L.D. 1977: Conodont color alteration – An index to organic meta- morphism. US Geological Survey Professional Paper **995**, 27 pp. *https://doi.org/10.3133/pp995*

Escher, J.C. 2001: Geological map of Greenland, 1:500 000, Sheet 11, Kong Oscar Fjord. Copenhagen: Geological Survey of Denmark and Greenland. *https://doi.org/10.22008/FK2/NKHZZN*

Flesche Kleiven, H., Jansen, E., Fronval, T. & Smith, T.M. 2002: Intensification of Northern Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma) – Ice-rafted detritus evidence. Palaeogeography, Palaeoclimatology, Palaeoecology **184**, 213–223. *https://doi.org/10.1016/s0031-0182(01)00407-2*

Ford, D.C. 1989: Paleokarst of Canada. In: Bosâk, P., Ford, D.C., Glazek, J. & Horâcek, I. (eds): Paleokarst. A Systematic and Regional Review. pp. 313–336. Amsterdam: Elsevier. *https://doi.org/10.1016/b978-0-444-98874-4.50025-2*

Fränkl, E. 1955: Weitere Beiträge zur Geologie von Kronprins Christians Land (NE-Grönland, zwischen 80° und 80°30'N). Meddelelser om Grønland **103**(7), 35 pp.

Frykman, P. 1979: Cambro-Ordovician rocks of C. H. Ostenfeld Nunatak, northern East Greenland. Rapport Grønlands Geologiske Undersøgelse **91**, 125–132. https://doi.org/10.34194/rapggu.v91.7632

Funder, S., Bennike, O., Böcher, J., Israelson, C., Petersen, K.S. & Símonarson, L.A. 2001: Late Pliocene Greenland – The Kap København Formation in North Greenland. Bulletin of the Geological Society of Denmark **48**, 117–134. https://doi.org/10.37570/bgsd-2001-48-06

Golonka, J. & Kiessling, W. 2002: Phanerozoic time scale and definition of time slices. In: Kiessling, W., Flügel, A. & Golonka, J. (eds): Phanerozoic reef patterns. SEPM (Society for Sedimentary Geology) Special Publication **72**, 11–20. *https://doi.org/10.2110/pec.02.72.0011*

Green, P.F., Japsen, P., Chalmers, J.A., Bonow, J.M. & Duddy, I.R. 2018: Post-breakup burial and exhumation of passive continental margins: Seven propositions to inform geodynamic models. Gondwana Research **53**, 58–81. https://doi.org/10.1016/j.gr.2017.03.007

Green, P.F., Lidmar-Bergström, K., Japsen, P., Bonow, J.M. & Chalmers, J.A. 2013: Stratigraphic landscape analysis, thermochronology and the episodic development of elevated passive continental margins. Geological Survey of Denmark and Greenland Bulletin **30**, 150 pp. *https://doi.org/10.34194/geusb.v30.4673*

Hambrey, M.J., Peel, J.S. & Smith, M.P. 1989: Upper Proterozoic and Lower Palaeozoic strata in northern East Greenland. Rapport Grønlands Geologiske Undersøgelse **145**, 103–108. *https://doi.org/10.34194/rapggu.v145.8086*

Harper, D.A.T., Hammarlund, E.U., Topper, T.P., Nielsen, A.T., Rasmussen, J.A., Park, T.-Y.S. & Smith, M.P. 2019: The Sirius Passet Lagerstätte of North Greenland: A remote window on the Cambrian Explosion. Journal of the Geological Society **176**, 1023–1037. *https://doi.org/10.1144/jgs2019-043*

Helland, P.E. & Holmes, M.A. 1997: Surface textural analysis of quartz sand grains from ODP site 918 off the southeast coast of Greenland suggests glaciation of southern Greenland at 11 Ma. Palaeogeography, Palaeoclimatology, Palaeoecology **135**, 109–121. *https://doi.org/10.1016/s0031-0182(97)00025-4*

Henriksen, N. 1989: Geological map of Greenland, 1:500 000, Sheet 7, Nyeboe Land. Copenhagen: Geological Survey of Greenland. *https://doi.org/10.22008/FK2/O16YSF*

Higgins, A.K., Ineson, J.R., Peel, J.S., Surlyk, F. & Sønderholm, M. 1991: The Franklinian Basin in North Greenland. Bulletin Grønlands Geologiske Undersøgelse **160**, 71–139. *https://doi.org/10.34194/bullggu.v160.6714*

Higgins, A.K., Gilotti, J.A. & Smith, M.P. (eds) 2008: The Greenland Caledonides – evolution of the northeast margin of Laurentia. Memoir of the Geological Society of America **202**, xvi + 368 pp. *https://doi.org/10.1130/mem202*

Higgins, A.K., Soper, N.J., Smith, M.P. & Rasmussen, J.A. 2004: The Caledonian thin-skinned thrust belt of Kronprins Christian Land, eastern North Greenland. Geological Survey of Denmark & Greenland Bulletin **6**, 41–56. https://doi.org/10.34194/geusb.v6.4817

Huselbee, M.Y. 1998: Late Cambrian to earliest Ordovician (Ibexian) conodont evolution and biogeography of Greenland and northwest Scotland. 296 pp. PhD thesis, University of Birmingham, UK.

Ineson, J.R. & Peel, J.S. 2011: Geological and depositional setting of the Sirius Passet Lagerstätte (Early Cambrian), North Greenland. Canadian Journal of Earth Sciences **48**, 1259–1281. *https://doi.org/10.1139/e11-018*

Japsen, P., Green, P.F., Bonow, J.M., Bjerager, M. & Hopper, J.R. 2021: Thermo-tectonic development of the Wandel Sea Basin, North Greenland. GEUS Bulletin **45**(1), 5298. *https://doi.org/10.34194/geusb.v45.5298*

Japsen, P., Green, P.F., Bonow, J.M., Nielsen, T.F.D. & Chalmers, J.A. 2014: From volcanic plains to glaciated peaks: Burial and exhumation history of southern East Greenland after opening of the NE Atlantic. Global and Planetary Change **116**, 91–114. *https://doi.org/10.1016/j.gloplacha.2014.01.012*

Jepsen, H.F. 2000: Geological map of Greenland, 1:500 000, Sheet 9, Lambert Land. Copenhagen: Geological Survey of Denmark and Greenland. *https://doi.org/10.22008/FK2/GDCZIS*

Larsen, H.C., Saunders, A.D., Clift, P.D., Beget, J., Wei, W. & Spezzaferri, S. 1994: Seven million years of glaciation in Greenland. Science **264**, 952–955. *https://doi.org/10.1126/science.264.5161.952*

Loubière, J.F. 1987: Observations préliminaires sur les cavités de la région du Lac Centrum. Karstologia **9**, 7–16. *https://doi.org/10.3406/karst.1987.2152*

Loucks, R.G. 2007: A review of coalesced, collapsed-paleocave systems and associated suprastratal deformation. Acta Carsologica **36**, 121–132. *https://doi.org/10.3986/ac.v36i1.214*

Lyck, J.M. & Stemmerik, L. 2000: Palynology and depositional history of the Paleocene? Thyra Ø Formation, Wandel Sea Basin, eastern North Greenland. Geology of Greenland Survey Bulletin **187**, 21–49. *https://doi.org/10.34194/ggub.v187.5193*

Mac Niocaill, C. & Smethurst, M.A. 1994: Palaeozoic palaeogeography of Laurentia and its margins: A reassessment of palaeomagnetic data. Geophysical Journal International **116**, 715–725. *https://doi.org/10.1111/j.1365-246x.1994.tb03292.x*

Miller, K.G., Kominz, M., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N. & Pekar, S.F. 2005: The Phanerozoic record of global sea-level change. Science **310**, 1293–1298. *https://doi.org/10.1126/science.1116412*

Moseley, G. 2016: Report on the findings of the Northeast Greenland Caves Project 2015 expedition to Kronprins Christian Land, Northeast Greenland. 91 pp. Innsbruck: Northeast Greenland Caves Project.

Moseley, G.E. *et al.* 2020: Cave discoveries and speleogenetic features in northeast Greenland. Cave and Karst Science **47**, 74–87.

Moseley, G.E., Edwards, R.L., Lord, N.S., Spötl, C. & Cheng, H. 2021: Speleothem record of mild and wet mid-Pleistocene climate in northeast Greenland. Science Advances **7**(13), eabe1260. *https://doi.org/10.1126/sciadv.abe1260*

Palmer, A.N. & Palmer, M.V. 2011: Paleokarst of the USA: A brief review. U.S. Geological Survey Scientific Investigations Report **2011-5031**, 7–16.

Palmer, A.R. 1981: Subdivision of the Sauk sequence. In: Taylor, M.E. (ed): Short Papers for the Second International Symposium on the Cambrian System. U.S. Geological Survey Open-File Report **81-743**, 160–162.

Palmer, M.V. & Palmer, A.N. 1989: Paleokarst of the United States. In: Bosâk, P., Ford, D.C., Glazek, J. & Horâcek, I. (eds): Paleokarst. A systematic and regional review. pp. 337–363. Amsterdam: Elsevier.

Pedersen, V.K., Larsen, N.K. & Egholm, D.L. 2019: The timing of fjord formation and early glaciations in North and Northeast Greenland. Geology **47**, 682–686. *https://doi.org/10.1130/g46064.1*

Peel, J.S. & Smith, M.P. 1988: The Wandel Valley Formation (Early–Middle Ordovician) of North Greenland and its correlatives. Rapport Grønlands Geologiske Undersøgelse **137**, 61–92. *https://doi.org/10.34194/rapggu.v137.8016*

Piasecki, S., Nøhr-Hansen, H. & Dalhoff, F. 2018: Revised stratigraphy of Kap Rigsdagen beds, Wandel Sea Basin, North Greenland. Newsletters on Stratigraphy **51**, 411–425. *https://doi.org/10.1127/nos/2018/0444*

Peters, S.E. & Gaines, R.R. 2012: Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion. Nature **484**, 363–366. *https://doi.org/10.1038/nature10969*

Porter, C. *et al.* 2018: ArcticDEM. Harvard Dataverse, V1. *https://doi.org/10.7910/DVN/OHHUKH*

Raine, R.J. & Smith, M.P. 2012: Sequence stratigraphy of the Scottish Laurentian margin and the recognition of the Sauk megasequences in the Scotland–Greenland sector. In: Derby, J.R. *et al.* (eds): The Great American Carbonate Bank: The geology and economic resources of the Cambrian–Ordovician Sauk megasequence of Laurentia. AAPG Memoir **98**, 575–596. *https://doi.org/10.1306/13331508m983507*

Rasmussen, J.A. & Smith, M.P. 2001: Conodont geothermometry and tectonic overburden in the northernmost East Greenland Caledonides. *Geological Magazine* **138**, 687–698. *https://doi.org/10.1017/s0016756801005908*

Sloss, L.L., 1963: Sequences in the cratonic interior of North America. Geological Society of America Bulletin **74**, 93–114.

Smith, M.P., 1985: Ibexian–Whiterockian (Ordovician) conodont palaeontology of East and eastern North Greenland, 372 pp. PhD thesis, University of Nottingham, UK.

Smith, M.P., 1991: Early Ordovician conodonts of East and North Greenland. Meddelelser om Grønland Geoscience **26**, 81 pp.

Smith, M.P. 2000: Cambro-Ordovician stratigraphy of Bjørnøya and North Greenland: Constraints on tectonic models for the Arctic Caledonides and the Tertiary opening of the Greenland Sea. Journal of the Geological Society of London **157**, 459–470. *https://doi.org/10.1144/jgs.157.2.459*

Smith, M.P. & Bjerreskov, M. 1994: The Ordovician System in Greenland. Correlation chart and stratigraphic lexicon. International Union of Geological Sciences Special Publication **29A**, 46 pp.

Smith, M.P. & Rasmussen, J.A. 2008: Cambrian–Silurian development of the Iapetus Ocean margin in Greenland and related areas. In:

Higgins, A.K., Gilotti, J.A. & Smith, M.P. (eds): The Greenland Caledonides – Evolution of the northeast margin of Laurentia. Memoir of the Geological Society of America, **202**, 137–167. *https://doi.org/10.1130/2008.1202(06)*

Smith, M.P. & Rasmussen, J.A. 2020: The geology of the Centrumsø area of Kronprins Christian Land, northeast Greenland, and lithological constraints on speleogenesis. Cave and Karst Science **47**, 60–65.

Smith, M.P., Rasmussen, J.A., Higgins, A.K. & Leslie, A.G. 2004: Lower Palaeozoic stratigraphy of the East Greenland Caledonides. Geological Survey of Denmark & Greenland Bulletin **6**, 5–28. *https://doi.org/10.34194/geusb.v6.4815*

Smith, M.P., Sønderholm, M. & Tull, S.J. 1989: The Morris Bugt Group (Middle Ordovician–Silurian) of North Greenland and its correlatives. Rapport Grønlands Geologiske Undersøgelse **143**, 5–20. *https://doi.org/10.34194/rapggu.v143.8055*

Smith, M.P., Soper, N.J., Higgins, A.K., Rasmussen, J.A. & Craig, L.E. 1999: Palaeokarst systems in the Neoproterozoic of eastern North Greenland in relation to extensional tectonics on the Laurentian margin. Journal of the Geological Society of London **156**, 113–124. *https://doi.org/10.1144/gsjgs.156.1.0113*

Solgaard, A.M., Bonow, J.M., Langen, P., Japsen, P. & Hvidberg, C. 2013: Mountain building and the initiation of the Greenland ice sheet. Palaeogeography Palaeoclimatology Palaeoecology **392**, 161–176. *https://doi.org/10.1016/j.palaeo.2013.09.019*

Sønderholm, M., Harland, T.L., Due, P.H., Jørgensen, L.N. & Peel, J.S. 1987: Lithostratigraphy and depositional history of Upper Ordovician–Silurian shelf carbonates in central and western North Greenland. Rapport Grønlands Geologiske Undersøgelse **133**, 27–40. *https://doi.org/10.34194/rapggu.v133.7973*

Studinger, M. 2011: *https://michaelstudinger.smugmug.com/Greenland-2011/i-JRmSrZm*.

Swett, K., 1981: Cambro-Ordovician strata in Ny Friesland, Spitsbergen and their palaeotectonic significance. Geological Magazine **118**, 225–250. *https://doi.org/10.1017/s001675680003572x*

Swett, K. & Smit, D.E. 1972: Paleogeography and depositional environments of the Cambro-Ordovician shallow marine facies of the North Atlantic. Geological Society of America Bulletin **83**, 3223–3248. *https://doi.org/10.1130/0016-7606(1972)83[3223:padeot]2.0.co;2*

Trettin, H.P. (ed.). 1991: Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland. Geology of Canada **3**. 569 pp. Ottawa: Geological Survey of Canada. *https://doi.org/10.1130/dnag-gna-e*

Tull, S.J. 1988: Conodont micropalaeontology of the Morris Bugt Group (Middle Ordovician–Early Silurian). 366 pp. PhD thesis, University of Nottingham, UK.

Webb, J.A. & James, J.M. 2006: Karst evolution of the Nullarbor Plain, Australia. In: Harmon, R.S. & Wicks, C. (eds): Perspectives on karst geomorphology, hydrology, and geochemistry – A tribute volume to Derek C. Ford and William B. White. Geological Society of America Special Paper **404**, 65–78. *https://doi.org/10.1130/2006.2404(07)*

Willman, S., Peel, J.S., Ineson, J.R., Schovsbo, N.H., Rugen, E.J. & Frei, R. 2020: Ediacaran Doushantuo-type biota discovered in Laurentia. Communications Biology **3**, 647. *https://doi.org/10.1038/s42003-020-01381-7*

Woodhead, J.D., Sniderman, J.M.K., Hellstrom, J., Drysdale, R.N., Maas, R., White, N., White, S. & Devine, P. 2019: The antiquity of Nullarbor speleothems and implications for karst palaeoclimate archives. Scientific Reports **9**, 603. *https://doi.org/10.1038/s41598-018-37097-2*