



Middle Jurassic sandstone deposition in the Wandel Sea Basin: evidence from cardioceratid and kosmoceratid ammonites in the Mågensfjeld Formation in Kilen, North Greenland

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Abstract

Age assessments from both palynostratigraphy and macrofossil biostratigraphy of the sandstone-dominated Mågensfjeld Formation, Wandel Sea Basin, North Greenland were hitherto hampered by post-burial thermal degradation of dinoflagellate cysts and a lack of well-preserved macrofossils. The formation was previously assigned to the Upper Cretaceous based on erroneous fossil identifications. Finds of cardioceratid and kosmoceratid ammonites during recent field work now provide the first age control of the unit, demonstrating it to be of late Bajocian – late Bathonian and perhaps Callovian (Middle Jurassic) age. This makes it among the oldest Jurassic units, perhaps even Mesozoic units, recorded in Kilen, North Greenland and eastern North Greenland. Previously, the complex structural and tectonic evolution of the area was poorly understood, and the structural relation of the Mågensfjeld Formation to the surrounding Mesozoic units was a puzzle. The new age assessment simplifies the structural situation in the area significantly. Further, the inference of a large reverse fault previously required to explain the proximity of the Mågensfjeld Formation to neighbouring Jurassic units is now unnecessary. The data show that the Wandel Sea Basin was influenced by the Middle Jurassic transgression and had sufficient accommodation space for marine deposition earlier than previously thought. The unit serves as a key datapoint and analogue for possible Middle Jurassic units in adjacent offshore basins.

1 Introduction

The first ever fossils reported from Kilen in eastern North Greenland (Fig. 1) were collected by the Greenarctic Consortium and included the ammonite *Cranocephalites vulgaris*, Spath and various bivalves (Dawes 1976; Dawes & Peel 1981). The fossils indicated the presence of a Middle Jurassic succession, but their exact location was not known. At this time, the geology of Kilen had been interpreted solely from aerial photos as Proterozoic–Palaeozoic strata deformed during the Caledonian orogeny (Haller 1970). Hence, the discovery of Mesozoic fossils prompted the need for further field observations in this remote and inaccessible area. During pioneering expeditions in 1980, 1985 and 1998, E. Håkansson and co-workers collected lithological,

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Received: 26 June 2020

Accepted: 17 Sept 2020

Published: 21 Dec 2020

Keywords: ammonite stratigraphy, Middle Jurassic, North Greenland, sandstone deposition, Wandel Sea Basin

Abbreviations:

NHMD: Natural History Museum of Denmark

MGUH: Museum Geologica Universitas Hafniensis/Geological Museum type collection (Copenhagen, Denmark)

FA: facies association

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Edited by: Sofie Lindström (GEUS, Denmark)

Reviewed by: Mikhail Rogov (Geological Institute of RAS, Russia) and one anonymous reviewer.

Funding: See page 15

Author contributions: See page 16

Competing interests: See page 16

Additional files: None provided

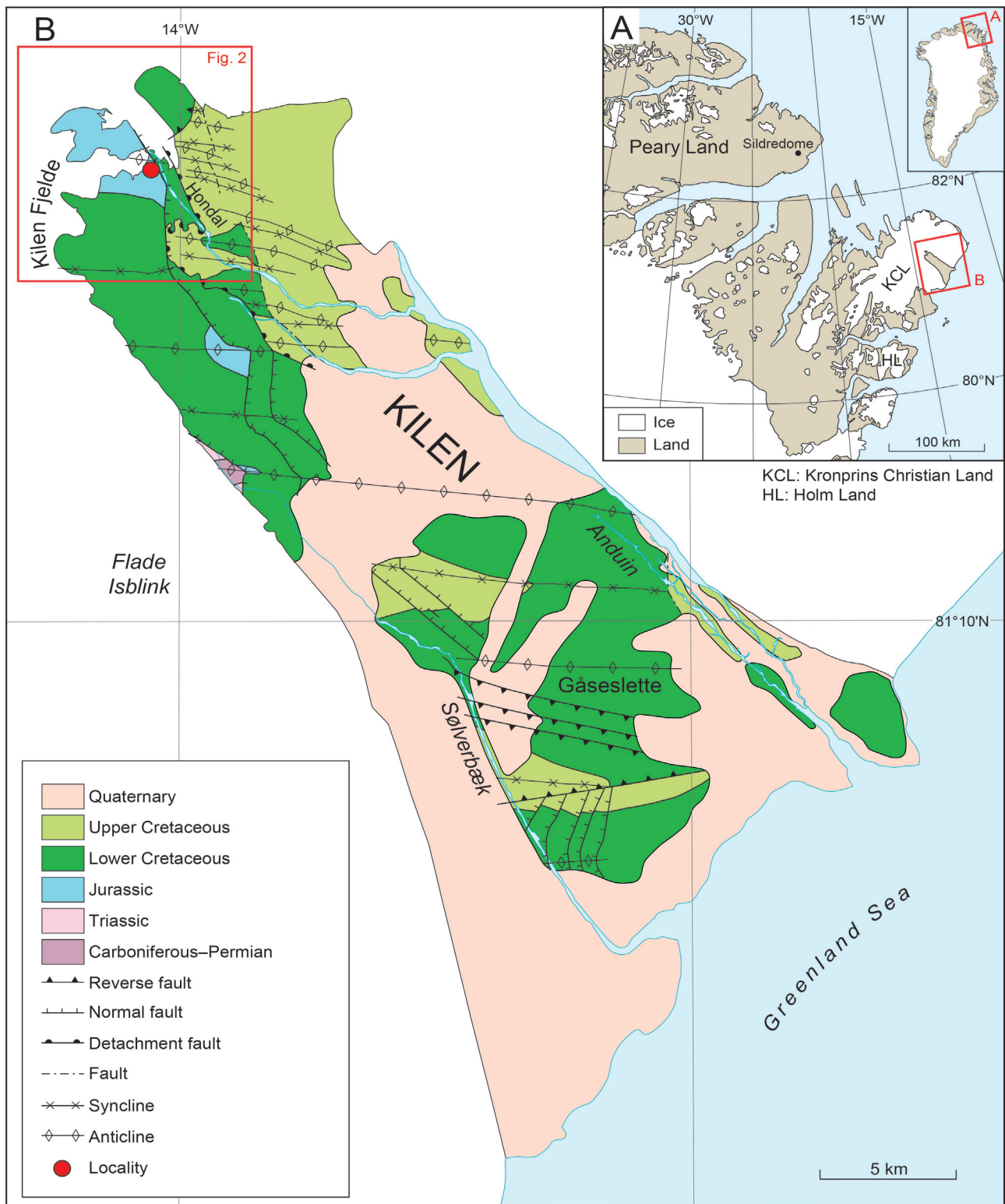


Fig. 1 Simplified geological map of Kilen in the Wandel Sea Basin. **A:** The Wandel Sea Basin is a post-Caledonian fault-bounded Carboniferous–Lower Palaeogene sedimentary basin in eastern North Greenland (Dawes & Soper 1973; Håkansson & Stemmerik 1989; Stemmerik *et al.* 1998). It covers the geographical areas of Holm Land (**HL**), Kronprins Christian Land (**KCL**) and eastern Peary Land. **B:** The location of the Mågensfjeld Formation outcrop locality and the area covered by Fig. 2 are shown. Modified from Svennevig *et al.* (2016).

sedimentological and biostratigraphic data in Kilen. They described an essentially Upper Jurassic – Upper Cretaceous succession (Håkansson *et al.* 1981b, 1991, 1993; Pedersen 1991; Dypvik *et al.* 2002), whereas the

“Middle Jurassic” ammonites reported by Dawes (1976) were identified as mid-Cretaceous (Albian) *Anahoplites* cf. *daviesi ornata*, Spath and a gastropplitinid (Birkelund & Håkansson 1983).

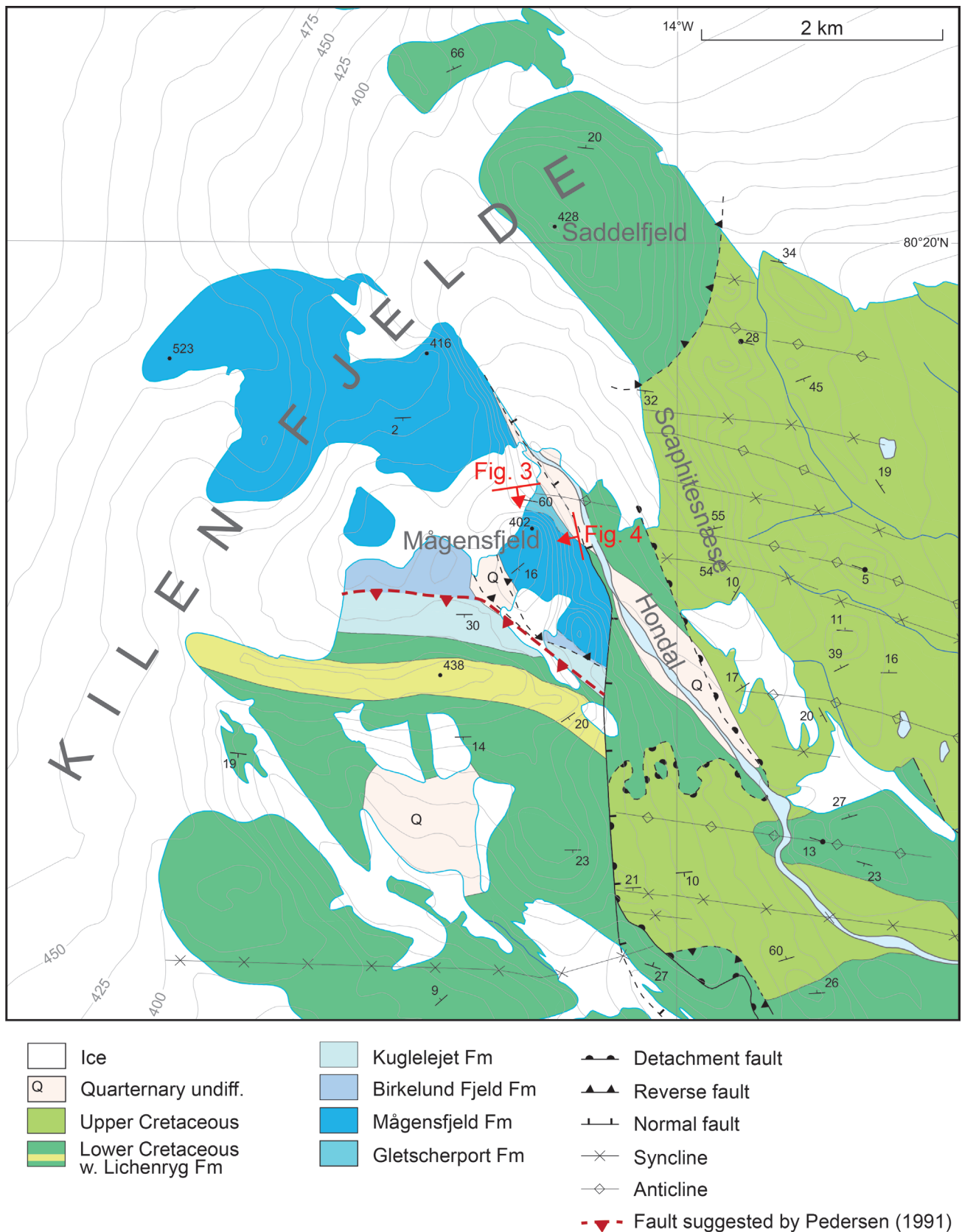


Fig. 2 Detailed geological map of northern Kilen Fjelde. The geological situation around the Mågensfjeld Formation outcrop and the position of Figs 3 and 4 are shown. The latter indicates the location of the Mågensfjeld type section, which was logged, and where ammonites were collected. The now redundant reverse fault suggested by Pedersen (1991) and Håkansson *et al.* (1993) is indicated by a red dashed line. Modified from Svennevig (2018).

During a recent field campaign in North Greenland, new data were retrieved from Kilen. This area is key for studying the Jurassic–Cretaceous of North Greenland and its relation to the conjugate Barents Margin, both lithologically and structurally. In 2012 and 2013, field teams sampled and logged all the sedimentary units described by Håkansson *et al.* (1981, 1991, 1993). The objective of the recent campaign was to refine the biostratigraphy and establish a formal lithostratigraphic framework for an improved understanding of the depositional evolution of the succession (Bojesen-Koefoed *et al.* 2014; Svennevig *et al.* 2016; Alsen *et al.* 2017; Hovikoski *et al.* 2018). Several Cretaceous intervals and units were poorly dated or not dated at all. The succession has been subject to significant thermal influence, which has removed organic palynomorphs hampering the use of dinoflagellate cysts stratigraphy (Håkansson & Pedersen 2001; Svennevig *et al.* 2017; Pedersen *et al.* 2018). Macrofossils are absent or scarce and poorly preserved in several units. Only a few intervals and units have published biostratigraphic ages (Birkelund & Håkansson 1983), whereas more detailed biostratigraphy were presented in unpublished reports (Håkansson 1994; Håkansson *et al.* 1994).

Parallel to the biostratigraphic and lithostratigraphic work, the structural geology of Kilen was revised based on mapping from oblique photogrammetry and field work (Svennevig *et al.* 2015). A new structural model for Kilen was published, in which it was shown that Late Cretaceous extension caused normal faulting followed by Eureka compression, which gave rise to folding and thrusting (Svennevig *et al.* 2016, 2017, 2018).

A thick sandstone succession in northwesternmost Kilen Fjelde (the northern part of Kilen) is informally referred to as Unit 7 by Håkansson *et al.* (1993) and forms the best exposed sediment succession in Kilen. The steep, vertical outcrops in cliffs with nesting ivory gulls gave the unit its name: Mågensfjeld Formation (Fig. 2). In Danish, Mågensfjeld refers to “mountain of the seagull.” Pioneer geologists working in the region used the name “Fuglefjeld” (Danish for bird cliff). The age of the unit was considered Coniacian (Late Cretaceous) due to the identification of inoceramid bivalves at the base of the section, and common imprints after belemnites and allegedly Late Cretaceous baculitid ammonites (Håkansson *et al.* 1994). A Late Cretaceous age of the Mågensfjeld Formation significantly added to the structural complexity of Kilen Fjelde, and a large reverse fault was introduced to explain its proximity to Upper Jurassic units (Pedersen 1991; Håkansson *et al.* 1993).

In this paper, we report new finds of fossils from Mågensfjeld in Kilen, collected in 2013, which demonstrate a Middle Jurassic age of the Mågensfjeld Formation. The dating of the unit has significant importance for the understanding of the structural geology of the area.

2 Geological setting

Kilen forms part of the Wandel Sea Basin in North Greenland. It is a fault-bound basin containing a Carboniferous – lower Palaeogene sedimentary succession (Dawes & Soper 1973; Håkansson & Stemmerik 1989; Stemmerik *et al.* 1998). The succession in Kilen is Triassic – Upper Cretaceous (Håkansson *et al.* 1993; Alsen *et al.* 2017; Hovikoski *et al.* 2018). The area was deformed by several structural events, namely latest Cretaceous extensional faulting followed by compression of presumably Paleocene age. It has been divided into two major thrust sheets, which contain numerous smaller fault-bound structural units (Svennevig *et al.* 2016, 2018). As a result, strata are folded and lithostratigraphic units are commonly fault bound (Svennevig *et al.* 2016; Hovikoski *et al.* 2018).

3 Locality

The Mågensfjeld Formation is exposed in the innermost, north-western part of the ice-bounded semi-nunatak Kilen, surrounded by the ice cap Flade Isblink. The type section is situated at the steep north-east-slope of Mågensfjeld in the uppermost reaches of the Hondal valley (Figs 1–4; Hovikoski *et al.* 2018; Svennevig 2018).

4 Materials and methods

4.1 3D mapping of Mågensfjeld

The structural mapping of the Mågensfjeld area builds on the geological map of Kilen (Svennevig 2018), which was mapped mainly by oblique photogrammetry (Svennevig *et al.* 2015). Oblique photographs were taken by a handheld digital camera from a helicopter, and triangulated and georeferenced, so that visible geological features such as bedding and faults could be mapped as 3D polylines. The polylines were used to calculate strike and dip of bedding and faults. These parameters were imported into a 3D modelling software along with the 3D polylines, an unpublished digitised field map (Pedersen 1991), a digital

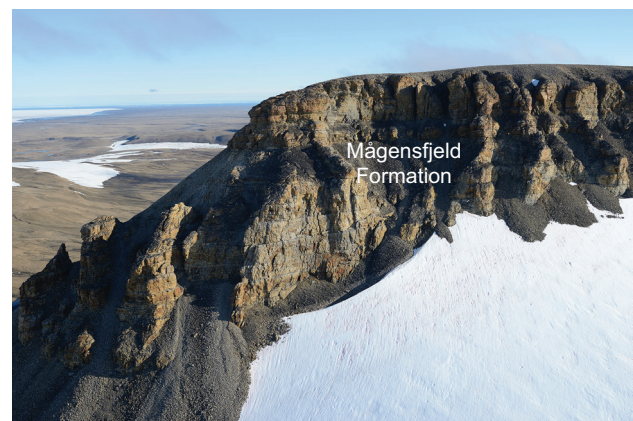


Fig. 3 View from helicopter of the Mågensfjeld Formation at the “bird cliff,” Mågensfjeld, looking south.

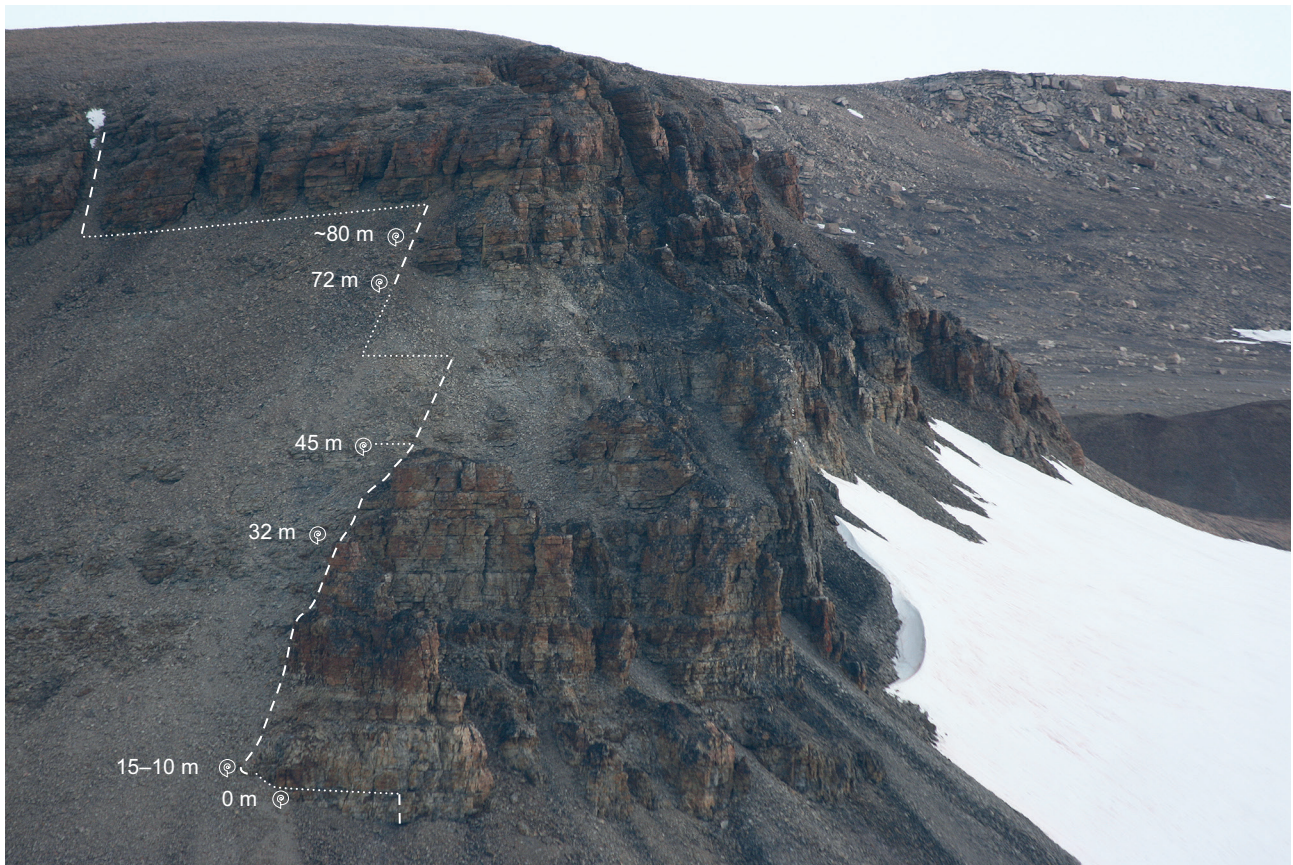


Fig. 4 View towards the west, showing the Mågensfjeld Formation type section at Mågensfjeld. This is perpendicular to the view shown in Fig. 3. Dashed line indicates the logged section (JHOV-5/2013). Ammonite-yielding levels are indicated.

elevation model and an orthophoto and georeferenced field observations. In the 3D modelling software, robust geological models (3D maps) were built and used for structural validation and to produce 2D maps and cross sections.

4.2 Ammonites

We were granted access to the ammonite collection established by the pioneer geologists working in the area. One sample from “Fuglefjeld” (now Mågensfjeld) was labelled “dissolved *Baculites* in sandstone” (the original label is in Danish), which is probably the reason for assigning the sample and the sandstone unit to the Upper Cretaceous (Coniacian). However, detailed inspection of the deeper part of the imprint of the dissolved supposed baculitid fossil shows the presence of a cone-shaped mould, which is clearly the filling of a belemnite alveolus. It adds to our own field observations that belemnites are common in the Mågensfjeld Formation, particularly in the lower part of the section. The report of Late Cretaceous inoceramids is also erroneous, as the inoceramid bivalves, which are relatively common, belong to the genus *Ret-roceramus*. Hence, there are no indications of Upper Cretaceous.

Our own collection contains 35 ammonite specimens collected in 2013 from the type section of the Mågensfjeld Formation. Some samples were found loose in the scree below the outcrop; other specimens were found *in situ* at various levels throughout the measured section (Figs 4 and 5). Most specimens are poorly preserved, broken and fragmented. The sandstone in which they are contained has undergone significant alteration through diagenesis with extensive quartz cementation. Fossils are commonly partly dissolved. The fossil material, however, contains readily identifiable specimens, which we have compared to the Jurassic ammonite reference collection curated by J.H. Callomon between 1960 and 2010 (Callomon 1961, 1985, 1993; Callomon *et al.* 2015). The reference collection is housed at the Geological Museum, Copenhagen, now part of the Natural History Museum of Denmark (NHMD). Specimens represent Middle Jurassic ammonites of the cardioceratid genera *Cranocephalites*, *Arctocephalites*, *Arc-tioceras*, *Cadoceras* and of the kosmocerotid genus *Kep-plerites*. Selected ammonite specimens from Mågensfjeld Formation in Kilen are shown in Figs 6 and 7.

5 Palaeontology

Our field work resulted in the discovery of numerous ammonites *in situ* in a number of levels throughout the

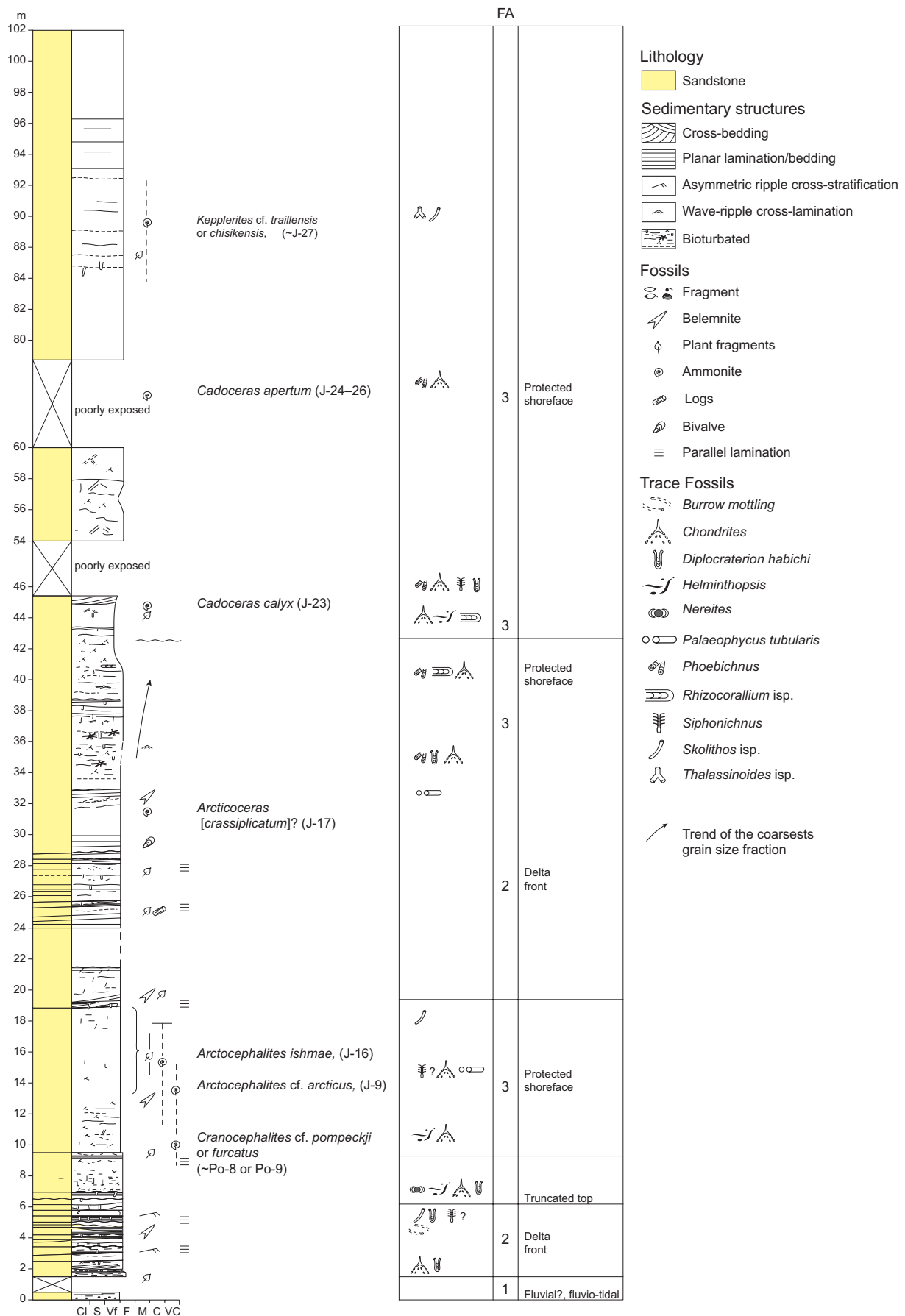


Fig. 5 Measured sedimentological log of the type section of the Mågensfjeld Formation (JHOV-5/2013). **FA**: facies association; **Po-8**, **Po-9**, **J-9** to **J-27**: Faunal horizons for North-East Greenland (see Fig. 8); **Po**: Pompeckji; **J**: Jameson Land. Modified from Hovikoski et al. (2018, fig. 8B).



Fig. 6 Selected cardioceratid ammonites from the Mågensfjeld Formation. **A–F**: *Cranocephalites* sp. cf. *pompeckji* or *furcatus* MGUH 33462–33467 (all from GEUS 545584). **G, g**: Side and ventral views, respectively, of *Arctocephalites* sp. *delicatus* or *arcticus* MGUH 33468 (from GEUS 545586). **H**: *Arctioceras ishmae*, MGUH 33469 (from GEUS 545569). **I, i** and **J, j**: Side and ventral views of two specimens of *Arctioceras* spp. MGUH 33470 and 33471, respectively (from GEUS 545568).

c. 100-m thick measured section at Mågensfjeld (Fig. 5; chosen as the type section, see Hovikoski *et al.* 2018, Fig. 8B).

Figured specimens are assigned official numbers from the Geological Museum type collection (MGUH), Copenhagen, Denmark. These specimens are held in the NHMD repository. The remaining collections are housed at the Geological Survey of Denmark and Greenland (GEUS) and are assigned samples codes with the prefix “GEUS.” In the following section, the following abbreviations apply: s.s:

sensu stricto; MS: *manuscriptum*; spp. indet: *species pluri-mae indeterminata*; sp. aff.: *species affinis*; cf.: *confer*.

5.1 Systematic taxonomy

Family *Cardioceratidae* Siemiradzki 1891

Genus *Cranocephalites* Spath 1932

Cranocephalites cf. *pompeckji* (Madsen 1902) or *C. furcatus* Spath 1932

Figs 6A–F

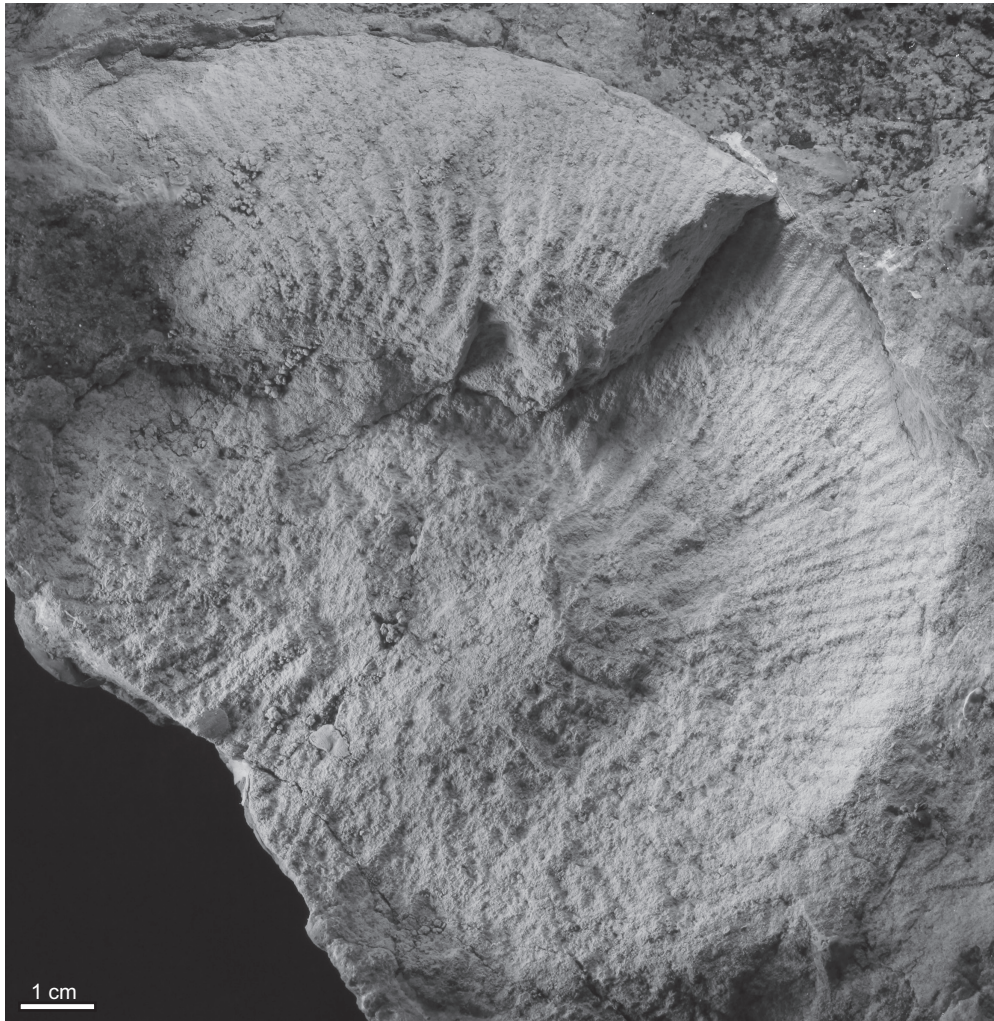


Fig. 7 *Keplerites* cf. *traillensis* or *chisikensis* from Mågensfjeld Formation, MGUH 33472 (from GEUS 545591).

Material and horizon. 15 specimens (11 body fossil fragments, 4 imprints) illustrated specimens include MGUH 33462–33467 (from GEUS 545584) found laterally at c. 10 m height in the measured section (JHOV-5/2013; Figs 4 and 5).

Description. Assemblage of relatively involute to moderately involute forms. Ribbing fairly dense with strong primaries that divide into two or three secondaries at approximately mid flank. Occasional intercalatories. In late stages, ribbing becomes coarser and blunt and fades on the venter. Larger specimens tend to develop an inflated body chamber, typical of *Cranocephalites*. The reference to the group of *C. pompeckji* and *furcatus* rests on the tendency towards relatively flattened sides, and general resemblance of the size, ribbing and coiling compared with specimens in the reference collection.

Occurrence and stratigraphy. The group of *C. pompeckji* and *furcatus* is common fossils in central East and North-East Greenland, in particular on Jameson Land (Callomon 1993; Callomon *et al.* 2015) and on Traill Ø. The group represents the lower faunal horizons

Po-8 and Po-9 of the *C. pompeckji* Zone (Fig. 8; Donovan 1953, 1957; Alsen 2000; Vosgerau *et al.* 2004). *C. pompeckji* and *furcatus* are also reported in Siberia (Voronets 1962; Meledina 1973), Novaya Zemlya, northern Russia (Cherkesov & Burdykina 1979) and Alaska (Imlay 1962).

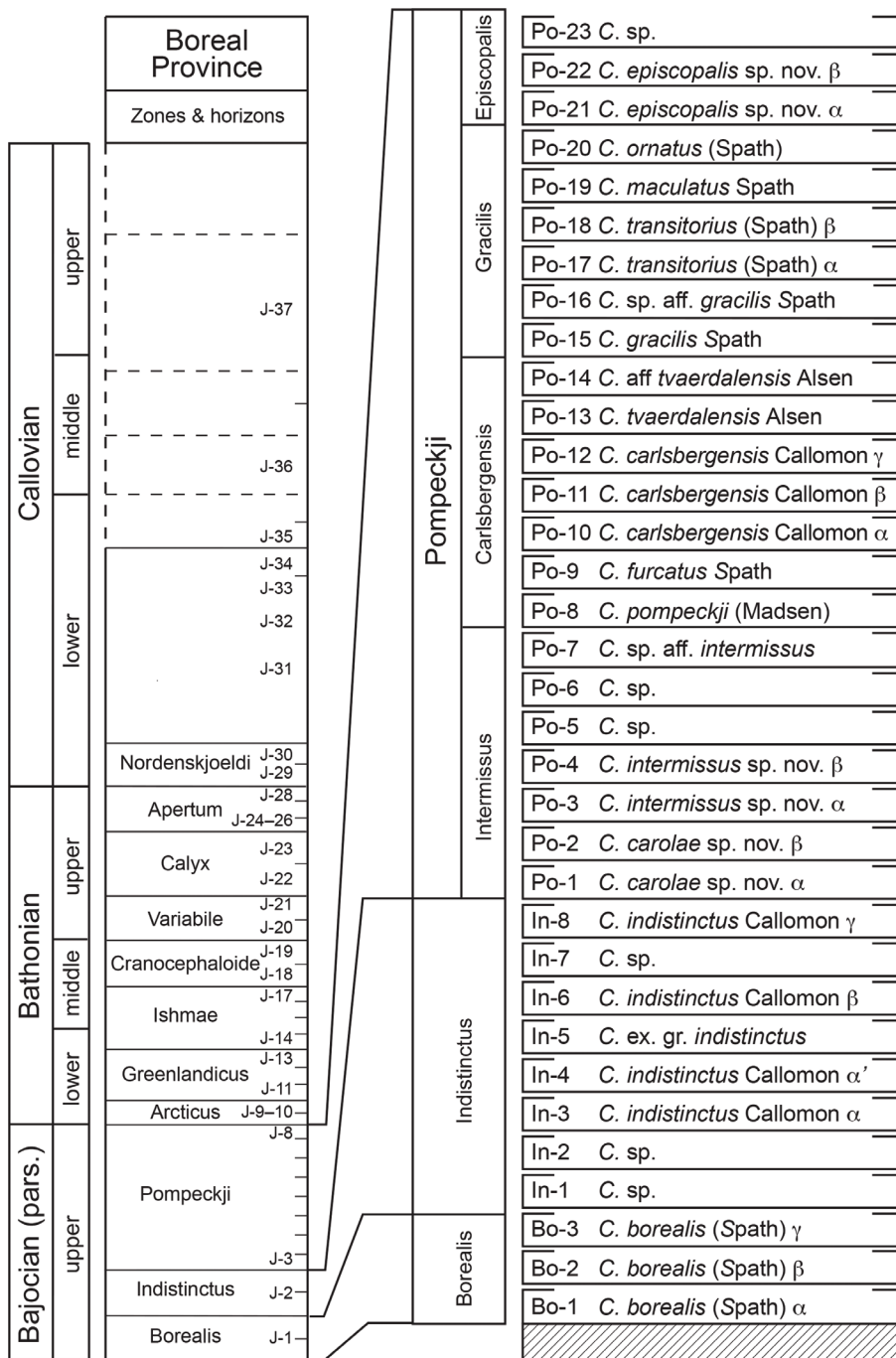
Remarks. Specimens of *C. pompeckji* Zone ammonites were found loose (*ex situ*) in Kilen and on Peary Land (Nygaard 2003).

Genus *Arctocephalites* Spath 1928
***Arctocephalites* cf. *arcticus* (Newton 1897)**

Figs 6G and g

Material and horizon. One specimen, MGUH 33468 (from GEUS 545586), found loose in scree in the lower part of the section JHOV-5/2013 (Fig. 4).

Description. A medium-sized specimen with rounded inflated whorls. It is crushed and the umbilicus is not visible, but it is clearly an involute form and the umbilicus must have been minute. It resembles mature forms



C.: *Cranocephalites* Spath 1932

Fig. 8 Middle Jurassic ammonite zonal scheme from North-East Greenland. **J-1-37**: succession of ammonite faunal horizons recorded on Jameson Land by Callomon (1993). The faunal horizons of the *C. borealis* – *C. pompeckji* zones (J-1-8) were subsequently revised into the Bo-1-Po-23 faunal horizons shown in the expanded column to the right (Callomon *et al.* 2015). J: Jameson Land; **Bo 1-3**: faunal horizons in the Borealis Zone; **In 1-8**: faunal horizons in the Indistinctus Zone; **Po-1-23**: faunal horizons in the Pompeckji Zone.

of the oldest *Cranocephalites*. However, upon comparison with the reference collection, it shows great resemblance with variants of *Arctocephalites arcticus*, which occur stratigraphically higher than the *Cranocephalites* of the *C. pompeckji* Zone found below (GEUS 545584, see previous description of *C. cf. pompeckji* or *furcatus*).

Occurrence. The specimen indicates faunal horizon J-9 of the lowermost Bathonian *A. arcticus* Zone (Callomon 1993; Callomon *et al.* 2015; Fig. 8). The species *A. arcticus* occurs in high latitudes in Franz Josef Land, northernmost Russia (Newton & Teall 1897; Whitfield 1906), Yukon, Canada (Poulton 1987), Sverdrup Basin, Arctic Canada

(Friebold 1964), Siberia (Meledina 1973) and Pechora, Russia (Mitta 2009). *A. arcticus* is also found further south in the northern North Sea (Callomon 1975).

Genus *Arcticoceras* Spath 1924

Arcticoceras ishmae (Keyserling 1846)

Fig. 6H

Material and horizon. One specimen, MGUH 33469 (from GEUS 545569), found *in situ* laterally of section JHOV-5/2013, approximately level with the 10-15 m interval in the measured section (Figs 4 and 5). We obtained a mould of the relatively well-preserved left side of the specimen.

Description. Medium-sized with little umbilicus, dense strong regular ribbing curving gently forward from the umbilical seam to the venter. Primaries bifurcate into secondaries at the mid-flank.

Occurrence. The taxon is the index species of the *A. ishmae* Zone and indicates the faunal horizon J-16 in North-East Greenland. *A. ishmae* is common from Jameson Land to the island of Store Koldewey, 500 km south of Kilen (Callomon 1993; Callomon *et al.* 2015; Fig. 8). *A. ishmae* is recognised widely throughout the Boreal from Yukon, Canada (Poulton 1987), northern Russia (e.g. Sokolov 1912; Meledina 1987; Mitta *et al.* 2015), Novaya Zemlya and northern Siberia (Meledina 1973), central Russia (Mitta *et al.* 2011) and the northern North Sea (Callomon 1975).

Remarks. Callomon (1993) distinguished between two slightly different forms, transients α and β , of *A. ishmae* – the latter being *A. ishmae* s.s. Together with the species *A. harlandi* Rawson, which occurs in Svalbard, northernmost Norway (Rawson 1982; Ershova 1983), they represent faunal horizons J-14–16 in East Greenland. Based on material from a condensed section on the Russian Platform, those three taxa were suggested to be synonymous and to represent the intraspecific variation of one single variable species (Kiselev 2020a, 2020b). This is not proven for the succession in Greenland, and in this work, we follow Callomon (1993).

***Arcticoceras* [*crassiplicatum* MS] Callomon?**

Material and horizon. Imprint of one specimen at 32 m in section JHOV-5/2013 (Figs 4 and 5). The imprint could not be collected from the section, so a rubber cast (GEUS 545588) was made.

Description. The imprint represents only a fragment of the side view of *c.* 1/5 of a whorl from a rather large form. The fragment is densely and fairly strongly ribbed on a broadly rounded whorl side. After comparison with specimens in the reference collection, it is tentatively referred to *A. [crassiplicatum MS]*, a species, introduced by Callomon (1993), that has neither been described nor figured and type specimens have not been chosen (see Remarks).

Occurrence. *A. [crassiplicatum MS]* occurs in the faunal horizon J-17 in the top of the *A. ishmae* zone, middle Bathonian (Callomon 1993; Callomon *et al.* 2015; Fig. 8).

Remarks. The taxon *A. [crassiplicatum MS]* is one of a series of undescribed and unfigured MS taxa introduced by Callomon (1993). He intended to properly establish them with formal descriptions later, along with detailed accounts of their levels in the East Greenland faunal succession.

Callomon succeeded with respect to formalising the *Cranocephalites* taxa posthumously (Callomon *et al.* 2015). Several other MS-taxa unfortunately remain undescribed, but are meticulously curated in the NHMD reference collection. They have been widely integrated in the literature; for example, *A. [delicatus MS]* is a marker fossil of a key surface in the biostratigraphic framework for sequence stratigraphic analysis in Engkilde & Surlyk (2003).

***Arcticoceras?* spp. indet.**

Figs 6l, i, j and j

Material and horizon. Three specimens (all from GEUS 545568), *ex situ*, found in the scree slope (*c.* 25 m below section JHOV-5/2013) below the steep outcrops of Mågensfjeld Formation (Fig. 4). Illustrated specimens include MGUH 33470–33471.

Description. Specimens with projected, somewhat coarser ribbing than *A. ishmae* but less coarse than *A. [crassiplicatum]* and less involute than *A. ishmae*. Ribbing fades or disappears fully, and the venter becomes smooth. Specimens have been crushed, resulting in a distorted shape, but they appear to have been relatively flat or discoidal compared with *A. ishmae*. Tentatively referred to *Arcticoceras*.

Genus *Cadoceras* Fischer 1882

***Cadoceras* cf. *calyx* Spath 1932**

Material and horizon. One specimen, GEUS 545589, found at 45 m in section JHOV-5/2013 (Figs 4 and 5). It is a fragmented, poorly preserved imprint.

Description. The fragment represents part of a relatively large shell with a relatively open umbilicus. Ribbing developed from forward curving bullae. Coarse to very coarse distant ribs on a rounded flank, which appear to be from a rounded, close to spherical whorl. Ornamentation fades and the venter appears smooth. Resembles the typical spherical forms of *C. calyx*. The preservation leaves some uncertainty, hence the cf.

Occurrence. Index species of the *C. calyx* Zone and occurring in faunal horizon J-23 in North-East Greenland (Callomon 1993; Callomon *et al.* 2015; Fig. 8). Kopik & Wierzbowski (1988) recorded *C. cf. victor* from assemblage with both *C. calyx* and *C. apertum* Zones ammonites in an ironstone layer in the Janusfjellet Formation on Svalbard, Norway. *Cadoceras victor* was subsequently considered synonymous with *C. calyx* by Callomon (1993). *C. calyx* was reported from east Siberia by Knyazev *et al.* (2009) and the Russia Platform (Mitta 2005; Kiselev & Rogov 2007).

***Cadoceras apertum* Callomon & Birkelund 1985**

Material and horizon. One specimen, GEUS 545590, found at 72 m in a poorly exposed part of the section JHOV-5/2013 (Figs 4 and 5). Fragment.

Description. The fragment is c. 1/5 of a whorl. Only the upper part of one side of the whorl and the venter are preserved. It is totally smooth. The venter is relatively narrow and arched. It does not resemble the thick-whorled holotype of *C. apertum*, but the reference collection includes smooth macroconch variants with slender, narrowly rounded venter.

Occurrence. Index of the *C. apertum* Zone in East Greenland, faunal horizon J-24–26 (Callomon 1993; Callomon *et al.* 2015; Fig. 8). Outside Greenland, the taxon occurs in the Janusfjellet Formation, Svalbard (Kopik & Wierzbowski 1988) and Russia (Mitta 2005).

Family Kosmoceratidae Haug 1887**Genus *Keplerites* Neumayr & Uhlig 1892*****Keplerites* cf. *traillensis* Donovan 1953 or *K. chisikensis* Imlay 1975**

Fig. 7

Material and horizon. One specimen, MGUH 33472 (from GEUS 545591), consists of part of the internal mould/steinkern only and imprints of the rest of the specimen, which are crushed and incomplete. Found at c. 80 m height in section JHOV-5/2013 (Figs 4 and 5).

Description. The last whorl is clearly uncoiling, showing the specimen to be an adult. Maximum diameter is 131.5 mm. Ribbing is fine and dense. Primary ribs are relatively prominent compared with the secondaries. It begins slightly rursiradiate to rectiradiate before crossing the gently sloping umbilical wall and shoulder with a gentle forward bend and becomes slightly prorsiradiate. The projection increases near the end or final peristome. The primary ribs divide low, about one-third, up the flank into forward leaning sheaves of four straight, evenly spaced and equally strong secondaries.

Comparisons. The specimen is close to both *K. traillensis* and *K. chisikensis*. The latter includes *Keplerites tenuifasciculatus* described from East Greenland (Callomon 2004), but *K. tenuifasciculatus* was recently considered a junior synonym of *K. chisikensis* Imlay by Mönning & Dietl (2017). *K. traillensis* is less densely ribbed than *K. chisikensis*; at last septum, *K. traillensis* has 31 primaries per whorl, whereas *K. chisikensis* has 40 (Callomon 2004). The collected specimen is too poorly preserved to be identified as either of those two species. Hence, it is referred to as *K. cf. traillensis* or *K. chisikensis*. The species *Keplerites*

vardekloeftensis Callomon has coarser secondaries and ornamentation that fades on the last body chamber. Adult *Keplerites svalbardensis* Sokolov & Bodylevsky is generally smaller. The studied specimen resembles *K. svalbardensis* in coiling and ribbing density. However, *K. svalbardensis* is smaller, and its ribbing differs in becoming backwards, curving on the upper flank, after the initial forward curving on the lower flank and after crossing the umbilical shoulder. Lastly, the specimen from Mågensfjeld is also close to some variants of *K. kepleri* (Oppel) with relatively delicate primaries (e.g. Quenstedt 1887, plate 77, Fig. 3; Tintant 1963, plate 1; Page 1989, Figs 5.1a, b) but differs from those with relatively coarser primaries (e.g. Tintant 1963, plate 2; Dietl & Gygi 1998, plate 1a).

Occurrence. *K. chisikensis* and *K. traillensis* indicate the faunal horizons J-24–27 in the *C. apertum* Zone (Callomon 1993, 2004; Fig. 8). Note that this zone was initially considered as Callovian, based on strong resemblance of *Keplerites* from this zone with *K. kepleri*, the appearance of which defines the base of the Callovian in Europe (Callomon 1993; Mönning & Dietl 2017). Mitta & Alsen (2013) tentatively placed the *C. apertum* Zone in the upper Bathonian, based on late Bathonian ornamentation recorded in material above *K. "tenuifasciculatus."* Considering that ornamentation in the genus developed progressively or regressively (Callomon 2004), thick ribs do not unequivocally demonstrate a Bathonian age. Reference of the *C. apertum* Zone to the Bathonian was supported by Mönning & Dietl (2017). *Keplerites dietli* Schairer is considered a junior synonym of *K. traillensis* that correlates the Greenland faunal horizon J-26 of Callomon (1993) in the *C. apertum* Zone to the lower part of the *C. discus* Zone in Germany. The *K. aff. traillensis* in faunal horizon J-28 is considered synonymous with *K. radiatus* Sakharov & Lominadze and thus correlates to the upper part of the *C. discus* Zone (Mönning & Dietl 2017). The possible presence of *K. kepleri* in the faunal horizon J-29 in the Nordenskjöldi Zone would provide correlation to the base Callovian *K. kepleri* fauna, defining the base of the Callovian in Europe (Mönning & Dietl 2017; Fig. 8). If the present specimen is actually *K. kepleri*, which cannot be determined from its preservation, it would be indicative of the fauna J-29–30 in the Nordenskjöldi Zone and the base Callovian. This fits with the studied section where it was found somewhat above *C. apertum* of the Apertum Zone (Fig. 5).

5.2 Biostratigraphic summary

The biostratigraphy at Mågensfjeld can be summarised as follows:

1. Late Bajocian *Cranocephalites* cf. *pompeckji* or *C. furcatus* represents the Po-8 or Po-9 faunal horizons of the *C. pompeckji* Zone (Callomon *et al.* 2015).
2. Bathonian *Arctocephalites* cf. *arcticus* represents the J-9 faunal horizon of the *A. arcticus* Zone.

3. Bathonian *Arcticoceras ishmae* and *Arcticoceras [crassiplicatum]* of the J-16 and J-17 horizons represent the *A. ishmae* Zone (Callomon 1993; Callomon et al. 2015).
4. The upper Bathonian *C. calyx* and *C. apertum* Zone are represented by a relatively thick interval ranging from the middle of the section to near the top of the outcrop. The ammonites include *C. calyx*,

indicating the J-23 horizon, *C. apertum* of the J-24–26 horizons and *Kepplerites cf. traillensis* or *chisikensis* of the J-27 horizon (Callomon 1993; Callomon et al. 2015; Fig. 7).

Nygaard (2003) recorded one loose *Cranocephalites aff. borealis* found loose in Kilen in an “area covered by Upper Cretaceous sediment” (Nygaard 2003, p. 6). It was

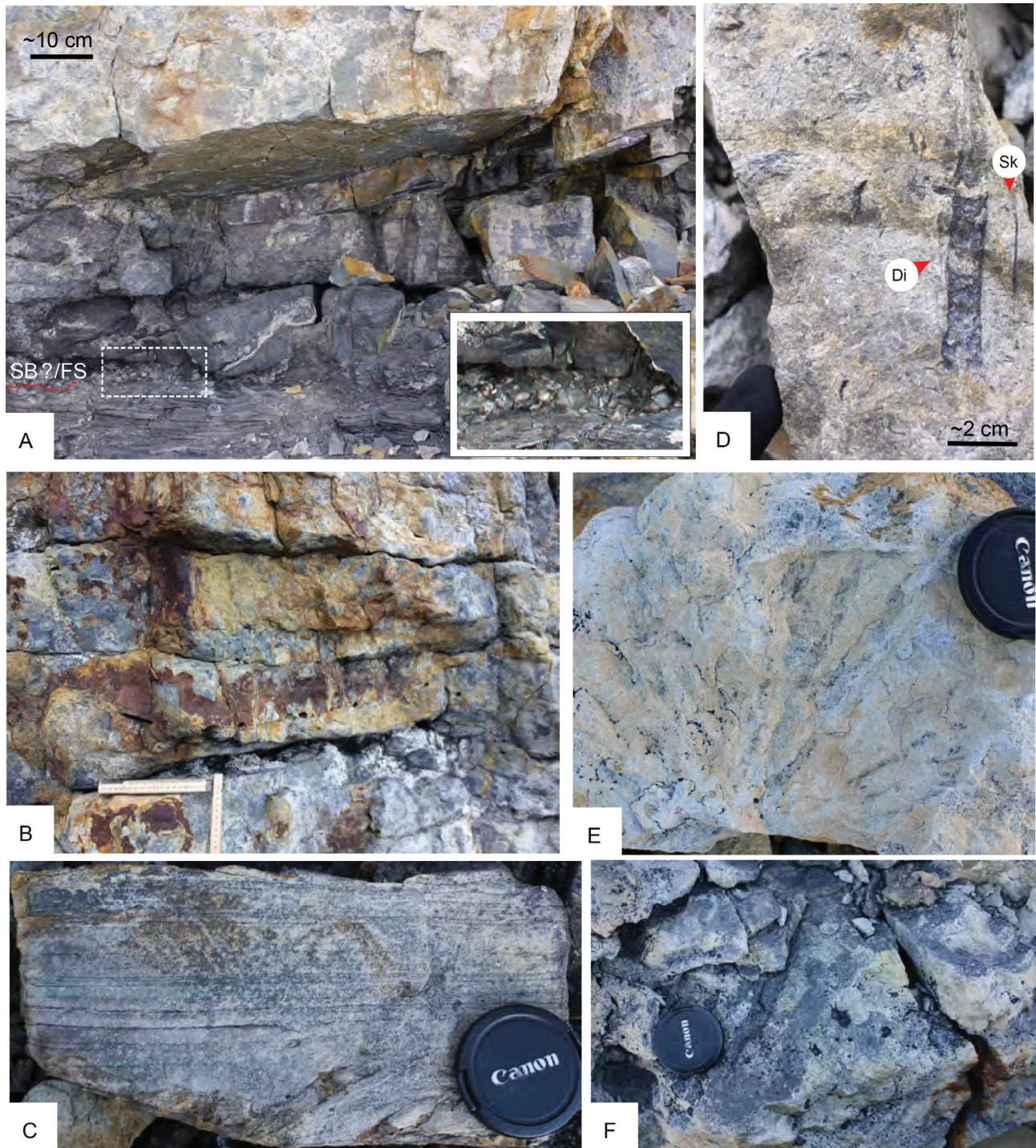


Fig. 9 Examples of facies from the Mågensfjeld Formation. **A:** Base of the succession showing the contact between facies association (FA) 1–2. **SB:** possible sequence boundary; **FS:** flooding surface. **B:** Typical coated expression of tabular beds of FA 2. **C:** Parallel-laminated sandstone that grades upwards into ripple cross-lamination, FA 2. **D–F:** Typical trace fossils of Mågensfjeld Formation. **D:** *Diplocraterion* isp. (**Di**) and *Skolithos* isp. (**Sk**) burrowing into burrow-mottled fine-grained sandstone. **E:** Bedding plane view to radiating burrow arms of *Phoebichnus* isp. **F:** *Rhizocorallium* isp. in fine-grained sandstone.

likely found beneath Mågensfjeld. The ammonite faunas described in the present study occur in the steep well-exposed cliffs in the top of the Mågensfjeld, but the scree-covered lower flanks of the hill leave room for older deposits – and a *Cranocephalites borealis* bearing horizon.

6 Depositional setting

The Mågenfjeld Formation outcrop is characterised by a weathered rock surface with a pale coating that commonly hinders detailed sedimentological data collection. Tentatively, the succession is divided into three facies associations (FA 1–3; Figs 8 and 9).

6.1 Facies association 1: fluvial or fluviotidal?

6.1.1 Description

FA 1 has a single occurrence at the base of the Mågensfjeld Formation succession. The deposits are poorly exposed and only a few metres can be studied in any detail. The unit is sharply overlain by FA 2 (see Section 6.2; Fig. 9A), but the lower boundary was not observed. The observable facies includes a few centimetre-thick, unbioturbated, mud-clast-bearing, fine-grained sandstone beds and lenticular bedding that is rich in plant debris. The mud-clasts are commonly concentrated at the base of the bed. The top of FA 1 is demarcated by an erosion-based extraformational pebble bed, a few centimetres thick.

6.1.2 Interpretation

Due to the limited data, we do not attempt to make a detailed palaeoenvironmental interpretation of FA 1, and the following discussion is considered tentative.

Lack of bioturbation in a periodically, relatively low-energy setting (e.g. post-event bed boundaries) may suggest that the endobenthic colonisation was limited by the freshwater setting. The upper erosional boundary and abrupt change in grain size from fine-grained sandstone to pebbles suggest truncation and development of an erosional lag. Such a surface may form, for instance, as a result of lateral changes in channel position in fluvial, estuarine or deltaic environments, or as a result of a progradational jump (even forced regression), and therefore could represent a sequence boundary. Furthermore, considering that the overlying deposits (FA 2) are marine, the surface is also associated with deepening. In summary, considering the aforementioned observations and the stratigraphic position below FA 2, the deposits are broadly interpreted to represent a fluvial or fluviotidal environment. The top of FA 1 represents a flooding surface and possibly a sequence boundary.

6.2 Facies association 2: delta front

6.2.1 Description

FA 2 is a common facies association type in the lower and middle parts of the Mågensfjeld Formation. It forms

aggradational to slightly upwards coarsening successions up to 10 m thick, which comprise decimetre-scale, tabular fine-grained sandstone beds (Figs 9B and C). The lower contact of FA 2 is sharp, and the limited exposure suggests a down-lapping pattern onto FA 3 (see Section 6.3) or FA 1. The upper contact to FA 3 is either sharp or gradational. The rock surface is usually covered hindering systematic data collection, but where observable, the beds are structureless or show parallel lamination capped with ripple-cross lamination (Fig. 9C). The beds show straight or trough-shaped bases. The beds appear to pinch-out towards the south-east. Similarly, sporadic palaeocurrent measurements tentatively suggest south-south-east oriented flow ($n = 3$). Bioturbation is commonly sporadic (bioturbation index 0–2, locally higher) and concentrated towards the top of the beds (data not shown). The suites are of low diversity and consist predominantly of vertical to inclined trace fossils such as *Diplocraterion* isp., *Skolithos* isp. and *?Siphonichnus* isp. (Fig. 9D). Sub-millimetre to millimetre-scale mud-filled branching burrows (*?Chondrites*) and indistinct burrow mottling are locally present. Plant fragments are common and include complete leaves. Reworked belemnites are locally concentrated at the base of the beds.

6.2.2 Interpretation

The trace fossil assemblage and the occurrence of marine fossils such as belemnites point to a general shallow marine setting. Tabular beds showing parallel lamination to ripple cross lamination may suggest an origin of a shallow marine gravity flow, whereas wave-generated structures are rare. Putative downlapping, the pinch-out nature of the beds and the presence of deposits, rich in plant material supports a distal delta front setting.

6.3 Facies association 3: protected shoreface

6.3.1 Description

FA 3 is a common facies association type in the middle and upper parts of the formation. It overlies FA 2 sharply or gradationally and is sharply overlain by the same association, where observable. The association forms aggradational or faintly upwards coarsening successions, comprised of bioturbated fine-grained sandstone. Distal expressions consist of intensively bioturbated muddy, very fine- to fine-grained sandstone. Common trace fossils include indistinct mud-filled grazing structures (*?Helminthopsis* isp. and *Nereites* isp.), mud-filled branching burrows (*?Chondrites*), *Palaeophycus tubularis* and *?Siphonichnus* isp. Proximal expressions consist of fine-grained sandstone burrowed with a low to moderate diversity assemblage, showing recurring *Phoebichnus* isp., *Rhizocorallium* isp., *Thalassinoides* isp., *Diplocraterion* isp., *Skolithos* isp. and *?Siphonichnus* isp. in addition to aforementioned structures (Figs 9E and F). Wave ripples and dune-scale cross bedding are rarely observed.

6.3.2 Interpretation

The trace fossil content generally points to a relatively low-energy, shallow marine environment periodically influenced by small-scale event sedimentation. The high bioturbation intensity and scarcity of preserved wave- or storm-generated structures probably point to a confined setting, where oscillation currents are subdued. FA 3 is burrowed with elements of the *Cruziana* ichnofacies, with increasing contribution of elements of the *Skolithos* ichnofacies towards proximal expressions and is interpreted to represent protected lower to middle shoreface-like environments.

6.4 Summary

In summary, FA 1 is recorded lowest in the measured section between 0 and 2 m, whereas the remaining overlying section belongs to alternations of FA 2 and FA 3. Overall, the succession reflects a backstepping to aggradational depositional evolution with a putative fluvial or fluviotidal base, overlain by deltaic and protected shoreface facies.

7 Discussion

7.1 Stratigraphic relations in Kilen

The Mågensfjeld Formation is only well-exposed at Mågensfjeld, on the upper slopes of the mountain. Below the exposures, the slope is covered by scree composed of blocks and slabs of thermally altered sandstone weathered out from the Mågensfjeld Formation. The scree covers the boundary to the underlying Gletscherport Formation, which has a restricted exposure near the foot of the slope towards the Hondal valley (Hovikoski *et al.* 2018; Fig. 2). The orientation of the strata of the Mågensfjeld Formation is close to horizontal (Figs 3 and 4), whereas the strata of the Gletscherport Formation are steeply dipping (up to 70°) towards the east. This is most likely due to fault drag as the Gletscherport Formation is exposed just west of the inferred position of a large normal fault in the Hondal valley (Normal Fault II of Svennevig *et al.* 2016). The fault has downthrown the mid- to Upper Cretaceous succession at Saddelfjeld to the east, relative to the Middle Jurassic succession at Mågensfjeld to the west. An alternative explanation for the marked difference in orientation between the Mågensfjeld and the Gletscherport formations could be an angular unconformity between the two units, covered by the scree, indicating a marked structural event between the depositions of the two units. However, we consider the fault drag explanation to be the most plausible.

The upper boundary of the Mågensfjeld Formation is not exposed. The succeeding unit in the Kilen succession is the Birkelund Fjeld Formation, which has yielded Kimmeridgian ammonites (Hovikoski *et al.* 2018). The lower part of the Birkelund Fjeld Formation is not exposed in outcrop, and the age of its base is thus unknown.

This leaves open the possibility of a depositional gap between the two formations, or for the presence of Callovian–Oxfordian strata in the interval between the Bathonian of the Mågensfjeld Formation and the Kimmeridgian, upper part, of the Birkelund Fjeld Formation.

7.2 Middle Jurassic in the neighbouring high Arctic

7.2.1 North-East Greenland

The nearest Middle Jurassic ammonite-bearing succession in Greenland is the Pelion Formation on Store Koldewey island (c. 76°N, North-East Greenland), where a rich ammonite fauna represents the Bathonian–Callovian (Ravn 1911; Piasecki *et al.* 2004). The Pelion Formation is a widespread deltaic to shallow marine sandstone unit with outcrops south of Store Koldewey on Hochstetter Forland, Kuhn Ø, Wollaston Forland, Hold with Hope, Geographical Society Ø, Traill Ø and as far south as Jameson Land (see Surlyk 2003; Surlyk *et al.* in press). A report of *C. aff. borealis* in Kilen indicated that Middle Jurassic deposition commenced in the *C. borealis* chron (Nygaard 2003). This would be isochronous with the onset of the huge marine flooding and deposition of the sand-dominated, shallow marine and deltaic system of the Pelion Formation (Callomon 1993; Surlyk 2003). The Pelion Formation probably extends offshore into the Danmarkshavn Basin north of Store Koldewey.

7.2.2 Peary Land

Middle Jurassic deposits may be present on Peary Land, making them the closest to Kilen. Håkansson & Pedersen (2015) subdivided the sedimentary succession of the Wandel Sea Basin into a series of separate, discrete basins, many of which they considered to be formed by strike-slip movements within the Kronprins Christian Land strike-slip mobile belt. In one restricted area of Sildredome, eastern Peary Land (Fig. 1), lies the so-called Sildredome Basin – so-named by Håkansson & Pedersen (2015). The area is a few square kilometres in size and contains a fault complex. Numerous Middle Jurassic *C. pompeckji* Zone ammonites have been recorded in the area (Nygaard 2003; Håkansson & Pedersen 2015) and found loose on a weathered surface mapped as the Ladegårdsåen Formation, Peary Land (Kokfelt *et al.* 2013). More than 20 such specimens have been counted from this small area, which is strongly indicative of the Middle Jurassic (upper Bajocian). However, outcrops are yet to be discovered. The oldest age of the Ladegårdsåen Formation has so far been dated middle Oxfordian (Håkansson *et al.* 1981; Dypvik *et al.* 2002).

7.2.3 Svalbard

Today, Svalbard and the Barents shelf are more than 600 km away from Kilen, but prior to the opening of the Atlantic, they were only 400 and 200 km away, respectively

(Svennevig *et al.* 2017, using Müller *et al.* 2016). The closest (onshore) correlative unit to the Wandel Sea Basin, geologically speaking, is probably found on Svalbard.

Middle Jurassic ammonites have been reported from Svalbard in the Oppdalen Member of the lower part of the Agardhfjellet Formation, immediately above thin (decimetre to a few metres thick) remanié deposits of the Brentskardhaugen Bed (Birkenmajer 1980; Birkenmajer *et al.* 1982). The Brentskardhaugen Bed is a conglomerate with reworked concretions containing Toarcian, Aalenian and Bajocian fossils (Bäckström & Nagy 1985). Dypvik *et al.* (1991a, 1991b) considered the Brentskardhaugen Bed deposited close to the Bathonian–Callovian transition. However, that age is in conflict with the occurrence of Cranocephaloide Zone ammonites in the overlying Agardhfjellet Formation (Kopik & Wierzbowski 1988). The Cranocephaloide Zone is now considered middle Bathonian (Callomon *et al.* 2015). The Agardhfjellet Formation is up to 290 m thick and is Bathonian to Ryazanian. The lower Oppdalen Member is a silt and fine-sand-dominated unit, 10–60 m thick and relatively coarse compared to the dominantly paper-shales of the Agardhfjellet Formation (Mørk *et al.* 1999). Kopik & Wierzbowski (1988) reported a succession of three assemblages from the lower 10 m of the Oppdalen Member of middle Bathonian Cranocephaloide Zone, Calyx–Apertum Zones and Callovian Coronatum–Athleta Zones, respectively, with several taxa related to those reported here from Kilen, North Greenland.

The documentation of a Middle Jurassic sandstone unit in Kilen provides an important data point for sandstone deposition and a reservoir unit analogue in the region. Kilen is part of the same depositional system as the northern part of the Store Koldewey platform bordering the Danmarkshavn Basin in the offshore area east and north of Store Koldewey island. The Danmarkshavn Basin was recently subject to petroleum exploration with five licence blocks issued. The Mågensfjeld Formation may be a more closely fitting analogue for sandstone units in the western Barents Sea (e.g. Stø Formation; Olausen *et al.* 1984; Gjelberg *et al.* 1987; Klausen *et al.* 2019) than the onshore analogues on Svalbard.

The presence of Bajocian–Bathonian shallow marine deposits in Kilen shows that the Wandel Sea Basin was influenced by the Middle Jurassic transgression and had sufficient accommodation space for marine deposition earlier than previously thought (cf. Dypvik *et al.* 2002). The palaeoenvironmental characteristics of the Middle Jurassic Mågensfjeld Formation and Upper Jurassic (Kimmeridgian) Birkelund Fjeld Formation in Kilen are strikingly similar. Both are comprised mainly of protected shallow marine and deltaic environments and show generally an aggradational stacking pattern. However, a deepening trend from a fluvial, fluviotidal and deltaic environment to a protected shoreface occurs in the Bajocian interval.

7.3 Structural implications

The new Middle Jurassic age for the Mågensfjeld Formation greatly simplifies the structural complexity of the area. The previous Late Cretaceous age called for the introduction of a large inferred reverse fault, bringing the Late Jurassic Kuglelejet Formation in contact with the previously dated Late Cretaceous Mågensfjeld Formation (Pedersen 1991; Håkansson *et al.* 1993; Fig. 2). Using the estimated thicknesses of the formations (Hovikoski *et al.* 2018; Svennevig *et al.* 2016), the vertical throw on the suggested fault would have been around 2000 m – by far the largest known from the area. The age of the Mågensfjeld Formation presented here, along with mapping from oblique photogrammetry and 3D modelling (Svennevig *et al.* 2015, 2016), demonstrate a simple, gentle and upright anticline with the Middle Jurassic Mågensfjeld at the core, truncated by a normal fault to the east and covered by ice to the west and north (Svennevig 2018; Figs 1 and 2). The normal fault is presumably of latest Cretaceous age and predates the Eurekan folding that likely occurred during the Paleocene–Eocene (Svennevig *et al.* 2016).

8 Conclusions

The sandstone succession exposed in the steep cliffs of Mågensfjeld, belonging to the Mågensfjeld Formation, records generally shallow marine depositional environments. The succession is fossil bearing, and the ammonites belonging to the genera *Cranocephalites*, *Arctocephalites*, *Arcticoceras*, *Cadoceras* and *Kepplerites* show a great affinity to the Middle Jurassic faunal succession in North-East Greenland. The ammonites allow the identification of the Bajocian *C. pompeckji* Zone, the Bathonian *A. arcticus*, *A. ishmae*, *C. calyx* and *C. apertum* Zones.

The Middle Jurassic age of the unit allows for a much more straightforward model of the structural evolution of this area of Kilen, compared with the previously proposed Late Cretaceous age. The structural evolution essentially records Late Cretaceous extension followed by Palaeogene folding (probably Eurekan, Paleocene–Eocene).

The deposition of the Mågensfjeld Formation records Middle Jurassic transgression in the Wandel Sea Basin and the development of accommodation space for marine deposition of a sand-dominated unit. The age of the unit is equivalent to the well-described reservoir unit analogues of the Middle Jurassic in North-East Greenland (e.g. Pelion Formation, Store Koldewey). As such, the Mågensfjeld Formation serves as a key data-point and analogue for possible Middle Jurassic units in offshore basins; for example, in the western Barents Sea, the Wandel Sea and the Danmarkshavn Basins.

Acknowledgements

We thank Jette Halskov for drafting of Figs 1, 2, 4, 5 and 8. We appreciate the useful comments of the two reviewers, M. Rogov and one anonymous reviewer, which greatly improved the final manuscript.

Additional information

Funding statement

Data were collected during the field work funded by the Geological Survey of Denmark and Greenland (GEUS) and undertaken within the collaboration project "Petroleum Geological Studies, Services and Data in East and North-East Greenland."

Author contributions

PA: conceptualisation. PA, JH and KS: formal analysis, investigation, writing – original draft, writing – review and editing.

Competing interests

The authors declare no competing interests

Additional files

None provided.

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