GEOLOGICAL SURVEY OF DENMARK AND GREENLAND MAP SERIES 8 · 2018

Descriptive text to the Geological map of Greenland, 1:100 000, Kilen 81 Ø.1 Syd

Kristian Svennevig, Peter Alsen, Pierpaolo Guarnieri, Jussi Hovikoski, Bodil Wesenberg Lauridsen, Gunver Krarup Pedersen, Henrik Nøhr-Hansen and Emma Sheldon

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Keywords
Keywords: Geological mapping, Kilen, North Greenland, Wandel Sea Basin, Upper Palaeozoic, Mesozoic, inversion tectonics, rifting, compression

Cover
Extract of the central part of the Kilen map sheet showing Triassic to Cretaceous rocks reworked by rifting and compression forming a complex structural pattern. Key observations are: 1) Rocks become younger towards the north-east due to NE–SW-oriented rifting of presumably Late Cretaceous age. 2) E–W-oriented fold axes cross normal faults unaffected and the normal faults form a characteristic zigzag pattern. This indicates that folding postdates extension and that the normal faults are passively folded. The folding is presumably of Palaeocene–Eocene age.

Frontispiece: facing page
Lone geologist camp in the barren central Kilen Fjelde. View towards the south-east. The hill Tove Birkelund Fjeld in the background is formed by resistant sandstone of the Galadriel Fjeld Formation folded in an E–W-oriented anticline, presumably during the Palaeocene–Eocene. In the background, the Gåseslette plain stretches for 20 km towards the coast to the south-east. The ice cap of Flade Isblink is visible in the far left. See Fig. 2 for location.

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Contents

Abstract

Svennevig, K., Alsen, P., Guarnieri, P., Hovikoski, J., Lauridsen, B.W., Pedersen, G.K., Nøhr-Hansen, H. & Sheldon, E.: Descriptive text to the Geological map of Greenland, 1:100 000, Kilen 81 Ø.1 Syd.
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The geological map sheet of Kilen in 1:100 000 scale covers the south-eastern part of the Carboniferous–Palaeogene Wandel Sea Basin in eastern North Greenland. The map area is dominated by the Flade Isblink ice cap, which separates several minor isolated landmasses. On the semi-nunatak of Kilen, the map is mainly based on oblique photogrammetry and stratigraphical field work while in Erik S. Henius Land, Nordostrundingen and northern Amdrup Land the map is based on field data collected during previous, 1:500 000 scale regional mapping. Twenty-one Palaeozoic–Mesozoic mappable units were identified on Kilen, while the surrounding areas comprise the Late Cretaceous Nakkehoved Formation to the north-east and the Late Carboniferous Foldedal Formation to the south-west. On Kilen, the description of Jurassic–Cretaceous units follows a recently published lithostratigraphy. The Upper Palaeozoic–lowermost Cretaceous strata comprise seven formations and an informal mélange unit. The overlying Lower–Upper Cretaceous succession comprises the Galadriel Fjeld and Sølverbæk Formations, which are subdivided into six and five units, respectively. In addition, the Quaternary Ymer Formation was mapped on south-east Kilen.

The Upper Palaeozoic to Mesozoic strata of Kilen are faulted and folded. Several post-Coniacian NNW–SSE-trending normal faults are identified and found to be passively folded by a later N–S compressional event. A prominent subhorizontal fault, the Central Detachment, separates two thrust sheets, the Kilen Thrust Sheet in the footwall and the Hondal Elv Thrust Sheet in the hanging wall. The style of deformation and the structures found on Kilen are caused by compressional tectonics resulting in post-extensional, presumably Early Eocene, folding and thrusting and basin inversion. The structural history of the surrounding areas and their relation to Kilen await further studies.

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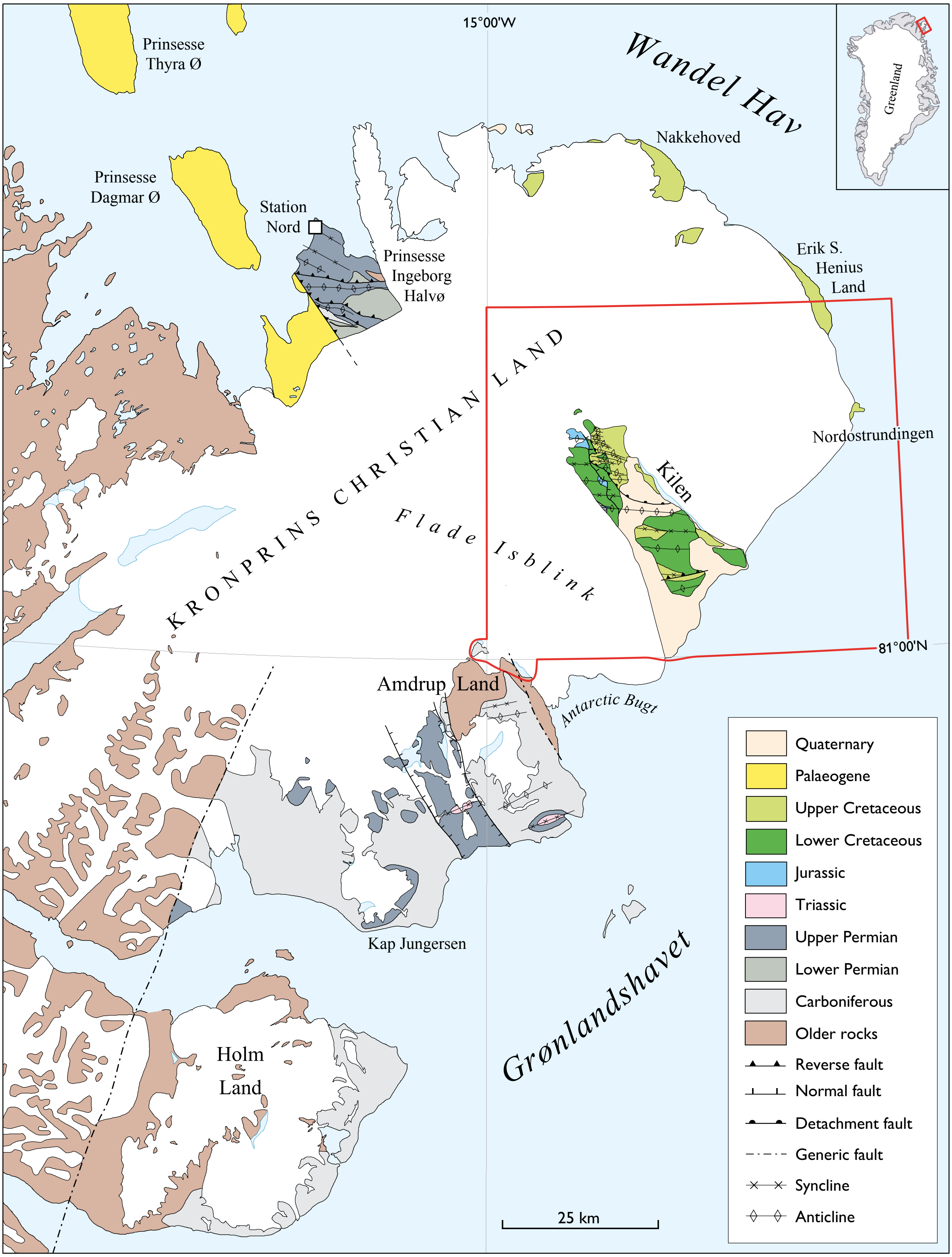


Fig. 1. Regional geological map of Kronprins Christian Land based mainly on Henriksen (2003) with modifications from Håkansson (1988), Pedersen (1994), Pedersen & Håkansson (1999) and Guarnieri (2015) for Prinsesse Ingeborg Halvø and from Stemmerik *et al.* (1998, 2000) and Alsen *et al.* (2017) for Amdrup Land along with the present data from Kilen. Red frame shows the present map area.

Introduction

The map is a pre-Quaternary geological bedrock map in 1:100 000 scale. The map area is located in easternmost North Greenland in the south-eastern part of Kronprins Christian Land, south-east of the Danish military base Station Nord (Fig. 1). The regional Flade Isblink ice cap separates four minor landmasses: Erik S. Henius Land and Nordostrundingen to the north-east, the semi-nunatak Kilen, centrally in the map, and the north-easternmost parts of Amdrup Land to the south-west. Only Kilen, covering *c.* 400 km^2, has been the subject of new mapping, and the emphasis of this map description is therefore on the Kilen area. East of Kilen, Erik S. Henius Land and Nordostrundingen were only briefly visited on a few helicopter reconnaissance stops in 1980 (Eckart Håkansson, personal communication 2017) as a contribution to the 1:500 000 scale geological map of Peary Land (Bengaard & Henriksen 1984). North-eastern Amdrup Land was mapped in greater detail by J.M. Hull and J.D. Friderichsen (Hull & Friderichsen 1995) for the 1:500 000 scale geological map of Lambert Land (Jepsen 2000). This field map is in the Geological Survey of Denmark and Greenland (GEUS) map archive.

The remapped strata on Kilen comprise folded Carboniferous – Upper Cretaceous sedimentary rocks of the Carboniferous–Paleocene Wandel Sea Basin (Fig. 2). A Pleistocene unit (Ymer Formation) established by Hjort & Feyling-Hanssen (1987) was also mapped. The mapping was carried out by helicopter-based oblique photogrammetry (Svennevig 2014; Svennevig *et al.* 2015) supplemented by stratigraphical field work (Alsen *et al.* 2017; Hovikoski *et al.* 2018). The main structural elements shown on the map have been verified by 3D modelling and have led to a new structural interpretation for Kilen (Svennevig *et al.* 2016, 2017). Some of the new observations affect the seamless regional 1:500 000 scale geological map of Greenland (Kokfelt *et al.* 2013; Pedersen *et al.* 2013); this has been updated accordingly and the changes described in a separate publication (Svennevig 2018).

Previous map

An unpublished, 1:100 000 scale geological map compiled by S.A.S. Pedersen (Pedersen 1991) is the only existing detailed geological map of Kilen older than the present map. It was based on field work in 1980 and 1985 and on photogrammetrical observations on 1:150 000 scale, black and white aerial photographs from 1978 (Bengtsson 1983). The status of the older map is not straightforward as it was printed but never published, and no map description was completed. It is available from GEUS' map archive and through the link in the reference list. It forms the basis for several figures in the literature (Håkansson *et al.* 1993; Pedersen & Håkansson 1999; Lyberis & Manby 1999; Manby & Lyberis 2000; Håkansson & Pedersen 2001; von Gosen & Piepjohn 2003; Håkansson & Pedersen 2015). It was also adapted for a 1:1 000 000 scale map of the Caledonian Orogen in East Greenland (Henriksen 2003). The geology of the north-eastern part of the present map area, east of Røde Bakker and north of the Splitbæk river, is adapted from the older map (Pedersen 1991), as this area was not visited during the recent field work and its scarce exposures are not suitable for oblique photogrammetry (Fig. 3).

The Kilen part of the present map sheet has previously been enclosed as a 1:50 000 scale map sheet as part of a PhD thesis (Svennevig 2016a) along with an earlier version of the present map sheet description (Svennevig 2016b).

Geological exploration history of Kilen

The multidisciplinary Kilen Expedition of 1985 was the first major effort to map and understand the geology of Kilen. It resulted in the above-mentioned map (Pedersen 1991) and the first systematic description of the geology of Kilen (Håkansson *et al.* 1993), as well as a comprehensive unpublished report on its geology (Håkansson *et al.* 1994a). The sporadic exploration history prior to the Kilen Expedition of 1985 is described in Håkansson *et al.* (1993) and Håkansson & Heinberg (2003).

Since 1985, Kilen has been the target of three larger expeditions: the Circum-Arctic Structural Events (CASE 2) Expedition in 1994, the Mjølnir Expedition in 1998 and the more recent GEUS field campaigns in 2012, 2013 and 2016. In addition to the above expeditions, several brief visits mentioned below have been made.

The CASE 2 expedition to North Greenland and the Wandel Sea Basin comprised two field teams working in Kilen for a two-week period focusing on the structural geology (Lyberis & Manby 1999; Manby & Lyberis 2000; von Gosen & Piepjohn 2003). The Mjølnir Expedition included visits to Kilen with the objective to search for sedimentary strata related to the tsunami generated by the Mjølnir meteorite impact into Lower Cretaceous strata (Dypvik *et al.* 2011a). No clear impact-related strata were found, but data on the Lower Cretaceous stratigraphy of Kilen were reported in three papers (Dypvik *et al.* 2002; Røhr *et al.* 2008; Dypvik & Zakharov 2012)

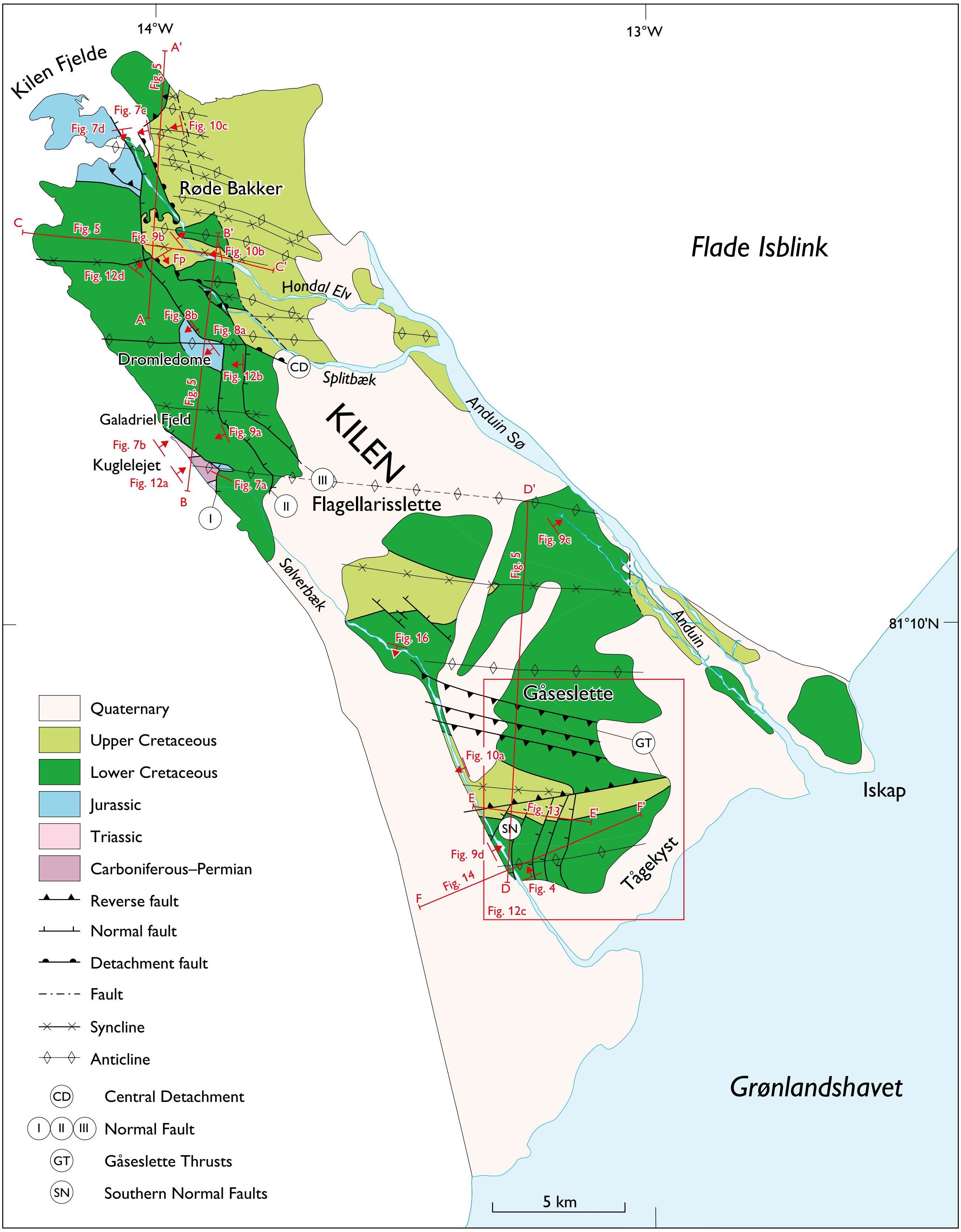


Fig. 2. Simplified geological map of Kilen. The Galadriel Fjeld Formation is included in the Lower Cretaceous, although it includes strata belonging to the lowermost Upper Cretaceous. The positions and direction of view of images on the frontispiece (**Fp**) and in Figs 4, 7–10, 12 and 16 along with cross-sections in Figs 5, 13 and 14 are shown. Modified from Svennevig *et al.* (2016).

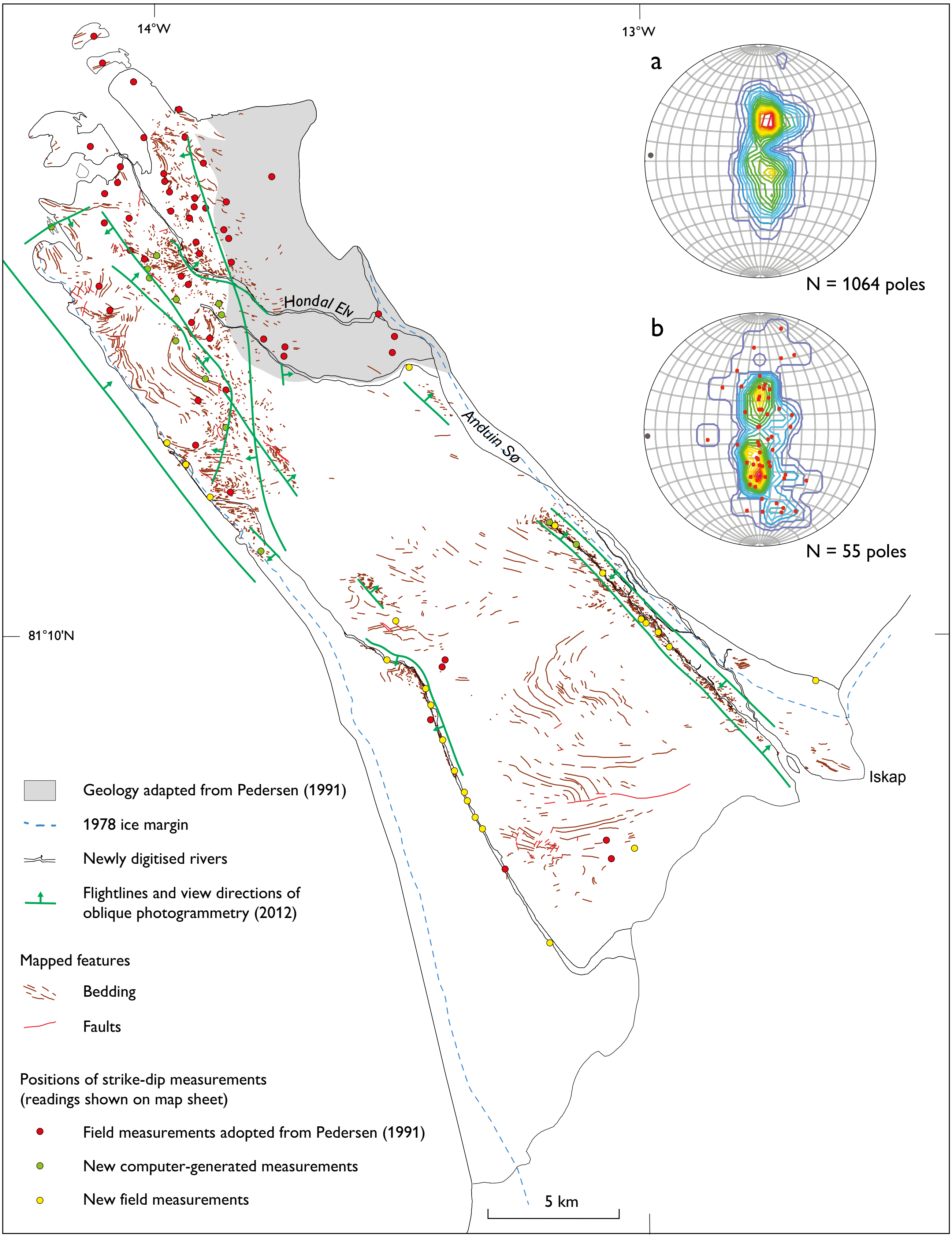


Fig. 3. Map of data coverage and sources for the Kilen part of the map sheet. Insets show (**a**) contoured plots of 1064 poles of structural measurements generated from digitised polylines and (**b**) 55 poles from structural measurements made in the field by Pedersen (1991). The contour interval is 1%. The poles are omitted in (a) for clarity. The insets are adapted from Svennevig *et al.* (2015) and please refer to this for further explanation.

and a book chapter (Dypvik *et al.* 2011b). Furthermore, the occurrence of a plesiosaur fossil was reported (Bruhn 1999).

A team of GEUS geologists made a brief visit to the outer parts of Kilen in 1995, where samples for thermal maturity studies were collected by S. Piasecki and F. Dalhoff (Stemmerik *et al.* 1997). In 2008, the previously reported plesiosaur fossil (Bruhn 1999) was further examined during a brief helicopter stop (Milán 2009; Marzola *et al.* 2018). In 2009, E. Håkansson and C. Heinberg visited Iskap (Fig. 2) to examine the rocks exposed there.

In addition to the geological expeditions to Kilen, a number of visits have focused on the populations of migrating birds, mainly geese, which use Kilen as an important breeding and moulting ground (Håkansson *et al.* 1993; Thing 2002; Boertmann *et al.* 2015).

Recent field work and mapping on Kilen

Field work contributing to the present map was carried out in 2012 and 2013 by geologists from GEUS as part of a larger expedition studying the geology of the Wandel Sea Basin (Bojesen-Koefoed *et al.* 2014a, b). In both field seasons, Kilen was visited for a month by two field teams, who collected sedimentological and palaeontological data. This led to a revision of the lithostratigraphy (Hovikoski *et al.* 2018). A team of structural geologists visited the central part of Kilen Fjelde at the start of the 2012 season and made a brief reconnaissance stop in 2013. In addition to the on-ground field work, extensive oblique photogrammetry coverage of Kilen was undertaken as part of a PhD project to study the structural evolution of Kilen through geological 3D modelling (Svennevig 2016b). A two-week GEUS expedition during the summer of 2016 visited the Tågekyst area and examined Triassic strata in Kilen Fjelde discovered during the 2013 field work (Fig. 2; Alsen *et al.* 2017). Data from the 2012, 2013 and 2016 field work and from the above-mentioned previous work along with 3D geological modelling from oblique photogrammetry (Svennevig *et al.* 2015, 2016, 2017) form the basis for the Kilen part of the new geological map.

Geological background and previous interpretations

The mapped area is part of the Carboniferous–Palaeogene Wandel Sea Basin in eastern North Greenland (Dawes & Soper 1973). The basin shares its geological history with basins in Arctic Canada, Svalbard and the western Barents Sea (Håkansson & Stemmerik 1989; Piepjohn & von Gosen 2001; von Gosen & Piepjohn 2003; Stemmerik & Worsley 2005; Piepjohn *et al.* 2015). The mid-Carboniferous–mid-Permian sedimentary rocks mainly comprise carbonates with minor siliciclastic intervals and local evaporites (Stemmerik *et al.* 1996) whereas the Upper Permian to Palaeogene strata are dominated by siliciclastic deposits (Håkansson *et al.* 1991).

Previous work in the Wandel Sea Basin has revealed a complex structural history of folded, faulted and thermally affected strata deformed during events of Mesozoic and younger age (Koch 1961; Dawes & Soper 1973; Dawes 1976; Pedersen 1991; Pedersen *et al.* 1994; Håkansson *et al.* 1994b; Lyberis & Manby 1999; Manby & Lyberis 2000; Piepjohn & von Gosen 2001; von Gosen & Piepjohn 2003; Guarnieri 2015). The Wandel Sea Basin was considered to have been subject to several post-Permian deformation events comprising at least four strike-slip phases and a terminal Late Cretaceous transpressional event (Pedersen 1988; Håkansson & Pedersen 2001, 2015). The Mesozoic succession was interpreted to represent deposition along a long-lived, strike-slip plate-boundary structure called the Wandel Hav Strike-Slip Mobile Belt (Håkansson & Pedersen 2001, 2015). At Kilen, the deformed succession comprises faulted and folded Mesozoic siliciclastic sediments and local small patches of Upper Palaeozoic gypsum and limestone.

Physiography

The mapped area is dominated by the ice cap of Flade Isblink, which covers 60% of the area. It is the second largest ice body in the northern hemisphere after the Greenland ice sheet (Koch 1935; Håkansson *et al.* 1993; Rinne *et al.* 2011). Erik S. Henius Land and Nordostrundingen are small low coastal forelands in the north-eastern part of the map area. In the south-west of the map area, the north-eastern part of Amdrup Land forms a low-lying area covered by thin subrecent deposits.

Kilen is the largest landmass in the map area and covers around 10%. The name Kilen ('the wedge' in Danish) refers to the shape of the landmass in the form of a semi-nunatak (Fig. 1). Kilen is divided into Kilen Fjelde in the north and Flagellarisslette and Gåseslette in the south. Kilen Fjelde comprise hills and ridges up to 500 m high, which are mainly made up of prominent Lower Cretaceous sandstones (the Lichenryg and Galadriel Fjeld Formations), which outline large folds. Three larger rivers: Skalbæk, Hondal Elv and Splitbæk run through the hills, draining Flade Isblink into the lake Anduin Sø (Fig. 2).

The southern and central parts of Kilen form a wide plain (slette in Danish) divided into the northern Flagellarisslette and the southern Gåseslette. Flagellarisslette is covered by Quaternary sandur deposits (Pedersen 1991) while the morphology of Gåseslette is dominated by sets of raised Quaternary beach ridges, most notably the Kangoq Ryg in the central part. Pre-Quaternary strata are visible between the ridges in the oblique and vertical aerial photos (Svennevig *et al.* 2015; Fig. 4; see also Figs 9d, 12c) probably due to aeolian removal of the fine-grained material between the ridges (see e.g. Rasmussen 2004). Pre-Quaternary strata are difficult to recognise when on the ground except in low cliffs along the rivers and streams. The only exception is the Lower Cretaceous mudstones at Iskap, which are not covered by Quaternary deposits.

Two large rivers, Sølverbæk and Anduin, run parallel to the eastern and western margins of the plain. On Gåseslette the rivers are nearly straight and incise the plain by up to a couple of metres, creating relatively good field-scale exposures. Sølverbæk drains the ice cap at Galadriel Fjeld while Anduin comprises an eastern active branch draining Anduin Sø and carrying a large amount of water, and a western abandoned branch. The active eastern branch is relatively young as Flade Isblink covered the area where it runs in 1978 as seen in black and white 1:150 000 scale aerial photographs from that year. Since then the ice cap has retreated by up to 1 km based on mapping from oblique images from 2012 (Fig. 3). Only the abandoned western branch of the river was briefly visited during the field work. However, good bedrock exposures were observed in the oblique images in low cliffs along the eastern branch of Anduin.

Fig. 4. Oblique image showing the landscape of Kilen and the exposures on the wide Gåseslette plain. The view is towards the north-west along the Sølverbæk river taken from an altitude of 330 m. The Kilen Fjelde in the background are 20 km away and reach an altitude of 500 m. The light-coloured intervals on the plain in the centre right of the image are more sandy intervals in the Kangoq Ryg Member that are truncated by faults of the Southern Normal Faults in the centre of the image. See also Figs 9d, 12c and Fig. 2 for location.

Map elements

Place names

Outside Kilen, the place names follow the official place names of eastern North Greenland (Higgins 2010). On Kilen itself most of the place names first appeared on the unpublished geological map (Pedersen 1991). The majority of these names are informal and are listed in Higgins (2010) as such. The names from the former map have been adapted for the present map with three additions: The cape formerly named Iver Pynt in the south-eastern part of Kilen is a junior synonym of the approved name Iskap (Higgins 2010), and the latter name is therefore used. The large, previously unnamed river running through the Hondal valley in Kilen Fjelde has been named Hondal Elv (Danish for Hondal River). A large, elongate, shallow, previously unnamed lake along the eastern margin of Kilen is named Anduin Sø (Danish for Anduin Lake) after the Anduin river draining the lake (Fig. 3).

Sources of topographic map elements

The minor rivers and lakes on Kilen have been adapted from GEUS' topographic database. Larger rivers with significant width and discharge along with topographic features along the ice margin have been remapped using the oblique images or the black and white 1:150 000 scale aerial photographs recorded in 1978. The eastern ice margin, the southern portion of Anduin Sø, the new branch of Anduin and the ice margin along the western part of Kilen Fjelde were mapped from oblique images. The ice margin along the south-western part of Gåseslette and the coastline were mapped using an ASTER satellite image from 2010. The rivers along the western margin of the ice cap were not mappable from the ASTER image and have been modified from the rivers in the GEUS topographic database to match the new ice margin.

A hut and an associated gravel landing strip were established in 1979 on Iskap by the Danish military Sirius Patrol and represent the only permanent infrastructure on Kilen. Their positions were mapped using the oblique images.

A 15 m-grid digital elevation model (DEM) was produced from stereo pairs of 1:150 000 scale black and white aerial photographs (Bengtsson 1983), and 50 m contours were interpolated from this in ArcGIS. The

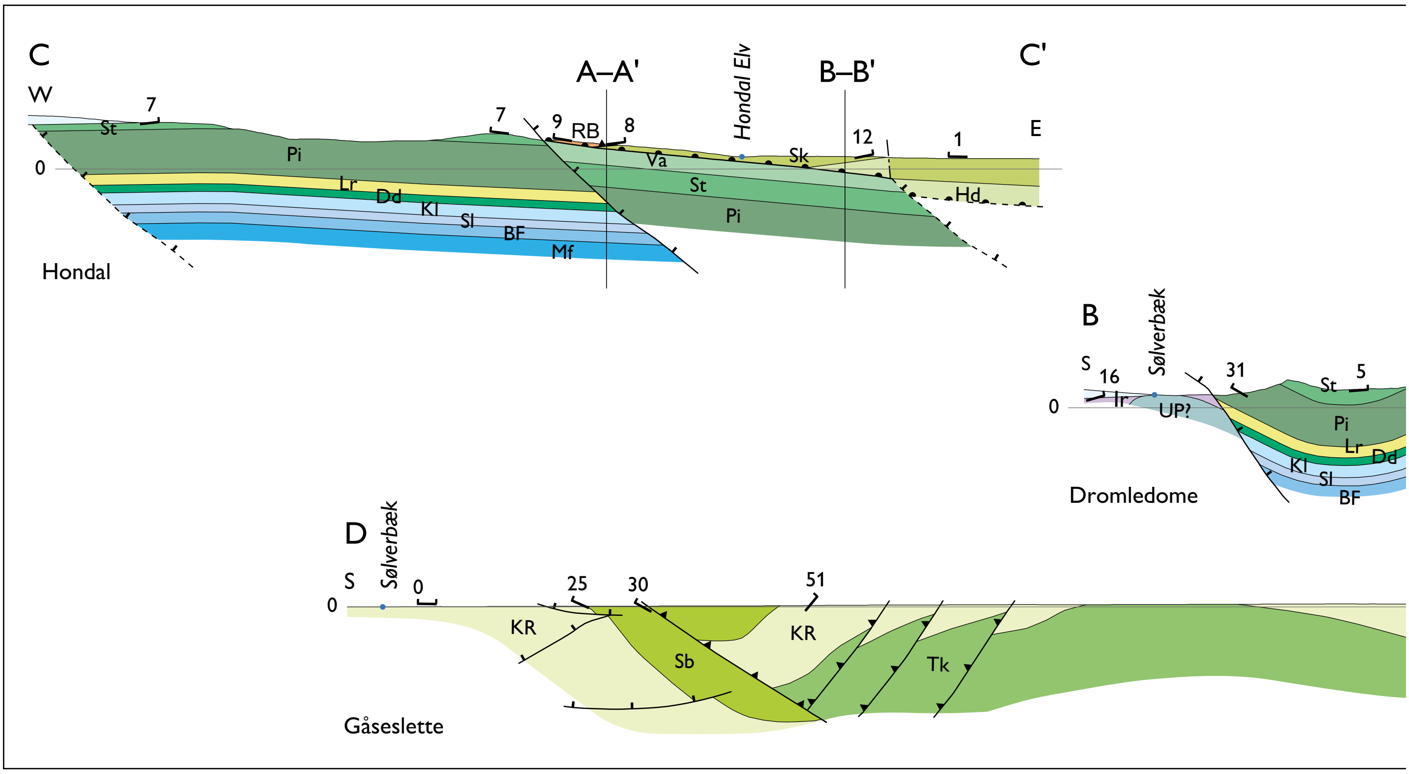


Fig. 5. (*first part)* Geological cross-sections from Kilen based on Svennevig *et al.* (2016). See inset map and Fig. 2 for location and Fig. 6 for key to the two-letter abbreviations. The cross-sections are also available on the enclosed Kilen map in 1:50 000 scale.

contours along the ice margin were edited by hand where necessary to fit the present ice margin. Outside Kilen the topography, outlined by 100 m contours, is adapted from the topographic database at GEUS.

There is an inconsistency between various topographic databases as to whether Nordostrundingen exists as a piece of land or it is just a bulge on Flade Isblink. The ice situation and low relief make it impossible to determine from aerial or satellite images which of these interpretations is correct; for the present map sheet the interpretation of Nordostrundingen as a point is adapted from the 1:500 000 scale geological map of Peary Land (Bengaard & Henriksen 1984).

Structural data

More than 80 strike-dip measurements are printed on the map. Fifty-five of these are incorporated from the unpublished map of Pedersen (1991) while 23 are new field measurements. More than 5000 strike-dip measurements were generated from the mapped 3D polylines as basis for the 3D modelling (Svennevig *et al.* 2015). The field measurements and a subset of structural measurements generated from 3D polylines are compared in Figs 3a, b. Thirteen of the latter are shown with a separate signature on the map where field measurements were not available (Fig. 3). The actual structural measurements are shown on the map sheet. On the nunatak in north-east Amdrup Land two strike-dip measurements are adapted from an unpublished field map (1995) by J.D. Friderichsen and J.M. Hull available from the GEUS map archive.

Geological cross-sections

Due to the interference of NNW–SSE-striking normal faults and E–W-striking compressional structures on Kilen four geological cross-sections had to be constructed to show the geological structure of Kilen (Fig. 5). Three of these, the Scaphitesnæse (A–A'), Dromledome (B–B'), and Gåseslette (D–D') cross-sections are oriented N–S, orthogonal to fold axes emphasising the compressive structures, while the fourth Hondal cross-section (C–C') is oriented W–E parallel to the fold axes, emphasising the pre-folding extensional architecture. The strike-dip measurements shown on the sections are projected from field measurements as well as computer-generated strikes and dips, not all of which are shown on the map. The construction of the cross-sections is described in Svennevig *et al.* (2015) and the cross-sections have previously been published in Svennevig *et al.* (2016).

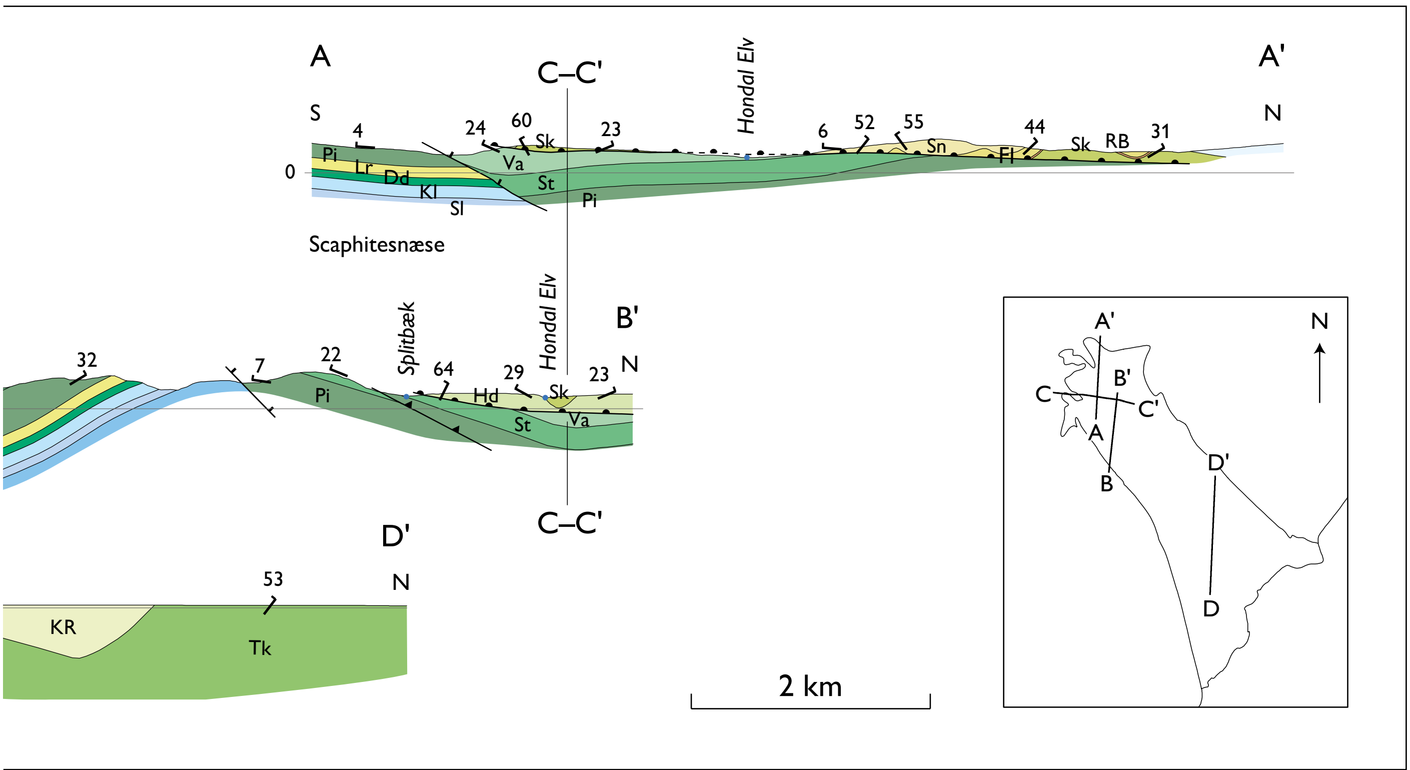


Fig. 5. (*second part*)

Map units

The lithostratigraphy of Kilen was initially established by Håkansson *et al.* (1993, 1994a) who subdivided the Carboniferous and Jurassic–Cretaceous deposits into 23 formations. Their distribution was shown on the unpublished map of Pedersen (1991) and in several subsequent publications (Dypvik *et al.* 2002; Røhr *et al.* 2008; Dypvik *et al.* 2011a; Dypvik & Zakharov 2012; Gjelberg & Steel 2012; Håkansson & Pedersen 2015). The lithostratigraphy for the Jurassic–Cretaceous deposits of Kilen has recently been revised and formalised by Hovikoski *et al.* (2018), and this subdivision is used here (Fig. 6). The formation names introduced by Pedersen (1991) and Håkansson *et al.* (1994a) have been retained where applicable. New names include the newly discovered Triassic Isrand Formation (Alsen *et al.* 2017), the Jurassic(?) Gletscherport Formation and the Pil, Stenbræk and Valmue Members of the Cretaceous Galadriel Fjeld Formation. The main changes with respect to Pedersen (1991) and Håkansson *et al.* (1994a) are within the Cretaceous succession, which is reduced from twelve to four formations.

Summing up the measured and modelled thicknesses the Mesozoic succession is at least 3260 m thick in Kilen Fjelde (Svennevig *et al.* 2015, 2016). The oldest rocks on Kilen are represented by a unit of polyphaser-deformed gypsiferous evaporite with limestone in a tectonic mélange unit tentatively thought to be of Carboniferous age (Håkansson *et al.* 1993). The Middle Triassic Isrand Formation consists of more than 200 m of mudstone and fine-grained sandstone (Alsen *et al.* 2017). The Jurassic strata include at least 535 m of sandstone and mudstone, and the Lower Cretaceous succession includes more than 1500 m of sandstone and mudstone. The Upper Cretaceous succession is at least 850 m thick and is dominated by mudstone, but also includes fine-grained sandstone and sideritic conglomerate.

On north-easternmost Amdrup Land, Erik S. Henius Land and Nordostrundingen the map units used on field maps and a 1:500 000 scale regional map (Bengaard & Henriksen 1984) have been adapted for the present map sheet.

Palaeozoic map units

Upper Palaeozoic tectonic mélange (UP)

Evaporites and limestones with evidence of polydeformation (Håkansson *et al.* 1993; Manby & Lyberis 2000; von Gosen & Piepjohn 2003) occur near the core of the Kuglelejet anticline (Fig. 2). The largest occurrence of evaporites is indicated on the map (**Ev**) and shown in Fig. 7a. The occurrence was first reported by Håkansson *et al.* (1993) who suggested a direct correlation with Upper Carboniferous (Moscovian) gypsiferous strata of the Kap Jungersen Formation in Amdrup Land 100 km to the south-west (Stemmerik & Håkansson 1989). The unit is thus tentatively referred to the Upper Carboniferous here. Alsen *et al.* (2017) discussed a possible Triassic age for the evaporites. The evaporites and limestones form part of a tectonic mélange, which is limited to the east by a fault (Fault I) and covered by Quaternary deposits to the west.

Foldedal Formation (Fd)

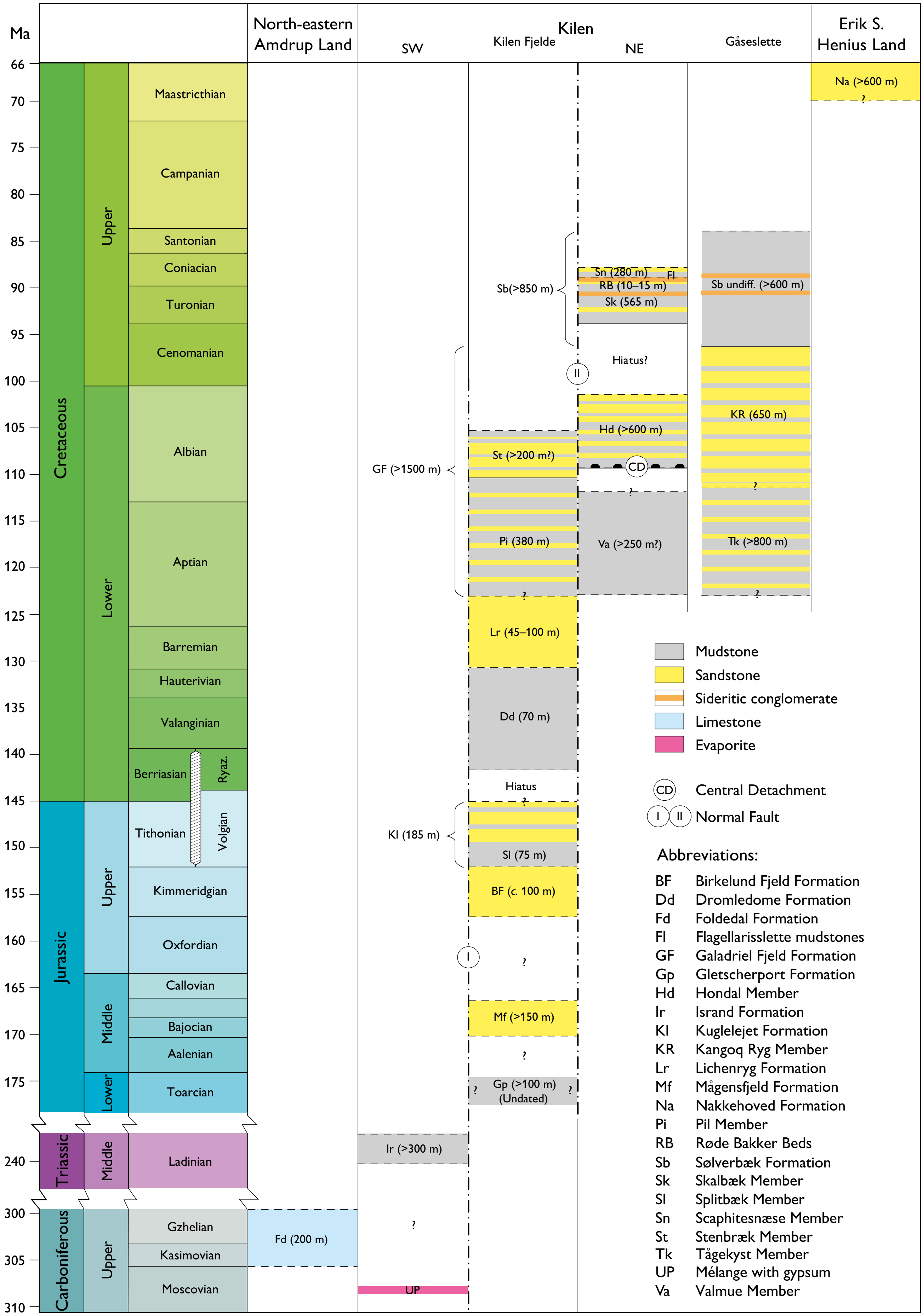
The Foldedal Formation in north-eastern Amdrup Land is an Upper Carboniferous (Kasimovian–Gzhelian) shallow marine, dolomitic limestone succession up to 200 m thick (Håkansson 1979; Stemmerik *et al.* 1996, 2000). The formation was deposited on isoclinally folded Proterozoic sedimentary rocks of the Independence Fjord Group (Hull & Friderichsen 1995; Stemmerik *et al.* 2000).

Mesozoic map units

Isrand Formation (Ir)

The Isrand Formation is found on Kilen immediately west of Fault I in the Kuglelejet anticline (Fig. 7b; Alsen *et al.* 2017). It comprises black mudstones with concretionary intervals. The strata were previously mapped as part of the Kuglelejet Formation (Pedersen 1991). The formation is at least 300 m thick and neither its top nor base is exposed. A late Ladinian, Middle Triassic age is obtained from halobiid bivalves and ammonoids (Alsen *et al.* 2017). The depositional environment is offshore, oxygen-deficient.

Facing page:
Fig. 6. Stratigraphic chart of the geological units shown on the map. Unit boundaries shown with full lines are biostratigraphically dated, whereas dashed unit boundaries indicate uncertain ages. The Central Detachment, Fault I and Fault II are indicated. Modified from Hovikoski *et al.* (2018) with additional data from Stemmerik *et al.* (1996) and Alsen *et al.* (2017). Note that the age of the Gletscherport Formation (Kilen Fjelde) is unknown; its age is constrained by the age of the overlying Mågensfjeld Formation.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Sb(>850 m)
Sn (280 m)
Fl
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GF (>1500 m)
Pi (380 m)
Va (>250 m?)
Tk (>800 m)
Lr (45–100 m)
Dd (70 m)
Hiatus
Kl (185 m)
Sl (75 m)
BF (c. 100 m)
Mf (>150 m)
Gp (>100 m) (Undated)
Ir (>300 m)
Fd (200 m)
UP
Mudstone
Sandstone
Sideritic conglomerate
Limestone
Evaporite
Central Detachment
Normal Fault
Abbreviations:
BF Birkelund Fjeld Formation
Dd Dromledome Formation
Fd Foldedal Formation
Fl Flagellarisslette mudstones
GF Galadriel Fjeld Formation
Gp Gletscherport Formation
Hd Hondal Member
Ir Isrand Formation
Kl Kuglelejet Formation
KR Kangoq Ryg Member
Lr Lichenryg Formation
Mf Mågensfjeld Formation
Na Nakkehoved Formation
Pi Pil Member
RB Røde Bakker Beds
Sb Sølverbæk Formation
Sk Skalbæk Member
Sl Splitbæk Member
Sn Scaphitesnæse Member
St Stenbræk Member
Tk Tågekyst Member
UP Mélange with gypsum
Va Valmue Member

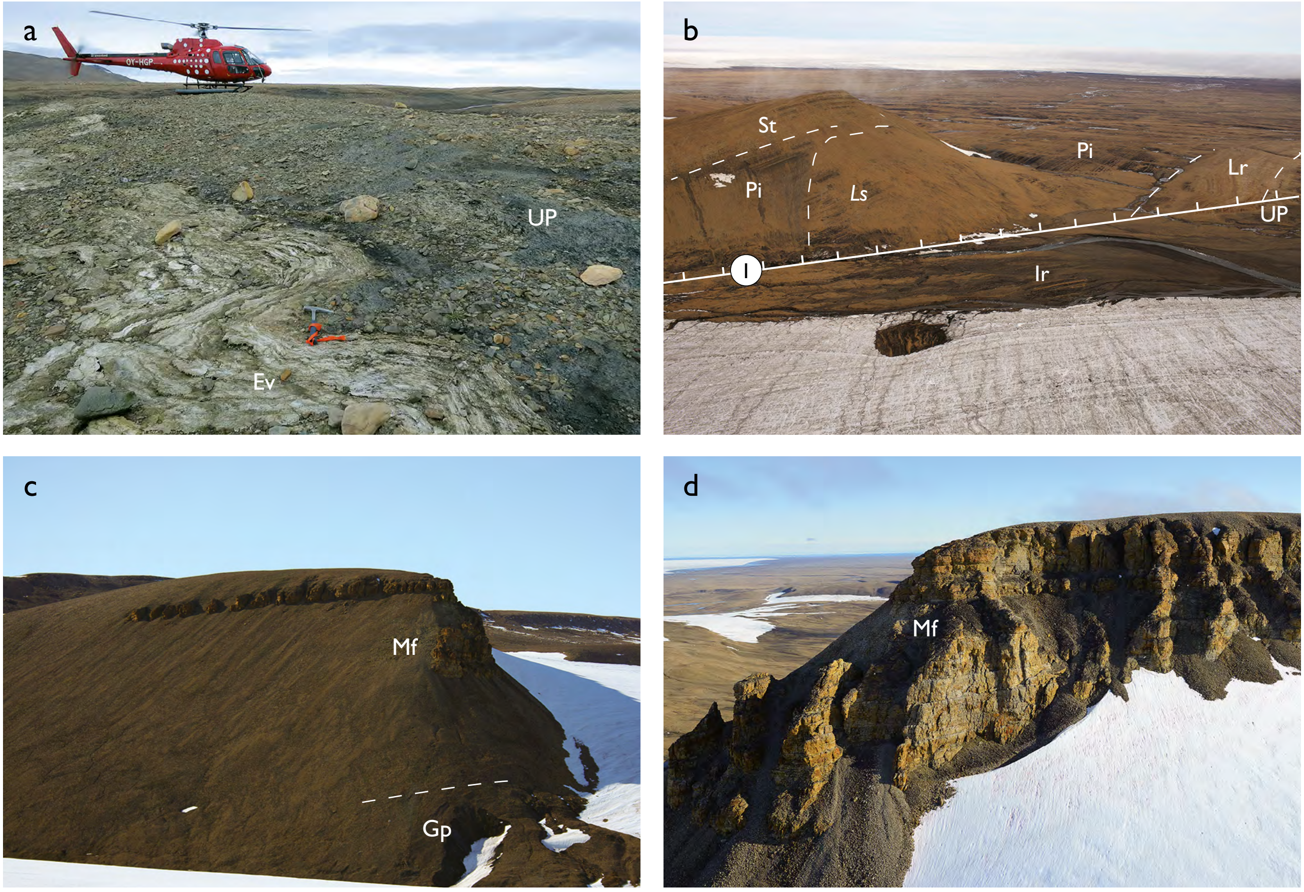


Fig. 7. Upper Palaeozoic – Middle Jurassic map units. **a**: Upper Palaeozoic tectonic mélange unit with polyphase deformed Carboniferous evaporites (**Ev**) in the core of the Kuglelejet anticline, looking north with Galadriel Fjeld in the background. **b**: The Isrand Formation in the footwall of Normal Fault I (**I**) at the foot of Galadriel Fjeld. A Quaternary landslide (**Ls**) is seen in the centre of the image. View towards the north-east; the Galadriel Fjeld 330 m high rises 200 m above the plain. It is made up of the Pil and Stenbræk Members of the Galadriel Fjeld Formation. The Lichenryg Formation constitutes the northern flank of the Kuglelejet anticline. **c**: Inclined bedding plane exposure of the Gletscherport Formation at the foot of the Mågensfjeld bird cliffs, overlain by the Mågensfjeld Formation. View towards the east. The valley is 150 m deep. **d**: Mågensfjeld Formation looking south-east at the type locality; Mågensfjeld, the same cliff as seen in the top of Fig. 7c. The cliff face measures *c.* 100 m from top to bottom. See Fig. 6 for key to the two-letter abbreviations and Fig. 2 for location.

Gletscherport Formation (Gp)

The Gletscherport Formation forms a variably exposed tectonic sliver at the foot of the north-east slope of the prominent cliff Mågensfjeld (Fig. 7c). The *c.* 70 m high exposure comprises steeply inclined sandstone and mudstone heteroliths with common plant fragments. The formation is located below the Middle Jurassic Mågensfjeld Formation but is undated. This exposure was previously mapped as the now abandoned Upper Cretaceous Sadelfjeld formation (Pedersen 1991). The inferred depositional environments include a wave- and tide-influenced, low-salinity to freshwater environment in a restricted setting such as a lagoon or bay (Hovikoski *et al.* 2018).

Mågensfjeld Formation (Mf)

The Mågensfjeld Formation is a fine-grained sandstone unit that forms a prominent bird cliff at Mågensfjeld (Fig. 7d; Pedersen 1991; Håkansson *et al.* 1994a). The formation is more than 150 m thick, of which the uppermost *c.* 100 m are well-exposed, whereas the lower part of the succession is covered by scree. Large belemnites are common. Ammonites occur locally and demonstrate a Middle Jurassic (Bajocian–Bathonian) age (Hovikoski *et al.* 2018). The formation was previously considered to be Upper Cretaceous (Coniacian; Pedersen 1991; Håkansson *et al.* 1994a). The interpreted depositional environments include protected lower–middle shoreface settings and deltaic intervals (Hovikoski *et al.* 2018).

Birkelund Fjeld Formation (BF)

The Birkelund Fjeld Formation is a dark grey to black, very fine- to fine-grained sandstone succession (Fig. 8a). Plant fragments are common and belemnites and ammonites locally occur and indicate a Late Jurassic (Kimmeridgian) age (Håkansson *et al.* 1994a; Hovikoski *et al.* 2018). The uppermost 45 m of the formation are exposed in the core of the Dromledome anticline where they are overlain by the Splitbæk Member of the Kuglelejet Formation. 3D modelling indicates that the formation is around 100 m thick. Sporadically bioturbated, stacked parallel-laminated beds may point to a gravity flow origin and a proximal prodelta-like environment, particularly in the top of the formation (Hovikoski *et al.* 2018).

Kuglelejet Formation (Kl)

The Kuglelejet Formation is a fine- to medium-grained sandstone succession that rests on the Birkelund Fjeld Formation (Fig. 8a). The deposits are commonly intensively bioturbated. Sporadically bioturbated, dune-scale cross-bedding occurs locally. Strata previously identified as the Multicoloured Unit (Pedersen 1991) near Lichenryg are now referred to the Kuglelejet Formation based on ammonites (Hovikoski *et al.* 2018). Exposures represent up to 90 m of the formation, but a thickness of 185 m, including parts covered by scree, is obtained from 3D modelling. Ammonites from the upper half of the formation indicate a Late Jurassic (Middle Volgian) age (Håkansson *et al.* 1994a; Hovikoski *et al.* 2018). The lower 75 m of the Kuglelejet Formation comprise a sandy mudstone succession, the Splitbæk Member (**Sl**), previously called the Splitbæk formation (Håkansson *et al.* 1994a). The deposits lack typical wave-generated sedimentary structures. This together with the trace fossil content and the high bioturbation intensity points to a sheltered setting such as an embayment or a bay (Hovikoski *et al.* 2018).

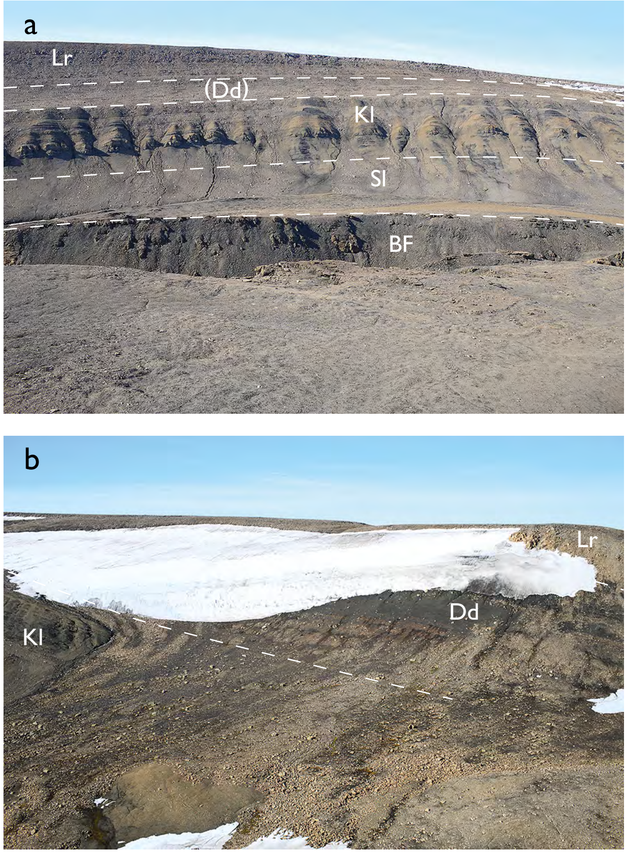


Fig. 8. Upper Jurassic – Lower Cretaceous map units. **a**: Birkelund Fjeld, Kuglelejet (with basal Splitbæk Member indicated) and Lichenryg Formations in the core of the Dromledome anticline looking west. The Dromledome Formation is covered by scree. The vertical distance from the top of Birkelundfjeld Formation to the top of the exposure is *c.* 150 m. **b**: Dromledome and Lichenryg Formations in the northern part of the Dromledome anticline looking west. The Dromledome Formation is *c.* 70 m thick for scale. See Fig. 6 for key to the two-letter abbreviations and Fig. 2 for location.

Dromledome Formation (Dd)

The Dromledome Formation is a black mudstone succession *c.* 70 m thick with concretionary intervals overlying the Kuglelejet Formation (Fig. 8b). The top of the formation shows local occurrences of hummocky cross-stratified beds. *Buchia* bivalves are common in the lower part of the formation along with foraminifera and ammonites indicating an Early Cretaceous age ranging from late Ryazanian – Hauterivian. The sedimentological characteristics as well as trace fossil and fossil content indicate a shelf to offshore environment (Hovikoski *et al.* 2018).

Lichenryg Formation (Lr)

The Lichenryg Formation is a succession of very coarse to coarse-grained, cross-bedded sandstone that overlies the Dromledome Formation (Figs 8a, 9a). The top of the formation is more fine-grained and heterolithic with mudstone interbeds. Plant fragments are common but no other macrofossils have been observed. The measured thickness in the northern part of the Dromledome anticline is 40–50 m. The modelled thickness, including scree and recessive parts, is 100 m. The age is confined by the bounding units to be Early Cretaceous (Hauterivian – late Aptian). The sedimentological characteristics as well as trace-fossil content point to fluvial and estuarine environments (Hovikoski *et al.* 2018).

Galadriel Fjeld Formation (GF)

The Galadriel Fjeld Formation was originally described by Håkansson *et al.* (1994a). The formation has been redefined by Hovikoski *et al.* (2018) and now includes the units, which were formerly assigned to the Kangoq Ryg, Tågekyst, Galadriel Fjeld and Hondal formations by Håkansson *et al.* (1994a). The Galadriel Fjeld Formation is now subdivided into six members: The Pil, Sten-

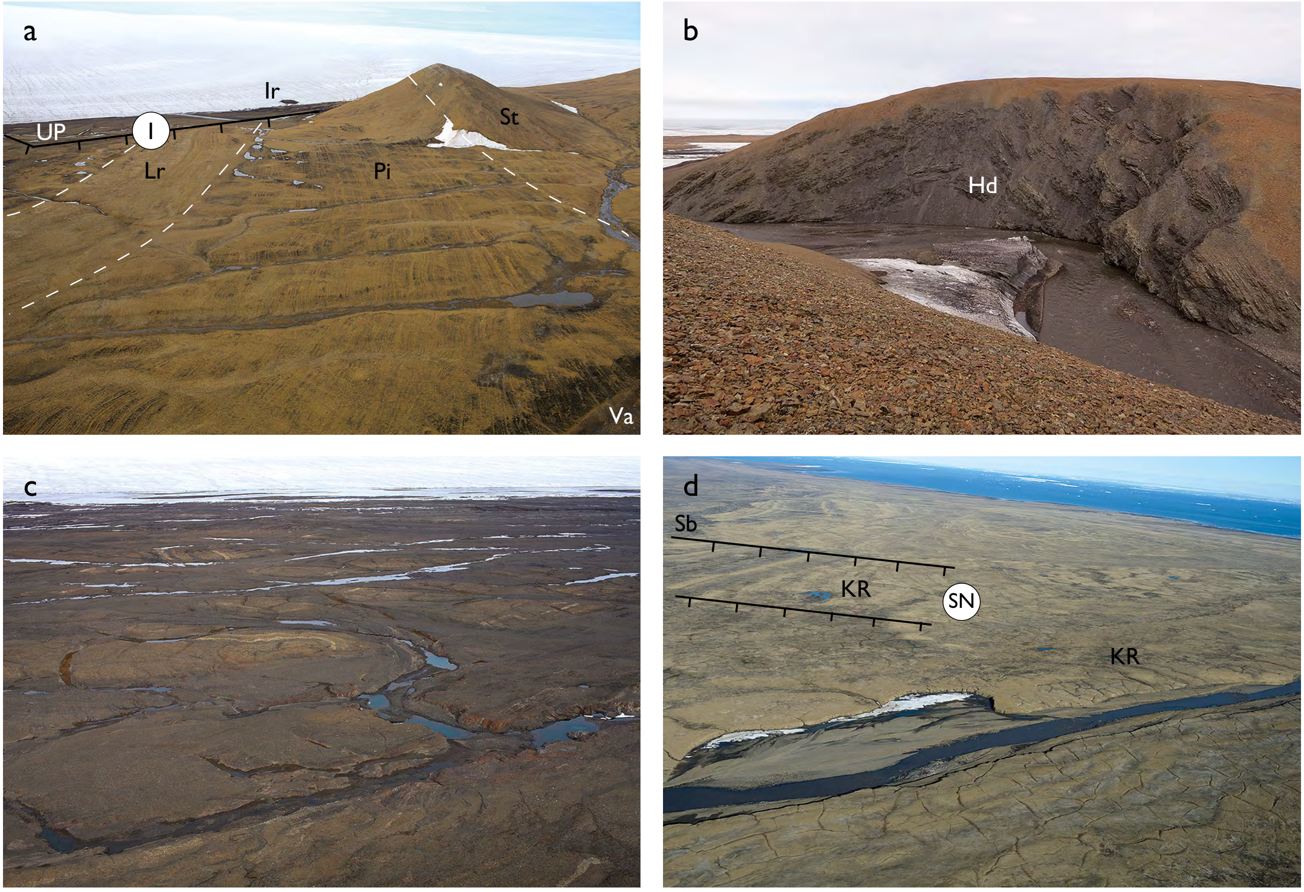


Fig. 9. The Cretaceous Galadriel Fjeld Formation. **a**: Lichenryg Formation and the Pil and Stenbræk Members of the Galadriel Fjeld Formation at the type locality, looking west. Galadriel Fjeld is 330 m high and rises 200 m above the plain. I: Normal Fault I. **b**: Well-exposed anticline within the uppermost, coarse-grained part of the Hondal Member in central Hondal valley. The view is towards the north; the cliff section is *c.* 50 m high. **c**: The Tågekyst Member at the northern part of the Anduin river looking east, showing the sandy beds in the otherwise fine-grained member. The base of the scene is *c.* 200 m across for scale. **d**: The Kangoq Ryg Member on southernmost Gåseslette showing bedding exposed on the plain and in the Sølverbæk river banks. The view is towards the east with the Iskap cape in the upper left of the photo. **SN** indicates the position of two of the Southern Normal Faults. The Sølverbæk river is up to 60 m wide for scale. See Fig. 6 for key to the two-letter abbreviations and Fig. 2 for location.

bræk, Valmue and Hondal Members in Kilen Fjelde, and the Kangoq Ryg and the Tågekyst Members in the Gåseslette area. Some of the members are time equivalent (Fig. 6).

A complete section through the Galadriel Fjeld Formation cannot be found. Its thickness is estimated to a minimum of 1500 m, but may vary in different fault blocks (Pedersen 1991; Svennevig *et al.* 2016). The formation includes several upwards-coarsening successions of mudstone to sandstone at various scales (Fig. 9). The formation ranges from the upper Lower Cretaceous (Late Aptian) to the lowermost Upper Cretaceous (early to middle Cenomanian), based on inoceramids, foraminifera, dinocysts, ammonites and belemnites. The formation is interpreted to represent storm-dominated offshore–shoreface environments (Hovikoski *et al.* 2018).

The *Pil Member* (**Pi**) comprises an upwards-coarsening succession of mudstones and very fine- to fine-grained sandstones containing glendonites (Fig. 9a). It corresponds to the lower and middle members of the Galadriel Fjeld formation of Pedersen (1991) and Håkansson *et al.* (1994b). The member is modelled to be 380 m thick at Galadriel Fjeld. East of Fault II at Tove Birkelund Fjeld the member may be even thicker.

The *Stenbræk Member* (**St**) comprises an upwards-coarsening succession of fine-grained sandstone with subordinate mudstone (Fig. 9a). It corresponds to the upper member of the Galadriel Fjeld formation of Pedersen (1991) and Håkansson *et al.* (1994b). Its top is not exposed but the member is more than 200 m thick in the syncline north of Kuglelejet. East of Fault II at Tove Birkelund Fjeld the member may be even thicker.

The *Valmue Member* (**Va**) comprises black mudstone with large concretions and glendonites (Fig. 9a). It was previously mapped as the Galadriel Fjeld lower member (Pedersen 1991), equivalent to the lower part of the present Pil Member but is here recognised as a separate member. The member is estimated to be at least 250 m thick, but its base and top are not exposed. It is separated from the Hondal Member by the Central Detachment Fault, which is observed north-north-east of Tove Birkelund Fjeld. The relation to the other members of the Galadriel Fjeld Formation is unclear.

The *Hondal Member* (**Hd**) comprises upwards-coarsening successions of sandy mudstone and fine- to coarse-grained sandstone (Fig. 9b). This member is the former Hondal formation of Håkansson *et al.* (1994a). The Dipperne formation of Pedersen (1991) and Håkansson *et al.* (1994a) is included in the Hondal Member based on sedimentological and palaeontological evidence (Hovikoski *et al.* 2018). The member is separated from the Valmue Member by the subhorizontal Central Detachment fault. The lower part of the member is correlated with the Stenbræk Member and possibly with the upper part of the Pil Member. The base of the Hondal Member is not exposed but the member is probably as thick as 600 m.

The *Tågekyst Member* (**Tk**) was mapped at Tågekyst and in the Anduin river areas as the Tågekyst formation by Pedersen (1991) and was described by Håkansson *et al.* (1994a). Outcrops along the Anduin river show that the member comprises sandy mudstones with interbedded fine-grained, locally coarse-grained sandstone beds (Fig. 9c). Its thickness is unknown but 3D modelling indicates that at least 800 m are present in the northern part of the Anduin river area (Svennevig *et al.* 2016). Areas mapped as Tågekyst formation in the Tågekyst area by Pedersen (1991) were found to be lower intervals of the Kangoq Ryg Member (see below). However, 3D modelling suggests that the Tågekyst Member is close to the surface here (Svennevig *et al.* 2016). The age of the member is unknown as fossils have yet to be found, but it is stratigraphically below the Kangoq Ryg Member.

The *Kangoq Ryg Member* (**KR**) is equivalent to the Kangoq Ryg formation of Pedersen (1991) and Håkansson *et al.* (1994a). Strata previously mapped as the Iver Pynt formation (Pedersen 1991) at Iskap are also included in the member based on a similar lithologies and age (Nygaard 2003). The member comprises bioturbated silty mudstones and fine-grained sandstones. It is exposed along the Sølverbæk river and is visible on the 1:150 000 scale aerial photograph of Gåseslette due to its light colour (Fig. 9d). The modelled thickness is around 650 m. The lower boundary towards the Tågekyst Member is not observed in the field but is inferred from aerial photographs of Gåseslette (see also Fig. 12c).

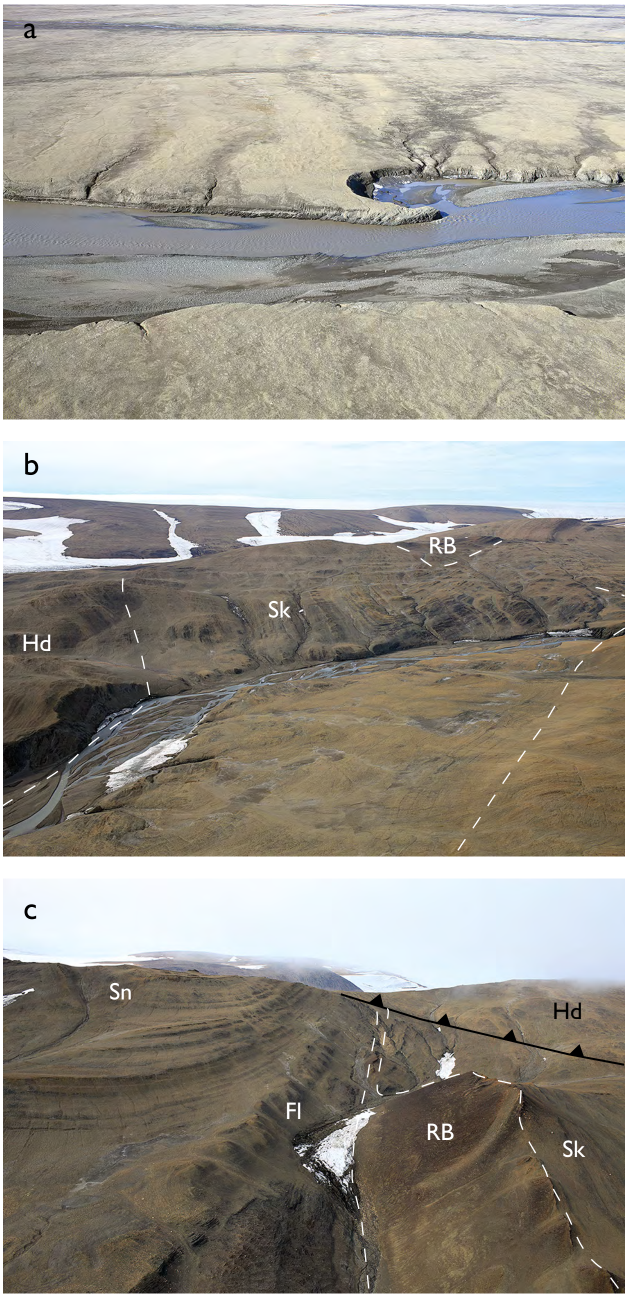


Fig. 10. The Upper Cretaceous Sølverbæk Formation. **a**: The Sølverbæk Formation in the Gåseslette plain in the banks of the Sølverbæk river viewed towards the west; the river is 50 m wide. **b**: The Skalbæk Member of the Sølverbæk Formation with the Røde Bakker Beds indicated in the core of the syncline in central Hondal valley looking west. The Skalbæk Member is 565 m thick for scale. **c**: Skalbæk Member, Røde Bakker Beds, Flagellarisslette mudstones and Scaphitesnæse Member at Saddelfjeld looking west. The Scaphitesnæse Member including the Flagellarisslette mudstones is 280 m thick for scale. The increased apparent thickness of the Røde Bakker Beds towards the viewer is caused by the erosional cut of the bedding. See Fig. 6 for key to the two-letter abbreviations and Fig. 2 for location.

Sølverbæk Formation (Sb)

The Sølverbæk Formation has been significantly expanded by Hovikoski *et al.* (2018) relative to its original description and extent (Pedersen 1991; Håkansson *et al.* 1994a). The sedimentary rocks of Kilen Fjelde, which were formerly referred to the Anduin, Skalbæk, Røde

Bakker, Scaphitesnæse, Flagellarisslette and Saddelfjeld formations (Pedersen 1991; Håkansson *et al.* 1994a), now make up the Sølverbæk Formation, which is subdivided into two new members: the Skalbæk Member and the Scaphitesnæse Member. In the Gåseslette area, the lithological variations were not large enough to justify subdivision into members (Figs 6, 10a). The formation is dominated by mudstone but also contains sandstone and thin marine conglomerates. The age is Late Cretaceous (Late Cenomanian to Late Santonian, possibly Early Campanian), based on inoceramids, ammonites and dinoflagellates. The youngest deposits found on Kilen (possibly Early Campanian), exposed along the central part of the Anduin river, are included in the Sølverbæk Formation (Hovikoski *et al.* 2018). The modelled minimum thickness in the southern syncline on Gåseslette is more than 600 m. In Kilen Fjelde, the formation is more than 850 m thick. Most of the formation represents shelf and offshore environments; nearshore settings occur locally (Hovikoski *et al.* 2018).

The *Skalbæk Member* **(Sk)** includes strata previously referred to the Anduin, Skalbæk and Røde Bakker formations by Pedersen (1991) and Håkansson *et al.* (1994a) and comprises up to 565 m of mudstone and sandstone with recurring sideritic conglomerates (Fig. 10b). *The Røde Bakker Beds* **(RB)** constitute the uppermost 10–15 m of the Skalbæk Member and comprise reddish to greyish sandstone, pebbly sandstone and conglomerate (Fig. 10c). They correspond to the Røde Bakker formation of Håkansson *et al.* (1994a) in the northernmost part of Kilen.

The *Scaphitesnæse Member* **(Sn)** includes sedimentary rocks previously referred to the Scaphitesnæse and Flagellarisslette formations by Pedersen (1991) and Håkansson *et al.* (1994a). The Scaphitesnæse Member is the uppermost member of the Sølverbæk Formation in Kilen Fjelde. It is more than 280 m thick and consists of interbedded mudstone and sandstone (Fig. 10c). The lower 130 m of the Scaphitesnæse Member comprise the informal unit *Flagellarisslette mudstones* **(Fl)** that corresponds to the Flagellarisslette formation of Håkansson *et al.* (1994a). The unit was not studied during the recent field work and is therefore not formalised by Hovikoski *et al.* (2018). The lithological description is adapted from Håkansson *et al.* (1994a, p. 7) without changes: "Very uniform upwards-coarsening sequence of greyish silty mudstone with storm-sand layers throughout. Topped by *c.* 10 m thick sandstone".

Nakkehoved Formation (Na)

The Nakkehoved Formation comprises a series of dark grey to almost black, fine-grained sandstones. At the type section at Nakkehoved, 40 km north of the mapped area, the formation is more than 600 m thick (Nielsen 1941; Dawes 1976; Håkansson 1979). A sparse marine fauna indicates a latest Cretaceous age (Håkansson 1979). Within the mapped area, the formation is recorded from Erik S. Henius Land and Nordostrundingen (Bengaard & Henriksen 1984) based on limited helicopter reconnaissance in 1980 by E. Håkansson and C. Heinberg. Only a few exposures were found here but the majority of the loose blocks are referred to the Nakkehoved Formation (E. Håkansson personal communication, 2017). There is no information on the depositional environment of the Nakkehoved Formation.

Quaternary map units

The Quaternary deposits on Kilen were not studied during the present mapping campaign and only the Ymer Formation (Hjort & Feyling-Hanssen 1987), a landslide at Galadriel Fjeld, the dried out branch of the Anduin river, deltas and generic Quaternary deposits have been differentiated on the map. The generic Quaternary unit comprises sandur, moraine, raised beaches and marine deposits. On Kilen these features were mapped by Pedersen (1991).

Ymer Formation (Y)

The Middle Pleistocene Ymer Formation was mapped in Ymer Klinter, forming the banks of the southern part of the Anduin river (Hjort & Feyling-Hanssen 1987). The position is based on Hjort & Feyling-Hanssen (1987), Håkansson *et al.* (1993) and oblique photogrammetry. The formation is 6–10 m thick and mainly consists of glaciomarine deposits.

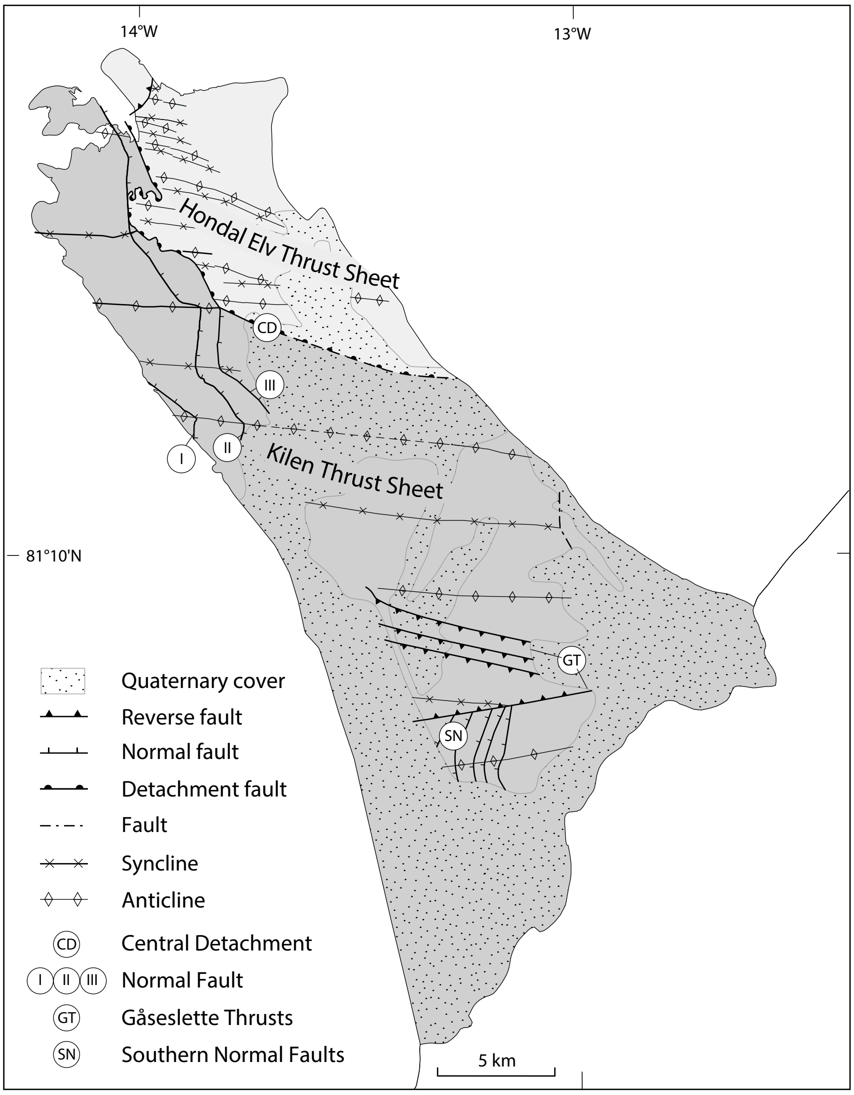
Landslide at Galadriel Fjeld

On the south-facing slope of Galadriel Fjeld a local feature interpreted as a Quaternary landslide is shown in the map (***Ls*** in Fig. 7b). This feature was previously mapped as a steep reverse fault associated with the compressional event (von Gosen & Piepjohn 2003, fig. 16b).

Structural elements

The structural geology of Kilen was discussed in detail by Svennevig *et al.* (2016). In general Kilen is characterised by large E–W-trending, symmetric, upright, parallel folds with horizontal or gently W-plunging fold axes associated with thrust faulting (Fig. 11). In the Sølverbæk and Anduin river sections small-scale folds with amplitudes of 30 m and wavelengths of 200 to 300 m, which dominate on outcrop scale, are interpreted as parasitic folds to the large-scale fold structures.

Fig. 11. Structural map of Kilen highlighting major faults and two thrust sheets separated by the Central Detachment identified by Svennevig *et al.* (2016).



The Central Detachment

On Gåseslette and in western Kilen Fjelde the Triassic–Lower Cretaceous strata form folds with amplitudes of 350 to 450 m and wavelengths of 4 to 6 km, whereas the upper Lower Cretaceous and Upper Cretaceous strata of eastern Kilen Fjelde are characterised by smaller folds with amplitudes of *c.* 175 m and wavelengths of up to 1.6 km. The two areas are separated by an overall NNW–SSE-striking thrust fault with a dip of 6°E, called the Central Detachment (Fig. 12d; Svennevig *et al.* 2016). The fault trace is complex due to the intersection of the low-angle fault with the terrain. The strata above the Central Detachment are referred to the Hondal Elv Thrust Sheet while the strata below are referred to the Kilen Thrust Sheet (Svennevig *et al.* 2016). Folds in both thrust sheets are truncated by the Central Detachment. The Kilen Thrust Sheet also includes the strata of the Gåseslette area as the large-scale folds here have the same wavelength as the folds in western Kilen Fjelde. This is further supported by the observation that the fold axis of the northernmost anticline in the Anduin river section can be traced across Flagellarisslette to the Kuglelejet anticline in Kilen Fjelde, and suggests that they are the eastern and western parts of the same large-scale fold (Figs 2, 11). Previously, the Central Detachment was mapped as several generic and strike-slip faults (Pedersen 1991; Håkansson *et al.* 1993).

The Gåseslette Thrusts

In the central part of Gåseslette, 10 km north-west of the shore, the Kangoq Ryg Member is thrust onto the Sølverbæk Formation in a S-verging frontal thrust and three imbricate backthrusts; the Gåseslette Thrusts (Fig. 12c; Svennevig *et al.* 2016). The dip-slip offset of the major reverse fault is estimated to be 1250 m in the cross-section, while the cumulative dip-slip offset on the three imbricate reverse faults amounts to 740 m.

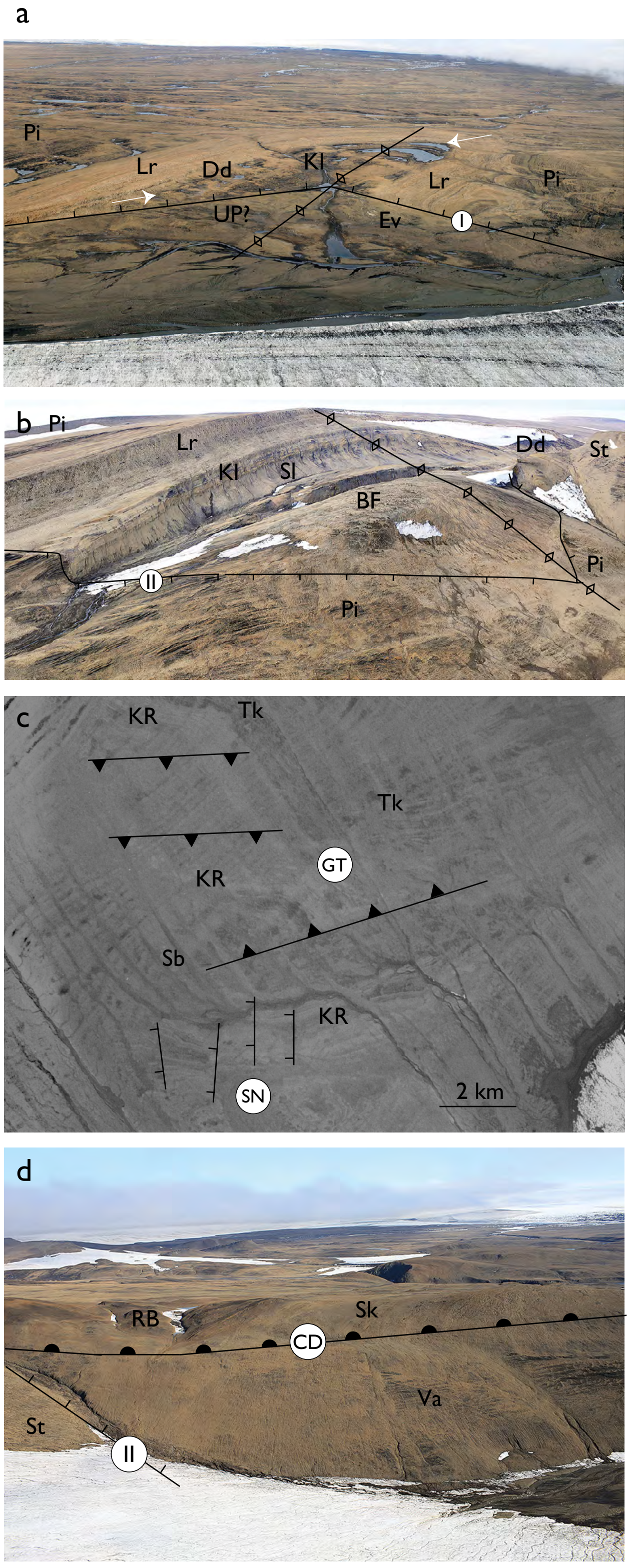


Fig. 12. The major faults on Kilen. **a**: Normal Fault I (**I**) in the Kuglelejet anticline. The fault changes strike exactly at the intersection with the fold axis. View towards north-east. For scale, the recessive darker part in the hanging wall of the fault is *c.* 400 m across (between the white arrows). Modified from Svennevig *et al.* (2016). **b**: Normal Fault II (**II**) in the Dromledome anticline. The fault changes strike where it intersects with the fold axis. View towards the west. The hill rises to 426 m above sea level; the section between the top of the Birkelund Fjeld Formation and the top of the Lichenryg Formation has a thickness of 275 m. From Svennevig *et al.* (2016). **c**: Black and white aerial photograph of southern Gåseslette plain showing the Southern Normal Faults (**SN**) and the Gåseslette Thrusts (**GT**). **d**: The Central Detachment bringing the Upper Cretaceous Skalbæk Member of the Hondal Elv Thrust Sheet into tectonic contact with the Lower Cretaceous Valmue Member of the Kilen Thrust Sheet. The view is towards the north-east. See Fig. 6 for key to the other two-letter abbreviations and Fig. 2 for location.

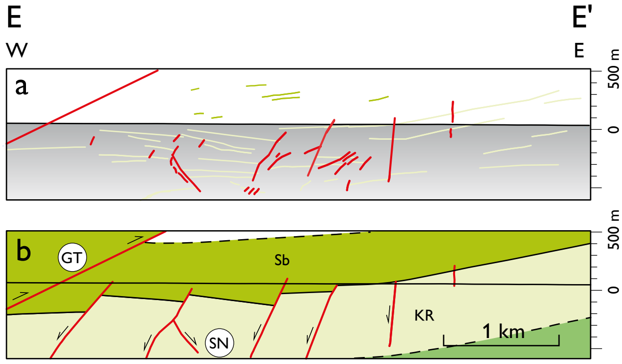


Fig. 13. Local cross-section E–E' of the Southern Normal Faults demonstrating the down-to-the W movement. **a**: Projected digitised polylines along the 53° dip of the northern flank of the anticline into the E–W-striking section. The grey area is below ground. **b**: Interpretation of a. See Fig. 2 for location. **GT**: Gåseslette Thrusts. **SN**: Southern Normal Faults. See Fig. 6 for key to the other two-letter abbreviations.

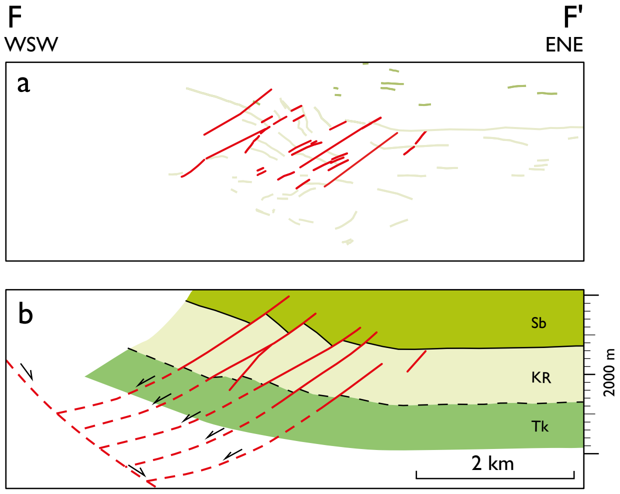


Fig. 14. Section F–F' showing the reconstruction of the Southern Normal Faults. **a**: Unfolded mapped polylines projected into a 55°-striking section (F–F'). **b**: Interpretation of a. Notice the decrease in dip of the normal faults from 48° in the north-east to 34° in the south-west. A large NE-dipping normal fault to the south-west (stippled red) is interpreted following the model of a reverse listric fan or counterfan (Gibbs 1984). See Fig. 2 for location and Fig. 6 for key to the two-letter abbreviations.

Normal Faults I, II and III

The Triassic – Lower Cretaceous succession in Kilen Fjelde is intersected by three normal faults with downthrow towards the NE (Svennevig *et al.* 2016). The faults all follow a regular zigzag-pattern striking roughly 130° on the northern limbs of the large-scale anticlines and 180° on the southern limbs, changing strike at the intersection with fold axes (Figs 12a, b). The fold axes of the large-scale folds are not offset by the faults. Svennevig *et al.* (2016) identified these faults as passively folded normal faults and named them Faults I, II and III, respectively. The westernmost Fault I has an estimated minimum offset of 1200 m. Fault II has an estimated minimum offset of 780 m. The easternmost Fault III is poorly exposed and its offset unknown but is estimated to be at least several hundred metres. On northern Gåseslette three minor normal faults follow the same trend as those described above. Håkansson *et al.* (1993) described mesoscale normal faults from central Sølverbæk, which may correlate with the normal faults observed on northern Gåseslette as indicated on the map. Previously Faults I and II were mapped as several generic and strike-slip faults (Pedersen 1991; Håkansson *et al.* 1993).

The Southern Normal Faults

Immediately east of the southern part of Sølverbæk river, in the northern limb of the southernmost anticline, a suite of at least six minor faults has been identified on black and white aerial photographs (Figs 4, 12c). The faults have variable strikes, changing gradually from 180° for the easternmost one to 20° for the westernmost one, with an average strike of 10°. These structures were also mapped by Pedersen (1991). In an E–W-striking cross-section (Fig. 13), the faults have a normal offset down-to-the W, which is opposite to the normal faults identified farther to the north. These faults are here called the *Southern Normal Faults*. Their limited offset and close spacing together with the general pattern of normal faults farther north suggest that they are folded antithetic faults.

The faults can be restored to their pre-folding state by unfolding the anticline in which they are exposed along with the mapped bedding and faults. When the mapped features are unfolded they are projected into a section oriented 55°N, orthogonal to the pre-folding strike of the normal faults farther north (Fig. 14). The cumulative offset in the restored section is several hundred metres. In their restored state, the antithetic faults outline at least five fault blocks (riders) with a sixth fault initiating to the north-east. The dip of the unfolded antithetic faults increases from 33° in the south-west to 48° in the north-east which could indicate that they are part of a listric counter fan where older faults (to the west-south-west) were rotated by successively younger faults as the fan evolved (Gibbs 1984). The fan would have been controlled by a larger, unexposed listric normal fault west of Sølverbæk. This fault is expected to link up with the Normal Faults I, II and III identified in Kilen Fjelde to the north.

Tectonic evolution

Previous structural models

The oldest deformational event previously identified at Kilen was a mid-Cretaceous extension observed in Lower Cretaceous units; the Kilen Event (Pedersen 1988). It was recognised by the presence of mesoscale normal faults in central Sølverbæk river and was linked to strike-slip movements resulting in the formation of an Upper Cretaceous pull-apart basin (Håkansson *et al.* 1993). Younger transpressional deformation was suggested to be of Late Cretaceous age as Paleocene–Eocene clastic strata of the Thyra Ø Formation 80 km north-west of Kilen were interpreted to rest undeformed on older deformed strata (Håkansson & Pedersen 1982). Three separate structural phases were recognised (Håkansson *et al.* 1993): (1) Anastomosing shear jointing of varying intensity with associated extensional planar joints. (2) En échelon domal folding with later minor thrust faulting in the synclinal areas with tectonic transport towards

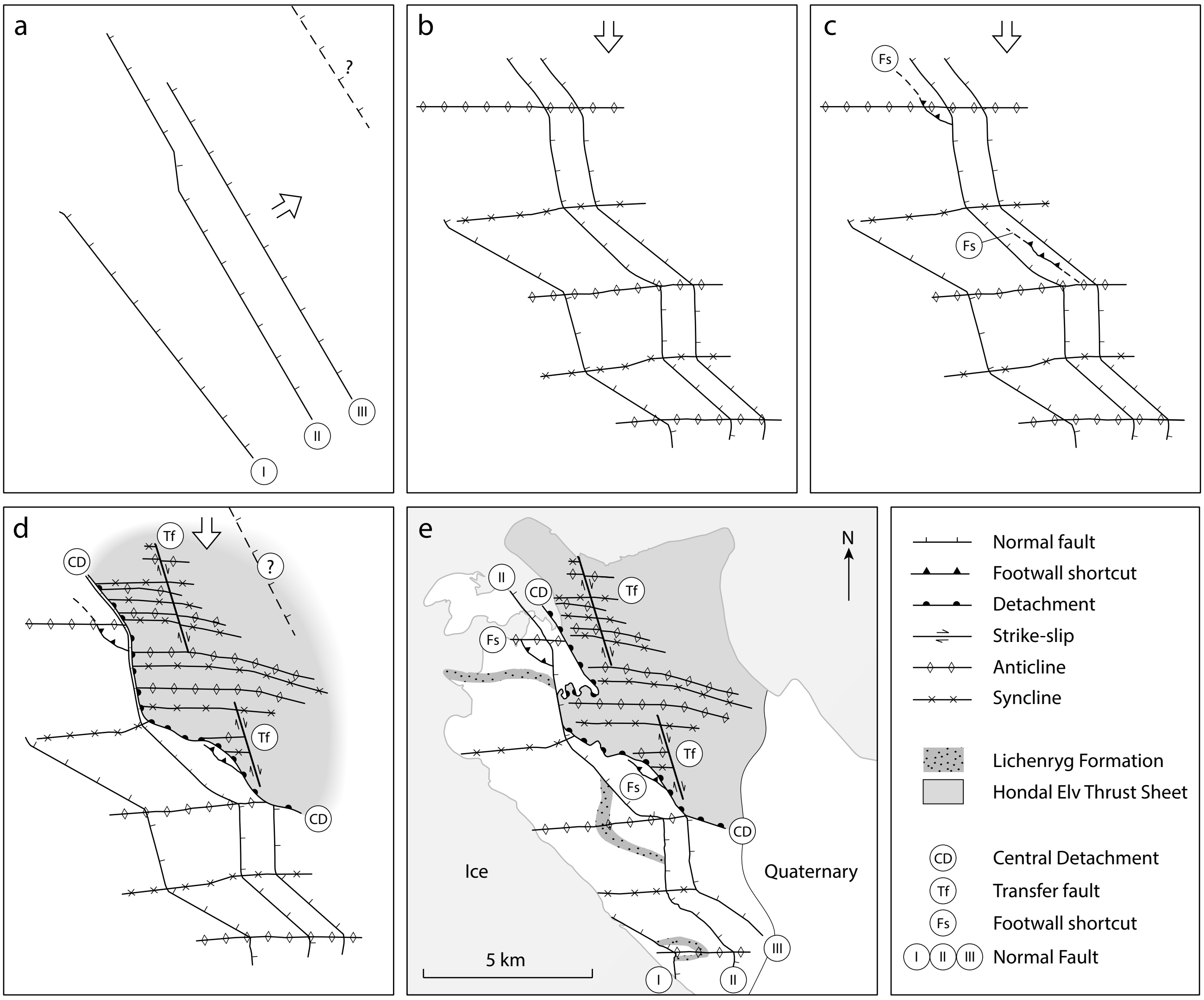


Fig. 15. Simplified step-by-step model of the tectonic evolution of Kilen Fjelde. **a**: Post-Coniacian extension forming NNW–SSE-trending normal faults. **b–d**: Post-extensional N–S compression forming folds and thrusts and passively folding the normal faults. **b**: Compression initiates large-scale folding of strata along with passive folding of normal faults. **c**: Continued shortening results in inversion on some of the 130°-striking limbs of the folded normal faults in the form of footwall shortcuts (**Fs**) in robust sandstone units. **d**: Folded Upper Cretaceous units are thrust up along an unknown inverted normal fault (**?** in Fig. a) to the present day position; minor transfer faults (**Tf**) accommodate differential shortening in the Hondal Elv Thrust Sheet and heterogeneities in the Central Detachment (**CD**). **e**: Present day situation with Lichenryg Formation shown for reference.

the north. (3) Dextral strike-slip faulting in the order of 1 km dividing the area into rhomb-shaped fault blocks. All three phases were interpreted to be the results of dextral transpressive strike-slip deformation (Pedersen & Håkansson 1999). East–west-striking folds and reverse faults from Kilen related to N–S compression were described by von Gosen & Piepjohn (2003). They inferred the presence of large-scale dextral strike-slip faults in the Sølverbæk and Anduin rivers and in Kuglelejet (Fig. 2). They also suggested that strike-slip-dominated transpression was related to the Eurekan orogeny. However, they did not find any structural evidence to support either strike-slip deformation or the generation of pull-apart basins during the Jurassic and Late Cretaceous.

New structural model

The recent mapping has emphasised the need for a new structural model of Kilen. The tectonic evolution was discussed in detail by Svennevig *et al.* (2016), who proposed a model where Kilen was subjected to an initial, post-Coniacian ENE–WSW extension forming the NNW–SSE-trending normal faults, and subsequently to a N–S compression generating the folds and thrusts and folding the normal faults. The younger-on-older relationship across the Central Detachment indicates that the strata in the Hondal Elv Thrust Sheet were down-faulted prior to the emplacement along the Central Detachment, suggesting that the overall tectonic pattern of Kilen is that of structural inversion. This model is supported by a recent study of thermal maturity data from Gåseslette showing that maximum burial occurred already during the Late Cretaceous, prior to the folding (Pedersen *et al.* 2018). The post-extensional N–S compression on Kilen has been suggested to be Paleocene–Eocene in age (Svennevig *et al.* 2016). No major strike-slip faults have been observed on Kilen and contrary to previous models (e.g. Håkansson *et al.* 1993; von Gosen & Piepjohn 2003; Håkansson & Pedersen 2015) strike-slip faults only play a very minor role in the overall tectonic evolution of Kilen. The tectonic evolution of Kilen Fjelde is summarised in Fig. 15.

Unresolved geological questions

The geological evolution of several of the map areas has not been resolved by the present mapping. Seven of these are briefly outlined below.

The tectonic boundary in Anduin river and the strata east of it

The large-scale folds characteristic of the Kilen Thrust Sheet have only been identified in the upper, north-western part of the dried-out branch of the Anduin river (Fig. 2). Along the central and southern parts of Anduin river and on Iskap, the photogrammetric mapping of large-scale folds is not well constrained by ground truthing. The previously ice-covered area to the east of the abandoned branch of the Anduin river has never been visited by geologists and was not mapped in detail through photogrammetry (Fig. 3). A series of E–W-striking folds with amplitudes of 50 m or more, a wavelength of up to 500 m and at least two E–W-striking faults are apparent and require further attention. The boundary between the large folds of Gåseslette and the smaller folds of southern Anduin river is not observed but seems to be composed of a northern segment striking 180° and a southern segment striking 165°. The change of strike appears to coincide with the fold axis of the major syncline on Gåseslette following the zigzag-pattern of folded Normal Faults I, II and III in Kilen Fjelde. This could indicate that the boundary is a folded normal fault. The strata west of the boundary belong to the Lower Cretaceous Tågekyst Member of uncertain age. On the eastern side of the Anduin river, the strata are Late Cretaceous in age and belong to the Sølverbæk Formation. This further supports the interpretation of the boundary as a down-to-the ENE, NNW–SSE-striking normal fault like the faults observed in Kilen Fjelde. However, due to the sparse field observations, the boundary is shown with a generic fault signature on the present map. Along the southernmost part of Anduin river and on Iskap, Lower Cretaceous strata are present (Nygaard 2003) but their relation to the rest of Kilen is at present unknown.

The thrust fault at Scaphitesnæse

In northernmost Kilen Fjelde, a thrust fault has been inferred, bringing strata of the Hondal Member up above the younger Sølverbæk Formation and truncating the folds below it (Figs 2, 10c). Previously this boundary was mapped as two generic strike-slip or intergroup extensional faults (Pedersen 1991). A thorough examination of the boundary including a study of kinematic indicators would help to establish where in the structural evolution the thrust fault belongs, and if the tectonic unit above it is a separate thrust sheet.

Uncharted area between Sølverbæk and the western ice margin

The area west of Sølverbæk towards the ice margin is shown as Quaternary in both the present map (Fig. 2) and the unpublished map (Pedersen 1991). The area has never been visited by geologists and deposits are interpreted as Quaternary from the 1:150 000 black and white aerial photographs. However, in the background of oblique images taken towards the south-west along Sølverbæk, some of the rivers close to the ice margin seem to cut several metres into the plain and it is possible that pre-Quaternary deposits could be exposed here (Fig. 16). If so, this would be a good place to look for the southern continuation of Normal Fault II.

Thickness variation across Normal Fault II

The thickness variations in the Galadriel Fjeld Formation across Normal Fault II (Pedersen 1991; Svennevig *et al.* 2016) call for further investigations including ground truthing and careful studying of similar units on either side of the faults to establish whether the normal faults were active in the Early Cretaceous.

Kinematics of modelled faults

More ground truthing in the form of kinematic data is needed to further examine the Central Detachment, the Gåseslette Thrust and the Southern Normal Faults to control the modelled and interpreted movement on these (Svennevig *et al.* 2016).

Erik S. Henius Land

Outside Kilen, especially in Erik S. Henius Land, the geology is poorly constrained and based on reconnaissance work in the early 1980s. A short reconnaissance stop in 2013 indicated that the geology may be more complex than indicated on the present and previous maps. Both carbonate rocks and small patches of igneous rocks

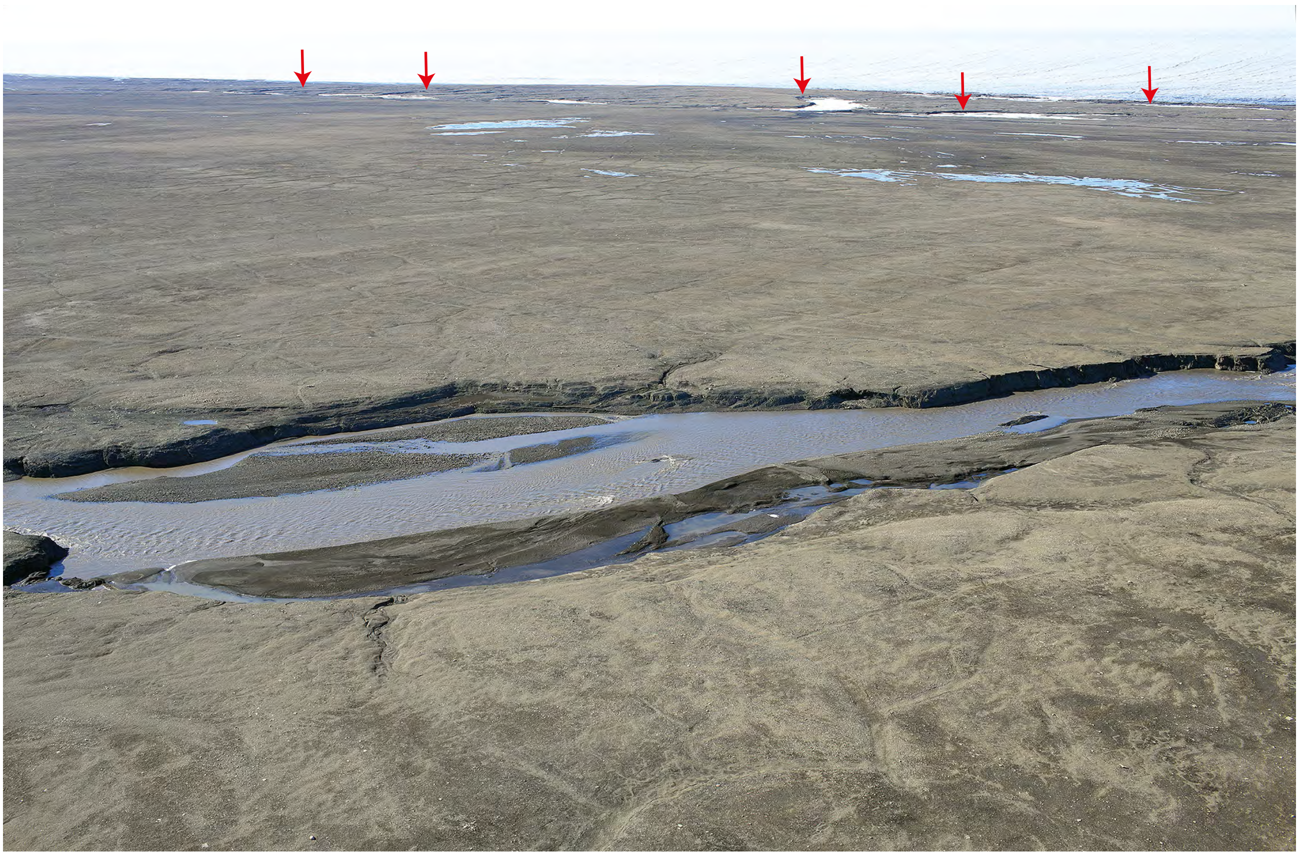


Fig. 16. Oblique image of Sølverbæk looking south-west with Flade Isblink in the background. Close to the ice margin, low cliffs are seen in the banks of minor streams where bedrock could be exposed (red arrows). The ice margin is 3–8 km away. See Fig. 2 for location.

were observed, and these are unlikely to be part of the Nakkehoved Formation.

Nordostrundingen

As mentioned above the existence of land at Nordostrundingen is questionable and should be confirmed by a visit to the area and some field work.

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