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Lithostratigraphy, geology and geochemistry of the Tertiary volcanic rocks on Svartenhuk Halvø and adjoining areas, West Greenland

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Abstract

The Palaeogene volcanic succession in the northern part of the Nuussuaq Basin in West Greenland comprises three formations: the Vaigat and Svartenhuk Formations of Paleocene age (61–58 Ma) and the Naqerloq Formation of Eocene age (57–54 Ma). In this study, we formalise and describe the volcanic stratigraphy on Svartenhuk Halvø and the areas with lavas that flowed across the basin boundary onto the adjoining basement areas in the north and east.

The Vaigat Formation comprises three members. The Kakilisaat and Nerutusoq Members are of minor volume and consist of, respectively, crustally contaminated basalts and chemically enriched basalts with relatively high contents of incompatible trace elements. They are overlain by the voluminous Nunavik Member of tholeiitic picrites (MgO ≥12 wt%) and subordinate magnesian basalts. The oldest volcanic deposits are commonly foreset-bedded hyaloclastites, and the overlying subaerial lavas are mainly thin, grey, crumbling flows. Eruption sites were mainly within the basin, with depocentres in the south and hyaloclastite and lava transport directions towards the north. Thicknesses vary from up to at least 2000 m in the south to ≥380 m in the northernmost exposures close to 72°N.

The Svartenhuk Formation comprises four members. The lowest, Kuugaartorfik Member, is up to 100 m thick and consists partly of quartzofeldspathic and partly volcanogenic sediments; it is restricted to northern Svartenhuk Halvø and the Innerit peninsula. The overlying volcanic Tunuarsuk, Nuuit and Skalø Members are voluminous and widespread, with a combined thickness of up to 1800 m. They consist of tholeiitic basalts with similar chemical compositions but with correlatable stratigraphic variation patterns. The Tunuarsuk Member consists of interspersed flow groups of thin, grey flows and massive, brown flows; the Nuuit Member comprises mainly massive brown flows, and the Skalø Member is dominated by light grey flows. The Svartenhuk Formation oversteps the Vaigat Formation on the basement in the north and east. In these distal areas the Tunuarsuk and Nuuit Members constitute the major volumes, and preserved thicknesses are up to 1400 m. In northern and eastern Svartenhuk Halvø and also farther to the north and east, foreset-bedded hyaloclastites indicate transport directions towards the north and possibly east from eruption sites within the basin.

The Naqerloq Formation comprises one member, the Arfertuarsuk Member, consisting of flows of brown basalt with relatively enriched chemistry and a single trachyte flow. The member is only found in western Svartenhuk Halvø and on Skalø, where it conformably overlies the older lavas with up to 350 m thickness preserved after erosion.

Dykes of all three formations are present. The distribution of dykes of the Naqerloq Formation suggests that this originally extended much farther east.

Picrites and basalts of the Vaigat and Svartenhuk Formations are geochemically related; the picritic lavas represent erupted primitive magmas, whereas the basaltic lavas represent fractionated melts formed in deep magma chambers. The melts formed from a geochemically depleted but heterogeneous mantle; in addition melts from enriched sources were occasionally incorporated. The enriched basalts of the Naqerloq Formation arose from another mantle source.

Low contents of V, Cu and Ni in some crustally contaminated lavas indicate that accumulation of these elements may be present at depth.

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Abbreviations
GEUS: Geological Survey of Denmark and Greenland
GPS: global positioning system
ICP-MS: inductively coupled plasma mass spectrometer
Loc.: locality
ODP: Ocean Drilling Program
REE: rare-earth element(s)
TAS: total-alkalis-silica
UTM: Universal Transverse Mercator
XRF: x-ray fluorescence

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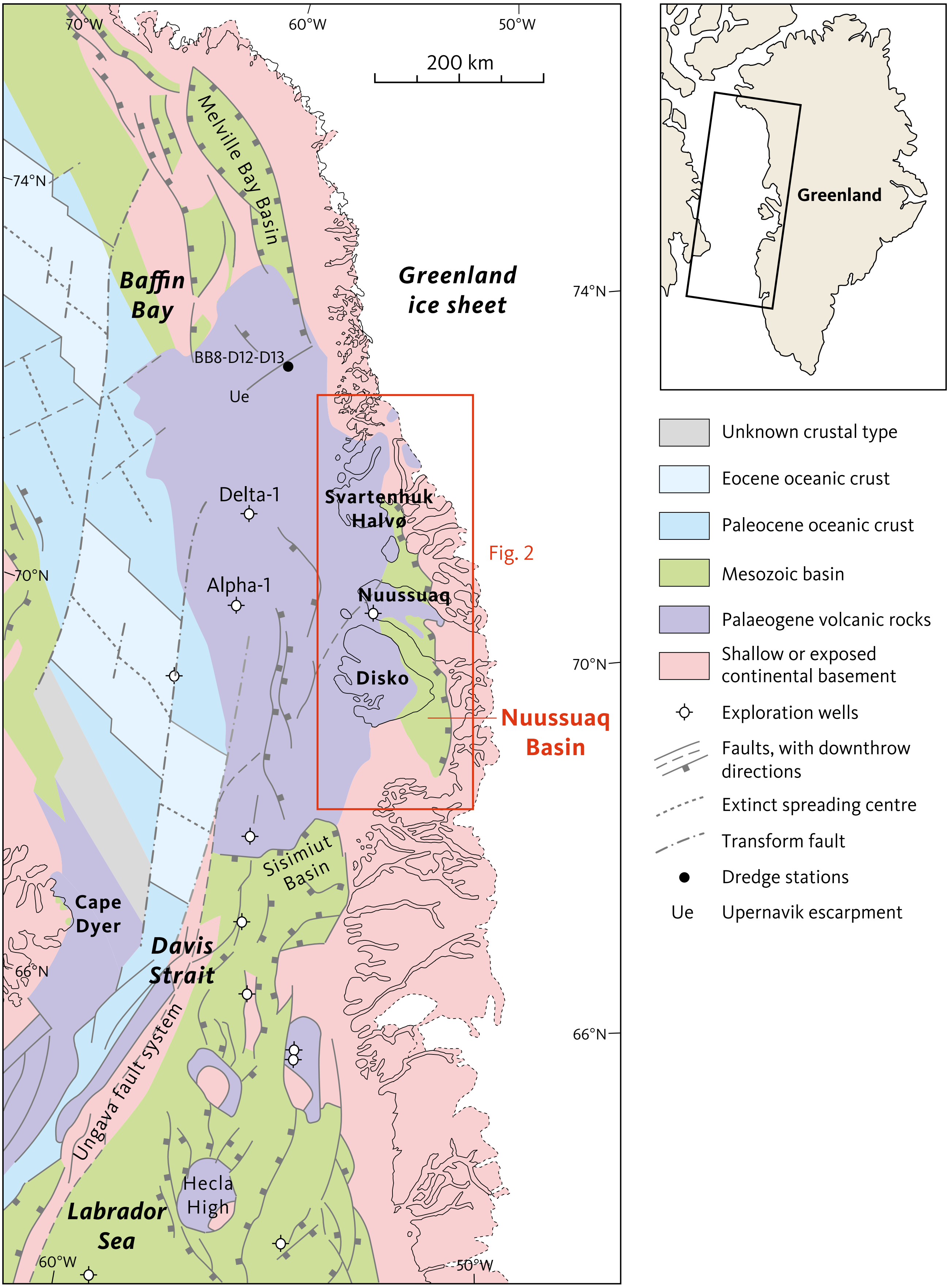

Fig. 1 Simplified geological map showing the regional and tectonic setting of the Nuussuaq Basin in West Greenland. Modified from fig. 1 in Dam *et al.* (2009) with results from Funck *et al.* (2012), Oakey & Chalmers (2012) and Gregersen *et al.* (2019). Dredge stations BB8-D12 and D13 on the Upernavik Escarpment from Polteau & Planke (2008).

Introduction

The Nuussuaq Basin is one of a series of linked basins that extend along the whole western continental margin of Greenland with a basin fill comprising Mesozoic to Tertiary sediments and Tertiary volcanic rocks (Chalmers & Pulvertaft 2001; Fig. 1). The basins are mainly situated in the offshore areas, but between 69° and 73°N the rocks of the Nuussuaq Basin are exposed on Disko (Qeqertarsuaq), Nuussuaq, Ubekendt Ejland (Illorsuit) and Svartenhuk Halvø (Nunavik or Sigguup Nunaa; halvø is peninsula in Danish; Fig. 2). The rocks have been studied since the mid-1850s because of occurrences of well-preserved fossils and coal in the sediments and of native iron in the volcanic rocks. In later years, hydrocarbons were discovered, mainly in the volcanic rocks. Moreover, the structures, lithologies and compositions of the exposed parts of the basin have been studied in order to provide clues and correlations to the geology of the large offshore areas where drilling has been carried out.

The volcanic rocks crop out over *c.* 20 000 km^2 within a basinal area of *c.* 120 km × 400 km (*c.* 50 000 km^2); including the sea-covered areas the volcanic rocks extend over a total area of *c.* 200 km × 550 km (*c.* 110 000 km^2; Chalmers *et al.* 1999; Oakey & Chalmers 2012). Offshore, they extend into the Melville Bay Basin in the north and the Sisimiut Basin in the south (Fig. 1).
The volcanic rocks in the Nuussuaq Basin were erupted at highly variable rates into a tectonically very active environment, and there was a complex interplay between the volcanic, sedimentary and tectonic evolution of the

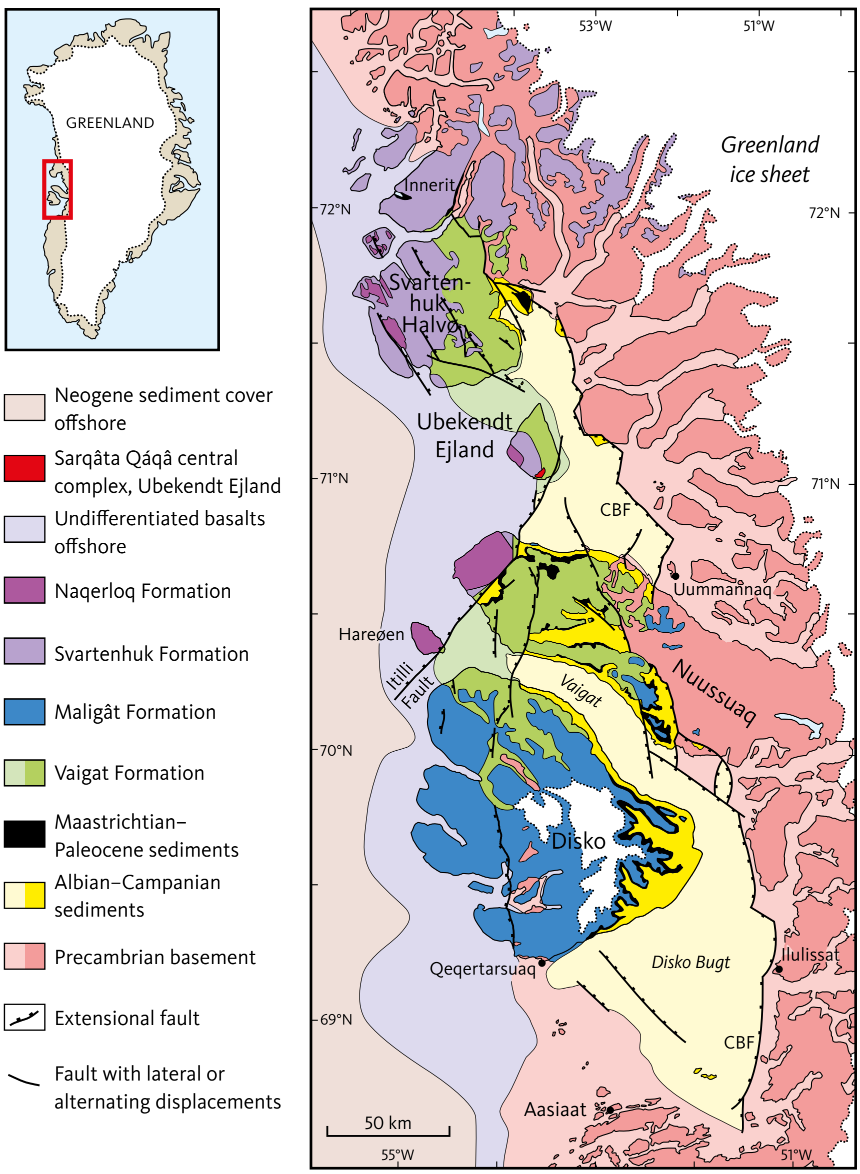

Fig. 2 Simplified geological map of the Nuussuaq Basin. Light colours: sea-covered areas. **CBF**: Cretaceous boundary fault system.

basin, which resulted in a complex architecture of the volcanic succession. Moreover, the range of magma compositions was large. West Greenland contains an unusually high proportion of primitive, Mg-rich picritic rocks that represent almost unmodified mantle melts (Drever 1953, 1956; Clarke 1970; Clarke & Upton 1971; Clarke & Pedersen 1976; Holm *et al.* 1992, 1993; Larsen & Pedersen 2000, 2009). However, repeated episodes of assimilation of crustal material, including organic-rich sediments, led to formation of units of silica-enriched volcanic rocks. On Disko and Nuussuaq these crustally contaminated rocks include native-iron- and graphite-bearing basalts, andesites, dacites and rhyolites (treated in detail by Pedersen *et al*. 2017, 2018).

The volcanic succession is divided into two major parts. The lower part is dominated by picrites and has been formalised as the Vaigat Formation, which is present from Disko and northwards to Svartenhuk Halvø and Innerit (Figs 2, 3; Hald & Pedersen 1975; Clarke & Pedersen 1976). The upper part is dominated by basalts and has been referred to different formations and members in different areas; according

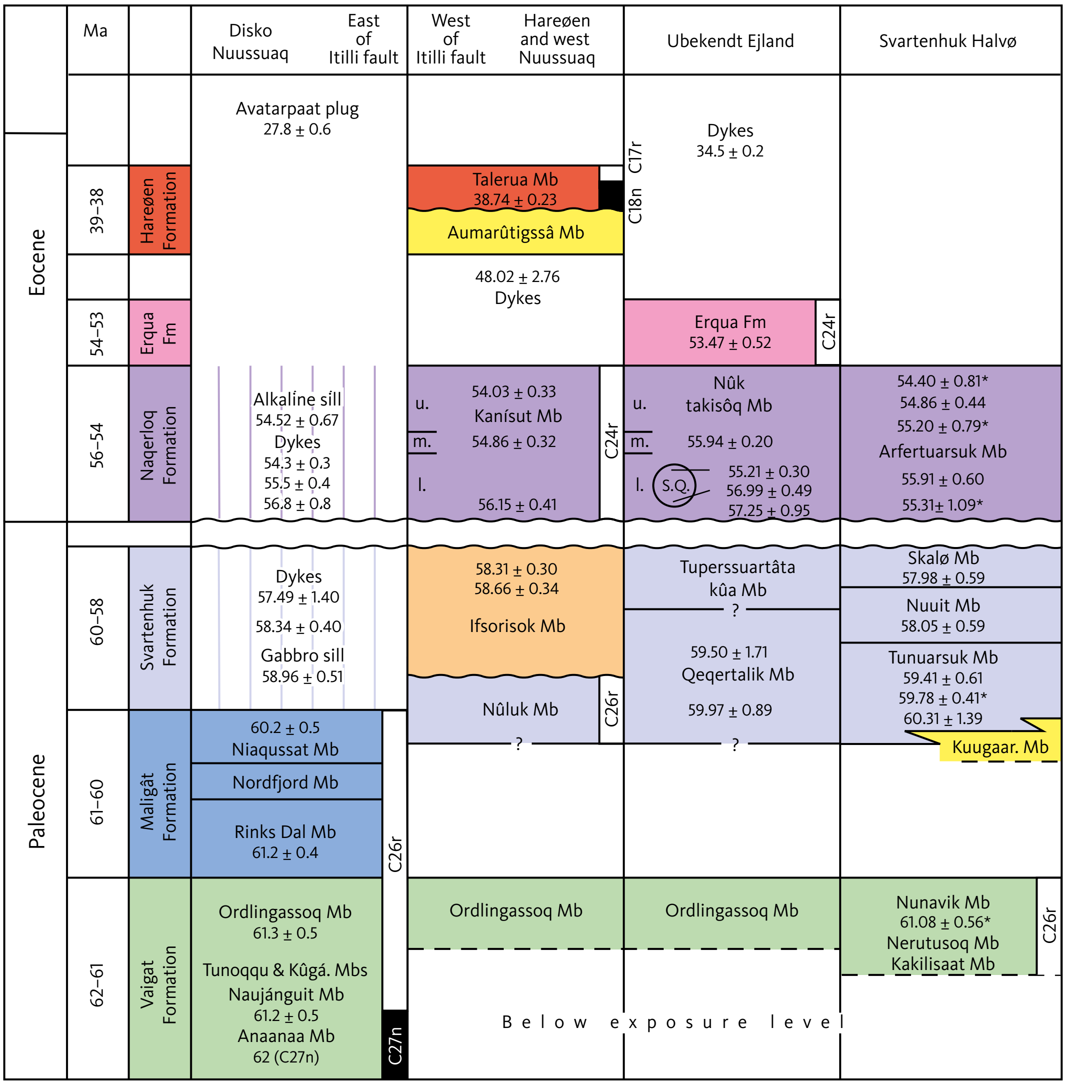

Fig. 3 Stratigraphic scheme and ^{40}Ar–^{39}Ar radiometric ages (in Ma) for the volcanic rocks in the Nuussuaq Basin, modified from Larsen *et al*. (2016). Radiometric ages with one digit after the decimal point are from Storey *et al*. (1998) and Larsen *et al*. (2009), ages with two digits after the decimal point (and no asterisk) are from Larsen *et al*. (2016) and ages marked with an asterisk are from Chauvet *et al*. (2019). The age for the Anaanaa Member is not radiometric but based on its normally magnetised character. Note that the vertical 'age scale' is not equidistant. Geological units are based on Hald & Pedersen (1975) for Disko and Nuussuaq, Hald (1976) for Hareøen and west Nuussuaq, Larsen (1977) for Ubekendt Ejland, and this study for Svartenhuk Halvø. **S.Q.**: Sarqâta qáqâ central complex; **Kuugaar. Mb**: Kuugaartorfik Member; **l.**, **m.** and **u.**: lower, middle and upper Nûk takisôq Member, respectively. Sediments with a quartzofeldspathic component are yellow and purely volcaniclastic sediments are brown. Wavy lines indicate unconformities. Narrow black and white columns on the right side of some lithological columns are normal and reversed palaeomagnetic directions, respectively, with magnetochrons indicated; data from Riisager & Abrahamsen (1999), Riisager *et al*. (1999, 2003), Schmidt *et al*. (2005), and P. Riisager (unpublished data, 2006).

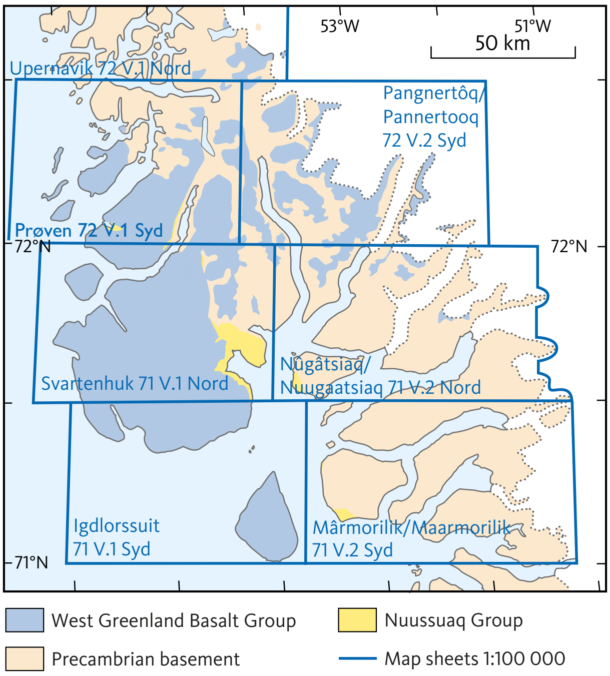

Fig. 4 Index map of geological maps covering Svartenhuk Halvø and the surrounding areas. Maps with names given in both old and new Greenlandic spelling were published 1970–1991 and in revised form in 2022 (Guarnieri *et al*. 2022 a,b,c). The Prøven and Upernavik maps are in compilation. The Igdlorssuit and Svartenhuk maps (Larsen 1983; Larsen & Grocott 1991) are provided in Supplementary files S1 and S2.

to the most recent dating and correlation by Larsen *et al*. (2016), the Maligât Formation is present on Disko and on Nuussuaq east of the Itilli Fault, whereas the Svartenhuk Formation is present on Nuussuaq west of the Itilli Fault, on Ubekendt Ejland, Svartenhuk Halvø and the areas farther north and east of this (Figs 2, 3). In this study, a new basalt formation of early Eocene age, the Naqerloq Formation, is established, which is present from Hareøen in the south through western Nuussuaq and Ubekendt Ejland to Svartenhuk Halvø in the north. The volcanic stratigraphy of Hareøen and westernmost Nuussuaq was described by Hald (1976), that of Ubekendt Ejland by Larsen (1977), and that of Disko and Nuussuaq by Pedersen *et al*. (2017, 2018).

In this study, we formalise and describe the volcanic stratigraphy of the northern part of the Nuussuaq Basin on Svartenhuk Halvø, including the lavas that flowed across the Cretaceous Boundary fault system to the adjoining areas in the north, north-east and east. The major part of the work was done south of 72°N on Svartenhuk Halvø and the southern part of the Innerit peninsula in connection with mapping for the two 1:100 000 scale geological maps that cover these areas: 71 V.1 Syd Igdlorssuit and 71 V.1 Nord Svartenhuk (Fig. 4). Basalt flows occur as far north as 72°43′N and as far east as 51°54′W (Fig. 5), but north of 72°N and east of 53°40′W, the data coverage is of reconnaissance character only. The extent of the volcanic rocks shown on the published 1:100 000 geological maps 71 V.2 Nord Nûgâtsiaq/Nuugaatsiaq and 72 V.2 Syd Pangnertôq/Pannertooq (Fig. 4) is mainly based on photo interpretation (Henderson & Pulvertaft 1987; Guarnieri *et al*. 2022a, b). The area north of 72°N and west of 54°W is at present only covered by the 1:500 000 geological map sheet 4 Upernavik Isfjord (Escher 1985).

Previous investigations of the Svartenhuk Halvø area

The earliest scientific descriptions of the volcanic rocks in West Greenland were published by Giesecke (1823; 1910) and Rink (1852) who used the terms "Floetz-trap" or "Trap-formation" and distinguished between "Trap-tuff" (hyaloclastite), "Basalt-tuff" (pillow breccia), "amygdaloid Basalt" and "columnar Basalt". The first geological map was produced by Steenstrup (1883) and shows the distribution of basement, sediments and volcanic rocks comprising "Traptuf (Palagonit?)" and "Trap" between 69°10′N and 72°35′N, with the major parts of the inland areas still unmapped.

In the first half of the 20th century, the general geology and structure of the Disko–Nuussuaq–Svartenhuk region was described by Koch (1929). Nieland (1931) described the mineralogy of an anorthoclase-rich trachyte flow from Arfertuarsuk and an olivine basalt dyke from south-east Svartenhuk Halvø and presented probably the first chemical analyses from the area. Rosenkrantz *et al.* (1942) presented a reconnaissance geological description of Svartenhuk Halvø. A more detailed study of the volcanic rocks of Svartenhuk Halvø was published by Noe-Nygaard (1942), distinguishing for the first time older picrites ("oceanites") from younger plagioclase-phyric basalts. Noe-Nygaard (1942, p. 67–68) estimated the thickness of the picrite succession exposed along the south coast of Svartenhuk Halvø to more than 10 km, based on the explicit assumption that there are no faults (no faults were observed due to foggy weather on the boat trip along the coast). Major faulting was indeed demonstrated by later workers (Rosenkrantz & Pulvertaft 1969; Münther 1973; Larsen 1983; Larsen & Grocott 1991).

After the Second World War, new expeditions to the area led to increased understanding and detailed knowledge of both the Nuussuaq Basin and the volcanic rocks, see e.g. Pulvertaft & Clarke (1966) and Münther (1973). Early reviews on the stratigraphy, tectonics and structure of the basin were given by Rosenkrantz & Pulvertaft (1969), Henderson (1973) and Henderson *et al.* (1981). Drever & Game (1948) and Drever & Johnston (1957), working on the picrites on Ubekendt Ejland, were the first to point out that the picrites must represent highly magnesian and very hot magmas. This view was supported by Clarke (1968, 1970), Clarke & Upton

(1971) and O'Nions & Clarke (1972) working on Baffin Island and Svartenhuk Halvø.

A comprehensive review of the volcanic rocks of West Greenland was published by Clarke & Pedersen (1976). This review is still essentially correct although many details have been added since then and, in particular, the stratigraphy and geochemistry of the volcanic succession are now much better documented and understood.

The two geological maps at scale 1:100 000 covering Svartenhuk Halvø were published by Larsen (1983) and Larsen & Grocott (1991). The geological basis for the maps was described in a comprehensive unpublished report by Larsen (1981a), and the present volume includes much information contained in that report without further reference to it.

An important paper, to which this study may be seen as complementary, is that of Larsen & Pulvertaft (2000). For the first time, the complicated structure of Svartenhuk Halvø is here described and interpreted in detail, with faulting and tilting of the sedimentary-volcanic succession. The paper also gives short overviews of the lithology of both sediments and volcanics based on Larsen (1981a) and later field work. Consequently, here we only treat the structure of Svartenhuk Halvø briefly and repeatedly refer to Larsen & Pulvertaft (2000).

In recent years, various aspects of the geology of Svartenhuk Halvø have been investigated. Gill *et al*. (1992) and Holm *et al*. (1992, 1993) presented petrological, geochemical and isotopic studies; Geoffroy *et al*. (2001), Abdelmalak *et al*. (2012) and Chauvet *et al*. (2019) investigated the structure of the faulted areas; Riisager *et al*. (2003) made palaeomagnetic profiles through the Vaigat Formation; Dam *et al*. (2009) established the formal lithostratigraphy of the Cretaceous–Tertiary sediments; Larsen *et al*. (2016) presented $^{40}Ar/^{39}Ar$ age determinations, and Agranier *et al*. (2019) presented geochemical data for a large sample set with a petrological interpretation of the magma genesis for the area.

Geological setting

General geology

The volcanic succession on Svartenhuk Halvø and adjoining areas belongs to the West Greenland Basalt Group (Hald & Pedersen 1975). This group extends onshore over a large area from Disko (69°15′N) in the south to inland areas east of Upernavik (72°43′N) in the north, a distance of nearly 400 km. It extends from the coastal areas and up to 150 km inland where basalt remnants cap the Precambrian basement at altitudes up to nearly 2000 m a.s.l.

The Nuussuaq Basin is bounded towards the Precambrian basement areas in the east by a system of large, deep faults, which run irregularly NNW–SSE and step repeatedly to the west (Fig. 2). These are referred to as the Cretaceous boundary fault system (Larsen & Pulvertaft 2000). This fault system runs through Svartenhuk Halvø and divides it into two parts: the Cretaceous–Tertiary basin in the west and the Precambrian basement covered by basalts in the north and east (Figs 2, 5, 6).

The Precambrian basement in the northern area considered here consists of Archaean and Proterozoic gneisses overlain by Proterozoic metasediments and metavolcanics of the Karrat Group (e.g. Grocott & Pulvertaft 1990; Thrane 2021; Guarnieri *et al*. 2022c). In the north, these rocks are cut by a large intrusion, the Prøven igneous complex, also of Proterozoic age (e.g. Escher 1985; Thrane *et al*. 2005). The surface of the Precambrian basement forms a broad, dissected dome with maximum altitudes around 2200 m east–north-east of Ubekendt Ejland, from where the surface slopes *c*. 1°NW and reaches sea level north of Innerit and Qeqertaq. This dome structure was first observed by Rink (1852, p. 20). From its maximum, the dome surface also slopes eastwards down to about 1500 m altitude before it disappears beneath the Greenland ice sheet (Fig. 5; Pulvertaft & Larsen 2002). The prevolcanic surface is uneven and constitutes a pre-Paleocene etch surface with irregular hilly relief (Fig. 5; Pulvertaft & Larsen 2002; Bonow 2005; Bonow *et al*. 2006), which has at least partly been covered by the basalts. The highest preserved basalt cover is at *c*. 1950 m altitude in the Umiammakku Sermia – Kangilleq area (Fig. 5; Pulvertaft & Larsen 2002). Any original basalt cover in the central dome area with altitudes above 1700–1950 m has been removed by erosion.

The south-western part of the area considered here, i.e. the northern Nuussuaq Basin area, comprises much of Svartenhuk Halvø and is dominated by volcanic rocks, which rest on Cretaceous–Paleocene sediments of the Nuussuaq Basin (Figs 2, 6). The prevolcanic sediments are exposed in the eastern part of Svartenhuk Halvø and have been described in overview by Larsen & Pulvertaft (2000). Dam *et al.* (2009) referred them to the Albian–Cenomanian Upernivik Næs Formation (deltaic sandstones interbedded with mudstones), the Turonian–Campanian Itilli Formation (marine mudstones), and the Maastrichtian–Danian Kangilia Formation (mudstones with conglomerates). Dam & Sønderholm (2021) reviewed the tectonostratigraphic evolution of the Nuussuaq Basin during the Cretaceous and Palaeogene with five phases of repeated rifting and faulting with concomitant sedimentation and finally breakup and volcanism.

The oldest exposed volcanic rocks in the Svartenhuk Halvø area are silicic basalts and picrites of the Vaigat Formation, which are correlated with the upper part of the Vaigat Formation on Nuussuaq and Disko (Fig. 3). Older parts of the Vaigat Formation may be present below exposure level to the west and to the south of Svartenhuk Halvø, but it is also likely that the volcanism of the Vaigat Formation spread gradually northwards from Nuussuaq. In any case, volcanism in the Nuussuaq Basin was well on its way at the time when the oldest volcanic rocks now exposed on Svartenhuk Halvø were deposited.

Offshore, the volcanic succession continues on the shelf south, west and north-west of Svartenhuk Halvø (Fig. 1) where seismic investigations have shown the presence of a volcanic package up to several kilometres thick (Whittaker 1996; Skaarup 2002; Skaarup & Pulvertaft 2007; Gregersen *et al*. 2013, 2019). Gregersen *et al*. (2013, fig. 5) pointed out a close connection between the onshore and offshore volcanic successions, and drilling and dredging have provided sample material. Basalt samples from the 2017 m volcanic succession in the drill hole Alpha-1 (location in Fig. 1) are compositionally similar to basalts from the Svartenhuk Formation (L.M. Larsen, unpublished data, 2011), and samples from the 1137 m volcanic succession in the drill hole Delta-1 (location in Fig. 1) are both compositionally and age-wise similar to basalts from the Naqerloq Formation (Nelson *et al.* 2015). Samples dredged on the Upernavik escarpment (Fig. 1) are compositionally similar to basalts from the Svartenhuk Formation (Polteau & Planke 2008).

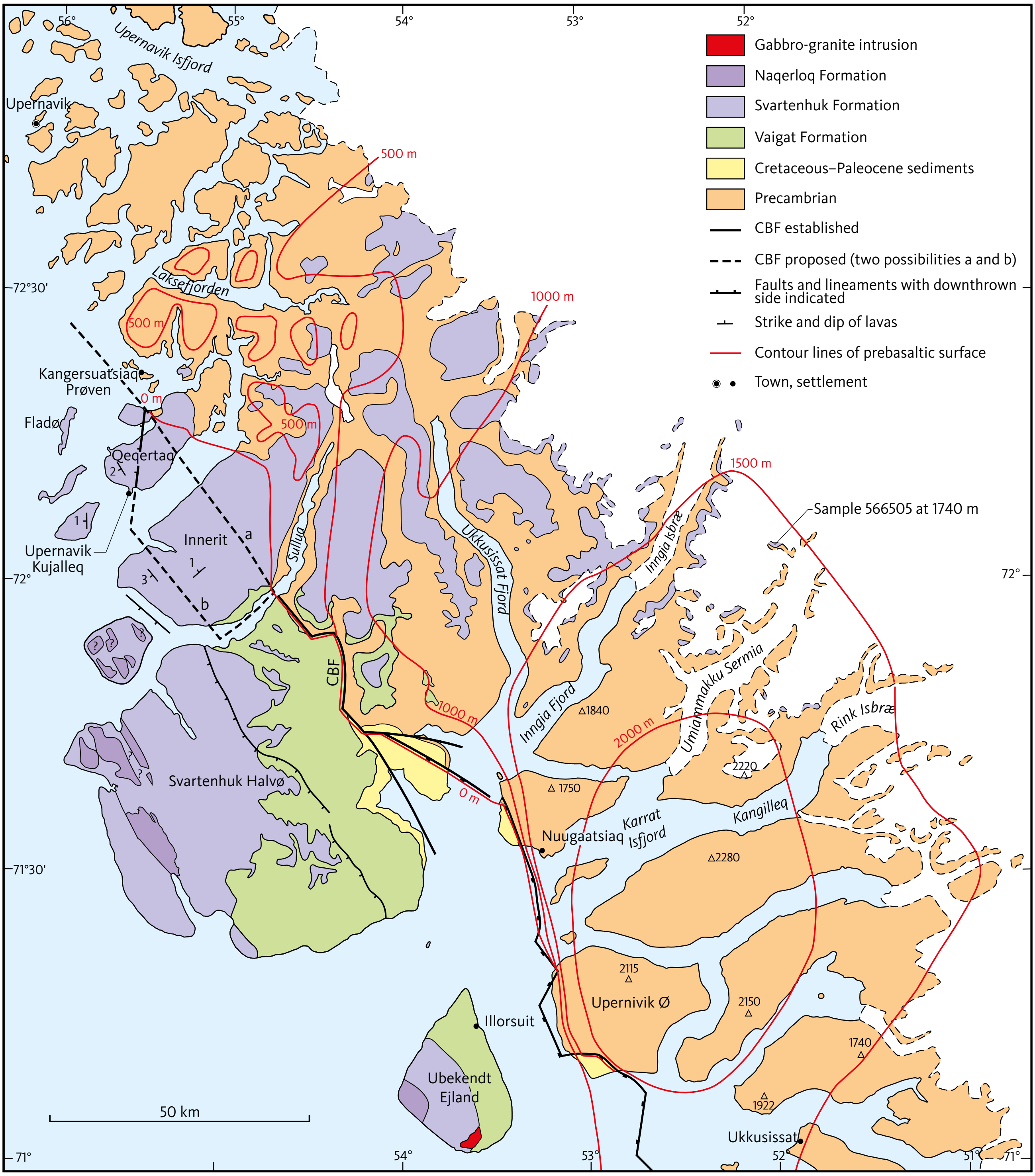

Fig. 5 Geological sketch map of West Greenland between 71° and 73°N. The northern and eastern extent of the volcanic rocks evidently continues farther to the north-east beneath the Greenland ice sheet. The location of the easternmost basalt sample 566505 is shown. The north-western extension of the Cretaceous boundary fault system (**CBF**) is uncertain and two possibilities are shown, which may both be part of the system. Red contour lines highlight the domal structure and uneven character of the prebasaltic surface; the red numbers are altitudes in m a.s.l.. The lines were constructed from the many closely spaced measurements of the altitude of this surface by Pulvertaft & Larsen (2002, plate 1) and, in the southern part, from the height of the basement peaks.

Structures

Basin area

In the basin south-west of the Cretaceous boundary fault system, the sedimentary-volcanic succession is heavily faulted, as described and analysed in detail by Larsen & Pulvertaft (2000). Prevolcanic faulting, uplift, downthrow and erosion in the basin area and along the boundary fault system is indicated by the fact that the volcanic rocks were deposited onto sediments ranging in age from Turonian to Paleocene; moreover, the sediments contain conglomerates and fanglomerates with basement clasts, some of which are cyclic. Locally the sediments show folding, which may be caused by gravity slumping or perhaps postvolcanic faulting (Larsen & Pulvertaft 2000, p. 12). Contemporaneous, interdigitating sediments and volcanic rocks are only found in a few places on south-eastern Svartenhuk Halvø (Larsen & Pulvertaft 2000, p. 12–13).

Syn- and particularly postvolcanic faulting is evident almost everywhere in the basin on Svartenhuk Halvø. Numerous postvolcanic extensional faults trending NW–SE have divided the area into a number of rotated fault blocks with SW-dipping strata with different dips (Fig. 6; Larsen & Pulvertaft 2000, figs 2, 9 and p. 23). Dips are smallest in the north-eastern and northern areas (2°–10°) and increase to 10°–45° south of some WNW–ESE-trending transfer faults. The largest fault is the NW–SE-trending Arfertuarsuk fault that runs through the Arfertuarsuk inlet in the south to Svartenhavn in the north (Fig. 6; names on Fig. 7) with a downthrow of the north-eastern block of at least 2 km at its south-eastern end (Larsen & Pulvertaft 2000, p. 24). Therefore, the youngest part of the succession is found on the north-eastern side of the Arfertuarsuk fault (Fig. 6) where the basalts dip 15–23°SW or more, and north thereof where the basalts dip only 0–10°. South-west of the Arfertuarsuk fault the Vaigat Formation reappears at Narsinganersua (Kap Cranstown) together with the older parts of the Svartenhuk Formation.

Northern extension of the Cretaceous boundary fault system

North of Svartenhuk Halvø, the Cretaceous boundary fault system is difficult to follow across the Innerit peninsula and Qeqertaq because of the largely unfaulted lava pile that has transgressed it. The most easterly possible location of the continuation of the boundary fault north of 72°N is along a SE–NW line running from the coast on south-eastern Innerit across Innerit and Qeqertaq, skirting a small exposure of basement at Itillia, and continuing out to sea in a nearly straight line (line a in Fig. 5). Another possibility is that the fault turns south-west in the Umiiarfik fjord between Svartenhuk Halvø and Innerit, then turns north-west and crosses southern Innerit to southern Qeqertaq, then turns north along a fault line there, and then out to sea (line b in Fig. 5). This position would explain some of the structures mentioned below (Locs D, E and F in Fig. 6). The anomaly pattern on the aeromagnetic map of Rasmussen (2002) makes a still more westerly position of the Cretaceous boundary fault system less likely.

Northern and eastern areas

East of the Cretaceous boundary fault system on Svartenhuk Halvø, the volcanic rocks resting on the high Precambrian basement are unfaulted and have a low average dip of 2.3°WNW (Larsen & Pulvertaft 2000). This is close to the overall slope of the prevolcanic basement surface, which dips 1.5°W to 2.1°WNW between Siuteqqut Kuuat and Kangiusap Aaffaa. The maximum preserved thickness is 1300 m beneath the 1700 m high mountain Siuteqqut (Fig. 7).

The volcanic succession north of 72°N is nearly flat-lying and with few exceptions unfaulted. In the western part of the area, the base of the lava pile is below sea level, and to the east, the lavas rest on the Precambrian basement that rises from sea level to an altitude of 2000 m close to the Greenland ice sheet. The overall dip of the lava succession here is around 1°NW to W, similar to the dip of the pre-basaltic basement surface.

In the following we describe some structural features in addition to those south of 72°N, which were treated by Larsen & Pulvertaft (2000). Locs A to G are shown in Fig. 6.

Loc. A. A prebasaltic, N–S-trending fault is presumably situated in Sullua fjord east of the Innerit peninsula. This is suggested from a jump in surface altitude of the basement across the fjord from 500 m a.s.l. on the eastern side to close to sea level on the western side of the fjord. The lava successions in the profiles 38 and 39 on the opposite fjord sides (Fig. 8) roughly correlate across the fjord with the elevation differences caused by the regional dip of 1°W of the lava pile.

Loc. B. There are indications of synvolcanic subsidence in the southern Innerit peninsula just east of the Paannivik profile (64, Fig. 8), where the lower part of the Tunuarsuk Member dips 4–6°SW with gradually decreasing dip up-section to 2°SW in the upper part and to 1°SW at the boundary between the Nuuit and Skalø Members on Paannivik, see dip measurements on the geological map of Larsen & Grocott (1991).

Loc. C. There is a weak anticline on the north-west coast of Innerit and the south-east coast of Qeqertaq, which could be a primary structure of a low lava shield.

Loc. D. One of the rare post-basaltic faults in the northern area crosses Qeqertaq with a direction close to N–S and a 25 m downthrow to the west. This fault

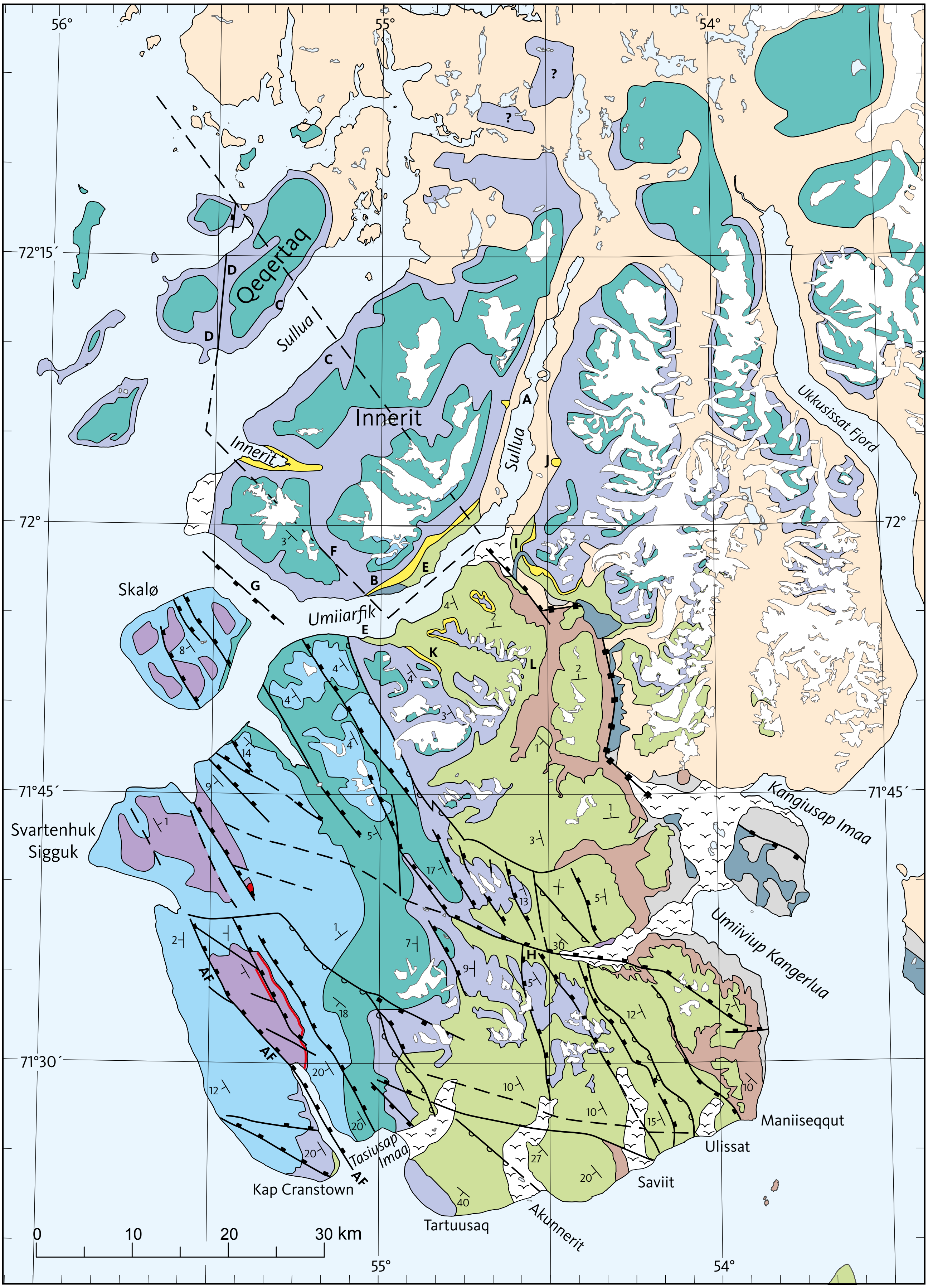

Fig. 6 Caption and legend on the next page

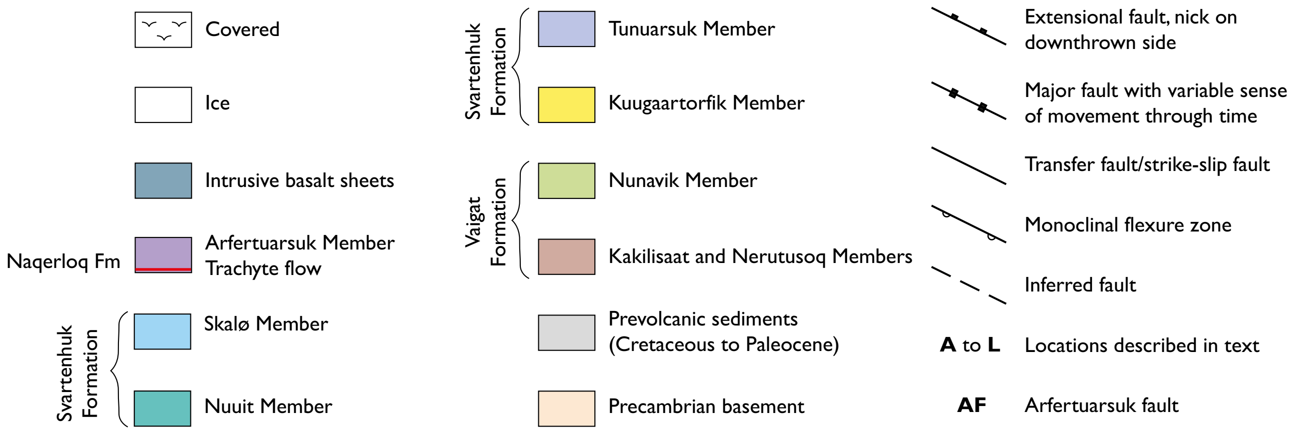

Fig. 6 (continued) Geological map of Svartenhuk Halvø and the northern volcanic areas. Geology south of 72°N after Larsen & Pulvertaft (2000, fig. 2). North of 72°N, the extent of the volcanic rocks is from Escher (1985); the boundary between the Tunuarsuk and Nuuit Members is extrapolated from the existing geological map south of 72°N, combined with the six sampled profiles north of 72°N (see Fig. 9), the nearly unfaulted and flat-lying state of the succession with a dip of c. 1°NW and the topographic map. Remnants of the Skalø Member are also present on several summits east of Sullua (Guarnieri et al. 2022a, b) but are mainly concealed beneath the ice. See Fig. 7 for place names mentioned in this study.

appears to form the boundary between 1°NW-dipping basalts to the east and 1–2°SW-dipping basalts to the west and may reflect the position of the buried Cretaceous boundary fault system, which must run out to sea immediately north-west of Qeqertaq (Fig. 5, line b). The lavas on Tukingasoq island also dip 1–2°SW whereas the lavas on Kigataq island dip *c.* 2°W.

Loc. E. Structural analysis of the boundary between the Vaigat and Svartenhuk Formations across Umiiarfik fjord indicates uplift (inversion) of the Svartenhuk Halvø side relative to Innerit, suggesting a hidden fault in Umiiarfik (Larsen & Pulvertaft 2000, p. 22). This fault could be part of the Cretaceous boundary fault system (Fig. 5, line b).

Loc. F. A concealed NW–SE-trending fault crosses southern Innerit. This is seen from the change in dip of the lavas across this line from 1°NW to 3°SW south-west of it, indicating a kink in the lava package. NW-trending dykes are common south of the line and rare north of it. This fault could also be part of the Cretaceous boundary fault system (Fig. 5, line b).

Loc. G. A postvolcanic fault probably trending NW–SE must be present in the sound between Innerit and Skalø, as indicated by the different dips of the lava packages on Innerit (3°SW) and eastern Skalø (close to 0°). The lava package on Skalø is downthrown *c.* 500 m relative to that on Innerit. This fault may be connected to the large flexure zone that runs through Svartenhuk Halvø from the south-east coast to the north-west coast (Fig. 5), with subsidence to the west of 600 m in northern Svartenhuk Halvø (Larsen & Pulvertaft 2000).

Methods

Field work, sample profiles and map compilation

This study is based on geological mapping by J.G. Larsen in 1974, 1976, 1980 and 1983, in 1983 together with T.F.D. Nielsen, and on geological mapping by K.A. Jørgensen in 1981. It is also based on earlier works, particularly by T.C.R. Pulvertaft, as described in Larsen & Pulvertaft (2000). Supplementary sampling was done by various field parties of the Geological Survey of Denmark and Greenland (GEUS) in the period 2009–2019. During mapping, the logging and sampling were preferentially done in traverses at locations where the stratigraphy was relatively undisturbed by faulting, although some profiles have been pieced together from shorter sections. Flow-by-flow sampling was applied when possible. Mapping and location of profiles and samples were done on aerial photographs on a scale of *c*. 1:40 000, and altitudes were measured with a traditional altimeter. Samples from 2009 and later were located and their altitudes measured with GPS (Global Positioning System). In total, 67 numbered and named profiles were measured and described in the field but not all of these were also sampled. The place names mentioned here are shown in Fig. 7 and the locations of all profiles are shown in Fig. 8.

About 1800 samples of mainly lava flows, hyaloclastites, intrusions and sediments were collected. Some of the most important and best sampled profiles are designated stratigraphic type and reference sections. For this study, these and some additional profiles mentioned in the text were located on the EOX Sentinel-2 cloudless satellite image data set available on the Greenland Portal (https://maps.greenmin.gl/geusmap/?mapname=greenland_portal). For each profile, the UTM (Universal Transverse Mercator) coordinates for the start and end points and some intermediate points were read. Altitudes were subsequently obtained from the Greenland Ice Mapping Project digital elevation model from NASA's National Snow and Ice Data Center (Howat *et al*. 2014). This data set has a resolution of 30 × 30 m, and as most profiles are situated on relatively steep mountain sides, the obtained heights are only moderately accurate. The geographical coordinates and altitudes and the digital elevation map showing the locations of these profiles (Fig. 9) were provided by Christian Brogaard Pedersen (GEUS). Their coordinates and approximate altitudes are given in Appendix 1 and in digital form in Supplementary file S3.

The digital elevation model in Fig. 9 gives an impression of the topography of the area; of particular notice are the mountainous areas separated by wide valleys with little or no exposure. A low-lying area seen in central western Svartenhuk Halvø presents a combination of poor exposures, faulting and steep and variable dips of the fault blocks; in this area some geological boundaries are only tentative or not placed at all, e.g. the boundary between the Nuuit and Skalø Members.

The most important sampled and analysed profiles are presented as vertical columns in Figs 10–13. The heights are m a.s.l., which deviate from true thicknesses in dipping successions; dips and strikes are therefore given below each profile. All the long and well-sampled and analysed profiles are included in the figures, whereas short and unsampled profiles are not.

The south and east coasts of Svartenhuk Halvø present a well exposed section through most of the volcanic stratigraphy in the area. The coastal exposures were photographed from the sea, and the photographs (diapositives) were subsequently projected onto a screen and traced by hand to produce pen drawings of five coastal sections (multi-model photogrammetry was not available at the time). The sections are shown in coloured versions in Figs 14–18. Their positions are indicated on Fig. 8. Due to complicated faulting and poor exposures, it was not possible to construct a similar picture of the part of the south coast between Akunnerit and Saviit.

The volcanic parts of the two geological maps at scale 1:100 000 covering Svartenhuk Halvø were compiled by J.G. Larsen using the 1:40 000 vertical aerial photographs, which were also used in the field. The Igdlorssuit map sheet was compiled with a Sketch Master, whereas for the Svartenhuk map sheet, the low-lying parts were compiled with a Sketch Master and the mountanous and difficult areas with a Kern PG2 stereo plotter. The Precambrian basement areas of the Svartenhuk map were compiled in a similar way by J. Grocott.

Geochemistry

Almost all major-element analyses presented here are by X-ray fluorescence spectrometry (XRF) and were made by Jørgen Kystol and Ib Sørensen at the rock geochemical laboratory at the Geological Survey of Greenland (GGU)/GEUS with analytical procedures as described by Kystol & Larsen (1999). Most elements were determined by XRF on fused glass discs with sodium tetraborate flux; Na_2O was determined by atomic absorption spectrometry, and FeO by potentiometric titration.

A subset of samples was analysed for trace elements by Jørgen Kystol and Olga Nielsen at GEUS using a PerkinElmer Elan 6100 DRC Quadrupole Inductively coupled Plasma Mass Spectrometer (ICP-MS). Sample dissolution followed a modified version of the procedure used by Turner *et al*. (1999) and Ottley *et al*. (2003). Calibration was done using two certified rare-earth element (REE) solutions and three international reference standards with reference values from Govindaraju (1994) supplemented with newer values for the REE from the GeoReM database (http://georem.mpch-mainz.gwdg.de). Results for reference samples processed and run simultaneously with the unknowns are normally within 5% of the reference value for most elements with concentrations >0.1 ppm.

Nearly all samples were ground in a tungsten carbide ball mill. This has introduced small amounts of Co and Ta into the powders. We estimate that 5–15 ppm Co has been added to the natural contents of 40–100 ppm Co, which does not conceal the natural variations. The amount of Ta added is mostly very small but may be significant in the picrites where the natural contents of Ta are only about 0.2 ppm.

Samples with numbers higher than 278607 had major elements analysed at the University of Edinburgh. All trace elements were analysed at GEUS except for samples 572001–572008, which were analysed at Actlabs Laboratories, Vancouver.

In total, about 900 samples were analysed for major elements and 300 for trace elements. From the Vaigat Formation, 166 samples were analysed for major elements and 48 for trace elements. From the Svartenhuk and Naqerloq Formations, 720 samples were analysed for major elements and 233 for trace elements. Twenty dyke samples were analysed for major elements and 14 for trace elements. All analytical data are available in Supplementary file S4.

In the chemical variation diagrams shown here, the elements have been recalculated to 100 wt% on a volatile-free basis. Samples with more than 7 wt% volatiles were as a rule not plotted and not analysed for trace elements. All *mg*-numbers and CIPW normative compositions given are calculated with Fe_2O_3/FeO adjusted to 0.15.

Nomenclature

The definition of igneous rock types is based on the Total-Alkalis-Silica (TAS) chemical classification of Le Maitre (2002) supplemented by a few extra terms. Picrites have MgO ≥12 wt% (Le Maitre 2002); we use 'magnesian basalts' for basalts with 10–12 wt% MgO, which are usually visibly olivine-phyric. 'Silicic basalts' have slightly increased SiO_2 = 51–52 wt% and have presumably been slightly crustally contaminated, as uncontaminated basalts in the region rarely have more than 51 wt% SiO_2. Rocks with SiO_2 >52 wt% are basaltic andesites.

We identify rocks, which are contaminated with continental crustal material by their elevated contents of SiO_2, K_2O, Rb, Ba, Th, U, light REE and Pb, and low MgO, CaO, TiO_2, FeO* (total iron as FeO), V, Cu and Ni relative to common mantle-derived rocks (Larsen & Pedersen 2009; Pedersen *et al*. 2018). High SiO_2, K_2O and Rb and low Nb are particularly diagnostic.

The term 'geochemically enriched' is applied to rocks with elevated contents of a number of incompatible elements such as P, Ba, Th, U, Nb, Zr, Sr, and the light REE relative to common mantle-derived tholeiitic basaltic rocks. High P, Nb and Sr are particularly diagnostic.

Pahoehoe lava flows are commonly thin and highly vesicular, particularly in their upper part. Their crust is smooth, with ropy and sometimes glassy top zones. Thin pahoehoe flows usually come in groups of flow lobes formed during the same eruption episode, and such groups are called compound lava flows (Walker 1971). Thick, massive flows with relatively thin and smooth flow tops are here called sheet flows following e.g. Self *et al*. (1997) and Sheth (2018). Lava flows of aa type are also thick and massive but have thick, highly scoriaceous top zones. On Svartenhuk Halvø, there is a morphological range between typical pahoehoe sheet flows and aa flows, but typical aa flows are rare.

Subaqueous lava flows are thick flows that commonly display various kinds of columnar jointing; they are usually brecciated in their upper part and capped by yellowish brown hyaloclastite; their top zones do not show red oxidation. Other fully or partly subaqueous flows are pillow lavas with pillows with glassy rims.

Entablature lava flows have tiers with a basal colonnade with vertical columns overlain by entablature zones showing irregular and fan-shaped columnar jointing. They are formed by emplacement into shallow water.

The lithological terms 'hyaloclastite' and 'pillow breccia' are frequently used synonymously. Following White & Houghton (2006), we use hyaloclastite as a general term to denote primary clastic subaqueous volcanic deposits. However, we frequently use 'pillow breccia' for coarse, clast-rich deposits even though these may include finer-grained clast-poor parts. The term 'volcaniclastic' is used as a nongenetic term to denote any clastic deposit with a large component of volcanic material, including both primary volcanic and nonvolcanic deposits such as mass-flows and other redeposited sediments.

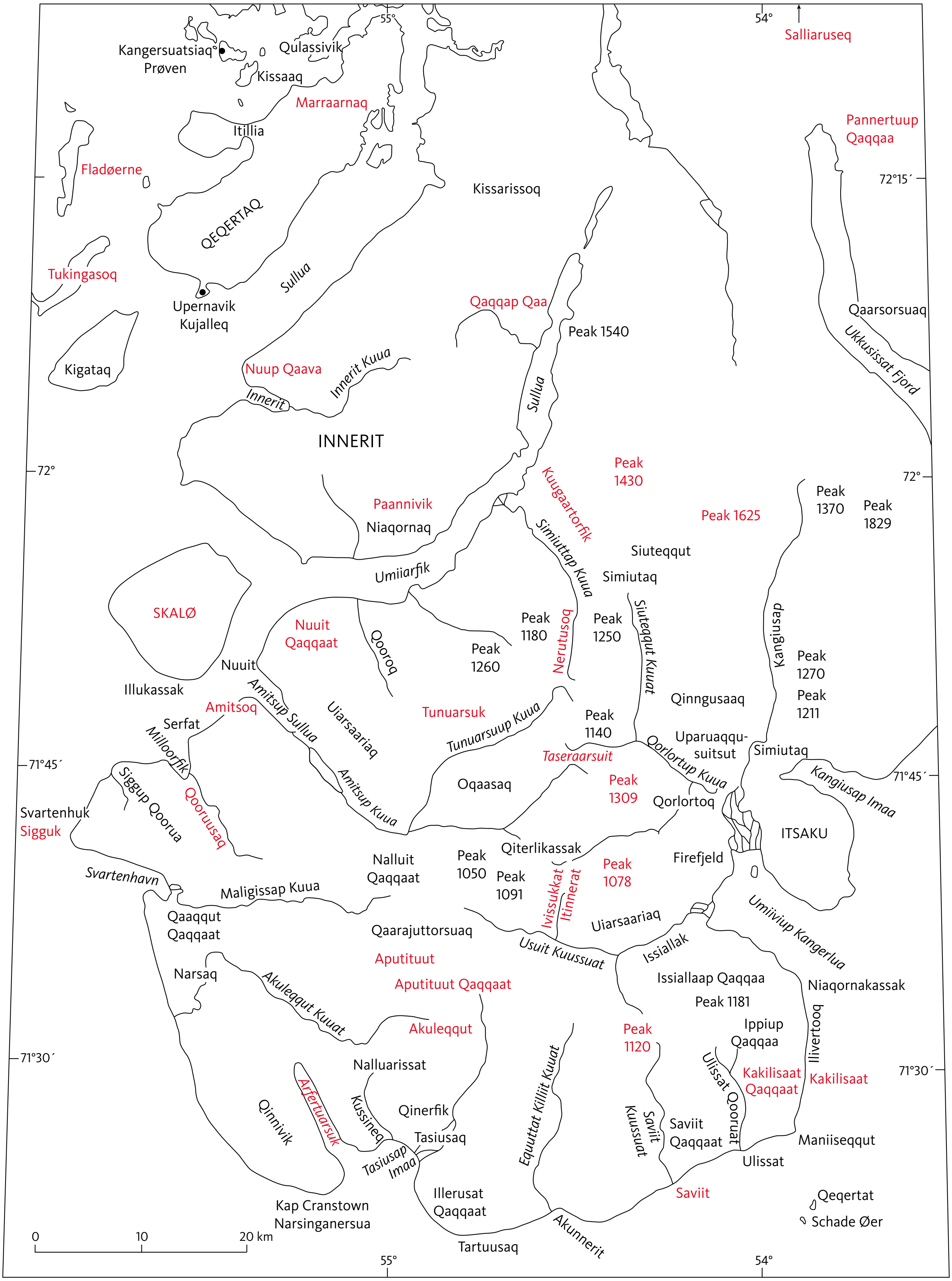

Fig. 7 Place names used in the text. Names in **red** are also profile names; their numbers are shown in Fig. 8.

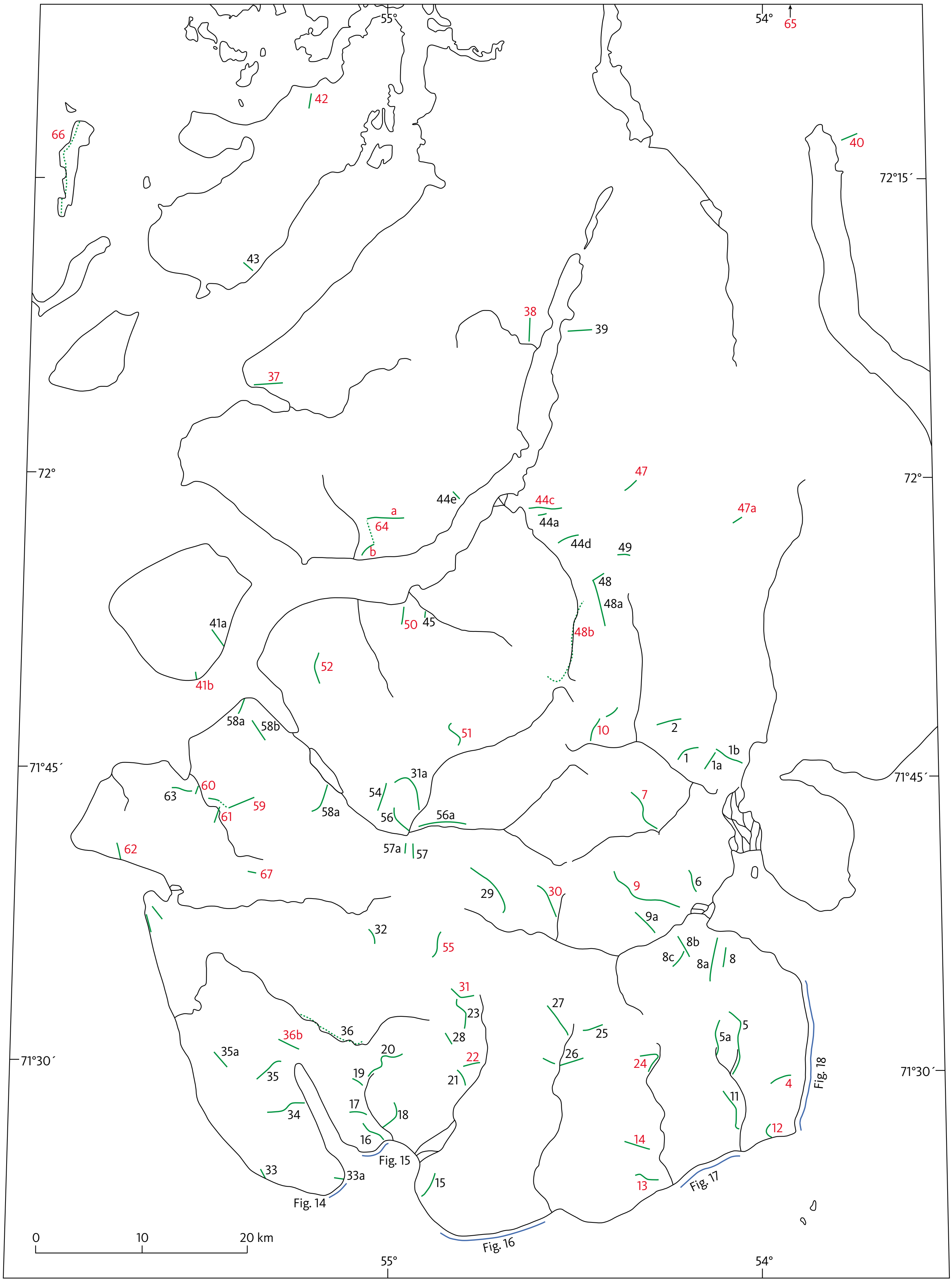

Fig. 8 Locations and numbers of all studied profiles through the volcanic succession. Profiles with **red numbers** are mentioned in the text and their names shown in Fig. 7. Most of these profiles are shown as vertical schematic 'logs' in Figs 10–13, and their coordinates are listed in Appendix 1.

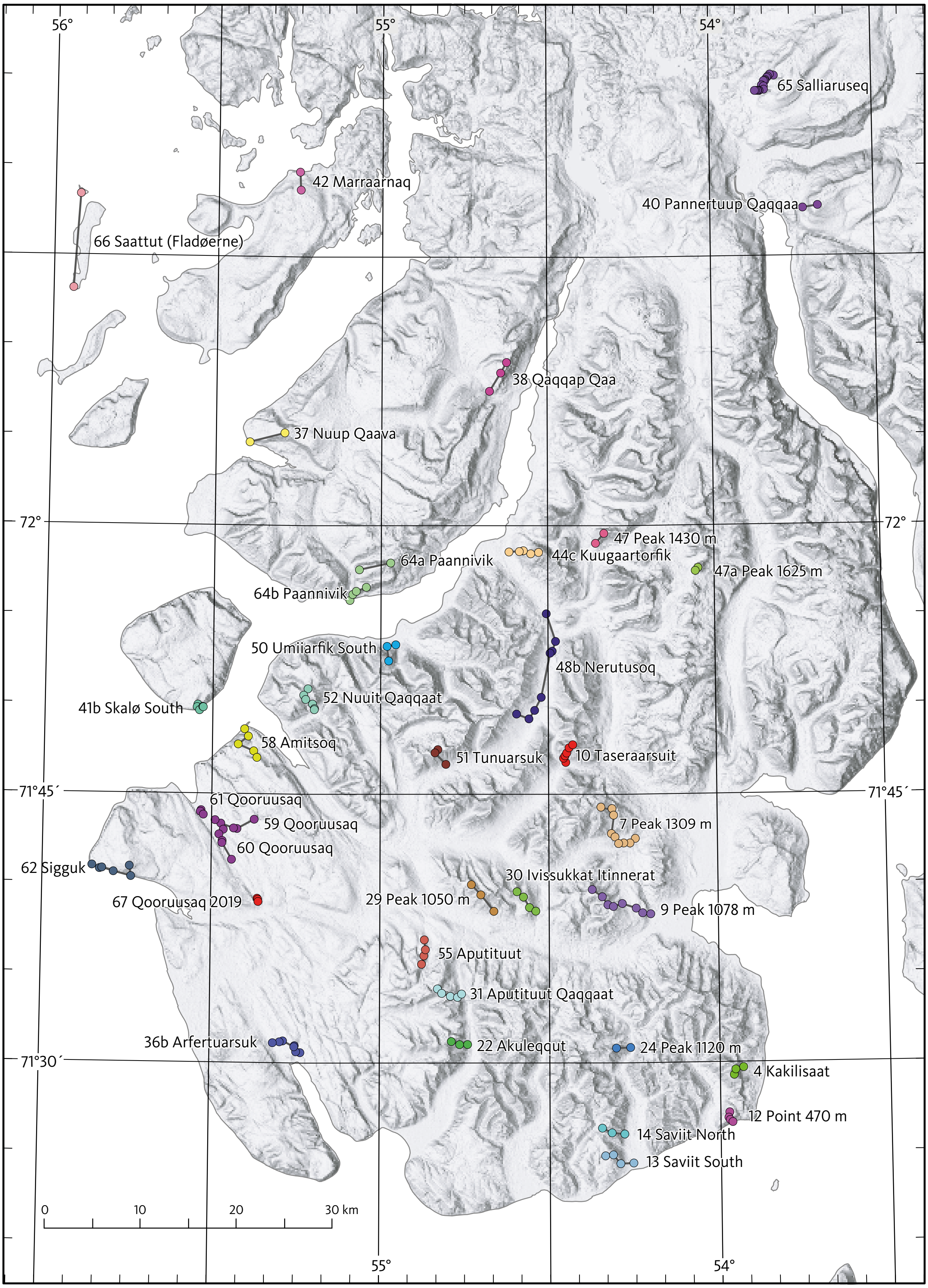

Fig. 9 Digital elevation model (from the Greenland Ice Mapping Project) of Svartenhuk Halvø with locations of the most important profiles such as type and reference sections. Dots are measured points along the profile lines, and colours distinguish individual profiles. See text for detailed explanations. Coordinates are in Appendix 1 and in digital form in Supplementary file S3.

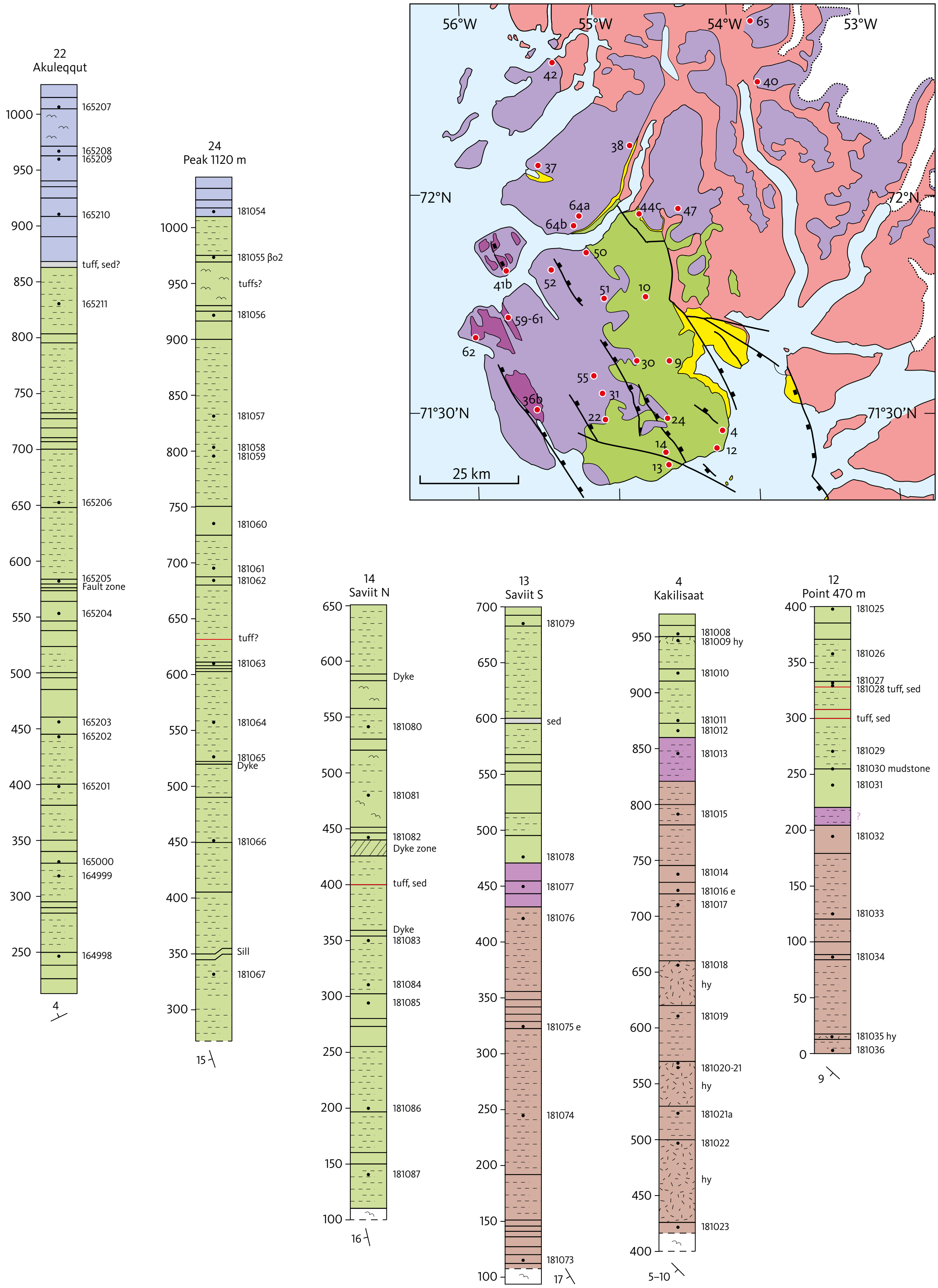

Fig. 10 Profiles through the volcanic succession in southern Svartenhuk Halvø. Vertical scale is m a.s.l. as measured. Dip and strike of the succession are shown below each profile. Legend in Fig. 13. Locations in Fig. 9 and coordinates listed in Appendix 1.

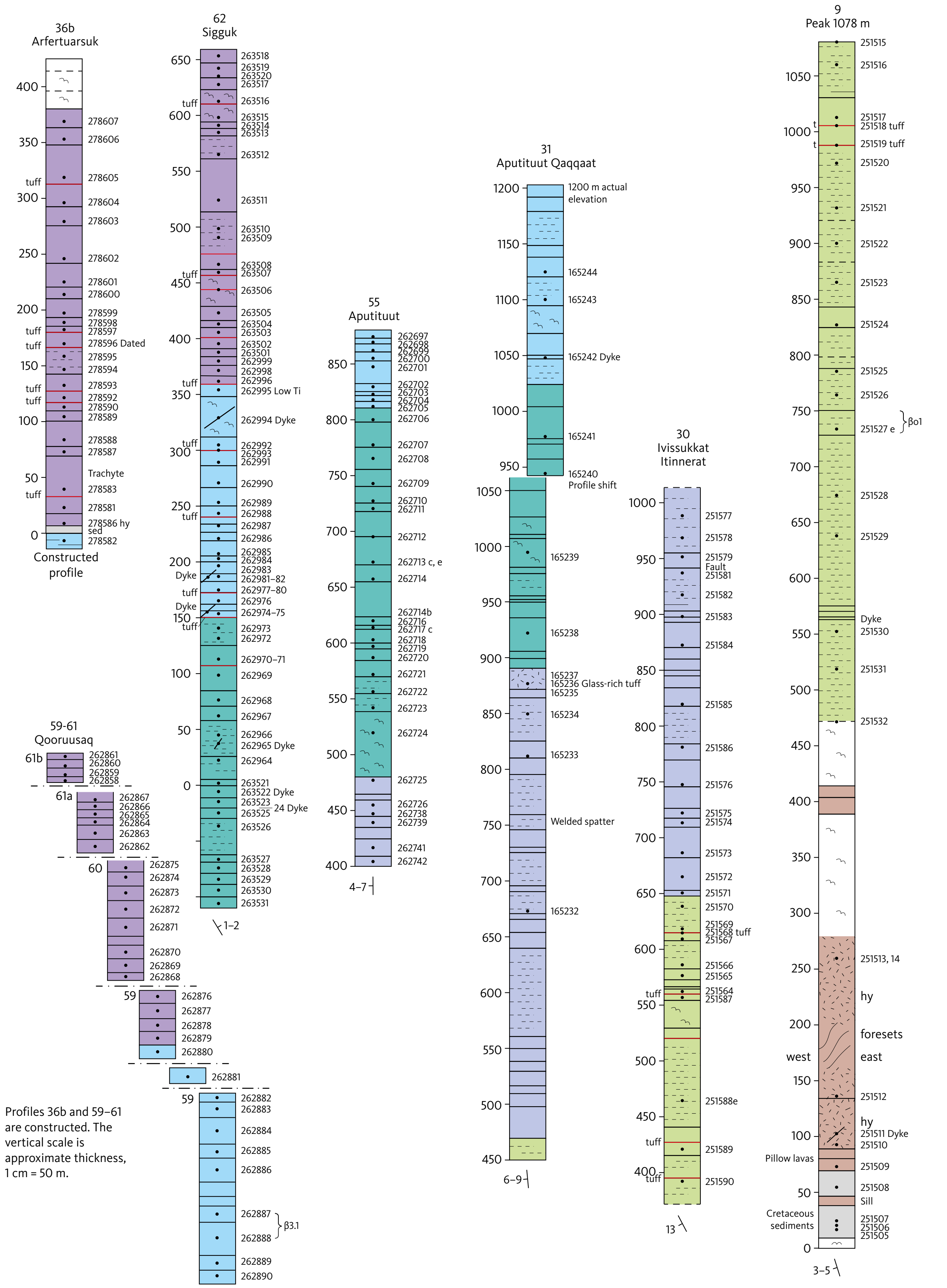

Fig. 11 Profiles through the volcanic succession in central and western Svartenhuk Halvø. Vertical scale is m a.s.l. as measured except for profiles 36b and 59–61. Dip and strike of the succession are shown below each profile. Legend in Fig. 13. Index map in Fig. 10. Locations in Fig. 9 and coordinates listed in Appendix 1.

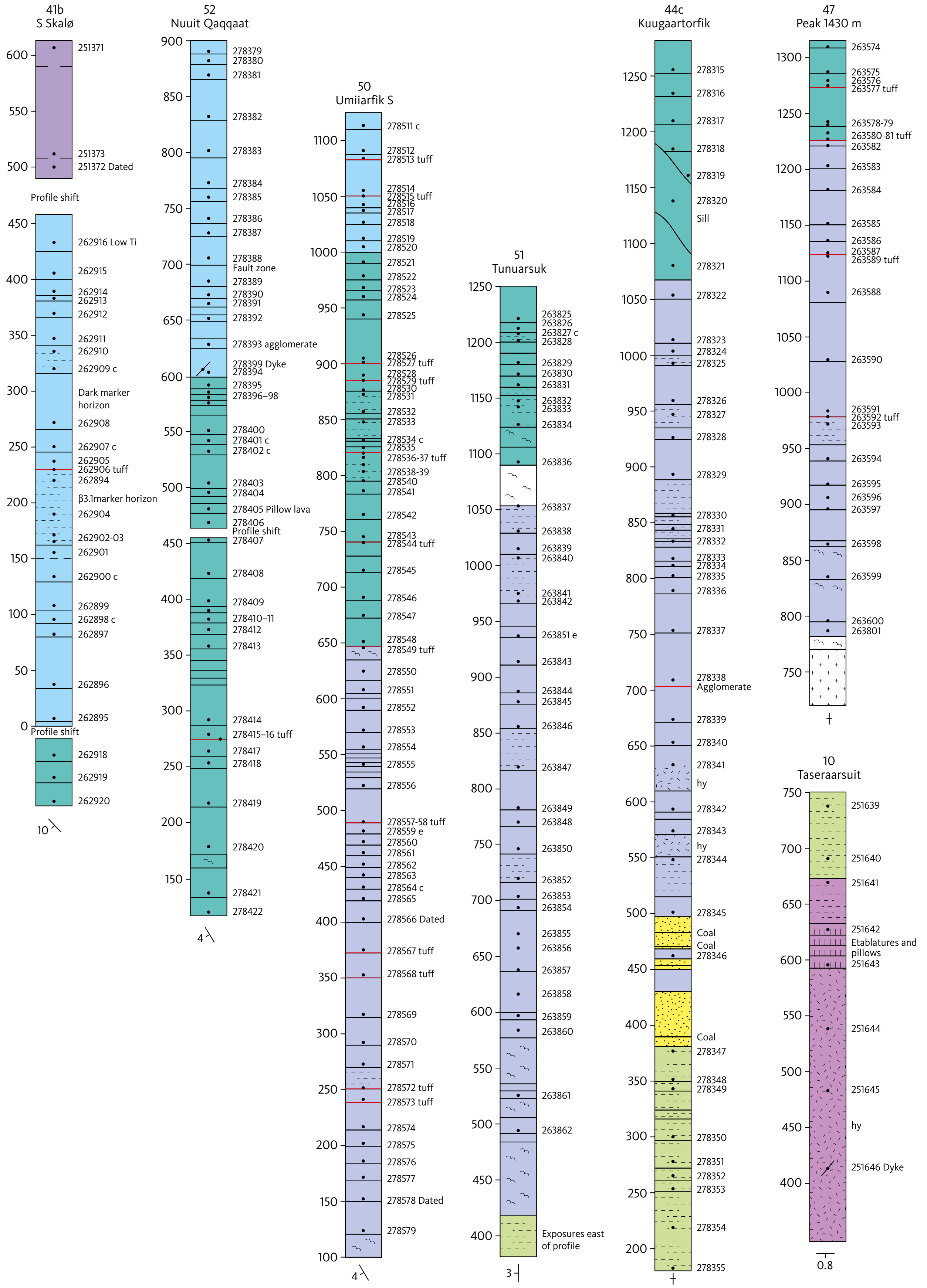

Fig. 12 Profiles through the volcanic succession in northern Svartenhuk Halvø. Vertical scale is m a.s.l. as measured. Dip and strike of the succession are shown below each profile. Legend in Fig. 13. Index map in Fig. 10. Locations in Fig. 9 and coordinates listed in Appendix 1.

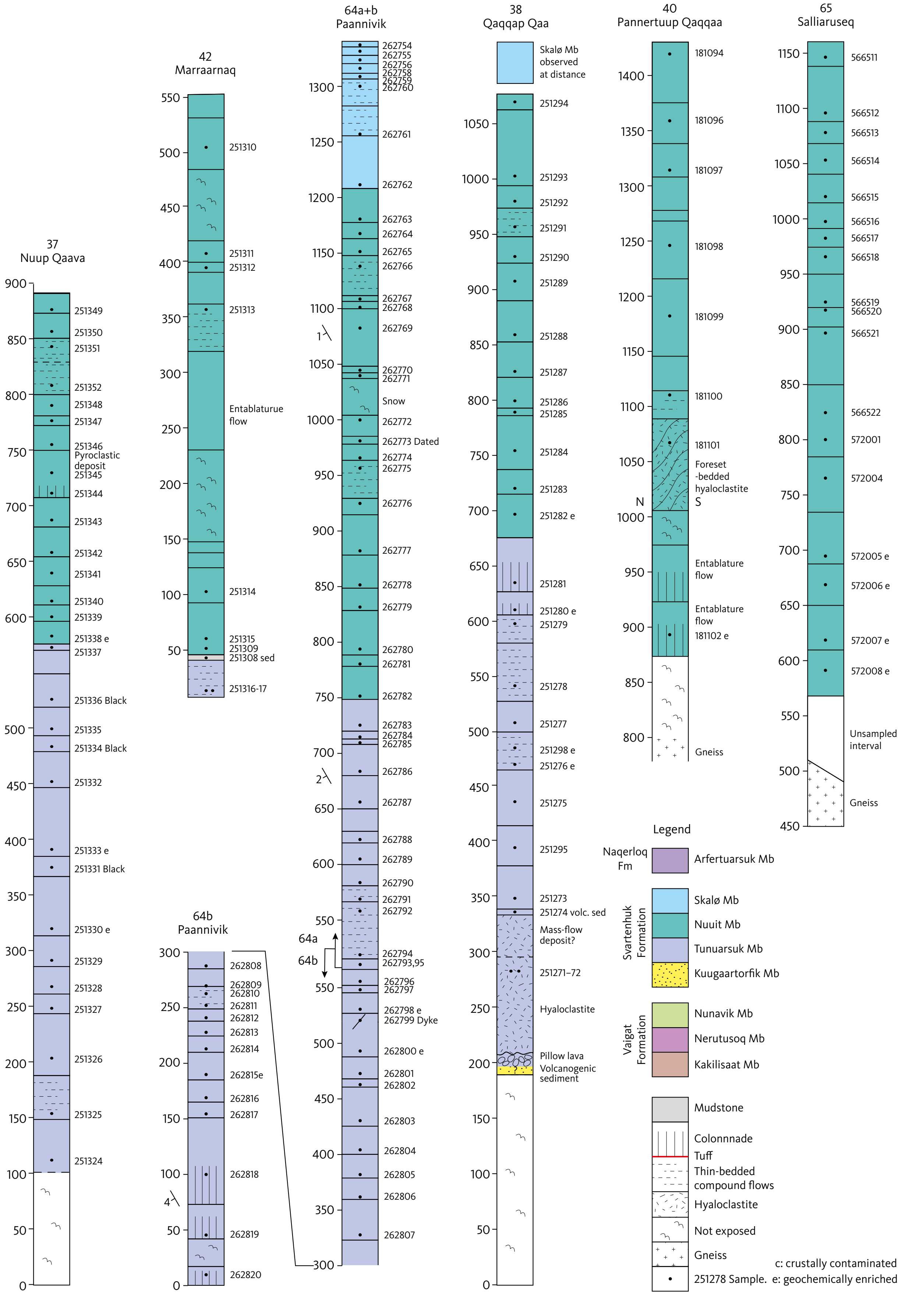

Fig. 13 Profiles through the volcanic succession north of Svartenhuk Halvø. Vertical scale is m a.s.l. as measured. In all profiles except Paannivik, the succession is near-horizontal, dipping 2° or less. Index map in Fig. 10. Locations in Fig. 9 and coordinates listed in Appendix 1. The legend applies to Figs 10–13. Definitions of 'crustally contaminated' and 'geochemically enriched' in the Nomenclature section. **volc. sed**.: volcanogenic sediment.

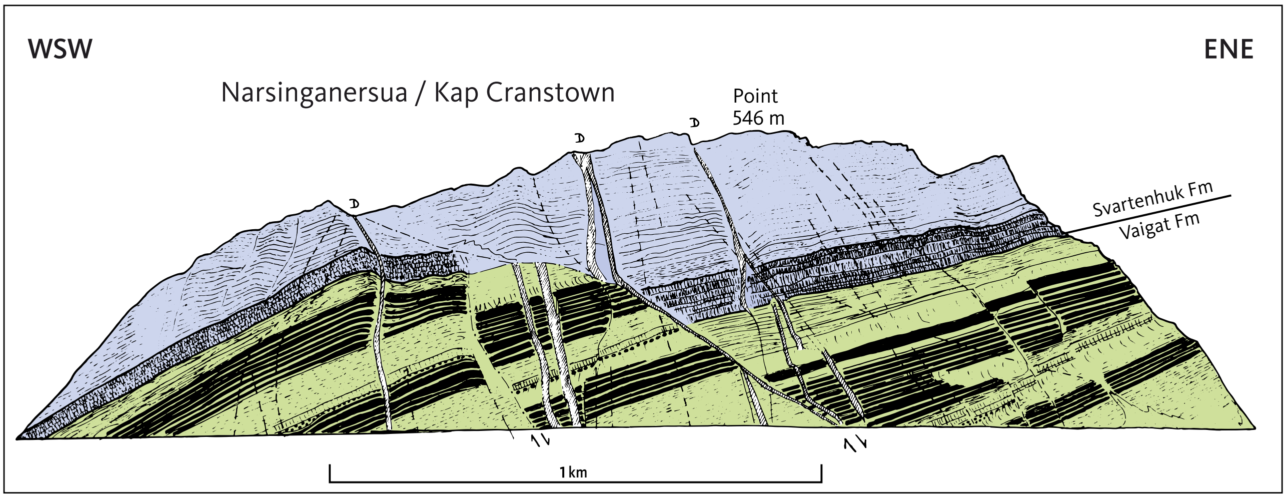

Fig. 14 The coastal section at Narsinganersua (Kap Cranstown). Location in Fig. 8. The faulted lava flows dip *c.* 20°SW. The succession comprises 280 m of the uppermost Nunavik Member of the Vaigat Formation and a similar thickness of the lowermost Tunuarsuk Member of the Svartenhuk Formation. **Solid black lines** denote groups of massive picrite flows that highlight the complicated fault structure. The **dotted line** is a tuff layer. The apparent low-angle fault in the centre of the section is a WNW–ESE-trending fault that cuts obliquely through the exposure (Fig. 6); it is partly intruded by a dyke. Vertically **hatched** flows are massive, plagioclase-phyric flows: the lowest flows in the Tunuarsuk Member and a single basalt flow in the Nunavik Member. The thickest dykes are indicated by **D**s. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales. See also photo in Fig. 34.

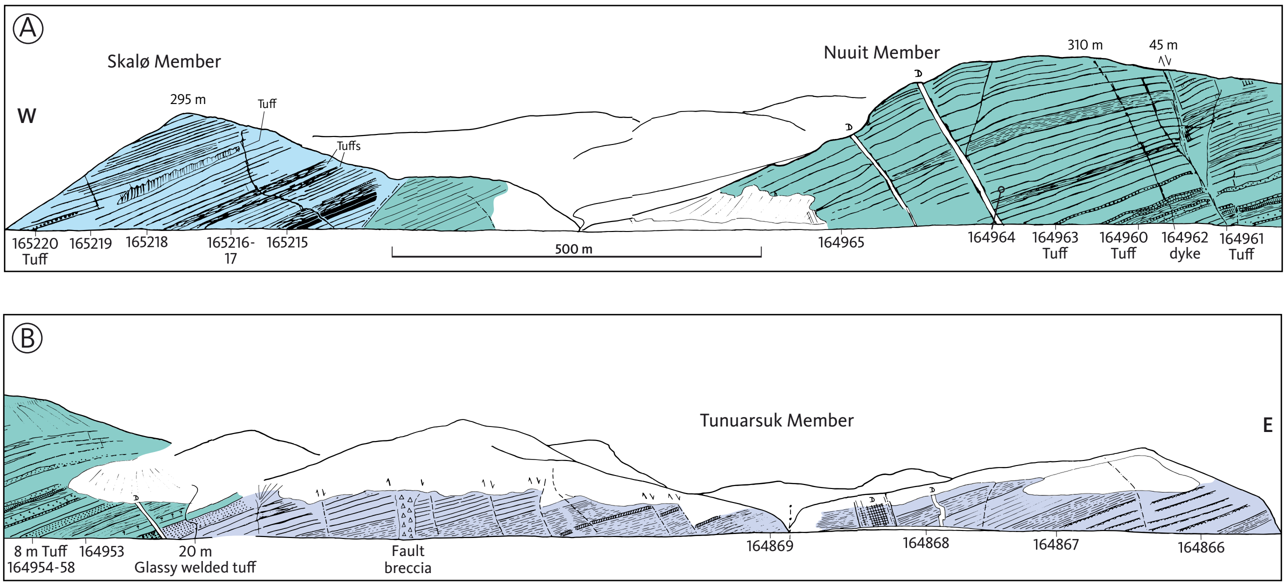

Fig. 15 Section along the north coast of Tasiusap Imaa, 15–20 km north-east of Kap Cranstown and east of the large fault in Arfertuarsuk fjord. Location in Fig. 8. **A**: western part. **B**: eastern part. All three volcanic members of the Svartenhuk Formation are present. The faulted lava flows dip *c.* 20°WSW. Groups of thin pahoehoe flows are shown with bed-parallel **hatching**, and tuff layers are **dotted**. Note the 20 m thick tuff at the boundary between the Tunuarsuk and Nuuit Members. The thickest dykes are indicated by **D**s. Samples and observations along the shore are indicated; analyses are in Supplementary file S4. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales.

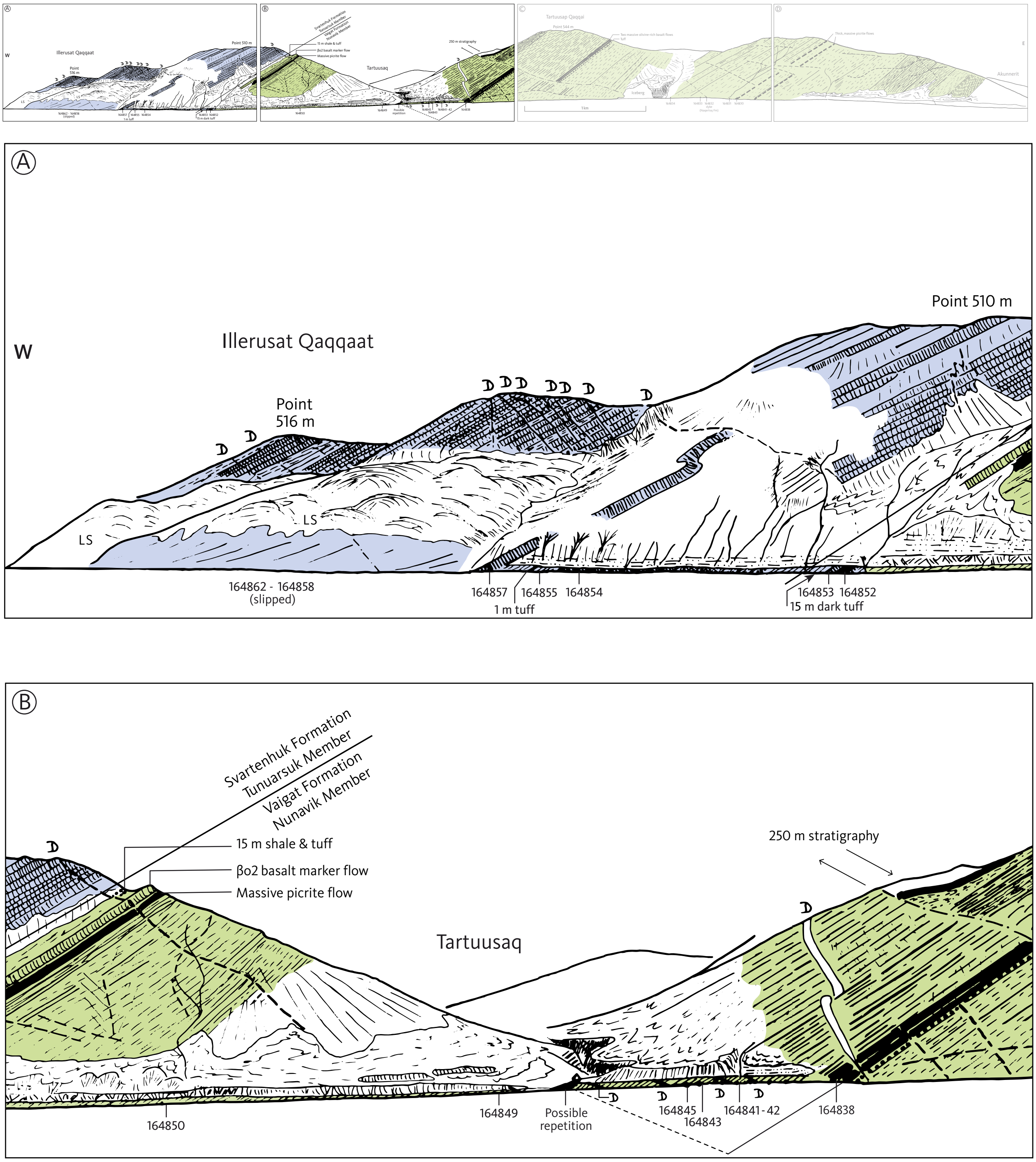

Fig. 16 Section along the south coast of Svartenhuk Halvø from Illerusat Qaqqaat to Akunnerit. Location in Fig. 8. The four panels should be read from west to east in the succession **A**, **B**, **C** and **D**. The faulted lava flows dip 30–40°SW. C and D show *c*. 2 km of unfaulted succession between the iceberg and Akunnerit, which is the thickest unfaulted succession encountered in the Vaigat Formation, without exposed top and base. Groups of thin pahoehoe flows are shown with different bed-parallel hatchings, massive picrite flows are black and massive basalt flows vertically hatched. βo2 is a mapped basalt marker flow near the top of the Vaigat Formation. Note the thick shale and tuff at the boundary between the Vaigat and Svartenhuk Formations. The thickest dykes are indicated by **D**s. **LS**: landslide. Samples along the shore are indicated; analyses are in Supplementary file S4. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales.

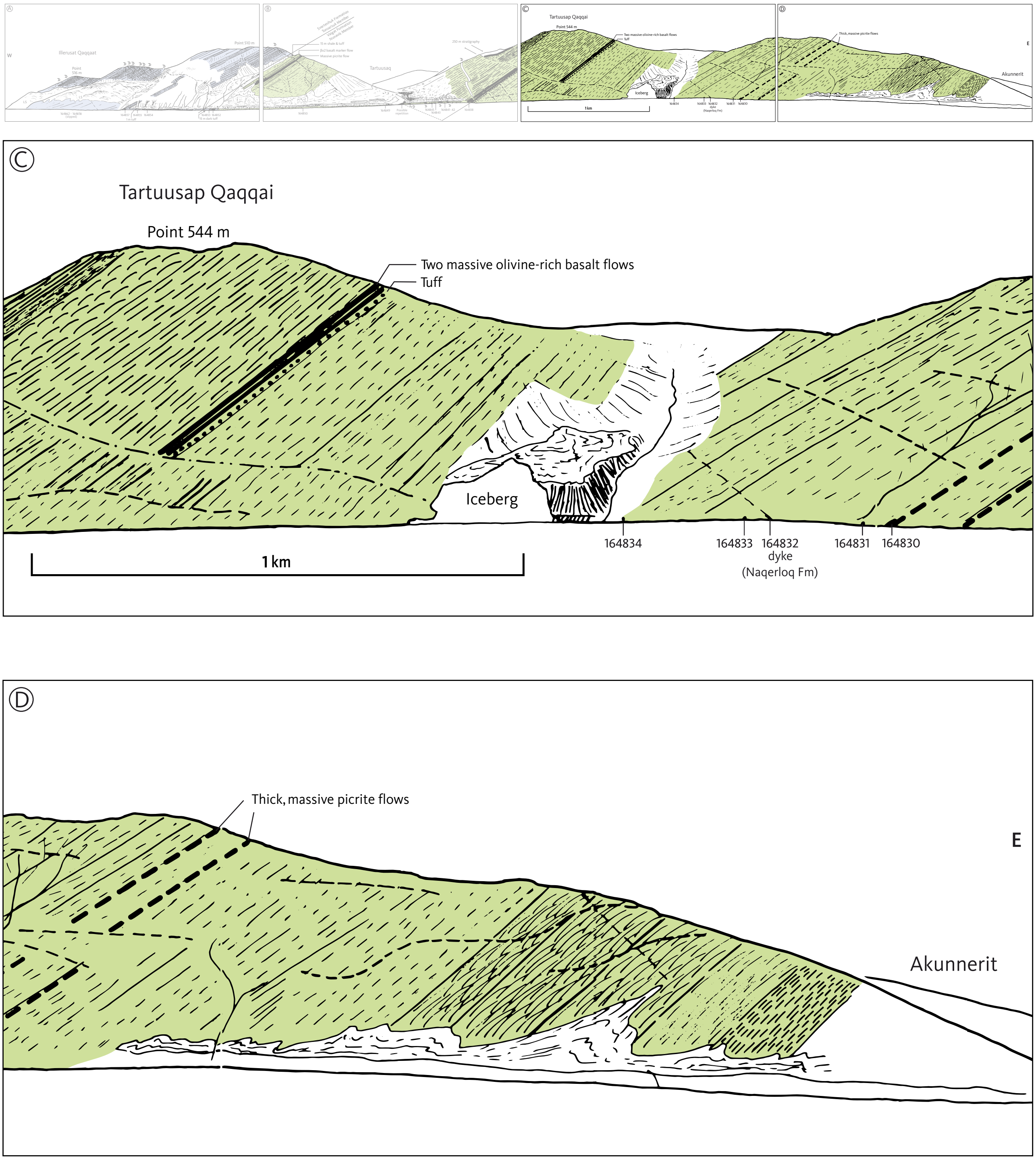

Fig. 16 (continued) Section along the south coast of Svartenhuk Halvø from Illerusat Qaqqaat to Akunnerit. Location in Fig. 8. The four panels should be read from west to east in the succession **A**, **B**, **C** and **D**. The faulted lava flows dip 30–40°SW. C and D show *c*. 2 km of unfaulted succession between the iceberg and Akunnerit, which is the thickest unfaulted succession encountered in the Vaigat Formation, without exposed top and base. Groups of thin pahoehoe flows are shown with different bed-parallel hatchings, massive picrite flows are black and massive basalt flows vertically hatched. βo2 is a mapped basalt marker flow near the top of the Vaigat Formation. Note the thick shale and tuff at the boundary between the Vaigat and Svartenhuk Formations. The thickest dykes are indicated by **D**s. **LS**: landslide. Samples along the shore are indicated; analyses are in Supplementary file S4. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales.

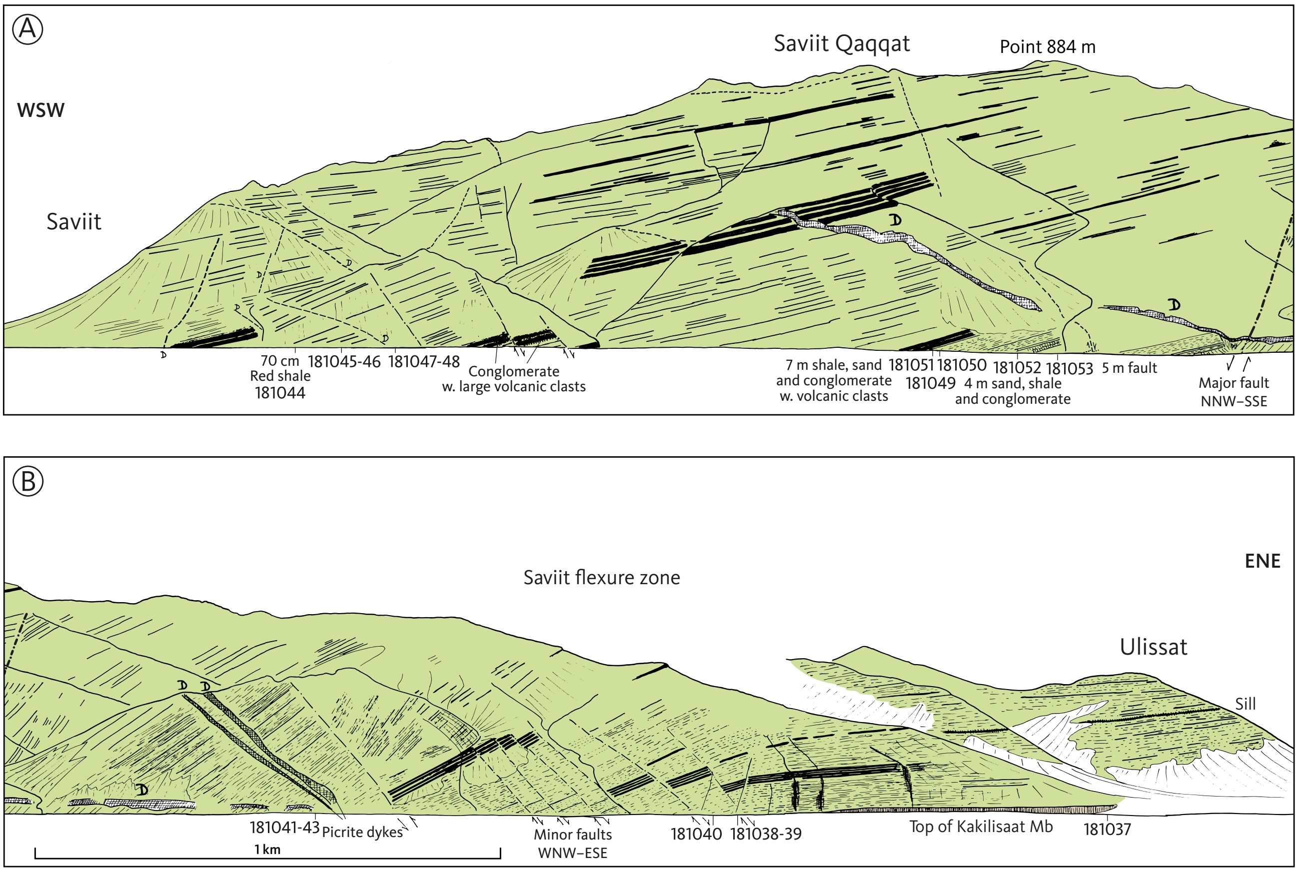

Fig. 17 Section along the south coast of Svartenhuk Halvø from Saviit to Ulissat. Location in Fig. 8. **A**: western part. **B**: eastern part. The succession comprises the lower part of the Nunavik Member. The top of the underlying Kakilisaat Member is just exposed on the shore in B. Panel B contains a cross section of the large flexure zone (here called the Saviit flexure zone) that runs NNW–SSE across the peninsula (Fig. 6) and was described in detail by Larsen & Pulvertaft (2000, p. 27–28). East of the flexure zone, the lava flows are nearly horizontal; within the zone, a series of WNW–ESE strike-slip faults with block rotation have resulted in westerly dips increasing towards the west to more than 40°WSW. West of the flexure zone, the lava flows are faulted but dip fairly regularly only 10–15°WSW. The WNW–ESE faults are near-vertical but appear here to be inclined towards ENE, which is an effect of the topography and the direction of view. The total offset produced by the faulting is impossible to calculate because of the lithological uniformity of the Nunavik Member and lack of reliable marker horizons. Groups of thin pahoehoe flows are shown with bed-parallel hatching, and massive picrite flows are black. The thickest dykes are indicated by **D**s. Samples and observations along the shore are indicated; analyses are in Supplementary file S4. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales.

Vaigat Formation

History. The presence of very olivine-rich volcanic rocks in the lower part of the volcanic succession in the West Greenland volcanic province has been known since the pioneering work by Steenstrup (1883). The olivine-rich succession was formalised as the Vaigat Formation by Hald & Pedersen (1975) with distribution throughout the province from Disko to Svartenhuk Halvø, and with its type area on the north coast of Disko between Kuugannguaq and Asuk.

The descriptions in the following are only concerned with the Vaigat Formation in the Svartenhuk Halvø area.

Synonymy. The 'lower basalt series' of Münther (1973); the 'lower formation' of Larsen (1981a, b) and Holm *et al*. (1993).

Subdivisions. The Vaigat Formation on Svartenhuk Halvø is divided into three members, from bottom to top:
Kakilisaat Member: brown to grey, silica-enriched, crustally contaminated basalts, basaltic andesites and a few picrites.
Nerutusoq Member: brown basalts and magnesian basalts enriched in incompatible elements.
Nunavik Member: grey picrites and magnesian basalts.

The Kakilisaat and Nerutusoq Members are combined into one unit on the geological maps because they cannot be visually distinguished from a distance in the field or on photographs. At close range the two members are distinguishable because the Kakilisaat Member comprises both plagioclase-phyric and aphyric rocks whereas all the Nerutusoq Member rocks are aphyric.

Distribution. The Vaigat Formation is exposed in the southern, eastern and north-eastern parts of Svartenhuk Halvø and the south-eastern part of the Innerit peninsula (Figs 6, 19). South-east of Svartenhuk Halvø the formation extends to the islands Schade Øer (Qeqertat). In the southern part of the peninsula the volcanic pile is faulted and the lavas dip SW (Figs 14–17); in its western part the Vaigat Formation is covered by the Svartenhuk Formation and disappears below sea level (Figs 14, 16). The westernmost exposure is on the southern tip of Qinnivik (Kap Cranstown) where the upper part of the Vaigat formation is exposed (Fig. 14). The oldest exposed part of the Vaigat Formation is situated in the eastern basinal area (Fig. 18) immediately west of the Cretaceous boundary fault system. Farther to the east, the formation has overstepped the Cretaceous boundary fault system; here it rests on the Precambrian basement and is overlain and overstepped by the Svartenhuk Formation. The Vaigat Formation presumably extends at depth beneath south-western Svartenhuk Halvø and beneath the sea to the south and west. Seismic sections in the sea south of Svartenhuk Halvø and west of Ubekendt Ejland show a thick package of faulted, W-dipping strata interpreted as lava flows of the Svartenhuk Formation (Skaarup & Pulvertaft 2007). The volcanic succession is most probably much thicker than the *c*. 800 m thickness, which is visible above the first sea-bed multiple, making the presence of the Vaigat Formation at depth entirely possible.

Type section. The type section is composed of five individual sections situated close to the coasts of the Vaigat strait (Pedersen *et al*. 2017, p. 26).

Reference sections. On Svartenhuk Halvø, **Kakilisaat** (profile 4) covers the Kakilisaat and Nerutusoq Members and the lowermost Nunavik Member. **Peak 1078 m** (profile 9) covers the main part of the Nunavik Member, and **Peak 1309 m** (Profile 7) covers the top part of the Nunavik Member and the boundary to the Svartenhuk Formation.

Thickness. In a swathe of land just west of the Cretaceous boundary fault system, the Vaigat Formation is exposed from bottom to top, dips are less than 5° and faulting is minimal so that thicknesses there can be reliably estimated. In the northern and central parts of this area, thicknesses of 950–1250 m are present, increasing southwards from Simiuttap Kuua to Peak 1309 m northwest of Firefjeld. Farther south the formation is at least 1250 m thick with no upper boundary preserved. At Saviit Qaqqaat close to the south-east coast the thickness may have been as much as 1500–1700 m, obtained by extrapolation from thicknesses in the northern part of the basin towards the southern area using a slope of 1° of the lava pile (see the later section on marker horizons in the Nunavik Member). Overall, thicknesses within the basin increase from north to south. The thickness of the subaerial part of the lava pile increases southwards from 200–300 m on Innerit, through 450 m in north-central Svartenhuk Halvø (at Peak 1250 m), to 600 m in east-central Svartenhuk Halvø (at Peak 1309 m).

On the Precambrian basement, the thickness is reduced to *c*. 500 m in the Qinngusaaq area, and the formation thins out at a height of 1100 m east of Siuteqqut.

The greatest thickness of the Vaigat Formation is presumed to be present in southern Svartenhuk Halvø. Unfortunately, this is an area where faulting and tilting are severe and prohibit the entire thickness of the formation to be measured in any one profile (Figs 16, 17).

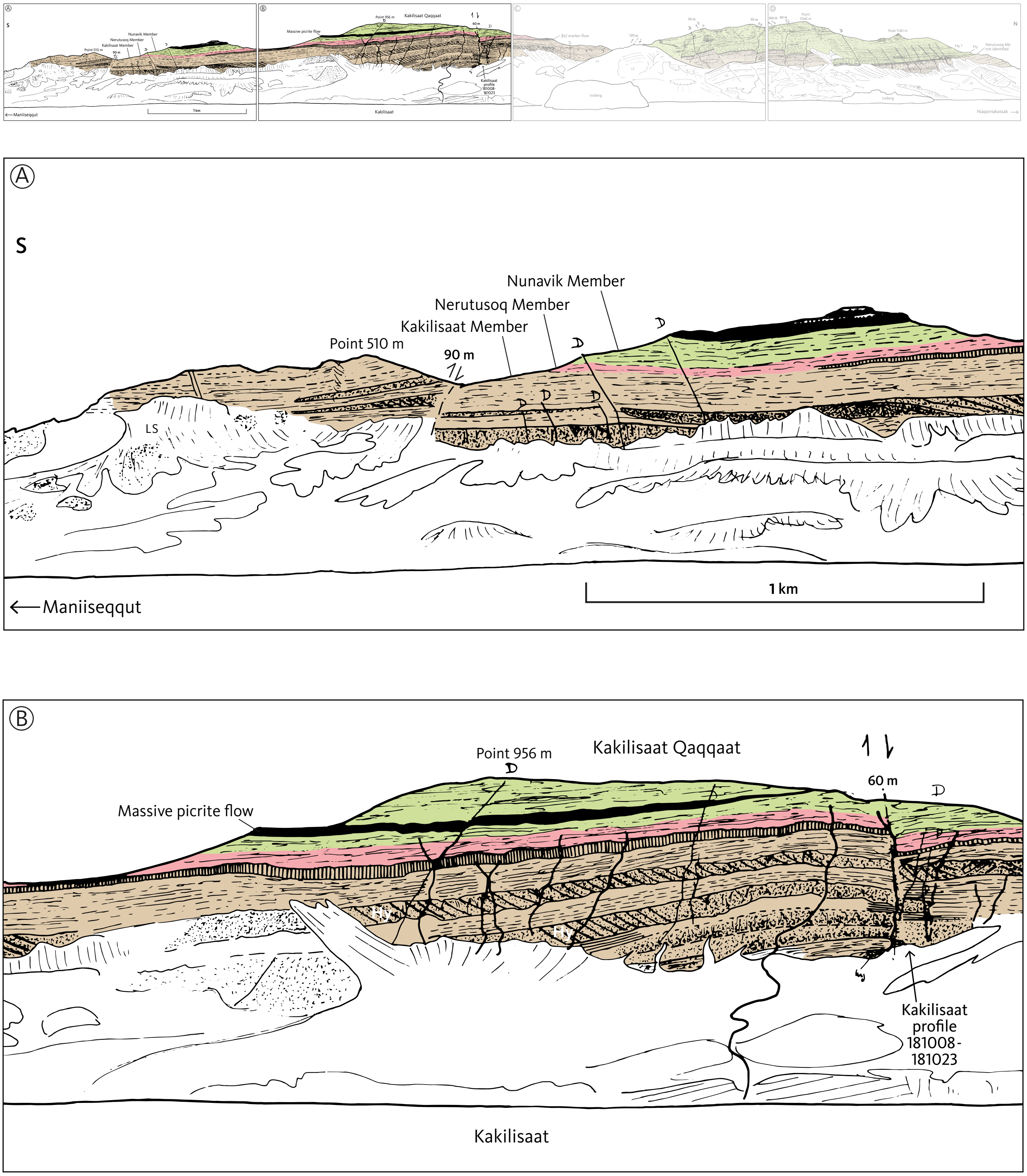

Fig. 18 Section along the east coast of southern Svartenhuk Halvø from Maniiseqqut in the south to Niaqornakassak in the north. Location in Fig. 8. The four panels should be read from south to north in the succession **A**, **B**, **C**, and **D**. The succession comprises the Kakilisaat and Nerutusoq Members and the lower part of the Nunavik Member, all belonging to the Vaigat Formation. The Kakilisaat Member contains three hyaloclastite horizons (**Hy**) of which the upper two are foreset-bedded with N-dipping foresets. In the north, the Nunavik Member contains one or two hyaloclastite horizons, also foreset-bedded with N-dipping foresets. The solid black flow is a massive picrite flow. The vertically hatched flow is a massive basalt flow (**βs2)** that forms the top of the Kakilisaat Member. The position of profile 4 (Kakilisaat) is indicated; it ascends just north of a fault scarp and continues along the mountain ridge to Point 956 m. See also Figs 10, 21. The thickest dykes are indicated by **D**s. **LS**: landslide. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales.

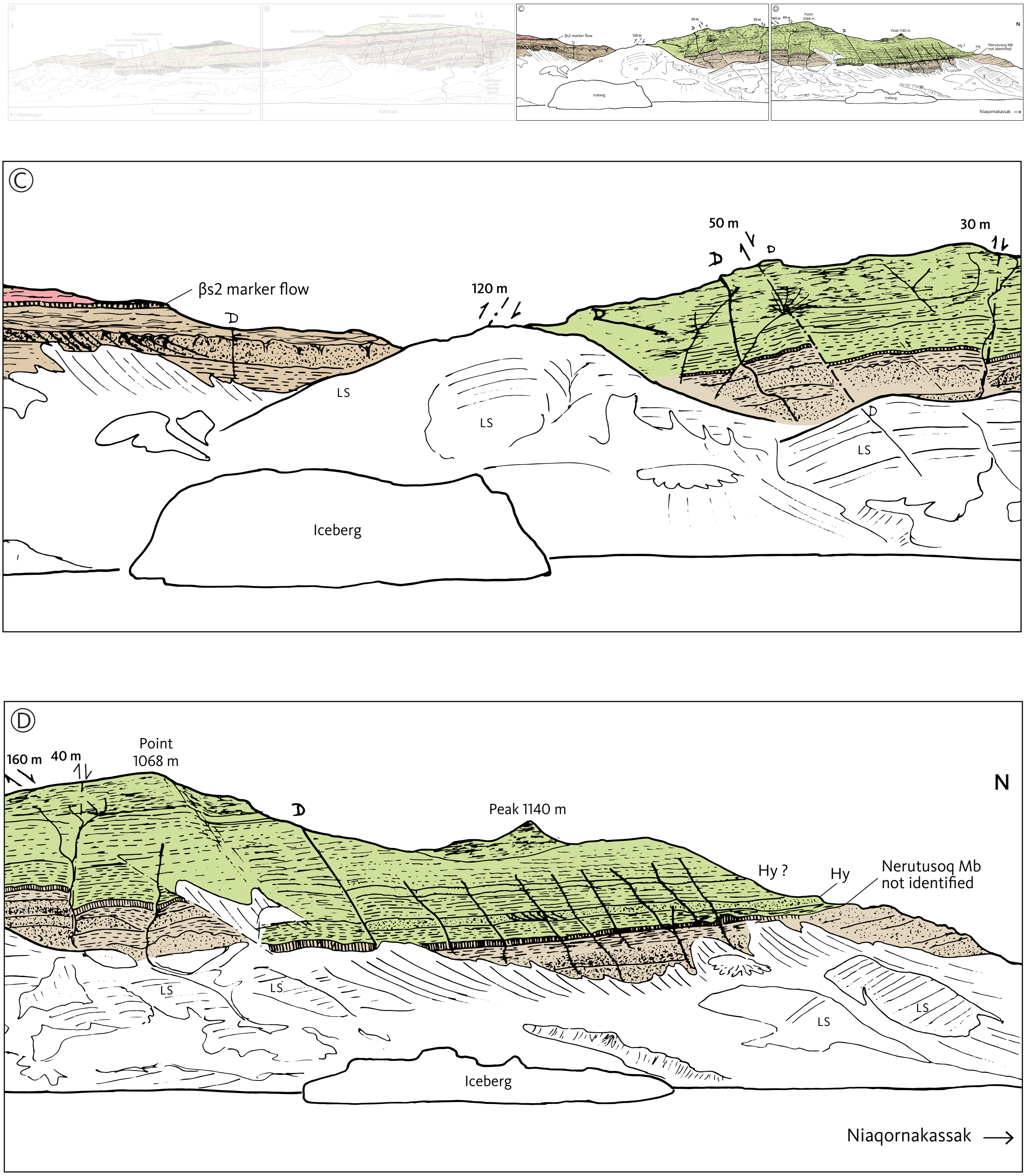

Fig. 18 (continued) Section along the east coast of southern Svartenhuk Halvø from Maniiseqqut in the south to Niaqornakassak in the north. Location in Fig. 8. The four panels should be read from south to north in the succession **A**, **B**, **C**, and **D**. The succession comprises the Kakilisaat and Nerutusoq Members and the lower part of the Nunavik Member, all belonging to the Vaigat Formation. The Kakilisaat Member contains three hyaloclastite horizons (**Hy**) of which the upper two are foreset-bedded with N-dipping foresets. In the north, the Nunavik Member contains one or two hyaloclastite horizons, also foreset-bedded with N-dipping foresets. The solid black flow is a massive picrite flow. The vertically hatched flow is a massive basalt flow (**βs2)** that forms the top of the Kakilisaat Member. The position of profile 4 (Kakilisaat) is indicated; it ascends just north of a fault scarp and continues along the mountain ridge to Point 956 m. See also Figs 10, 21. The thickest dykes are indicated by **D**s. **LS**: landslide. Hand traced from colour slides projected onto a screen and therefore not with constant horizontal and vertical scales.

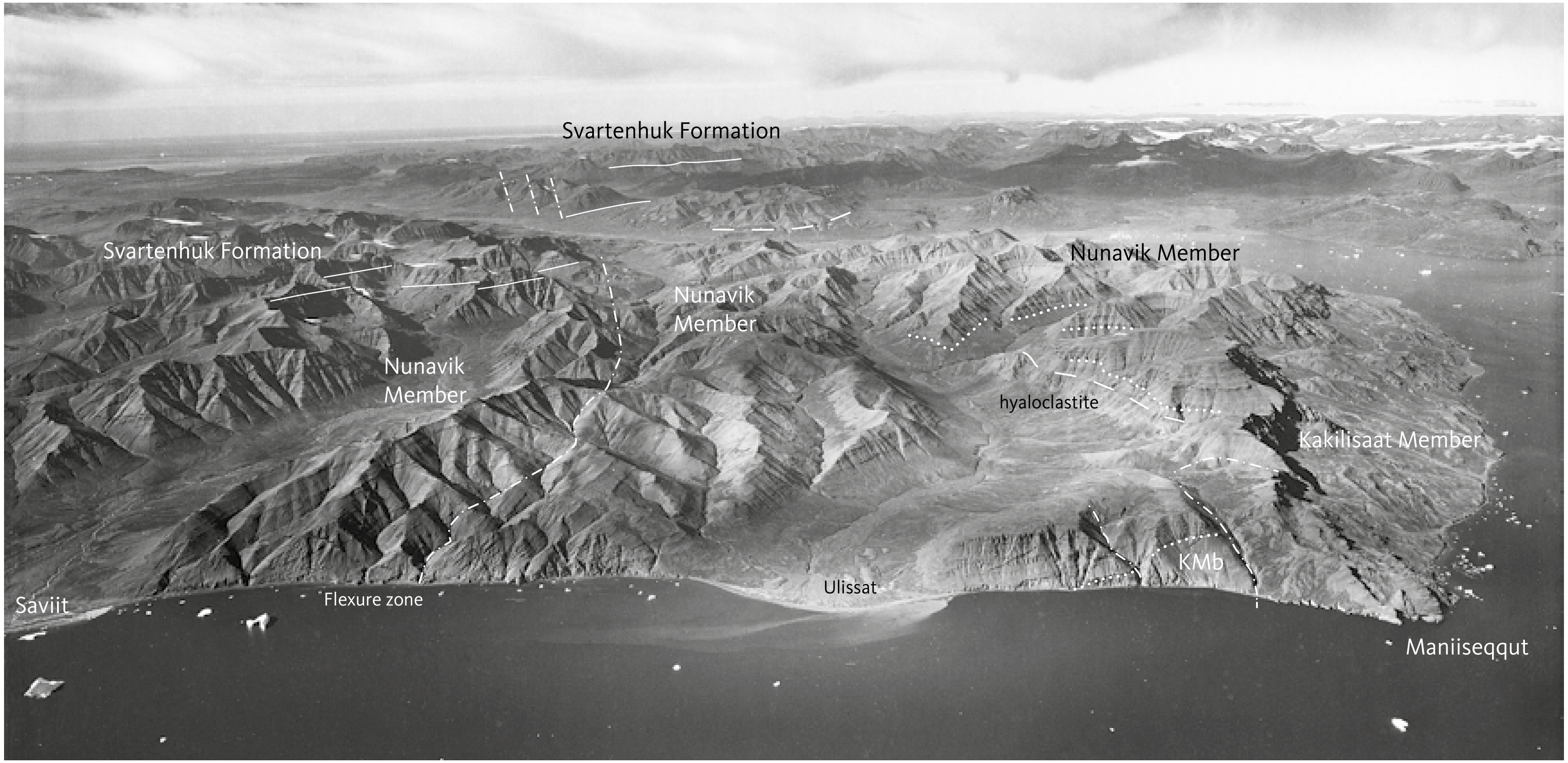

Fig. 19 The south coast of Svartenhuk Halvø between Saviit and Maniiseqqut (location in Fig. 7). The Vaigat Formation (Kakilisaat and Nunavik Members) is strongly and repeatedly faulted, and the lavas dip up to 40°W. **Dashed white lines**: upper limit of hyaloclastite horizons. **Dotted white line**: Upper boundary of the Kakilisaat Member (**KMb**). **Full white lines**: boundary between the Vaigat and Svartenhuk Formations. Geodetic Institute oblique aerial photograph 526DN/9465.

The thickest unfaulted succession encountered in the Vaigat Formation is *c*. 2 km without exposed top and base, found on the south coast west of Akunnerit (Fig. 16). Despite good exposures along the south coast of the peninsula the crumbling and monotonous character of the lithologies in many places make repetitions due to faulting very difficult to detect. Noe-Nygaard's (1942) estimated thickness of more than 10 km, ignoring any repetitions due to faulting, is definitely too high. The estimate was reduced to at least 8 km by Pulvertaft & Clarke (1966) and to 2.5–3 km by Münther (1973). Larsen & Pulvertaft (2000) estimated a thickness in the order of 4–4.5 km taking the known repetitions into account. Until more studies have been made, we can only conclude that the formation is at least up to more than 2000 m and perhaps up to 3000 m thick.

Lithology. The lower part of the formation comprises brown to grey hyaloclastites and pillow lavas with subordinate lava flows comprising brown, aphyric and plagioclase-phyric, Si-enriched, contaminated basalts, magnesian basalts and subordinate picrites of the Kakilisaat Member, overlain by brown, aphyric, trace-element-enriched basalts of the Nerutusoq Member (Fig. 18). Subaerial lava flows dominate at the south coast west of Ulissat.

In the lowermost part of the formation minor thin, intervolcanic, tuffaceous and coarse volcaniclastic sediments, sand-, silt- and mudstones are present, e.g. on Uparuaqqusuitsut (Larsen 1981a; Dam e*t al*. 2020), south of Qorlortoq, on Firefjeld and in Usuit Kuussuat.

The upper part of the formation is composed of mostly greenish grey picrites and magnesian basalts of the Nunavik Member. These form hyaloclastites and overlying subaerial pahoehoe lava flows in the eastern part of the basin.

Boundaries. The lower boundary of the Vaigat Formation is the base of the volcanic succession, and the basal lithology is most commonly hyaloclastite. Within the basinal area the volcanic succession rests on sediments of Cretaceous and Danian/Selandian age (Larsen & Pulvertaft 2000; Dam *et al*. 2009, p. 30), but contacts are rarely exposed. A conformable relation between Paleocene sediments and the volcanic rocks has been observed in a few places. On the eastern slope of Firefjeld, the hyaloclastites rest on a Paleocene conglomerate that itself overlies Cretaceous mudstones (Larsen & Pulvertaft 2000; Dam *et al*. 2009, pp. 90 and 115). In south-eastern Svartenhuk Halvø, a small exposure on the western bank of the river in Ulissat Qooruat, 5.5 km north of Ulissat (shown on the geological map of Larsen 1983), shows an ochre-coloured quartzofeldspathic sandstone overlain by black to dark green tuff and dark sandstone with molluscs and ophiomorphae burrows indicating a marine environment, overlain by hyaloclastites (Larsen & Pulvertaft 2000, p. 13). A conformable transition to hyaloclastites also appears to be present on top of Itsaku. Interbedded mudstones and hyaloclastites occur along the south-west side of the valley of Qorlortup Kuua and at Issiallak. In other exposures within the basin area prevolcanic tectonic uplift and erosion have removed the upper Campanian – Maastrichtian and lowermost Paleocene sediments.

East of the Cretaceous boundary fault system, almost all Mesozoic–Paleocene sediments pre-dating the volcanism have been removed as a result of prevolcanic uplift and erosion. Here, the upper part of the Vaigat Formation rests directly on elevated Archaean gneisses and Proterozoic metasediments with a substantial surface topography. The lowest volcanic rocks are most commonly hyaloclastites. North of Kangiusap Imaa, the Vaigat Formation dominantly consists of hyaloclastites up to 270 m thick, situated at altitudes up to more than 1210 m, the highest level for the hyaloclastites in the Vaigat Formation, caused by postvolcanic uplift.

The upper boundary is marked by the first occurrence of brown, olivine-poor basalts of the Svartenhuk Formation or, in the northern area, the first occurrence of yellow, quartzofeldspathic sand beds with mudstones and coal seams. The boundary is placed at the base of the sediments because these are interbedded with the basal lava flows of the Svartenhuk Formation and were presumably deposited during an uplift of the basement rocks east of the Cretaceous boundary fault system associated with the earliest eruptions of the Svartenhuk Formation. In the southern area, no erosion has been recorded to indicate a longer break in the volcanism before the eruption of the Svartenhuk Formation. However, a sediment/tuff horizon is commonly present at the boundary, for example at Tartuusaq (Fig. 16) and Aputituut Qaqqaat (profile 31, Fig. 11).

The highest altitude of the upper boundary is close to 1300 m and is found at Peak 1309 m within the basin in central eastern Svartenhuk Halvø. The same altitude of the upper boundary is found on the basement near Qinngusaaq 12 km north-east of Peak 1309 m (Larsen & Grocott 1991). This shows that the inversion of the basinal area noted by Münther (1973) and Larsen & Pulvertaft (2000, p. 22) is differential with the largest altitude differences in the north, decreasing towards the south-east.

Geological age. Paleocene (Danian to Selandian). A marine sandstone–tuff–mudstone succession underlying the base of the volcanic succession in Ulissat Qooruat has provided an Early Paleocene age: The tuffaceous rocks yielded a dinoflagellate cyst assemblage, which belongs to the Deflandrea striata zonule (Hansen 1977, 1980, p. 92), now the Cerodinium striatum interval biozone referred to the upper part of the Lower Paleocene (middle NP4, Powell 1992), corresponding to an age of around 62 Ma according to Gradstein *et al*. (2004) and subsequent time scale revisions. Chauvet *et al*. (2019) obtained a $^{40}Ar/^{39}Ar$ age of 61.08 ± 0.56 Ma for a basalt flow from the lowest part of the Vaigat Formation at the eastern south coast of Svartenhuk Halvø.

The upper age limit of the Vaigat Formation is not well constrained. It is estimated to be about 60–61 Ma based on the radiometric ($^{40}Ar/^{39}Ar$) ages for basalts low in the overlying Tunuarsuk Member of the Svartenhuk Formation (between 60.3 ± 1.4 Ma and 59.4 ± 0.6 Ma, Larsen *et al*. 2016) and an intervening hiatus indicated by a sediment horizon in the northern area.

Radiometric ($^{40}Ar/^{39}Ar$) dating of the Vaigat Formation in the Disko–Nuussuaq area (Storey *et al*. 1998) yielded ages of 61–62 Ma ± 0.5–1 Ma, similar to and slightly older than the radiometric age obtained by Chauvet *et al*. (2019) for the Vaigat Formation on Svartenhuk Halvø. The entire Vaigat Formation was probably deposited within a relatively short time interval (Storey *et al*. 1998; Pedersen *et al*. 2002).

Age constraints from palaeomagnetic results are described in the section on correlation below.

Correlation. Palaeomagnetic investigations have shown that the lower part of the Vaigat Formation on Nuussuaq is normally magnetised in magnetochron C27n (Riisager & Abrahamsen 1999), the upper boundary of which is placed at 62.2 Ma (Vandenberghe *et al*. 2012; Speijer *et al*. 2020). Two palaeomagnetic profiles covering almost the entire lava succession of the Vaigat Formation on Svartenhuk Halvø show reversed magnetisation (C26r) throughout (Riisager *et al*. 2003, 2004). Also the aeromagnetic pattern of the volcanic areas shows a reversed signature (Rasmussen 2002). This indicates that the Vaigat Formation on Svartenhuk Halvø correlates with the upper part of the Vaigat Formation in the Disko–Nuussuaq area as shown in Fig. 3. The palaeomagnetic profiles are located on the southern flank of Kakilisaat Qaqqaat and the eastern side of Peak 1309 m (profile 7, Fig. 9).

Kakilisaat Member

New member

History. On the geological map 71 V.1 Syd Igdlorssuit (Larsen 1983) the Kakilisaat Member is combined with the overlying Nerutusoq Member and shown as the units βp, βf1 and βf2. On the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991), the Kakilisaat and Nerutusoq Members are shown as the units βp, βp1, βs1 and βs2. See the two maps provided in Supplementary files S1 and S2. The name Kakilisaat Member was used by Larsen & Pulvertaft (2000) with the same meaning as here, but the member was not formally defined.

Name. After Kakilisaat Qaqqaat, a 956 m high mountain on the coast of south-eastern Svartenhuk Halvø where the member is well developed.

Distribution. The Kakilisaat Member is present in south-eastern Svartenhuk Halvø and the eastern south coast. It is also present on Qeqertat (Schade Øer) south-east of the peninsula. Very similar and perhaps correlative rocks occur as far south as the south coast of Ubekendt Ejland. The member is covered by younger units to the west as a result of the general westerly dip of the lava pile (Fig. 20). The member reappears on the south coast west of the river delta at Saviit as a result of a major repetition caused by faulting (Fig. 6).

The extension of the member north of Firefjeld is uncertain because, as already mentioned, it cannot be distinguished from the overlying Nerutusoq Member from a distance. The absence of the capping βs2 lava flow north of Firefjeld and at Peak 1309 m (Larsen & Grocott 1991) suggests that the northward progradation of the Kakilisaat Member flows stopped here, but this does not exclude that subaquous eruption products could be present farther to the north beneath the Nerutusoq Member. The Kakilisaat Member may thus be present in the lowermost hyaloclastite unit along the west side of the valley of Siuteqqut Kuuat. Other possible occurrences include small hyaloclastite remnants on the top of Itsaku and on the mountain slope north-west of Itsaku; chemical data from these areas are not available. Nowhere is the Kakilisaat Member seen to overstep the Cretaceous boundary fault system (see also Fig. 26).

Type section. **Kakilisaat** (profile 4, Fig. 10) in south-eastern Svartenhuk Halvø, in a gully on the east side of the 956 m high mountain Kakilisaat Qaqqaat, between 420 and 820 m altitude. Coordinates in Appendix 1. The profile follows the northern side of a fault where the base of the member is covered by scree (Figs 18, 21). However, an additional 50 m is exposed near the base of the member, resting on Cretaceous sediments at 280 m altitude on the east slope of Ulissat Qooruat 3 km south-west of the fault.

Reference sections. **Saviit South** (profile 13, Fig. 10) west of Saviit; this comprises *c*. 450 m of subaerial lava flows of the Kakilisaat Member and includes two picritic lava flows at the base of the profile. **Peak 1078 m** (profile 9, Fig. 11) south-west of Firefjeld below *c*. 420 m alti-

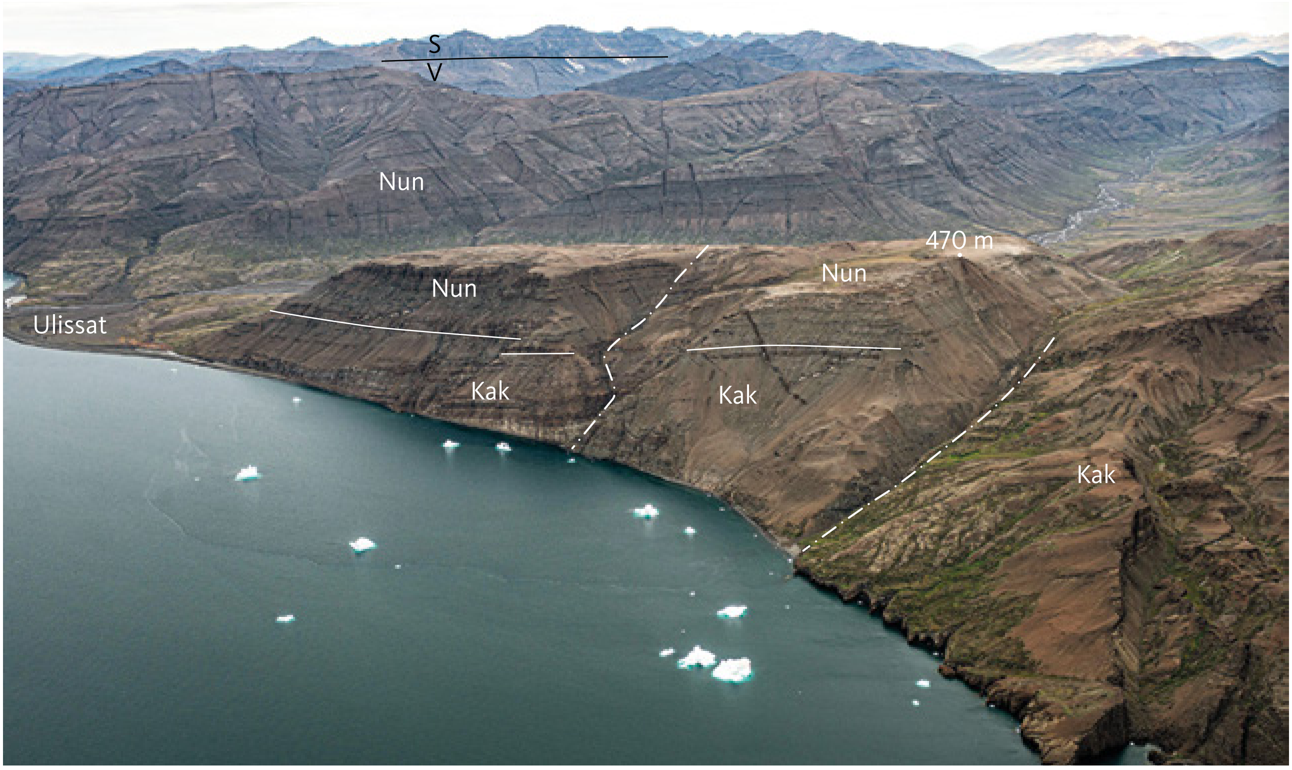

Fig. 20 Faulted lava flows of the Kakilisaat (**Kak**) and Nunavik (**Nun**) Members of the Vaigat Formation in southeasternmost Svartenhuk Halvø, looking north-west (compare Fig. 19). The Nerutusoq Member is presumed to be present but is unsampled (profile 12, Fig. 10). The wide valley running across the picture is Ulissat Qooruat. Beyond this, grey crumbling lava flows of the Nunavik Member dip westward. In the far background, dark lava flows of the Svartenhuk Formation (**S**) overlie grey flows of the Vaigat Formation (**V**). Photo: Kristian Svennevig.

Fig. 21 The three members of the Vaigat Formation in the east wall of the mountain Kakilisaat Qaqqaat, south-east Svartenhuk Halvø, looking north-west. The Kakilisaat Member (**Kak**) comprises alternating horizons of hyaloclastites (**hy**) and subaerial lava flows (**La**), whereas the Nerutusoq (**Ner**) and Nunavik (**Nun**) Members solely comprise subaerial lava flows. Foreset-bedding in the hyaloclastites dips north. A fault is indicated by the dash-dot line. The type profile for the Kakilisaat Member runs uphill just north of the fault and then southwards along the plateau to the summit at 956 m. Height of exposed mountain wall *c*. 560 m (400–956 m). Note large masses of slipped material at the foot of the wall. Photo: Kristian Svennevig.

tude; this includes about 200 m of hyaloclastites at the base, resting on Cretaceous heterolithic mudstones. Coordinates in Appendix 1.

Thickness. A thickness of more than 450 m of lava flows is present along the south coast west of Saviit where the base of the member is not exposed. A thickness of 400 m of hyaloclastite and lava flows is found in the type section at Kakilisaat Qaqqaat; there are more than 400 m of hyaloclastite and lava flows in the northern part of Ulissat Qooruat, and 300 m or more of hyaloclastite and lava flows west of Firefjeld. Thicknesses decrease to 270–200 m of hyaloclastite capped by a few lava flows on the northern slopes of Issiallaap Qaqqaa, to 170 m of hyaloclastite on southern Firefjeld and to only 150 m of hyaloclastites and lava flows along the southern side of eastern Usuit Kuussuat (Fig. 7; see also Fig. 26). The rather large variation in thickness was at least partly caused by block faulting of the bedrock prior to the extrusion of the member.

Lithology. The Kakilisaat Member is composed of hyaloclastites, pillow lavas and subaerial lava flows of thin pahoehoe and thicker sheet flow types. The member is dominated by basalts and basaltic andesites with brownish weathering colours, but there are also a few magnesian basalts and picrites. The rocks are plagioclase ± olivine-phyric and aphyric; a few carry orthopyroxene phenocrysts. The sheet flows have a distinct brown colour, whereas the thin pahoehoe flows are brownish grey to greenish grey for the more MgO-rich types. The low-viscous magmas of the pahoehoe flows gave rise to well-bedded (foreset-bedded) hyaloclastites, whereas the more viscous magmas of the thicker sheet flows produced weakly bedded hyaloclastites and pillow lavas. It is the distinct, brown sheet flows and their associated brown hyaloclastites that make the member identifiable in the field. The hyaloclastite beds range from 40 m to more than 200 m in thickness, whereas the pahoehoe lava sequences may form up to 60 m thick compound flows; the sheet flows are 10–30 m thick. Black mudstones up to several metres in thickness are locally interbedded with the basal subaqueous volcanic deposits. Sediment xenoliths are present in a picritic hyaloclastite in a gully on the northern west side of the valley of Qorlortup Kuua at *c*. 71°46′20″N, 54°20′30″W.

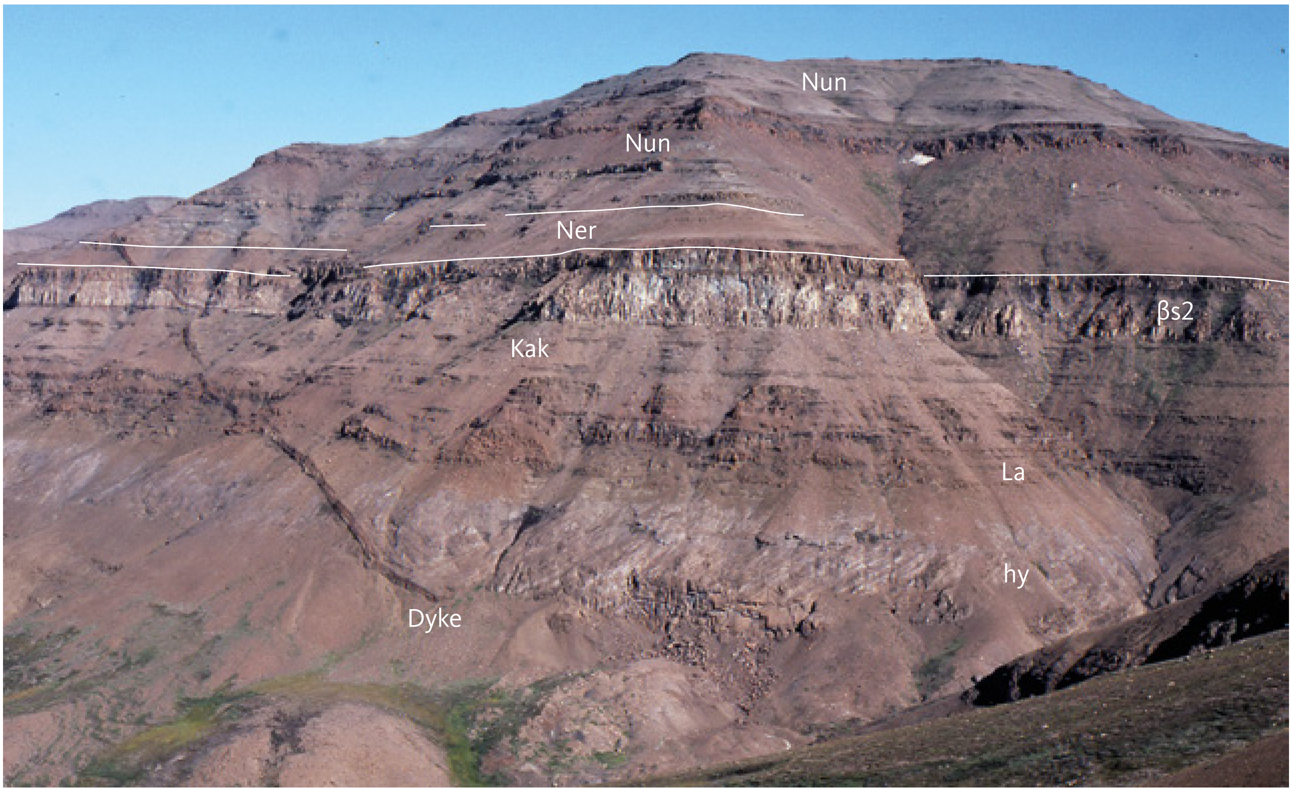

Fig. 22 The three members of the Vaigat Formation on the western slope of the mountain Kakilisaat Qaqqaat, south-east Svartenhuk Halvø. The lowest exposure is the uppermost hyaloclastite horizon (**hy**) in the Kakilisaat Member (**Kak**); the north-dipping foresets showing the direction of progradation are clearly visible. The hyaloclastites are capped by their associated subaerial lava flows (**La**). The two uppermost flows in the Kakilisaat Member with white and brown weathering colours (**βs2**) are recognisable also in Fig. 21. The thin brown flows of the Nerutusoq Member (**Ner**) are poorly exposed. The normally grey Nunavik Member (**Nun**) contains a massive brown lava flow, which is an MgO-poor picrite. Height of exposure *c*. 500 m. Photo: Asger Ken Pedersen.

Subaerial and subaqueous facies of the member show regional variations, with subaerial lava flows dominating in the south and south-west. Towards the north, the subaerial lava flows transform to hyaloclastite facies with a general north-dipping foreset-bedding. Thus the lavas flowed northwards, overriding their prograding hyaloclastites, possibly from a topographical high established close to the eruption sites in the southern area and farther south (see Fig. 26). The topmost brown lava flows including the βs2 marker flow (Larsen & Grocott 1991) reached as far north as south-west of Firefjeld before they entered the water, and north of this the entire member is in hyaloclastite facies. The basin in the north presumably formed a fault-bounded trough along the eastern part of the basin. Along the south side of Usuit Kuussuat, a hyaloclastite bed prograded eastwards from dry land in the west (Larsen 1981a, fig. 14).

Subaerial and subaqueous lava facies are interbedded in the area of the type profile at Kakilisaat Qaqqaat (Fig. 21). The type profile is composed of three eruptive units each consisting of thick, foreset-bedded pillow breccias overlain by pillow lava and pahoehoe lava flows. Each unit reflects an episode of filling of a basin with a water depth of 35–80 m, indicating basin subsidence between each episode. The north-dipping hyaloclastite foresets also here indicate filling from south towards north (Fig. 22). Upwards in the profile the hyaloclastites decrease in thickness and the proportion of subaerial lava flows increases. Towards the west the amount of hyaloclastite also decreases, and west of Ulissat the entire succession is subaerial as in the Saviit South profile (Fig. 10).

Near Maniiseqqut, the south-easternmost point of Svartenhuk Halvø, and on Schade Øer 15–25 km south of Maniiseqqut, spectacular pillow lavas, pillow breccias and pillow-rich hyaloclastites are exposed and easily accessible along the shores (Figs 23–25).

The rocks on Schade Øer show weak but significant oil staining. An oil seep, several localities with oil staining as well as carbonate veins with oil are also found on the south-eastern shores of Svartenhuk Halvø, particularly near Maniiseqqut (Christiansen *et al*. 1998, 2000). It appears that the lithologies of the Kakilisaat Member are particularly favourable for trapping of migrating oil.

Sediments, commonly poorly exposed, are found within the member at several localities.

Several metres of shaly sediments including gritty layers occur in the lower part of the member at Issiallak below the brown breccia and on top of an olivine-phyric hyaloclastite (71°35′26″N, 54°14′32″W, *c*. 175 m a.s.l.).

On the north-eastern part of Firefjeld between 390 and 510 m a.s.l., three hyaloclastite layers each about 40 m in thickness are interbedded with and overlain by shaly mudstone and intruded by a sill at 510 m a.s.l.

Fig. 23 Pillow lava with close-lying pillows up to 1 m in diameter developed in the lower part of the flow. The middle part shows flow banding and the upper part is rubbly due to abundant vesicles. Height of exposure *c*. 20 m. Kakilisaat Member, eastern south coast of Svartenhuk Halvø near Maniiseqqut. Photo: Asger Ken Pedersen.

Fig. 24 Elongate pillows reminiscent of seals on the shore. Kakilisaat Member, Schade Øer, south of eastern Svartenhuk Halvø. Length of hammer 29 cm. Photo: Asger Ken Pedersen.

Fig. 25 Pillow breccia with abundant, up to metre-sized pillows, pillow fragments and lava fragments in a glass-rich matrix. Kakilisaat Member, eastern south coast of Svartenhuk Halvø near Maniiseqqut. Height of the vertical part of the cliff *c*. 15 m. Photo: Asger Ken Pedersen.

A 0.5 m thick shale layer with plant remains and intruded by a basalt sill is present within the brown hyaloclastite in the southern south-west side of the valley of Qorlortup Kuua at *c*. 300 m a.s.l., and another 0.5 m thick shale layer with a white surface colour is present on top of the brown hyaloclastite at 337 m a.s.l (71°43′53″N, 54°14′35″W). The latter can be followed towards the north-west due to its white surface colour. It may correspond to a 1.5 m thick shale horizon between the brown and the grey hyaloclastites *c*. 14 km farther south on the northern flank of Issiallaap Qaqqaa, as reported by S. Munck in Rosenkrantz *et al*. (1942, p. 49, where the mountain was misnamed as Umîviup qáqai).

In the upstream part of the valley of Qorlortup Kuua, on the south-western valley side, a 5 m thick silty shale layer is present between an aphyric basaltic hyaloclastite with sediment inclusions and an overlying olivine-phyric hyaloclastite with a loose shale layer on top. The top of the basaltic hyaloclastite appears to be chilled against the sediment, indicating it is intrusive (71°46′23″N, 54°19′34″W, *c*. 165–184 m a.s.l.).

On the north-west side of Simiutaq by Simiuttap Kuua two sedimentary beds at 300–400 m a.s.l. were noted but not visited. They may perhaps correlate with those described here, but could also belong to the overlying Nerutusoq Member.

Eruption sites. There is clear evidence from the dip directions of the foreset-bedding in the hyaloclastites and the general stratigraphy that the lava flows of the south-eastern area flowed north and east from a central area around Ulissat Qooruat and Usuit Kuussuat, indicating that eruption sites should be present in the southern part of the peninsula and probably also farther south (Larsen 1981b; Fig. 26). Eruptions may have occurred over most of the area occupied by the member because dykes with similar appearance and composition are found at several localities within the member. One eruption site was identified on the lower eastern flank of Peak 1309 m where numerous closely spaced small dykes or thin lava sheets cut the hyaloclastites (Fig. 26; Larsen 1981a, fig. 16).

A local eruption site somewhere east of Peak 1078 m presumably emitted lavas flowing westwards where they changed into hyaloclastite facies south-east of Peak 1078 m (profile 9). A dyke in profile 9 with a chemical composition corresponding to that of the Kakilisaat Member is probably part of the feeder system for these flows (Fig. 26).

Chemistry and chemostratigraphy. The rocks of the Kakilisaat Member are dominantly silicic basalts and basaltic andesites; a few picrites extend the total MgO range to 6–13 wt% MgO. Relative to the normal rocks of the Nunavik Member most of the rocks have elevated contents of SiO_2 and K_2O and low MgO, CaO, TiO_2

and FeO* (total iron as FeO). The elevated contents of SiO_2, K_2O and many trace elements suggest that the rocks have been crustally contaminated (see the earlier Nomenclature section and the later Geochemistry chapter); the presence of sediment xenoliths in the rocks supports this suggestion. Representative analyses are given in the Geochemistry chapter.

No clear evolution trend with time can be seen in the TiO_2 contents, whereas the MgO content tends to decrease upwards but with the uppermost basalts being more magnesian again.

Boundaries. The lower boundary is identical to that of the Vaigat Formation within the basin, and the sediments underlying the Kakilisaat Member include marine Paleocene mudstones and black, tuffaceous material. The earliest volcanic rocks in the region were therefore deposited in a marine basin.

The upper boundary is placed at the top of the uppermost of two massive brown marker lava flows underlying the grey picrites along the south-east coast of Svartenhuk Halvø; in some areas one of these lava flows may have a white colour due to zeolite-filled cracks (Fig. 22). These brown lava flows are designated βf1 on the 1:100 000 Igdlorssuit map sheet (Larsen 1983) and βs2 on the 1:100 000 Svartenhuk map sheet (Larsen & Grocott 1991). Note that the contaminated basalts below βf1 are not distinguished from the picrites on the Igdlorssuit map sheet. In the area west of Saviit other brown lava flows form the top of the member.

In the field, distinction between the Kakilisaat and Nerutusoq Members is difficult based on lithology alone. However, the occurrence of interspersed plagioclase-phyric and aphyric rocks is indicative for the Kakilisaat Member basalts, whereas the Nerutusoq Member basalts are all aphyric. Definitive distinction between the two members requires chemical analyses; the Nerutusoq Member rocks have lower SiO_2 and higher CaO than the Kakilisaat Member rocks and different trace-element patterns (see the Geochemistry chapter).

Geological age. Paleocene (Danian to Selandian). The Kakilisaat Member is reversely magnetised and was erupted during magnetic polarity chron C26r (Riisager *et al*. 2003). Its age is thus constrained to the interval 62.2–61 Ma, based on the lower age boundary of C26r and the upper age boundary of the Vaigat Formation. Chauvet *et al*. (2019) presented an $^{40}Ar/^{39}Ar$ age of 61.08 ± 0.56 Ma in accordance with this for a silicic basalt lava flow from the lower part of the Vaigat Formation at the eastern south coast of Svartenhuk Halvø. The location and chemical composition of the basalt (Agranier *et al*. 2019, their Site 42) indicate that it belongs to the Kakilisaat Member.

Correlation. The Kakilisaat Member is suggested to be time-correlated with the crustally contaminated Tunoqqu and Kûgánguaq Members of the Vaigat Formation on Nuussuaq and Disko (Fig. 3). All were erupted within a period when the conditions for high-level magma storage and reaction with crustal rocks were favourable.

Nerutusoq Member

New member

History. On the geological maps of Larsen (1983) and Larsen & Grocott (1991) the member is combined with the underlying Kakilisaat Member because the two members can only be visually distinguished at close range. The name Nerutusoq Member was first used by Larsen & Pulvertaft (2000) in the same sense as here, but the member was not formally defined.

Name. After the large, NNE–SSW-oriented inland valley Nerutusoq in northern Svartenhuk Halvø (Figs 7–9).

Distribution. The member is present in the northern part of Svartenhuk Halvø along the valley of Nerutusoq (Fig. 27; see also Larsen & Pulvertaft 2000, plate 1, profile C–D) and around the Simiutaq hill. It is also present in the short valley that extends W–E from just north of the lake Taseraarsuit around 71°47′N, 54°25′W to the valley of Siuteqqut Kuuat (see also Fig. 40). The member is inferred to be present in the valley of Siuteqqut Kuuat, exposed on the western valley side close to the Cretaceous boundary fault system, and also in the broad area around Firefjeld. The member is present in south-eastern Svartenhuk Halvø, where a few flows have been identified in profiles 4 and 13 at Kakilisaat and Saviit South (Fig. 10). The extension of the member to the west, north-west and north is unknown.

Type section. **Nerutusoq** (profile 48b) in the northern part of Svartenhuk Halvø along the Nerutusoq valley (Figs 7–9, 27, coordinates in Appendix 1). No vertical profile such as those in Figs 10–13 could be constructed because a major part of the profile is near-horizontal, although it is up-section through inclined hyaloclastites.

The lower boundary of the member is placed on top of Cretaceous sediments *c*. 100 m a.s.l. at the south-eastern end of Simiuttap Kuua, just west of the hill Simiutaq. The profile follows the eastern riverside in the Nerutusoq valley 10.5 km southward until a gully in the western valley side, which is then followed uphill (Fig. 28). Most of the profile transects SW-dipping hyaloclastites, but in the gully these are capped by brown aphyric basalt flows at 595 m a.s.l. (Fig. 28). At 670 m a.s.l. the brown basalts are overlain by thin grey pahoehoe flows of the Nunavik Member. Here the exposure is downwarped along a NW–SE fault and dips to the south. On the north-eastern side of the fault the boundary is horizontal with an elevation of 750 m a.s.l..

The lower boundary in the type profile was not visited in the field, and therefore we cannot know if the lower part of the section includes brown hyaloclastites of the Kakilisaat Member. The lowest analysed sample (GGU 263818) in the type profile is from 360 m altitude in a small drainage stream *c.* 2.8 km north-west of Peak 1250 m. The undifferentiated βp hyaloclastite of the map sheet (Larsen & Grocott 1991) reflects the uncertainty concerning the field distinction between the Kakilisaat and Nerutusoq Members (see the description of the boundaries of the Kakilisaat Member).

Reference sections. **Taseraarsuit** (profile 10) on the south-west side of Peak 1140 m, 2–3 km north of lake Taseraarsuit (Figs 7–9, 12; coordinates in Appendix 1). At 350–670 m a.s.l., this profile is mostly well exposed and presents 320 m of the upper part of the member, including 240 m of hyaloclastites, 40 m entablature flows, 40 m fully subaerial, thin lava flows and the boundary to picrite lava flows of the overlying Nunavik Member. A second reference section is **Kakilisaat** (profile 4) in south-eastern Svartenhuk Halvø. At 825–860 m a.s.l. the Nerutusoq Member here has a strongly reduced thickness of only 35 m of subaerial lava flows without a significant break in the volcanism (Figs 10, 18).

Thickness. An estimated maximum thickness of up to 650 m may be present in the southern part of the

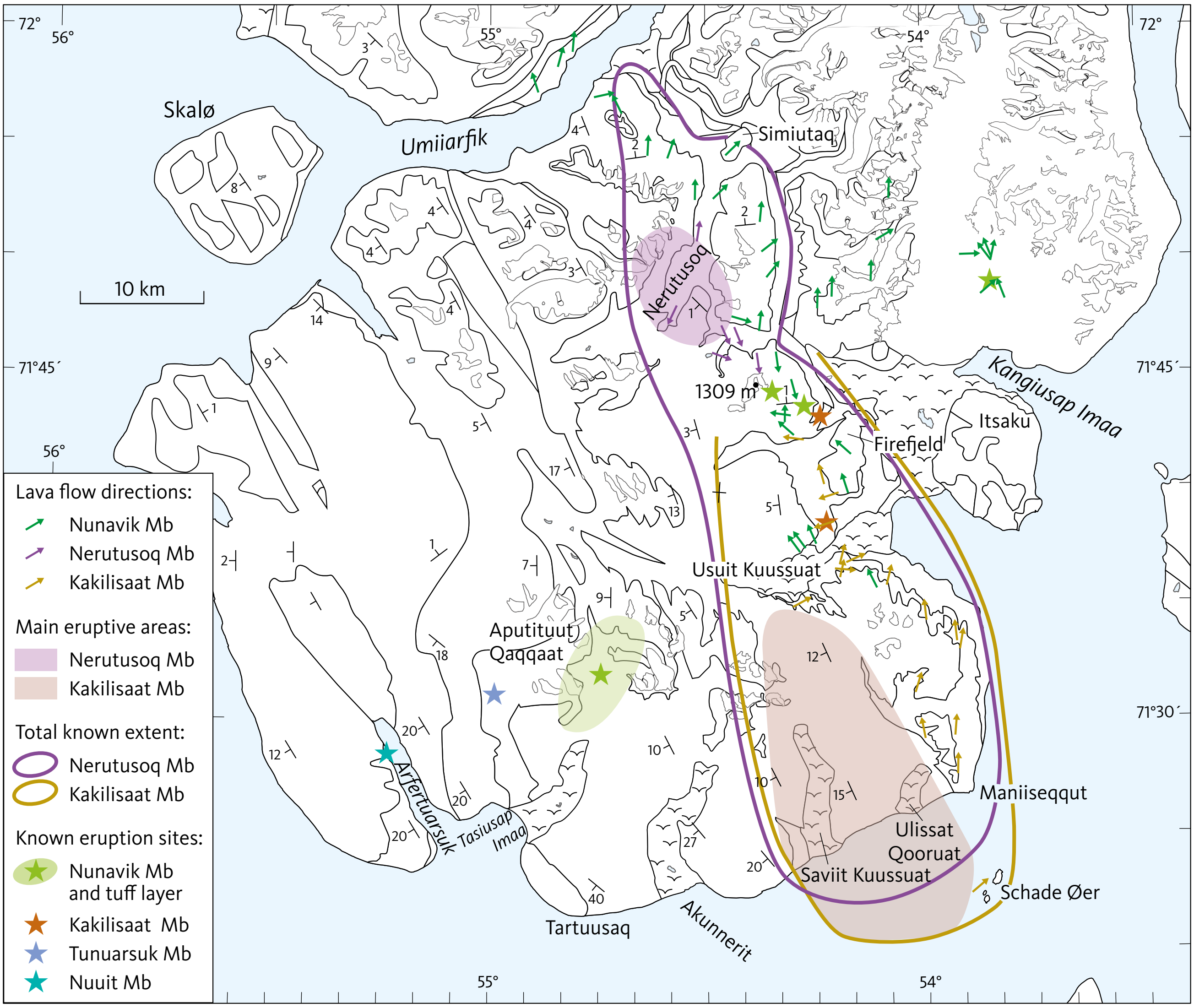

Fig. 26 Map showing flow directions as indicated by dips of foreset-bedding in hyaloclastites of the Vaigat Formation and the main eruptive areas and total known extents of the Kakilisaat and Nerutusoq Members. The coloured area at Nerutusoq is the 'table mountain' with subaerial lava flows described in the text. Both members probably continue below exposure level to the west. The Kakilisaat Member may also be present farther north than shown. The Nunavik Member is considered to extend across the entire area. Also shown are known eruption sites for the volcanic succession.

Nerutusoq valley, dependent on the absence or presence of the Kakilisaat Member beneath it and the topography of the bedrock. With the same reservations, the thickness in the northern part of Nerutusoq is about 300 m. Towards north-west along the south-west side of the valley of Simiuttap Kuua the thickness decreases from 300 m to 100 m. Near lake Taseraarsuit the thickness is more than 230 m, and along the west side of the valley of Siuteqqut Kuuat the member is inferred to be present with a thickness of more than 200 m. The member is strongly reduced in thickness to the south-east and south, where it is 60 m thick at Kakilisaat (profile 4) and 40 m thick at Saviit South (profile 13).

Lithology. The Nerutusoq Member is composed of brown aphyric basalts and magnesian basalts forming hyaloclastites and pillow lava tongues, which in places are capped by an up to 50 m thick succession of subaerial, thin, vesicular pahoehoe lava flows. The lowermost lava flows were emplaced into shallow water and are entablature lavas with irregular and fan-shaped columnar jointing and an uneven top topography; the flow tops have a dark brown colour and are presumably glass-rich.

In the southern part of the Nerutusoq valley, the member consists of southerly dipping hyaloclastites capped by lava flows at altitudes of 720–750 m. This succession can be followed northwards on the western valley side; 2 km farther north the brown lava flows have all transformed into hyaloclastites, which dip northwards below hyaloclastites of the overlying Nunavik Member at altitudes of 720–400 m, decreasing northwards. The

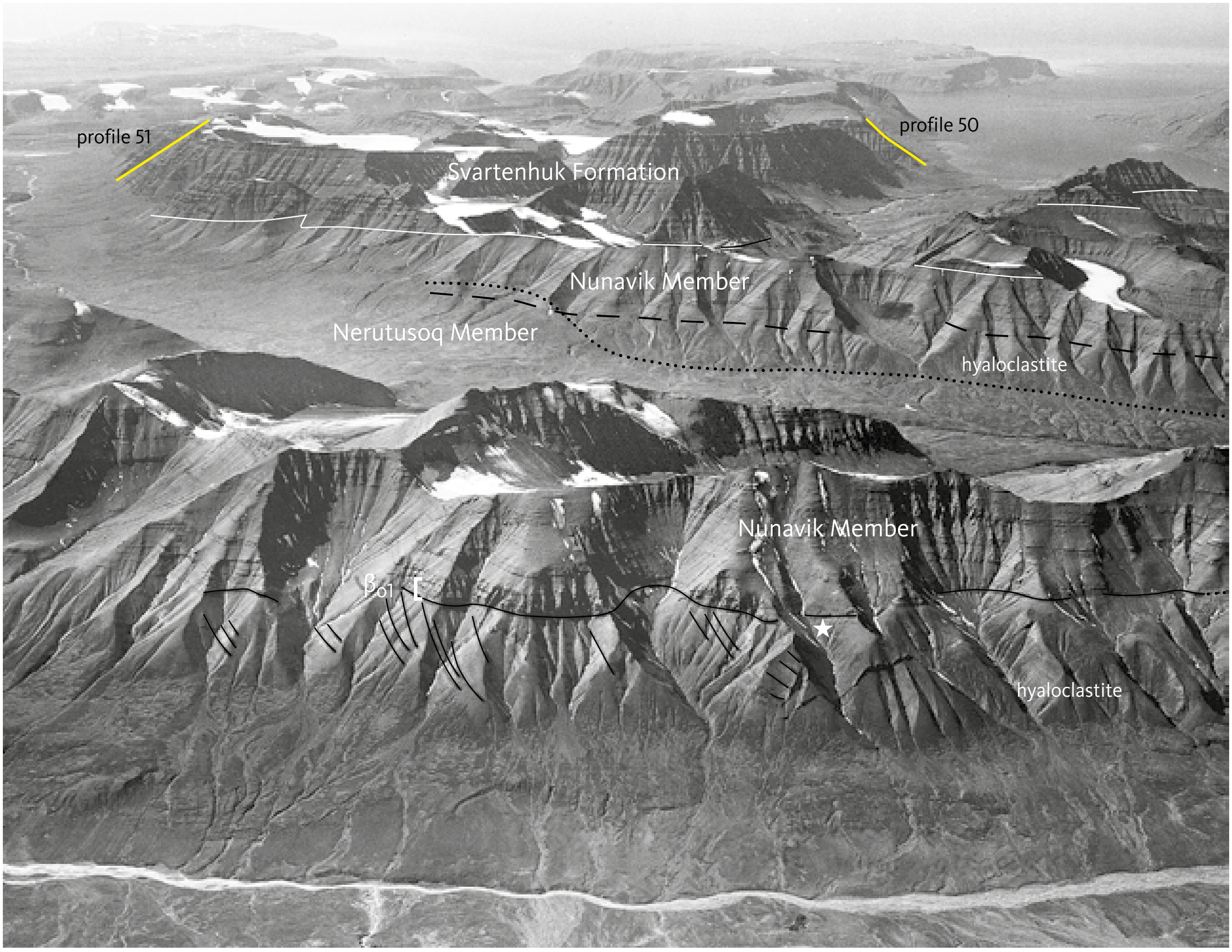

Fig. 27 The Vaigat Formation west of the Siuteqqut Kuuat valley, looking west. In the foreground subaerial thin pahoehoe lavas of the Nunavik Member overlie 300 m of associated hyaloclastites with large-scale foreset-bedding indicating volcanic progradation to the north (enhanced by drawn, black lines). The marker unit **βo1** with dark flows is indicated by a white **[**; the unit disappears into hyaloclastite facies at the position of the **white star**. In the middle ground is the wide Nerutusoq valley. In its western mountainside lavas and hyaloclastites of the Nerutusoq Member are exposed in a small area on the low slope, overlain by the Nunavik Member. The **dashed black line** is the upper boundary of the hyaloclastite facies; the facies boundary crosses the member boundary (**dotted black line**). In the distant mountains thick-bedded lava successions of the Svartenhuk Formation overlie the Nunavik Member above the **white line**. Profiles 50 (Umiiarfik south) and 51 (Tunuarsuk) are indicated with **yellow lines**. Geodetic Institute oblique aerial photograph 524CV/8298.

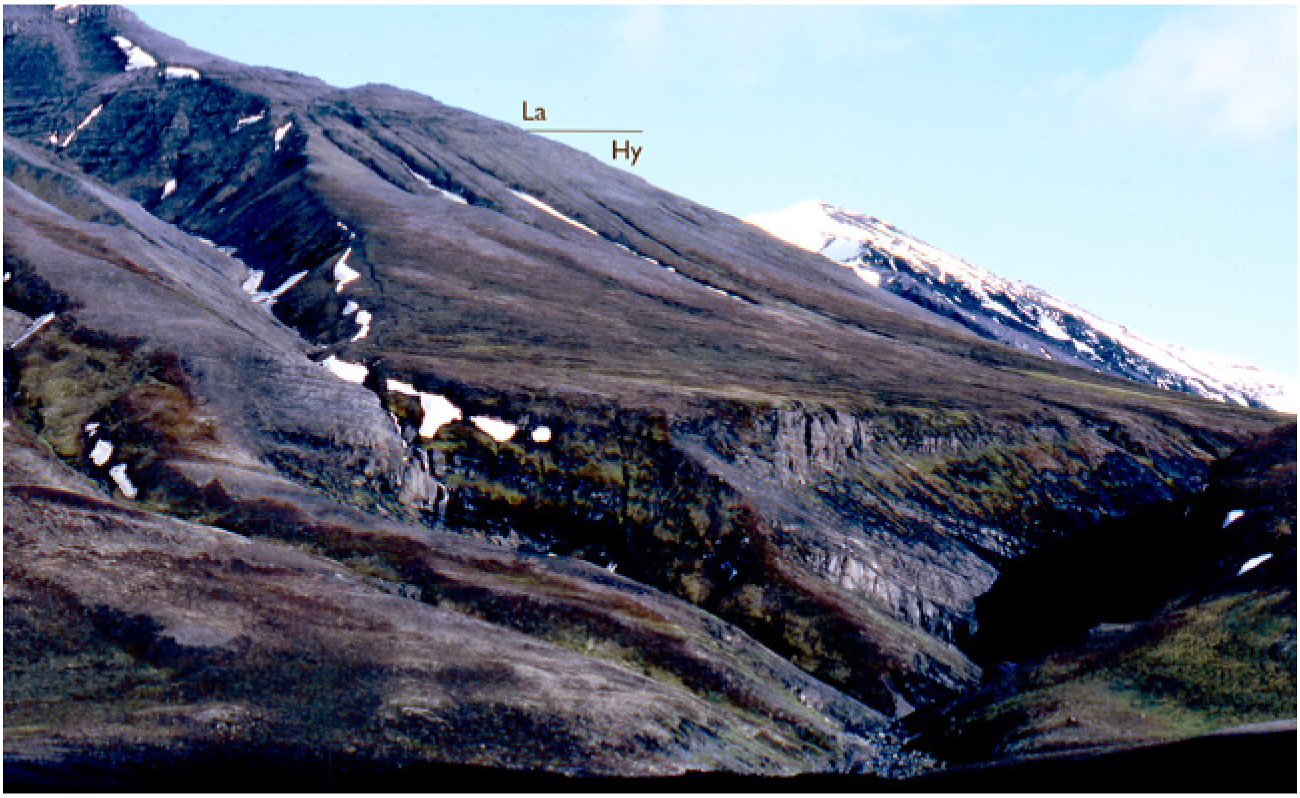

Fig. 28 The middle part of the type profile (48b, Fig. 9) for the Nerutusoq Member. The location is where the profile leaves the riverbed in the main valley and climbs uphill through a gully in the hyaloclastites (**Hy**) and into the subaerial lava succession (**La**). Western slope of the southern Nerutusoq valley, central Svartenhuk Halvø.

hyaloclastites of the two members appear to interdigitate (see cross-section in Larsen & Pulvertaft 2000, plate 1, profile C–D). The two members were erupted at a time with similar water levels, at least partly contemporaneously, and thus formed hyaloclastites up to the same altitude of 720 m, covered by lava flows. A similar situation exists in the valley of lake Taseraarsuit where more than 250 m of east-dipping, brown, aphyric hyaloclastites are interdigitated with grey hyaloclastites of the Nunavik Member down to 400 m a.s.l. on both sides of the valley (Fig. 29). Here, the top of the hyaloclastites of the two members reaches an altitude of 600 m. Profile 10 in the northern side of the valley has large pillows with south-dipping longitudinal axes. Thus, the hyaloclastites and pillow lavas dip away from a common centre located in the southern Nerutusoq valley (Fig. 26). In the southernmost part of the Nerutusoq valley, the member appears to end in a steep cliff against the picrites to the north-west; this may be a secondary feature caused by faulting or landslipped Nunavik Member lava flows.

In the southern part of Svartenhuk Halvø a few subaerial lava flows of the Nerutusoq Member were deposited on elevated dry land formed by the Kakilisaat Member basalts. The reduced thickness of the member in this area may also be caused by its distal position relative to the main source area in the north.

Eruption sites. As described above, the hyaloclastites and pillow lavas dip away from a common centre located in the southern Nerutusoq valley. This was probably a major eruption centre for the member. Overall, the major volume of the Nerutusoq Member forms a NW–SE-elongated ‘table mountain’ of hyaloclastite capped by cogenetic lava flows, centred on a major eruption area in the Nerutusoq valley area (Fig. 26). This mountain acted as a barrier for the extension of the lower part of the Nunavik Member. The barrier presumably terminated in the area north-west of Firefjeld and was not important in the south. The situation to the west and north-west is unknown.

In the northern Nerutusoq valley and along the west side of the valley of Siuteqqut Kuuat, the brown hyaloclastites show mainly westerly-dipping foreset-bedding and have no capping subaerial lava flows of the member. They were probably fed from a number of NNW–SSE- to NE–SW-trending, aphyric basalt dykes, which cut the hyaloclastites. Several thin, N–S-trending possible feeder dykes are also present in the Taseraarsuit valley. An early, widespread eruptive phase through the dykes therefore appears to have taken place before the volcanism was concentrated in the table-mountain area.

Chemistry and chemostratigraphy. The Nerutusoq Member consists of basalts and magnesian basalts with

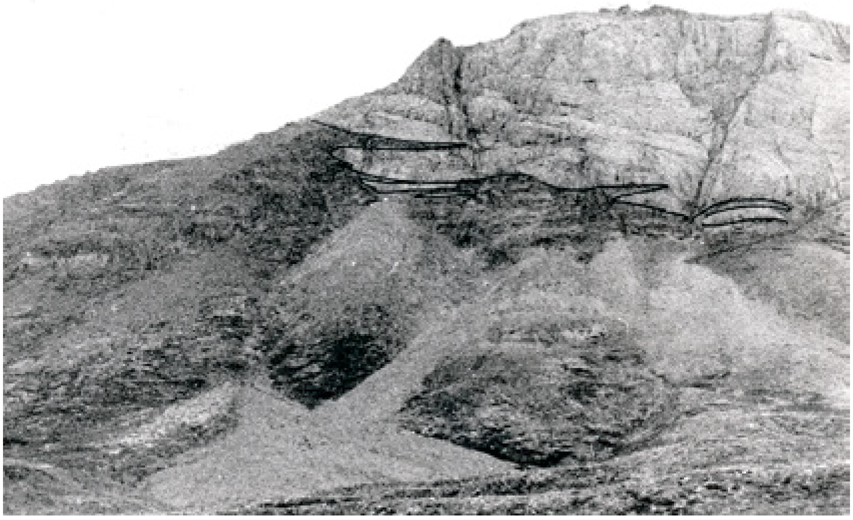

Fig. 29 Brown hyaloclastites (dark) of the Nerutusoq Member interdigitated with grey hyaloclastites (light) of the Nunavik Member. Both units with east-dipping layering. The boundary between brown and grey units is traced with a thin black pen for clarity. North-eastern corner of the valley with the lake Taseraarsuit, bordering to the Siuteqqut Kuuat valley. Height of exposure about 200 m.

8–12 wt% MgO, normal SiO_2 contents of 48–49 wt%, relatively high contents of CaO (12–13.6 wt%), and high P_2O_5 (0.20–0.32 wt%). The P_2O_5/TiO_2 ratios are high, 0.116–0.17. Besides P_2O_5, the member is relatively enriched in a number of trace elements such as Ba, Th, U, Nb, Zr, Sr and the light rare-earth elements. Representative analyses are given in the Geochemistry chapter.

Boundaries. The Nerutusoq Member rests on lava flows and hyaloclastites of the Kakilisaat Member and in the valley of Simiuttap Kuua possibly on sediments of Paleocene or Cretaceous age. As described above, distinction in the field between the Kakilisaat and Nerutusoq Members is difficult except at close range; they are therefore shown as one unit on the published geological maps. Well-defined boundaries to lava flows of the Kakilisaat Member are exposed at Kakilisaat (profile 4) and Saviit South (profile 13) in south-eastern Svartenhuk Halvø (Fig. 10); there is no indication of a break in the volcanic activity at the boundary.

In the type profile (48b) the lower boundary, which was not visited in the field, is belived to be present along the south-west side of the Simiuttap Kuua valley, with contact towards either Cretaceous sediments or the top of the Kakilisaat Member, if this is present here. Two sedimentary beds between 300 m and 400 m a.s.l. on the north-west side of Simiutaq may be close to the lower boundary. In other places the boundary is not exposed or has not been identified. A 0.5 m thick bed of black mudstone within the brown hyaloclastite south-east of Peak 1309 m may form the lower boundary towards the Kakilisaat Member here.

The upper boundary is best exposed in the valley sides of Nerutusoq in the type profile (48b) and in profile 10. The boundary is distinct because of the colour contrast between the brown lavas of the Nerutusoq Member and the overlying grey picrites of the Nunavik Member. In both profiles there is no indication of any break in the volcanism at the upper boundary; rather, the Nerutusoq Member appears to be partly contemporaneous with the Nunavik Member. A break in the volcanism may be indicated by a shale layer with plant remains at the boundary between a brown and a grey hyaloclastite 3.8 km east-south-east of Peak 1309 m (71°43′53″N, 54°14′35″W, *c*. 337 m a.s.l.). However, the brown hyaloclastite could also belong to the Kakilisaat Member. The upper boundary reaches a maximum altitude of 860 m at Kakilisaat, 750 m in southern Nerutusoq and 600–650 m in the valley of Taseraarsuit.

Geological age. Paleocene (Danian to Selandian). The Nerutusoq Member is reversely magnetised and was erupted during magnetic polarity chron C26r (Riisager *et al*. 2003). Its age is thus constrained to the interval 62.2–61 Ma, based on the lower age boundary of C26r and the upper age boundary of the Vaigat Formation. No reliable radiometric age has been obtained for the member.

Correlation. None known.

Nunavik Member

New member

History. On the geological map 71 V.1 Syd Igdlorssuit (Larsen 1983) the Nunavik Member is shown as part of the unit βp (hyaloclastites) and as the unit βo (lava flows). On the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991) the member is shown as the units βp2 (hyaloclastites) and βo (lava flows); hyaloclastites of the member may also be included in the unit βp (undifferentiated hyaloclastites).

Name. After Nunavik, the former Greenlandic name for Svartenhuk Halvø (now Sigguup Nunaa).

Distribution. The Nunavik Member is exposed over large areas in the eastern half of Svartenhuk Halvø. The member dominates the south coast as far west as Tartuusaq. The westernmost exposure is a small outlier on south-western Svartenhuk Halvø at Narsinganersua/Kap Cranstown. To the north, the member reaches the southern part of the Innerit peninsula where the dips of the hyaloclastite bedding indicate mostly northerly flow directions. Its extension below exposure level north of 72°00′N may be up to 10 km, based on a northward reduction in thickness (see the section on *thickness*). A significant extension of the member occurs east of the Cretaceous boundary fault system from Kuugaartorfik in the north-west to Qinngusaaq and Uparuaqqusuitsut in the south-east. Due north of Itsaku, the easternmost extension of the member consists of erosional remnants in two small outliers at peaks 1211 and 1270 m (Figs 6, 7), up to 17 km east of the boundary fault. These rocks are situated at some of the highest altitudes for the member due to the postvolcanic uplift discussed by Pulvertaft & Larsen (2002). Altitudes reach *c*. 1300 m in a small erosional remnant 2.5 km north-east of Qinngusaaq where the upper boundary of the member is preserved (Larsen & Grocott 1991).

Due to the general westerly dip of the volcanic succession, the lower part of the member is well exposed in the eastern part of the basin including the south coast of Svartenhuk Halvø (Fig. 30). The upper part of the member is exposed towards west and south-west, on the Precambrian basement to the east, and on the Innerit peninsula (Fig. 31) to the north. The entire member is exposed in the nearly flat-lying areas of the central and north-eastern parts of the basin.

Type section. Due to faulting, especially in the southern part of the peninsula, it has not been possible to establish a type section that includes the maximum thickness and entire stratigraphy of the Nunavik Member. **Peak 1078 m** (profile 9) is designated as type section because it is unfaulted, well-sampled and analysed. The profile runs along the south-east side of Peak 1078 m, from 470 m to 1078 m a.s.l. (Figs 9, 11; coordinates in Appendix 1). The lower 600 m of the member are exposed here, but the top is missing; the base is not exposed but is seen 1–2 km south-west of the profile.

Reference sections. Both base and top of the Nunavik Member are exposed in the central and northern areas where the thickness is reduced. A profile on the south side of **Peak 1309 m** (profile 7; coordinates in Appendix 1) is a reference section; it includes the thickest undisturbed succession in the area, and dips are only 1–2°NNW. The profile was not sampled for geochemical analysis and is not shown in Figs 10–11. The upper boundary is well exposed. The position of the lower boundary cannot be determined on the basis of the present knowledge because grey and brown hyaloclastites of unknown composition are intercalated here. The entire profile is *c*. 1100 m in thickness. It begins at *c*. 170 m altitude in a river north-west of Firefjeld, where Cretaceous sediments are overlain by olivine-phyric pillow lavas succeeded up-river by intercalated grey and brown hyaloclastites. At 230 m the profile turns north and follows a side stream uphill; from 450 m grey picritic hyaloclastites belong to the Nunavik Member. At *c*. 570 m the grey hyaloclastites are overlain by subaerial lava flows of the Nunavik Member. From here the profile climbs the hillside to the top at 1309 m (Figs 9, 32; see also Fig. 40). At the top about 10 m of the lowest flow of plagioclase-phyric basalt of the overlying Tunuarsuk Member is preserved. A palaeomagnetic sample profile by Riisager *et al*. (2003, 2004) was collected from the subaerial part of this profile.

The second reference section is **Peak 1120 m** (profile 24) on the north-western valley side of the headwaters of Saviit Kuussuat, where the upper 700 m of the member are exposed from 270 m to 970 m altitude (Figs 9, 10; coordinates in Appendix 1). The profiles cannot be correlated by field observations or chemical data, a fact which applies to most profiles in this member in areas where faulting is common. Profile 24 is located west of a flexure zone south of Usuit Kuussuat, which has caused a downthrow of at least 90 m of the lavas to the west (Fig. 33; Larsen & Pulvertaft 2000, p. 27 and fig. 11).

Thickness. From south to north in the basinal area, thicknesses decrease from in excess of 930 m (including 120 m hyaloclastite) in the Issiallaap Qaqqaa area, to 855 m (300 m hyaloclastite) in the profile of Peak 1309 m, to 800 m (250 m hyaloclastite) at Peak 1250 m south of Simiutaq, and 600–900 m (*c*. 300 m hyaloclastite) on the south-west side of the Simiuttap Kuua valley. On Innerit the exposed thickness is 380 m, including 180 m of hyaloclastite, and a total thickness of around 500 m is possible if the hyaloclastites continue below sea level to attain a thickness of 300 m, similar to that on Svartenhuk Halvø. The reduced thickness of the subaerial lava succession on Innerit corresponds to a lava shield with a northerly slope of 1° (as argued in the description of marker horizon βo1). By extrapolating the decreasing thickness of the subaerial lava pile to the north, it is inferred that the lava flows of the member may have travelled up to 10 km farther north before the uppermost flow had reached sea level and the progradation stopped.

In the central area around Nerutusoq, the thickness is only 325 m because an eruption centre of the underlying Nerutusoq Member formed a local high (Fig. 26) around which the lowest Nunavik Member lavas flowed.

On southern Svartenhuk Halvø, the western outlier at Kap Cranstown comprises 280 m of the upper part of the member (Fig. 34). Along the south coast from Tartuusaq to Maniiseqqut, uplift along numerous NW–SE- and WNW–ESE-trending faults has exposed the Nunavik Member for 32 km (Fig. 30). It is difficult to estimate the thickness of the member in the southern area due to the faulting and lack of marker horizons.

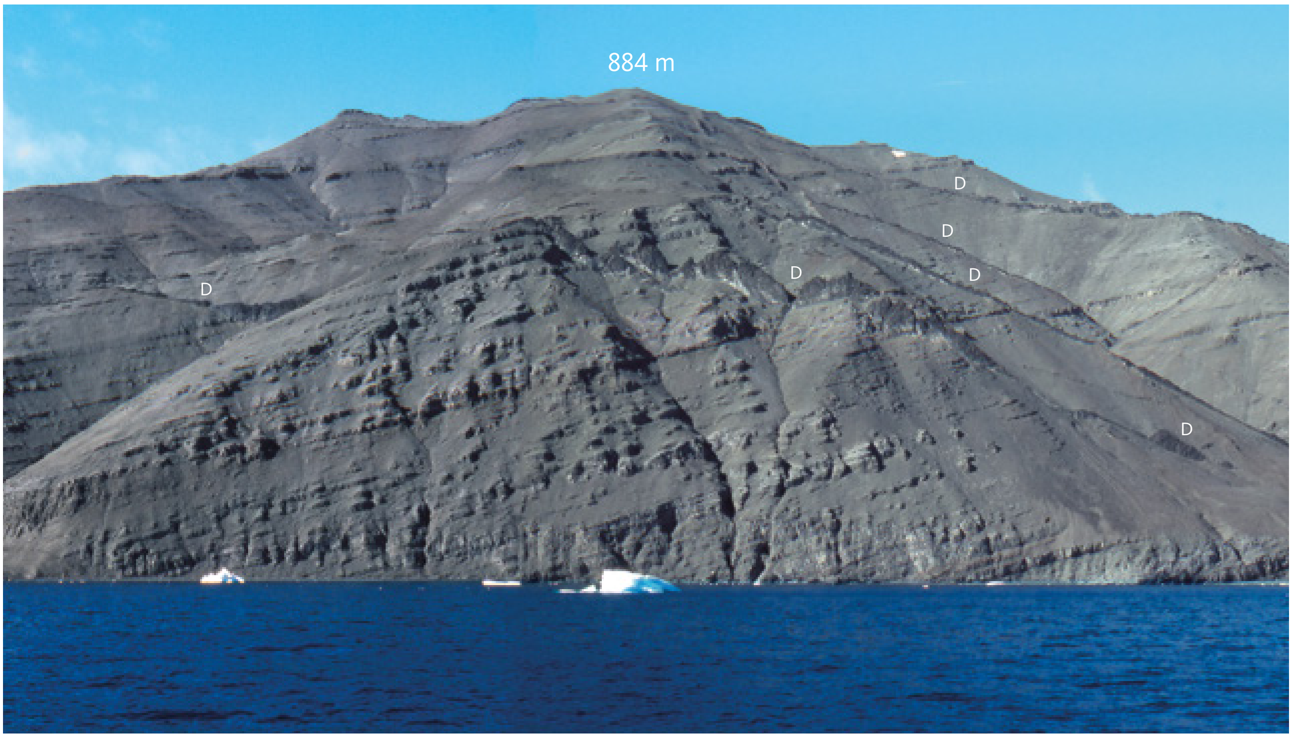

Fig. 30 Picrites typical of the Nunavik Member forming a thick succession of grey, crumbling, compound pahoehoe lava flows dipping 15–20°WSW. Several dark dykes (**D**) cut the succession. South coast of Svartenhuk Halvø between Saviit and Ulissat; the mountain is Saviit Qaqqaat (884 m). See also Fig. 17.

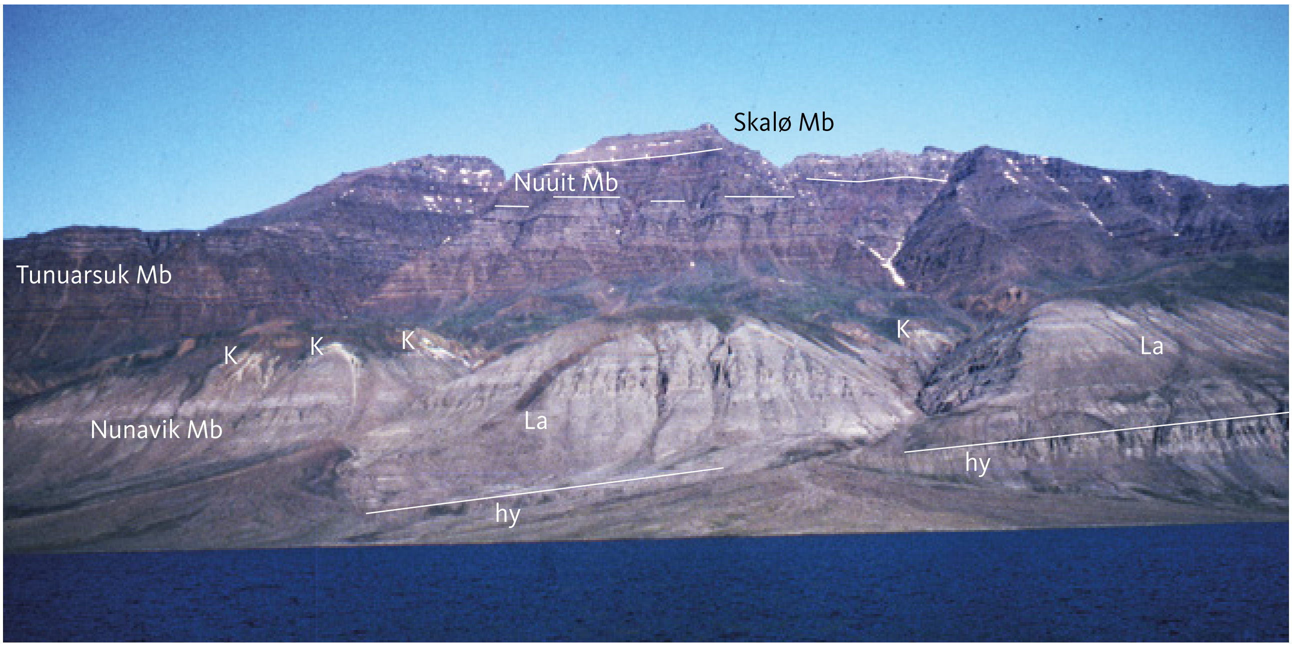

Fig. 31 The northernmost exposures of the Vaigat Formation on the Innerit peninsula. The formation here comprises 300–350 m of hyaloclastites (**hy**) and subaerial picrite lava flows (**La**) of the Nunavik Member. These are overlain by the Svartenhuk Formation, which comprises poorly exposed, whitish quartzofeldspathic sediments of the Kuugaartorfik Member (**K**) overlain by lava flows of the Tunuarsuk, Nuuit and Skalø Members. South-eastern Innerit peninsula beneath the Paannivik mountain; compare Fig. 46. The highest peak on the skyline is at 1288 m.

Fig. 32 The Nunavik Member close to reference profile 7. The succession of thin, grey, subaerial picrite lava flows is *c*. 690 m thick; the underlying hyaloclastites are exposed in the river gully in the lower part of the photo. The mapped marker horizon of dark flows, **βo1**, is indicated. The **βo2** flow near the top is a widespread basalt marker flow in the Nunavik Member. The topmost small remnant of a lava flow is the lowest plagioclase-phyric basalt of the Tunuarsuk Member. Peak 1309 m, central-eastern Svartenhuk Halvø, viewed from the south. The position of profile 7 cannot be shown here but is indicated in Fig. 40. The mountain slope seen here is the site of an important palaeomagnetic profile located on a similar photo in Riisager *et al*. (2003, fig. 4). Photo: Asger Ken Pedersen.

Fig. 33 Well-exposed lavas of the Nunavik Member in the large flexure zone that runs SSE from Usuit Kuussuat to the south coast west of Ulissat (Fig. 6). Over the about 700 m from right to left in the photo, the dip of the lava flows changes from 5°WSW to 30°WSW through two sets of closely spaced faults oriented WNW–SSE and NNW–SSE (Larsen & Pulvertaft 2000). Displacements on the faults are difficult to see due to the monotonous lithology of the Nunavik Member; an interpretation is shown in Fig. 17 (Saviit flexure zone). South coast of Svartenhuk Halvø just west of Ulissat.

The maximum thickness in a single fault block is around 2000 m without the presence of either base or top (Fig. 16 east of Tartuusaq). Thus the thickness of the Nunavik Member in the southern area is certainly more than 2000 m. Calculation of the actual thickness depends on estimates of the throw on many faults and subsidence in flexure zones. Possible shingling of the lava pile, i.e. lateral shift of volcanic deposits with time, would be another complicating factor because it makes the stratigraphic thickness different from actual thicknesses at any location. Further discussion is found in Larsen & Pulvertaft (2000, p. 34–35).

On the Precambrian basement, thicknesses decrease eastwards from about 400–500 m in the west on Qinngusaaq and Kuugaartorfik, and the member wedges out at an altitude of around 1100 m in the north-east. In the easternmost outliers at Peaks 1211 m and 1270 m, 250–270 m of picrites comprising hyaloclastites, pillow lavas and subaerial flows were erupted through local feeder dykes (Fig. 26).

Lithology. The Nunavik Member is characterised by olivine-rich tholeiitic picrites and olivine-phyric to olivine-microphyric magnesian basalts and subordinate basalts. The member consists of hyaloclastites and coarser pillow breccias overlain by subaerial lava flows of compound pahoehoe type together with a few prominent, thick sheet flows. Tuffs and soils are relatively rare, forming red beds 5–20 cm in thickness between the lava flows. Other sediments are scarce and include volcanogenic conglomerates (Fig. 35) and sandstones, and more fine-grained silty beds. The member has light greenish grey or purplish grey weathering colours. The light grey colour is due to zeolite-filled vesicles. A few erosion-resistant picritic lava flows may have brown weathering colours and may therefore resemble brown basaltic, MgO-poor lava flows from a distance (Fig. 22).

Compound pahoehoe lava flows. The lava pile is built up of compound pahoehoe flows in packages that may reach thicknesses exceeding 100 m without any indication of an eruptive pause. The average package thickness in different profiles ranges from 26 m to 55 m. Individual flow units range from flow lobes 20 cm thick (Fig. 36) to sheet flows 25 m thick, but most flow units are below 5 m and generally 1–3 m thick. Thinning of the flow units is apparent in the distal areas on the southern Innerit peninsula where the flow units are about 1–2 m thick. The pahoehoe flow units commonly have basal zones that are *c*. 10 cm thick with pipe amygdales, which are strongly inclined in the flow direction in the upper part of the zone. The orientation of these pipe amygdales has been used to determine the flow direction of the lavas (Larsen 1981b). Above this basal zone about half of each flow is massive and the upper half is crumbling and highly amygdaloidal, with amygdale banding parallel to the lava top. This banding was formed by upwards concentration of gas released from the still-flowing liquid lava under the solidifying crust. The flow units may

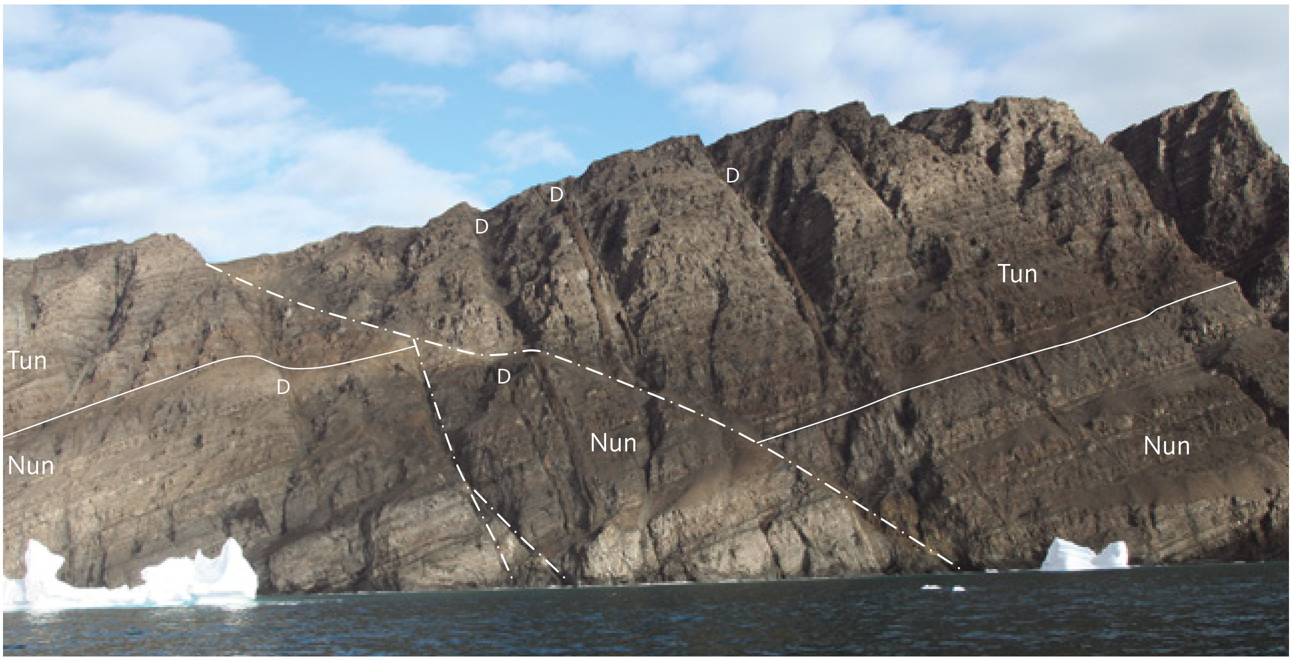

Fig. 34 Subaerial lava flows of the upper part of the Nunavik Member of the Vaigat Formation (**Nun**) overlain by subaerial lava flows of Tunuarsuk Member of the Svartenhuk Formation (**Tun**) at Narsinganersua/Kap Cranstown, south-western Svartenhuk Halvø. The sedimentary Kuugaartorfik Member is not present here. The succession is repeatedly faulted; the apparent low-angle fault is a WNW–ESE-trending fault that cuts obliquely through the exposure. Note several crosscutting dykes (**D**) perpendicular to the orientation of the lava flows. The colour differences seen are partly caused by superficial alteration. The exposed section of the Nunavik Member is 280 m thick. Compare Fig. 14. Photo: Asger Ken Pedersen.

Fig. 35 Conglomerate with large clasts of volcanic rocks in a matrix of reddish volcanogenic sandstone and with a red-oxidised soil layer on top. The overlying rock is a massive picrite lava flow. The sediment is interpreted as a mass-flow deposit formed in connection with early tectonic movements along faults in the Saviit flexure zone. Field assistant for scale. South coast of Svartenhuk Halvø beneath Saviit Qaqqaat, sample number 181052 in Fig. 17.

be continuous through fully exposed fields of view of 50–100 m or more, reflecting their highly fluid nature as well as a planar and nearly horizontal topography during eruption. In other places the flow units are lensoid and of short lateral extent because they represent cross-sections through pahoehoe flow lobes (Fig. 36).

Massive sheet flows. These sheet flows are mostly 4–16 m thick, with a few reaching 25 m in thickness. They are fine-grained and form erosion-resistant horizons. Columnar jointing may be present. A scoriaceous top zone forms approximately one-fifth of the thickness of a single lava flow, whereas a scoriaceous base is missing or strongly reduced. The two types of flows are illustrated in Fig. 37.

Subaqueous volcanic rocks. The subaqueous products comprise hyaloclastites, coarser pillow breccias and pillow lavas (Fig. 38). The hyaloclastites are commonly characterised by gigantic foreset-bedding and form deposits with a thickness of up to several hundred metres, similar to hyaloclastites of the Vaigat Formation on Disko and Nuussuaq (Pedersen *et al*. 2017, 2018). The foreset-bedding dips from 33° to nearly horizontal. Steeper dips have also been recorded. The bedding is brought about by trains of material with greater concentration of coarse clasts of pillow fragments interspersed with layers of finer material with fewer of such fragments. The distal bottomsets have low dips and are composed of relatively fine material, and sediment intercalations may be found. In several places (e.g. along Simiuttap Kuua) the compound pahoehoe lava flows can be followed into steeply north-dipping pillow beds and pillow breccias with foresets with a vertical height of more than 200 m. No contemporaneous coastal erosion of the hyaloclastite layers has been observed, which suggests a very short period of eruption.

Tuffaceous and other fine-grained volcaniclastic deposits. Tuffaceous and soil beds are rare and are generally too thin and poorly exposed to be mapped. Most tuff and soil beds are 5–20 cm in thickness and in a subaerial environment they have generally been baked to a brick-red colour by the overlying lava flow. The beds are characterised by an even thickness over the whole surface of the underlying lava flow. Together with the thicker sediments mentioned below, these beds represent the only certain pauses in deposition of the lava beds. They are most frequent in the upper part of the member in the central area, where one horizon every 50 m in the upper part of the member has been recorded. The higher frequency of sedimentary beds between flows suggests longer time intervals between eruptions and decreasing magma production rates towards the top of the member.

A few thicker sedimentary beds occur. Some of these are brown or black; the most significant tuff bed is 8–15 m thick. In the south-eastern area a 14 m thick sedimentary bed is situated 540 m above the base of the member (profile 5). The bed consists of ellipsoidal basalt pebbles at the base, followed by volcanogenic sandstones and shales with plant fossils, e.g. *Ginkgoites*. On the south coast south of Saviit Qaqqaat, two 4–7 m thick sedimentary beds occur west of the Saviit–Qooroq fault zone (Figs 17, 35). They consist of volcanogenic sandstone and conglomerate with basalt boulders, possibly slide deposits. The fact that coarse clastic beds of local aspect are present in the area west of the Saviit–Qooroq fault zone may relate them to early uplift of the

Fig. 36 Overlapping flow lobes in a compound pahoehoe lava flow. Note the numerous zeolite-filled vesicles and thorough red-oxidation, strongest at the tops of individual flow lobes. Height of picture *c*. 1 m. Cliff at Kap Cranstown, south-western Svartenhuk Halvø. Photo: Asger Ken Pedersen.

Fig. 37 Lava succession comprising alternating groups of thick, massive sheet flows and compound pahoehoe flows built up of many individual, thin flow lobes. The lower pahoehoe flow group is topped by a dark grey sediment horizon. The overlying sheet flows have red soil horizons between them. Dykes cut the flows at approximately right angles. Height of section *c*. 60 m. Upper part of Nunavik Member at Kap Cranstown, south-western Svartenhuk Halvø. Photo: Asger Ken Pedersen.

Fig. 38 Typical coarse hyaloclastite with unsorted pillow fragments in a matrix of glass grains and rich in zeolites. The rock is an olivine-rich picrite. Note the 1 cm glass rind on the largest pillow fragment. Length of hammer 32 cm. Upper Nunavik Member, southern Innerit. Photo: Asger Ken Pedersen.

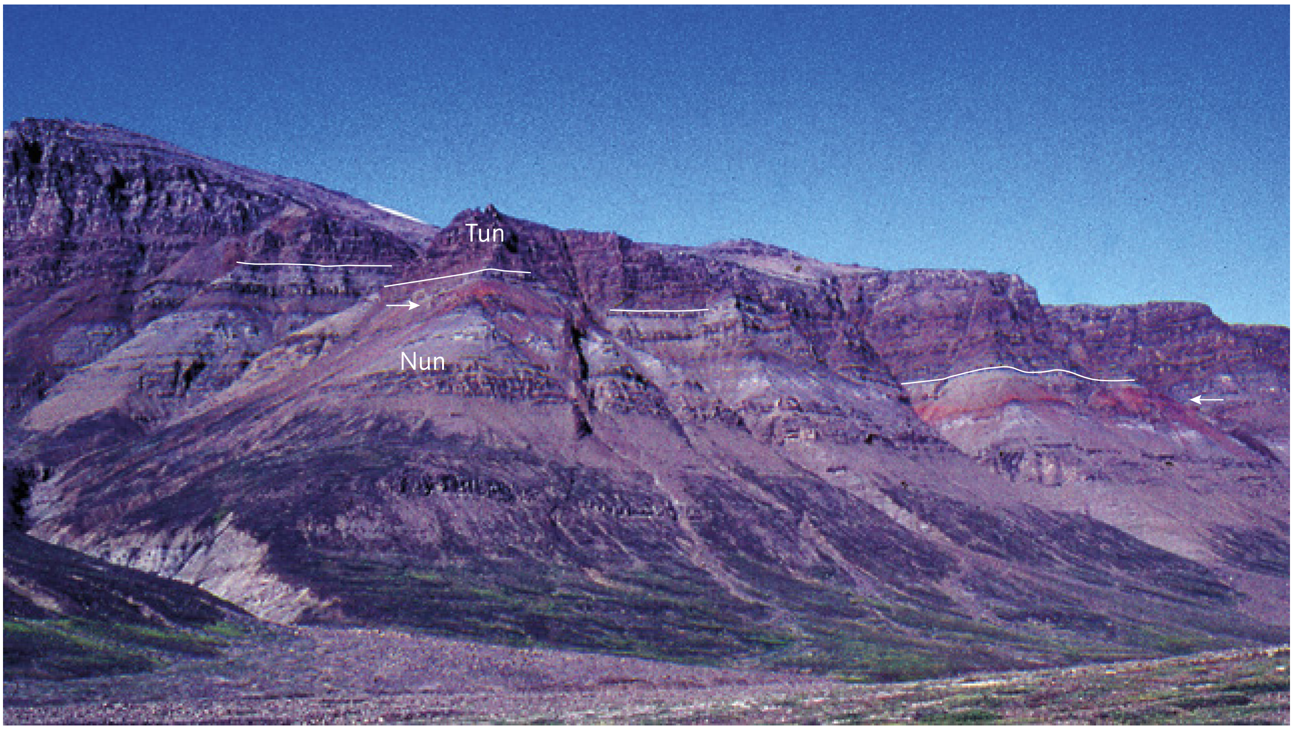

Fig. 39 The upper part of the Nunavik Member (**Nun**) containing a crimson-red bed *c*. 8 m thick of welded basaltic tuff (**white arrows**) within grey pahoehoe flows near the boundary to the Tunuarsuk Member (**Tun**). The boundary is traced with white lines. Akuleqqut, southern Svartenhuk Halvø.

block east of the fault. On the south coast at Tartuusaq, a 2–3 m thick tuff layer is present in the upper part of the member where it appears to reveal a stratigraphic repetition (Fig. 16). In the same section a 15 m thick bed of shale and tuff is situated at the upper boundary of the Vaigat Formation.

A crimson-red bed *c*. 8 m thick of welded basaltic tuff very near the upper boundary of the member was mapped by Larsen & Grocott (1991) within an area of *c*. 10 × 3 km in the upper reaches of the valley that leads into Tasiusap Imaa (Figs 26, 39).

Marker horizons. The hyaloclastites in the basal or lower part of the member form distinct beds, which can be used as marker horizons. Tuffs and sediments are well exposed along the south coast where they are useful for short-distance correlation across faults.

Some lava flows can be used as markers:

1. In the southern, south-eastern and central eastern areas, a distinct, dark green, massive picrite lava flow or sill 15–30 m thick containing equant olivine phenocrysts up to 1 cm across occurs immediately above the Nerutusoq Member.
2. On the southern side of Peak 1309 m in the central area, and in part of the south-eastern area, a characteristic 70 m thick, dark group of flows with many thin pahoehoe flow lobes occurs 300 m above the hyaloclastite (Fig. 32). This horizon is easy to identify from a distance and on the oblique aerial photographs and is shown as βo1 on the geological map 1:100 000 Svartenhuk. It can be followed over a distance of 26 km from a location 400 m above the hyaloclastite south of Peak 1078 m and northwards to the west side of the valley of Siuteqqut Kuuat, where it goes into hyaloclastite facies (Fig. 27). The dark flows also have a distinctly enriched chemical composition (see the Geochemistry chapter), and their palaeomagnetic properties are different from those of the underlying grey flows, suggesting a considerable time lapse between the two parts (Riisager *et al*. 2003, 2004). The topographic slope of the flows was 0.9°N.
3. Overlying the dark βo1 flow group is a 80 m thick, grey, zeolite-rich group of picrite lava flows comprising thick flow units with segregation veins. It has an areal distribution similar to the βo1 flow group.
4. Some picritic sheet flows with olivine-rich nodules occur about 200 m below the top of the member and some tens of metres below a significant tuff horizon in the west at Kap Cranstown and in the central area on the south side of Usuit Kuussuat.
5. The uppermost part of the member is dominated by less olivine-rich basalts with a persistent, nearly aphyric, massive basalt flow (βo2) present in many profiles in the central area (Fig. 10, profile 24) and at Tartuusaq (Fig. 16).

Eruption sites. In general, picritic dykes are spatially restricted to the Nunavik Member. They are therefore regarded as feeder dykes for the member, and this re-

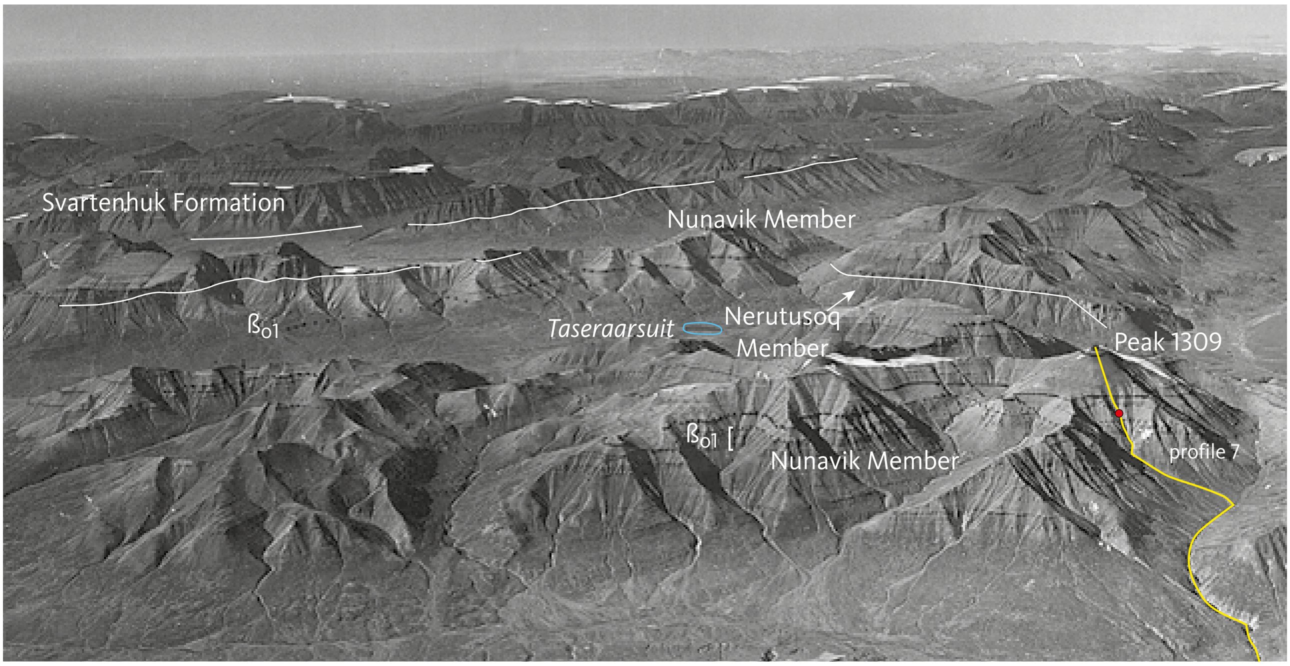

Fig. 40 Nunavik Member in central Svartenhuk Halvø around the Taseraarsuit lake (**blue oval**), viewed towards north-west. The Nunavik Member is underlain by lava flows and hyaloclastites of the Nerutusoq Member. The marker horizon **βo1** is indicated both in the foreground and in the middle ground. Other local markers are traced in black on the original photograph. The white lines indicate the boundary between the Nunavik Member and the Svartenhuk Formation. Profile 7, Peak 1309 m, is indicated with a yellow line in the right foreground. The small red dot on the profile line indicates a feeder dyke for the lowest flows in the βo1 marker horizon. Geodetic Institute oblique aerial photograph 526FN/3759.

lationship has been observed in a few places. North of Kangiusap Imaa, a picrite dyke cutting the hyaloclastites shows a gradual change into pillow facies at an altitude above 900 m. On the south side of Peak 1309 m, a dyke changes laterally into a picrite lava flow of the βo1 marker horizon (Fig. 40). Also in this area (for example at 71°44′N, 54°16–17′W, Larsen & Grocott 1991) dense swarms of thin, irregular, WSW–ENE-trending picrite dykes with 1–2 mm sized olivine phenocrysts appear to be feeder dykes for the picritic hyaloclastite as most of them terminate below the lavas. Such swarms of feeder dykes terminating in hyaloclastite heaps are similar to eruption sites mapped and described from Nuussuaq (Pedersen *et al*. 2007a,b, 2017).

The crimson-red bed of welded basaltic tuff mentioned above, which occurs close to the top of the member in a *c*. 10 × 3 km area in south-central Svartenhuk Halvø (Fig. 39), must have been produced from a local eruption site within that area (approximately 71°34′N, 54°42′W, Fig. 26), probably a fissure that was waterlogged at the time of eruption.

Volcanic evolution of the Nunavik Member. At the start of the deposition of the Nunavik Member a water-filled basin was situated along the Cretaceous boundary fault system. Its extent towards the north and west is unknown because the relevant rocks are below exposure level, and it is also not clear whether the basin was still marine. On Nuussuaq 100 km to the south, a similar marine basin had at this time just been sealed off from the sea and changed into a large lake into which hyaloclastites and lava flows of the Ordlingassoq Member, the correlative to the Nunavik Member, were deposited (Pedersen *et al*. 1996, 2017). It is possible that the basin north of this seal was still connected to the sea; this remains to be investigated.

When the eruption of the Nunavik Member began, a topographic high of earlier volcanic products existed in the south and south-west, from where subaerial lavas flowed towards the east, north-east and north and into the water-filled basin along the Cretaceous boundary fault system. The stratigraphy, inclination of the foreset beds of the hyaloclastites and flow directions of the lava flows (Fig. 26; Larsen 1981b) all support this picture. The advancing lava flows filled the basin with prograding hyaloclastite deposits several hundred metres thick, and only after this filling was achieved could the lava flows advance further. In this way a large part of the subaerial flows of the southern area were converted into equivalent hyaloclastite breccias towards the north and east. Thus, the thickness of the subaerial lava pile decreases to the north and east. At a later stage, the Precambrian basement was covered by both hyaloclastites and subaerial lava flows.

Hyaloclastites. The thickness of the hyaloclastites increases from 50 m to 120 m from south to north along the east coast of Svartenhuk Halvø. Farther north, the hyaloclastites are more than 400 m thick on Firefjeld and 300–400 m in the central and north-eastern basin areas at Siuteqqut Kuuat and the south-west side of the Simiuttap Kuua valley. West of Firefjeld, however, only 50 m of picritic hyaloclastites are found, indicating that a topographic high existed here. To the north-west, the local large depocentre of the Nerutusoq Member (Fig. 26) blocked for deposition of the picritic hyaloclastites of the lower Nunavik Member. Hyaloclastites overlie the Precambrian basement at two stratigraphic levels, which both increase in thickness northwards, where they have filled a depression in the highland south-east of Siuteqqut. The foreset-bedding of both hyaloclastite horizons indicates northerly and north-easterly transport directions. In conclusion, while the Precambrian basement as a whole acted as a barrier for the early volcanism of the Vaigat Formation it was either partly submerged below sea level, covered by a lake or cut by river channels when the first picrites reached the area or were emplaced locally. After the first infilling and subsequent formation of subaerial lava flows, submergence recurred from the east and caused the formation of the second hyaloclastite horizon. Thus, a general subsidence of the eastern and north-eastern part of the Precambrian basement took place during this period.

The lava pile. The lava pile appears to have formed a lava shield with a low-angle slope of 1° to the north. A study of the flow thicknesses shows that the thickest pahoehoe compound flows are found in the lower part of the member in the south-eastern and central-eastern areas. The thinner compound flows in the upper part of the member presumably reflect decreasing erupted volumes and possibly also thinning of the lava flows in the distal areas. On Innerit, the lava flows are thin, *c*. 1–2 m, and very fine-grained to aphanitic and thus appear to have been chilled quickly. These features are presumably a consequence of the distal position of the flows far from the extrusion sites in the south.

Thicker sheet flows are much more abundant to the west. In the Tasiusaq area they form 37% of the lava flows, and a similar value is found on Qinnivik. Elsewhere, they represent less than 5%, which could indicate different source areas.

Chemistry and chemostratigraphy. The Nunavik Member is strongly dominated by picrites; basalts are subordinate. The total range in MgO is 7.5–29.8 wt% with an average content of 17.5 wt% MgO. Other major elements such as TiO_2 and FeO* are correspondingly low relative to the MgO-poorer Svartenhuk Formation basalts (see the Geochemistry chapter). The Nunavik Member is generally not crustally contaminated, but a few exceptions occur in the lower part of the succession. Representative analyses are given in the Geochemistry chapter.

Some flows have slightly higher TiO_2 contents than the main part (for similar contents of MgO). These occur interspersed within the succession; it has not been possible to establish a detailed chemical stratigraphy of the member.

Lava flows, which are geochemically enriched in incompatible trace elements, occur sporadically as single flows or groups of flows. The dark picrite flows in the βo1 marker horizon are distinctly enriched in these elements (see data for sample 251527 in the Geochemistry chapter).

Boundaries. The lower boundary of the Nunavik Member is placed at the base of greyish picrite lava flows or hyaloclastites overlying the brown basaltic lava flows or hyaloclastites of the Nerutusoq or Kakilisaat Members. In reference profile 7 (Peak 1309 m), grey hyaloclastites and pillow lavas rest directly on Cretaceous sediments, but the relation of these rocks to the Nunavik Member is uncertain.

The upper boundary is defined by the occurrence of the first evolved basalts of the overlying Tunuarsuk Member of the Svartenhuk Formation, which have a distinctive brown weathering colour. In the northern area, the boundary is marked by the first deposits of white to yellow sands of the Kuugaartorfik Member. In this area, there is a small angular unconformity at the boundary as described in the section on the lower boundary of the Svartenhuk Fomation.

Geological age. Paleocene (Danian to Selandian).The age of the Nunavik Member is constrained to the interval 62.2–60 Ma based on its eruption later than magnetic polarity chron C27n (Riisager *et al*. 2003) and the age of the overlying Svartenhuk Formation. The $^{40}Ar/^{39}Ar$ age of 61.08 ± 0.56 Ma obtained by Chauvet *et al*. (2019) for a silicic basalt flow is within this age interval, regardless of whether the flow is from the Nunavik or the Kakilisaat Member.

Correlation. The Nunavik Member is correlated with the Ordlingassoq Member of the Vaigat Formation on Ubekendt Ejland, Nuussuaq and Disko, based on its stratigraphic position within the lava pile and similarities in the chemical compositions illustrated in the Geochemistry chapter (see also Figs 83, 84). Both these members are relatively heterogeneous and not quite as depleted in incompatible trace elements as the older Anaanaa and Naujánguit Members of the Vaigat Formation on Disko and Nuussuaq (Larsen & Pedersen 2009, 2017).

Svartenhuk Formation

New formation

History. On the geological map 71 V.1 Syd Igdlorssuit (Larsen 1983), the Svartenhuk Formation is shown as the units βf3 to βf6. On the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991), the Svartenhuk Formation comprises the sedimentary unit T (for Tertiary) and the volcanic units β1 to β3, i.e. the entire basalt succession overlying the Vaigat Formation. The name Svartenhuk Formation was used in the same sense by Larsen & Pulvertaft (2000), but the formation was not formally defined. Larsen *et al*. (2016) found that the basalt succession consisted of two parts of, respectively, Paleocene and Eocene age and restricted the Svartenhuk Formation to comprise only the Paleocene part (Fig. 3). Here the Svartenhuk Formation is defined to comprise the Paleocene part of the succession, whereas the Eocene part is defined as the Naqerloq Formation in a later chapter.

Name. After Svartenhuk (Sigguk), the most westerly point on the peninsula of Svartenhuk Halvø.

Synonymy. The informal 'middle formation' and a part of the 'upper formation' of Larsen (1981a) and Holm *et al*. (1993).

Subdivisions. The Svartenhuk Formation is divided into four members based on lithological and chemical characters (TiO_2 contents). These are from base to top:
Kuugaartorfik Member: Quartzofeldspathic sands, mudstones, coal seams, volcanogenic sediments and tuffs. The sediments are interspersed with hyaloclastites and subaqueous and probably invasive lava flows of the Tunuarsuk Member.
Tunuarsuk Member: Brown basalts, grey olivine-phyric basalts and subordinate dark greenish grey picrites. The lowest part of the member in the northern area comprises hyaloclastites and subaqueous and invasive lava flows, whereas the main part of the member comprises subaerial lava flows.
Nuuit Member: Brown aphyric and plagioclase-phyric basalts, mainly subaerial lava flows.
Skalø Member: Mostly light grey to yellowish, plagioclase-phyric basalts, subaerial lava flows.

Distribution. The Svartenhuk Formation is found in central, northern and western Svartenhuk Halvø but has been eroded away in the eastern part of the basin area. The formation is widely distributed north of Svartenhuk Halvø where it occurs as far north as 72°43′N (Figs 5, 6). The formation extends from the coastal islands in the west at 56°W and eastwards onto the Precambrian basement areas as far east as at least 51°35′W at 72°N (Fig. 5); the extent of the volcanic rocks farther east and north-east beneath the Greenland ice sheet is unknown. To the west and north-west, the formation is considered to continue on the shelf, which is supported by a seismic section reaching as close as 10 km from the west coast of Svartenhuk Halvø (Gregersen *et al*. 2013, fig. 5), and by the composition of basalt samples dredged on the Upernavik Escarpment (Fig. 1; Polteau & Planke 2008; analytical data are given in the Geochemistry chapter). In the sea south of Svartenhuk Halvø, the formation is interpreted as a more than *c*. 800 m thick package of west-dipping strata seen in seismic section GEUS00-50 (Skaarup & Pulvertaft 2007). Some volcanic units on western Ubekendt Ejland and western Nuussuaq are also included in the Svartenhuk Formation based on their age (see the section on *Correlation*).

Type area. The south-east coast of the Innerit peninsula. This coastal stretch shows the most complete section through the formation, with all four members present in a well-exposed, flat-lying, unfaulted succession (Fig. 41). Here 100–200 m of sediments and subaqueous volcanic deposits are overlain by *c*. 1350 m of lava flows sampled in profile 64 **Paannivik** (Figs 13, 41). The Paannivik profile is the type section for the Tunuarsuk and Nuuit Members, whereas the Skalø Member is incomplete and the Kuugaartorfik Member is partly exposed 4 km east of the profile.

Thickness. The sum of the greatest thicknesses of the four members of the Svartenhuk Formation in the basinal area is 110 + 850 + 480 + 450 = 1890 m. There is not one single area in which this thickness is attained. The most complete profile (no 64 Paannivik) has a thickness of *c*. 1350 m for the volcanic succession, but the upper boundary has been removed by erosion. Distal thicknesses in the northern areas are up to 1000 m, for example at Qaqqap Qaa (Figs 9, 13). Farther to the north-east, the preserved thickness is *c*. 600 m at Pannertuup Qaqqa and 660 m at Salliaruseq, in both places constituted by relatively few, thick, presumably ponded flows. In the eastern and north-eastern areas, an unknown thickness of basalt has been removed by erosion and in the most distal areas only remnants of basalt are left. In the domal area east-south-east of Svartenhuk Halvø (Fig. 5), no volcanic rocks are preserved.

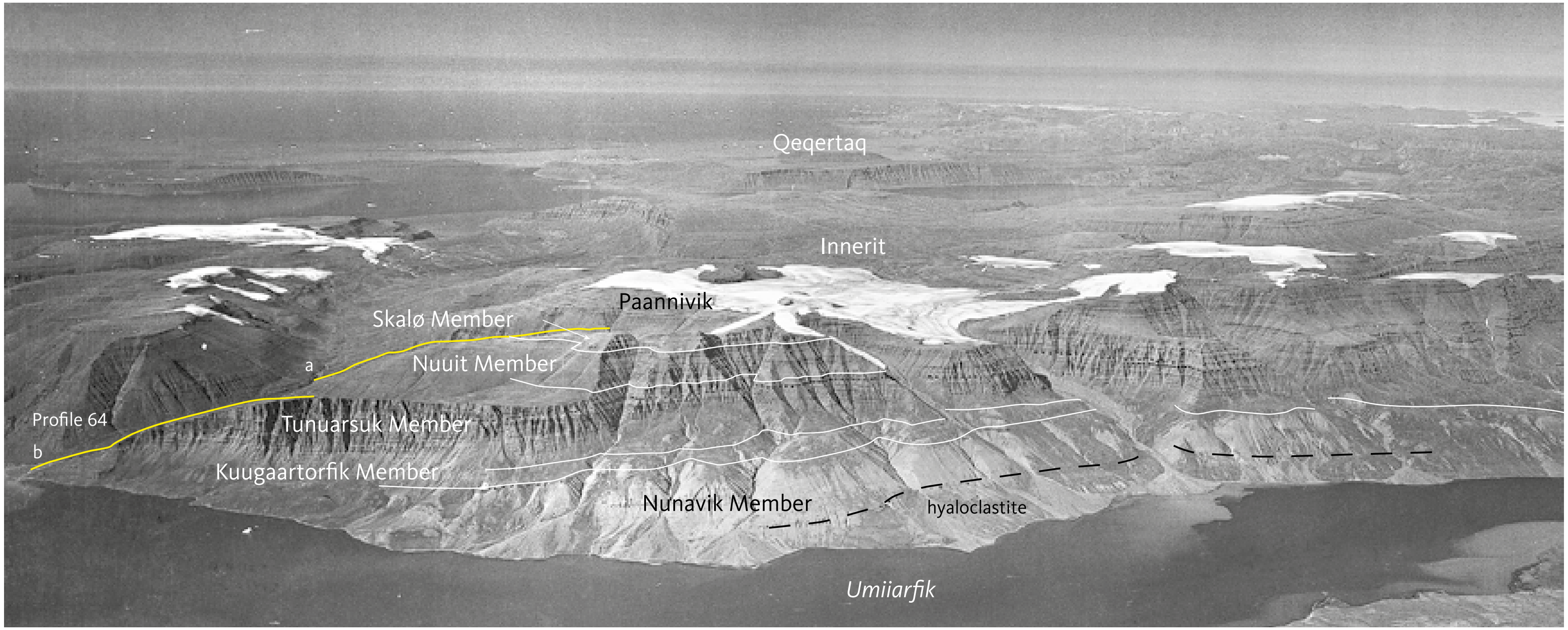

Fig. 41 The most complete exposed section through the Svartenhuk Formation, resting on the Vaigat Formation and with all four members present. Profile 64 a and b are shown with yellow lines; the profile is depicted in Fig. 13. South-eastern Innerit peninsula. The Paannivik mountain reaches 1288 m altitude. Geodetic Institute oblique aerial photograph 526HN/5634.

Lithology. The volcanic rocks are brown and grey aphyric and plagioclase + olivine ± clinopyroxene-phyric, mainly subaerial tholeiitic basalts and subordinate olivine-phyric magnesian basalts and picrites. Subaqueous lava flows and hyaloclastites are present in the lower part of the formation in the northern and north-eastern areas. Quartzofeldspathic sediments are present in the north-western and north-eastern areas. Thin horizons of tuffs and sediments are present throughout the formation.

Eruption sites. In contrast to the picrite successions of the Vaigat Formation, for which several eruption sites are known, only very few eruption sites have been identified for the basalts of the Svartenhuk Formation. This is a feature shared with flood basalt successions worldwide, including those on Nuussuaq and Disko (Pedersen *et al*. 2017, 2018), presumably caused by the effusive character of the fissure eruptions, which fed the lava flows. The oxidised products of more explosive eruptions from central vents are more easily visible, and some sites of this character have been identified.

Basalt dykes cutting the older parts of the volcanic successions, with compositions matching those of the Svartenhuk Formation, can be regarded as feeders for this. Such dykes exist, but the data are too sparse to give a reliable impression of the extent of the lava production areas. However, no dykes are known more than 10 km east of the boundary fault, and the large volcanic areas to the north and east were presumably sourced from eruption sites within the basin area on Svartenhuk Halvø and just outside it close to the boundary fault.

Chemistry and chemostratigraphy. The volcanic rocks of the Svartenhuk Formation consist of evolved tholeiitic basalts with 3.5–10 wt% MgO and, in the lowest member, also magnesian basalts and picrites with 10–18 wt% MgO. The rocks have low contents of incompatible elements such as K_2O (0.08–0.5 wt%) and low P_2O_5/TiO_2 ratios (0.07–0.12). A few scattered lavas enriched in incompatible elements occur throughout the succession. Representative analyses are given in the Geochemistry chapter.

The formation shows subtle chemostratigraphic variations up-section, which are recognisable throughout the area and have been an important help in the validation of the field-based stratigraphy. The variations are best seen in plots of TiO_2 contents vs. height in sample profiles as shown in Fig. 42.

Boundaries. The lower boundary in southern and central Svartenhuk Halvø is placed at the first occurrence of subaerial, brown-weathering, olivine-poor, plagioclase-phyric basalts above the main picrite series of the underlying Vaigat Formation. In northern Svartenhuk Halvø, where subaqueous and fluvial conditions prevailed, the lower boundary is placed at the base of a succession of white quartzofeldspathic sand, volcanogenic sediments and olivine-poor hylaoclastites that overlie the picrites of the Vaigat Formation.

Tectonic movements prior to the emplacement of the Svartenhuk Formation (Larsen & Pulvertaft 2000) gave rise to minor unconformities between the two formations. This is seen at two localities labelled H and I, shown on Fig. 6. Loc. H: Between 71°36′N, 54°33′W and 71°35.5′N, 54°29′W along the southern side of the central part of Usuit Kuussuat, 11–17°S- to SE-dipping picrite flows underlie 5–8°W- to SW-dipping flows of the Svartenhuk Formation. Loc. I: On the west side of the Kuugaartorfik mountain east of the inner Umiiarfik fjord and north-east of the Cretaceous boundary fault system, lava flows of the Nunavik Member dip 8–10°NE, whereas the Svartenhuk Formation is nearly horizontal with low NW-dips.

An unconformity is seen on south-eastern Innerit between Locs B and E (Fig. 6). Here, lavas of the Nunavik Member appear to dip NW whereas the Svartenhuk Formation has a low dip of 2–4°SW, decreasing up-section. This is interpreted as a depositional unconformity, with the lavas of the Svartenhuk Formation drowning the domed lava shield of the Vaigat Formation.

The upper boundary is defined in the Sigguk profile in western Svartenhuk Halvø (Fig. 11). The boundary here is placed at the base of a series of brown-weathering, geochemially enriched basalts of the Naqerloq Formation (Arfertuarsuk Member) characterised by higher contents of incompatible elements than the basalts of the Svartenhuk Formation. The brown basalts rest on a poorly exposed tuffaceous sediment horizon 5–10 m in thickness, which constitutes the top of the Skalø Member of the Svartenhuk Formation. In south-western Svartenhuk Halvø north of Arfertuarsuk, a similar, but coarser, volcaniclastic sediment horizon is *c*. 20 m thick. It is overlain by 0–2 flows with chemical compositions corresponding to the Naqerloq Formation, followed by the thick marker flow of the Arfertuarsuk trachyte. In the upper reaches of the Qooruusaq valley at *c*. 180 m a.s.l. the sediment horizon (inferred, 10–15 m unexposed) is directly overlain by an erosional remnant of the Arfertuarsuk trachyte. The boundary is also present on Skalø; it has not been mapped there and is not shown on the 1:100 000 map of Larsen & Grocott (1991) but was identified by sampling and chemistry. Its inferred position is shown on Fig. 6.

Geological age. Paleocene (Selandian to Thanetian). Radiometric age determinations ($^{40}Ar/^{39}Ar$) of the Svartenhuk Formation range from 59.78 ± 0.41 Ma

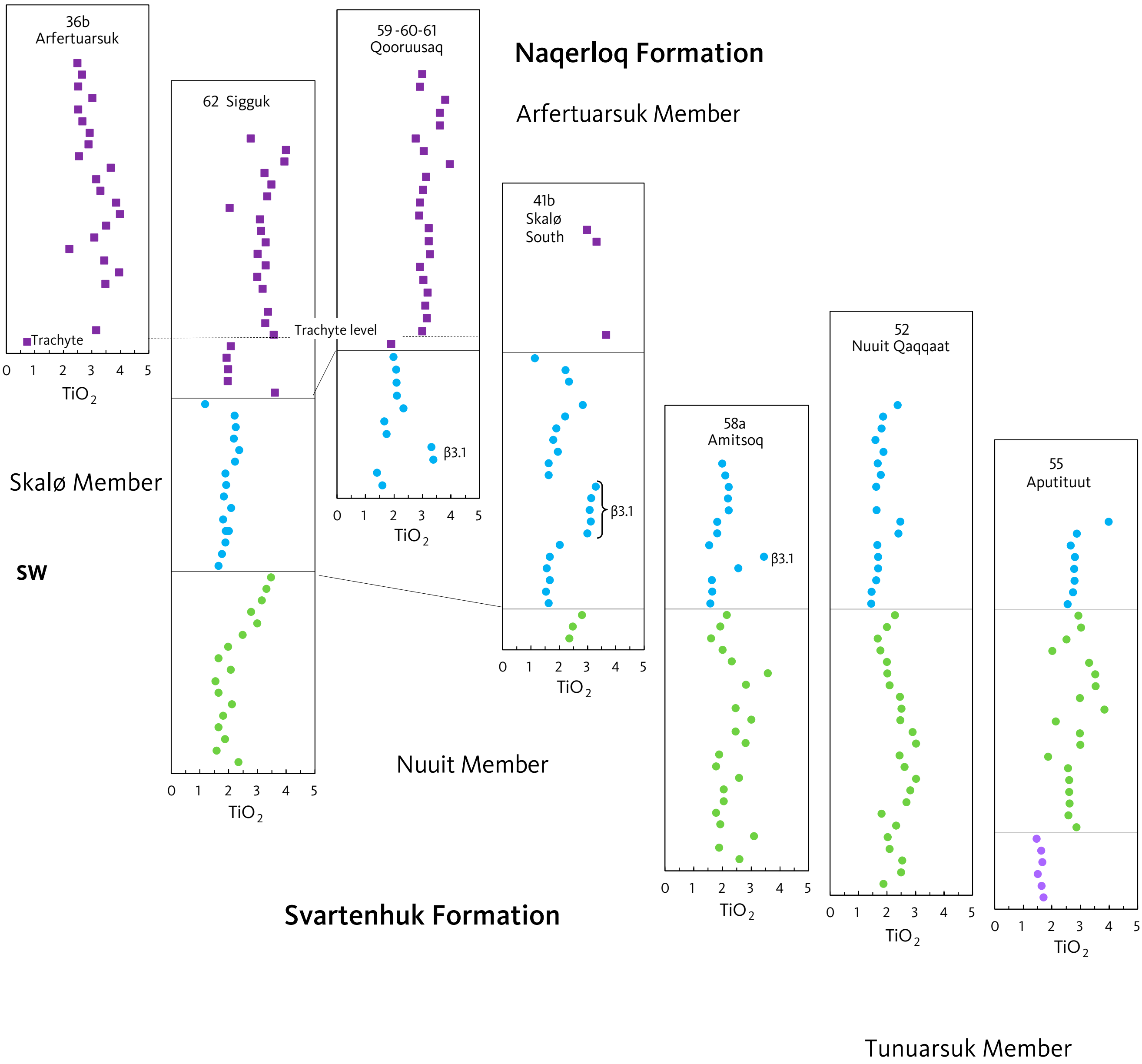

Fig. 42 TiO_2 (wt%) for profiles through the Svartenhuk and Naqerloq Formations. The profiles in the lower panel are arranged as projected on a SW–NE line through central Svartenhuk Halvø. The profiles north of 72°N in the upper panel are arranged as projected on a W–E line around 72°15′N. The vertical scale is the number, starting from 1, assigned to each of the successive flows in a profile. The profiles are aligned on member boundaries, as feasible. Dot colours and shapes as in the geochemistry diagrams, see legends in Fig. 83. Dark green dots in the Tunuarsuk Member are picrites.

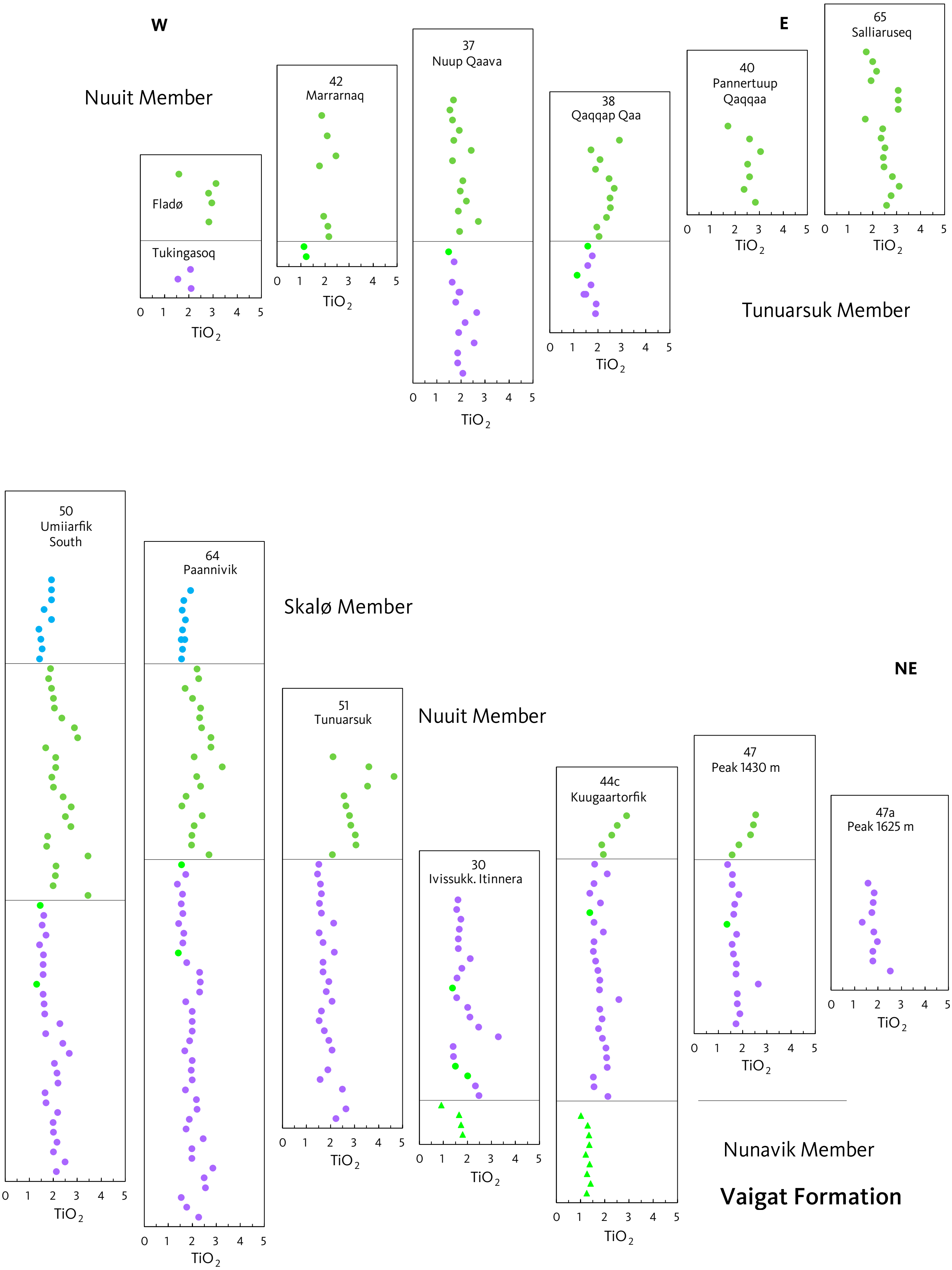

Fig. 42 (continued) TiO_2 (wt%) for profiles through the Svartenhuk and Naqerloq Formations. The profiles in the lower panel are arranged as projected on a SW–NE line through central Svartenhuk Halvø. The profiles north of 72°N in the upper panel are arranged as projected on a W–E line around 72°15′N. The vertical scale is the number, starting from 1, assigned to each of the successive flows in a profile. The profiles are aligned on member boundaries, as feasible. Dot colours and shapes as in the geochemistry diagrams, see legends in Fig. 83. Dark green dots in the Tunuarsuk Member are picrites.

(Chauvet *et al*. 2019), 60.31 ± 1.39 Ma and 59.05 ± 0.61 Ma for the lowermost part (Tunuarsuk Member) to 57.98 ± 0.59 Ma for the upper part (Skalø Member) of the formation (Larsen *et al*. 2016). $^{40}Ar/^{39}Ar$ age determinations of the Maligât Formation above the Vaigat Formation in the Disko–Nuussuaq area range from 61.2 ± 0.4 Ma to 60.2 ± 0.5 Ma (Storey *et al*. 1998). This shows that most of the Svartenhuk Formation is younger than the Maligât Formation and that there is a possible overlap in time for the oldest basalts of the Svartenhuk Formation (Fig. 3).

Correlation. The Qeqertalik and Tuperssuartâta kûa Members on Ubekendt Ejland and the Nûluk and Ifsorisoq Members on Nuussuaq west of the Itilli fault have been placed within the Svartenhuk Formation based on their radiometric ages (Fig. 3; Larsen *et al*. 2016).

The thick tuffaceous sediment horizon at the top of the Svartenhuk Formation is tentatively correlated with the sediments of the Ifsorisok Member on Nuussuaq (Hald 1976; Larsen *et al*. 2016). The horizon is thus potentially of regional extent and is interpreted as representing a break in the volcanic activity.

Kuugaartorfik Member

New member

History. The member is shown as intravolcanic sediments (T) on the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991).

Name. After the mountain Kuugaartorfik in northern Svartenhuk Halvø.

Distribution. The Kuugaartorfik Member is exposed in northern Svartenhuk Halvø and the south-eastern part of the Innerit peninsula, in both areas resting on lava flows of the Vaigat Formation (Larsen & Grocott 1991; Fig. 6). North of 72°N, along the coasts of the Innerit inlet, sediments of the member are exposed at sea level below the lavas of the Svartenhuk Formation. Isolated outcrops of the member rest on basement gneiss on both sides of Sullua, the northern arm of the Umiiarfik fjord (Fig. 6). The southern delimitation is depositional; to the west the member disappears below exposure level and to the north and east its extent is unknown.

Type section. **Kuugaartorfik** (profile 44c, Fig. 12), located in a well-exposed west-facing gully on the north-west slope of Kuugaartorfik mountain between 380 and 490 m a.s.l. (Fig. 43). Coordinates in Appendix 1.

Reference section. **Profile 44a**, just 600 m south of profile 44c.

Thickness. The sediment-bearing interval is up to 110 m thick as in the type section, which consists of 80 m of sediment and 30 m of lava flows (Fig. 43), but in most areas the accumulated sediment thickness is less than 50 m.

Lithology. The Kuugaartorfik Member is composed of white to grey to yellow quartz- and quartzofeldspathic sands, black mudstones and coal seams, and grey, ochre or red volcanogenic sand and gravel. The Kuugaartorfik Member interdigitates with approximately 50% of volcanic rocks including tuffs, lava flows, pillow lavas and hyaloclastites belonging to the Tunuarsuk Member.

The reference profile 44a was visited by both Andreasen (1981) and the first author of this volume. It is very similar to profile 44c. The lower part of the member is dominated by 20–50 m of yellow-white, unconsolidated sand layers with minor, thin coal beds overlain by a thick olivine-phyric basalt flow with pronounced columnar jointing. This basalt has a very thin vesicular top zone which, from a distance, makes it look like a sill, but the sediments above are loose with no signs of contact metamorphism. Above this lava flow there is a 50 m thick succession of interbedded, unconsolidated quart-

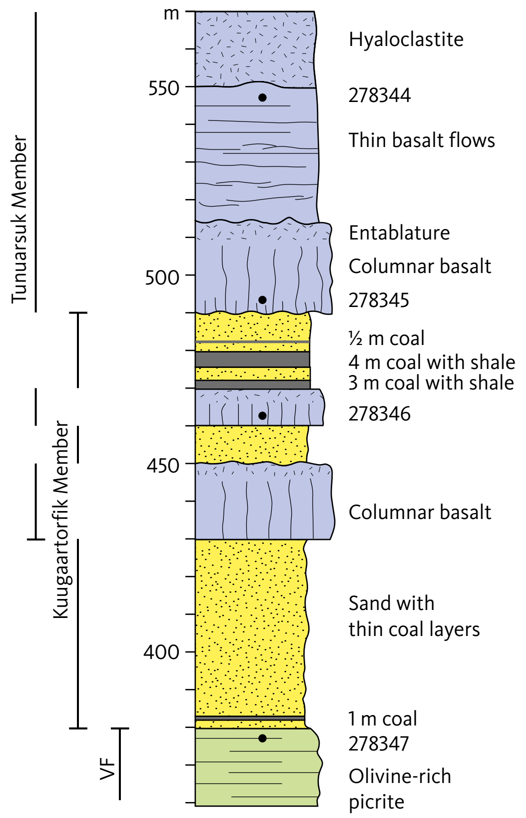

Fig. 43 Type section for the Kuugaartorfik Member in profile 44c, Kuugaartorfik. **VF**: Vaigat Formation (Nunavik Member). Sediments of the Kuugaartorfik Member and lava flows of the Tunuarsuk Member interdigitate. Enlarged interval of profile 44c shown in Fig. 12. Legend in Fig. 13.

zofeldspathic sand horizons, coal seams up to 5 m thick and a single lava flow. The coal seams lack root horizons and contain flat-lying fragments of coal with wood structure, clearly indicating that the coal is allochthonous. Coal seams of considerable thickness occur along the south-west side of Kuugaartorfik. Stratigraphic correlation within the member is difficult due to contemporaneous sedimentation and lava deposition on a flood plain with lakes formed by lava damming, perhaps aided by faulting (Andreasen 1981).

About 10 km north of Kuugaartorfik (Loc. J in Fig. 6), 130 m of yellow sandstone, siltstone, sand and mudstone beds and a low-grade coal seam cut by a dolerite sill are preserved in a palaeo-valley in the Precambrian basement (Croxton 1978). A palynological analysis yielded *Alnipollenites* and *Betulaceiopollenites*; the sediments are therefore of Paleocene age and were tentatively correlated with the intrabasaltic sediments (here referred to the Kuugaartorfik Member) by Croxton (1978, p. 65).

South-west of Kuugaartorfik the member is composed of volcanogenic sediments including volcanic pebbles (Pulvertaft 1966) with grey, brown to ochre and red colours and coal seams. On the south-west side of a wide valley leading into Umiiarfik fjord (Loc. K in Fig. 6), the member is 40 m thick and rests on an olivine-phyric hyaloclastite of the Nunavik Member. It comprises a basal coal seam overlain by black tuff and welded tuff (15 m), followed by a brownish volcanogenic sediment (lahaar deposit?) with coal fragments (15 m), and overlain by coal and mudstone scree (10 m). The base of the overlying Tunuarsuk Member comprises a subaqueous basalt lava flow and hyaloclastite typical of the north-eastern area.

The sediments are exposed along the shores of the Innerit inlet on the western Innerit peninsula around 72°04′N and along the river banks of Innerit Kuua at the head of the inlet (Fig. 44). They have a low westerly dip. The lower part is >20 m thick and comprises cross-bedded yellow sand and gravel layers indicating a fluvial origin with erosion products from the basement. Dark siltstones and dark muddy sandstones from near the head of the inlet (samples 456108–456110, Fig. 45) contain bisaccate pollen and a few small triporate pollen, all somewhat corroded and difficult to place in age. Two corroded examples of the green alga *Pediastrum*, which commonly occurs in lake deposits, support a non-marine or brackish environment (H. Nøhr-Hansen, personal communication 2020). In the valley *c.* 4 km east of the bottom of the inlet, on the southern side of the river, the upper part of the member rests on a basaltic sill and is *c.* 30 m thick. It is composed of grey sand with dark bands rich in garnet (most probably derived from the large Proterozoic Prøven igneous complex immediately north of Innerit), black heterolithic mudstone and a 0.5 m thick coal seam close to the top. A thin whitish layer of devitrified glass is present near the top. This succession is overlain by a thick, subaqueous columnar-jointed basalt lava flow at the base of the Tunuarsuk Member. The sediments in the valley close to the inlet are disturbed by broad folding, presumably caused by a Quaternary glacier, as they are not protected by the lava pile.

On the south-eastern coast of the Innerit peninsula, the Kuugaartorfik Member is identified where the top of the picrites is overlain by yellow sand, which is partly concealed by scree of volcanic material (Figs 31, 41, 46). The exposed thickness of the member is 50–100 m, but the total thickness must be greater. On the geological map, the top of the member was placed *c.* 100–300 m above the base in the eastern part of the occurrence. Thereby the member occupies a plateau from 300 to 500 m a.s.l. below the steep mountainside with massive basalts of the Tunuarsuk Member. Entablature lavas and hyaloclastites of the lower part of the Tunuarsuk Member may thus have been included in the 'intravolcanic sediments' shown on the 1:100 000 map.

The Kuugaartorfik Member is strongly reduced in thickness or missing in the central part of Svartenhuk Halvø. The member has a greatly reduced thickness at Peak 1180 m on the west side of the Nerutusoq valley (Pulvertaft 1966; Loc. L in Fig. 6). A conglomerate with volcanic pebbles occurs south-west of Simiuttap Kuua. The member has not been identified at the Tunuarsuk mountain.

Sediments possibly belonging to the Kuugaartorfik Member. A slipped block with at least 10 m of a bedded, coarse volcanogenic sediment with coal clasts is present at sea level by Qaqqap Qaa. At 190 m a.s.l. above a scree, a similar sediment including coal clasts is referred to the Kuugaartorfik Member (Fig. 13, profile 38). It is overlain by lava sheets, pillow lava and hyaloclastites of the Tunuarsuk Member. At 300–340 m in the same profile a volcaniclastic breccia interpreted as a mass-flow deposit is referred to the Tunuarsuk Member and described later.

A number of other sediment horizons occur at or near the boundary between the Vaigat and Svartenhuk Formations. A black sediment horizon (tuff?) 5 m in thickness is present on top of the Vaigat Formation in the south-western area on eastern Aputituut (Fig. 10, profile 22) and extends 8 km farther to the south. A black, coarsely fissile sediment and tuff horizon 15 m in thickness is present at the boundary between the Nunavik and Tunuarsuk Members at the south coast west of Tartuusaq (Fig. 16).

Origin of the sediments. The sediments of the Kuugaartorfik Member apparently represent a break in the volcanism and a tectonic event in the northern ar-

Fig. 44 Yellow and dark grey sediments of the Kuugaartorfik Member dipping west, well exposed in the 8 m high coastal cliff on the north side of the Innerit inlet on the peninsula of the same name. The lava succession in the mountain wall above the sediments belongs to the Tunuarsuk (**Tun**) and Nuuit (**Nu**) Members. Profile 37 (Fig. 13) was taken along the shoulder of the wall, which leads up to the 894 m high Nuup Qaava mountain. Photo: Asger Ken Pedersen.

Fig. 45 Siltstone-dominated sediments of the Kuugaartorfik Member on the north coast of the Innerit inlet. The cliff is *c*. 8 m high. Photo: Asger Ken Pedersen.

eas. Presumably the basement to the east was uplifted, and ensuing erosion coupled with flooding led to deposition of quartzofeldspathic sand, mud and coal seams in fluvial plains and lakes in lows in the irregular basement surface and on the exposed surface of the Vaigat Formation. Evidence for tectonic movements after the volcanism of the Vaigat Formation is provided by the angular unconformity between the Vaigat Formation and the Svartenhuk Formation as described here. The mass-flow-like volcanic deposits at Qaqqap Qaa and south-east of Umiiarfik (Loc. K in Fig. 6) also suggest a period of erosion and significant local topography. The volcanogenic sediments mostly appear to be reworked hyaloclastite material and rounded blocks of basalt, which may have been extruded contemporaneously farther south or west.

It appears that the early eruptions of the Tunuarsuk Member in southern Svartenhuk Halvø took place simultaneously with the deposition of the Kuugaartorfik Member in northern Svartenhuk Halvø, and that the volcanic rocks arrived later in the northern areas.

Boundaries. The lower boundary is placed at the first occurrence of clastic sediments, including tuffaceous deposits, overlying the main series of picritic lavas of the Nunavik Member or directly lying on the Precambrian basement.

The upper boundary is placed at the base of the massive succession of basalts of the Tunuarsuk Member, although yellow sand sediments similar to those of the Kuugaartorfik Member occur higher in the sequence with very reduced thicknesses. From a distance, and even close by, it may be diffucult to distinguish between brown soil and palagonitic sediments of the Kuugaartorfik Member and hyaloclastites of the Tunuarsuk Member.

Geological age. Paleocene (Selandian), close to 60 Ma, bracketed between the $^{40}Ar/^{39}Ar$ ages of 61.08 ± 0.56 Ma for the lower Vaigat Formation (Chauvet *et al*. 2019) and 60.31 ± 1.39 Ma for the lowest Tunuarsuk Member (Larsen *et al*. 2016).

Correlation. None known.

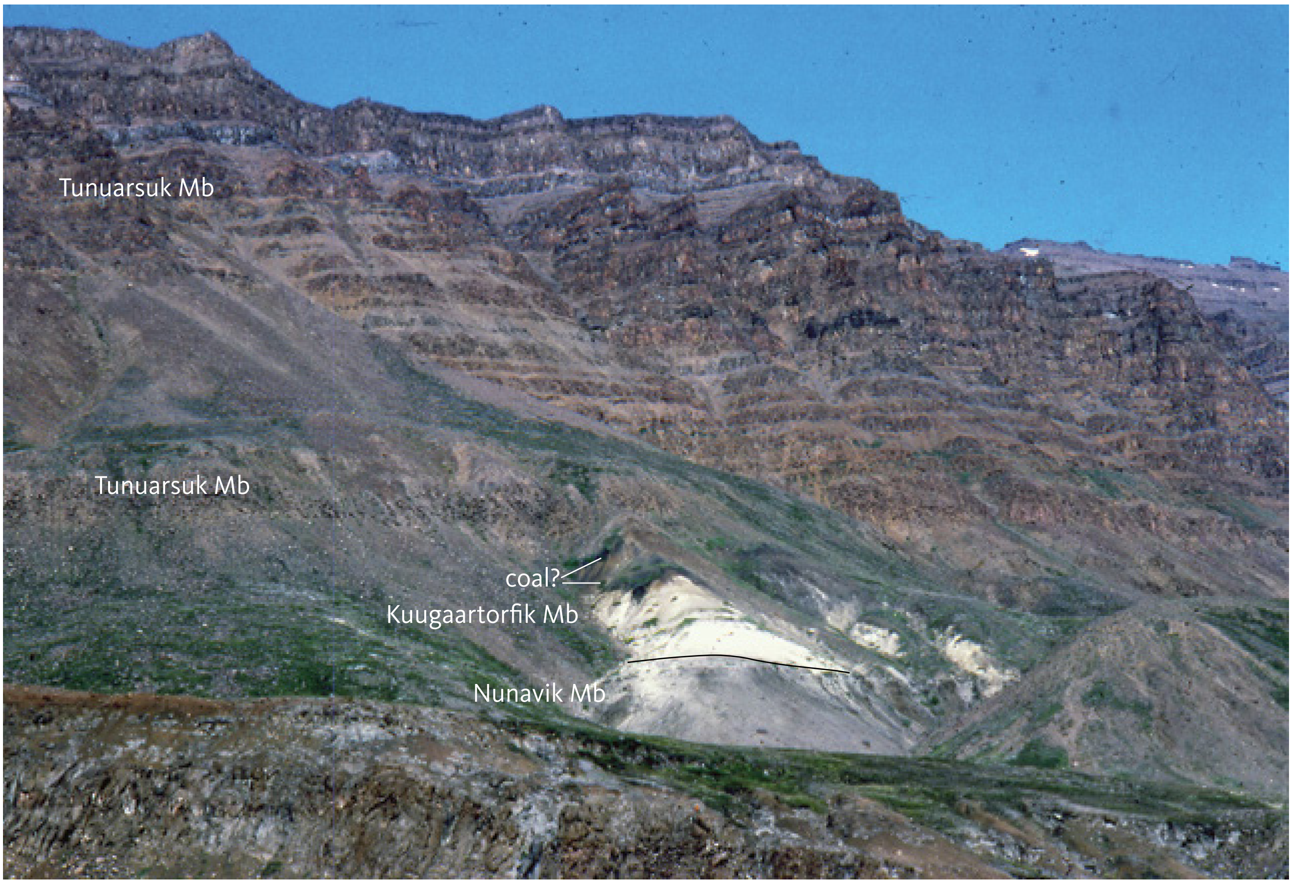

Fig. 46 White quartzofeldspathic, poorly consolidated sandstones of the Kuugaartorfik Member overlying grey pahoehoe lava flows of the Nunavik Member of the Vaigat Formation. The Kuugaartorfik Member is topped by a black layer of sediment, probably rich in coal, and overlain by lava sheet flows of the Tunuarsuk Member. South-eastern Innerit peninsula beneath the Paannivik mountain; compare with Fig. 31. Photo: Asger Ken Pedersen.

Tunuarsuk Member

New member

History. The Tunuarsuk Member is shown as the units βf3 and βf4 on the geological map 71 V.1 Syd Igdlorssuit (Larsen 1983). The member is shown as the unit β1 on the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991).

Name. After the 1260 m high mountain Tunuarsuk in the northern part of central Svartenhuk Halvø. The member is here well exposed from its base on the south-east side of the mountain to its upper boundary where it is overlain by the Nuuit Member.

Synonymy. The informal 'middle formation' of Larsen (1981a) and Holm *et al*. (1993).

Distribution. The Tunuarsuk Member is present in a S–N-extending area on Svartenhuk Halvø from the south coast to Umiiarfik; it extends northwards on Innerit and Qeqertaq and eastwards in a widespread but dissected capping on the high Precambrian basement (Fig. 6). The member marks the onset of extrusion of voluminous lavas that overstepped the Cretaceous boundary fault system and spread to the north and east. The member is found as far north as at 72°20′N on Qeqertaq (Marraarnaq, profile 42) and the inner Ukkusissat Fjord, but not at Pannertuup Qaqqaa (profile 40). Farther north its presence is undetermined. To the east, recent hand-held aerial photographs (see also Fig. 49) and geological maps (Guarnieri *et al*. 2022a, b) show that the Tunuarsuk Member extends east across Ukkusissat Fjord to Qaarsorsuaq and farther as a series of grey hyaloclastites and lava flows resting on Precambrian basement and in some places on sediments of unknown character. The series can be followed east to Inngia Isbræ but not farther (Fig. 5). It has not been visited on the ground.

Type section. **Paannivik** (profiles 64a and b) on the south coast of Innerit (Figs 9, 13, 41; coordinates in Appendix 1). The lower and middle parts follow the south-western edge of the Niaqornaq ridge (profile 64b) from sea level where a thick basalt lava flow with columnar jointing is present, to a height of 575 m a.s.l., while the upper part (profile 64a) follows the edge of the glacier valley north of Paannivik from 515 m to 750 m a.s.l.. The base of the member must be just below sea level in the profile itself and is exposed in the cliffs 3.5–9 km north-east of the profile, where the top of the Kuugaartorfik Member is exposed.

Reference sections. **Tunuarsuk** (profile 51); this does not include the basal 50–100 m, which, however, are exposed just 2 km farther east. **Kuugaartorfik** (profile 44c), where both the lower and upper boundaries are exposed. **Aputituut Qaqqaat** (profile 31) in the southern area, where the member comprises many more thin pahoehoe flows than in the northern areas. Profiles in Figs 11, 12; coordinates in Appendix 1.

Thickness. A maximum thickness of *c*. 850 m is found on the south coast of Svartenhuk Halvø between Tartuusaq and Illerusat Qaqqaat (Fig. 16). Thicknesses are reduced in central Svartenhuk Halvø to between 500 m (e.g. at Oqaasaq south of Tunuarsuk) and 380 m in the mountains between Qiterlikassak and Usuit Kuussuat, possibly because this area formed a topographic high. To the north, the member is *c*. 700 m thick at Tunuarsuk; in southern Innerit, it is 750 m thick in profile 64 on the western shoulder of the Paannivik mountain (Fig. 13) but thins to 300–400 m in south-eastern Innerit above the lava shield of the Vaigat Formation. North of 72°N, the member is *c*. 500 m thick on western Innerit (Nuup Qaava), >470 m on eastern Innerit (Qaqqap Qaa), and >40 m in northern Qeqertaq (Marraarnaq). Eastwards on the Precambrian highland, thicknesses are between 600 and 450 m at Kuugaartorfik, Siuteqqut and Peak 1430 m. Farther to the east, the member is around 300 m thick at Peak 1625 m, Peak 1370 m and Peak 1829 m (Fig. 7). On the Precambrian highland between Siuteqqut Kuuat and Kangiusap Aaffaa, where the overlying Nuuit Member is not preserved, the Tunuarsuk Member has been at least 300–600 m thick, dependent on the topography and elevation of the basement.

Lithology. In the following, the subaerial and subaqueous lithologies of the member are described separately.

Subaerial lithologies. The subaerial lava flows of the Tunuarsuk Member are mostly brown- or grey-weathering, plagioclase-phyric or aphyric basalt lava flows of either compound pahoehoe or sheet flow type, interspersed with dark grey to greenish grey, olivine-rich compound pahoehoe flows of magnesian basalt and subordinate picrite (Fig. 47). A few flows appear to be welded spatter flows that presumably occur close to eruption sites.

The sheet flows are 5–80 m thick, whereas thin pahoehoe lobes form compound flow groups 10–130 m in thickness. The average lava flow thickness in the individual measured profiles is 9–25 m on Svartenhuk Halvø, with the thinner flows dominating in the southern and central areas (average 14 m) and the thicker flows dominating in the northern areas (average 22 m). Farther to the north (profile 37, Nuup Qaava) and north-east (profile 38, Qaqqap Qaa) the average lava flow thickness increases to 33 m and 37 m, respectively, indicating ponding of the lava flows in low-lying areas. Sheet flows dominate here (Figs 44, 48).

The plagioclase-phyric basalts contain glomerocrysts up to 10 mm in size of plagioclase laths intergrown with small olivine grains. The groundmass of the basaltic compound pahoehoe flows is fine- to medium-grained and vesicular, with dark green alteration products possibly after glass; from a distance such greenish rocks may be mistaken as olivine-rich types. The basaltic compound pahoehoe flows have plagioclase and olivine phenocrysts that are unevenly distributed between the individual flow lobes; this may indicate magma pulses from stratified magma chambers with very fluid magmas or crystal segregation during flowage, or both. In any case, it indicates a close genetic relationship between the olivine-poor and olivine-rich and picritic magmas. We also consider that the sheet flows and compound flows are closely related genetically. Differences are caused by different magma viscosities, commonly in connection with different degrees of evolution. Less evolved, Mg-rich magmas tend to form compound pahoehoe flows, whereas more evolved, Mg-poor and Ti-rich magmas tend to form massive sheet flows.

The lava pile can be roughly divided into three intervals in which lava flows of different morphologies dominate. Boundaries between the intervals are gradational.

The lower interval (1) comprises a 90–200 m thick succession of brown-weathering sheet flows, mostly of plagioclase-phyric basalt. Compound pahoehoe flows are subordinate. Particularly in southern Svartenhuk Halvø, the basal flows of the Tunuarsuk Member form a group of thick, brown sheet flows, seen for example in the coastal profiles at Kap Cranstown and Tartuusaq (Figs 14, 16). To the north, in the Umiiarfik region, the lower part is in semi- or subaqueous facies with two thick entablature lavas constituting the base of the member over a large area.

A middle interval (2) forms a 80–370 m thick succession of grey-weathering, interdigitating compound pahoehoe flows and sheet flows.

The upper interval (3) is a 190–310 m thick succession dominated by dark greenish-grey compound pahoehoe flows: sheet flows are subordinate. This interval comprises olivine-phyric basalt and a few picrites alternating with grey, aphyric or plagioclase-phyric basalts.

In the northern area, a division into a lower succession (interval 1 and 2) of mainly olivine-poor basalts (MgO <8 wt% and TiO_2 >1.80 wt%) and an upper suc-

Fig. 47 Lava flows of the Tunuarsuk Member comprising intervals with massive sheet flows interspersed with intervals with thin, crumbling compound flows. Height of foreground field of view *c*. 400 m. In the background, the exposed lava succession comprises the Vaigat Formation **(VF)**, the Tunuarsuk Member (**Tun**) and the Nuuit Member (**Nuuit**) in the 1000–1170 m high mountains. Northern Svartenhuk Halvø looking south-west, with Umiiarfik fjord to the right. Photo: Kristian Svennevig.

Fig. 48 The lava succession in the steep east wall of Qaqqap Qaa, eastern Innerit peninsula. Profile 38 runs along the ridge to the left through 480 m of light brownish grey Tunuarsuk Member **(Tun)** flows (left of photo) and 390 m of brown Nuuit Member flows. Light yellowish flows of presumed Skalø Member were observed from a distance overlying the Nuuit Member but were not sampled. Note the lack of exposures on the lower slopes, where both Precambrian basement and sediments of the Kuugaartorfik Member may be concealed. The water in the lower right-hand corner is the Sullua fjord; the peak of Qaqqap Qaa to the right is at 1210 m altitude. Photo: Erik Vest Sørensen.

cession (interval 3) of mainly olivine-phyric basalts (MgO >8 wt% and TiO_2 <1.80 wt%) is possible from both field observations and chemical analyses. Table 1 gives thicknesses of the lower and upper successions of the member together with the number of lava flows and average thicknesses.

Whereas thick lava flows of both types dominate in the northern area, lava flows in the southern area are mostly of compound pahoehoe type and generally thinner than in the north. In addition, there seems to be a more frequent interdigitation between MgO-poor and MgO-rich basalts. Thus the Tunuarsuk Member may have been built up by interdigitating flows from two major volcanic sources, one of them with a fluid magma in which transitions from olivine-rich to plagioclase-phyric flow units, or the reverse, can be observed within the same compound lava flow. A southern origin for this suite is suggested. The northern dominance of MgO-poor sheet flows in the lower part of the member may reflect a northern origin of this lava type or alternatively that the large erupted volumes filled topographic lows to the north and east. In this case, either the MgO-poor lavas were of the sheet flow type throughout, or degassing of more fluid magma produced the more viscous lava flows. A transition between the two types within one sheet flow has, however, not been seen. Remarkably, the highest flow in the member on eastern Innerit (at Qaqqap Qaa) is a picrite with 12.0 wt% MgO that forms a massive sheet flow 50 m in thickness (see Fig. 52).

Subaqueous lithologies. East and north of the Cretaceous boundary fault system subaqueous lava flows, pillow lavas, pillow breccias, hyaloclastites and invasive lava sheets are widespread at the base of the member (Figs 49, 50). All indicate a general transport direction towards the north. This implies that the whole northern area was more or less flooded before the extrusion of the Svartenhuk Formation; widespread wetlands existed on the eroded and irregular surface of the

Table 1 Tunuarsuk Member thicknesses and number of flows with greater and lesser than 8 wt% MgO

Profile		Lower part of member				Upper part of member				Whole member
	Total member thickness	Thickness	No.of flows	No.of flows	Ave. flow thickness	Thickness	No.of flows	No.of flows	Ave. flow thickness	Accumulated thickness
No. Name			MgO ≥8.0%	MgO <8.0%			MgO ≥8.0%	MgO <8.0%		MgO ≥8.0%
39 Peak 1540 m	320	125	0	3	42	195	3	4	28	94
38 Qaqqap Qaa	470	263	0	5	53	207	3	1	52	154
37 Nuup Qaava	434	254	0	7	36	180	3	3	30	70
47 Peak 1430 m	440	120	1	4	24	320	9	4	25	214
44c Kuugaartorfik	570	320	1	12	25	250	9	6	17	140
64 Paannivik	810	575	1	24	23	235	10	2	20	170
50 Umiiarfik South	>520	>330	1	16	19	190	8	4	16	114
51 Tunuarsuk	600	325	5	11	20	275	10	4	20	206
30 Ivissukkat Itin.[a]	294	134	1	8	15	160	10	4	11	98
29 Peak 1050 m	334	158	3	5	20	176	8	5	14	138
31 Aputituut Qaq.	420	90	0	7	13	330	4	10	24	142
22 Akuleqqut	400	150	1	15	9	248	8	7	16	160
25 Equuttat K.K [b].	>330	>157	>3	>9	13	>173	3?	4?	25	108

No.: number. Ave.: average. [a] Ivissukkat Itinnerat. [b] Equuttat Killiit Kuuat. All thicknesses in metres. Distinction between flows with MgO <8.0% and MgO ≥8.0% is based on a combination of chemical analyses and visual criteria such as phenocrysts, colour and morphology. Profiles are arranged from north to south.

Precambrian basement and also on top of the Vaigat Formation.

The thickness of the subaqueous deposits increases towards the north, indicating greater water depths here. Hyaloclastites and subaqueous lava flows are now exposed from sea level to 1300–1400 m a.s.l. due to uplift and postvolcanic tilting of the lava pile (Fig. 5).

In the Qaqqap Qaa profile (38; Fig. 13) a coarse volcanogenic sediment with coal clasts at 190–200 m a.s.l. is referred to the Kuugaartorfik Member. It is overlain by Tunuarsuk Member pillow lava and hyaloclastites with invasive lava sheets at the base (Figs 13, 50). The subaqueous succession is 140 m thick; the upper 40 m is a volcaniclastic, palagonite-rich breccia with transported basalt blocks up to 40 cm in diameter (Larsen 1981b, fig. 26), probably a mass-flow deposit (Fig. 13). It is here referred to the Tunuarsuk Member but may as well represent the uppermost part of the Kuugaartorfik Member. The mass-flow activity may have been caused by movements on a nearby fault in Sullua, perhaps connected to the fault in Umiiarfik inferred by Larsen & Pulvertaft (2000, p. 22).

In the type profile at Paannivik (64) just south of 72°N the basal lava flows have solidified under subaqueous to semi-submerged conditions forming entablature lavas. Entablature flows are also seen at the present sea level on Kigataq island west of Innerit (Fig. 51). Megapillows up to 4–5 m in diameter occur in the valley east of the Innerit inlet.

Subaqueous deposits do not occur in the central and southern areas.

Eruption sites. Eruption sites for the Tunuarsuk Member have rarely been observed. Welded spatter flows indicating proximity to an eruption site occur in profiles in south-central Svartenhuk Halvø, e.g. at Peak 1050 m (profile 29 at 885–900 m, not shown) and Aputituut Qaqqaat (profile 31 at 750–760 m, Fig. 11).

Also in profile 31 at 872–890 m a deposit of more or less welded, glass-rich, palagonitised tuff 18 m in thickness forms the uppermost unit in the Tunuarsuk Member. The deposit has in part the character of a basaltic ignimbrite and is recognised in other profiles in southern Svartenhuk Halvø. An analysis of the glass (sample 164917 from profile 18 at Kussineq) with relatively high MgO (9.1 wt%) and low TiO_2 (1.9 wt%) confirms the affiliation to the Tunuarsuk Member. The deposit is probably related to an eruption site in the

Fig. 49 Volcanic rocks of the Svartenhuk Formation overlying Precambrian metasediments of the Karrat Group (**PC**) at around 1000 m altitude. The volcanic succession of the Tunuarsuk Member (**Tun**) comprises two dark subaqueous lava flows in entablature facies (**Sub1** and **Sub2**), overlain by light grey hyaloclastites (**hy**), which presumably displaced the water in a local basin and are overlain by associated subaerial lava flows (**La**). The overlying brown flows of the Nuuit Member are all subaerial. The uppermost flows are grey and are assumed to belong to the Skalø Member, but this part of the succession has not been visited on the ground. There are traces of sediment at the base of the volcanic succession and between the subaqueous flows. Western wall of Ukkusissat Fjord around 72°05′N, 53°40′W; the top level in the background is around 1700 m altitude. Photo: Erik Vest Sørensen.

Fig. 50 Irregular, columnar-jointed lava sheets invading volcanogenic sediments (**vs**). Lower part of the Tunuarsuk Member, base of profile 38, Qaqqap Qaa, at 190 to *c*. 220 m altitude (Fig. 10).

area at 71°31′N, 55°00′W (Fig. 26). Here a one-kilometre-long, WNW–ESE-oriented, 10 m wide, dyke-like row of ochre-coloured palagonite breccias with black glass clasts, presumably near-surface crater deposits, cuts lava flows of the Tunuarsuk Member. The row is indicated by a line of stars on the geological map of Larsen & Grocott (1991). The breccia is interpreted as having formed by interaction between a magma erupting through a fissure and ground or surface water.

Chemistry and chemostratigraphy. The Tunuarsuk Member comprises tholeiitic basalts with 5–10 wt% MgO, magnesian basalts with 10–12 wt% MgO and scattered picrites with 12–22 wt% MgO. The average MgO content is 8.4 wt%. TiO_2 is in the range 1.1–3.3 wt% with an average of 1.8 wt%. A few flows scattered throughout the area are distinctly enriched in incompatible elements, and very few flows are crustally contaminated (see the Nomenclature section for definition of these types). Representative analyses are given in the

Fig. 51 Lava flow with a basal colonnade of coarse columns along the shore, changing upwards to slender columns in an entablature zone with a wavy column pattern. The overlying part of the flow is thoroughly brecciated. Despite these signs of emplacement into water, the flow is capped by a red-oxidised sediment layer (**white arrow**) indicating that the top of the flow was above water level after emplacement. Height of field of view *c*. 15 m. East side of Kigataq island. Photo: Asger Ken Pedersen.

Geochemistry chapter.

The most complete chemical profiles are those of Paannivik (profile 64), Umiiarfik South (profile 50), Tunuarsuk (profile 51), Kuugaartorfik (profile 44c), Peak 1430 m (profile 47) and Ivissukkat Itinnerat (profile 30). There is generally a decreasing TiO_2 content with height in all profiles (Fig. 42), ranging from about 2.5 wt% TiO_2 (maximum 3.3 wt%) in the lower part to about 1.5 wt% TiO_2 in the upper part with the more magnesian basalts. To the north, where lava flows with higher TiO_2 contents are lacking, the variation is best described as a slightly bumpy trend of decreasing TiO_2 with height. In contrast, profile 30 in the central area exhibits two consecutive intervals each starting with high and ending with low TiO_2 values, followed by a third interval with almost constant TiO_2. The different patterns of stratigraphic development in the northern and southern areas may indicate the existence of two separate or poorly connected, deep-seated magma chambers.

Boundaries. The base of the Tunuarsuk Member is defined by the first occurrence of brown, olivine-poor, dominantly plagioclase-phyric lava flows or hyaloclastites overlying the picrites of the Vaigat Formation. In areas where sediments of the Kuugaartorfik Member are present, the two members interdigitate. In the central area (Usuit Kuussuat) a single, dark grey, sparsely olivine-phyric to aphyric basalt flow (βo2) interbedded near the top of the picrites has been included in the underlying Nunavik Member. The Tunuarsuk Member appears to overlie the Nunavik Member conformably in most areas, although there are exceptions as described in *Boundaries* of the Svartenhuk Formation.

The upper boundary has been placed at the top of the succession of the olivine-phyric basalts underlying thick, brown basalts of the Nuuit Member (Figs 48, 52).

Geological age. Paleocene (Selandian to Thanetian). Radiometric ($^{40}Ar/^{39}Ar$) age determinations of the Tunuarsuk Member yielded ages of 60.31 ± 1.39 Ma (Larsen *et al*. 2016) and 59.78 ± 0.41 Ma (Chauvet *et al*. 2019) for the lower part of the member and 59.05 ± 0.61 Ma for the middle part of the member (Larsen *et al*. 2016).

Correlation. The Tunuarsuk Member is suggested to be

Fig. 52 The boundary between lava flows of the Tunuarsuk Member **(Tun)** and the more brownish lava flows of the Nuuit Member in profile 38 (Qaqqap Qaa). The thick, columnar-jointed uppermost flow in the Tunuarsuk Member is Mg-rich with 12.0 wt% MgO, i.e. it classifies as a picrite despite its massive morphology. The flow is 50 m thick (Fig. 13). The boundary is seen at a distance in Fig. 48.

time-equivalent to the Qeqertalik Member on Ubekendt Ejland and the Nûluk Member on Nuussuaq west of the Itilli fault (Larsen *et al*. 2016; Fig. 3).

Nuuit Member

New member

History. On the geological map 71 V.1 Syd Igdlorssuit (Larsen 1983), the Nuuit Member is included in the unit βf6. On the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991), the member is partly shown as the green unit β2. In southern Svartenhuk Halvø where the boundary between the Nuuit Member and the Skalø Member (β3) was not mapped, lavas of the Nuuit Member are included in the blue unit (β3) and labelled β2.1. In the north-eastern area of the map, an upper boundary of the Nuuit Member was not definable during mapping, and here the Nuuit Member has been given the blue colour of the Skalø Member and is not labelled.

Name. After Nuuit, the point forming the northern corner of the inlet Amitsup Sullua on the north-west coast of Svartenhuk Halvø. The member is well exposed on the slopes of the nearby mountain Nuuit Qaqqaat.

Distribution. The Nuuit Member has been recognised in southern, central and northern Svartenhuk Halvø from Tasiusap Imaa in the south to the north coast and farther north on Innerit and Qeqertaq and the coastal islands (Fig. 6). In north-western Svartenhuk Halvø (north of Maligissap Kuua) and south-western Skalø, the member is below exposure level. The member is present in south-western Svartenhuk Halvø (Qinnivik) west of the large fault through the Arfertuarsuk inlet, and it is also present in southern Svartenhuk Halvø north of Tasiusap

Imaa; however, in these two areas, it has not been mapped because of poor exposures and strong faulting. On the map of Larsen & Grocott (1991) the Nuuit Member in these two areas is included in the western part of the Skalø Member area (β3). In Fig. 6, we have drawn a tentative boundary between the Nuuit and Skalø Members in southern Svartenhuk Halvø, but this was not possible for the Qinnivik area.

In eastern Svartenhuk Halvø, the Nuuit Member is eroded away west of the Cretaceous boundary fault system. The member reappears east and north-east of the boundary fault where it overlies the Tunuarsuk Member (profiles 44c, 47 and 38). North of around 72°15′N (profiles 40 and 65) the Nuuit Member has overstepped the Tunuarsuk Member and rests directly on basement gneiss (Figs 6, 13). Its presence north of 72°20′N is undetermined. In the unvisited areas east of Ukkusissat Fjord, recent aerial photographs (Fig. 49) and geological maps (Guarnieri *et al*. 2022a, b) show that a series of grey flows of presumed Tunuarsuk Member is overlain by brown lava flows with a visual character similar to flows of the Nuuit Member to which we presume they belong. These brown flows extend east to Inngia Isbræ and farther (Fig. 5; Guarnieri *et al*. 2022a, b). East of Inngia Isbræ the Nuuit Member appears to be the only member of the Svartenhuk Formation present. A single reconnaissance sample from a nunatak above the headland of the glacier Umiammakku Sermia at 72°04.2′N, 51°54.5′E (Fig. 5, sample 566505) is virtually chemically identical to the uppermost flow in the Salliaruseq profile (65) at 72°25.0′N, 53°47.9′E (sample 566511). Considering the distance of 77 km between the two localities it is possible, but not provable, that the two represent the same lava flow.

Type section. **Paannivik** (profile 64a, Figs 13, 41) on southern Innerit. Here the Nuuit Member is present between 750 m and 1210 m a.s.l., and both base and top of the member are exposed. Coordinates in Appendix 1.

Reference sections. **Nuuit Qaqqaat** (profile 52) between 120 m and 600 m a.s.l.; the base of the member is not exposed (Fig. 53). **Umiiarfik South** (profile 50) between 650 m and 1000 m a.s.l.. This profile is of relatively easy access near the coast (Fig. 27), and both base and top of the member are exposed. Profiles in Fig. 12; coordinates in Appendix 1.

Thickness. The member is 460 m thick in the type section. Thicknesses of 300–500 m are commonly found, e.g in the Nuuit Qaqqaat, Umiiarfik South and Aputituut profiles (Figs 11, 12; Table 2). Thicknesses in the northern areas are similar or greater, with 460 m at Paannivik, >380 m at Nuup Qaava, >400 m at Qaqqap Qaa, and >550 m at Marraarnaq. In the far north-east the formation has even greater thicknesses, with >580 m at Salliaruseq and >630 m at Pannertuup Qaqqaa; the latter profile comprises thick sheet flows, subaqueous entablature flows and a hyaloclastite bed more than 100 m thick that was fed by a compound pahoehoe flow. The increased thicknesses in the north are probably caused by ponding of flows in more or less water-filled depressions. The lava flows, or at least some of them, came from the south as indicated by the north-dipping foreset-bedding of the hyaloclastites north of Qaqqap Qaa and at Pannertuup Qaqqaa.

Table 2 Nuuit Member thicknesses, number of lava flows and average flow thicknesses

Profile No.	Name	Total thickness (m)	No. of lava flows	Average flow thickness (m)
65	Salliaruseq	>590	17	35
42	Marraarnaq	>500	*c*. 13	38
40	Pannertuup Qaqqaa	>560	*c*. 13	43
39	Peak 1540 m	450	13	35
38	Qaqqap Qaa	380	11	35
37	Nuup Qaava	>340	15	23
64	Paannivik	460	19	24
50	Umiiarfik South	350	21	17
52	Nuuit Qaqqaat	>480	29	16
62	Sigguk	>250	16	16
55	Aputituut	330	20	17
31	Aputituut Qaqqaat	280	19	15

Profiles are arranged from north to south

Lithology. The Nuuit Member is dominated by brown-weathering aphyric and plagioclase-phyric basalt flows that generally form relatively thick sheet flows with thick scoriaceous tops with reddish-orange colours (Fig. 54). Most flows are subaerial but subaqueous units are present, mainly in the northern areas, e.g. hyaloclastites at Pannertuup Qaqqaa (Fig. 13, profile 40). A few tuff layers are also found.

In the type profile at Paannivik, the lower part of the Nuuit Member is dominated by sheet flows up to 50 m in thickness of plagioclase-glomerophyric and less frequent aphyric basalt. The lowest flow has entablature structure. Higher up there are a few compound pahoehoe flows *c*. 30 m thick. In the profile at Nuuit Qaqqaat a pillow horizon is present. In the Umiiarfik South profile several tuff beds up to 1 to 2 m thick are present.

The northernmost coastal exposures of lava flows

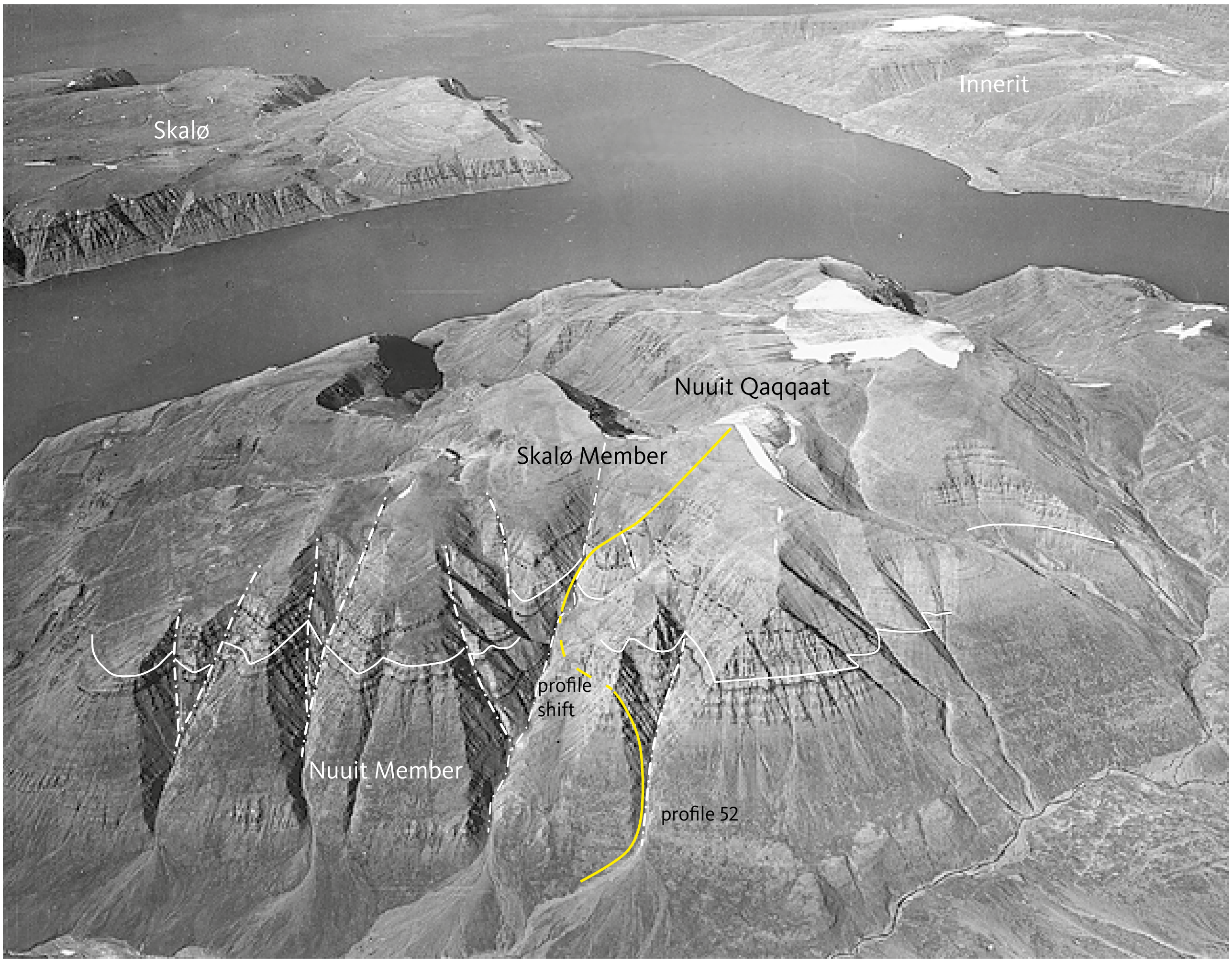

Fig. 53 The Nuuit and Skalø Members of the Svartenhuk Formation at Nuuit Qaqqaat, looking NNW. The white line is the boundary between the two members. Some local marker flows are traced in black dotted lines on the original photograph. Profile 52 (Fig. 12) is indicated with a yellow line. Height of section 780 m. Geodetic Institute oblique aerial photograph 526HN/5641.

are found around 72°22′N on the western tip of the Qulassivik peninsula, 20 km east of the Kangersuatsiaq settlement (Prøven, Fig. 7). Here lava flows of the Nuuit Member ran into water and developed megapillows up to 5 m in diameter, spectacular colonnades, tiered colonnades (Figs 55, 56) and entablatures before they were banked up against steep hillocks of the Precambrian basement (Fig. 57).

Some horizons form the following markers:

- Two lava flows in the lower part of the member contain large plagioclase glomerocrysts with stellate outlines as well as individual platy plagioclase crystals *c.* 1 cm long or larger (profiles 38, 39, 47, 64).
- Two thick lava flows contain *c.* 0.5 cm plagioclase glomerocrysts together with platy olivine phenocrysts; these occur at Paannivik, on Skalø and on the south side of Uiarsaariaq (profiles 64, 41b and 54).

Eruption sites. The average lava flow thickness in individual profiles south of 72°N varies between 15 and 24 m, with the lower values found in southern and central Svartenhuk Halvø and the larger values on the Innerit peninsula. Average lava flow thicknesses north of 72°N range from 23 to 43 m (Table 2). This situation is similar to that in the Tunuarsuk Member of the same profiles, suggesting that the eruption sites for both members were situated close to or within the southern areas, giving rise to many small and thin flows in the south, whereas only the most voluminous flows reached north to the Innerit area and farther to the northern and north-eastern areas.

A volcanic plug was found by Münther (1973) in the coastal cliffs on the western side of the Arfertuarsuk inlet in south-western Svartenhuk Halvø (Figs 26, 58). The plug cuts vertically through lava flows of the Tunuarsuk Member and one or two flows of the Nuuit Member. It has a doleritic core and a chilled margin with weak columnar jointing perpendicular to the outer contacts. Towards the highest flow in contact with the plug, a purple to blackish agglomerate is developed that passes

Fig. 54 Characteristic brown, massive lava flows of the Nuuit Member overlying thinner and more variable lava flows of the Tunuarsuk Member **(Tun).** Northern Svartenhuk Halvø with the Qooroq valley to the left, looking north towards the Umiiarfik fjord. Photo: Asger Ken Pedersen.

laterally into a lava flow, one of the lowest flows in the Nuuit Member. Higher lava flows are unaffected. In the scree below the plug some gabbro nodules were found. Further description is given by Münther (1973, p. 15).

Chemistry and chemostratigraphy. The Nuuit Member comprises tholeiitic basalts with 3.4–11 wt% MgO; the average MgO content is 6.4 wt%. TiO_2 is in the range 1.5–3.8 wt% with an average of 2.4 wt%. A few scattered flows are crustally contaminated. The magmas were relatively depleted in incompatible trace elements such as Rb, Ba, Th, U, Nb, and light REE. Some flows in the northern areas are enriched in the same elements, which has stratigraphic significance as discussed in the later section on petrology. Representative analyses are given in the Geochemistry chapter.

A common pattern of TiO_2 variation with height in the Nuuit Member is seen in several profiles (Fig. 42). With some irregularities, the lower part of the member shows constant to increasing TiO_2 with height, reaching a maximum around the middle of the member. TiO_2 decreases in the upper part of the member, until a reversal to increasing TiO_2 is seen in a few flows at the top of the member. This is particularly clear in the Nuuit Qaqqaat and Paannivik profiles. If this is a general trend, the upper part with decreasing TiO_2 seems to be missing in the Sigguk profile, whereas the reversal at the top is well developed (the lower part of the Nuuit Member is not exposed in this profile). Similarly, the erosional remains of the member in the eastern profiles Kuugaartorfik and Peak 1430 m represent the lowest part of the member, whereas the northern profile at Qaqqap Qaa seems to represent a condensed succession. The Umiiarfik South profile is different, with two cycles of decreasing TiO_2 present.

The basalts in the Aputituut profile are characterised by relatively high TiO_2 contents of 2.5 to >3.0 wt% in both the Nuuit Member and the overlying Skalø Member (Fig. 42). The boundary between them is placed where the flow morphology changes to flows with yellow-brown top zones and plagioclase aggregates typical of Skalø Member flows.

Boundaries. The lower boundary is placed where the dark greenish-grey olivine-phyric basalts of the Tunuarsuk Member give way to brown sheet flows of plagioclase-phyric and aphyric basalt. The boundary is well exposed and easy to identify in most areas due to the colour contrast between the two members.

The upper boundary is defined by the appearance of grey-weathering, thin pahoehoe lava flows with yellow flow tops of the Skalø Member. The boundary is well exposed in north-western Svartenhuk Halvø around the estuary and river of Amitsup Sullua and Amitsup Kuua

Fig. 55 Thick lava flow with a 20–25 m high colonnade with bent column tops. Nuuit Member at Asungasungaa, west coast of Qulassivik peninsula, 9 km east of the Kangersuatsiaq (Prøven) settlement. Photo: Asger Ken Pedersen.

Fig. 56 Multi-tiered columns in a thick, ponded lava flow, probably the same flow as in Fig. 55. Height of section 20–30 m. Nuuit Member at Asungasungaa, west coast of Qulassivik peninsula, 9 km east of the Kangersuatsiaq (Prøven) settlement. Photo: Asger Ken Pedersen.

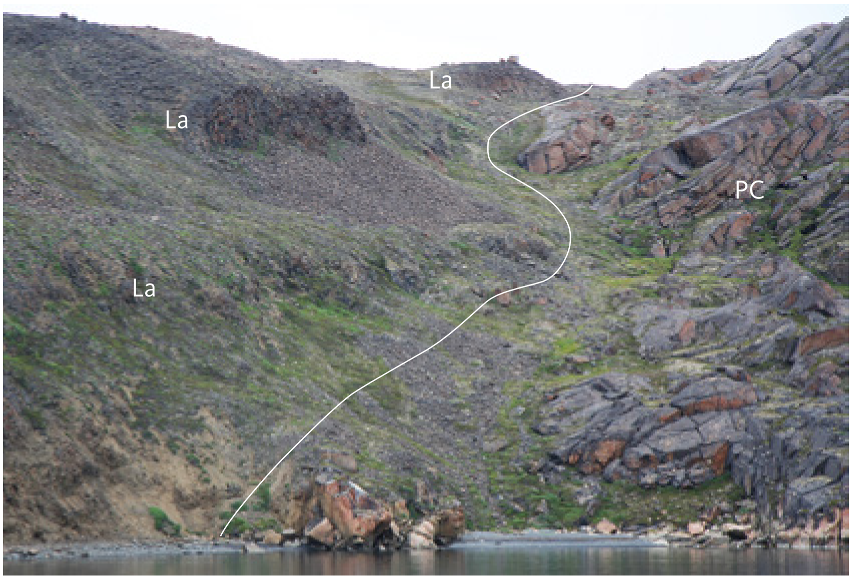

Fig. 57 Three successive lava flows (**La**) of the Nuuit Member banked up against a steep hill of Precambrian basement gneiss (**PC**). Southwest coast of Qulassivik peninsula, 10 km ESE of the Kangersuatsiaq/Prøven settlement. Photo: Asger Ken Pedersen.

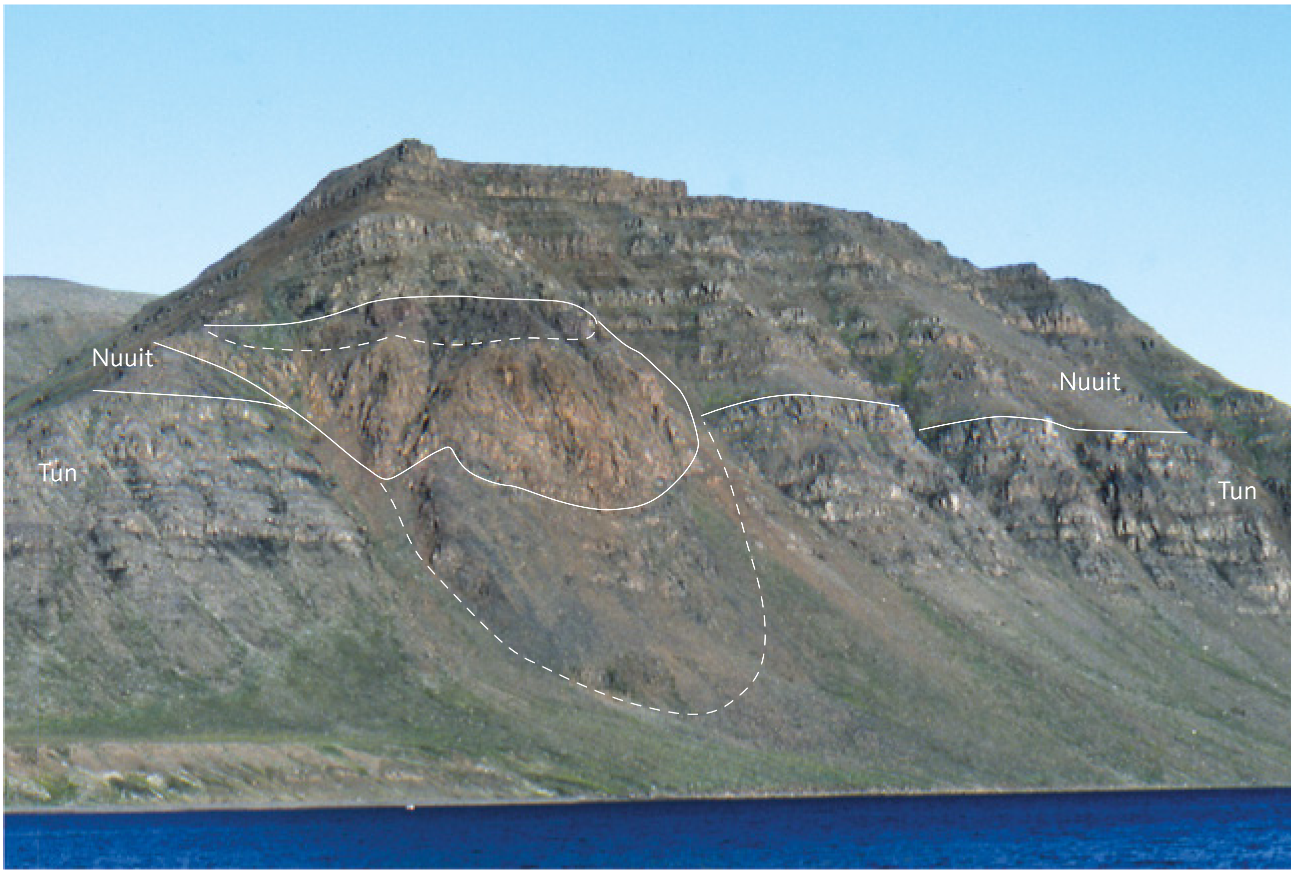

Fig. 58 Volcanic plug feeding one of the lowest lava flows in the Nuuit Member near the boundary to the Tunuarsuk Member (**Tun**). The plug is traced in white; the dashed lines are approximate. The central plug is light brown with a diameter of *c*. 150 m. The upper zone is a purple agglomerate that passes laterally (to the left) into a lava flow. The character of the lower zone is uncertain; it was described by Münther (1973) as a "mixed contact". See text for further description. Coastal cliff on the western side of the Arfertuarsuk inlet, south-western Svartenhuk Halvø.

(Fig. 59) and on the south coast of Skalø (Fig. 60). The top flow of the Nuuit Member is a distinct, thick, dark brown sheet flow on Skalø and at the coast west of Amitsoq; this is overlain by a thin sheet flow and yellow-topped pahoehoe flows referred to the overlying Skalø Member. In the Nuuit Qaqqaat area, some yellow-weathering lava flows are also present below the top of the member, which is comprised of the same thick, massive, brown lava flow that is the top flow west of Amitsoq. On northern Skalø, the top of the Nuuit Member has been placed on top of 2–3 thick brown lava flows overlying some yellow-weathering flows and overlain by thin yellow flows referred to the overlying Skalø Member.

The upper boundary has not been mapped in southern Svartenhuk Halvø due to poor exposures and many faults. In this area, the geological map of Larsen & Grocott (1991) shows lavas of the Nuuit Member labelled β2.1 and included in the blue areas of the overlying younger lavas (β3) with no boundary drawn between them.

Geological age. Paleocene (Thanetian). A radiometric (^{40}Ar/^{39}Ar) age determination of the Nuuit Member yielded an age of 58.08 ± 0.59 Ma (Larsen *et al*. 2016).

Correlation. The Nuuit Member is considered to be time-equivalent to the upper part of the Qeqertalik Member and/or the Tuperssuartâta kûa Member on Ubekendt Ejland, and to part of the Ifsorisok Member on Nuussuaq west of the Itilli fault (Fig. 3; Larsen *et al*. 2016).

Skalø Member

New member

History. The Skalø Member is included in the unit βf6 on the geological map 71 V.1 Syd Igdlorssuit (Larsen 1983). It is included in the unit β3 on the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991).

Name. After the island Skalø north-west of Svartenhuk Halvø where the member is well exposed along the south-east and north-west coasts.

Distribution. The Skalø Member has been recognised in north-western and northern Svartenhuk Halvø, Skalø and southern and eastern Innerit. It is inferred to be present across all of western Svartenhuk Halvø, but field relations to the south-west are poorly constrained due

Fig. 59 The upper lava flows of the Nuuit Member and the conformable boundary to the Skalø Member at Amitsoq just west of the Amitsup Sullua inlet, looking SE. The water in the foreground is the Umiiarfik fjord. Note that the lava package west of Amitsup Sullua is tilted 14°W, whereas the lava package east of Amitsup Sullua is nearly flat-lying (Figs 53, 54). Photo: Kristian Svennevig.

to intense faulting and poor exposure. The northern and eastern delimitations are erosional. Recent aerial photographs (Fig. 49) and geological maps (Guarnieri *et al*. 2022a, b) show remnants of a series of lava flows with a visual character similar to flows of the Skalø Member capping the highest peaks in the area east of Sullua and extending east across Ukkusissat Fjord to Inngia Isbræ but not farther (Fig. 5). These flows rest on brown flows presumed to belong to the Nuuit Member. They have not been sampled, but their stratigraphic position and comparison with Innerit (Paannivik and Qaqqap Qaa) suggest that they belong to the Skalø Member.

As the boundaries to the under- and overlying members have not always been mapped, the areas that represent the Skalø Member on the geological maps (Larsen 1983, βf6; Larsen & Grocott 1991, β3) include parts of the Nuuit Member in southern Svartenhuk Halvø and parts of the Arfertuarsuk Member in western and south-western Svartenhuk Halvø and on Skalø.

Type section. **Sigguk** (profile 62) on the southern side of the 643 m hill in westernmost Svartenhuk Halvø; the base is at 150 m a.s.l. and the top is at 360 m a.s.l. (Fig. 11; coordinates in Appendix 1). Both base and top of the member are well exposed, see Fig. 64. No other profiles include a well-exposed top of the member.

Reference sections. South-eastern **Skalø** (profile 41b, Fig. 60) contains a marker horizon of many thin pahoehoe units (mapped as β3.1), which is absent in the type profile at Sigguk. **Nuuit Qaqqaat** (profile 52, Fig. 53) contains a 300 m long, well-exposed and well-analysed section through the member. Profiles in Fig. 12; coordinates in Appendix 1.

Thickness. The greatest thickness encountered is 460 m, found on Skalø. In the type section at Sigguk, the Skalø Member is 210 m thick. In central and northern Svartenhuk Halvø and Innerit, erosion has left thicknesses from 300 m at Nuuit Qaqqaat to 200 m at Aputituut Qaqqaat to 125 m at Umiiarfik South and 130 m at Paannivik. Thicknesses are summarised in Table 3.

Lithology. The dominant lithology of the Skalø Member is plagioclase-glomerophyric basalt lava flows of either compound pahoehoe or sheet flow type. The phenocryst contents (commonly >10%) are generally higher than in the other members. The glomerocrysts are *c*. 5 mm in size or larger. A distinctive basalt type contains characteristic platy olivine phenocrysts and commonly also plagioclase aggregates. This type is found in the middle of the member and is present on Skalø and on both sides of the westernmost NW–SE-trending fault on the coast between Amitsoq and Serfat. A similar flow is present on the south-eastern side of the Arfertuarsuk inlet (Fig. 15, sample 165215).

Weathering colours are light grey, and a distinct pale yellow colouring of flow tops occurs in many areas, typically on south-eastern Skalø and east of Amitsup Sullua (Fig. 61). The yellow colour appears to be due to altered glassy flow tops of relatively thin lava flows or flow units. Red flow tops are common in other areas, e.g. in profile 50 (Umiiarfik South). The lavas are more grey on south-western Skalø. Tuff beds are few, and one or two pillow breccias and agglomerates are present on Skalø (profile 41a) and at Nuuit Qaqqaat (profile 52). A single coal seam 0.5 m thick has been recognised on south-eastern Skalø (at 310 m a.s.l. east of profile 41b).

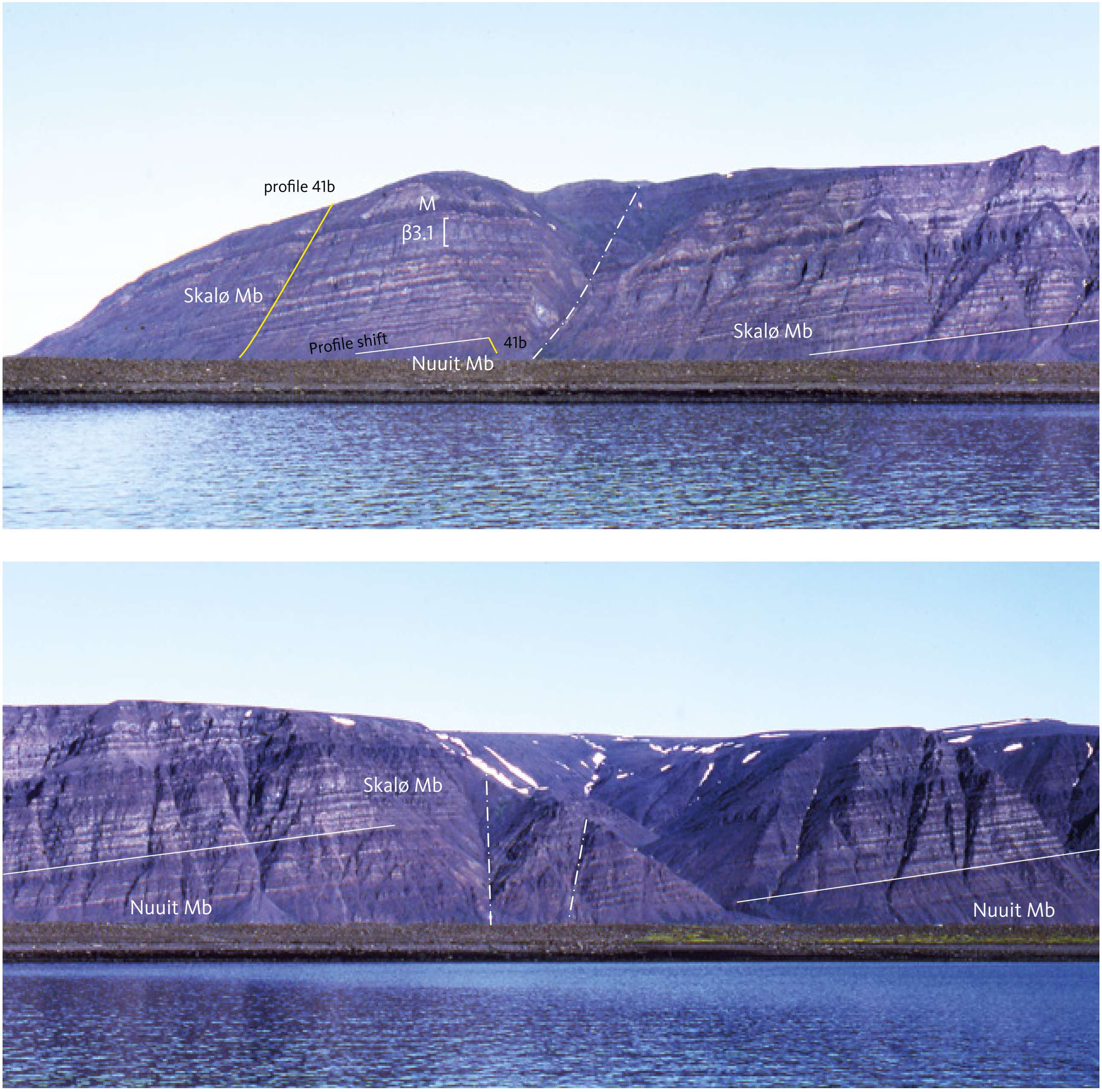

Fig. 60 Light grey lava flows of the Skalø Member overlying massive brown flows of the Nuuit Member on the south-east coast of Skalø. The succession is faulted (**dash-dot lines**) and dips 10°SW. The location of **profile 41b** is indicated (**yellow line**). Marker horizons **β3.1** and the dark flow **M** are described in the text. The coastal section in view is 4.5 km long and the cliffs are 400–450 m high.

Table 3 Skalø Member thicknesses, number of lava flows and average flow thicknesses

Profile No. Name	Total thickness (m)	No. of lava flows	Average flow thickness (m)
64 Paannivik	>140	9	15
50 Umiiarfik South	>120	9	12
52 Nuuit Qaqqaat	>300	17	17
41b Skalø south	460	19	24
58 Amitsoq	>375	19	19
62 Sigguk	210	18	12
31 Aputituut Qaqqaat	>200	11	18

The Skalø Member contains two marker horizons, which make correlation possible between Skalø and the coast of Svartenhuk Halvø west of Amitsoq and one horizon that correlates between Skalø (profile 41b) and Sigguk (profile 62).

A marker flow named β3.1 on the map occurs *c*. 160 m above the base of the member on Skalø (profile 41b, Figs 12, 60). It is a prominent, grey, compound pahoehoe lava flow that is almost aphyric in its lower flow units, whereas the upper flow units have large stellate plagioclase aggregates ('star basalt') and a relatively coarse groundmass. This unit is 70 m thick on south-eastern Skalø and 20 m thick at Amitsoq 5 km to the south-east. The flow has higher TiO_2 content (>3 wt%) than most other Skalø Member flows and is clearly identified in Fig. 42. Two 'star basalt' sheet flows with a combined thickness of 45 m in Qooruusaq (profile 59) have a similar composition and are considered to be part of the same horizon (Fig. 42).

Distinctive, dark flows with platy olivine phenocrysts and commonly plagioclase aggregates occur at two levels in the member on Skalø, one above and one below the β3.1 marker (Fig. 60; the upper dark flow is labelled M) and along the coast between Amitsoq and Serfat.

The uppermost flow of the Skalø Member in the two profiles at Sigguk (62) and Skalø (41b) are compositionally identical and unique for the whole formation (Fig. 42). They have anomalously low TiO_2 contents (1.15 wt%) at 7.6 wt% MgO (*mg*-number 58.7; see the TiO_2 diagram in the Geochemistry chapter); Al_2O_3 (15.4 wt%) and CaO (12.6 wt%) are high but not anomalously so and do not indicate plagioclase accumulation. We consider that these samples, located 19 km apart, represent the same lava flow.

In the Aputituut area where the boundary between the Nuuit and Skalø Members is difficult to trace, the uppermost *c*. 70 m of the flows in the Aputituut profile (55) have yellow-brown top zones and contain large stellate aggregates of plagioclase phenocrysts; they have therefore been placed in the Skalø Member. They constitute a coherent group of lava flows with high TiO_2 contents (2.5–2.9 wt%, Fig. 42) and are very similar to the flows in the Skalø Member marker horizon β3.1. The distance to the latter exposures is *c*. 25 km, and it is uncertain whether they represent the same horizon.

In the same difficult area in central-western Svartenhuk Halvø, the yellow-weathering colours of the basalts along the river Akuleqqut Kuuat, and their chemical compositions, confirm the presence of the Skalø Member (Jørgensen 1981).

Along the north-eastern side of the Arfertuarsuk inlet, the SW-dipping succession of lava flows consists of dark grey, olivine-bearing flows and yellow-brown pahoehoe flows with a physical appearance and chemical compositions corresponding to the Skalø Member, as indicated by three analysed samples (165217–219; Fig. 15). Because of the presence of olivine in some of these basalts, a small part of the succession was classified as picrite and olivine basalt (βo) on the map of Larsen (1983); these flows are, however, normal Svartenhuk Formation basalts with 6–7.5 wt% MgO. The succession dips below sea level along the eastern side of Arfertuarsuk, where the lavas are overlain by sediments some metres thick, followed by a number of brown, SW-dipping basalt flows that are well exposed in a SE-facing cliff (Fig.15). These brown basalts also appear to belong to the Skalø Member according to chemical analyses by Agranier *et al*. (2019, their Loc. 11).

There is a positive correlation between the total thickness of the member at different localities and the average lava flow thickness (Table 3). Thus the larger flow thicknesses measured on Skalø, at Amitsoq and Nuuit Qaqqaat, and perhaps on southern Innerit, may indicate a topographically low-lying area where lava flows could accumulate, in contrast to the environment at Sigguk (profile 62) where the individual lava flows are thin, as is the whole member.

A horizon of volcaniclastic sediments 5–20 m in thickness is widespread at the top of the member. In the area north of the Arfertuarsuk inlet, the sediments are *c*. 20 m thick (Fig. 62) and include rounded cobbles up to 10 cm in size of different basalt types and hyalotuffs. The age of the sediments is not known; the horizon is tentatively included in the Skalø Member.

Eruption sites. None have been found.

Chemistry and chemostratigraphy. The Skalø Member comprises basalts with 4.5–10 wt% MgO, and the aver-

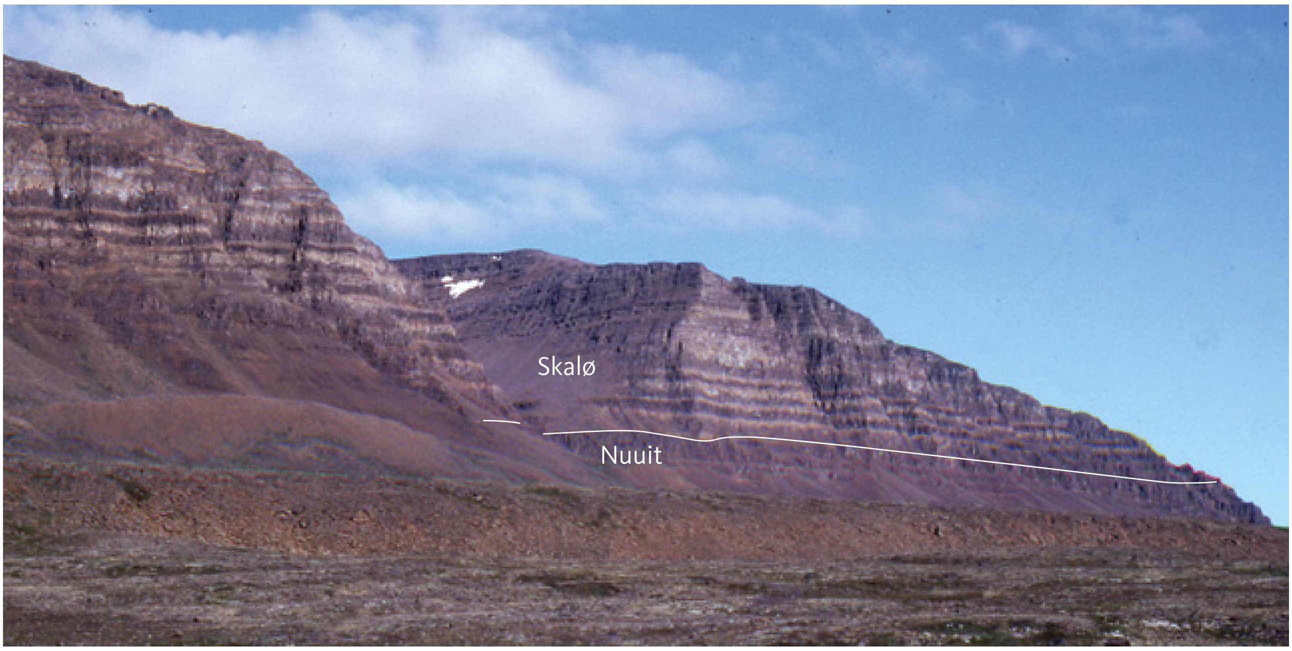

Fig. 61 Lava flows of the Skalø Member with characteristic yellow-tinted, light top zones, overlying brown flows of the Nuuit Member. North-east side of the Amitsup Kuua valley, north-western Svartenhuk Halvø, looking south. The succession is unfaulted and nearly flat-lying, dipping 3°SW. Length of cliff section 2.5 km and height of section *c*. 300–400 m. Photo: Karl Aage Jørgensen.

age MgO content is 6.5 wt%. TiO_2 is in the range 1.1–3.5 wt%, and the average TiO_2 content is 2.0 wt%. The magmas were relatively depleted in incompatible trace elements such as Rb, Ba, Th, U, Nb, and light REE, as in basalts of the Tunuarsuk and Nuuit Members. A few flows may be crustally contaminated. Representative analyses are given in the Geochemistry chapter.

The TiO_2 stratigraphy shows an increase from low TiO_2 contents of around 1.5 wt% at the base to 2.4% upwards in the member (Fig. 42), with the exception of the 'star basalt' marker flow (β3.1) in the Skalø profile with values above 3% TiO_2, and a very-low-TiO_2 basalt with 1.1% TiO_2 at the top of the member in the Skalø and Sigguk profiles. The Sigguk profile lacks the high-Ti β3.1 marker flow and, except for the uppermost low-Ti flow, shows a very regular increase in TiO_2 with height, indicating that the flows form a coherent sequence and presumably were erupted from the same magma chamber.

Boundaries. The lower boundary of the Skalø Member is placed at the top of the brown-weathering basalts of the Nuuit Member with its red flow tops and tuffs. The boundary is distinct in the north-western and northern areas (Figs 48, 59–61). It is less distinct and not mapped in the faulted and poorly exposed parts of southern Svartenhuk Halvø. Here, much, or all, of the Nuuit Member was included in the Skalø Member area on the map and labelled β2.1, as described previously for the Nuuit Member.

The upper boundary is placed at the base of the brown basalts of the Arfertuarsuk Member of the Naqerloq Formation. In the type section at Sigguk, a poorly exposed volcaniclastic sediment horizon 5–10 m in thickness constitutes the top of the Skalø Member. In the area north of Arfertuarsuk, the top of the member comprises a volcaniclastic sediment horizon of reworked hyaloclastite material *c*. 20 m in thickness (Fig. 62). In the southern Qooruusaq valley a scree-covered horizon 10–15 m in thickness, presumably of sediment, forms the top of the Skalø Member and is directly overlain by the Arfertuarsuk trachyte flow of the Arfertuarsuk Member of the Naqerloq Formation. The sediment horizon probably represents a break in the volcanic activity and is included in the Svartenhuk Formation.

The upper boundary has only been mapped in westernmost Svartenhuk Halvø in the area between Sigguk, Svartenhavn and Milloorfik. Its extent shown on the map of Larsen & Grocott (1991) is based on long-distance visual correlation and on aerial photographs from the well-exposed boundaries in profile 62 and Siggup Qoorua (7.5 km north of profile 62, Figs 7, 8) and eastwards to the Qooruusaq valley.

The boundary is also present, though unmapped, in the Qooruusaq valley and on Skalø. On Skalø, it is poorly exposed on the top of the plateau, from where a few analysed samples belong to the overlying Arfertuarsuk Member. Fig. 6 shows our present best estimate of the position of the boundary between the Skalø and Arfertuarsuk Members.

Geological age. Paleocene (Thanetian). A radiometric ($^{40}Ar/^{39}Ar$) age determination of the Skalø Member yield-

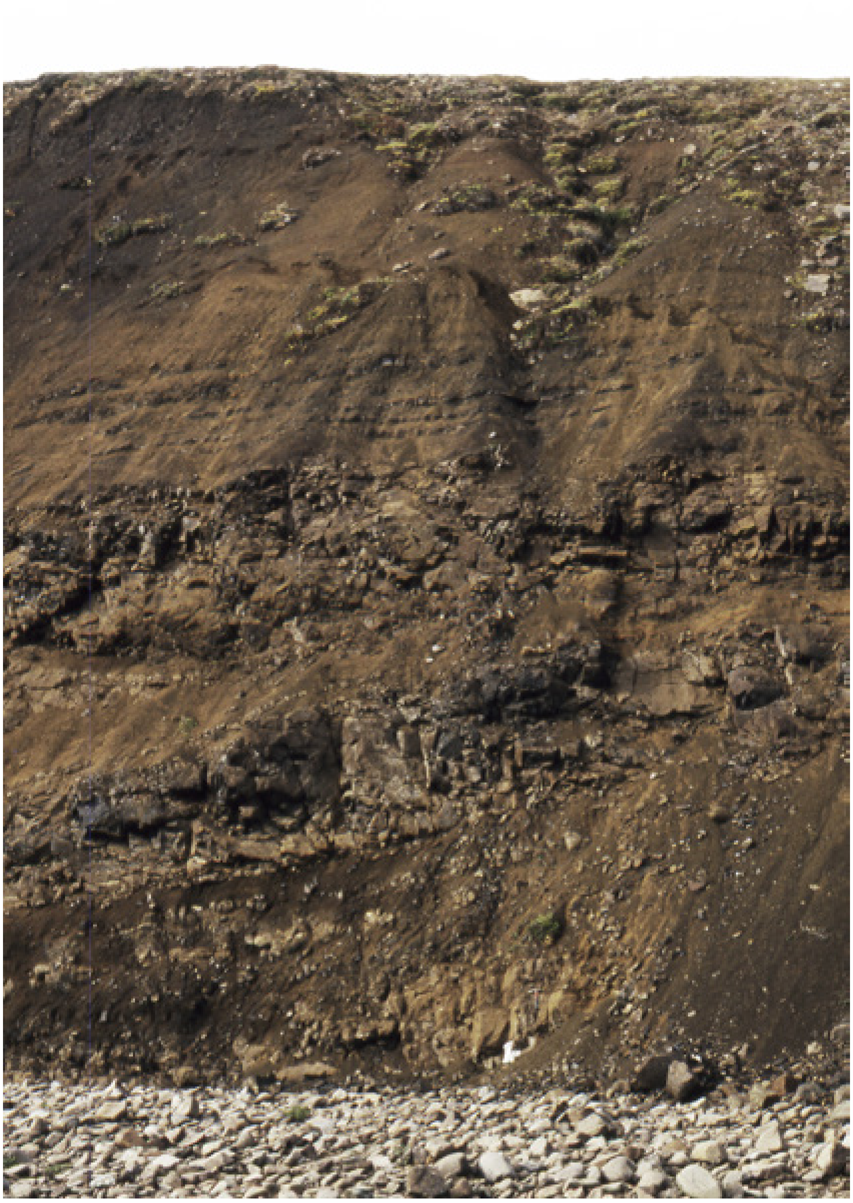

Fig. 62 Heterogeneous volcaniclastic sediments that form the uppermost horizon of the Skalø Member. Height of field of view 14 m; the full thickness of the sediment horizon here is about 15 m. Riverbank c. 5 km north of the end of the Arfertuarsuk inlet.

ed an age of 57.98 ± 0.59 Ma (Larsen *et al*. 2016).

Correlation. The Skalø Member is considered to be time-equivalent to the Tuperssuartâta kûa Member on Ubekendt Ejland and to part of the Ifsorisoq Member on Nuussuaq west of the Itilli fault (Fig. 3; Larsen *et al*. 2016).

Naqerloq Formation

New formation

History. The formation was introduced, but not formalised, by Larsen *et al*. (2016) and comprises those parts of the original Maligât and Svartenhuk Formations, which had at that time turned out to be of Eocene age. The reduced Maligât and Svartenhuk Formations, of Paleocene age only, are formally revised by Pedersen *et al*. (2018, Maligât Formation) and in this work (Svartenhuk Formation). The existing names for the members on Nuussuaq and Hareøen (Kanísut Member, Hald 1976) and Ubekendt Ejland (Nûk takisôq Member, Larsen 1977) are unchanged. On Svartenhuk Halvø, Larsen & Larsen (2010) introduced two new informal members, the Sigguk and Arfertuarsuk members, for the Eocene part of the volcanic succession. However, new field and compositional data described below have led to new interpretations, and distinction between these two members cannot be upheld. Consequently, in this work the Naqerloq Formation on Svartenhuk Halvø is not subdivided and the Arfertuarsuk Member is defined to comprise the entire Eocene succession.

Name. After the 7–8 km long Naqerloq valley in westernmost Nuussuaq.

Subdivisions. The Naqerloq Formation contains three members, which are considered to be approximately laterally equivalent:
Arfertuarsuk Member on Svartenhuk Halvø and Skalø.
Nûk takisôq Member on Ubekendt Ejland.
Kanísut Member on Nuussuaq and Hareøen.

Distribution. The Naqerloq Formation is present from Skalø in the north and southwards across western Svartenhuk Halvø, through western Ubekendt Ejland to Nuussuaq west of the Itilli fault and to Hareøen in the south, a N–S distance of around 170 km. The E–W width of the strip of land where the formation is exposed is only 5–15 km. The formation is faulted and variably tilted in all subareas. It is delimited towards the sea or towards faults, and in the north, the eastern delimitation is erosional.

Type area. The type area is the **Naqerloq** valley in westernmost Nuussuaq. The valley is oriented SE–NW, it is *c*. 7 km long and opens into the sea in the north-west. Here, a succession of W-dipping lava flows of the Naqerloq Formation (Kanísut Member) is relatively easily accessible (Hald 1976).

Reference sections. On Ubekendt Ejland a reference section in the Nûk takisôq Member is situated along the south-west coast of the island where the succession dips 32°WSW; the base is situated 5.8 km south-east of the point Eqqua (old spelling Erqua), up-section is towards NW, and the top of the member is situated 3.0 km south-east of Eqqua where it is overlain by lava flows of the Erqua Formation (Larsen 1977).

On Svartenhuk Halvø, the **Arfertuarsuk** profile (36b) and the **Sigguk** profile (62) are described in the section on the Naqerloq Formation on Svartenhuk Halvø.

Thickness. The Naqerloq Formation is thickest on western Nuussuaq where a succession more than 2000 m thick is preserved (Hald 1976). On western Ubekendt Ejland Larsen (1977) reported a thickness of *c*. 900 m. On Svartenhuk Halvø 300–400 m of succession are preserved.

Lithology. The Naqerloq Formation is dominated by massive, brown, subaerial basalt lava flows of sheet flow type. The basalts are plagioclase-olivine-clinopyroxene-phyric, microphyric or aphyric. Intermediate and acid tuffs are present at some levels (Hald 1976; Larsen 1977; Larsen *et al*. 2016), which has significantly contributed to the accuracy of the radiometric age determinations.

Chemistry. The most important characteristic that distinguishes the basalts of the Naqerloq Formation throughout the province from the underlying Paleocene basalts is their chemical composition. The Naqerloq Formation comprises tholeiitic basalts enriched in incompatible elements such as K, P, Sr, Ba, Zr, Nb and light REE. Petrogenetically important element ratios such as P_2O_5/TiO_2, Ba/Sr, Zr/Y, Nb/Y, Nb/Zr, Nb/La, La/Sm and Gd/Lu are all significantly higher in the Naqerloq Formation basalts than in the Paleocene basalts.

Boundaries. The lower boundary is rarely observed because of faulting and poor exposures. On Nuussuaq, the Eocene basalts rest on a thick deposit of volcaniclastic sediments, tuffs and mudstones, which form the Ifsorisok Member of the Svartenhuk Formation (Hald 1976; Larsen *et al*. 2016). On Svartenhuk Halvø, the Eocene basalts similarly rest on a horizon of volcaniclastic sediments 5–20 m thick, referred to the uppermost

Svartenhuk Formation and perhaps a lateral equivalent of the Ifsorisok Member.

The upper boundary is erosional on Skalø, Svartenhuk Halvø and Nuussuaq. On Ubekendt Ejland, basalts of the Nûk takisôq Member are concordantly overlain by alkali basalts of the Erqua Formation (Larsen 1977). On Hareøen, lava flows of the Kanísut Member are overlain by sediments of the Aumarûtigssâ Member (Hald 1976).

Geological age. Eocene, earliest Ypresian. Larsen et *al*. (2016) reported seven radiometric ($^{40}Ar/^{39}Ar$) age determinations of basalts from the Naqerloq Formation, ranging from 57.25 ± 0.95 Ma to 54.03 ± 0.33 Ma, generally younging upwards (Fig. 3). Chauvet *et al*. (2019) reported two basalt ages within the same interval (Fig. 3). Dating of the Arfertuarsuk trachyte flow on Svartenhuk Halvø has been problematic because of stratigraphic misfit, but this flow is now considered to be situated very close to the base of the formation with an age of 56–57 Ma. The flow is considered in detail below.
The Kanísut Member on Nuussuaq is reversely magnetised, and the radiometric ages indicate that the magnetochron is C24r (Riisager *et al*. 2003).

Correlation. A large part of the offshore volcanic succession penetrated in the Delta-1 drill hole has ages (56–50 Ma) and chemical compositions similar to the Naqerloq Formation (Nelson *et al*. 2015; see Table 7).

Naqerloq Formation on Svartenhuk Halvø

A large part of the Naqerloq Formation on Svartenhuk Halvø is situated in a strongly faulted area in south-western Svartenhuk Halvø. There is no direct connection to the more northerly part of the formation that is less faulted and situated in nearly flat-lying areas immediately east of Sigguk/Svartenhuk and on Skalø (Fig. 6). The unique Arfertuarsuk trachyte flow near the base of the succession in the southern area is an excellent marker horizon, but, except for a small erosional remnant, it is not present north of Maligissap Kuua. Interpretation of the stratigraphy of the Naqerloq Formation has therefore been difficult. Larsen & Larsen (2010) suggested that the succession in the area north of Maligissap Kuua is older than the trachyte and that the succession in the southern area is younger, with the Arfertuarsuk trachyte flow situated at the base of the younger part, stratigraphically around the middle of the combined succession and thus removed by erosion in the northern areas. This interpretation was based on the relations in the Qooruusaq valley 12–14 km east of Sigguk and *c*. 20 km north of Arfertuarsuk, where the two parts of the succession almost meet each other. In this down-faulted valley the composite Qooruusaq profile (59–61, Fig. 11) extends from the coast in Milloorfik towards the south-east, uphill and up-section through the NW–SE-striking, SW-dipping lava pile. It ends at poor exposures less than 3 km north-west of, and below, a northern outlier of the trachyte flow (Fig. 6), leaving only 50–75 m stratigraphy below the trachyte unsampled. The sampled flows represent *c*. 250 m of stratigraphic thickness and all have the enriched geochemical character of the Naqerloq Formation, apparently supporting the stratigraphic model with the trachyte flow in the middle of the combined succession.

Larsen *et al*. (2016) obtained $^{40}Ar/^{39}Ar$ ages for a basalt flow on Skalø (sample 251372) of 54.86 ± 0.44 Ma and a basalt flow in the Arfertuarsuk profile (sample 278596) of 55.91 ± 0.60 Ma. The Arfertuarsuk trachyte flow itself has been repeatedly dated with strangely scattered results ranging from Paleocene, 58.4 Ma, for the large anorthoclase phenocrysts to Eocene, 55.3 Ma, for a laser analysis of groundmass alkali feldspar (Table 4). The large anorthoclase phenocrysts are sieve-textured and contain many dark inclusions. An explanation of the results may be that these inclusions contain excess argon that was released uniformly through the successive heating steps; there are fewer inclusions in the groundmass feldspar and the inclusions are avoided in the laser analysis. If this is the case, the laser result is the most reliable and the trachyte flow is of earliest Eocene age. The question remains, however, how close to the base of the Eocene succession is the trachyte flow situated?

The northern outlier of the trachyte in the Qooruusaq

Table 4 $^{40}Ar/^{39}Ar$ age determinations for the Arfertuarsuk trachyte flow

Sample	Material	Plateau age ± 2σ (Ma)	% ^{39}Ar released	Reference
456207	Anorthoclase	58.43 ± 0.31 [a]	96	Author, unpublished data
1931.1	Anorthoclase	57.51 ± 0.24 [a]	80	Larsen *et al*. (2016)
1931.1	Groundmass feldspar	56.85 ± 0.13 [a]	31	Author, unpublished data
S29-E2	Alkali feldspar	55.31 ± 1.09 [b]	Laser analysis	Chauvet *et al*. (2019)

All ages are calculated relative to an age of 28.201 Ma for the Fish Canyon tuff standard. [a] Incremental step heating result from Oregon State University dating laboratory. [b] Inverse isochron age.

valley was briefly visited in 2019 by K. Svennevig (Fig. 63). Below the trachyte, there is an unexposed horizon 10–15 m in thickness, which may represent a sediment horizon although no sediment was seen. Two basalt flows below this horizon and a single basalt flow overlying the trachyte were sampled (profile 67 in Fig. 9). The geochemical analyses showed that whereas the flow above the trachyte has the enriched character of the Naqerloq Formation, the two flows below the trachyte have not; they have the typical character of the Paleocene basalts and are considered to belong to the Skalø Member of the Svartenhuk Formation. The trachyte flow is therefore the oldest Eocene lava flow at this locality. The apparent stratigraphic continuity to the Eocene flow succession in profile 59–61 farther north in the Qooruusaq valley is therefore lost. We must assume that an unexposed fault crosses the valley between the trachyte outlier and the Qooruusaq sample profile (Fig. 11), with a relative downthrow of *c*. 300 m of the succession to the north (Fig. 6).

In the area north of the Arfertuarsuk inlet where the trachyte and the overlying lava flows have been mapped (Larsen & Grocott 1991), the trachyte flow is underlain by two or three lava flows with hyaloclastite and hyalotuffs resting on *c*. 20 m of reworked volcaniclastic sediment. This sediment has been referred to the uppermost Skalø Member of the Svartenhuk Formation. The flows below the trachyte and above the sediments have the chemical character of the Naqerloq Formation but have significantly lower TiO_2 (1.8–2.06 wt%) than the flows above the trachyte (>2.4 wt% TiO_2; see Fig. 42 and the Geochemistry chapter). Flows with similar low-Ti compositions occur at the base of the Naqerloq Formation at Sigguk (profile 62) and in the northern Qooruusaq valley (profile 59–61). We therefore consider it most probable that the trachyte flow did not reach the northern areas, and that the top of the low-Ti flows marks the level corresponding to the trachyte. This means that the three profiles, Sigguk (62), Arfertuarsuk (36b) and Qooruusaq (59–61), are laterally equivalent. Indeed, their basalts are compositionally very similar although no single flows are correlatable and the TiO_2 developments up-section are different (Fig. 42).

In view of the probable lateral equivalence of the exposed parts of the Naqerloq Formation, we prefer to define them within the framework of one member only. We therefore extend the Arfertuarsuk Member *sensu* Larsen & Larsen (2010) to cover the entire Eocene

Fig. 63 The northern outlier of the Arfertuarsuk trachyte in the uppermost reaches of the Qooruusaq valley (Fig. 9, profile 67). The exposed trachyte is traced with **a solid white line**; it is black due to lichen coverage. The presumed total extent of the trachyte is indicated with a **dashed white line**. See text for descriptions. Note the flat country with almost no exposures in the background; this is part of the low-lying area in central western Svartenhuk Halvø seen in the digital elevation model (Fig. 9), where mapping was very difficult and some geological boundaries are only tentative or not placed at all. Photo: Kristian Svennevig.

succession on Svartenhuk Halvø and Skalø. The Sigguk member *sensu* Larsen & Larsen (2010) is discontinued.

Arfertuarsuk Member

New member

History. On the geological map 71 V.1 Nord Svartenhuk (Larsen & Grocott 1991), the Arfertuarsuk Member is shown in the area between Sigguk and Qooruusaq as the unit β3.3, and in the area between Maligissap Kuua and the Arfertuarsuk inlet as the unit β4. The trachyte flow is mapped as a separate, unlabelled unit.

Name. After the Arfertuarsuk inlet on south-western Svartenhuk Halvø.

Distribution. The Arfertuarsuk Member is present in the western part of Svartenhuk Halvø from Skalø in the north to the bottom of the Arfertuarsuk inlet in the south. The member has been mapped in the strongly faulted and tilted areas north-west of Arfertuarsuk and traced on aerial photographs on the Sigguk peninsula west of the Qooruusaq valley (Larsen & Grocott 1991). However, the formation is also present and sampled on Skalø and in the eastern Qooruusaq valley where the lower boundary was not sufficiently established to be shown on the map. Thus, the western part of the Skalø Member area (β3 on the map) includes many more areas with lavas of the Arfertuarsuk Member than shown. Our present best estimate of the distribution of the Arfertuarsuk Member is shown in Fig. 6.

Type section. **Arfertuarsuk** (profile 36b) north of the bottom of the Arfertuarsuk inlet. The profile runs across a ridge and follows the south-west side of a WNW–ESE-trending fault, changing midway to a WSW direction (Fig. 9; coordinates in Appendix 1). The lava succession is strongly tilted with dips around 20°SW and locally more, and the profile shown in Fig. 11 is composed of several parts. The profile contains a thick, mappable trachyte flow, the Arfertuarsuk trachyte, near the base of the Arfertuarsuk Member.

Reference section. **Sigguk** (profile 62). The lava pile here is unfaulted and flat-lying with a low dip to the east (Figs 11, 64). Lava flows of the Arfertuarsuk Member here concordantly overlie lava flows and a sediment horizon of the Skalø Member and extend from *c.* 360 m a.s.l. to the geodetic point at 643 m a.s.l. where a distinctly porphyritic flow occurs at the top of the profile. No trachyte flow is present.

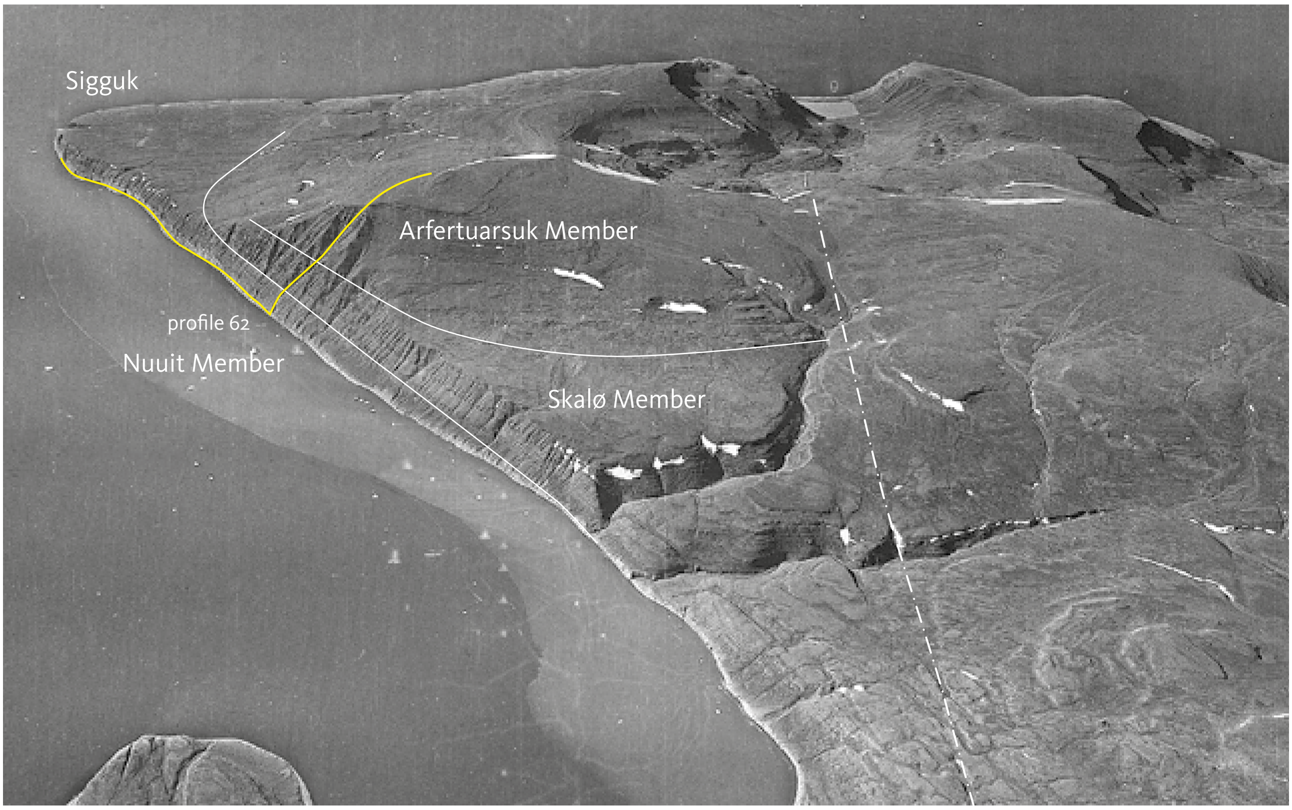

Fig. 64 Lava flows of the Paleocene Nuuit and Skalø Members of the Svartenhuk Formation conformably overlain by lava flows of the Eocene Arfertuarsuk Member of the Naqerloq Formation. Profile 62 is indicated with a **yellow line**. Western Svartenhuk Halvø with the point Sigguk (Svartenhuk) looking NW. Length of the coast from the foreground to Sigguk is 10 km. Dash-dot lines are faults. Geodetic Institute oblique aerial photograph 526GN/6272.

Fig. 65 The Arfertuarsuk trachyte flow exposed on the beach, east side of the northern end of the Arfertuarsuk inlet. Height of section *c*. 15 m. Photo: Karl Aage Jørgensen.

Thickness. The preserved thickness of the Arfertuarsuk Member is *c*. 300 m in the Sigguk area and more than 350 m in the area north of Arfertuarsuk.

Lithology. Basalts of the Arfertuarsuk Member are dominantly brownish sheet flows or compound pahoehoe flows, which are plagioclase ± olivine ± clinopyroxene glomerophyric or aphyric. A few flows with large (>1 cm) platy plagioclase phenocrysts are present at the top of the Sigguk profile. Sheet flows dominate in the Arfertuarsuk profile. Flows of the member are mostly glomerophyric, and one flow has box-shaped plagioclase phenocrysts several centimetres in size with reaction rims. Two olivine-plagioclase-phyric basalts are present, one of which is a compound flow. One lava flow with relatively high MgO (11 wt%) has ankaramitic affinity with only olivine and clinopyroxene phenocrysts. Aphyric basalts dominate the upper part of the profile. Several well-exposed tuff beds are present. A dark doleritic basalt flow is present near the top of the succession.

In the area north of the Arfertuarsuk inlet, a trachyte flow up to 40 m in thickness is present near the base of the Arfertuarsuk Member (Fig. 6). It is the only one of its kind in the region and is important for the stratigraphy of the member, as discussed in the previous section. It was first described and analysed by Nieland (1931), who showed it to be an anorthoclase trachyte. The flow is present for 12 km along the SE–NW strike direction (Larsen & Grocott 1991) and thins towards the north. A small erosional remnant is present 7 km farther north in another fault block in the southernmost Qooruusaq valley (Fig. 6), but except for this, the trachyte flow is missing north of Maligissap Kuua. The flow is well exposed on the coast at the northern end of the Arfertuarsuk inlet. It is composed of several units, of which the basal unit is a more or less welded and devitrified vitrophyre that may be classified as a rheomorphic ignimbrite (Jørgensen 1982). The major part of the trachyte is a more normal, massive flow (Fig. 65); it is rich in anorthoclase crystals up to several centimetres in size; these large phenocrysts are dotted with dark inclusions in a sieve-texture. Microphenocrysts of pale brown clinopyroxene and magnetite are present, and the medium-grained groundmass is very rich in alkali feldspar. The flow contains up to cobble-sized xenoliths of intermediate igneous rock types (sample 278668.1) and syenite (sample 278669.2; Fig. 66). The trachyte outlier in Qooruusoq contains several 2–6 cm-sized, irregular, fine-grained, dark grey inclusions of extremely evolved composition (sample 568601.2 in Fig. 67; see the Geochemistry chapter). A fine-grained, dark grey vein cutting the trachyte (Fig. 68) likely consists of similar material.

Eruption sites. None have been found.

Chemistry and chemostratigraphy. The Arfertuarsuk Member comprises tholeiitic basalts with 3.8–8.6 wt% MgO and an average of 5.8 wt% MgO. TiO_2 is in the range 1.8–4.0 wt%, and the average TiO_2 content is 3.0 wt%. K_2O and P_2O_5 contents are high, with on average 0.80 wt% K_2O and 0.39 wt% P_2O_5. The Arfertuarsuk Member basalts are also enriched in other incompatible elements such as Sr, Ba, Zr, Nb and light REE, and element ratios such as P_2O_5/TiO_2, Ba/Sr, Zr/Y, Nb/Y, Nb/Zr, Nb/La, La/Sm and Gd/Lu are significantly increased relative to basalts of the Svartenhuk Formation. Representative analyses are given in the Geochemistry chapter.

The trachyte flow contains on average 65.7 wt% SiO_2, 0.83 wt% TiO_2, 0.24 wt% MgO, 16.4 wt% Al_2O_3, 6.1 wt% Na_2O and 5.2 wt% K_2O.

A group of less evolved basalts with low TiO_2 (around 2 wt%) and P_2O_5 (around 0.25 wt%) and with the same enriched geochemical character as the more evolved basalts of the member is clearly distinguished in the chemistry diagrams (see the Geochemistry chapter). As explained in the earlier section on the Naqerloq Formation on Svartenhuk Halvø, these basalts occur below the trachyte flow in the Arfertuarsuk area and are used to define an interpreted trachyte level in the northern areas (Sigguk and Qooruusaq profiles).

According to our interpretation, the analysed sample profiles through the Eocene basalts from the northern and the southern areas, mainly the Sigguk, Qooruusaq and Arfertuarsuk profiles (62, 61, 36b), are nearly laterally equivalent (Figs 11, 42). They are geochemically similar but do not show any obvious mutual correlation.

Boundaries. The lower boundary is depositional and is placed at the base of a succession of brown lava flows of geochemically enriched basalts and above a volcaniclastic sediment horizon 5–20 m in thickness included in the Skalø Member. The upper boundary is erosional.

Geological age. Eocene (earliest Ypresian), perhaps reaching back into the uppermost Paleocene. Two radiometric ($^{40}Ar/^{39}Ar$) age determinations of basalts yielded ages of 55.91 ± 0.60 Ma and 54.86 ± 0.44 Ma (Larsen *et al*. 2016), and one of the Arfertuarsuk trachyte flow yielded an age of 55.31 ± 1.09 Ma (Chauvet *et al*. 2019). See Table 4 and the corresponding text for a discussion of the age of the trachyte.

Correlation. The Arfertuarsuk Member was erupted in a similar time interval (57–54 Ma) and has the same geochemical character as the Nûk takisôq Member on Ubekendt Ejland and the Kanísut Member on Nuussuaq and Hareøen, and is thus in a general way correlatable with these.

Fig. 66 Feldspar-rich xenolith, probably cognate, of syenite in the Arfertuarsuk trachyte flow. Length of steel rod 16 cm. East side of the northern end of the Arfertuarsuk inlet. Photo: Karl Aage Jørgensen.

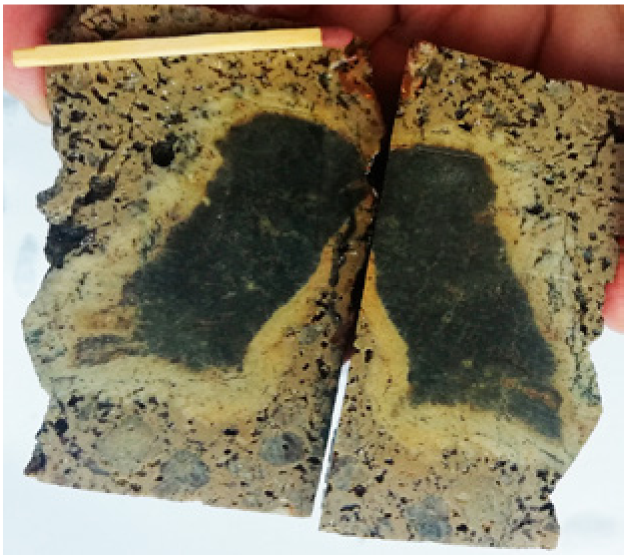

Fig. 67 Fine-grained, dark grey inclusion in trachyte from the outlier in Qooruusaq, cut into two. The inclusion is surrounded by a light-coloured rim almost exclusively of coarse alkali feldspar; contrary to intuition the dark central part consists of about as much feldspar as the rim; the major difference is the grain size. The analysis (278669.2) represents the dark part. Length of match 4.7 cm. Photo: Erik Vest Sørensen.

Fig. 68 Fine-grained, dark grey vein cutting the Arfertuarsuk trachyte flow. East side of the northern end of the Arfertuarsuk inlet. Length of hammer 45 cm. Photo: Karl Aage Jørgensen.

Intrusions

Svartenhuk Halvø is cut by numerous dykes. The dyke distribution map in Fig. 69 from Larsen & Pulvertaft (2000) shows the distribution and directions of dykes as identified on aerial photographs. The map gives an overall impression of dyke patterns, but as stressed by these authors, dykes are much easier to locate in the areas with crumbling picrites of the Vaigat Formation than in the areas with robust basalt flows of the Svartenhuk and Naqerloq Formations. The relative sparsity of dykes located in the basalt areas in central and western Svartenhuk Halvø may therefore not be real. The dykes extend north to Skalø and southern Innerit and also cut the basement and volcanic rocks north-east of the Cretaceous boundary fault system, but they quickly die out to the north and east where reconnaissance work revealed very few dykes. The dyke distribution pattern,

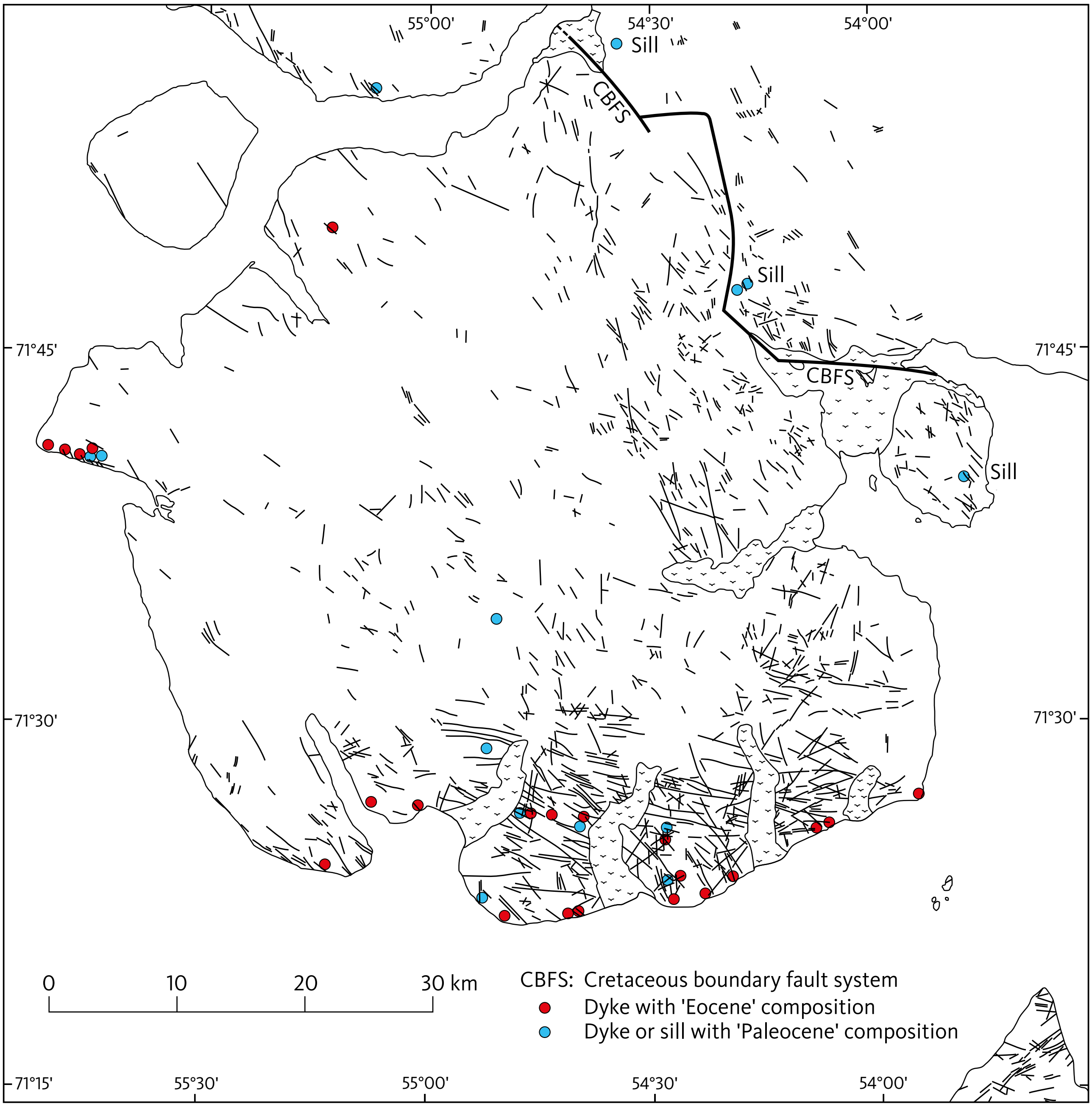

Fig. 69 Distribution and directions of dykes on Svartenhuk Halvø as identified on aerial photographs, from Larsen & Pulvertaft (2000, fig. 4). The relative sparsity of dykes in the basalt areas in central and western Svartenhuk Halvø may not be real, see text for explanation. We have added the locations of analysed basalt dykes and sills of two different compositional groups that are supposed to represent two age groups, as indicated in the legend. Analytical data from this study and Agranier *et al*. (2019).

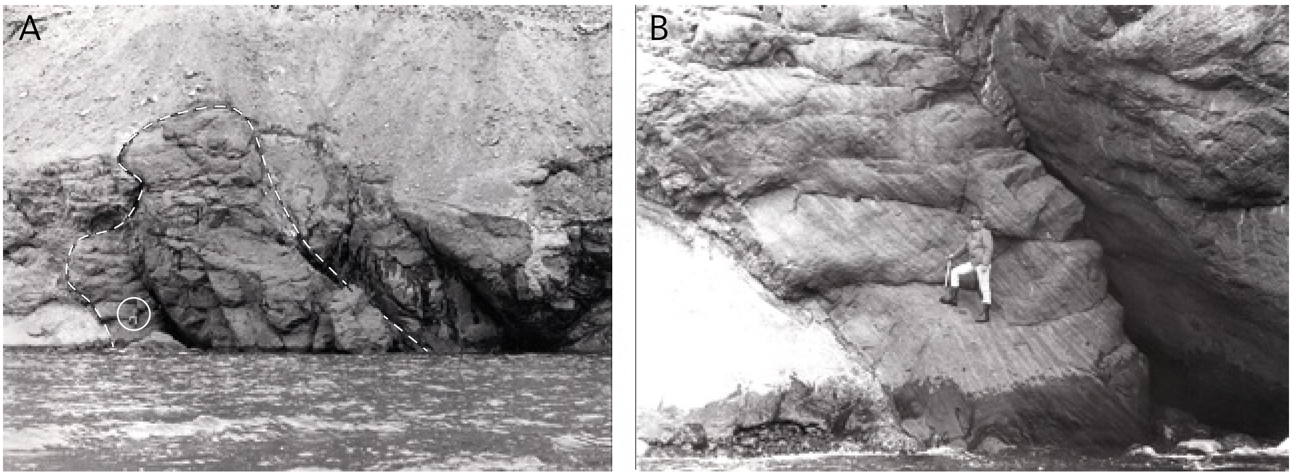

Fig. 70 An intrusion of magnesian basalt into lava flows of the Tunuarsuk Member. **A**: The entire exposure, showing the cupola-like shape. **B**: The chilled marginal zone with contact-parallel mineral layering. The person (encircled in A) is standing in the same place in both photos. South coast of Svartenhuk Halvø *c*. 3.5 km south of Tasiusap Imaa; the intrusion is shown with a size of 1 × 0.5 mm on the geological map (Larsen 1983).

including the scarcity of Tertiary dykes in the northern and eastern areas, confirms the impression gained from the hyaloclastites and lava flows that eruption sites were centred in the basinal areas, from where the lavas flowed to the north and east over distances of up to 80 km for the most voluminous flows.

Larsen & Pulvertaft (2000) presented a detailed structural analysis of the dyke orientations and concluded that several dyke generations are present. The dykes comprise picrites and feldspar-phyric and aphyric basalts petrographically similar to the lava flows, and their chemical compositions (see the Geochemistry chapter) comply with the assumption of Larsen & Pulvertaft (2000) that many dykes are feeders to the lava flows. Accordingly, the dykes most commonly have dips perpendicular to the lava flows, which they cut (e.g. Figs 15, 16, 37), and the fault zones are generally not intruded by dykes. Feeder dykes and eruption sites for all three members of the Vaigat Formation have been identified in the field and confirmed chemically. In contrast, eruption sites for the Svartenhuk Formation have rarely been observed, and none are known for the Naqerloq Formation.

Picrite dykes and strongly contaminated dykes similar to the Kakilisaat Member are only found in the areas of the Vaigat Formation, whereas basaltic dykes are found all over Svartenhuk Halvø.

As described in the Geochemistry chapter, the basaltic dykes form two groups with compositions corresponding to those of respectively the Svartenhuk and Naqerloq Formations. This enables us to distinguish between basalt dykes of presumed Paleocene age (Svartenhuk Formation) and of presumed Eocene age (Naqerloq Formation) and thus to confirm the presence of at least two distinct dyke generations. Our analysed dykes with Naqerloq Formation chemistry are all situated in the Svartenhuk Formation in western Svartenhuk Halvø, but Agranier *et al*. (2019) published analyses of samples with Naqerloq Formation chemistry from areas in the Vaigat Formation along the entire south coast of Svartenhuk Halvø from Tartuusaq to Maniiseqqut (Fig. 69). This suggests that the Eocene lava succession originally extended much farther eastwards on the continent than the present outcrops, as also found for Nuussuaq and Disko (Larsen *et al*. 2016; Pedersen *et al*. 2018). Unfortunately, dyke compositions are unknown in large areas, but it should be possible to map the true distribution of both the Eocene and the Paleocene dykes by analysing a larger number of dyke samples distributed over the Svartenhuk Halvø. Additionally, even younger dykes may be identified if they are compostionally different from the older lavas and dykes.

The Cretaceous boundary fault system has apparently facilitated the intrusion of magmas, as seen from a number of large basalt sills intruded close to the fault at Simiutaq, along the Siuteqqut Kuuat valley, near Firefjeld and on Itsaku (Fig. 6). These sills are compositionally identical to the Svartenhuk Formation and we therefore consider that they are also of late Paleocene age.

A small intrusion of magnesian basalt is exposed at sea level on the south coast of Svartenhuk Halvø *c*. 3.5 km south of Tasiusap Imaa (Fig. 70). It has a cupola-like structure and is *c*. 20 m wide and 25 m high. It intrudes lava flows of the Tunuarsuk Member and has a similar chemical composition (10.8 wt% MgO, sample 164863). It is chilled towards the lavas in a *c*. 5 m wide zone, which has a distinct layering with decimetre-thick, alternating light and dark layers parallel to the contact.

A few alkaline dykes (alkali basalt and camptonite) are found on the south coast of Svartenhuk Halvø (Larsen 1983; L.M. Larsen 2006). The ages of these dykes are not known and they could be very young. The youngest dykes identified in the region are *c*. 34 Ma old camptonite and monchiquite dykes from Ubekendt Ejland (Larsen 1981c, 1982; Clarke *et al*. 1983; Storey *et al*. 1998).

Geochemistry and petrology of the volcanic rocks

Identification of crustal contamination and geochemical enrichment

The volcanic rocks in the Nuussuaq Basin consist predominantly of tholeiitic basalts and picrites such as those generated by melting of common asthenospheric mantle (e.g. McKenzie & Bickle 1988). However, as mentioned frequently in this study and defined in the Nomenclature section, there are also rocks, which are considered to be contaminated with continental crustal material, as well as geochemically enriched rocks with elevated contents of a number of incompatible elements. Identification of the two rock groups is best achieved using trace-element ratios. A diagram showing Th/Nb vs. Nb/Zr is particularly useful because the crustal-contamination and enrichment vectors are perpendicular to each other (Fig. 71). In this figure crustally contaminated samples generally have Th/Nb >0.12, whereas most enriched samples have Nb/Zr >0.10. Small degrees of crustal contamination and enrichment are difficult to detect.

In the Vaigat Formation (Fig. 71A) the Kakilisaat Member is clearly crustally contaminated, and the extension of the plot field towards the enriched components indicates that some samples are also enriched. The Nerutusoq Member is enriched but not crustally contaminated. Fig. 71B shows that the Svartenhuk Formation basalts analysed for trace elements are generally uncontaminated although a number of samples have Th/Nb *c*. 0.12 and may perhaps be slightly crustally contaminated. There is a trail of enriched samples towards the enriched component field; one sample (262713) has high Th/Nb (0.16) and low Nb/Zr (0.09) and is both contaminated and enriched. The enriched character of the Naqerloq Formation is clearly seen.

Vaigat Formation

The volcanic rocks of the Vaigat Formation on Svartenhuk Halvø comprise tholeiitic picrites and subordinate basalts. Major element variation diagrams for the Vaigat Formation are shown in Fig. 72, trace- element variation diagrams in Figs 73 and 74, and REE and multi-element plots in Fig. 75. These figures are designed to be comparable with the similar geochemistry diagrams for the Vaigat Formation on Disko and Nuussuaq in Pedersen *et al*. (2017). Representative chemical analyses are shown in Table 5.

Nunavik Member

The Nunavik Member is described first because it constitutes the bulk and 'normal' part of the Vaigat Formation in the area. The two other members are considered to be derived from magmas similar to those of the Nunavik Member with some additions of material from the crust and upper mantle.

The Nunavik Member is dominated by picrites. The total MgO range is 6.4–29.8 wt% MgO, and the average

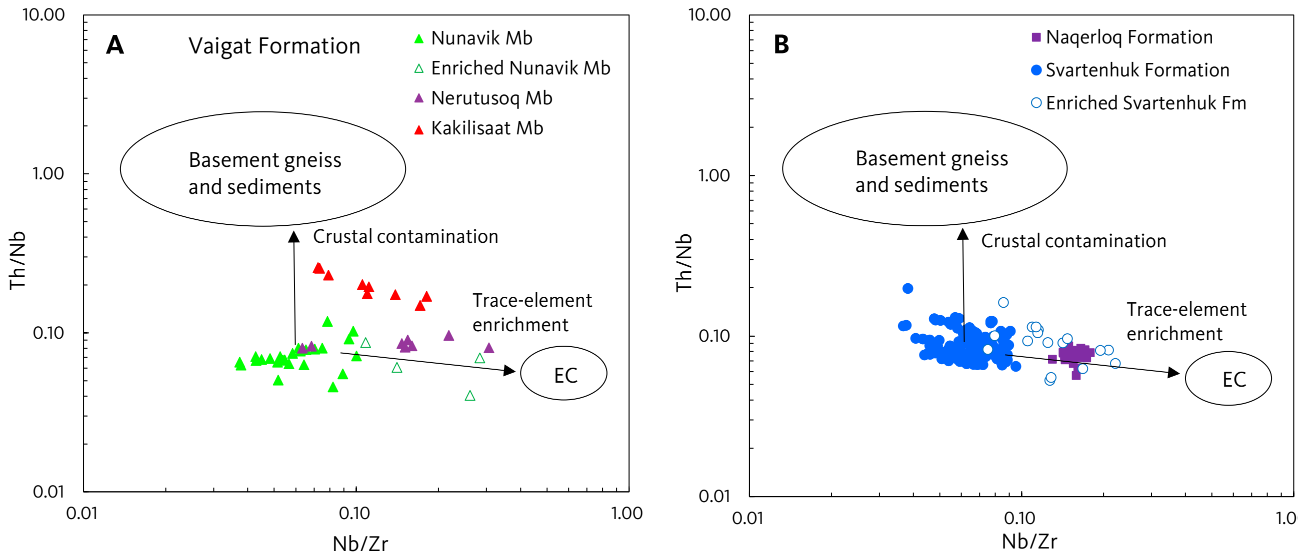

Fig. 71 Th/Nb vs. Nb/Zr diagram showing discrimination between crustally contaminated and geochemically enriched samples. **A**: Vaigat Formation. **B**: Svartenhuk and Naqerloq Formations. The crustal contamination vector points upwards because basement gneiss and sediments have high Th/Nb, whereas the enrichment vector points towards enriched components (**EC**) with high Nb/Zr. Data for basement gneiss and sediments from Larsen & Pedersen (2009). The EC field represents a number of presumed local enriched components.

MgO content of 130 analyses is 17.5 wt% MgO, which is probably not far from the parental magma composition (Larsen & Pedersen 2000, 2009; Herzberg & O'Hara 1998, 2002; Herzberg *et al*. 2007). The well-defined trends, particularly in the major-element diagrams (Fig. 72), are caused by olivine fractionation and accumulation, as already noted by Clarke (1970). When the fractionating magma reached 7–8 wt% MgO, plagioclase started to crystallise, which removed CaO and Al_2O_3 from the magma. Figure 72 shows that most of the magmas of the Nunavik Member did not reach the stage of plagioclase fractionation, with the βo2 basalt marker flow near the top of the member as an exception (6.4 wt% MgO, 13.6 wt% Al_2O_3, 10.6 wt% CaO and 2.9 wt% TiO_2). A couple of samples with low CaO also have high SiO_2 and are crustally contaminated. Relatively scattered K_2O contents are due to secondary alteration.

With some exceptions, the rocks have a relatively depleted geochemical character, meaning that they have low contents of incompatible elements. The incompatible trace elements (Figs 71, 73, 75) show a general increase with increasing fractionation. A few scattered flows are enriched in some elements (Rb, Ba, Sr, Zr, Nb, REE and U); these flows are not distinguishable by their major elements but are clearly distinguished in the trace-element diagrams (Figs 71, 73, 75). The dark marker horizon βo1 in the Nunavik Member has a Nb/Zr ratio of 0.26–0.28 and is one of the most enriched flows of all (Fig. 71); the two samples analysed from βo1 are situated *c*. 15 km apart.

The only trace elements that are fractionated out of the picrite magmas are Ni and Co in olivine and Cr in chromite (Fig. 74).

The low contents of incompatible elements in the common rocks of the Nunavik Member are reflected in the REE and multi-element patterns in Fig. 75. Most REE patterns for the Nunavik Member have chondrite-normalised (with subscript $_N$) La_N <Sm_N so that the La–Sm limbs have positive slopes, giving the patterns an overall humpback-like shape. Likewise, the multi-element patterns have Rb–La limbs with positive slopes. However, some samples have La_N ≥Sm_N and near-horizontal to negative slopes of the La–Sm and Rb–La limbs. The deep troughs at K and Pb are characteristic of asthenosphere-derived magmas from the North Atlantic Tertiary Igneous Province (e.g. Saunders *et al*. 1997).

The distribution of La_N/Sm_N ratios of the Nunavik Member, with most samples having values less than 1 and some samples having values above 1 (see also Fig. 83), is similar to that found in the Ordlingassoq Member of the Vaigat Formation on Nuussuaq and Disko (Larsen & Pedersen 2009; Pedersen *et al*. 2017; see also contour line for the Ordlingassoq Member in Fig. 83). In contrast, the earlier members of the Vaigat Formation (the Anaanaa and Naujánguit Members) have La_N/Sm_N consistently less than 1 and are thus somewhat more geochemically depleted than the Ordlingassoq and Nunavik Members. This is a key feature in the correlation of the last-named members.

Nerutusoq Member

The Nerutusoq Member consists of basalts with 8–12 wt% MgO, normal SiO_2 contents of 48–49 wt% and relatively high contents of CaO (12–13.6 wt%; Fig. 72). The rocks have distinctly high P_2O_5 (0.20–0.32 wt%) and are also enriched in incompatible elements such as Ba, Th, U, Nb, light REE, Pb and Sr relative to the Nunavik Member rocks (Figs 72, 73, 75). The patterns of enrichment in the Nerutusoq Member lack the high Nb–Ta peak and the deep Pb trough seen in the enriched rocks of the Nunavik Member, suggesting that the sources of the enrichment for the two members are different. Our analysed samples from the Nerutusoq Member are not crustally contaminated; however, Agranier *et al*. (2019) reported contaminated, enriched samples presumably from this member (their Site 40). It is thus possible that small degrees of crustal contamination have contributed to the differences in enrichment pattern between the two members. The Nerutusoq Member shows notable similarities to some enriched rock units on Nuussuaq and Disko (Larsen *et al*. 2003; Larsen & Pedersen 2009; Pedersen *et al*. 2017).

Kakilisaat Member

The Kakilisaat Member consists of silicic basalts, basaltic andesites and a few Si-enriched picrites; MgO is in the range 6–13 wt%. The rocks have elevated SiO_2, K_2O, Rb, Ba, Th, U, light REE and Pb, and low MgO, CaO, TiO_2, FeO* (total iron as FeO), V, Cu and Ni relative to the rocks of the Nunavik Member (Figs 72–75). These features are typical for rocks that are contaminated with continental crustal material, either crystalline basement or clastic sediments (e.g. Larsen & Pedersen 2009; Pedersen *et al*. 2018). The occurrence of sediment xenoliths in the volcanic rocks suggests that the contamination took place in high-level magma chambers in the crust, presumably within the sediments of the Nuussuaq Basin. The low contents of V, Cu, Ni and Co (Fig. 74) indicate a possibility that the contamination process may have resulted in the formation at depth of mineral deposits with these elements. The relatively high Nb contents (Fig. 73) suggest that the original magmas had a somewhat enriched character akin to that of the Nerutusoq Member. The rocks of the Kakilisaat Member show compositional similarities to the crustally contaminated basalts of the Tunoqqu and Kûgánguaq Members on Nuussuaq and Disko (Larsen & Pedersen 2009; Pedersen *et al*. 2017).

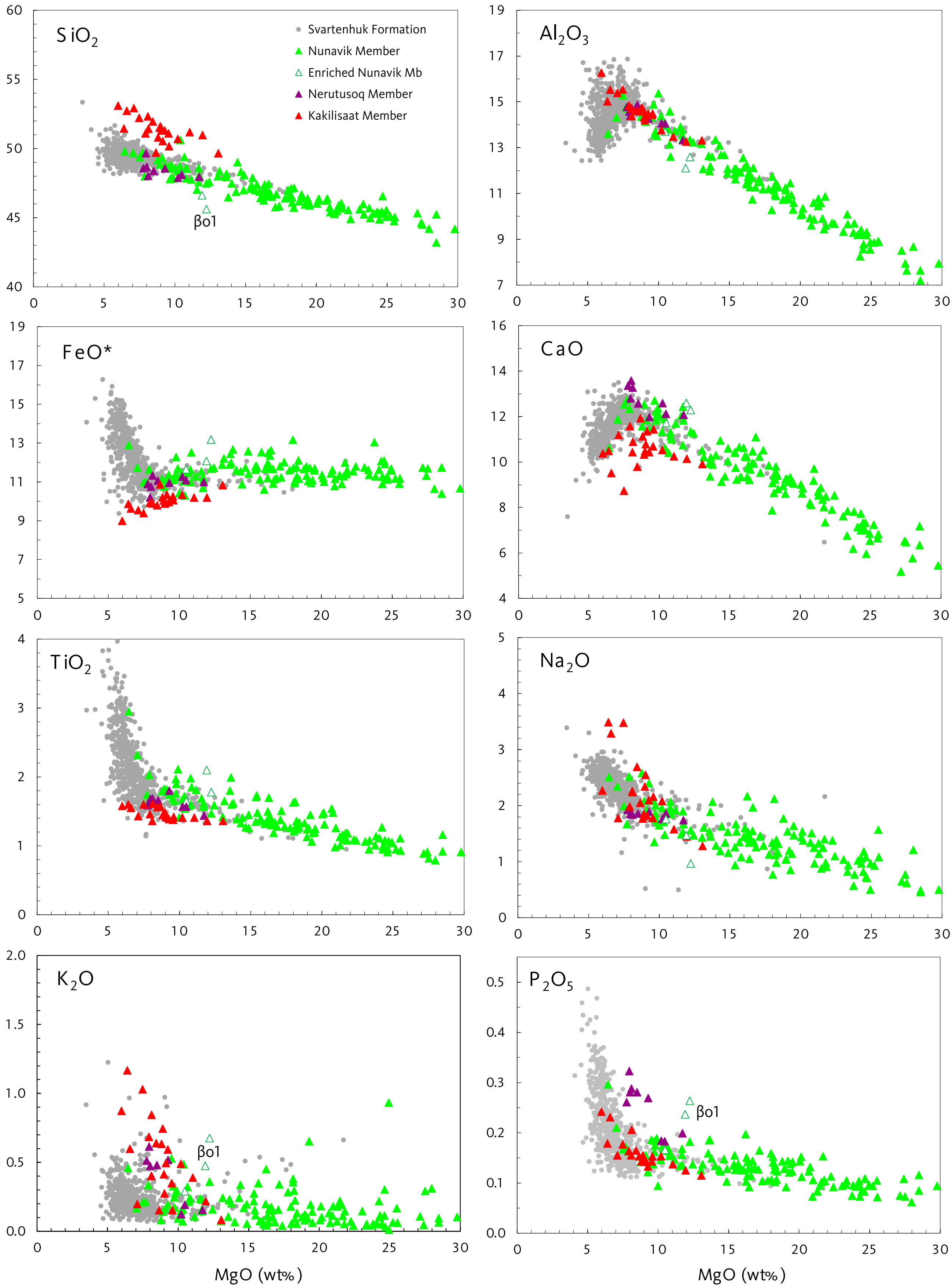

Fig. 72 Major-element variation diagrams for rocks of the Vaigat Formation. Note the MgO-rich character of the Nunavik Member, the high CaO and P_2O_5 in the Nerutusoq Member and the high SiO_2 and low FeO* and CaO in the crustally contaminated Kakilisaat Member. **βo1** is a marker horizon in the Nunavik Member. Data points for the Svartenhuk Formation are shown in grey for comparison. Data in wt% oxides.

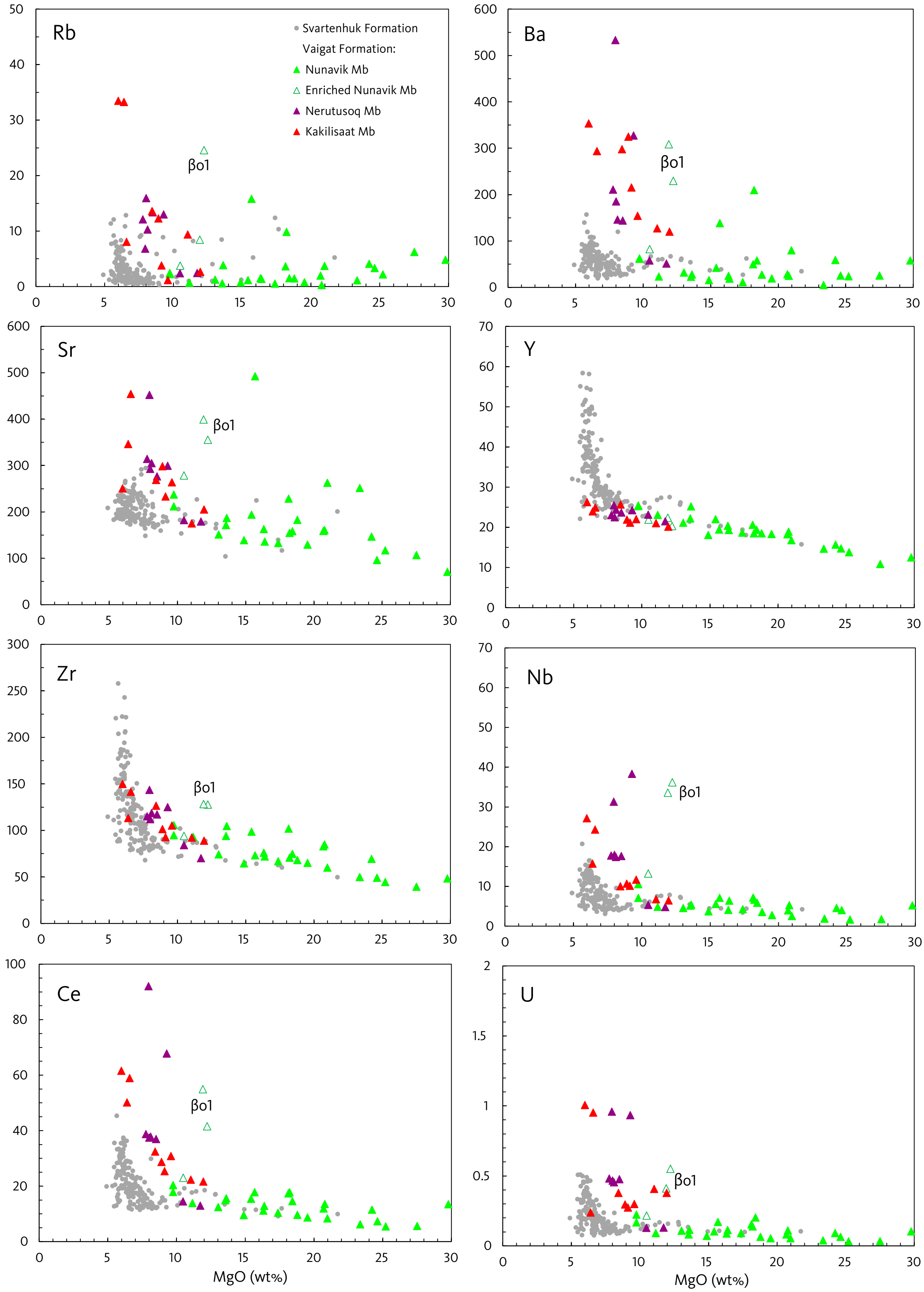

Fig. 73 Incompatible trace-element variation diagrams for rocks of the Vaigat Formation. The Nunavik Member has low concentrations of these elements, but scattered lavas are enriched in Sr, Nb, Ba and Ce, akin to the Nerutusoq Member. The marker horizon **βo1** has a unique, very enriched composition. The crustally contaminated Kakilisaat Member has unusually high Nb, suggesting that some of these magmas are enriched in addition to being contaminated. Data points for the Svartenhuk Formation are shown in grey for comparison. Vertical axes in ppm.

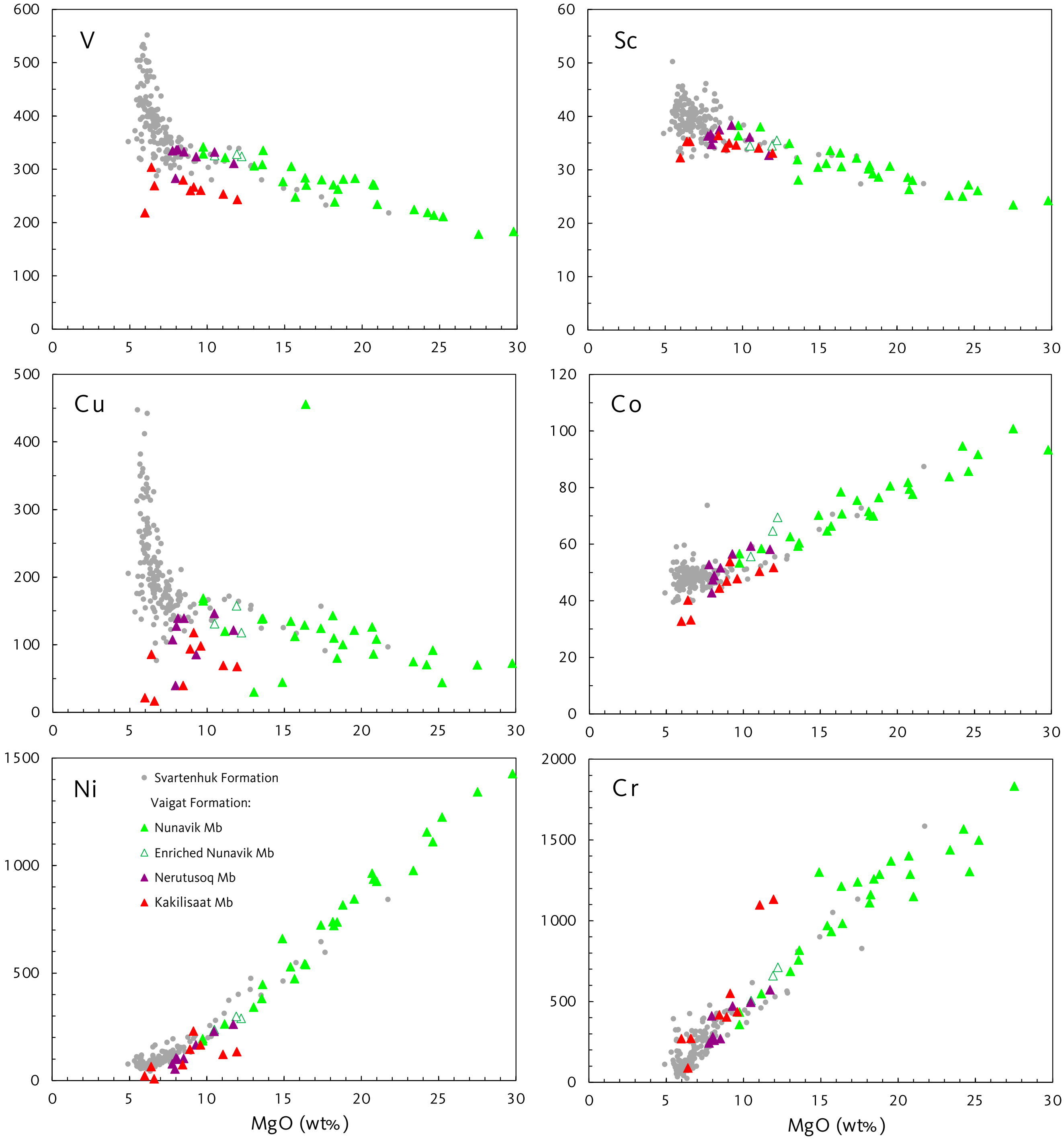

Fig. 74 Transition-element variation diagrams for rocks of the Vaigat Formation. Note the apparent loss of V, Cu, Co and Ni in the Kakilisaat Member. Data points for the Svartenhuk Formation are shown in grey for comparison. Vertical axes in ppm.

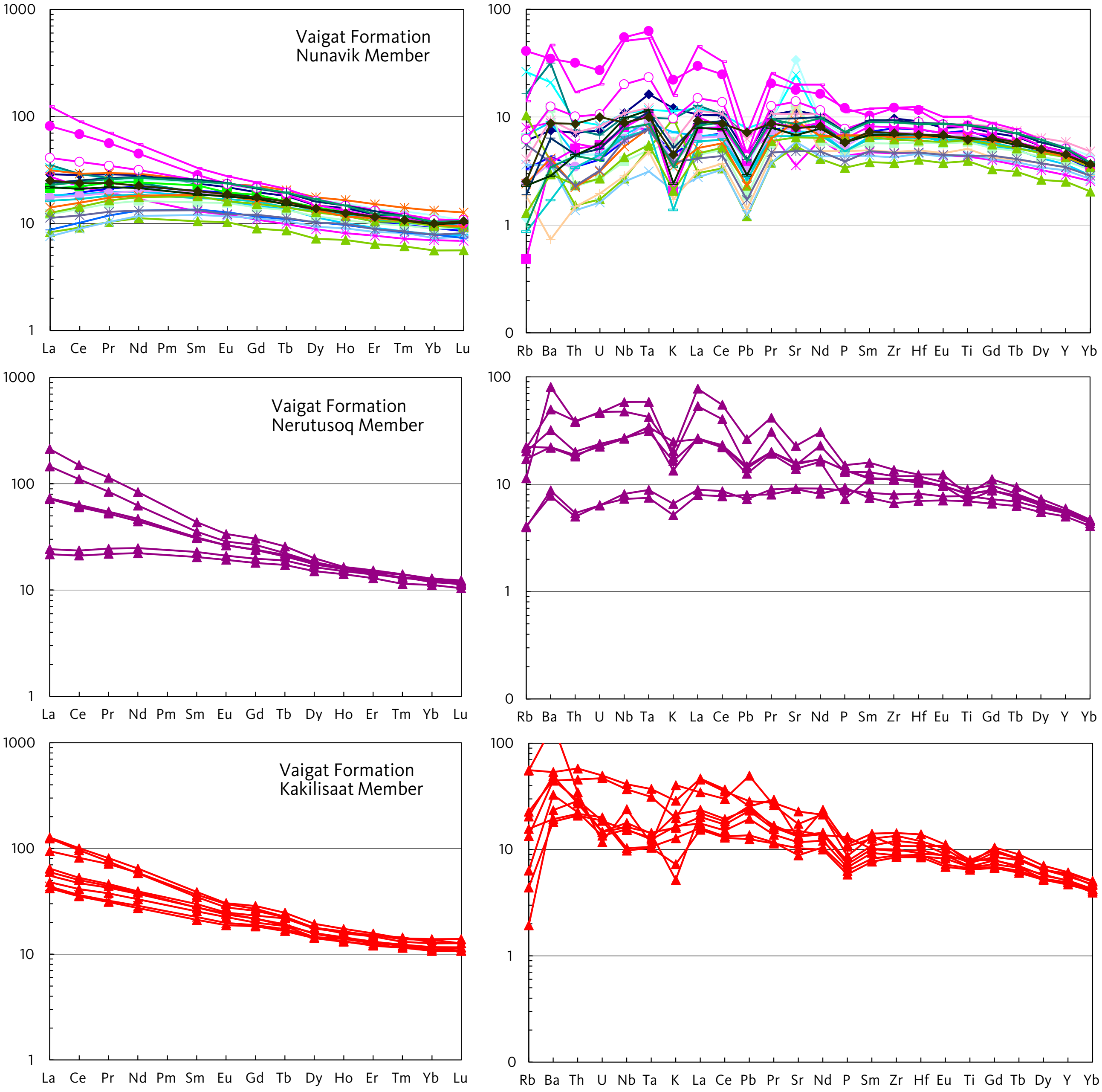

Fig. 75 REE and multi-element diagrams for representative rocks of the Vaigat Formation. Different colours of curves in the Nunavik Member diagrams are intended to aid the distinction of the individual samples. The magenta samples in the Nunavik Member are incompatible-element-enriched; the two with the highest values are from the βo1 marker horizon. **Left** diagrams: chondrite normalised. **Right** diagrams: primitive mantle normalised. Normalisation factors from McDonough & Sun (1995).

Table 5 Chemical analyses of rocks from the Vaigat Formation

Member	**Kakilisaat Member**						**Nerutusoq Member**					
GGU no.	**181015**	**181019**	**181022**	**181037**	**181073**	**181075**	**263818**	**181077**	**263822**	**263823**	**181013**	**263821**
Profile no.	4	4	4	-	13	13	48b	13	48b	48b	4	48b
Name	Kakilisaat	Kakilisaat	Kakilisaat	Saviit Qaq.	Saviit S.	Saviit S.	Nerutusoq	Saviit S.	Nerutusoq	Nerutusoq	Kakilisaat	Nerutusoq
	Major elements in wt% (XRF analyses)											
SiO_2	48.87	49.11	49.88	50.42	48.97	50.55	46.20	46.93	46.67	46.34	47.71	47.64
TiO_2	1.30	1.39	1.41	1.51	1.52	1.50	1.39	1.74	1.60	1.63	1.61	1.56
Al_2O_3	12.71	14.19	14.19	14.19	14.30	15.49	12.84	13.79	14.35	14.20	14.01	14.50
Fe_2O_3	4.42	3.22	2.39	2.62	3.38	1.42	3.23	4.73	4.58	4.89	4.63	3.34
FeO	5.80	6.95	7.57	7.15	6.35	7.28	7.69	6.33	6.56	6.53	5.64	7.69
MnO	0.20	0.24	0.20	0.20	0.20	0.20	0.22	0.29	0.17	0.17	0.20	0.19
MgO	11.46	9.39	8.63	8.19	6.09	5.69	11.29	8.98	8.20	7.82	7.64	7.62
CaO	9.72	11.20	10.00	9.50	9.98	9.88	11.64	11.57	12.14	12.80	12.30	13.11
Na_2O	1.39	2.11	1.79	2.61	3.32	2.16	1.68	1.83	1.79	1.78	1.78	1.88
K_2O	0.21	0.15	0.72	0.62	1.11	0.83	0.15	0.50	0.46	0.39	0.59	0.50
P_2O_5	0.12	0.15	0.15	0.16	0.17	0.23	0.19	0.26	0.27	0.28	0.31	0.26
Volatiles	3.03	1.78	3.05	2.53	3.53	3.95	3.65	2.54	3.25	2.93	2.12	1.70
Sum	99.23	99.88	99.98	99.70	98.92	99.18	100.17	99.49	100.04	99.75	98.54	99.99
FeO*	9.78	9.85	9.72	9.51	9.39	8.56	10.60	10.59	10.68	10.93	9.81	10.70
mg-no.	70.34	65.85	64.24	63.53	56.74	57.36	68.31	63.18	60.83	59.14	61.18	59.03
	Trace elements in ppm (ICP-MS analyses)											
Sc	33.1	34.6	34.1	36.4	35.3	32.3	32.7	38.3	37.5	35.9	36.7	36.3
V	243	260	260	280	304	219	311	324	333	337	283	335
Cr	1134	436	405	418	88.1	269	572	471	271	260	411	243
Co	51.8	47.8	47.0	44.4	40.2	32.8	58.2	56.6	51.7	48.9	42.8	52.8
Ni	134	165	146	74.1	64.4	22.6	262	166	103	99.5	54.0	77.86
Cu	67.6	98.2	93.8	39.7	86.0	21.5	122	85.3	139	139	39.7	107
Zn	73.5	95.9	73.6	80.7	68.5	76.1	89.0	71.4	88.9	88.6	75.4	76.0
Ga	17.7	18.2	18.4	18.1	17.8	21.3	21.0	19.1	21.5	22.0	20.7	24.0
Rb	2.64	1.16	12.3	13.6	33.2	33.5	2.44	13.0	13.4	10.3	6.81	12.1
Sr	205	264	298	269	346	251	179	299	276	305	452	314
Y	20.2	22.1	21.9	25.7	24.0	26.3	21.5	24.3	23.7	24.4	25.5	23.0
Zr	89.0	105	101	127	113	150	70.1	125	117	119	143	115
Nb	6.45	11.7	10.7	10.0	15.8	27.13	4.80	38.3	17.7	17.4	31.3	17.8
Cs	0.009	0.027	0.157	0.067	0.119	0.773	0.041	0.102	0.041	0.193	0.033	0.218
Ba	120	154	325	298	984	354	51.5	328	144	146	533	211
La	10.0	14.2	13.1	15.3	22.4	30.2	5.15	34.6	17.1	17.4	50.4	17.3
Ce	21.6	30.9	28.7	32.5	50.2	61.6	13.0	67.8	37.0	37.8	92.1	38.8
Pr	2.90	4.09	3.95	4.28	6.62	7.51	2.04	7.82	4.88	5.07	10.6	5.09
Nd	12.5	17.5	17.0	18.0	26.9	29.5	10.2	28.6	20.3	21.4	38.3	21.2
Sm	3.12	4.10	4.10	4.41	5.40	5.73	3.02	5.26	4.54	4.59	6.45	4.66
Eu	1.06	1.36	1.33	1.39	1.68	1.72	1.09	1.61	1.49	1.49	1.90	1.49
Gd	3.65	4.31	4.33	4.62	5.35	5.69	3.59	5.30	4.74	4.77	6.06	4.79
Tb	0.598	0.692	0.675	0.788	0.815	0.891	0.622	0.807	0.747	0.777	0.932	0.766
Dy	3.50	3.84	3.90	4.31	4.37	4.76	3.70	4.51	4.31	4.49	4.90	4.28
Ho	0.717	0.769	0.787	0.880	0.897	0.947	0.771	0.884	0.886	0.879	0.902	0.862
Er	1.97	2.12	2.10	2.43	2.39	2.51	2.07	2.34	2.28	2.40	2.46	2.30
Tm	0.284	0.292	0.305	0.342	0.357	0.349	0.283	0.347	0.320	0.346	0.348	0.323
Yb	1.79	1.87	1.87	2.20	2.08	2.24	1.80	2.06	2.00	2.04	2.06	2.08
Lu	0.268	0.286	0.286	0.312	0.312	0.342	0.256	0.304	0.276	0.287	0.302	0.296
Hf	2.39	2.59	2.78	3.22	3.05	3.94	1.98	3.38	2.93	3.01	3.49	3.10
Ta	0.384	0.522	0.531	0.478	0.424	1.37	0.277	2.17	1.27	1.26	1.56	1.15
Pb	1.87	3.85	3.49	3.62	7.42	3.81	1.19	2.19	1.88	2.11	3.95	2.21
Th	1.66	2.28	2.15	2.31	2.74	4.60	0.396	3.09	1.44	1.49	3.02	1.60
U	0.379	0.299	0.296	0.378	0.238	1.007	0.130	0.934	0.477	0.455	0.959	0.481

FeO*= total iron calculated as FeO.

mg-number = 100 × atomic Mg/(Mg+Fe^{2+}), with the iron oxidation ratio adjusted to Fe_2O_3/FeO = 0.15.

For notes on the samples, see next pages.

Table 5 (continued) Chemical analyses of rocks from the Vaigat Formation

Member	**Nunavik Member**											
GGU no.	**181066**	**181067**	**251515**	**251525**	**251529**	**278353**	**181085**	**251589**	**278354**	**251527**	**251588**	**181056**
Profile no.	24	24	9	9	9	44c	14	30	44c	9	30	24
Name	Pk 1120	Pk 1120	Pk 1078	Pk 1078	Pk 1078	Kuugartorf.	Saviit N.	Iviss. Itinn.	Kuugartorf.	Pk 1078	Iviss.Itinn.	Pk 1120
	Major elements in wt% (XRF analyses)											
SiO_2	42.73	43.18	45.55	45.10	45.21	45.92	45.16	45.87	45.68	43.16	46.46	47.40
TiO_2	0.79	0.91	1.45	1.23	1.30	1.24	1.39	1.68	1.35	1.68	1.59	1.92
Al_2O_3	7.34	8.48	9.44	10.41	10.50	10.98	11.33	11.26	12.54	11.91	13.20	13.24
Fe_2O_3	2.38	3.00	3.59	3.52	2.15	2.49	4.93	4.43	5.05	6.28	3.48	6.60
FeO	9.08	7.99	8.18	8.32	9.49	8.63	7.03	7.48	6.77	6.82	8.10	5.04
MnO	0.22	0.21	0.17	0.17	0.17	0.17	0.22	0.17	0.19	0.22	0.17	0.23
MgO	26.42	24.14	20.41	19.19	18.39	17.95	15.77	14.94	12.40	11.57	10.10	9.51
CaO	6.21	6.93	7.98	8.90	8.76	8.58	9.53	9.45	10.01	11.63	11.29	11.94
Na_2O	0.60	0.89	1.48	1.44	1.73	1.29	1.37	1.62	1.36	0.92	1.70	1.82
K_2O	0.28	0.06	0.06	0.06	0.10	0.13	0.11	0.15	0.07	0.64	0.28	0.24
P_2O_5	0.07	0.09	0.13	0.14	0.14	0.12	0.11	0.15	0.12	0.25	0.16	0.18
Volatiles	3.78	3.68	1.76	1.71	2.00	2.32	2.70	2.76	4.59	5.51	3.73	1.72
Sum	99.89	99.55	100.20	100.19	99.94	99.82	99.65	99.96	100.13	100.59	100.26	99.84
FeO*	11.22	10.69	11.41	11.49	11.42	10.87	11.47	11.47	11.31	12.47	11.23	10.98
mg-no.	82.64	82.04	78.35	77.17	76.50	76.96	73.56	72.49	68.91	65.25	64.53	63.66
	Trace elements in ppm (ICP-MS analyses)											
Sc	23.4	26.1	26.3	30.7	28.7	29.3	33.2	31.2	34.9	35.5	34.5	38.3
V	178	211	271	283	282	262	284	306	306	324	326	329
Cr	1834	1499	1287	1370	1287	1258	1214	971	686	711	505	358
Co	101	91.7	79.4	80.6	76.5	70.0	78.5	64.7	62.6	69.5	55.6	53.3
Ni	1343	1225	937	844	817	737	543	529	341	289	236	195
Cu	70.2	43.9	86.3	121	100	80.3	129	135	30.1	118	131	169
Zn	74.3	76.1	81.5	88.3	86.0	77.4	82.1	86.3	83.7	91.3	82.1	88.1
Ga	8.1	11.9	15.2	16.6	16.8	15.5	16.9	17.0	16.8	17.6	19.3	19.8
Rb	6.21	2.17	0.29	0.77	1.45	1.52	1.49	1.15	1.27	24.6	3.75	2.24
Sr	107	117	161	129	183	158	163	194	151	356	279	237
Y	10.9	13.8	18.9	18.3	18.5	19.4	20.4	22.0	21.1	20.3	21.9	25.4
Zr	39.5	44.6	84.8	65.2	68.2	74.7	76.1	98.6	74.3	128	94.0	106
Nb	1.78	1.67	5.29	2.80	3.53	5.85	4.10	5.59	4.56	36.2	13.3	10.6
Cs	0.013	0.016	0.005	0.037	0.062	0.042	0.013	0.025	0.046	0.114	0.011	0.005
Ba	25.6	23.9	24.9	19.5	27.4	57.9	24.7	42.2	32.1	230	82.3	62.7
La	1.96	1.80	5.05	2.98	3.34	5.98	4.15	5.66	4.87	19.2	9.71	8.14
Ce	5.61	5.47	13.6	8.74	9.60	14.6	11.2	15.4	12.4	41.6	23.0	20.3
Pr	0.96	0.96	2.24	1.53	1.62	2.22	1.78	2.45	1.95	5.20	3.21	3.11
Nd	5.12	5.38	11.1	8.04	8.30	10.3	9.21	12.5	9.67	20.5	14.4	14.7
Sm	1.55	1.78	3.34	2.65	2.75	2.97	2.92	3.80	2.93	4.18	3.77	4.10
Eu	0.578	0.659	1.10	0.905	1.02	1.06	1.03	1.34	1.06	1.32	1.31	1.46
Gd	1.78	2.22	3.69	3.03	3.25	3.49	3.25	4.21	3.59	4.38	4.24	4.60
Tb	0.310	0.380	0.580	0.508	0.559	0.577	0.570	0.697	0.586	0.668	0.689	0.770
Dy	1.77	2.30	3.49	3.14	3.29	3.39	3.42	3.93	3.54	3.67	3.99	4.48
Ho	0.383	0.493	0.696	0.642	0.636	0.679	0.698	0.802	0.723	0.720	0.796	0.902
Er	1.03	1.33	1.83	1.67	1.79	1.84	1.84	2.08	1.95	1.86	2.09	2.40
Tm	0.151	0.202	0.259	0.258	0.262	0.266	0.289	0.290	0.285	0.277	0.277	0.338
Yb	0.90	1.17	1.54	1.52	1.58	1.61	1.68	1.64	1.72	1.67	1.72	2.09
Lu	0.138	0.185	0.226	0.226	0.230	0.258	0.246	0.260	0.264	0.243	0.265	0.307
Hf	1.14	1.30	2.19	1.72	1.86	1.94	1.99	2.49	1.93	3.28	2.54	2.86
Ta	0.190	0.116	0.395	0.204	0.292	0.371	0.339	0.411	0.284	2.33	0.866	0.689
Pb	0.180	0.185	0.581	0.348	0.345	1.09	0.475	0.604	0.722	0.672	0.633	0.662
Th	0.121	0.109	0.406	0.187	0.178	0.689	0.276	0.358	0.366	2.520	0.806	0.758
U	0.035	0.033	0.111	0.055	0.064	0.203	0.088	0.103	0.108	0.551	0.216	0.224
$^{87}Sr/^{86}Sr$	0.703473	0.703340	0.703310	0.703232	0.703275							
$^{143}Nd/^{144}Nd$	0.513081	0.513103	0.513045	0.513082	0.513070							

Sr-Nd isotope data (as measured) from Holm *et al.* (1993).

Table 5 (continued) Notes on analysed samples from the Vaigat Formation

181015	Fine-grained olivine-phyric magnesian basalt, slightly crustally contaminated. Thick, compound pahoehoe flow, uppermost flow in the Kakilisaat Member. Profile 4, Kakilisaat, south-east Svartenhuk Halvø.
181019	Fine-grained olivine-phyric magnesian basalt, crustally contaminated. Compound pahoehoe flow beneath the uppermost hyaloclastite horizon in the Kakilisaat Member. Profile 4, Kakilisaat, south-east Svartenhuk Halvø.
181022	Fine-grained aphyric silicic basalt, crustally contaminated. Pillow lava horizon on top of 75 m foreset-bedded hyaloclastite low in the Kakilisaat Member. Profile 4, Kakilisaat, south-east Svartenhuk Halvø.
181037	Fine-grained aphyric silicic basalt, crustally contaminated. Lava flow in the upper Kakilisaat Member, western corner of the mouth of Ulissat Qooruat, south-east coast of Svartenhuk Halvø. Located on Fig. 17.
181073	Fine-grained aphyric silicic basalt, crustally contaminated. Kakilisaat Member lava flow low in profile 13, Saviit South, southern Svartenhuk Halvø.
181075	Plagioclase-olivine-phyric basaltic andesite, crustally contaminated and enriched in incompatible trace elements (Th, U, Nb, REE). Kakilisaat Member lava flow in profile 13, Saviit South, southern Svartenhuk Halvø.
263818	Aphyric magnesian basalt. Brown hyaloclastite, Nerutusoq Member in profile 48b, Nerutusoq valley at 360 m altitude, northern Svartenhuk Halvø.
181077	Aphyric basalt distinctly enriched in incompatible trace elements (Ba, Th, U, Nb, REE). lava flow, Nerutusoq Member in Profile 13, Saviit South, southern Svartenhuk Halvø.
263822	Aphyric basalt enriched in incompatible trace elements (Ba, Th, U, Nb, REE). Brown pillow breccia, Nerutusoq Member in profile 48b, Nerutusoq valley, northern Svartenhuk Halvø.
263823	Aphyric basalt enriched in incompatible trace elements (Ba, Th, U, Nb, REE). Brown lava flow, Nerutusoq Member in profile 48b, Nerutusoq valley, northern Svartenhuk Halvø.
181013	Fine-grained aphyric basalt distinctly enriched in incompatible trace elements (Ba, Th, U, Nb, REE). Pahoehoe lava flow, Nerutusoq Member in profile 4, Kakilisaat, south-east Svartenhuk Halvø.
263821	Aphyric basalt enriched in incompatible trace elements (Ba, Th, U, Nb, REE). Black hyaloclastite, Nerutusoq Member in profile 48b, Nerutusoq valley, northern Svartenhuk Halvø.
181066	Olivine-rich picrite. Pahoehoe flow lobe in grey compound lava flow, lower Nunavik Member in profile 24, Peak 1120 m, southern Svartenhuk Halvø.
181067	Olivine-rich picrite. Pahoehoe flow lobe in grey compound lava flow, lower Nunavik Member in profile 24, Peak 1120 m, southern Svartenhuk Halvø.
251515	Olivine-rich picrite. Pahoehoe flow lobe in grey compound lava flow, upper Nunavik Member in profile 9, Peak 1078 m, eastern Svartenhuk Halvø.
251525	Olivine-microphyric picrite. Pahoehoe flow lobe in grey compound lava flow, middle Nunavik Member in profile 9, Peak 1078 m, eastern Svartenhuk Halvø.
251529	Medium-grained picrite. Pahoehoe flow lobe in grey compound lava flow, lower Nunavik Member in profile 9, Peak 1078 m, eastern Svartenhuk Halvø.
278353	Picrite. Pahoehoe flow lobe in greenish grey, compound lava flow, upper Nunavik Member in profile 44c, Kuugaartorfik, northern Svartenhuk Halvø.
181085	Olivine-poor picrite. Sheet flow 25 m in thickness, middle Nunavik Member in profile 14, Saviit North, southern Svartenhuk Halvø.
251589	Medium-grained picrite. Pahoehoe flow lobe in grey compound lava flow, upper Nunavik Member in profile 30, Ivissukkat Itinnerat, east-central Svartenhuk Halvø.
278354	Mg-poor picrite. Pahoehoe flow lobe in crumbling compound lava flow, upper Nunavik Member in profile 44c, Kuugaartorfik, northern Svartenhuk Halvø.
251527	Olivine-microphyric magnesian basalt distinctly enriched in incompatible trace elements (Ba, Th, U, Nb, Zr, Sr, REE). Pahoehoe flow lobe at base of dark marker horizon βo1. Compound lava flow, middle Nunavik Member in profile 9, Peak 1078 m, eastern Svartenhuk Halvø.
251588	Medium-grained magnesian basalt. Pahoehoe flow lobe in grey compound lava flow, upper Nunavik Member in profile 30, Ivissukkat Itinnerat, east-central Svartenhuk Halvø.
181056	Olivine-phyric basalt. Lava flow with pseudopillow structure, upper Nunavik Member in profile 24, Peak 1120 m, southern Svartenhuk Halvø.

Svartenhuk Formation

The volcanic rocks of the Svartenhuk Formation comprise tholeiitic basalts, subordinate picrites and a few basaltic andesites. They have a total range of 3.4–21.7 wt% MgO with an average of 7.2 wt% MgO (620 analyses). A few basalts are crustally contaminated and some scattered basalts are geochemically enriched. Major element variation diagrams for the Svartenhuk Formation are shown in Fig. 76, trace-element variation diagrams in Figs 77 and 78, and REE and multi-element diagrams in Fig. 79. Note that Figs 76–78 use the *mg*-number as abscissa and not the MgO content as in the plots of the Vaigat Formation; this is because the major part of the basalts have a limited variation in MgO content (5–9 wt% MgO), which does not produce a sufficiently large spread on the abscissa. The figures are designed to be comparable with the similar geochemistry diagrams for the Maligât Formation in Pedersen *et al*. (2018). Representative chemical analyses are shown in Table 6.

Tunuarsuk Member

The Tunuarsuk Member comprises basalts with 5–10 wt% MgO grading into magnesian basalts with 10–12 wt% MgO and scattered picrites with 12–16 wt% MgO; a few rocks with up to 22 wt% MgO probably contain accumulated olivine. The average MgO content is 8.4 wt%, and the majority of the rocks are olivine normative. TiO_2 is in the range 1.1–3.3 wt% with an average of 1.8 wt% TiO_2, and with few exceptions the P_2O_5/TiO_2 ratio is less than 0.11. The magmas were relatively depleted in incompatible trace elements such as Rb, Ba, Th, U, Nb, and light REE (Fig. 79). Some flows scattered throughout the region are distinctly enriched in these same elements, and very few flows (2 analyses) are crustally contaminated. Many REE and multi-element curves in Fig. 79 cross each other.

Nuuit Member

The Nuuit Member comprises basalts with 3.4–11 wt% MgO; only 3 out of 220 analyses have more than 9 wt% MgO and the average MgO content is 6.4 wt%. TiO_2 is in the range 1.5–3.8 wt%, and the average TiO_2 content is 2.4 wt%. The basalts are similar in composition to the more Ti-rich (TiO_2 >2.0 wt%) basalts of the Tunuarsuk Member. The magmas were relatively depleted in incompatible trace elements such as Rb, Ba, Th, U, Nb and light REE, similar to the basalts of the Tunuarsuk Member. Some flows are enriched in the same elements, as discussed below. With the exception of these, the REE and multi-element curves in Fig. 79 are near-parallel and do not cross each other. This is in contrast to the same curves for the Tunuarsuk Member. A few scattered flows are crustally contaminated (4 analyses have SiO_2 ≥51 wt%) and some more may be slightly contaminated.

Skalø Member

The Skalø Member comprises basalts with 4.5–10 wt% MgO; only 3 out of 127 analyses have more than 9 wt% MgO and the average MgO content is 6.5 wt%. TiO_2 is in the range 1.1–3.5 wt%, and the average TiO_2 content is 2.0 wt%. These compositions are very similar to those of the Nuuit Member, with slightly lower TiO_2 in the Skalø Member. SiO_2, Al_2O_3 and CaO range to slightly higher values than in the Nuuit Member, and many Skalø Member flows probably have relatively high contents of plagioclase. The magmas were relatively depleted in incompatible trace elements such as Rb, Ba, Th, U, Nb and light REE, similar to the basalts of the Tunuarsuk and Nuuit Members. A single flow is enriched in the same elements (Fig. 79). A few flows may be crustally contaminated; 6 analyses have SiO_2 slightly higher than 51 wt% but still form part of the main compositional trends. With some exceptions the REE and multi-element curves in Fig. 79 are near-parallel and in this respect more similar to the curves of the Nuuit Member than to the Tunuarsuk Member.

The Skalø Member flows at Aputituut (profile 55) have relatively evolved compositions with high TiO_2 and P_2O_5. The uppermost flow is extreme, with 4.0 wt% TiO_2 and 0.47 wt% P_2O_5 at 5.7 wt% MgO. These values are similar to those in the overlying Arfertuarsuk Member. However, the trace-element ratios (REE and Zr-Nb-Y) clearly indicate that all the flows belong to the Skalø Member and the top flow is just highly evolved.

Discussion

The three volcanic members of the Svartenhuk Formation are compositionally very similar in their major and trace elements, and what defines the chemostratigraphy is the pattern of variation up-section. For example, the major difference between the Skalø and Nuuit Members is the variable TiO_2 compositional profiles in the Nuuit Member compared to the near-constant profiles in the Skalø Member (Fig. 42).

The basalts of the Svartenhuk Formation represent

Fig. 76 (Figure on next page) Major-element variation diagrams for rocks of the Svartenhuk Formation. Crustally contaminated and enriched rocks are included in the main members because their major elements are as a rule not distinguishable from those of the main members. A few exceptions are labelled **e**: enriched, and **c**: crustally contaminated. Note that the abscissa is the *mg*-number (atomic 100×MgO/(MgO+FeO)), not the simple MgO as in the Vaigat Formation plots. The Skalø Member partly conceals the Nuuit and Tunuarsuk Members because it is plotted on top of them. Fractionation goes from right to left. The fractionation trends bend at *mg*-numbers around 57 (7–8 wt% MgO) because at that stage the fractionating olivine is joined by plagioclase and shortly afterwards by clinopyroxene. Vertical axes in wt% oxides.

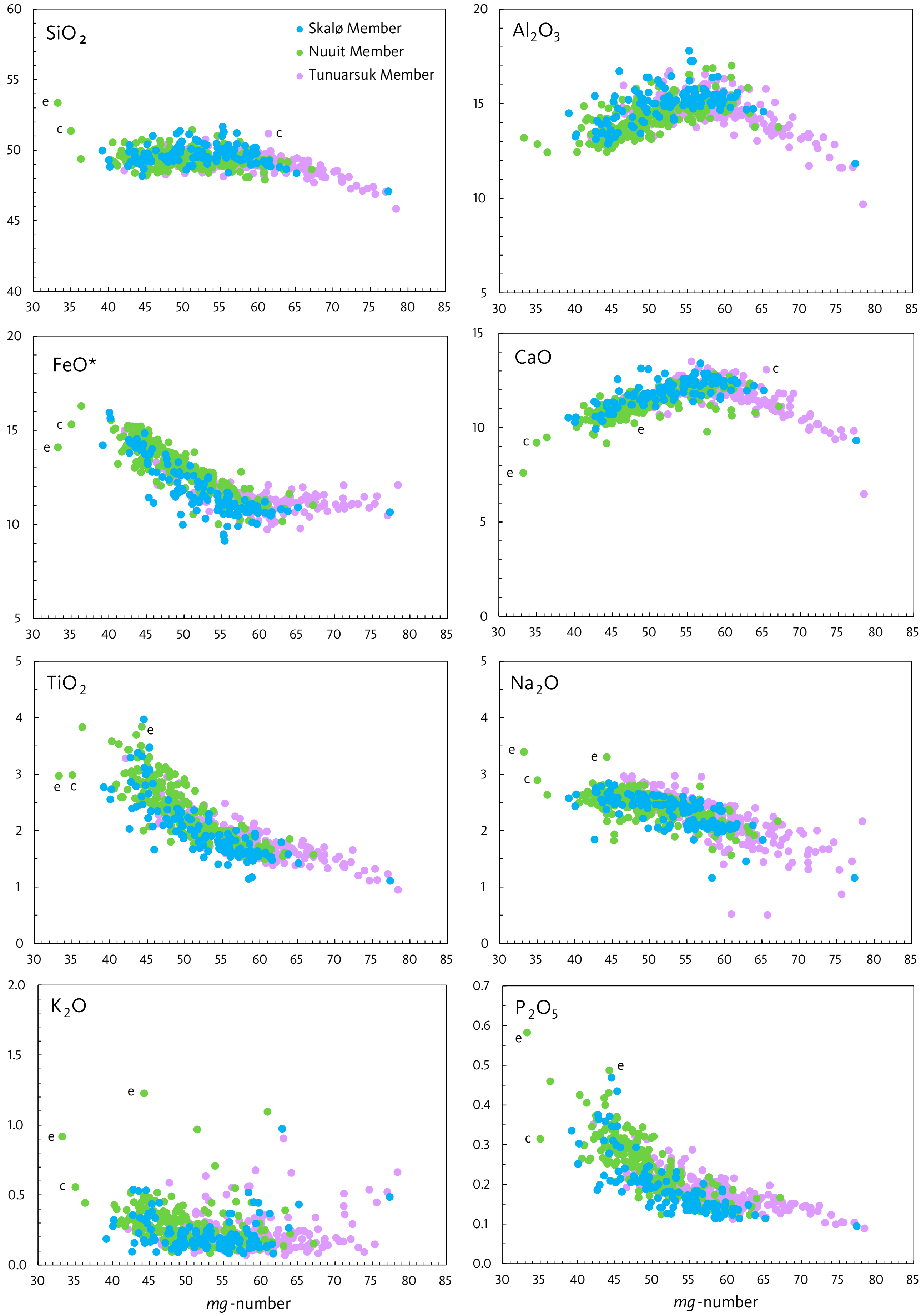

Fig. 76 (Caption on previous page)

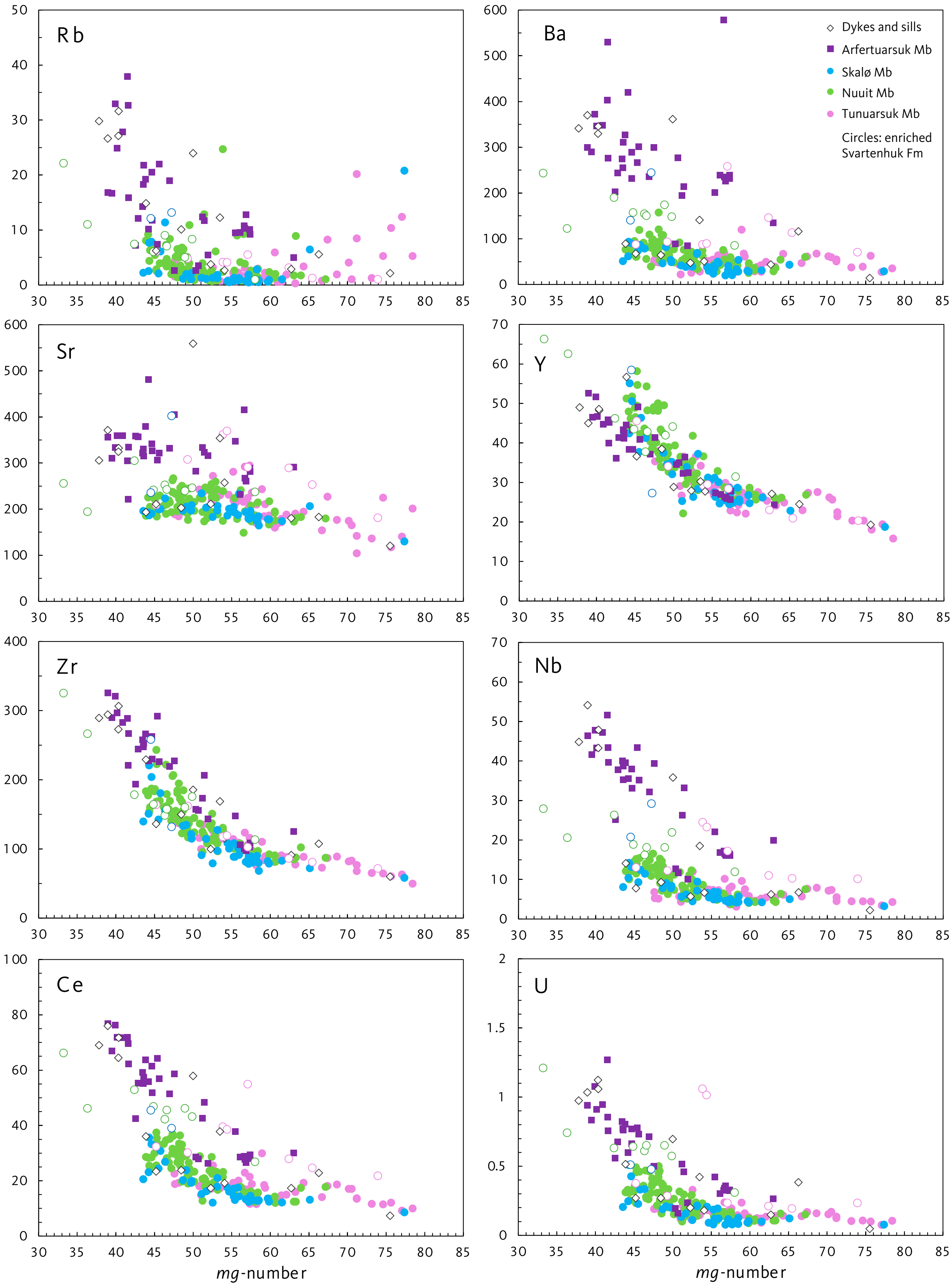

Fig. 77 Incompatible trace-element variation diagrams for rocks of the Svartenhuk and Naqerloq Formations and intrusions. The Tunuarsuk, Nuuit and Skalø Members have similar low element concentrations, but scattered lavas in all three members are enriched (open circles). The Arfertuarsuk Member has significantly higher concentrations of these elements. Intrusions compositionally similar to both formations are present. Vertical axes in ppm.

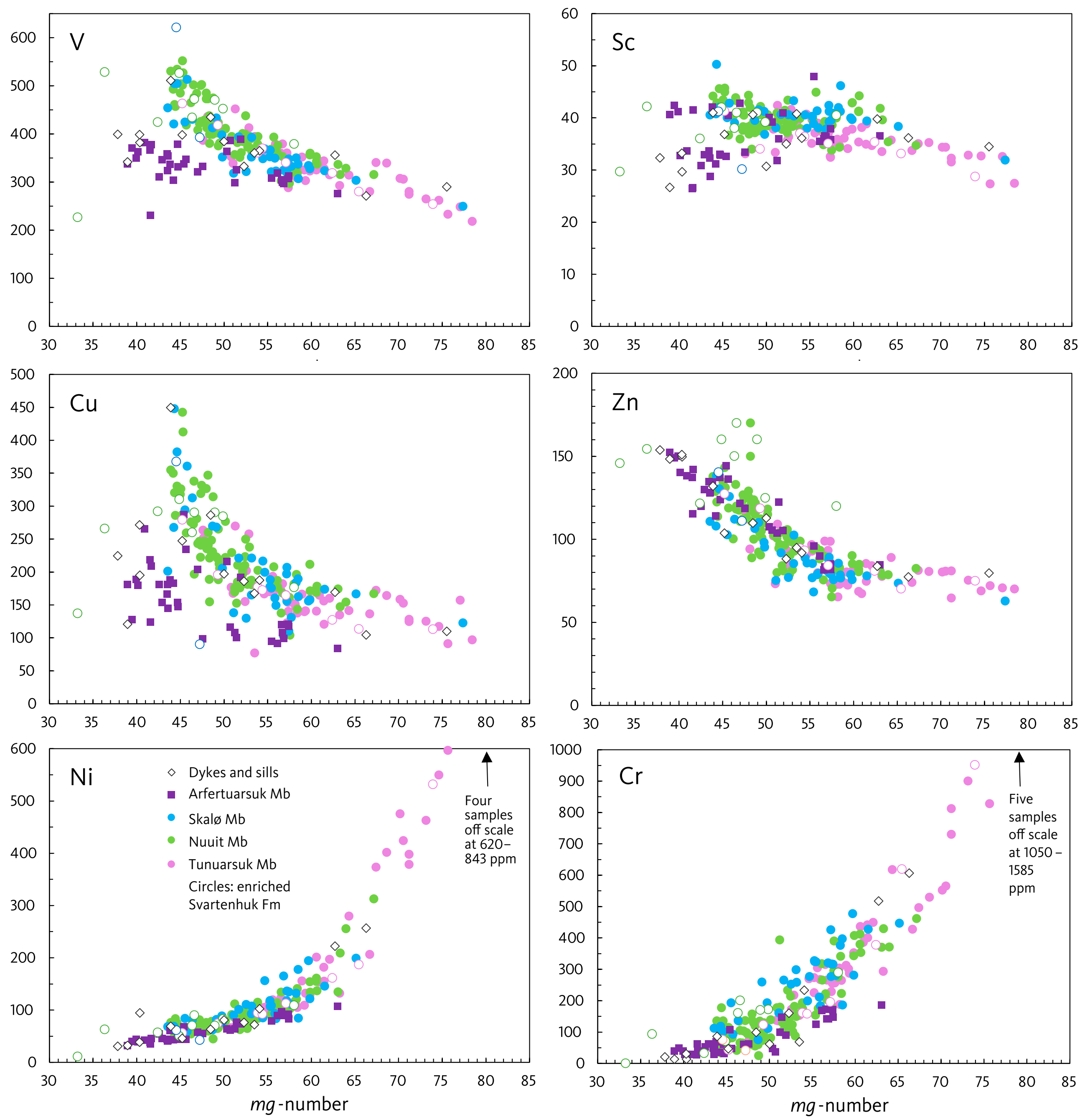

Fig. 78 Transition-element variation diagrams for rocks of the Svartenhuk and Naqerloq Formations and intrusions. Vertical axes in ppm.

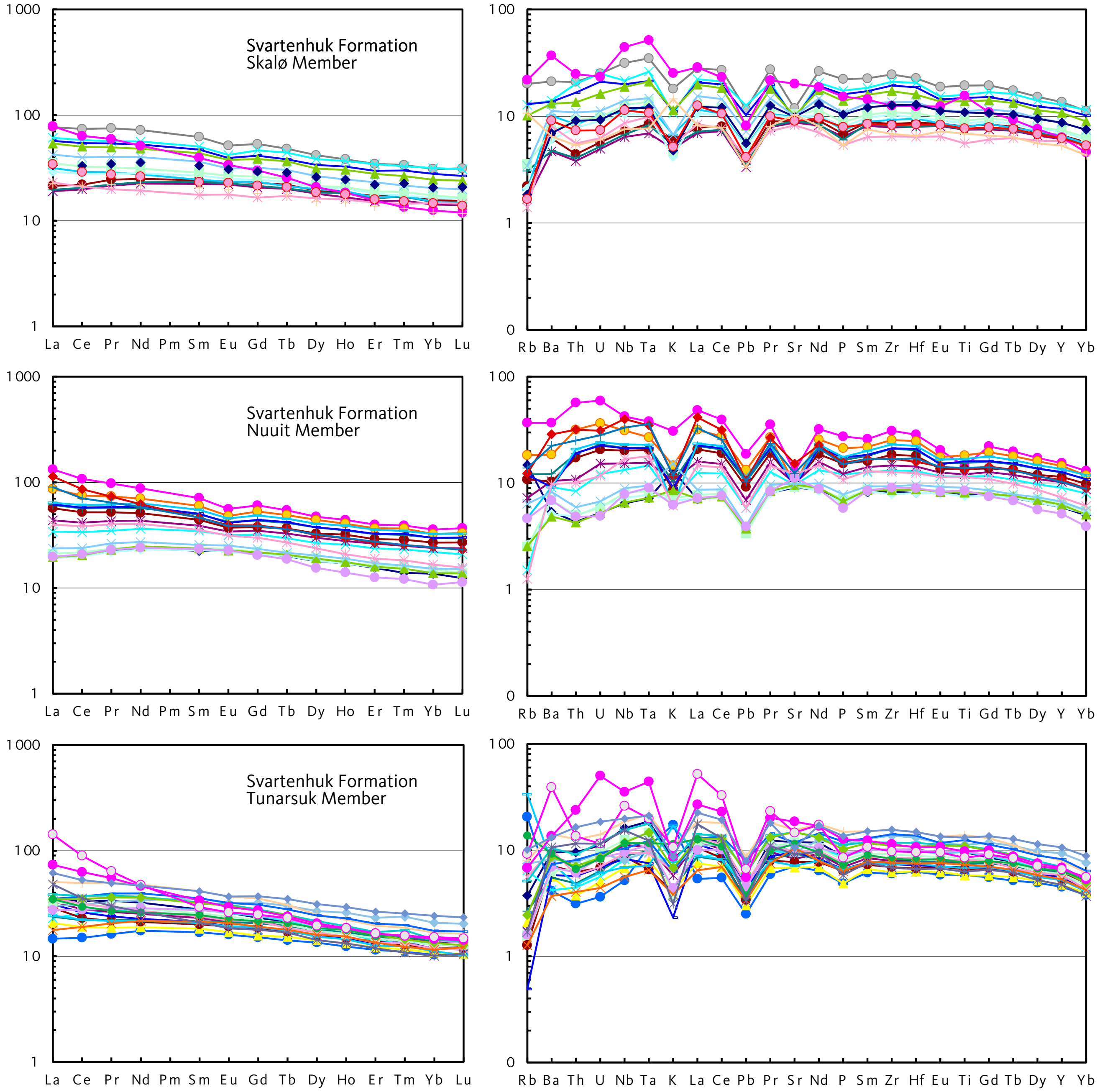

Fig. 79 REE and multi-element diagrams for representative rocks of the Svartenhuk Formation. The different colours of the curves are intended to aid the distinction of the individual samples. The magenta samples are incompatible-element-enriched. Note the particularly variable slope of the La–Sm limb of the REE curve for the Tunuarsuk Member. **Left** diagrams: chondrite normalised. **Right** diagrams: primitive mantle normalised. Normalisation factors from McDonough & Sun (1995).

Table 6 Chemical analyses of rocks from the Svartenhuk Formation

Member	**Tunuarsuk Member**										**Nuuit Member**	
GGU no.	**181120**	**278559**	**251317**	**251281**	**262803**	**251295**	**278343**	**251333**	**262815**	**262793**	**566511**	**566505**
Profile no.	-	50	42	38	64b	38	44c	37	64b	64a	65	Reconn.
Name	Qinnivik	Umiiarfik	Marraarn.	Qaqqap Q.	Paannivik	Qaqqap Q.	Kuugaart.	Nuup Qaa.	Paannivik	Paannivik	Salliaruseq	E Nunatak
	Major elements in wt% (XRF analyses)											
SiO_2	45.19	45.98	45.89	47.74	47.62	48.39	47.92	48.16	47.89	49.08	48.07	48.66
TiO_2	1.18	1.26	1.16	1.55	1.64	1.86	2.06	1.92	2.78	2.26	1.69	1.47
Al_2O_3	11.18	11.86	12.78	13.09	12.70	14.24	14.02	14.19	13.63	13.88	14.56	14.87
Fe_2O_3	2.56	5.60	5.18	12.15*	4.88	12.70*	4.07	5.46	5.05	4.76	12.28*	11.79*
FeO	7.75	6.14	6.05		7.16		8.15	6.72	8.35	8.19		
MnO	0.21	0.18	0.17	0.19	0.18	0.191	0.18	0.18	0.21	0.23	0.19	0.19
MgO	16.70	15.69	14.43	11.83	10.29	7.34	7.20	6.72	6.20	5.62	8.14	8.09
CaO	9.44	9.47	9.54	10.52	11.13	11.88	11.77	12.57	11.04	10.70	11.80	12.37
Na_2O	1.39	1.63	1.61	1.93	1.87	2.22	2.40	2.47	2.61	2.63	1.98	1.93
K_2O	0.50	0.09	0.12	0.18	0.19	0.21	0.24	0.28	0.31	0.19	0.111	0.164
P_2O_5	0.10	0.12	0.10	0.15	0.16	0.17	0.21	0.25	0.31	0.23	0.135	0.123
Volatiles	3.25	2.10	2.92	0.41	2.27	0.36	1.68	1.36	1.51	2.41	0.80	-0.02
Sum	99.45	100.12	99.95	99.73	100.08	99.56	99.90	100.28	99.89	100.17	99.75	99.64
FeO*	10.05	11.18	10.71	10.93	11.55	11.43	11.81	11.63	12.89	12.47	11.05	10.61
mg-no.	77.06	73.95	73.15	68.65	64.30	56.51	55.22	53.89	49.30	47.68	59.85	60.67
	Trace elements in ppm (ICP-MS analyses)											
Sc	32.6	28.7	32.8	35.2	35.7	37.1	35.1	37.0	34.0	38.1	42.8	44.2
V	248	254	264	339	314	360	355	361	418	427	356	337
Cr	1134	951	900	529	617	315	273	161	122	86.4	343	353
Co	70.1	65.7	65.2	55.5	59.2	48.7	48.0	46.8	48.3	45.1	49.5	49.4
Ni	645	531	462	401	280	123	113	93.8	73.9	64.9	154	136
Cu	157	113	125	164	141	172	170	177	196	251	211	178
Zn	70.7	74.9	75.3	80.6	89.0	90.6	96.7	94.4	119	116	90.1	84.9
Ga	14.9	15.8	16.1	18.5	17.9	20.5	21.7	22.0	23.0	22.1	19.7	18.9
Rb	12.4	1.01	1.25	1.90	3.36	1.60	2.22	4.13	4.76	4.45	0.63	2.00
Sr	140	181	136	177	194	216	281	361	307	188	167	175
Y	19.4	20.3	20.3	27.5	24.9	28.9	26.8	29.2	34.1	40.1	28.6	25.6
Zr	62.7	71.4	65.1	88.9	88.4	102	114	117	162	143	91.3	81.0
Nb	3.41	10.1	4.47	7.87	6.13	6.39	7.34	24.4	12.2	5.28	4.02	4.30
Cs	0.043	0.080	0.014	0.026	0.150	0.012	0.032	0.069	0.054	0.071	0.007	0.006
Ba	27.3	70.0	37.0	67.2	66.8	47.5	53.8	87.1	93.1	54.1	25.0	30.7
La	3.47	11.4	4.89	8.46	8.43	6.91	7.29	17.8	12.0	7.14	4.54	4.34
Ce	9.18	21.7	11.6	18.6	19.2	17.0	19.2	39.4	30.1	18.8	12.8	11.9
Pr	1.50	2.78	1.73	2.62	2.68	2.58	3.05	5.25	4.62	3.05	2.14	1.92
Nd	7.98	12.0	8.63	12.1	12.3	12.9	15.0	21.6	21.8	15.5	11.3	10.2
Sm	2.49	3.09	2.70	3.50	3.54	4.02	4.55	5.03	6.12	5.21	3.70	3.31
Eu	0.901	1.03	0.955	1.25	1.22	1.41	1.60	1.67	2.07	1.79	1.37	1.23
Gd	3.00	3.56	3.13	4.29	4.28	4.62	5.06	5.53	7.03	6.40	4.68	4.09
Tb	0.511	0.606	0.552	0.751	0.667	0.808	0.841	0.890	1.10	1.09	0.775	0.712
Dy	3.32	3.51	3.49	4.71	4.15	4.71	4.88	5.19	6.10	6.58	5.10	4.42
Ho	0.677	0.724	0.723	0.963	0.837	1.00	0.941	1.04	1.21	1.41	1.03	0.922
Er	1.84	1.91	1.94	2.61	2.15	2.53	2.52	2.69	3.12	3.70	2.77	2.51
Tm	0.273	0.268	0.287	0.375	0.328	0.372	0.340	0.387	0.459	0.585	0.426	0.378
Yb	1.66	1.63	1.74	2.41	1.90	2.27	2.07	2.38	2.69	3.34	2.52	2.26
Lu	0.255	0.259	0.259	0.362	0.289	0.342	0.314	0.349	0.402	0.500	0.376	0.344
Hf	1.77	1.87	1.78	2.36	2.38	2.75	2.88	2.97	4.19	3.71	2.53	2.22
Ta	0.403	0.454	0.295	0.511	0.345	0.567	0.487	1.65	0.800	0.363	0.318	0.585
Pb	0.374	0.497	0.452	0.644	0.727	0.643	0.769	0.814	1.30	1.06	0.490	0.499
Th	0.249	0.914	0.296	0.560	0.467	0.448	0.580	2.00	1.01	0.611	0.306	0.334
U	0.074	0.233	0.102	0.159	0.141	0.142	0.164	1.06	0.283	0.191	0.087	0.112
$^{87}Sr/^{86}Sr$	0.703407	0.703650	0.703611									
$^{143}Nd/^{144}Nd$	0.513045	0.512832	0.512974									

FeO*= total iron calculated as FeO. Total iron determined as Fe_2O_3 is marked by an *

mg-number = 100 × atomic Mg/(Mg+Fe^{2+}), with the iron oxidation ratio adjusted to Fe_2O_3/FeO = 0.15.

For notes on the samples, see next page.

Sr-Nd isotope data (as measured) from Holm *et al*. (1993).

Table 6 (continued) Chemical analyses of rocks from the Svartenhuk Formation

Unit	**Nuuit Member**						**Skalø Member**					
GGU no.	**263525**	**181097**	**181102**	**566520**	**262973**	**251338**	**278520**	**262896**	**262754**	**262988**	**262912**	**262697**
Profile no.	62	40	40	65	62	37	50	41b	64a	62	41b	55
Name	Sigguk	Pann.Qaq.	Pann.Qaq.	Salliaruseq	Sigguk	Nuup Q.	Umiiarfik	Skalø	Paannivik	Sigguk	Skalø	Aputituut
	Major elements in wt% (XRF analyses)											
SiO_2	48.40	47.57	48.74	48.45	47.28	48.52	47.04	48.16	48.54	48.80	48.25	47.27
TiO_2	1.61	2.99	2.79	2.29	3.39	2.68	1.38	1.50	1.87	2.19	2.78	3.90
Al_2O_3	14.96	12.79	12.99	13.49	13.30	13.94	14.18	15.12	15.23	14.87	13.20	12.77
Fe_2O_3	6.58	6.90	3.08	14.81*	6.53	8.33	4.98	4.43	4.84	4.55	4.25	5.58
FeO	5.00	7.87	10.03		8.78	6.54	6.11	6.23	6.32	8.56	9.90	8.92
MnO	0.20	0.28	0.26	0.23	0.26	0.20	0.17	0.18	0.16	0.23	0.24	0.24
MgO	7.55	6.42	6.30	6.30	5.99	5.11	9.79	8.08	6.37	5.94	5.73	5.54
CaO	12.19	10.89	10.89	11.06	10.45	10.57	11.64	12.06	11.98	11.38	10.84	10.52
Na_2O	2.25	2.40	2.60	2.22	1.78	2.80	1.78	2.01	2.39	2.53	2.53	2.79
K_2O	0.21	0.22	0.34	0.24	0.18	0.34	0.42	0.14	0.11	0.14	0.33	0.52
P_2O_5	0.15	0.30	0.31	0.22	0.36	0.32	0.11	0.13	0.17	0.21	0.29	0.46
Volatiles	1.35	1.19	1.14	0.33	2.08	1.15	2.59	1.99	2.02	1.16	1.66	2.01
Sum	100.45	99.82	99.47	99.64	100.38	100.50	100.19	100.03	100.00	100.56	100.00	100.52
FeO*	10.92	14.08	12.80	13.32	14.66	14.04	10.59	10.22	10.67	12.65	13.72	13.94
mg-no.	58.31	47.99	49.89	48.89	45.26	42.42	65.16	61.54	54.70	48.72	45.80	44.58
	Trace elements in ppm (ICP-MS analyses)											
Sc	41.2	42.9	39.2	40.4	45.0	36.0	38.4	39.4	38.0	39.5	42.8	41.2
V	330	473	452	411	552	424	304	323	369	412	513	621
Cr	341	157	171	135	115	31.6	447	427	277	75.3	92.9	74.7
Co	44.9	49.7	46.5	47.7	45.9	46.1	51.0	47.1	46.6	48.1	50.7	59.0
Ni	121	73.0	82.4	78.5	66.8	57.0	199	146	156	62.1	58.8	60.8
Cu	196	326	284	224	442	292	167	174	200	269	360	367
Zn	81.0	129	125	117	143	122	73.5	77.9	85.7	106	126	140
Ga	20.0	22.7	24.0	21.4	23.3	24.7	18.3	18.9	20.5	21.5	22.3	24.7
Rb	1.51	1.37	8.31	4.99	2.82	7.41	6.42	1.00	0.49	1.11	6.09	12.08
Sr	181	195	246	194	191	304	206	174	200	197	200	236
Y	27.8	48.1	44.1	37.8	58.2	46.2	22.8	26.2	30.3	37.5	46.3	58.4
Zr	90.9	180	175	138	243	178	71.8	82.7	100	133	180	258
Nb	5.30	12.2	21.9	10.7	15.2	26.3	5.00	4.21	5.45	7.83	12.4	20.7
Cs	0.005	0.020	0.085	0.063	0.073	0.141	0.062	0.016	0.001	0.011	0.069	0.143
Ba	45.6	67.7	148	61.3	60.5	190	42.9	30.9	29.6	45.8	86.5	140
La	5.00	10.3	21.3	9.82	15.2	26.9	5.31	4.50	5.89	7.93	12.8	18.2
Ce	13.4	26.6	43.1	24.0	37.4	52.8	13.1	12.1	16.0	20.2	30.8	45.4
Pr	2.19	4.25	5.97	3.55	5.74	6.79	2.04	2.00	2.52	3.19	4.59	6.97
Nd	11.2	21.7	26.6	17.6	28.8	28.4	10.1	10.3	13.1	16.2	22.0	33.0
Sm	3.54	6.65	6.86	5.27	8.15	6.84	3.05	3.30	4.03	4.92	6.46	9.20
Eu	1.32	2.20	2.18	1.80	2.57	2.21	1.11	1.24	1.45	1.73	2.12	2.90
Gd	4.35	7.71	7.69	6.47	9.68	7.80	3.60	4.10	5.12	5.82	7.65	10.59
Tb	0.734	1.34	1.29	1.08	1.63	1.31	0.629	0.722	0.867	1.03	1.32	1.73
Dy	4.71	8.24	7.89	6.68	9.97	7.76	3.76	4.45	5.43	6.39	7.67	10.26
Ho	0.957	1.72	1.63	1.35	2.12	1.61	0.817	0.912	1.13	1.34	1.66	2.08
Er	2.62	4.67	4.38	3.64	5.71	4.28	2.21	2.44	3.01	3.53	4.44	5.53
Tm	0.399	0.681	0.630	0.533	0.857	0.629	0.324	0.382	0.444	0.556	0.654	0.834
Yb	2.42	4.33	3.89	3.31	5.23	3.92	1.91	2.29	2.69	3.31	3.95	4.96
Lu	0.339	0.609	0.566	0.506	0.801	0.565	0.287	0.346	0.415	0.511	0.590	0.770
Hf	2.44	4.74	4.84	3.64	6.33	4.48	1.86	2.26	2.84	3.65	4.53	6.41
Ta	0.316	0.780	1.33	0.844	0.846	1.29	0.286	0.256	0.342	0.444	0.784	1.29
Pb	0.502	1.13	1.55	0.825	1.71	1.59	0.501	0.501	0.676	0.841	1.23	1.74
Th	0.398	0.900	1.99	0.988	1.66	2.53	0.424	0.303	0.449	0.723	1.08	1.67
U	0.119	0.215	0.573	0.290	0.491	0.630	0.122	0.100	0.091	0.188	0.330	0.509

Table 6 (continued) Notes on analysed samples from the Svartenhuk Formation

181120	Picrite with platy and equant olivine phenocrysts. Single olivin-rich lava flow within a succession of plagioclase glomerophyric and aphyric basalts. Tunuarsuk Member, Qinnivik peninsula 1 km WSW of point 631 m, south-western Svartenhuk Halvø, indicated on the geological map (Larsen 1983) as βo.
278559	Aphyric picrite distinctly enriched in incompatible trace elements (Ba, Th, U, Nb, Sr, REE). Pahoehoe flow lobe in compound flow c. 10 m thick and with 1 m dark red scoriaceous top zone. Tunuarsuk Member in profile 50, Umiiarfik South, northern Svartenhuk Halvø.
251317	Medium-grained picrite. Pahoehoe flow lobe, part of dark greenish compound flow, uppermost Tunuarsuk Member in profile 42, Marrarnaq, northern Qeqertaq peninsula 11 km south-east of the settlement Kangersuatsiaq (Prøven).
251281	Olivine-phyric magnesian basalt. Massive lava flow 50 m thick and with 10 m scoriaceous top zone, uppermost flow in Tunuarsuk Member in profile 38, Qaqqap Qaa, east coast of the Innerit peninsula.
262803	Plagioclase-phyric magnesian basalt. Massive lava flow *c*. 40 m thick, middle Tunuarsuk Member in profile 64, Paannivik, southern Innerit.
251295	Plagioclase-phyric basalt. Massive lava flow *c*. 40 m thick, middle Tunuarsuk Member in profile 38, Qaqqap Qaa, east coast of the Innerit peninsula.
278343	Aphyric basalt. Massive lava flow *c*. 20 m thick, between hyaloclastite horizons, lower Tunuarsuk Member in profile 44c, Kuugaartorfik, northern Svartenhuk Halvø.
251333	Weakly plagioclase-phyric basalt enriched in incompatible trace elements (Ba, Th, U, Nb, Sr, REE). Massive lava flow *c*. 60 m thick, middle Tunuarsuk Member in profile 37, Nuup Qaava, northern side of the Innerit inlet on the west side of the Innerit peninsula.
262815	Aphyric basalt slightly enriched in incompatible trace elements (Ba, Th, U, Nb, Sr, REE, Ti). Massive lava flow *c*. 25 m thick, middle Tunuarsuk Member in profile 64, Paannivik, southern Innerit.
262793	Plagioclase-phyric Mg-poor basalt. Lava flow 5-10 m thick, middle Tunuarsuk Member in profile 64, Paannivik, southern Innerit.
566511	Aphyric basalt, Nuuit Member. Highest lava flow in profile 65, Salliaruseq, north-east of Svartenhuk Halvø.
566505	Plagioclase microphyric basalt lava flow. Reconnaissance sample, nunatak in side valley at the upper reaches of Umiammakku Sermia (glacier), GPS coordinates 72°4.3′N, 51°58.8′W, altitude 1740 m (Fig. 5), Member status not certain, but note close similarity to sample 566511 from Salliaruseq 75 km to the north-west.
263525	Plagioclase-phyric basalt lava flow. Middle part of Nuuit Member in profile 62, Sigguk, western Svartenhuk Halvø.
181097	Aphyric basalt lava flow. Upper part of Nuuit Member in profile 40, Pannertuup Qaqqaa, east of the northernmost extension of Ukkusissat Fjord, north-east of Svartenhuk Halvø.
181102	Plagioclase-glomerophyric basalt lava flow enriched in incompatible trace elements (Ba, Th, U, Nb, Sr, REE). Lowest flow in Nuuit Member in profile 40, Pannertuup Qaqqaa, east of the northernmost extension of Ukkusissat Fjord, north-east of Svartenhuk Halvø.
566520	Sparsely plagioclase-glomerophyric basalt lava flow, middle part of Nuuit Member in profile 65, Salliaruseq, north-east of Svartenhuk Halvø.
262973	Plagioclase-glomerophyric basalt lava flow. Highest flow in Nuuit Member in profile 62, Sigguk, western Svartenhuk Halvø.
251338	Plagioclase-glomerophyric basalt lava flow enriched in incompatible trace elements (Ba, Th, U, Nb, Sr, REE). Lowest flow in Nuuit Member in profile 37, Nuup Qaava, western Innerit peninsula.
278520	Weakly plagioclase-phyric magnesian basalt lava, lowest flow in Skalø Member in profile 50, Umiiarfik South, northern Svartenhuk Halvø.
262896	Plagioclase-phyric, 50 m thick basalt lava flow. Lower Skalø Member in profile 41b, Skalø South, southern Skalø.
262754	Plagioclase-phyric basalt lava flow. Top flow in profile 64, Paannivik, southern Innerit peninsula.
262988	Plagioclase-phyric basalt lava flow. Middle Skalø Member in profile 62, Sigguk, western Svartenhuk Halvø.
262912	Plagioclase-phyric basalt lava flow. Upper Skalø Member in profile 41b, Skalø South, southern Skalø.
262697	Plagioclase-phyric basalt lava flow with very high TiO_2. Skalø Member, highest preserved flow in profile 55, Aputituut, central Svartenhuk Halvø,

relatively evolved magmas produced by fractionation in large, presumably deep-seated magma chambers. The decrease in Al_2O_3 and CaO and increase in FeO* in basalts with *mg*-number <57 reflect plagioclase fractionation (Fig. 76). The stratigraphic variations in TiO_2 with height, as seen in Fig. 42, reflect slow variations in the input/output ratio of magma in the chamber.

The Tunuarsuk Member contains a significant component of picrites (with *mg*-numbers > *c*. 68), which the two younger members do not. This may be a result of decreasing magma production rates with time and thus longer residence times in the magma chambers. The very evolved lava flows on top of the Skalø Member on Aputituut (profile 55) mentioned above may be interpreted as the products of prolonged fractionation in a dying magma chamber that was no longer replenished from deeper levels.

Concentrations of incompatible elements increase with increasing fractionation of the magma, and all three members follow similar fractionation trends (Fig. 77). The significance of some relatively enriched samples and crossing and parallel REE and multi-element curves (Fig. 79) is discussed in the later section on enriched mantle components.

Naqerloq Formation

Arfertuarsuk Member

The Arfertuarsuk Member comprises tholeiitic basalts with relatively high contents of many incompatible elements. Their levels of silica saturation (5–20 wt% normative hypersthene, average 13.0 wt%) are only slightly lower than for the basalts of the Svartenhuk Formation (5–23 wt% normative hypersthene, average 16.2 wt%). They are thus not alkaline, as alkali basalts by definition do not have normative hypersthene (Le Maitre 2002). Most of them are not even transitional (i.e. with low normative hypersthene), although Icelandic basalts with similar compositions are often called transitional or alkaline. Major element variation diagrams for the Arfertuarsuk Member are shown in Fig. 80 and REE and multi-element diagrams in Fig. 81. Other trace-element data are included in the variation diagrams for the Svartenhuk Formation in Figs 77 and 78. The Arfertuarsuk trachyte and its inclusions are compositionally far off scale in the variation diagrams but are shown in the REE and multi-element diagrams. Representative chemical analyses are shown in Table 7.

The Arfertuarsuk Member basalts have 3.8–8.6 wt% MgO with an average of 5.8 wt% MgO. TiO_2 is in the range 1.8–4.0 wt%, and the average TiO_2 content is 3.0 wt% (79 analyses). The member is thus on average slightly more evolved to lower MgO and higher TiO_2 contents than the basalts of the Svartenhuk Formation, though there are large compositional overlaps for these elements (Fig. 80). K_2O and P_2O_5 contents are notably high, with averages of 0.80 wt% K_2O and 0.39 wt% P_2O_5 compared to the Svartenhuk Formation with averages of 0.24 wt% K_2O and 0.21 wt% P_2O_5; there are only small compositional overlaps for these elements (Fig. 80). The P_2O_5/TiO_2 ratio is useful for distinguishing samples that have not been analysed for trace elements because this ratio is on average 0.10 ± 0.01 for the Svartenhuk Formation and 0.13 ± 0.01 for the Arfertuarsuk Member.

The concentrations of other incompatible elements are also significantly higher in the basalts of the Arfertuarsuk Member than in those of the Svartenhuk Formation (Fig. 77). Moreover, many petrogenetically important element ratios such as P_2O_5/TiO_2, Ba/Sr, Zr/Y, Nb/Y, Nb/Zr, Nb/La, La/Sm and Tb/Lu are significantly increased relative to basalts of the Svartenhuk Formation. All Arfertuarsuk Member basalts have La_N/Sm_N >1 (see also Figs 81, 83). The three uppermost flows in the Arfertuarsuk profile show a reversal to less enriched compositions with element ratios moved towards those in the Svartenhuk Formation; these three flows are distinguishable in several diagrams, particularly in Fig. 81.

The basalt flows below and above the trachyte level are compositionally different; those below the trachyte level are less evolved than those above it. The former flows have *mg*-numbers of 55–58 and plot in tight clusters in many diagrams (Figs 77, 80, 81).

The Arfertuarsuk trachyte flow has a very evolved composition and contains on average (5 analyses) 65.7 wt% SiO_2, 0.83 wt% TiO_2, 0.24 wt% MgO, 16.4 wt% Al_2O_3, 6.1 wt% Na_2O, 5.2 wt% K_2O and 0.26 wt% P_2O_5. It is anorthite normative and is thus not peralkaline; the normative content of albite + orthoclase is 85.5 %, reflecting the very high modal content of alkali feldspar. The trachyte magma had fractionated plagioclase, apatite and Fe-Ti oxide, as seen in the low concentrations of Sr, P, and Ti in the trace and multi-element diagrams (Fig. 81). The composition of the syenite xenolith (Table 7) shows that the xenoliths are closely related to the trachyte itself. They may represent fragments of deposits along the sidewall or in the top zone of the magma chamber where the trachyte melt fractionated.

The dark, fine-grained inclusion (Fig. 67) has the most extreme trace-element composition of all samples; its REE and multi-element patterns are parallel to those of the trachyte but at much higher levels, and relative losses of Rb, Ba, K, Sr, P, Eu and Ti are evident. One possible explanation for this is that the inclusion represents the result of filter pressing of residual liquid into available pockets (a sort of aplite veins without quartz) that in the process left feldspar behind. This would increase the concentration of incompatible elements in the liquid and also explain the negative Eu anomaly and the low Rb, Ba and K contents.

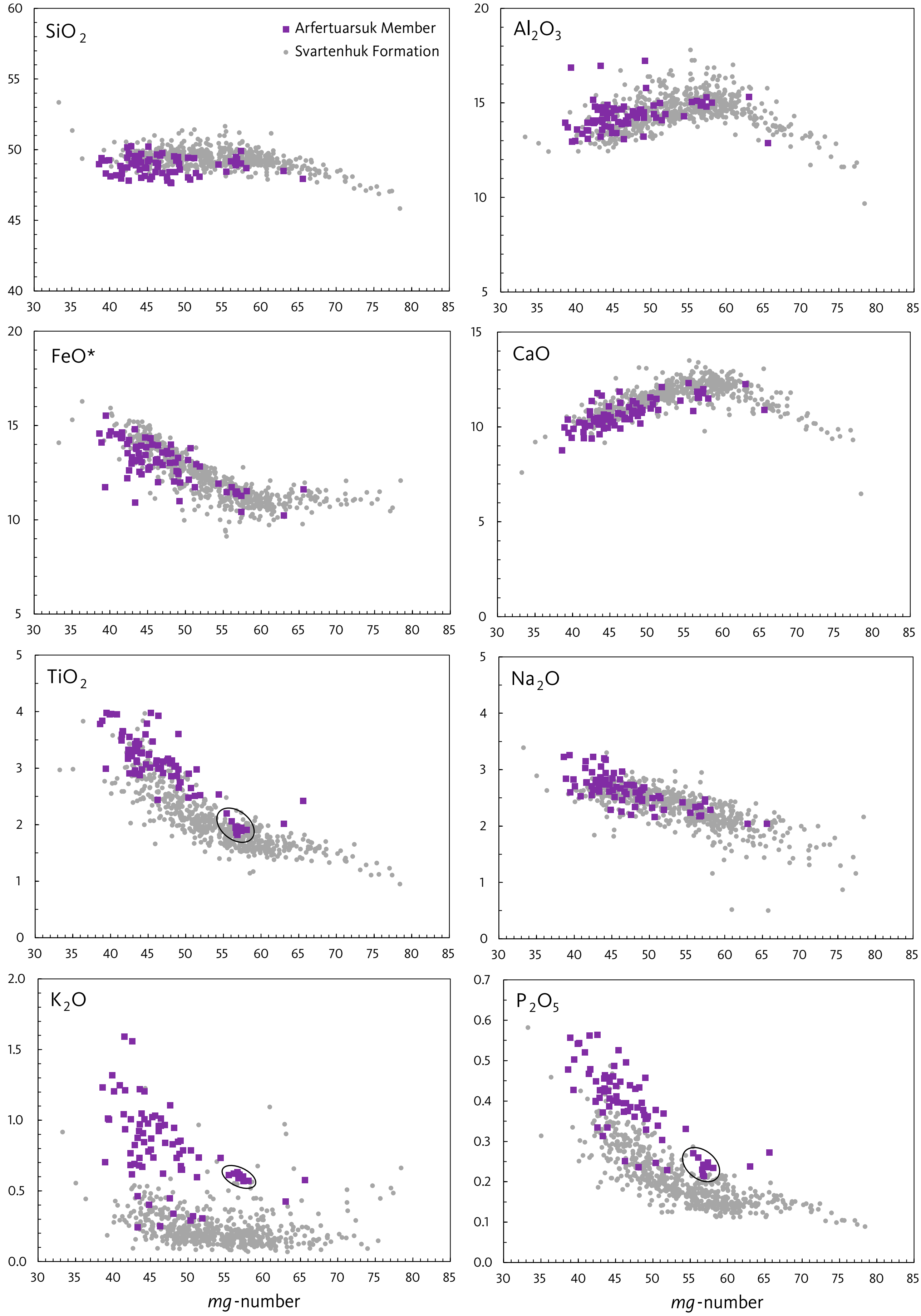

Fig. 80 Major-element variation diagrams for basalts of the Naqerloq Formation. A group of low-Ti basalts from the lowest part of the formation below the Arfertuarsuk trachyte flow is encircled in some diagrams. Data for the Svartenhuk Formation in grey for comparison. Vertical axes in wt% oxides.

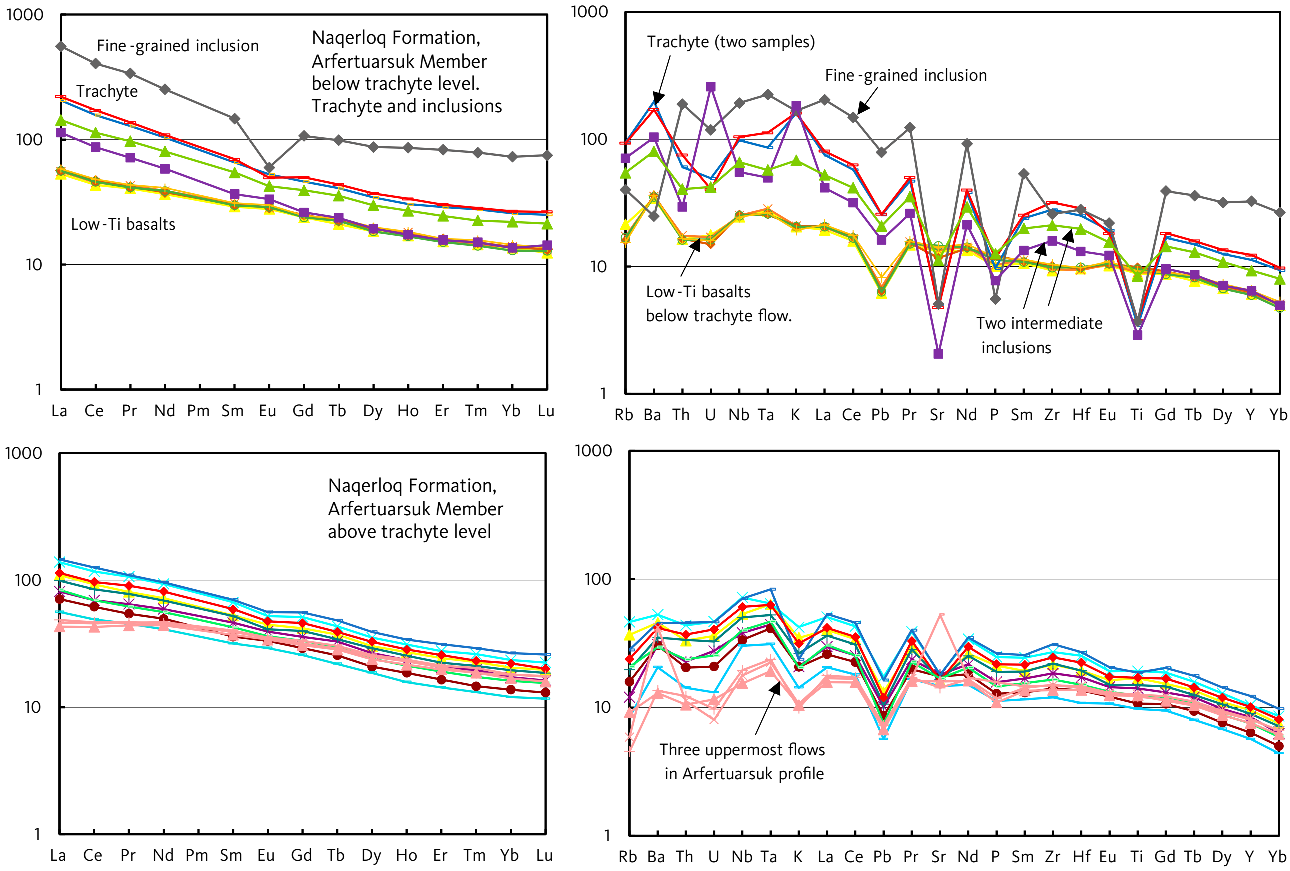

Fig. 81 REE and multi-element diagrams for representative rocks of the Naqerloq Formation. The different colours of the curves are intended to aid the distinction of the individual samples. **Left** diagrams: chondrite normalised. **Right** diagrams: primitive mantle normalised. Normalisation factors from McDonough & Sun (1995).

Table 7 Notes on analysed samples from the Naqerloq Formation and the Delta-1 drill hole

262998	Brown aphyric basalt relatively low in TiO_2. Second lava flow in Arfertuarsuk Member, profile 62, Sigguk, western Svartenhuk Halvø.
262879	Brown aphyric basalt relatively low in TiO_2. First lava flow in Arfertuarsuk Member, profile 59, Qooruusaq, western Svartenhuk Halvø.
278607	Brown aphyric basalt, unlike other rocks in Arfertuarsuk Member not enriched in incompatible elements. One of three flows with this character, the three highest lava flows in profile 36b, Arfertuarsuk, south-western Svartenhuk Halvø.
278601	Brown aphyric basalt with an enriched composition typical of Arfertuarsuk Member. Lava flow in the middle of profile 36b, Arfertuarsuk, south-western Svartenhuk Halvø.
263512	Strongly plagioclase-glomerophyric basalt. Lava flow in the middle part of Arfertuarsuk Member in profile 62, Sigguk, western Svartenhuk Halvø.
251372	Plagioclase-clinopyroxene-phyric basalt. Lava flow in the lower part of Arfertuarsuk Member in profile 41b, southern Skalø. Dated sample: 54.86 ± 0.44 Ma (Larsen *et al*. 2016).
263516	Plagioclase-glomerophyric basalt. Lava flow in the upper part of Arfertuarsuk Member in profile 62, Sigguk, western Svartenhuk Halvø.
278588	Plagioclase-glomerophyric basalt. Lava flow in the middle part of Arfertuarsuk Member in profile 36b, Arfertuarsuk, south-western Svartenhuk Halvø.
278660	Anorthoclase trachyte lava flow, sample from the top of the flow. Coastal exposure in innermost Arfertuarsuk inlet, south-western Svartenhuk Halvø.
278669.2	Decimetre-sized syenite xenolith in the Arfertuarsuk trachyte flow near its base. Coastal exposure in innermost Arfertuarsuk inlet, south-western Svartenhuk Halvø.
568601.2	Dark, fine-grained xenolith in the Arfertuarsuk trachyte flow (Fig. 67). Profile 67 in the upper Qooruusaq valley, western Svartenhuk Halvø.
SWC-17	Sidewall core at 2598 m depth in the Delta-1 well. The sample is dated at 54.5 ± 1.5 Ma. Data from Nelson et al. (2015). Note the compositional similarity to the onshore Naqerloq Formation. The Delta-1 well is situated *c*. 100 km WSW of Svartenhuk Halvø (Fig. 1).

Table 7 (continued) Chemical analyses of rocks from the Naqerloq Formation and the Delta-1 drill hole

Unit	**Arfertuarsuk Memer**											**Offshore**
GGU no.	**262998**	**262879**	**278607**	**278601**	**263512**	**251372**	**263516**	**278588**	**278660**	**278669.2**	**568601.2**	**SWC-17**
Profile no.	62	59	36b	36b	62	41b top	62	36b	-	-	67	Well
Name	Sigguk	Qooruus.	Arfertuar.	Arfertuar.	Sigguk	Skalø	Sigguk	Arfertuar.	Arfertuar.	Arfertuar.	Qooruus.	Delta-1
	Major elements in wt% (XRF analyses)											
SiO_2	48.13	48.98	47.00	49.28	48.31	48.17	48.19	48.27	62.65	61.39	61.11	47.41
TiO_2	1.91	1.85	2.43	2.89	3.06	3.26	3.42	3.87	0.69	0.58	0.74	3.57
Al_2O_3	14.53	15.01	14.54	13.79	13.78	14.38	13.35	12.73	15.74	16.40	17.38	13.44
Fe_2O_3	3.88	4.48	5.17	6.65	6.40	5.42	5.74	5.62	2.22	2.66	8.17	15.35*
FeO	7.58	6.19	8.24	6.81	7.80	8.21	8.39	9.14	2.10	0.85		
MnO	0.19	0.16	0.21	0.19	0.26	0.19	0.22	0.22	0.15	0.49	0.12	0.22
MgO	7.36	6.80	6.46	5.60	5.17	4.86	5.15	4.66	0.50	0.27	0.08	4.83
CaO	11.57	11.76	11.32	10.38	9.98	10.13	9.98	9.25	1.69	2.94	0.40	10.21
Na_2O	2.42	2.39	2.28	2.70	2.79	2.77	2.82	2.77	5.82	5.87	6.36	2.67
K_2O	0.59	0.56	0.29	0.83	0.96	0.81	0.91	1.29	4.63	5.29	4.83	0.95
P_2O_5	0.23	0.24	0.24	0.38	0.42	0.42	0.45	0.53	0.20	0.16	0.11	0.45
Volatiles	1.64	1.56	2.10	1.16	1.21	1.32	1.42	1.30	1.74	1.82	0.46	0.29
Sum	100.03	99.98	100.28	100.66	100.14	99.94	100.04	99.66	98.14	98.73	99.77	99.39
FeO*	11.07	10.22	12.89	12.80	13.56	13.09	13.55	14.20	4.10	3.24	7.35	13.81
mg-no.	57.37	57.39	50.35	46.95	43.54	42.89	43.46	39.92	19.80	14.41	2.19	41.44
	Trace elements in ppm (ICP-MS analyses)											*XRF anal.*
Sc	35.9	37.98	40.0	42.8	32.38	32.96	33.68	41.2	6.19	5.58	5.54	27
V	308	312	364	321	324	347	359	350	13.4	6.14	24.9	336
Cr	172	149	48.5	61.6	28.9	62.0	48.6	39.9	1.99	1.73	6.51	42
Co	46.5	44.8	51.8	50.1	47.2	43.0	44.8	49.0	13.4	13.5	10.4	37
Ni	92.3	83.8	64.5	57.7	41.4	45.9	44.1	44.1	1.44	1.55	11.3	46
Cu	121	118	216	204	181	154	167	189	4.94	4.41	8.03	201
Zn	82	85.3	108	122	128	130	135	150	62.7	55.6	306	123
Ga	18.6	19.6	21.3	21.7	22.4	24.4	22.9	24.6	29.9	27.2	35.2	24
Rb	10.1	9.26	2.71	18.9	18.3	12.1	14.3	33.0	56.3	42.5	24.1	9
Sr	289	282	282	332	331	357	322	334	100	40.8	101	378
Y	25.7	27.8	34.6	37.2	41.2	41.4	43.4	51.6	48.5	27.7	140	44.5
Zr	103	109	157	219	248	244	258	321	293	167	271	275
Nb	16.5	16.1	12.8	32.2	35.2	37.8	40.0	47.8	64.3	36.3	126	41.1
Cs	0.030	0.118	0.041	0.091	0.056	0.124	0.092	0.259	0.108	0.107	0.084	
Ba	232	240	89.2	236	255	244	275	372	1303	684	164	348
La	13.3	13.8	11.5	23.3	25.4	25.0	27.0	35.2	48.7	26.9	132	
Ce	28.1	29.4	28.6	51.5	55.2	55.3	59.3	76.3	96.2	53.2	248	
Pr	3.83	4.01	4.33	6.97	7.51	7.83	8.38	10.2	11.9	6.64	31.3	
Nd	17.7	18.7	20.8	30.9	33.4	34.4	37.1	45.2	47.4	26.6	115	
Sm	4.40	4.60	5.77	7.38	8.16	8.25	8.74	10.6	9.70	5.43	21.7	
Eu	1.62	1.68	1.97	2.34	2.45	2.59	2.67	3.12	2.96	1.88	3.37	
Gd	4.74	4.89	6.29	7.92	8.49	8.76	9.12	11.2	9.15	5.20	21.2	
Tb	0.808	0.839	1.05	1.25	1.32	1.34	1.41	1.81	1.47	0.854	3.57	
Dy	4.52	4.90	6.13	7.01	7.45	7.61	8.05	9.65	8.44	4.77	21.4	
Ho	0.918	1.00	1.26	1.38	1.47	1.50	1.55	1.90	1.66	0.946	4.68	
Er	2.42	2.57	3.31	3.62	3.83	3.86	4.12	5.05	4.60	2.51	13.2	
Tm	0.349	0.388	0.458	0.505	0.566	0.569	0.574	0.702	0.682	0.372	1.94	
Yb	2.08	2.32	2.92	3.10	3.31	3.40	3.56	4.23	4.12	2.18	11.7	
Lu	0.317	0.336	0.432	0.457	0.477	0.486	0.494	0.597	0.614	0.352	1.84	
Hf	2.79	2.77	4.01	5.41	5.76	5.98	6.32	8.02	7.10	3.72	7.92	
Ta	0.957	0.980	0.876	2.23	2.08	2.15	2.33	3.24	3.17	1.84	8.30	
Pb	0.947	1.24	1.09	1.72	1.69	1.71	1.79	2.71	3.81	2.42	11.8	4
Th	1.29	1.31	0.975	2.66	2.81	2.55	2.93	4.14	4.81	2.33	15.0	3
U	0.330	0.324	0.198	0.714	0.772	0.678	0.824	1.08	1.00	5.25	2.39	1

FeO*= total iron calculated as FeO. Total iron determined as Fe_2O_3 is marked by an *

mg-number = 100 × atomic Mg/(Mg+Fe^{2+}), with the iron oxidation ratio adjusted to Fe_2O_3/FeO = 0.15.

For notes on the samples, see previous page.

Intrusions

The relatively few trace-element analyses of dykes and sills are plotted in Figs 77, 78 and 82. Representative chemical analyses are shown in Table 8. A picrite dyke from the Nunavik Member and two strongly contaminated dykes similar to the Kakilisaat Member are easily identified chemically. The basaltic dykes form two compositional groups, one with a depleted and one with an enriched trace-element pattern, similar to the compositions of the Svartenhuk Formation and the Naqerloq Formation, respectively. Presumably the dykes of the two groups fed the respective formations, and the compositional difference is therefore also an age indicator. This is supported by the results of Chauvet *et al*. (2019) who presented ^{40}Ar–^{39}Ar ages for two dykes, one with 'Svartenhuk chemistry' and an age of 58.98 ± 0.93 Ma, and one with 'Naqerloq chemistry' and an age of 54.41 ± 0.99 Ma.

The large sills along the Cretaceous boundary fault system have compositions identical to the Svartenhuk Formation basalts (Table 8). We therefore consider that these intrusions represent the Svartenhuk Formation and thus are of late Paleocene age. This is in contrast to the sills intruded in a similar setting along the boundary fault on Nuussuaq, which are of Eocene age and have corresponding enriched compositions (Storey *et al*. 1998; Larsen *et al*. 2009).

Primary magmas, melting conditions and development with time

Vaigat Formation

As described above, the earliest volcanic unit deposited in eastern Svartenhuk Halvø, the Kakilisaat Member of the Vaigat Formation, is thoroughly crustally contaminated and also bears an imprint of an enriched component. The following unit, the Nerutusoq Member, is much less contaminated and contains a distinct enriched component. We consider that these two members are related and ultimately derived from similar parental magmas generated in the asthenosphere. Crustal contamination and trace-element enrichment are post-generation modifications, and consequently the asthenosphere-derived primary magma for the Kakilisaat and Nerutusoq Members cannot be characterised in detail. It was, however, picritic because the high Cr contents (>1000 ppm) in the least contaminated samples indicate derivation from magmas with ≥15 wt% MgO (Fig. 74). The simplest assumption is that the primary magma was similar to that of the overlying Nunavik Member. There is no evidence of smaller degrees of melting than in the Nunavik Member as suggested by Agranier *et al*. (2019). The post-melting modifications were achieved when the magmas intruded the local lithosphere and came into contact with crustal material and old enriched material. After this stage, the magmas of the Nunavik Member were able to pass unchanged through the lithosphere to the surface without stalling in magma chambers and becoming contaminated on the way.

The unmodified parental magma of the Nunavik Member was neither crustally contaminated nor did it contain a very enriched component. The strong compositional similarity to the Ordlingassoq Member of the Vaigat Formation on Nuussuaq and Disko includes the slope of both the light REE and the heavy REE patterns, with Tb_N/Lu_N averaging 1.61 ± 0.15 for the Nunavik Member and 1.63 ± 0.15 for the Ordlingassoq Member (Pedersen *et al*. 2018), indicating residual garnet in the source mantle (Fig. 83). The Sr-Nd isotope ratios are also similar, with both members mostly having $^{87}Sr/^{86}Sr$ = 0.7031–0.7034 and $^{143}Nd/^{144}Nd$ = 0.5129–0.5130 (Holm *et al*. 1993; Lightfoot *et al*. 1997; Larsen & Pedersen 2009; Agranier *et al*. 2019). The melting conditions for

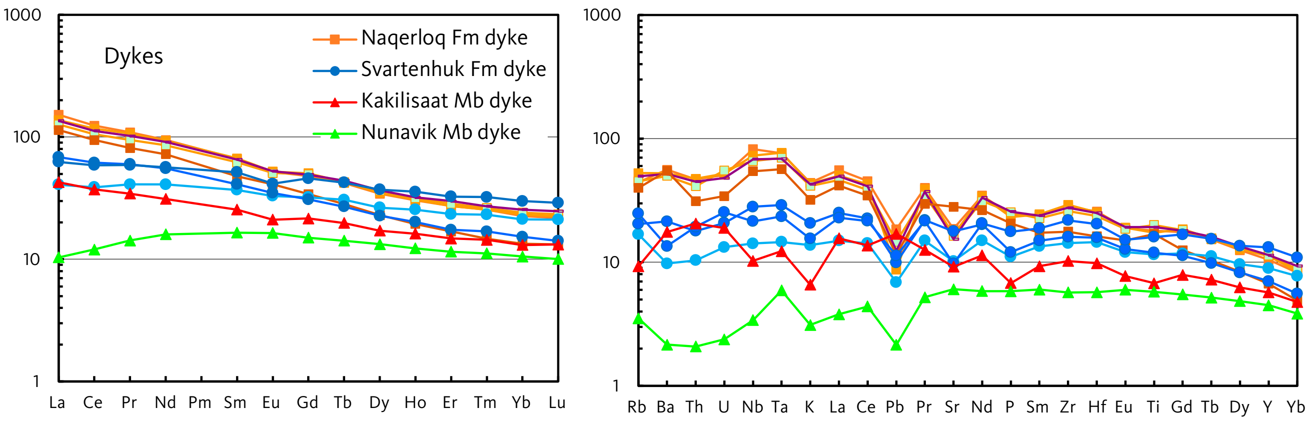

Fig. 82 REE and multi-element diagrams for dykes. The distinction between dykes of the Svartenhuk and Naqerloq Formations is described in the text; see also Fig. 85. The Ta peak in the multi-element pattern of the Nunavik Member picrite dyke is a slight contamination from the grinding vessel. **Left** diagram: chondrite normalised. **Right** diagram: primitive mantle normalised. Normalisation factors from McDonough & Sun (1995).

Table 8 Chemical analyses of dykes, sills and samples dredged from Baffin Bay

Unit	Dykes								Sills		Dredged samples	
GGU no.	**251511**	**251387**	**165242**	**262982**	**262799**	**262994**	**263522**	**278399**	**278320**	**251385**	**BB8-13D8**	**BB8-12D2**
Profile no.	9	2	31	62	64b	62	62	52	44c		Upernavik Escarpment	
Location	Pk 1078	Qinngusa.	Aputit.Qaq.	Sigguk	Paannivik	Sigguk	Sigguk	Nuuit Qaq.	Simiutaq	Qinngusa.	Baffin Bay	Baffin Bay
Affinity	Kakilis. Mb	Nunav. Mb	Sva. Fm	Sva. Fm	Sva. Fm	Naq. Fm	Naq. Fm	Naq. Fm	Sva. Fm	Sva. Fm	Sva. Fm	Sva. Fm
SiO_2	49.63	46.11	48.32	49.48	48.59	45.18	46.85	48.60	47.86	48.86	47.77	48.21
TiO_2	1.36	1.16	1.72	2.32	3.22	3.41	4.03	3.49	1.88	2.26	2.77	2.53
Al_2O_3	13.67	12.08	13.65	14.12	13.39	14.16	12.60	13.60	15.56	14.83	13.28	13.20
Fe_2O_3	2.26	3.52	3.25	4.80	3.74	2.69	5.39	6.25	3.80	5.12	16.01*	16.22*
FeO	7.94	7.48	8.15	8.50	10.73	10.87	10.03	6.79	7.68	8.09		
MnO	0.16	0.17	0.22	0.23	0.23	0.22	0.23	0.20	0.17	0.20	0.251	0.191
MgO	9.69	16.24	9.21	5.96	5.45	6.57	4.97	4.15	6.46	5.18	6.16	5.21
CaO	10.41	9.69	11.69	11.02	10.22	11.66	9.93	9.14	11.96	10.68	10.35	9.58
Na_2O	1.99	1.63	2.02	2.68	2.51	2.39	2.93	3.11	2.27	2.64	2.67	2.90
K_2O	0.19	0.09	0.17	0.40	0.45	0.93	1.20	1.25	0.19	0.33	0.25	0.53
P_2O_5	0.14	0.12	0.15	0.23	0.37	0.43	0.52	0.48	0.19	0.23	0.27	0.30
Volatiles	2.32	1.82	1.07	0.84	1.23	1.45	1.30	2.61	2.24	1.57	-	-
Sum	99.76	100.11	99.62	100.57	100.12	99.95	99.98	99.67	100.26	99.99	99.78	98.87
FeO*	9.97	10.65	11.07	12.82	14.09	13.29	14.88	12.41	11.10	12.70	14.41	14.59
mg-no	66.28	75.53	62.71	48.47	43.89	50.00	40.32	40.34	54.07	45.21	46.39	41.94
	Trace elements in ppm (ICP-MS analyses)											
Sc	36.2	34.5	39.8	40.6	41.0	30.7	33.2	29.7	36.1	36.9	45	42
V	272	290	356	435	511	384	399	382	365	398	487	416
Cr	607	1202	518	99.4	86.5	61.9	30.5	13.5	234	46.8	89	45
Co	52.1	68.8	54.1	47.1	45.8	53.4	48.5	79.6	44.8	40.6	60	57
Ni	257	621	222	63.0	69.0	81.1	38.6	94.6	102	45.7	68	52
Cu	104	110	169	286	449	197	271	195	188	247	291	301
Zn	77.3	79.6	83.7	110	132	113	151	150	91.9	104	127	121
Ga	18.9	17.6	18.4	21.2	22.9	20.5	23.9	24.4	21.4	21.9	-	-
Rb	5.56	2.12	2.89	10.1	14.9	24.0	27.1	31.6	2.68	6.25	2.0	7.5
Sr	183	121	180	203	194	559	324	332	257	211	203	209
Y	24.5	19.3	27.1	38.5	56.7	28.9	48.6	48.3	27.7	36.7	46	46
Zr	107	59.8	91.0	150	229	185	273	306	115	136	163	164
Nb	6.75	2.24	6.29	9.33	14.1	35.8	43.3	47.9	6.72	7.82	11.4	13.0
Cs	0.247	0.088	0.059	0.286	0.217	0.203	0.158	0.175	0.058	0.064	0.04	0.06
Ba	116	14.22	43.6	64.4	89.0	361	330	346	50.5	67.3	73	88
La	10.1	2.46	7.24	9.68	14.8	27.0	30.1	32.6	7.15	9.53	14.1	13.4
Ce	22.9	7.36	17.3	23.8	36.1	57.9	64.4	71.7	19.2	23.4	35.7	33.5
Pr	3.20	1.32	2.53	3.80	5.48	7.55	8.79	9.89	2.99	3.61	4.9	4.7
Nd	14.2	7.30	12.3	18.7	25.9	33.0	39.0	42.6	15.1	17.2	24.1	24.3
Sm	3.77	2.44	3.61	5.46	7.63	7.04	9.20	9.92	4.43	5.22	6.68	6.98
Eu	1.19	0.92	1.30	1.86	2.34	2.31	2.86	2.94	1.55	1.81	2.41	2.57
Gd	4.30	2.99	4.60	6.41	9.14	6.80	9.92	10.1	5.21	6.46	6.43	6.39
Tb	0.714	0.513	0.772	1.11	1.53	1.02	1.52	1.55	0.850	1.08	1.31	1.31
Dy	4.22	3.27	4.88	6.50	9.14	5.65	8.94	8.59	5.14	6.76	7.58	7.57
Ho	0.885	0.671	1.01	1.39	1.95	1.06	1.73	1.68	1.03	1.38	1.59	1.57
Er	2.36	1.84	2.71	3.75	5.20	2.70	4.55	4.35	2.73	3.80	4.53	4.39
Tm	0.356	0.276	0.402	0.572	0.797	0.363	0.649	0.627	0.389	0.545	0.63	0.58
Yb	2.10	1.70	2.44	3.41	4.81	2.16	3.87	3.72	2.38	3.36	3.69	3.61
Lu	0.325	0.247	0.373	0.520	0.713	0.325	0.575	0.553	0.341	0.517	0.44	0.44
Hf	2.78	1.62	2.60	4.12	5.77	4.58	6.67	7.16	3.08	3.67	4.18	4.40
Ta	0.455	0.219	0.514	0.540	0.867	2.09	2.58	2.85	0.453	0.514	0.65	0.75
Pb	2.55	0.323	0.695	1.03	1.70	1.73	2.20	1.30	0.846	1.58	3	2
Th	1.64	0.165	0.479	0.824	1.54	2.47	3.27	3.76	0.546	0.946	2.26	1.34
U	0.384	0.048	0.147	0.269	0.515	0.696	1.12	1.06	0.176	0.273	0.49	0.39

FeO*= total iron calculated as FeO. Total iron determined as Fe_2O_3 is marked by an *

mg-number = 100 × atomic Mg/(Mg+Fe^{2+}), with the iron oxidation ratio adjusted to Fe_2O_3/FeO = 0.15.

For notes on the samples, see next page.

Table 8 (continued) Notes on analysed samples of dykes and sills and samples dredged from Baffin Bay

251511	Silicic magnesian basalt, 40 cm wide dyke in hyaloclastite of the Kakilisaat Member of the Vaigat Formation, probably a feeder dyke for this member. Profile 9, Peak 1078 m, eastern Svartenhuk Halvø.
251387	Olivine-phyric picrite, 3 m wide dyke in picrite lava flows of the Nunavik Member of the Vaigat Formation, probably a feeder dyke for this member. Qinngusaaq mountain, eastern Svartenhuk Halvø east of the Cretaceous boundary fault system.
165242	Olivine-phyric basalt, 5–6 m wide dyke in lava flows of the Skalø Member of the Svartenhuk Formation. Geochemical affinity to the Svartenhuk Formation. Profile 31, Aputituut Qaqqaat, south-central Svartenhuk Halvø.
262982	Plagioclase-glomerophyric basalt, 2 m wide, coast-parallel dyke in lava flows of the Skalø Member of the Svartenhuk Formation. Geochemical affinity to the Svartenhuk Formation. Profile 62, Sigguk, western Svartenhuk Halvø.
262799	Basalt dyke in lava flows of the Tunuarsuk Member of the Svartenhuk Formation. Geochemical affinity to the Svartenhuk Formation. Profile 64, Paannivik, southern Innerit peninsula.
262994	Aphyric basalt, 1.2 m wide, NW-striking dyke in lava flows of the Skalø Member of the Svartenhuk Formation. Geochemical affinity to the Naqerloq Formation. Profile 62, Sigguk, western Svartenhuk Halvø.
263522	Aphyric basalt dyke in lava flows of the Nuuit Member of the Svartenhuk Formation. Geochemical affinity to the Naqerloq Formation. Coastal cliff in profile 62, Sigguk, western Svartenhuk Halvø.
278399	Aphyric basalt, 2.5 m wide dyke in fault zone in lava flows of the Skalø Member of the Svartenhuk Formation. Geochemical affinity to the Naqerloq Formation. Profile 52, Nuuit Qaqqaat, north-western Svartenhuk Halvø.
278320	Basalt (dolerite), *c*. 50 m thick transgressive sill in lava flows of the Nuuit Member of the Svartenhuk Formation close to the Cretaceous boundary fault system (Fig. 6). Geochemical affinity to the Svartenhuk Formation. Profile 44c, Kuugaartorfik, northern Svartenhk Halvø.
251385	Plagioclase-glomerophyric basalt, up to 30 m thick sill in contact with gneiss and cutting pillow breccias and lava flows of the Vaigat Formation (Fig. 6). Geochemical affinity to the Svartenhuk Formation. Qinngusaaq mountain, eastern Svartenhuk Halvø east of the Cretaceous boundary fault system.
BB8-13D8	Basalt dredged on the Upernavik escarpment in Baffin Bay at 73°05.5′ N, 58°09.1′ W, *c*. 80 km north-west of Upernavik. Full sample number BBS08-13D-8. Data from Polteau & Planke 2008. Note geochemical affinity to the Svartenhuk Formation.
BB8-12D2	Basalt dredged on the Upernavik escarpment in Baffin Bay at 73°06.6′ N, 58°16.2′ W, *c*. 80 km north-west of Upernavik. Full sample number BBS08-12D-2. Data from Polteau & Planke 2008. Note geochemical affinity to the Svartenhuk Formation.

the primary magmas of the Vaigat Formation modelled by Larsen & Pedersen (2009) can thus be directly applied to the Svartenhuk Halvø area: the melts were formed beneath a lithospheric lid 80–100 km thick by 15–20% melting of an asthenospheric mantle with residual garnet in the source. The mantle was probably heterogeneous, with highly depleted parts giving rise to magmas with La_N/Sm_N <1 (Fig. 83) and Zr/Y and Nb/Y ratios below the Iceland field (Fig. 84). Less-depleted parts (the 'Icelandic' component of Holm *et al*. 1993) gave rise to magmas with La_N/Sm_N >1 (Fig. 83) and Zr/Y and Nb/Y ratios inside the Iceland field (Fig. 84), all within the same upwelling melting column. The resulting melts were picritic with about 17.5 wt% MgO and passed quickly through the lithosphere to the surface.

Svartenhuk Formation

The Svartenhuk Formation is 1–2 million years younger than the Vaigat Formation (Fig. 3). The change from dominantly picritic magmas of the Vaigat Formation to dominantly basaltic magmas of the Svartenhuk Formation must have involved establishment of large, deep magma chambers, probably at the mantle/crust boundary, in which the magmas fractionated. The same change took place between the Vaigat Formation and the Maligât Formation on Nuussuaq and Disko (Larsen & Pedersen 2009). Considering the age difference between the Maligât and Svartenhuk Formations (Fig. 3), this change was connected with the demise of the Vaigat Formation magmatism and could have been caused by changed tectonic conditions.

Conditions for magma generation in the asthenosphere stayed much the same, as evidenced by key incompatible element ratios. The light and heavy REE ratios for the Svartenhuk Formation plot mainly in the same area as the Nunavik Member (Fig. 83), suggesting similar melting conditions and that the primary magmas were still picritic. Samples with relatively high La_N/Sm_N ratios are discussed below. The Zr/Y vs. Nb/Y relations likewise suggest a mantle source similar to that of the Nunavik Member, with compositions plotting both within and below the Iceland field (Fig. 84). Sr-Nd isotope data for the Svartenhuk Formation are sparse, but the available results suggest isotope ratios similar to those of the Nunavik Member (O'Nions & Clarke 1972; Holm *et al*. 1993; Agranier *et al*. 2019).

A development with time is seen in decreasing heavy REE ratios. Whereas the Nunavik Member has an average Tb_N/Lu_N of 1.61 ± 0.15 (enriched samples excluded), Tb_N/Lu_N averages decrease from 1.56 ± 0.15 in the Tunuarsuk Member to 1.50 ± 0.18 in the Nuuit Member and 1.45 ± 0.08 in the Skalø Member (Fig. 83). As the mantle source was apparently similar to the source of the Nunavik Member, the temporal development in

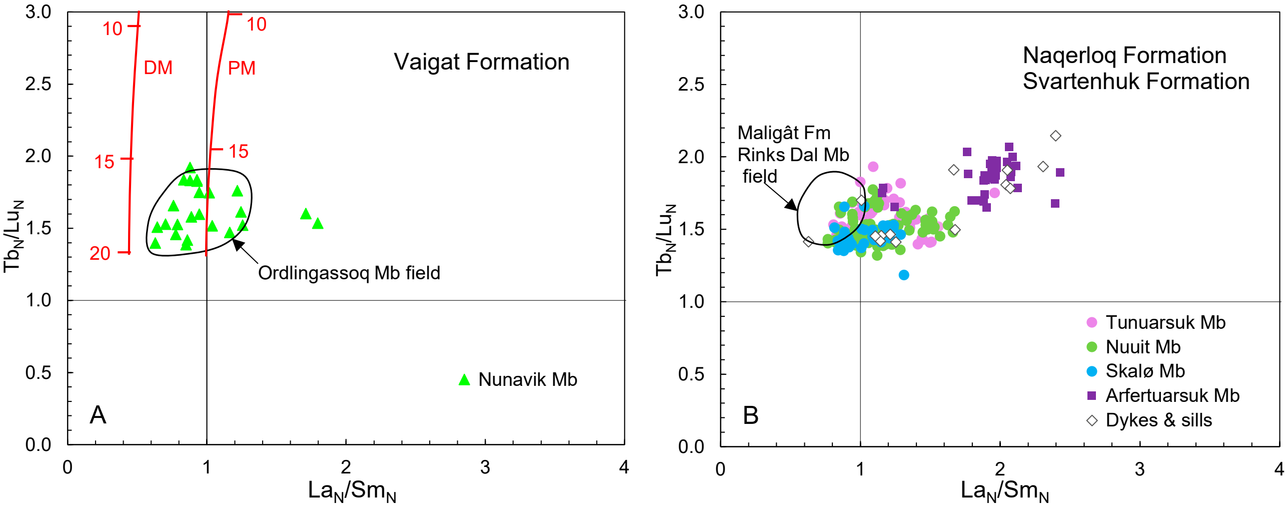

Fig. 83 REE cross plots and mantle melting models for the primary melts of the volcanic rocks of the Svartenhuk region; enriched and crustally contaminated samples are not plotted. Data are chondrite normalised ($_N$). **A**: Nunavik Member of the Vaigat Formation. The black contour line is the field of the Ordlingassoq Member of the Vaigat Formation on Nuussuaq and Disko, with which the Nunavik Member is correlated. **Red curves** for melting in garnet facies are shown for depleted mantle (**DM**) and primitive mantle (**PM**). Numbers on the melting curves indicate degrees of melting (%). Same melting models as in Larsen & Pedersen (2009). Mantle modes and melting modes are from McKenzie & O'Nions (1991). Melting type is non-modal batch melting. DM trace-element starting composition is from McKenzie & O'Nions (1991). PM starting composition is from McDonough & Sun (1995). Partition coefficients are from McKenzie & O'Nions (1991). **B**: Svartenhuk and Naqerloq Formations. The **black contour line** is the field of the Rinks Dal Member of the Maligât Formation on Nuussuaq and Disko; note the difference in La_N/Sm_N between the Svartenhuk and Maligât Formations and their similar values of Tb_N/Lu_N.

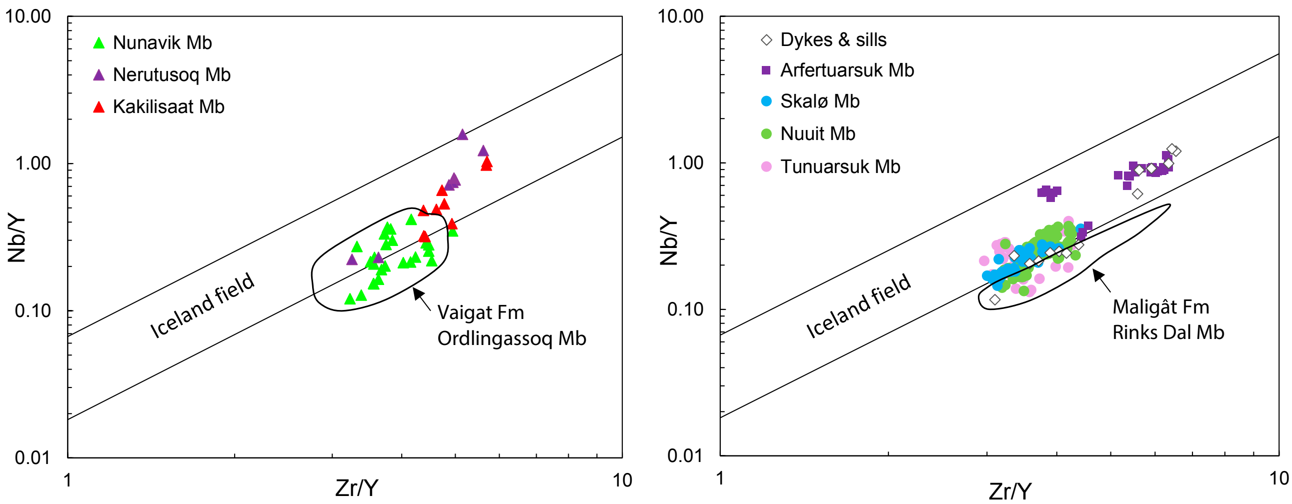

Fig. 84 Nb/Y vs. Zr/Y diagrams. **A**: Vaigat Formation. Black contour line is the field of the Ordlingassoq Member on Nuussuaq and Disko; note the exact resemblance to the Nunavik Member. **B**: Svartenhuk and Naqerloq Formations. Black contour line is the field of the Rinks Dal Member of the Maligât Formation on Nuussuaq and Disko; note the difference to the Svartenhuk Formation. The **two parallel lines** are the upper and lower bounds of the empirical field of data from Iceland, after Fitton *et al*. (1997). Rocks more depleted in Nb, such as many mid-ocean-ridge basalts, plot below the Iceland field. This diagram is useful for distinguishing between 'Icelandic-type' mantle sources and more depleted sources (e.g. Saunders *et al*. 1997; Fitton *et al*. 1997, 1998; Larsen & Pedersen 2009).

Tb_N/Lu_N must have been caused by melting dynamics and is interpreted to indicate a thinning lithospheric lid and shallowing melting in the garnet-to-spinel transition interval at 100–80 km depth, with decreasing amounts of garnet in the source.

The basalts of the Svartenhuk Formation show small but significant compositional differences from the uncontaminated basalts of the Maligât Formation (the Rinks Dal Member) on Disko and Nuussuaq. Whereas in practice the major elements are indistinguishable, trace-element ratios (Figs 83 and 84) show that the Svartenhuk Formation basalts are shifted to higher La_N/Sm_N and higher Nb/Y than most of the Maligât Formation basalts, although there is a partial overlap with the Maligât Formation. The Svartenhuk Formation basalts have La_N/Sm_N in the range 0.8–1.6 and therefore the light REE curves cross each other, as illustrated in Fig. 79. In contrast almost all Maligât Formation basalts have La_N/Sm_N <1 and near-parallel REE curves (Larsen & Pedersen 2009; Pedersen *et al*. 2018). The two formations are best discriminated in a plot of Ce/Y vs. Zr/Nb (Fig. 85) where they occupy separate fields for Zr/Nb <19; the overlap area with Zr/Nb >19 is only sparsely occupied by Svartenhuk Formation basalts. The Naqerloq Formation occupies a separate field. Based on this diagram, Larsen *et al*. (2016) and Pedersen *et al*. (2018, fig. 101) found that the basalt dykes on Disko and Nuussuaq are different from the basalt lava flows of the Maligât Formation but similar to the lava flows of the Svartenhuk and Naqerloq Formations. The dyke ages yield similar results (Fig. 3). The basalt dykes on Disko and Nuussuaq are therefore thought to have fed lava flows of the Svartenhuk and Naqerloq Formations, which must have been present in that area but are now removed by erosion.

A possible interpretation of Fig. 85 is that the Svartenhuk Formation basalts are mixed with an enriched component that is not present in the Maligât Formation basalts.

Naqerloq Formation

The Naqerloq Formation is 2–3 million years younger than the Svartenhuk Formation and the basalts of the two formations are significantly different. As described above, the Naqerloq Formation basalts have higher contents of incompatible elements (Figs 77, 80), higher Zr/Y and Nb/Y ratios plotting within the Iceland field (Fig. 84), higher La/Sm and Tb/Lu ratios (Fig. 83) with a Tb_N/Lu_N average of 1.85 ± 0.12, higher Ce/Y and lower Zr/Nb (Fig. 85). The $^{87}Sr/^{86}Sr$ ratios are slightly higher, around 0.7036, whereas the $^{143}Nd/^{144}Nd$ ratios are similar, 0.5129–0.5130 (Holm *et al*. 1992, p. 352 (Kanísut Member); Agranier *et al*. 2019). The Naqerloq Formation melts must have been generated either by smaller degrees of melting of a mantle source similar to the earlier source, or by melting of an enriched mantle source with higher contents of trace elements than primitive mantle (Fig. 83). Smaller degrees of melting of a mantle source similar to the earlier one should produce differences in the major elements, for example higher Na_2O, which are not seen (Fig. 80), and the small differences in the Sr isotope ratios also favour a different mantle source. The melting modelling in Fig. 83 is based on depleted and primitive mantle compositions, and therefore the degrees and depths of melting of the primary magmas of the Naqerloq Formation cannot be modelled. It is possible that the degrees of melting were smaller than for the magmas of the Svartenhuk Formation, as suggested by Agranier *et al*. (2019), but this is not necessary to explain the data.

Storey *et al*. (1998) suggested that the 'new' mantle material from which the Naqerloq Formation was derived, was a remnant of the Iceland plume head left stranded beneath the West Greenland lithosphere. However, deposition of the Naqerloq Formation was not a local phenomenon, and volcanic rocks chemically similar to those of the Naqerloq Formation are found at several places in and around Greenland. They were drilled in the Delta-1 well offshore Svartenhuk Halvø (Nelson *et al*. 2015) and dredged in the Labrador Sea south of the Hecla High volcanic centre, which was interpreted as their most probable source (Fig. 1; Larsen

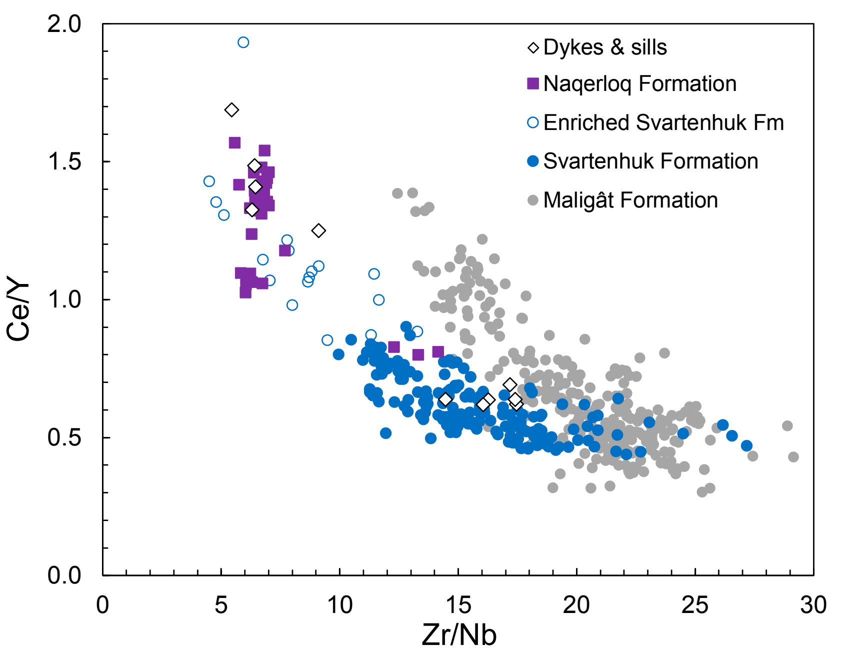

Fig. 85 Ce/Y vs. Zr/Nb diagram demonstrating the compositional differences between the Svartenhuk Formation and the Rinks Dal Member of the Maligât Formation on Disko and Nuussuaq. There is an area of overlap at high Zr/Nb, but for Zr/Nb <19 the separation of the two formations is good. The enriched Svartenhuk Formation basalts form a field extending towards the Naqerloq Formation, which occupies a separate field. The intrusions form two groups corresponding to the Svartenhuk and Naqerloq Formations.

& Dalhoff 2006). Ocean Drilling Program (ODP) Hole 918 offshore south-east Greenland contains a sill with a similar composition (Fitton *et al*. 1998), and the flood basalts in the Scoresbysund area include similar units, particularly the Rømer Fjord Formation (Larsen *et al*. 1989). As far as these rocks have been dated they are of earliest Eocene age, 56–50 Ma. Thus the 'new' mantle can rather be interpreted as a major part of the Iceland plume that spread through the North Atlantic during the phase of plate rearrangement and change of spreading direction from NE–SW to nearly N–S, that took place at the transition from Paleocene to Eocene (Oakey & Chalmers 2012).

Enriched mantle components

Basalts with a chemical imprint of material enriched in the most incompatible trace elements occur in all members of the Vaigat and Svartenhuk Formations and are most common in the Tunuarsuk Member. The patterns of enrichment are variable, as illustrated by the multi-element patterns for selected samples in Fig. 86. Compared to the normal basalts with Nb_N/La_N ~ 1 , some samples have Nb_N/La_N <1, others have Nb_N/La_N >1. Some samples have Ba peaks, one has a U peak, the Nunavik picrite has a distinct Nb–Ta peak, some samples have no extra Pb and Ti shows both peaks and troughs. All samples have increased light REE (La–Sm), and many except the enriched Nuuit Member samples have steeper heavy REE limbs (Gd–Yb) and even lower Y and Yb than the normal basalt. Because of the variability it has not been possible to make a rigid definition of 'enriched' samples; they are generally characterised by having high Nb and high La–Nd relative to their degree of fractionation.

Three enriched samples from the Nunavik and Tunuarsuk Members were analysed for Sr and Nd isotopes by Holm *et al*. (1993); they have high $^{87}Sr/^{86}Sr$ ratios (0.7036–0.7041) and low $^{143}Nd/^{144}Nd$ ratios (0.5128–0.5129) relative to the normal basalts and picrites, indicating a separate source of the enriched material.

Sporadic addition of enriched lithospheric material

In the Nunavik, Tunuarsuk and Skalø Members chemically enriched lavas occur as individual flows surrounded by flows that are chemically normal. We consider it most probable that the magmas of these flows have acquired their enrichment on their way to the surface after they left the melting column (Nunavik Member, the β01 marker unit) and the deep-seated magma chambers (Tunuarsuk and Skalø Members). The enriched components therefore resided in the lithospheric mantle or crust and represent veins or dykes of older alkaline rocks, which could easily be partially melted and assimilated by batches of passing hot basaltic and picritic melts on their way to the surface. The resulting enrichment patterns would depend on the melting mineral assemblage. Older alkaline carbonate-rich rocks are reported from the region, e.g. from the islands of Qinngusaaq and Qeqertarsuaq, both *c*. 30 km east of southern Svartenhuk Halvø (Henderson & Pulvertaft 1987; Knudsen *et al*. 2010; Mott *et al*. 2013).

A similar origin has been proposed for variously enriched rocks akin to those on Svartenhuk Halvø from the Manîtdlat Member in the Vaigat Formation on Disko, some 150 km farther south (Larsen *et al*. 2003; this minor member is associated with the Ordlingassoq Member but not listed in Fig. 3). In detail, however, the occurrences are different; the rocks of the Manîtdlat Member are mostly more enriched than those on

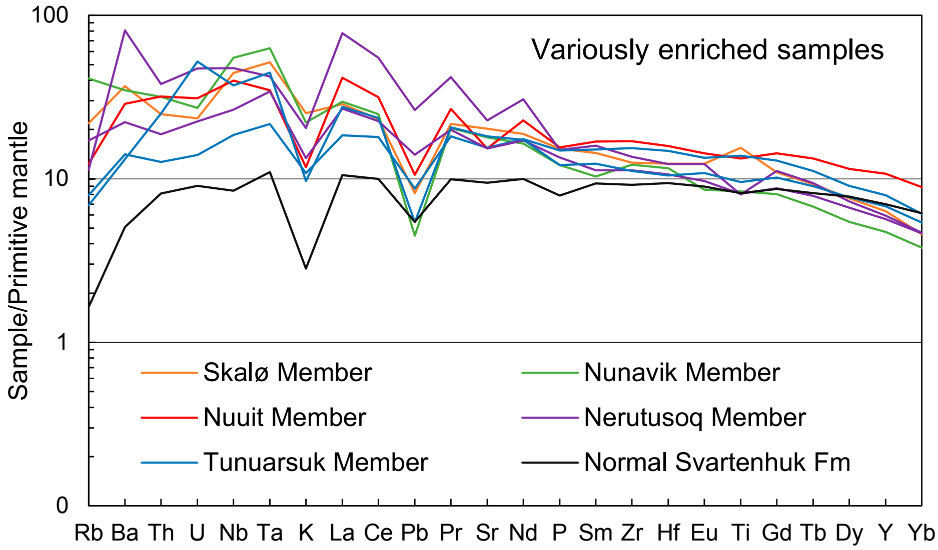

Fig. 86 Multi-element diagram for selected samples showing variable patterns of element enrichment. Ratios between normalised elements such as Nb/La and Th/U vary from greater than one to less than one. Two samples show no Pb enrichment, Ti shows troughs, plains or peaks, and the steepness of the Gd–Yb limb is variable. Samples as as follows: **Nunavik Member**: 251527 (β01 flow); **Nerutusoq Member**: 181013 and 263823; **normal Svartenhuk Formation**: 566518; **Tunuarsuk Member**: 251333 and 262815; **Nuuit Member**: 251338; **Skalø Member**: 278622.

Svartenhuk Halvø, and their Sr-Nd isotope compositions are dissimilar to the few results published by Holm *et al.* (1993).

An enriched asthenospheric mantle component

The Nuuit Member shows a systematic up-section variation of the most incompatible trace elements in most analysed profiles (Fig. 87). The basalts identified as enriched all occur at the base of the member, but not all basal samples are classified as enriched. The lowest samples, whether they are enriched or normal, have relatively high La_N/Nd_N, Nb/Zr, Ba/Sr and other incompatible-element ratios, and with few exceptions the ratios decline systematically up-section. The variation is most clearly seen in the La_N/Nd_N ratio (Fig. 87). This development is seen in six out of eight profiles analysed systematically for trace elements. In contrast, the heavy REE ratios (Tb_N/Lu_N) of all samples are near-constant, suggesting melt generation at near-similar depths. There is no correlation between La_N/Nd_N and the degree of fractionation of the erupted magma as indicated by the MgO and TiO_2 contents (compare Fig. 87 with the TiO_2 profiles in Fig. 42). If the cause of the variation is increasing degrees of melting up-section there should also be differences in other elements, which are not seen. The simplest explanation of the data is that the melting asthenospheric mantle comprised two components, one relatively depleted in incompatible trace elements and another relatively enriched in such elements. Melt from the enriched component was mainly produced at the start of the Nuuit Member and gradually diminished during continued melting.

The two profiles closest to the coast (Sigguk and Fladø) do not show the same pattern as the others, which suggests separate magma chambers beneath the coastal and inland areas.

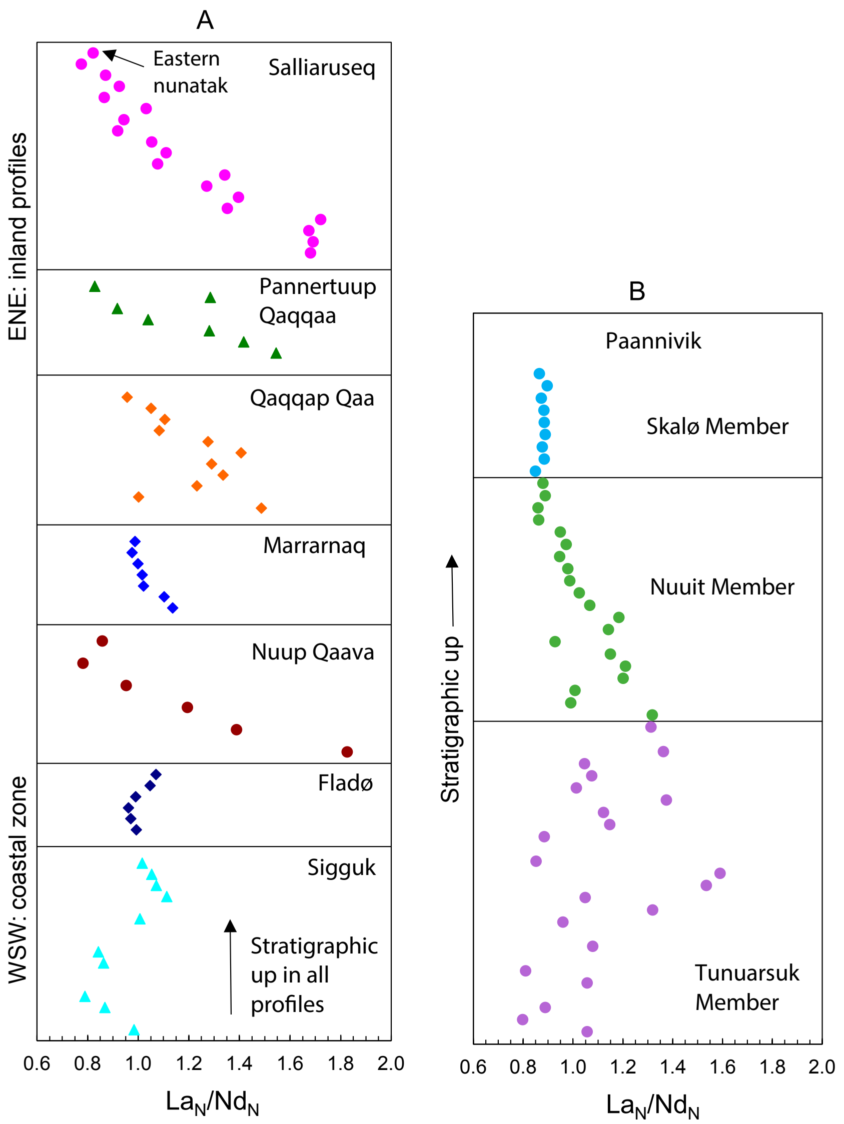

Fig. 87 Stratigraphic variation up-section of La_N/Nd_N (chondrite normalised) in eight densely sampled and analysed profiles. **A**: Data for the Nuuit Member in seven profiles stacked vertically in a WSW–ENE succession. The lowest profiles are those within the coastal zone and the highest profiles are those farthest inland. Different colours and shapes are for clarity. **B**: Up-section variation through the whole Svartenhuk Formation in the Paannivik profile.

Melting and mixing relations in the Svartenhuk Formation

Only one analysed sample profile covers all three volcanic members of the Svartenhuk Formation: the Paannivik profile (64). The plot of La_N/Nd_N vs. stratigraphic height for this profile (Fig. 87B) shows that the three members have different styles of up-section variation. The Tunuarsuk Member shows a large compositional spread and no systematic up-section variation; the Nuuit Member shows the systematic decrease in La_N/Nd_N described above, and the Skalø Member has constant La_N/Nd_N throughout. Other analysed profiles through the Tunuarsuk and Skalø Members are less complete but indicate the same pattern of overall variation as at Paannivik. The data may be interpreted in terms of melting and mixing dynamics. In the Tunuarsuk Member, the melt batches from the mantle did not mix efficiently in the magma chamber where they fractionated, and both very depleted melts with La_N/Nd_N around 0.8 and very enriched melts with La_N/Nd_N up to 1.6 were preserved and erupted. This may have been caused by relatively short residence times in the magma chamber, which also led to more magnesian basalts than in the two subsequent members. In the Nuuit Member mixing of the individual melt batches intruded into the magma chamber became much more efficient, though not complete in the beginning, and at the same time the amount of enriched melt gradually diminished with further melting. In the Skalø Member, mixing was either perfect or the enriched mantle component had been exhausted; the low La_N/Nd_N ratio of 0.9 suggests the latter.

Our interpretations can be tested with isotope data, which are, however, currently not available. A corollary of the interpretations is that the enriched flows in the Tunuarsuk Member may have acquired their enrichment in two different ways, in the asthenosphere and in the lithosphere, which would contribute to their observed compositional variability. The existence of one or more enriched components in the basalts is precisely the reason why basalts of the Svartenhuk Formation can be chemically distinguished from basalts of the Maligât Formation, which lack such a component.

Concluding remarks

The volcanic succession in the northern part of the Nuussuaq Basin, on Svartenhuk Halvø and the areas north and north-east of this, was deposited during a series of geological events that affected the entire basin. The northern succession is therefore in general correlatable to the more southerly parts, but on the formation and member level there are also distinct differences in the geological evolution.

Volcanism on Svartenhuk Halvø may have started somewhat later than in the southern Nuussuaq Basin. The Nunavik Member correlates excellently with the upper part of the Vaigat Formation (Ordlingassoq Member) in the south, but older members of the Vaigat Formation exposed on Disko and Nuussuaq may be present at depth beneath the western Svartenhuk Halvø. At the end of the volcanic activity of the Vaigat Formation, the Mg-rich volcanic rocks formed a N–S elongated, mainly subaerially exposed dome that extended for *c*. 250 km from central Disko and Nuussuaq over Ubekendt Ejland, where thicknesses appear to be greatest, and across Svartenhuk Halvø to the southern Innerit peninsula, where the formation thins and tapers out.

After this stage, the conditions that had allowed picritic magmas to pass relatively unmodified to the surface in the whole Nuussuaq Basin changed. Deep magma chambers developed, in which the picritic magmas evolved to basaltic compositions, and the modes of evolution in the north and south diverged. Volcanism in the south continued with the extrusion of the basalts of the Maligât Formation, whereas in the north there was a hiatus during which quartzofeldspathic sediments were deposited. When volcanism resumed in the north, the basalts of the Svartenhuk Formation were deposited; the bulk of these are younger than the Maligât Formation. The three members of the Svartenhuk Formation are mappable because of morphological and colour differences. They show a large compositional overlap, but up-section variations produced by processes in the magma chambers support the individual nature of the members. The Svartenhuk Formation is probably extensively present offshore where it has been recognised in drill hole Alpha-1 and in dredged samples. Onshore the formation is also present on Ubekendt Ejland and probably in western Nuussuaq and as dykes on Disko and Nuussuaq.

At the transition from Paleocene to Eocene time, there was a volcanic hiatus that lasted for *c*. 1–2 Ma during which tectonic movements and reorganisation of plate spreading directions took place. Volcanism resumed with extrusion of the Naqerloq Formation basalts, which are compositionally different from the Paleocene basalts and were generated in a different mantle. Lava successions of the Naqerloq Formation are preserved only in the westernmost parts of the Nuussuaq Basin from Hareøen to Svartenhuk Halvø and mainly as erosional remnants, but dykes throughout Disko, Nuussuaq and Svartenhuk Halvø show that the formation was erupted over large parts of the Nuussuaq Basin. It is probably also extensively present offshore where it has been recognised in the drill hole Delta-1.

Further studies in the northern part of the Nuussuaq Basin may provide a better understanding of some aspects of the geology. First, the volcanic succession east of *c*. 54°W is poorly known. Our present knowledge is based on extensive photogrammetric studies whereas ground studies only comprise two sampled profiles. Second, formation boundaries with sediments should be systematically investigated to provide a more precise understanding of the events that took place at the time; this is particularly true for the Paleocene–Eocene transition. Third, the uncertainties concerning the internal stratigraphy of the Naqerloq Formation in the western Svartenhuk Halvø area may be resolved with more detailed work. Fourth, the northernmost area (north of 72°30′N) remains completely unvisited.

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Author contributions
JGL: Field work, map compilation, writing - original draft, revision. LML: Writing - revision of original draft, new chapter on geochemistry and petrology, figures, revision, editing.

Additional files
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Appendix 1

Appendix 1 Svartenhuk profile coordinates

			Altitude	Geographical coordinates, WGS 84				UTM zone 22*	
No	Profile name	Note	m	Latitude	Longitude	Lat. °N	Long. °W	Easting	Northing
4	Kakilisaat	Top	936	71° 29.3011' N	053° 57.553' W	71.48837	53.9592	395173	7934433
			907	71° 29.6013' N	053° 57.270' W	71.49336	53.9545	395368	7934981
		Base	401	71° 29.7219' N	053° 55.887' W	71.49536	53.9315	396194	7935165
7	Peak 1309 m	Top flow	1275	71° 44.2424' N	054° 20.678' W	71.73737	54.3446	383070	7962881
		Flow	694	71° 44.1487' N	054° 18.739' W	71.73581	54.3123	384190	7962645
		Flow	569	71° 43.7773' N	054° 18.362' W	71.72962	54.3060	384371	7961943
		hyaloclastite	372	71° 42.7672' N	054° 18.814' W	71.71279	54.3136	384005	7960083
		hyaloclastite	296	71° 42.5761' N	054° 18.197' W	71.70960	54.3033	384345	7959708
		hyaloclastite	236	71° 42.2035' N	054° 17.984' W	71.70339	54.2997	384432	7959009
		hyaloclastite	227	71° 42.2230' N	054° 17.575' W	71.70372	54.2929	384672	7959033
		hyaloclastite	217	71° 42.2535' N	054° 17.052' W	71.70422	54.2842	384980	7959073
		hyaloclastite	208	71° 42.2414' N	054° 16.670' W	71.70402	54.2778	385202	7959038
		hyaloclastite	193	71° 42.3096' N	054° 15.982' W	71.70516	54.2664	385610	7959143
		hyaloclastite	188	71° 42.2356' N	054° 15.530' W	71.70393	54.2588	385866	7958991
		hyaloclastite	181	71° 42.2771' N	054° 15.252' W	71.70462	54.2542	386032	7959059
		Base on sediment	169	71° 42.4850' N	054° 14.581' W	71.70808	54.2430	386445	7959424
9	Peak 1078 m	Top	1089	71° 39.6959' N	054° 22.319' W	71.66160	54.3720	381643	7954494
			978	71° 39.2889' N	054° 20.536' W	71.65481	54.3423	382643	7953681
			929	71° 38.8403' N	054° 19.561' W	71.64734	54.3260	383167	7952817
			873	71° 38.7421' N	054° 18.583' W	71.64570	54.3097	383729	7952603
			454	71° 38.9028' N	054° 16.998' W	71.64838	54.2833	384673	7952850
			345	71° 38.6420' N	054° 14.541' W	71.64403	54.2424	386084	7952288
			302	71° 38.3777' N	054° 13.408' W	71.63963	54.2235	386721	7951762
		Base	51	71° 38.3167' N	054° 11.974' W	71.63861	54.1996	387554	7951604
10	Taseraarsuit	Base	385	71° 46.8924' N	054° 26.917' W	71.78154	54.4486	379720	7968005
			455	71° 47.0278' N	054° 27.267' W	71.78380	54.4544	379532	7968268
			566	71° 47.1832' N	054° 27.122' W	71.78639	54.4520	379632	7968552
		Top Nerutusoq Mb	723	71° 47.3462' N	054° 26.589' W	71.78910	54.4432	379959	7968836
			750	71° 47.3790' N	054° 26.539' W	71.78965	54.4423	379991	7968896
			1037	71° 47.6918' N	054° 26.172' W	71.79486	54.4362	380237	7969464
		Top	1164	71° 47.8158' N	054° 25.409' W	71.79693	54.4235	380693	7969669
12	Point 470 m	Top	403	71° 27.2084' N	053° 58.434' W	71.45347	53.9739	394462	7930571
			289	71° 26.9113' N	053° 58.599' W	71.44852	53.9766	394338	7930024
			208	71° 26.7809' N	053° 58.358' W	71.44635	53.9726	394468	7929775
		Base	29	71° 26.6616' N	053° 57.903' W	71.44436	53.9651	394726	7929540
13	Saviit South	Top	579	71° 24.8203' N	054° 20.276' W	71.41367	54.3379	381309	7926813
			509	71° 24.8696' N	054° 18.899' W	71.41449	54.3150	382129	7926859
			217	71° 24.3754' N	054° 17.630' W	71.40626	54.2938	382831	7925901
		Base	33	71° 24.4074' N	054° 15.346' W	71.40679	54.2558	384187	7925887
14	Saviit North	Top	601	71° 26.3664' N	054° 20.801' W	71.43944	54.3467	381157	7929700
			345	71° 26.1009' N	054° 19.105' W	71.43501	54.3184	382133	7929152
		Base	99	71° 26.0300' N	054° 16.887' W	71.43383	54.2814	383438	7928948
22	Tasiusaq	Top	804	71° 31.2318' N	054° 47.320' W	71.52053	54.7887	366047	7939655
			622	71° 31.0606' N	054° 45.854' W	71.51768	54.7642	366889	7939284
		Base	137	71° 31.0651' N	054° 44.449' W	71.51775	54.7408	367718	7939240
24	Anilaarfissuaq	Top	841	71° 30.8326' N	054° 18.234' W	71.51388	54.3039	383129	7937908
		Base	244	71° 30.8580' N	054° 15.736' W	71.51430	54.2623	384603	7937875
29	Qiterlikassak	Top	1041	71° 39.9905' N	054° 43.758' W	71.66651	54.7293	369148	7955779
			1012	71° 39.4229' N	054° 42.084' W	71.65705	54.7014	370062	7954665
		Base	438	71° 38.5019' N	054° 39.780' W	71.64170	54.6630	371304	7952874

Appendix 1 (continued) Svartenhuk profile coordinates

				Geographical coordinates, WGS 84				UTM zone 22*	
No	Profile name	Note	Altitude m	Latitude	Longitude	Lat. °N	Long. °W	Easting	Northing
30	Ivissukkat	Top 1000 m	955	71° 39.5928' N	054° 35.675' W	71.65988	54.5946	373826	7954754
	Itinnerat		951	71° 39.2945' N	054° 34.525' W	71.65491	54.5754	374466	7954160
			825	71° 38.7064' N	054° 33.465' W	71.64511	54.5577	375021	7953032
		Base	430	71° 38.5045' N	054° 32.340' W	71.64174	54.5390	375657	7952619
31	Aputituut	Top (Trig. point)	1195	71° 34.1699' N	054° 49.769' W	71.56950	54.8295	364952	7945198
	Qaqqaat		976	71° 33.9223' N	054° 49.013' W	71.56537	54.8169	365366	7944711
			893	71° 33.7554' N	054° 47.497' W	71.56259	54.7916	366237	7944345
			587	71° 33.6988' N	054° 46.228' W	71.56165	54.7705	366975	7944193
		Base	360	71° 33.8835' N	054° 45.503' W	71.56472	54.7584	367423	7944509
36b	Arfertuarsuk	Base	52	71° 30.5771' N	055° 13.955' W	71.50962	55.2326	350288	7939483
		Top of trachyte	86	71° 30.6259' N	055° 14.711' W	71.51043	55.2452	349849	7939605
		Top of trachyte	167	71° 30.9653' N	055° 14.968' W	71.51609	55.2495	349742	7940245
		Gully	172	71° 30.9041' N	055° 15.044' W	71.51507	55.2507	349689	7940135
		Gully	133	71° 31.2278' N	055° 17.025' W	71.52046	55.2837	348567	7940818
		Topographic top	110	71° 31.1758' N	055° 17.616' W	71.51960	55.2936	348212	7940746
		Stratigraphic top	52	71° 31.1226' N	055° 18.828' W	71.51871	55.3138	347492	7940698
37	Nuup Qaava	Top	867	72° 05.1707' N	055° 17.568' W	72.08618	55.2928	352736	8003797
		Base	31	72° 04.6531' N	055° 23.878' W	72.07755	55.3980	349064	8003098
38	Qaqqap Qaa	Top	1154	72° 09.1463' N	054° 37.346' W	72.15244	54.6224	376150	8009664
			1011	72° 08.5581' N	054° 38.422' W	72.14263	54.6404	375472	8008609
		Base	279	72° 07.5396' N	054° 40.446' W	72.12566	54.6741	374204	8006789
40	Pannertuup	Top	1385	72° 17.8153' N	053° 40.214' W	72.29692	53.6702	409398	8024064
	Qaqqaa	Base	739	72° 17.6842' N	053° 42.957' W	72.29474	53.7160	407837	8023890
41b	Skalø South	Top, western gully	463	71° 49.9775' N	055° 32.700' W	71.83296	55.5450	341970	7976260
		Plateau edge, w. gully	371	71° 49.8377' N	055° 32.820' W	71.83063	55.5470	341881	7976006
		Base, western gully	0	71° 49.6648' N	055° 32.382' W	71.82775	55.5397	342110	7975666
	Profile shift	Eastern gully	51	71° 49.8523' N	055° 31.807' W	71.83087	55.5301	342469	7975989
		Base, eastern gully	0	71° 49.8340' N	055° 31.725' W	71.83057	55.5287	342514	7975951
42	Marraarnaq	Top	479	72° 18.7330' N	055° 15.003' W	72.31222	55.2500	355981	8028850
		Base	37	72° 19.7348' N	055° 15.173' W	72.32891	55.2529	356016	8030715
44c	Kuugaartorfik	Highest	1185	71° 58.5361' N	054° 31.628' W	71.97560	54.5271	378251	7989776
			799	71° 58.4615' N	054° 33.040' W	71.97436	54.5507	377431	7989685
			433	71° 58.6189' N	054° 34.455' W	71.97698	54.5742	376635	7990025
		Lowest	62	71° 58.5665' N	054° 36.955' W	71.97611	54.6159	375192	7990014
		Top sediments	454	71° 58.6322' N	054° 34.361' W	71.97720	54.5727	376691	7990047
		Base sediments	317	71° 58.5882' N	054° 35.091' W	71.97647	54.5849	376266	7989990
47	Peak 1430 m	Highest	1329	71° 59.5814' N	054° 19.829' W	71.99302	54.3305	385139	7991330
		Lowest	777	71° 59.0298' N	054° 21.343' W	71.98383	54.3557	384213	7990355
47a	Peak 1625 m	Highest	1469	71° 57.6395' N	054° 02.906' W	71.96066	54.0484	394677	7987209
		Lowest	1223	71° 57.4732' N	054° 03.392' W	71.95789	54.0565	394381	7986914
48b	Nerutusoq	Lowest, in river	108	71° 55.1077' N	054° 30.278' W	71.91846	54.5046	378656	7983367
		Hyaloclastite in river	293	71° 53.5627' N	054° 28.632' W	71.89271	54.4772	379439	7980444
		Hyaloclastite in river	334	71° 53.0149' N	054° 29.236' W	71.88358	54.4873	379031	7979447
		Hyaloclastite in river	352	71° 52.9096' N	054° 29.621' W	71.88183	54.4937	378798	7979265
		Hyaloclastite in river	485	71° 50.4418' N	054° 31.237' W	71.84070	54.5206	377596	7974738
		Hyaloclastite in river	504	71° 49.7162' N	054° 32.427' W	71.82860	54.5405	376829	7973432
		Hyaloclastite in river	502	71° 49.2440' N	054° 33.446' W	71.82073	54.5574	376186	7972590
		Highest, on mount. side	658	71° 49.5137' N	054° 35.658' W	71.82523	54.5943	374935	7973167
50	Umiiarfik South	Top	873	71° 52.4722' N	054° 58.579' W	71.87454	54.9763	362021	7979491
			150	71° 53.2864' N	054° 58.868' W	71.88811	54.9811	361954	7981012
		Base	121	71° 53.3771' N	054° 57.310' W	71.88962	54.9552	362864	7981121
51	Tunuarsuk	Top	1278	71° 47.5299' N	054° 49.737' W	71.79216	54.8289	366546	7969988
			1157	71° 47.3509' N	054° 50.254' W	71.78918	54.8376	366224	7969675
		Base	456	71° 46.7082' N	054° 48.302' W	71.77847	54.8050	367281	7968411

Appendix 1 (continued) Svartenhuk profile coordinates

No	Profile name	Note	Altitude m	Geographical coordinates, WGS 84 Latitude	Longitude	Lat. °N	Long. °W	UTM zone 22* Easting	Northing
52	Nuuit Qaqqaat	Top sub-profile 1	905	71° 50.8945' N	055° 13.008' W	71.84824	55.2168	353483	7977131
		East side of mountain	725	71° 50.5362' N	055° 13.771' W	71.84227	55.2295	352995	7976498
		Base sub-profile 1	534	71° 50.2978' N	055° 13.415' W	71.83830	55.2236	353170	7976041
		Top sub-profile 2	423	71° 50.0397' N	055° 12.185' W	71.83400	55.2031	353848	7975512
			268	71° 49.7904' N	055° 11.832' W	71.82984	55.1972	354020	7975036
		Base sub-profile 2	244	71° 49.7304' N	055° 11.858' W	71.82884	55.1976	353998	7974925
55	Aputituut	Top	848	71° 35.5437' N	054° 52.583' W	71.59240	54.8764	363464	7947853
			801	71° 36.0127' N	054° 52.180' W	71.60021	54.8697	363755	7948708
			663	71° 36.3566' N	054° 51.903' W	71.60594	54.8650	363959	7949336
		Base	487	71° 36.9067' N	054° 52.098' W	71.61511	54.8683	363910	7950364
58	Amitsoq	Base	43	71° 48.6321' N	055° 24.281' W	71.81054	55.4047	346658	7973403
			167	71° 48.2264' N	055° 23.601' W	71.80377	55.3934	346997	7972621
		Top sub-profile 1	412	71° 47.7829' N	055° 25.403' W	71.79638	55.4234	345892	7971875
		Base sub-profile 2	367	71° 47.4048' N	055° 22.625' W	71.79008	55.3771	347452	7971056
		Top	610	71° 47.0412' N	055° 22.043' W	71.78402	55.3674	347741	7970357
59	Qooruusaq	Strat. lowest	253	71° 43.5862' N	055° 22.416' W	71.72644	55.3736	347059	7963965
			132	71° 43.0601' N	055° 25.459' W	71.71767	55.4243	345216	7963119
			138	71° 43.0894' N	055° 26.076' W	71.71816	55.4346	344861	7963200
			79	71° 43.3524' N	055° 28.348' W	71.72254	55.4725	343575	7963785
		Strat. highest	124	71° 43.5403' N	055° 29.373' W	71.72567	55.4896	343004	7964178
60	Qooruusaq	Strat. lowest	71	71° 43.0127' N	055° 27.895' W	71.71688	55.4649	343792	7963136
			80	71° 42.7501' N	055° 28.665' W	71.71250	55.4778	343307	7962682
			107	71° 42.3854' N	055° 28.073' W	71.70642	55.4679	343601	7961980
			120	71° 42.2702' N	055° 28.118' W	71.70450	55.4686	343560	7961769
		Strat. highest	176	71° 41.3399' N	055° 26.374' W	71.68900	55.4396	344449	7959968
61	Qooruusaq	Strat. lowest	34	71° 44.0873' N	055° 31.890' W	71.73479	55.5315	341616	7965302
			58	71° 44.0032' N	055° 32.022' W	71.73339	55.5337	341528	7965152
		Strat. highest	73	71° 43.8406' N	055° 31.482' W	71.73068	55.5247	341819	7964827
62	Sigguk	1. Base, coast in NW	0	71° 40.9634' N	055° 51.152' W	71.68272	55.8525	329949	7960385
		2. Coast SE of 1.	0	71° 40.7685' N	055° 49.812' W	71.67948	55.8302	330702	7959961
		3. Coast SE of 2.	73	71° 40.8071' N	055° 49.385' W	71.68012	55.8231	330957	7960012
		4. Coast SE of 3.	0	71° 40.6040' N	055° 47.336' W	71.67673	55.7889	332121	7959540
		5. Base vertical part	32	71° 40.3537' N	055° 44.234' W	71.67256	55.7372	333894	7958933
		6. Top	640	71° 40.9337' N	055° 44.507' W	71.68223	55.7418	333819	7960021
64a	Paannivik	Top of 64a	1292	71° 57.9423' N	054° 58.282' W	71.96570	54.9714	362862	7989629
		Base of 64a	611	71° 57.5581' N	055° 03.915' W	71.95930	55.0652	359577	7989132
		Base of 64b	0	71° 55.8438' N	055° 05.582' W	71.93073	55.0930	358402	7986017
			197	71° 56.1749' N	055° 05.099' W	71.93625	55.0850	358722	7986612
			423	71° 56.3526' N	055° 04.461' W	71.93921	55.0743	359111	7986917
		Top of 64b	703	71° 56.5799' N	055° 02.653' W	71.94300	55.0442	360180	7987268
66	Saattut	'Base' (coastal profile)	0	72° 13.1650' N	055° 56.399' W	72.21942	55.9400	331796	8020317
	(Fladøerne)	'Top'	28	72° 18.4205' N	055° 55.364' W	72.30701	55.9227	333181	8030010
	Easternmost	Heli-reconnaissance							
	nunatak	566505	1739	72° 04.2366' N	051° 54.493' W	72.07061	51.9082	468803	7997087
65	Salliaruseq	Sample no. and notes							
		566511, highest	1144	72° 25.0812' N	053° 47.968' W	72.41802	53.7995	405661	8037755
		566512	1093	72° 25.1172' N	053° 48.676' W	72.41862	53.8113	405262	8037885
		566513	1080	72° 25.0080' N	053° 49.033' W	72.41680	53.8172	405049	8037672
		566514	1089	72° 24.9396' N	053° 49.172' W	72.41566	53.8195	404943	8037565
		566515		72° 24.8256' N	053° 49.528' W	72.41376	53.8255	404764	8037350
		566516	993	72° 24.7962' N	053° 49.564' W	72.41327	53.8261	404725	8037241
		566517	981	72° 24.7836' N	053° 49.535' W	72.41306	53.8256	404725	8037241
		566518	964	72° 24.7590' N	053° 49.788' W	72.41265	53.8298	404590	8037247
		566519	918	72° 24.5148' N	053° 50.131' W	72.40858	53.8355	404367	8036811

Appendix 1 (continued) Svartenhuk profile coordinates

No	Profile name	Note	Altitude m	Geographical coordinates, WGS 84 Latitude	Longitude	Lat. °N	Long. °W	UTM zone 22* Easting	Northing
		566520	918	72° 24.5148' N	053° 50.131' W	72.40858	53.8355	404367	8036811
		566521	895	72° 24.5058' N	053° 49.783' W	72.40843	53.8297	404564	8036690
		566522 } Same flow	826	72° 24.3120' N	053° 49.826' W	72.40520	53.8304	404548	8036355
		572001 } Same flow	710	72° 24.2460' N	053° 50.627' W	72.40410	53.8438	404071	8036266
		572002	710	72° 24.2460' N	053° 50.627' W	72.40410	53.8438	404071	8036266
		572003	700	72° 24.2364' N	053° 50.660' W	72.40394	53.8443	404071	8036266
		572004	700	72° 24.2364' N	053° 50.660' W	72.40394	53.8443	404071	8036266
		572005	680	72° 24.2508' N	053° 50.872' W	72.40418	53.8479	403936	8036273
		572006	670	72° 24.2664' N	053° 50.942' W	72.40444	53.8490	403903	8036274
		572007	620	72° 24.2382' N	053° 51.251' W	72.40397	53.8542	403734	8036282
		572008. lowest	590	72° 24.2292' N	053° 51.458' W	72.40382	53.8576	403599	8036289
67	Qooruusaq	Sample no. and notes							
	2019	568604 above trachyte	179	71° 39.1572' N	055° 21.750' W	71.65262	55.3625	346837	7955767
		568601 trachyte	191	71° 39.1206' N	055° 21.668' W	71.65201	55.3611	346899	7955650
		568602 below trachyte	121	71° 39.0090' N	055° 21.647' W	71.65015	55.3609	346883	7955428
		568603 below previous	119	71° 38.9952' N	055° 21.600' W	71.64992	55.3600	346918	7955425

* UTM zone 22 coordinates as used for the other onshore parts of the Nuussuaq Basin.