

Pedersen 1978). The beds are usually structureless, but cross-bedding has been recognised locally. Volcaniclastic sandstones also occur as thin streaks in the mudstones and may include spherules of volcanic glass or tuff with a distinct chemical composition known only from the Asuk Member erupted from the Ilugissoq graphite andesite volcano (A.K. Pedersen 1985; A.K. Pedersen & Larsen 2006). In the lower part of the member, the mudstones are very dark, fossiliferous and rich in concretions. At one horizon, *in situ* corals are present in small bioherms, 10–20 cm high and less than 1 m wide (Plate 3, section 4). This horizon can be followed for more than a kilometre on the eastern bank of Qaersutjægerdal. The content of volcaniclastic sandstones increases upwards in the section.

*Fossils.* A sparse but diverse marine fauna and flora has been recorded from the Abraham Member, comprising scleractinian corals, echinoids, bivalves, gastropods, crustaceans, fish remains and palynomorphs (Bendix-Almgreen 1969; Rosenkrantz 1970; Floris 1972; Kollmann & Peel 1983; Piasecki *et al.* 1992; Petersen & Vedelsby 2000).

*Depositional environment.* The macrofossil content in the lower part of the member indicates a marine depositional environment. However, an increase up-section in terrestrially derived palynomorphs indicates that the environment became increasingly brackish with time.

Sedimentary structures in the volcaniclastic sandstones indicate deposition from turbidity currents. The corals suggest a shallow water (50?–80 m) marine environment in a warm temperate climate (Floris 1972), but where the corals were redeposited the water depth may well have exceeded 80 m.

*Boundaries.* A sharp lithological boundary occurs between the sandstones of the Agatdal Formation and the interbedded mudstones and volcaniclastic sandstones of the Abraham Member (Figs 114, 115). At Qilakitsoq and in the northern part of Agatdalen, the Abraham Member is succeeded by hyaloclastites of the Naujánguit Member, whereas in the eastern part of Agatdalen the Abraham Member is succeeded by hyaloclastites of the Tunoqqu Member (A.K. Pedersen 1978; Piasecki *et al.* 1992; A.K. Pedersen, personal communication 1999).

*Geological age.* As for the Eqaulluk Formation, i.e. latest Danian to early Selandian.

*Correlation.* The geochemical correlation of the Abraham Member with the hyaloclastites of the Asuk Member of the Vaigat Formation (A.K. Pedersen 1978, 1985; A.K. Pedersen & Larsen 2006) ties these isolated outcrops to the mapped volcanic succession on the south coast of Nuussuaq (A.K. Pedersen *et al.* 1993).

## Atanikerluk Formation

new formation

*History.* The Atanikerluk Formation comprises the syn-volcanic non-marine sediments in the Nuussuaq Basin; in the eastern part of the basin, it includes almost all the sediments overlying the Atane Formation (Fig. 16). It is divided into five members (Fig. 123), which are correlated to members in the volcanic Vaigat and Maligât Formations (Fig. 131). The intra- and post-volcanic sediments of the Nuussuaq Basin are not included in the Nuussuaq Group and are therefore not discussed here.

Koch 1959		This paper		
Nuussuaq		Nuussuaq	Disko	
Upper Atanikerluk Formation	Point 976 Member	Assoq Member	Assoq Member	Atanikerluk Formation
	Aussivik Member			
	Umiussat Member	Umiussat Member	Umiussat Member	
	Naujât Member	Naujât Member	Pingu Member Akunneq Member Naujât Mb	
	Quikavsak Member	Quikavsak Formation	Not present	

Fig. 123. Lithostratigraphical subdivisions of the synvolcanic, non-marine deposits of the Nuussuaq Basin.



Fig. 124. Geological map showing the distribution of the Atane and Atanikerluk Formations on eastern Disko, simplified from A.K. Pedersen *et al.* (2001). Note that the outcrops of the Atanikerluk Formation are discontinuous. Contour interval is 200 m. For location, see Fig. 2.

In detail, however, the boundary between the Atanikerluk Formation and the volcanic formations can be complex, hyaloclastite breccias and invasive lavas interdigitating with the sedimentary succession. These sediments, interstratified locally with the lowermost volcanic layers, are intimately associated with the uppermost Nuussuaq Group strata and are thus referred to the Atanikerluk Formation where demonstrably related to an interdigitating volcanic–sediment facies front (Figs 17, 131).

Two new formations, the Quikavsak Formation and the Atanikerluk Formation, replace the ‘Upper Atanikerdluk Formation’ of Nordenskiöld (1871), Troelsen (1956) and Koch (1959). The term ‘Upper Atanikerdluk Formation’ dates back to Nordenskiöld (1871), who used this name for the beds (Öfre Atanekerdluklagren) containing the upper flora in the Atanikerluk area. The plant fossils occur in concretions that are dark grey on fresh surfaces but weather to a dark red colour (Nordenskiöld 1871 pp. 1051–52). Koch (1959) reported that these concretions contain the Upper Atanikerdluk A flora of Heer (1883a, b) and that they occur in his Quikavsak Member, i.e. the Quikavsak Formation of the present paper. The name Atanikerluk Formation is proposed because it does not imply the existence of a ‘Lower Atanikerdluk Formation’. Although a Lower Atanikerdluk Flora was mentioned by Heer (1868), this originated from the Atane Formation as recognised as early as 1871 by Nordenskiöld.

Koch (1959) subdivided the Upper Atanikerdluk Formation into five members on Nuussuaq (Fig. 123) but attempted no subdivision of the formation on Disko. His Quikavsak Member is here established as the Quikavsak Formation. Two of Koch’s members on Nuussuaq are retained (the Naujât and Umiussat Members), whereas the Aussivik and Point 976 Members are abandoned and the sediments are referred to the new Assoq Member. The reason for this is that the Aussivik and Point 976 Members are only found in a very small area of south-eastern Nuussuaq (A.K. Pedersen *et al.* 2007b). On Disko, a subdivision into five members is proposed (the Naujât, Akunneq, Pingu, Umiussat, and Assoq Members; Fig. 123). The subdivision of the Atanikerluk Formation into five members reflects the dramatic palaeogeographic changes that accompanied the intense volcanic activity.

*Name.* The formation is named after the Atanikerluk peninsula formed by a sill on the south coast of Nuussuaq (Fig. 40). The name was formerly spelled Atanekerdluk or Atanikerdluk.

*Distribution.* The Atanikerluk Formation is known on south-east Nuussuaq (Saqqaqdalen, Atanikerluk, Kingittoq, Paatuut, and Ataata Kuua), on central Nuussuaq (Nassaat and locally in Aaffarsuaq), on eastern Disko (Assoq, Tuapaat Qaqqaat, Gule Ryg, Pingu, Nuugaarsuk, Frederik Lange Dal) and central Disko (Daugaard Jensen Dal and Sorte Hak; Figs 2, 40, 124). In the Atanikerluk area, the formation was mapped in great detail by Koch & Pedersen (1960). Paleocene siliciclastic sediments are also present on Svartenhuk Halvø, where they are overlain by the volcanic Vaigat and Svartenhuk Formations (J.G. Larsen, personal communication 2008). These sediments remain unstudied in detail and the distribution of marine pre-volcanic, marine synvolcanic and non-marine synvolcanic deposits is not known at present. In the future, Paleocene non-marine, synvolcanic sediments on Svartenhuk Halvø may be established as one or more members within the Atanikerluk Formation.

*Type section.* The section in the south-facing slope between Atanikerluk and Tartunaq on south-east Nuussuaq is retained as the type section (Figs 125, 126) for the Atanikerluk Formation. This was described in detail by Koch (1959), who defined type sections for several members of the formation in this area. The type section is located at 70° 03.63’N, 52° 13.53’W.

*Reference sections.* Reference sections of the Atanikerluk Formation are found at Kingittoq, at Pingu and in the Tuapaat area (Figs 7, 132, 140). The stratigraphic succession in north-east Disko has been compiled from the (mainly sedimentary) sections on both sides of Akunneq and the volcanic succession at Aqajaruata Qaqqaa, south of Akunneq (A.K. Pedersen *et al.* 2005) (Figs 124, 131).

*Thickness.* The Atanikerluk Formation is up to 500 m thick in a composite section, but individual outcrops reach thicknesses of *c.* 400 m (Pingu), *c.* 300 m (Kingittoq, Atanikerluk) and 200–250 m (Saqqaqdalen) (Figs 126, 128). At Tuapaat Qaqqaat, the thickness is difficult to measure due to landslides and interbedding of sediments and invasive lava flows (Fig. 140). Invasive lava flows are discussed below under ‘Lithology’.

*Lithology.* The Atanikerluk Formation comprises mudstones, heterolithic sandstones, and fine-grained, loosely cemented sandstones. Mudstones are dominant in the Naujât and Pingu Members (Fig. 127) and in the lower part of the Assoq Member, whereas very friable sandstones characterise the Akunneq and Umiussat Members and the upper part of the Assoq Member. On a regional

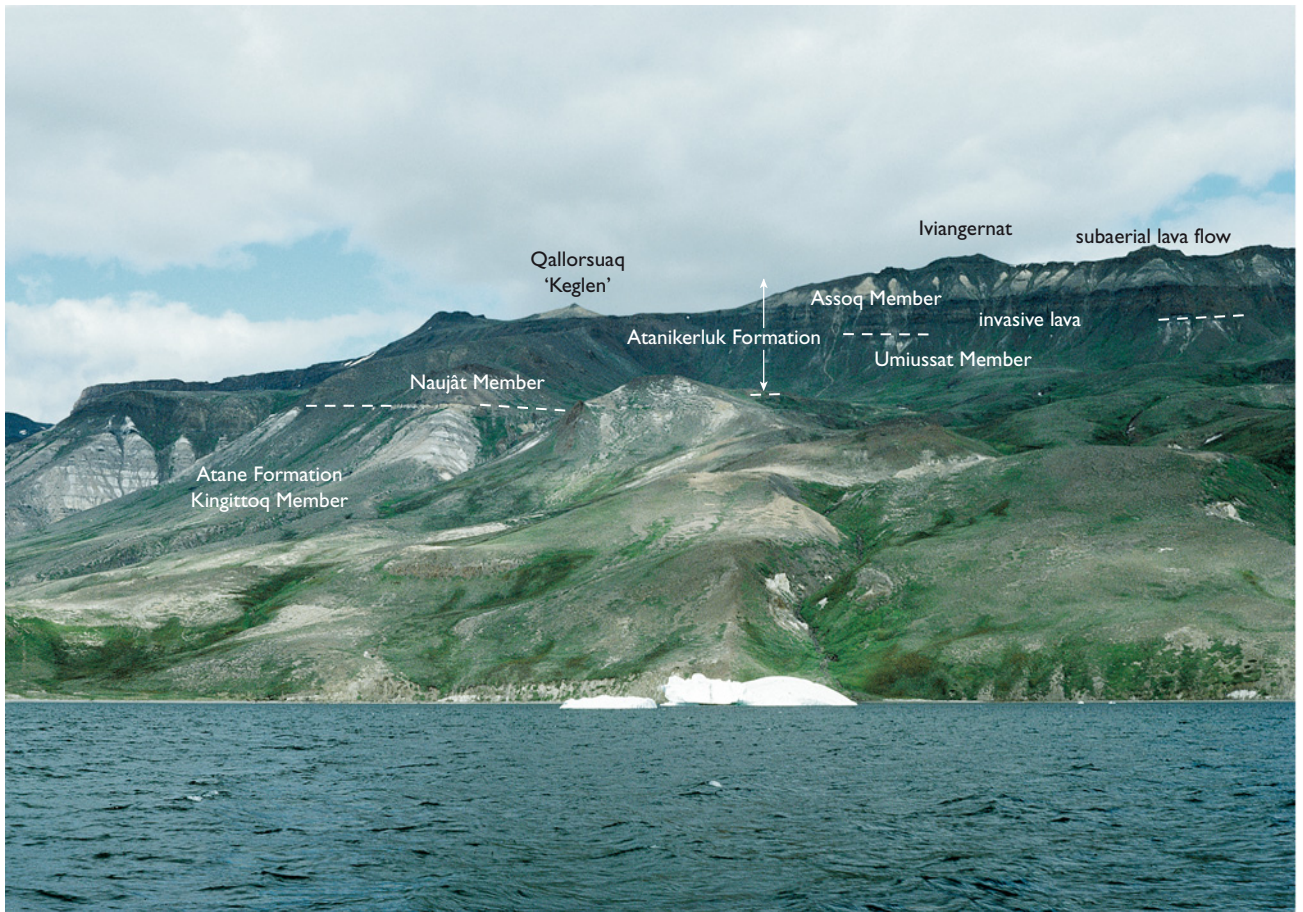


Fig. 125. The coastal slope above Atanikerluk where Koch (1959) described the strata of the Atanikerluk Formation (for location, see Fig. 40). The peak at Iviangernat is 1031 m a.s.l. The Albian to Cenomanian Kingittoq Member of the Atane Formation is up to 500 m thick and is overlain by the Paleocene Atanikerluk Formation (see Figs 16, 17).

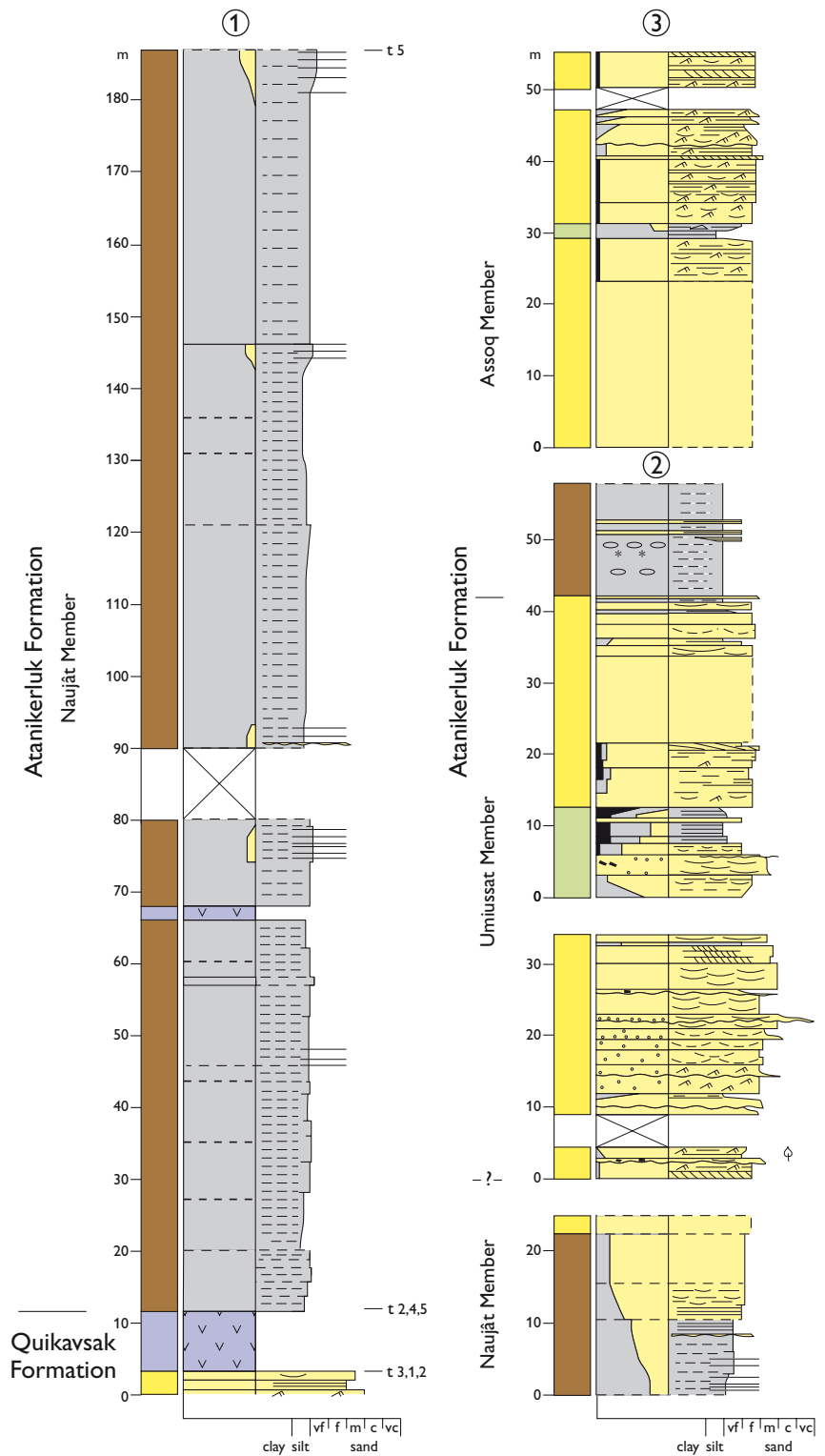
scale, the formation comprises two coarsening-upward successions that may include thinner, coarsening-upward successions on a local scale (Figs 16, 131).

The mudstones are grey to dark grey, with abundant silt-sized particles and with kaolinite and quartz as the dominant minerals. In addition, gibbsite in subordinate amounts has been detected consistently in samples from the Pingu Member and commonly in the Assoq Member. Locally, rows of small, yellowish brown siderite concretions occur in the mudstones (G.K. Pedersen 1989; G.K. Pedersen *et al.* 1998). Reworked Cretaceous palynomorphs are found in the lowest part of the Atanikerluk Formation at Akunneq (Hjortkjær 1991), suggesting that the formation also contains redeposited silt and clay. Interbedded with the mudstones are thin layers of tuff. The particles are in the coarse sand fraction and have a brownish colour that weathers to pale buff or white. The strong alteration precludes a determination of the original chemical composition of the volcanic glass.

The sandstones are weakly cemented, and in several outcrops the lithology may be better described as sand. Colours range from pale grey to deep yellow, and fine coal debris is common. The sand or sandstones are generally fine- to medium-grained; coarser grain sizes occur but are volumetrically insignificant. Chert pebbles derived from Ordovician sediments occur in the coarser facies, as also seen locally in the Atane Formation. The sediments of the Atanikerluk Formation could therefore include material reworked from Cretaceous Atane Formation sand or sandstones. This is supported by the occurrences of few Paleocene palynomorphs together with more numerous Cretaceous spores and pollen in the lower part of the Akunneq Member at Pingu (Fig. 132, 285–355 m).

The siliciclastic sediments are interbedded with volcanic rocks such as hyaloclastite breccias, invasive or subaqueous lava flows and tuffs. Hyaloclastite breccias comprise particles ranging from boulder-sized pillow fragments to sand-sized grains of glass; these rocks formed

Fig. 126. Composite type section of the Atanikerluk Formation from the Atanikerluk area between Naajaat and Umiusat, south-eastern Nuussuaq (for location, see Fig. 40). 1: Section through the Naujât Member from Saqqaqdalen at the type locality defined by Koch (1959) (Fig. 129). 2: Sections through the Umiussat Member from discontinuous outcrops in the Umiusat area (Figs 136, 137). 3: Section through the upper part of the Naujât Member and the upper part of the Assoq Member, formerly the Point 976 Member of Koch (1959) from discontinuous outcrops below Keglen (Fig. 125). For legend, see Plate 1.



when lava flowed into water. The breccias are often fore-set-bedded and the height of the foresets provides an indication of water depth (Jones & Nelson 1970; A.K. Pedersen *et al.* 1996; G.K. Pedersen *et al.* 1998). Invasive or subaqueous lava flows formed from large volumes of

lava that reached the lake floor and continued into (invaded) the unconsolidated sediment without forming breccias (Schmincke 1967; Duffield *et al.* 1986; L.M. Larsen & Pedersen 1990; Tucker & Scott 2009). Invasive or subaqueous lava flows can be traced laterally into sub-

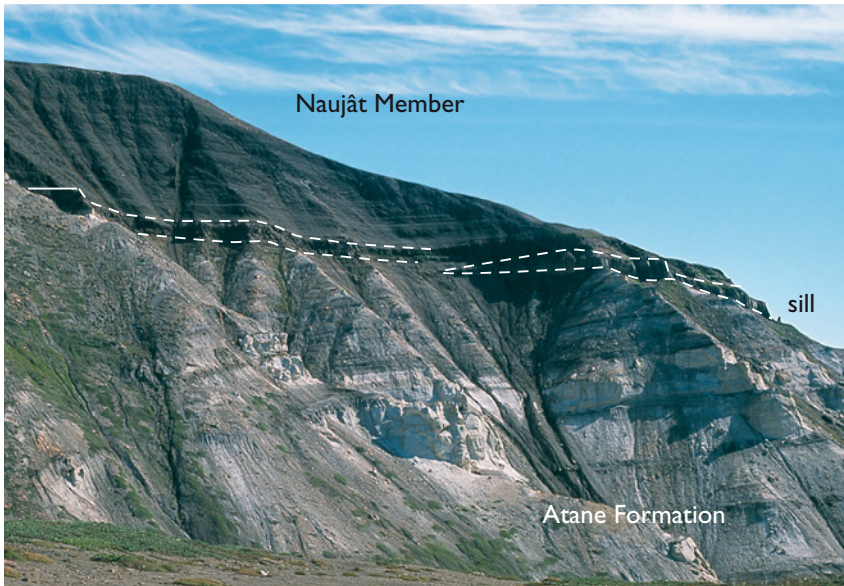


Fig. 127. Reference locality of the Naujât Member (Atanikerluk Formation) at Kingittoq where lacustrine mudstones overlie the Atane Formation (see also G.K. Pedersen *et al.* 1998 fig. 7). For location, see Fig. 2.

aerial lava flows and are thus different from sills, and are only slightly younger than the sediments they invade. Many of the invasive lava flows have retained their chemical composition and may thus be correlated to the volcanic lithostratigraphy. Layers of tuff are composed of sand-sized particles, and typically are less than 3 cm thick. The volcanic glass is strongly altered, and it is rarely possible to determine the original chemical composition of the glass.

*Fossils.* The Atanikerluk Formation contains a rich macroflora (Koch 1959, 1963, 1964), which Koch referred to the Paleocene Macclintockia Zone characterised by *Meta-sequoia occidentalis*, *Cercidiphyllum arcticum*, *Macclintockia Kanei*, *Macclintockia Lyalli* and *Dicotylophyllum bellum* (Koch 1959, 1963). Koch identified the Upper Atanikerdluk A flora and the Upper Atanikerdluk B flora of Heer (1883a, b) in the basal part of the formation (lowermost Naujât Member). The Upper Atanikerdluk A flora is also present in the Nuuk Qiterleq Member of the Quikavsak Formation. The difference between the two floras reflects changes in depositional environments, but the floras are essentially coeval (Koch 1963). The diagnostic species of the Macclintockia Zone occur in the Naujât Member but have also been found in the Abraham Member of the Eqalulik Formation (Koch 1963 p. 112).

The palynomorphs (mainly spores and pollen) of the Atanikerluk Formation have been described by Croxton (1978a, b), Hjortkjær (1991), L.M. Larsen *et al.* (1992), Piasecki *et al.* (1992), Lanstorp (1999) and D.J. McIntyre, personal communication 2009. Marine dinocysts and rare bivalves have been reported locally from the Assoq Member.

*Depositional environment.* The mudstones are interpreted as lacustrine deposits on the basis of the high C/S ratios, the absence of pyrite, the presence of terrestrial fossils (macrofossil plants, spores and pollen) and the general absence of marine dinocysts (Hjortkjær 1991; Piasecki *et al.* 1992; G.K. Pedersen *et al.* 1998). The sandstones are interpreted as dominantly fluvial and lacustrine in origin on the basis of the current-generated sedimentary structures, the lack of marine trace fossils, and their stratigraphic position relative to the lacustrine mudstones. Periodic marine inundations are indicated by the presence of marine fossils in the mudstones of the Assoq Member (Piasecki *et al.* 1992).

*Boundaries.* Over large areas, the Atanikerluk Formation rests on an unconformity that defines the upper boundary of the Atane Formation and which reflects a hiatus of varying duration. In more restricted areas, the Atanikerluk Formation conformably overlies the Quikavsak and Eqalulik Formations, or the volcanic Vaigat Formation (Fig. 16). On south-eastern Nuussuaq, the Atanikerluk Formation overlies either the Atane or the Quikavsak Formation. Strata of the Atane Formation dip towards the north-east, whereas the strata of the Atanikerluk Formation are sub-horizontal (Fig. 129). Where the Quikavsak Formation is present, its upper boundary is also horizontal, indicating that the angular unconformity between the Atane and Atanikerluk Formations formed prior to the Danian. At other outcrops, the lacustrine mudstones of the Naujât Member drape erosional relief at the top of the Atane Formation (Figs 127, 130; Pulvertaft 1989a; A.K. Pedersen *et al.* 2007a). The lower boundary of the Atanikerluk Formation on Nuussuaq is

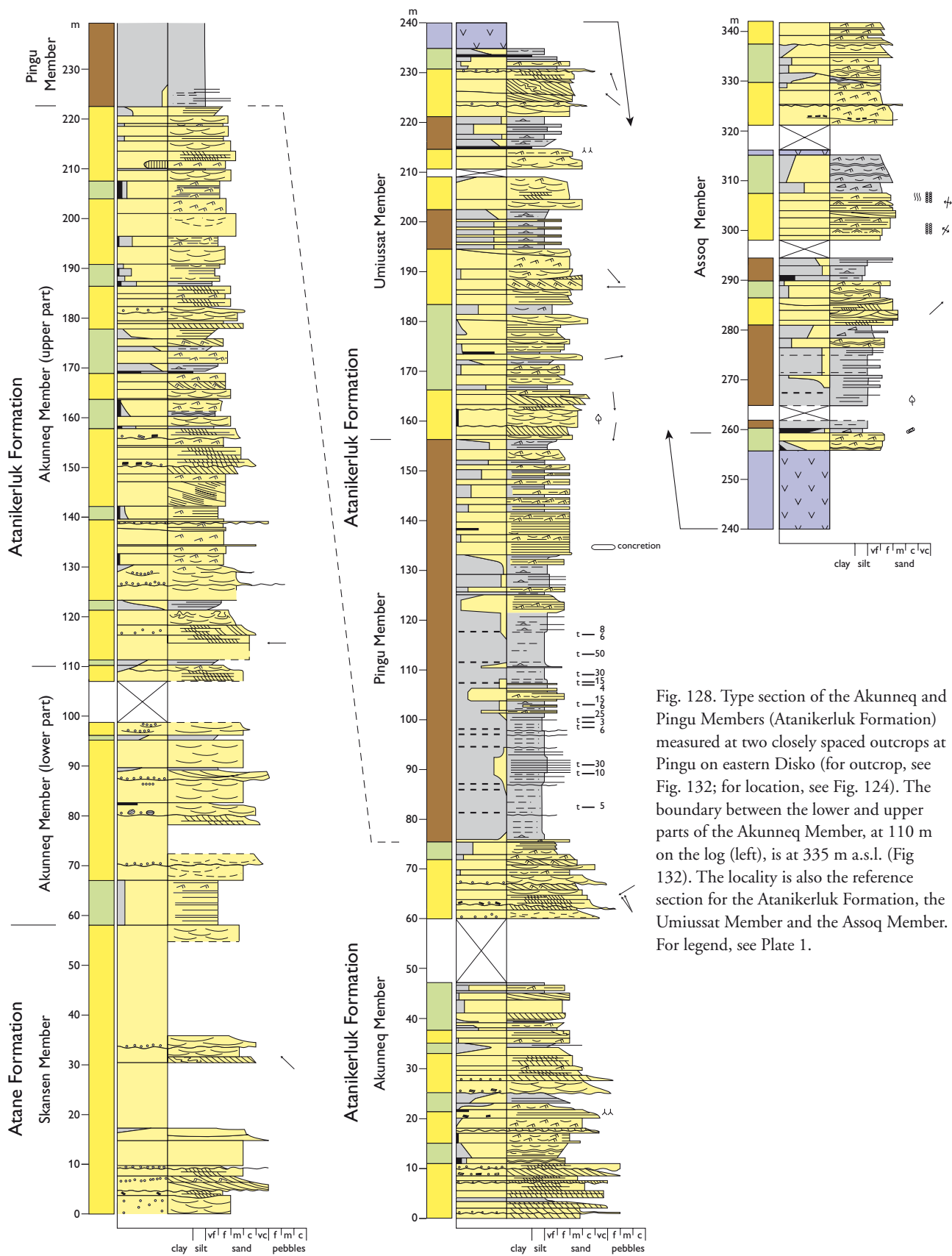


Fig. 128. Type section of the Akunneq and Pingu Members (Atanikerluk Formation) measured at two closely spaced outcrops at Pingu on eastern Disko (for outcrop, see Fig. 132; for location, see Fig. 124). The boundary between the lower and upper parts of the Akunneq Member, at 110 m on the log (left), is at 335 m a.s.l. (Fig. 132). The locality is also the reference section for the Atanikerluk Formation, the Umiussat Member and the Assoq Member. For legend, see Plate 1.

interpreted as a lacustrine flooding surface which can be mapped westwards into the volcanic terrain where it separates subaerial lavas of the Naujánguit Member from overlying hyaloclastite breccias at or just above the base of the Ordlingassoq Member (A.K. Pedersen 1985; A.K. Pedersen *et al.* 1993; G.K. Pedersen *et al.* 1998) (Fig. 131). On eastern Disko, the lowest member of the Atanikerluk Formation is the dominantly fluvial Akunneq Member, and the base of this member constitutes the lower boundary of the formation; this is well exposed in the coastal section from Pingu to Nuugaarsuk (Figs 132, 133). The upper boundary of the Atanikerluk Formation is either a recent erosion surface or the boundary with volcanic or volcanoclastic deposits of the Vaigat or Maligât Formations (Figs 16, 131).

*Geological age.* The Atanikerluk Formation is dated by dinocysts, pollen or plant macrofossils, and is constrained by magnetostratigraphic and radiometric dating of the correlative volcanic units. A maximum age for the Atanikerluk Formation is obtained from the NP4 – possibly early NP5 marine dinocysts in the underlying Eقالulik Formation (Nøhr-Hansen *et al.* 2002). Samples from the volcanic Ordlingassoq and Rinks Dal Members give radiometric ages of  $60.7\text{--}61.1 \pm 0.5\text{--}1.0$  Ma, recalculated from Storey *et al.* (1998). This indicates an early to mid-Paleocene (possibly Selandian) age for the Atanikerluk Formation according to the timescale of Gradstein *et al.* (2004) and Ogg *et al.* (2008).

*Correlation.* The two regional, coarsening-upward successions recognised in the Atanikerluk Formation cor-

relate with the volcanic Ordlingassoq and Rinks Dal Members of the Vaigat and Maligât Formations respectively (Fig. 131). Correlation of individual members of the Atanikerluk Formation to strata of the Vaigat Formation on Disko presents some difficulties due to lack of exposures along the north coast of the island. The Atanikerluk Formation is younger than the Eقالulik Formation despite the similarity in macroplant fossils between the Abraham and the Naujât Members.

*Subdivision.* The Atanikerluk Formation is subdivided into five members: the Naujât, Akunneq, Pingu, Umiussat and Assoq Members (Fig. 123).

## Naujât Member

revised member

*History.* The Naujât Member was established by Koch (1959). Its distribution is expanded here, but otherwise the definition of the member is retained.

*Name.* The member is named from a small cove (modern spelling Naajaat) on the south coast of Nuussuaq, just west of Saqqaqdalen (Fig. 40; Koch 1955).

*Distribution.* The distribution of the Naujât Member along the south-east coast of Nuussuaq was mapped by Koch (1959 plates 5–7). He recognised the Naujât Member in almost continuous outcrops and scree-covered slopes on the western side of Saqqaqdalen and along

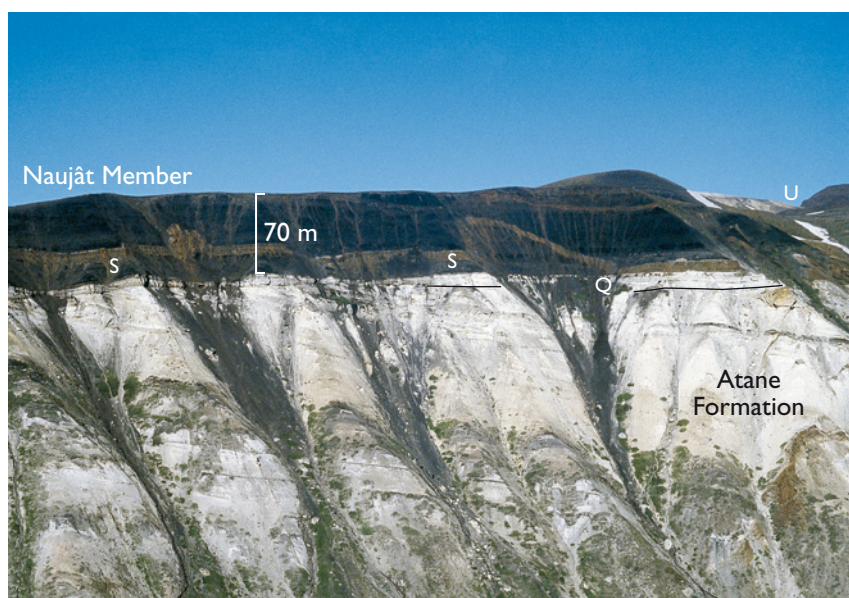


Fig. 129. Type locality of the Naujât Member (Atanikerluk Formation) along the western slope of Saqqaqdalen near Naajaat (for location, see Fig. 40). An angular unconformity is seen between the Atane Formation and the Quikavsak Formation (Q). The latter is conformably overlain by lacustrine mudstones of the Naujât Member, which is cut by a sill (S). The outcrop of pale yellow sandstones in the distance belongs to the Umiussat Member (U).



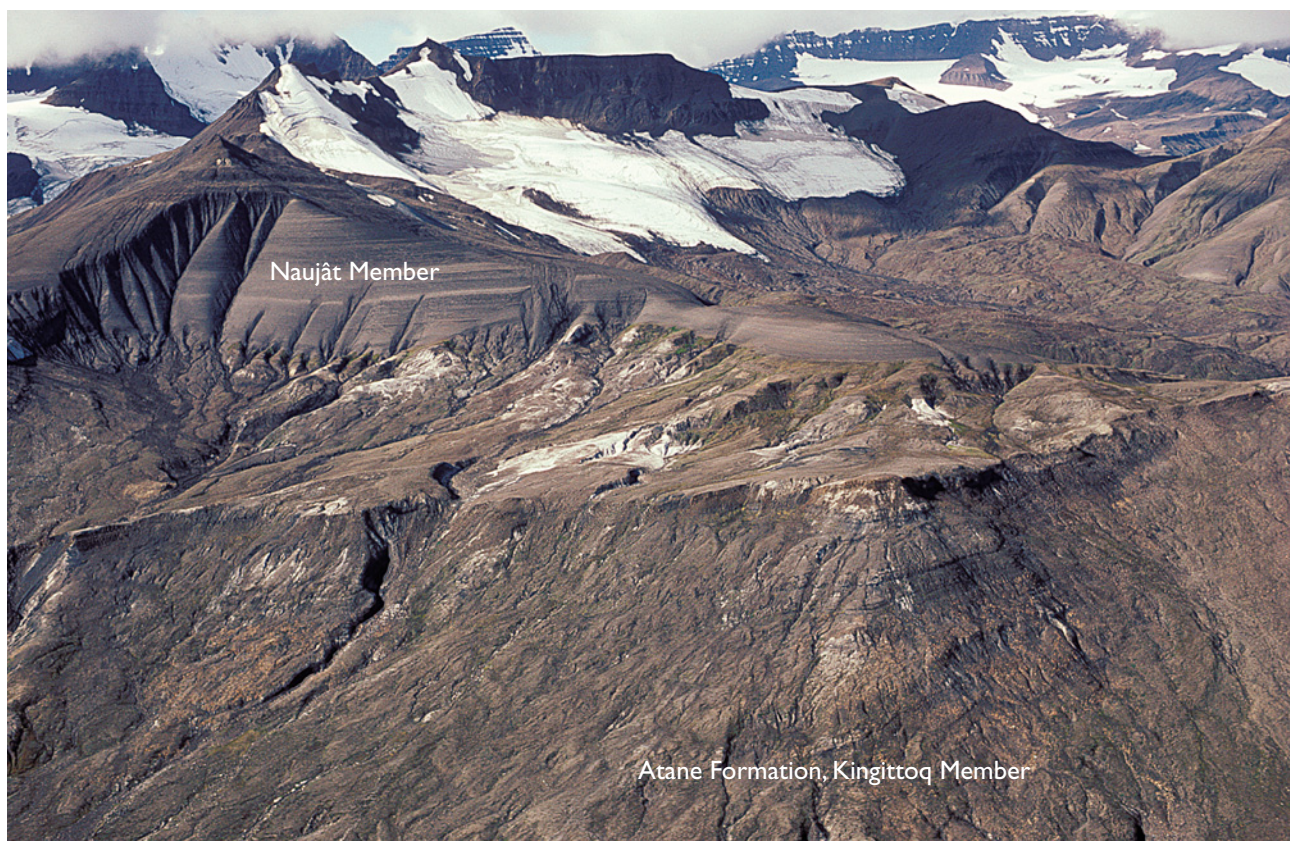


Fig. 130. Outcrop of the Naujât Member overlying the Atane Formation at Eqip Inaarsuata Qaqqaa, at the northern end of the Saqqaqdalen valley (located as EIQ in Fig. 2). The lacustrine mudstones drape erosional relief on the top of the Atane Formation. The Naujât Member is c. 200 m thick.

the coast from Naajaat to Kingittoq (Fig. 40). The member was traced in scree and landslides in the Paatuut area, and, at Ataata Kuua, in a thin succession between the mudstones of the Eقالulik Formation and the hyaloclastite breccias of the Ordlingassoq Member below Point 1010 m (Figs 15, 16; A.K. Pedersen *et al.* 1993, 2007b). In Saqqaqdalen, the Naujât Member continues northwards for about 25 km along the upper western slopes of the valley (A.K. Pedersen *et al.* 2007a).

On Disko, the Naujât Member is known from scattered outcrops along the north coast at Qorlortorsuaq and towards Nuugaarsuk (G.K. Pedersen *et al.* 1998 fig. 12). The delineation of the member on Disko is also discussed under the distribution of the Pingu Member.

*Type section.* The type section was described in the southwestern end of Saqqaqdalen, above Naajaat, by Koch (1959; Figs 124, 129). The type section is located at 70°04.10'N, 52°10.78'W.

*Reference section.* A reference section is proposed at Kingittoq (Fig. 127). A sedimentological log is shown in G.K. Pedersen *et al.* (1998 fig. 10).

*Thickness.* The Naujât Member is thickest on Nuussuaq, up to 230 m at Kingittoq (Koch 1959) and in Saqqaqdalen (G.K. Pedersen *et al.* 1998). On Disko, the member is thin; up to 10 m are preserved at Qorlortorsuaq on the north coast between Qullissat and Asuk (A.K. Pedersen 1985).

*Lithology.* The Naujât Member comprises dark grey to black mudstones with thin, discontinuous layers of sandstones and thin tuff beds. The tuffs are strongly altered and the original chemical composition cannot be determined, but examination of thin sections suggests that the tuffs correlate with the Vaigat Formation. Mineralogically, the mudstones are dominated by kaolinite and quartz with minor feldspar, illite and smectite. Gibbsite has only been identified in 15% of the samples, mostly from the upper part of the member. Pyrite has not been detected.

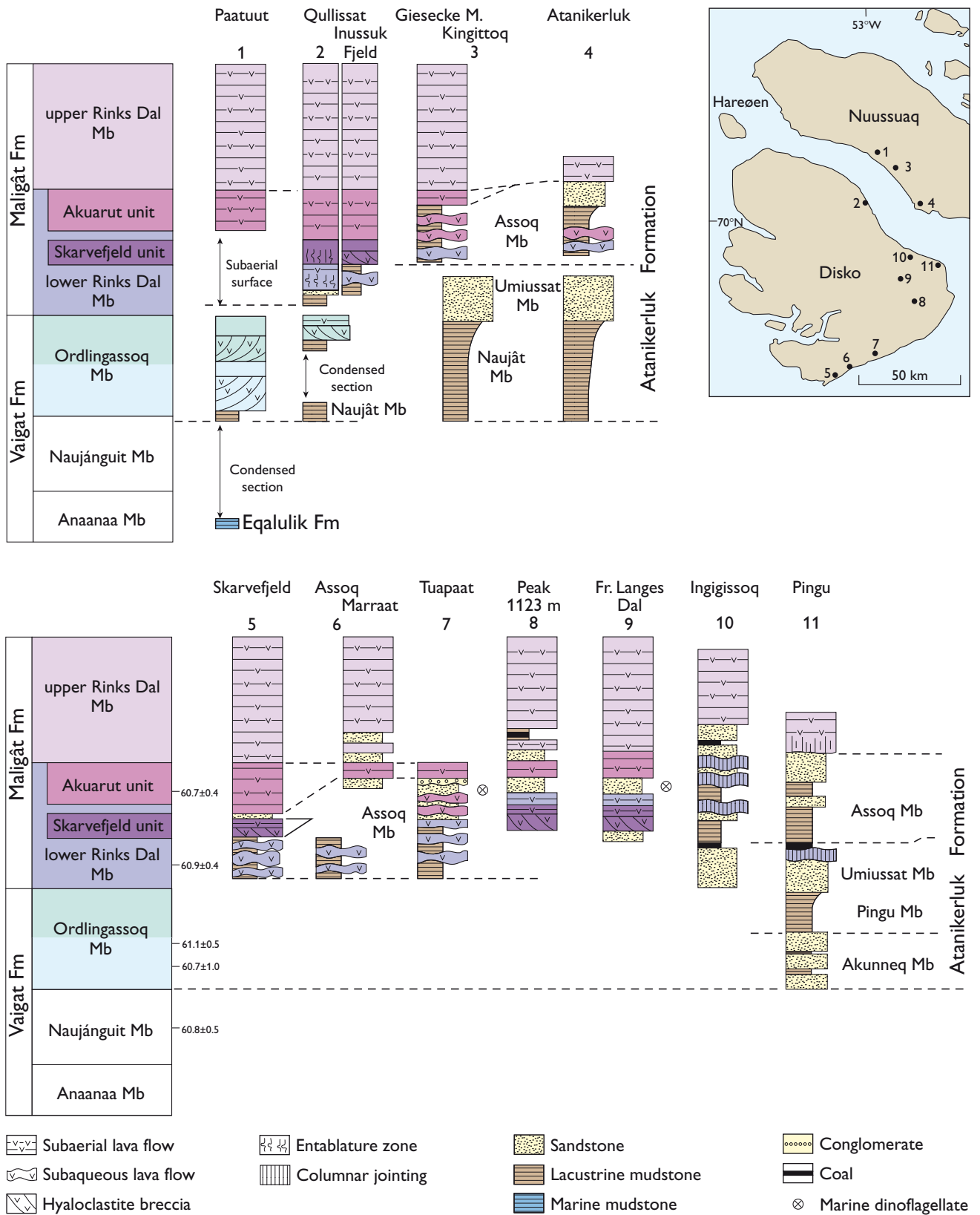


Fig. 131. Simplified stratigraphic sections showing the relationships between the volcanic rocks (colour coded) of the Vaigat and Maligat Formations (West Greenland Basalt Group) and the Atanikerluk Formation. The upper boundary of the Assoq Member is indicated (dashed line). The invasive, subaqueous lavas are all assigned to the Maligat Formation. The radiometric ages are recalculated from Storey *et al.* (1998).

The TOC [Total Organic Carbon] content is high (up to 11%) and C/S ratios are high (G.K. Pedersen *et al.* 1998). Perregaard & Schiener (1979) noted that the organic matter is immature, consisting of exinite (*c.* 50%), vitrinite (*c.* 35%) and inertinite (*c.* 15%), and that it is chemically dominated by saturated and aromatic hydrocarbons. A study of palynofacies indicates a predominance of brown and black lignite (Hjortkjær 1991).

**Fossils.** The Naujât Member has yielded well-preserved macroplant fossils, the Upper Atanikerdluk flora A and B of Heer (1883a, b; Koch 1959, 1963). Leaves from deciduous trees are an important constituent in the flora which includes: *Cladophlebis groenlandica*, *Metasequoia occidentalis*, *Cercidiphyllum arcticum*, *Dicotylophyllum bellum*, *Dicotylophyllum Steenstrupianum*, *Macclintokia Kanei*, *Macclintockia Lyalli* and *Credneria spectabilis* (Koch 1963).

The assemblage of spores and pollen in the Naujât Member was studied by Hjortkjær (1991). The flora is dominated by palynomorphs of terrestrial origin, whereas remains of lacustrine plants and algae are rare. Pollen of *Taxodium* spp. are abundant. The stratigraphically important mid-Paleocene species *Momipites actinus* and *Carya-pollenites wodehouseia* are present in this member.

**Depositional environment.** The Naujât Member is interpreted as a succession of lacustrine mudstones (Koch 1959; Schiener & Leythaeuser, 1978; G.K. Pedersen *et al.* 1998). The lake formed through damming by the volcanic rocks of the Ordlingassoq Member, and it was filled simultaneously by hyaloclastite breccias from the west and siliciclastic mud from the east and south-east (G.K. Pedersen *et al.* 1998). The abundance of kaolinite among the clay minerals suggests that these have the same provenance as the mudstones of the Cretaceous Atane Formation, probably areas of deeply weathered crystalline rocks east of the basin boundary fault.

**Boundaries.** The lower boundary of the Naujât Member corresponds to the lower boundary of the Atanikerdluk Formation in the area where the Naujât Member occurs (Figs 126, 129, 130). Mapping of the lower boundary is difficult in the Paatuut and Ataata Kuua areas where the member overlies marine mudstones of the Eقالulik Formation. In this area, the Naujât Member is also interbedded with the tosets of hyaloclastite breccias of the Ordlingassoq Member (Fig. 17, locality 5). The upper boundary of the Naujât Member is everywhere towards

either the Umiussat Member or the Ordlingassoq Member of the Vaigat Formation (Fig. 136).

**Geological age.** Within the resolution of the dating methods, the age of the Naujât Member lies within the age range of the Atanikerdluk Formation (i.e. early to mid-Paleocene, see p. 146).

**Correlation.** The Naujât Member is coeval with the volcanic breccias of the Ordlingassoq Member; both members overlie the same lacustrine flooding surface (A.K. Pedersen *et al.* 1993; G.K. Pedersen *et al.* 1998). The lacustrine Naujât Member on Nuussuaq correlates with the fluvial Akunneq Member on north-eastern Disko. The palynomorph assemblages of the Naujât, Akunneq and Pingu Members are similar, and the upper part of the Naujât Member correlates with the Pingu Member (Figs 123, 131).

## Akunneq Member

new member

**History.** The sediments now referred to the Akunneq Member were formerly referred to the Upper Atanikerdluk Formation (Koch 1964; Croxton 1978a section C2).

**Name.** The member is named after the Akunneq valley between the Pingu and Inngigissoq mountains on the north-east coast of Disko.

**Distribution.** The Akunneq Member is known from the north-east coast of Disko (Pingu to Nuugaarsuk) and southwards to Gule Ryg (Fig. 124).

**Type section.** The section at Pingu on the eastern side of Akunneq is chosen as the type section (Figs 128, 132). The type section is located at 69°47.53'N, 52°05.43'W.

**Reference section.** The section on the western side of Akunneq is chosen as the reference section.

**Thickness.** The Akunneq Member is *c.* 165 m thick at Pingu but only *c.* 145 m at Nuugaarsuk. Thus the member decreases in thickness towards the west (Fig. 133).

**Lithology.** The Akunneq Member is dominated by very friable sandstone. It comprises a coarse-grained lower part and a finer-grained upper part, separated by a mudstone horizon at 335 m a.s.l. in the Pingu–Akunneq sec-

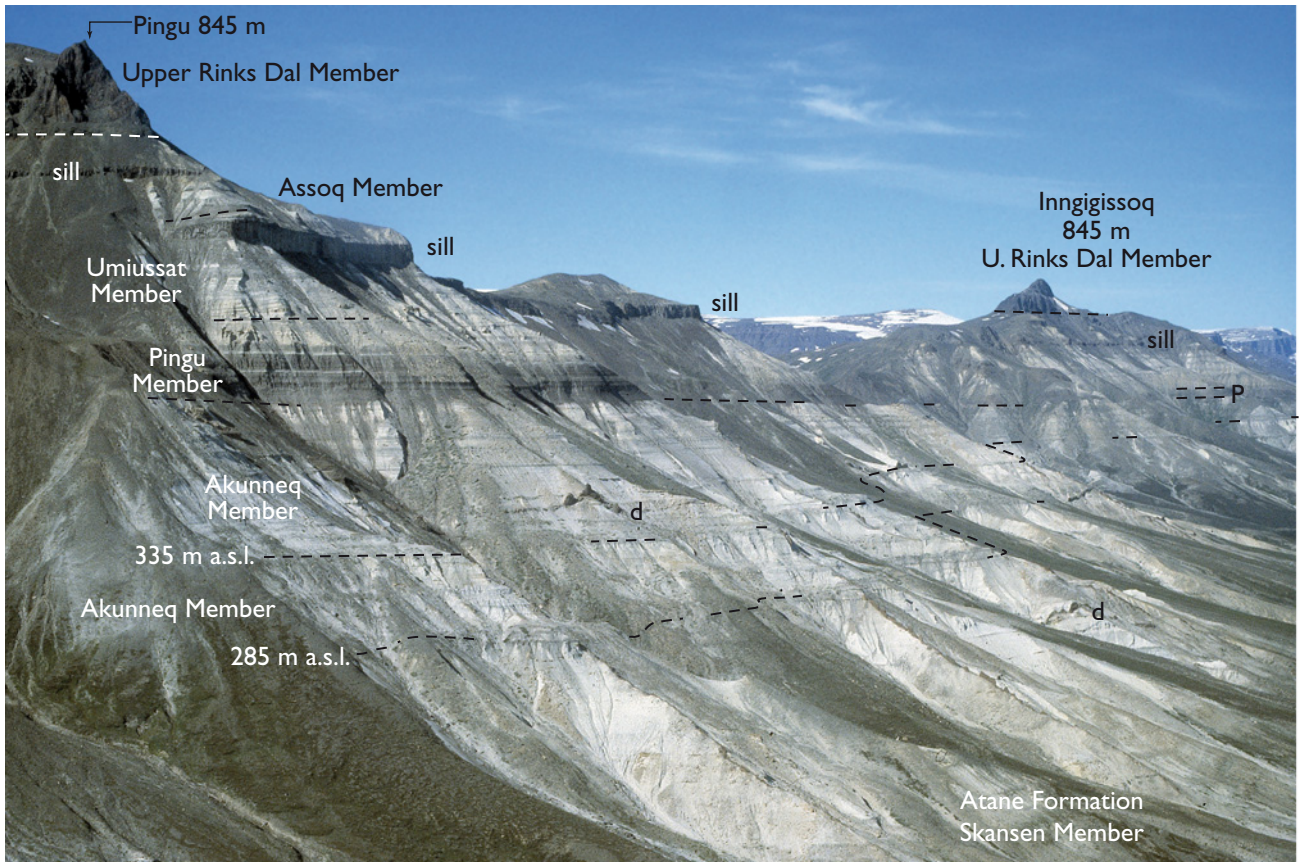


Fig. 132. Outcrop of Atanikerluk Formation in the area between Pingu and Inngigissoq on eastern Disko cut by several dykes (d) and sills (for location, see Fig. 124). The boundary between the Atane Formation (Skansen Member) and the Atanikerluk Formation is set at 285 m a.s.l. The boundary at 335 m a.s.l. separates the lower and upper parts of the Akunneq Member (for section, see Fig. 128). P, Pingu Member.

tion (Figs 132, 133). The lower part consists of large-scale cross-bedded, coarse-grained sandstones that differ little from the fluvial sandstones of the Atane Formation (Figs 128, 134). The upper part is dominated by fine-grained white sands interbedded with thinner horizons of mudstone, carbonaceous mudstone or thin coal seams. Bedding planes in the sandstone are often draped by coaly plant debris. Photogrammetric work shows that the c. 5 m thick mudstones are laterally continuous over a distance of 10 km, and that the proportion of fine-grained facies increases in a westerly direction from Pingu to Nuugaarsuk. Locally, the upper sandstones include 2–3 m thick beds with low-angle, composite cross-bedding. Bedform migration directions suggest westerly palaeocurrents.

*Fossils.* Thin mudstone horizons in the Akunneq Member contain Paleocene spores and pollen as well as reworked species of Cretaceous (Cenomanian) age (Croxtton 1978a, b; Hjortkjær 1991, D.J. McIntyre, personal communication 2009). The upper part of the Akunneq Member

is dominated by Paleocene species identical to those occurring in the Naujât and Pingu Members (Hjortkjær 1991; B.F. Hjortkjær, personal communication 1999). The lower part of the Akunneq Member is dominated by reworked Cenomanian species, and unquestionable Paleocene species are scarce (B.F. Hjortkjær, personal communication 1999; D.J. McIntyre, personal communication 2009).

*Depositional environment.* The Akunneq Member is interpreted as a succession of sandy fluvial deposits interbedded with thin lacustrine mudstones. The sandstones in the lower part of the Akunneq Member are interpreted as deposited in braided channels. The change in grain-size and the ubiquitous coaly plant debris indicate lower energy, and the occasional occurrence of sandy point bar deposits suggests deposition in meandering fluvial channels. The thin but laterally widespread mudstones are interpreted as reflecting short-lived phases of lake formation, and the coal beds represent peat formation. Towards the west, in a downstream direction, the Akunneq

Fig. 133. Correlation of the members within the Atanikerluk Formation on north-east Disko. Note the general thinning of units westwards from Pingu to Nuugaarsuk. Altitudes above sea level are indicated. For location, see Fig. 124; for legend, see Plate 1.

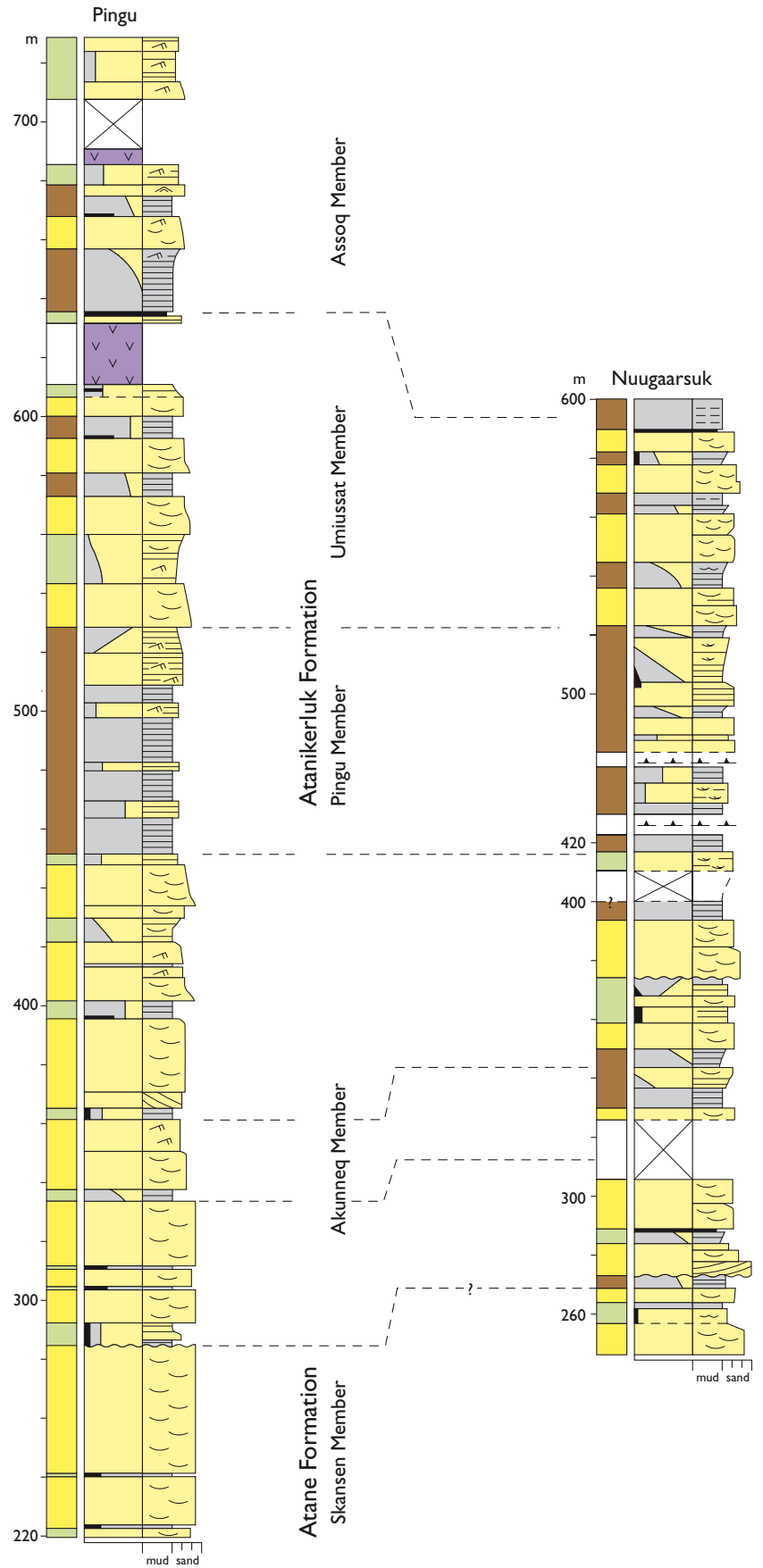




Fig. 134. The illustrated, coarse-grained, fluvial sandstone unit, *c.* 30 m thick, showing large-scale cross-bedding is characteristic of the lower part of the Akunneq Member on the western side of Akunneq. The sandstone is abruptly overlain by grey muddy sandstones, also referred to the Akunneq Member. For location, see Fig. 124.

Member becomes thinner with an increasing amount of mudstone, which suggests that it was deposited on a floodplain adjacent to the 'Naujât lake'.

*Boundaries.* The lower boundary of the Akunneq Member corresponds to the lower boundary of the Atanikerluk Formation in the area of distribution of the Akunneq Member (Fig. 132). The geological map of the Pingu area shows that both the Atane and the Atanikerluk Formations are subhorizontal in north-east Disko (A.K. Pedersen *et al.* 2001). The boundary between the fluvial Skansen Member and the fluvial Akunneq Member may be difficult to identify in outcrops. In the Pingu area, the lower boundary of the Akunneq Member is placed at the base of a *c.* 3 m thick unit of bluish grey, laterally continuous mudstones, which forms a terrace with a steep front. The upper boundary of the Akunneq Member is placed at the base of the mudstones of the Pingu Member (Figs 132, 133, 135).

*Geological age.* Reworked Cretaceous spores and pollen dominate the lower part of the Akunneq Member, but the few Paleocene forms show that the age of the Akunneq Member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see above).

*Correlation.* The Akunneq Member is interpreted to correlate with the lower or middle part of the Naujât Member. Abundant landslides on the north coast of Disko obscure the relationships between the Akunneq Member and the Ordlingassoq Member of the Vaigat Formation (A.K. Pedersen *et al.* 2005).

## Pingu Member

new member

*History.* Sediments referred to the Pingu Member were earlier described by Croxton (1978a section C2). Their sedimentary facies and depositional environment were discussed by G.K. Pedersen (1987, 1989). The deposits were tentatively referred to the Naujât Member by G.K. Pedersen (1987). The difference in mineralogy, the lack of positive evidence that the Pingu and Naujât Members are continuous, and the prominence of this mudstone unit on north-east Disko are the reasons for erecting the Pingu Member.

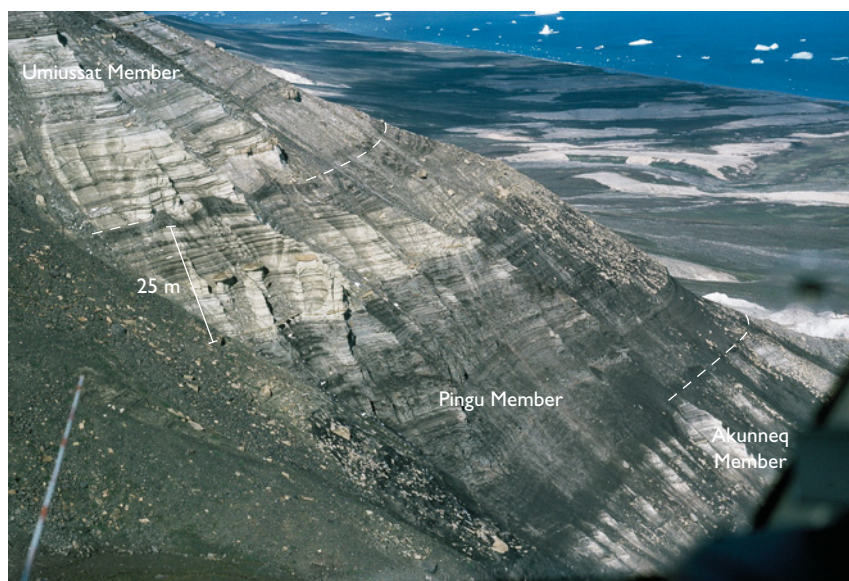
*Name.* The member is named from the mountain of Pingu on north-east Disko (Figs 124, 132).

*Distribution.* The Pingu Member is only known from outcrops on Disko. It is continuously exposed in the coastal section from Pingu to Nuugaarsuk and can be traced south-west of Pingu to Gule Ryg (Fig. 124).

*Type section.* The section on the north side of Pingu (east of Akunneq) is chosen as the type section of the Pingu Member (Figs 128, 135). The type section is located at 69°47.13'N, 52°02.12'W.

*Reference section.* The section between Akunneq and Nuugaarsuk is chosen as the reference section of the Pingu Member (Figs 124, 133).

Fig. 135. Type locality of the Pingu Member on the north side of Pingu (for location, see Fig. 124). Note the sharp lower boundary with the Akunneq Member and the transitional upper boundary with the Umiussat Member.



*Thickness.* The Pingu Member is 85 m thick at Pingu, probably thinning towards Nuugaarsuk, although the thickness is difficult to measure at the latter locality due to landslides (Fig. 133). The member is more than 30 m thick at Gule Ryg.

*Lithology.* The Pingu Member consists of dark grey mudstones interbedded with thin layers of tuff and fine-grained sandstone beds that increase in frequency upwards. The member thus constitutes an overall coarsening-upward succession (Fig. 128; G.K. Pedersen 1989).

Mineralogically, the mudstones consist of kaolinite and quartz with a little illite and feldspar; neither calcite nor pyrite has been detected. Gibbsite is found in 96% of the samples where it makes up 5–10% of the sediment. Siderite occurs in small concretions that weather bright yellow. The mudstones are rich in organic matter (up to 8%), most of which is terrestrial (G.K. Pedersen 1989). A palynofacies study demonstrated the predominance of brown and black wood (Hjortkjær 1991). The sandstones are fine-grained, well-sorted and form thin beds showing parallel lamination or current ripple cross-lamination.

*Fossils.* The assemblage of spores and pollen in the Pingu Member was studied by Hjortkjær (1991), who found that it corresponds to that of the Naujât Member. The flora is dominated by palynomorphs of terrestrial origin, whereas remains of lacustrine plants and algae are rare. Pollen of *Taxodium* spp. are abundant. The stratigraphically important mid-Paleocene species *Momipites actinus* and *Caryapollenites wodehouseia* occur together with a few specimens of the mid- to late Paleocene *Insulapolle-*

*nites rugulatus* (Hjortkjær 1991). Neither Croxton (1978a, b) nor Hjortkjær (1991) observed marine dinocysts in samples from the Pingu Member.

*Depositional environment.* The Pingu Member represents a predominantly low energy depositional environment characterised by settling of mud from suspension and occasional deposition of sand from low energy sediment gravity flows. The lack of marine fossils coupled with the absence of both pyrite and its weathering product jarosite indicates a lacustrine depositional environment. The increasing number of sand layers up-section are interpreted to record gradual progradation of the shoreline and consequent filling of the lake (G.K. Pedersen 1989). The supply of gibbsite to the lacustrine mud suggests input from a new provenance area. The expanding areas of subaerial basalt flows may have weathered to lateritic soils that could have supplied gibbsite during deposition in the ‘Pingu lake’. This new provenance area is also reflected in the mineralogy of the top of the lacustrine Naujât Member.

*Boundaries.* The Pingu Member has a sharp lower and a gradational upper boundary (Figs 128, 132, 135). The lower boundary separates the lacustrine mudstones of the Pingu Member from the underlying sandy fluvial Akunneq Member; this abrupt boundary is overlain either directly by mudstones or by a thin succession of mudstones interbedded with sandstone layers and it is interpreted as an erosional surface formed during lacustrine drowning (Figs 128, 135). The upper boundary is defined by the base of the Umiussat Member (Figs 128, 132, 133, 134, 135).

*Geological age.* The age of the Pingu Member is the same that of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

*Correlation.* The deposits assigned here to the Pingu Member have been correlated with the Naujât Member (Henderson *et al.* 1981 fig. 4). The assemblages of spores and pollen in the two members are similar (Hjortkjær 1991), but the mineralogy differs, especially with respect to the distribution of gibbsite. We interpret the Pingu Member on Disko as correlating with the upper part of the Naujât Member on Nuussuaq.

A correlation between the Pingu Member and the volcanic Ordlingassoq Member cannot be proven because the north coast of Disko is ravaged by landslides and rock glaciers between Nuugaarsuk and Qullissat (A.K. Pedersen *et al.* 2005). Between Pingu and Nuugaarsuk, the oldest magmatic rocks have a composition corresponding to the Maligât Formation (Fig. 131).

## Umiussat Member

revised member

*History.* The Umiussat Member was established by Koch (1959) on south-east Nuussuaq where it overlies the Naujât Member. In the present paper the definition of the Umiussat Member is retained, but its geographical distribution is expanded.

*Name.* The member is named from the Umiusat ridge on south-eastern Nuussuaq (Fig. 40).

*Distribution.* The Umiussat Member is known on south-east Nuussuaq in the area between Naajaat and Kingittoq, and in Saqqaq dalen. It covers a smaller area than the Naujât Member. The Umiussat Member is also present on eastern Disko between Nuugaarsuk and Pingu, and at Gule Ryg (Figs 40, 124).

*Type section.* The type section of the Umiussat Member of Koch (1959) at Umiusat is retained (Figs 126, 136). The type section is located at 70°09.00'N, 52°26.57'W.

*Reference section.* The section on the north side of Pingu, east of Akunneq, is suggested as a reference section for the Umiussat Member (Figs 128, 132).

*Thickness.* The Umiussat Member is 70–100 m thick. It is rarely well exposed, hence lateral variations in thickness are not documented. The member is *c.* 80 m thick at Pingu (Fig. 128) and *c.* 100 m thick in the Atanikerluk area (Koch 1959).

*Lithology.* The Umiussat Member is dominated by fine- to medium-grained sands or sandstones which range in colour from white or pale grey on Disko to yellow on Nuussuaq. Comminuted plant debris is abundant and outlines bedding planes and sedimentary structures such as cross-lamination and cross-bedding. The sands or sandstones are interbedded with 1–5 m thick mudstones,

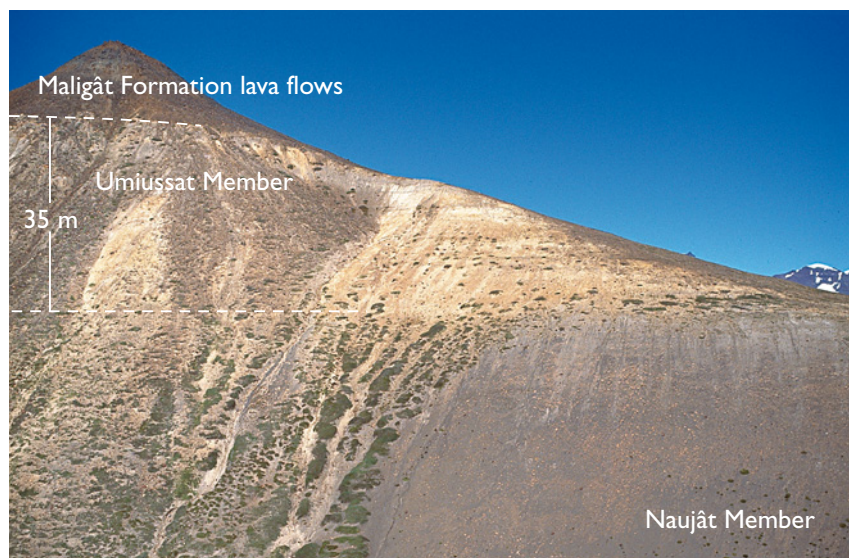
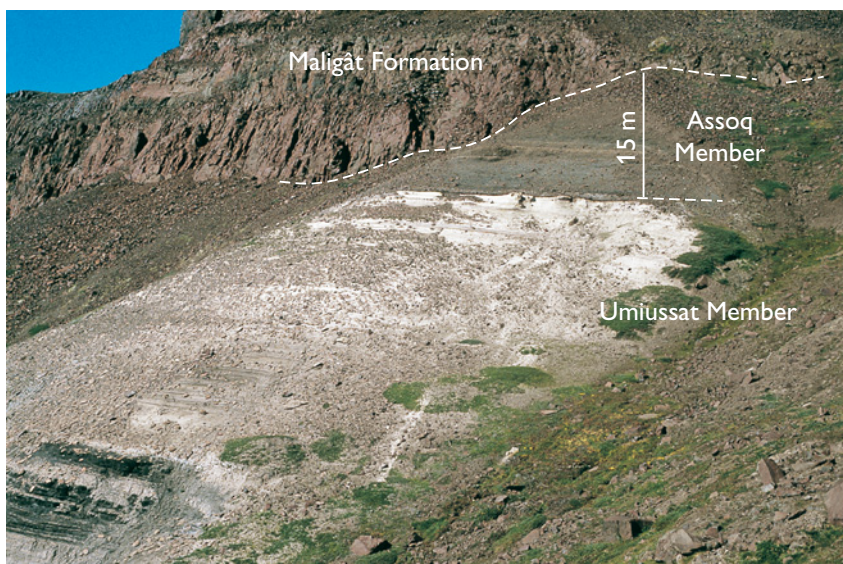


Fig. 136. Type locality of the Umiussat Member (Atanikerluk Formation) at Umiusat, south-eastern Nuussuaq (for location, see Fig. 40). At the top of the Naujât Member, an increase in the number of thin sandstone beds results in a transitional boundary between the two members.



Fig. 137. Lower, sharp boundary of the Assoq Member with the Umiussat Member at Umiussat. See section 2 in the composite sedimentological log in Fig. 126.



some of which include thin coal beds (Figs 126, 128, 137). A 120 cm thick coal bed forms the top of the Umiussat Member on north-east Disko (Fig. 131).

*Fossils.* No fossils have been reported from the Umiussat Member.

*Depositional environment.* The sediments of the Umiussat Member are interpreted to have been deposited in predominantly braided fluvial channels and on floodplains.

*Boundaries.* The lower boundary with the Naujât Member is transitional and is rarely well exposed (Fig. 136; Koch 1959). The lower boundary with the Pingu Member is placed at an erosional surface separating the heterolithic sandy mudstones at the top of the Pingu Member from the overlying fluvial sandstones of the Umiussat Member (Figs 128, 135). The upper boundary of the Umiussat Member is placed at the drowning surface which forms the lower boundary of the Assoq Member (Figs 133, 137).

*Geological age.* The age of the member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

*Correlation.* The Umiussat Member is interpreted as coeval with the uppermost subaerial lava flows of the Ordlingassoq Member, and deposition of the Umiussat Member probably continued during the break in volcanic activity between the Vaigat and the Maligât Formations (Fig. 131).

## Assoq Member

new member

*History.* The sediments referred to the Assoq Member include those overlying the Umiussat Member on Disko as well as those referred to the Aussivik Member and the Point 976 Member of Koch (1959) (Fig. 123). The Aussivik and Point 976 Members are abandoned because they are poorly exposed and only cover small areas on south-eastern Nuussuaq.

*Name.* The member is named from the coastal mountain slope at Assoq on southern Disko (Fig. 124).

*Distribution.* The geological map sheets 1:100 000 Uiffaq and 1:100 000 Pingu show that the Assoq Member covers most of Disko, east of the Disko Gneiss Ridge (A.K. Pedersen *et al.* 2000, 2001). The area in which the Assoq Member is distributed is strongly affected by landslides and reliable outcrops are discontinuous (Fig. 124). On Nuussuaq, the Assoq Member is present at Kingittoq, between Umiussat and Saqqaq dalen, in the Atanikerluk area and probably also on central Nuussuaq, east of the Ikorfat fault (Fig. 40; A.K. Pedersen *et al.* 1993, 2002, 2007b).

*Type section.* The type section is at Assoq within a huge landslipped block (Fig. 138). This locality has the best exposures of the fissile mudstones, but neither the lower nor the upper boundary of the Assoq Member is confi-

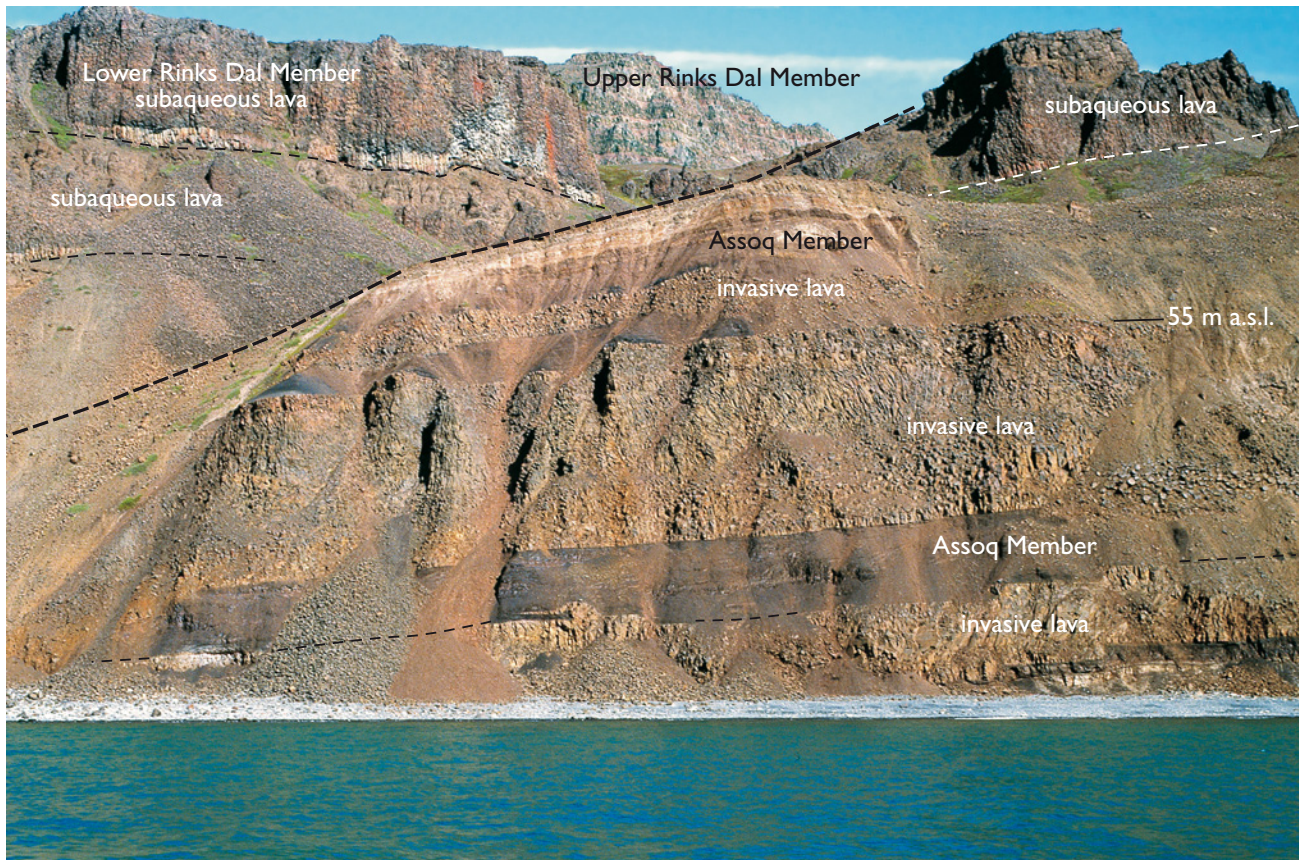


Fig. 138. Type locality of the Assoq Member at Assoq on the south coast of Disko (for location, see Fig. 124). The brownish black mudstones of the Assoq Member are interbedded with invasive lava flows and overlain by subaqueous lava flows of the lower Rinks Dal Member of the Maligât Formation (see Fig. 131). Sediments and interbedded volcanic rocks are part of a huge landslide, two blocks of which are separated by the dash-dot line. The Assoq Member is also found at higher altitudes away from the coast (A.K. Pedersen *et al.* 2003). For log, see Fig. 139.

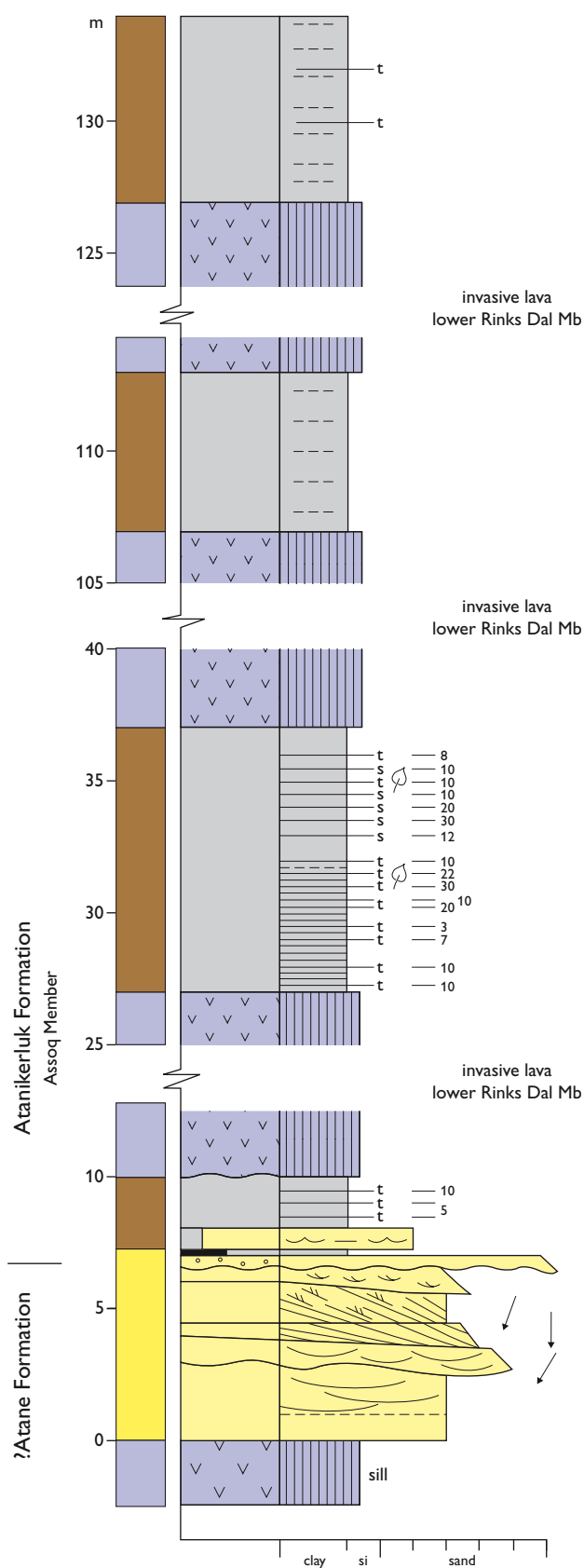
dently identified (Fig. 139). The type section is located at 69°19.23'N, 53°09.10'W.

*Reference sections.* Reference sections are exposed on southern Disko east of Assoq (Fig. 139), on northern Disko at Pingu (Figs 124, 128), and on southern Nuussuaq at Qallorsuaq (Keglen). The sediments here were formerly referred to the Aussivik and Point 976 Members of Koch (1959) (Figs 40, 125).

*Thickness.* The Assoq Member is up to *c.* 200 m thick, but the thickness is difficult to measure in areas where the sediments are interbedded with volcanic or intrusive rocks and are subject to landslides.

*Lithology.* The Assoq Member constitutes a major, coarsening-upward succession with a lower part dominated by brownish black fissile mudstones, and an upper part

that is dominated by sands but also includes a single, 3 m thick, coal seam (Figs 126, 128, 138, 140). The mudstones have TOC contents of up to 7%. The dominant clay mineral is kaolinite, but gibbsite is also present in most samples. Thin beds are cemented by siderite. Numerous thin tuff layers are interbedded with the mudstones. They are typically a few millimetres to a few centimetres thick, deposited by settling through the water column. Examination of thin sections shows that the tuff is strongly altered diagenetically. The mudstones are interbedded with hyaloclastite breccias and subaqueous lava flows which formed where lava flows of the lower Rinks Dal Member entered the 'Assoq lake' (L.M. Larsen *et al.* 2006). Based on their chemical composition, the invasive lava flows are correlated with various units within the volcanic lower Rinks Dal Member (Figs 131, 139, 140).

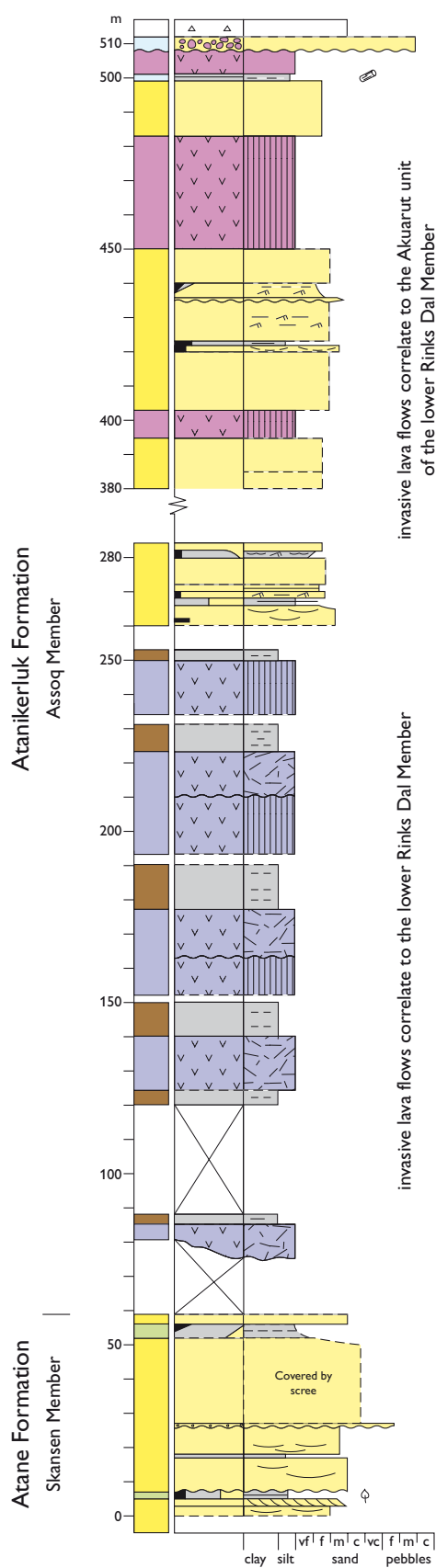


The upper part of the Assoq Member is dominated by sands, often with comminuted plant debris. In the scree-covered slopes at Tuapaat Qaqqaat and Qallorsuaq (Keglen), the sands are yellow and fine-grained, but rarely well exposed. At Pingu and Gule Ryg, the sedimentary structures suggest deposition from traction currents in a low-energy environment (Fig. 128). A thick coal bed has been observed at the top of the Assoq Member (Fig. 141) which probably correlates to coal beds interbedded with volcanic rocks at several localities west of Gule Ryg, eastern Disko (L.M. Larsen & Pedersen 1990; A.K. Pedersen *et al.* 2001) (Fig. 131). These sediments are considered part of the Atanikerluk Formation as they can be traced from continuous sedimentary successions into the basal part of the subaerial lava flow succession. The chemistry of these volcanic rocks corresponds to the lower part of the upper Rinks Dal Member.

*Fossils.* Plant macrofossils are unevenly distributed in the Assoq Member, but they are generally scarce. From the Atanikerluk area, Koch (1959) reported a leaf of *Cercidiphyllum arcticum* from the lower part (his Aussvik Member) and pieces of fossil wood of *Taxodioxylon* type from his Point 976 member. Bedding planes covered by plant remains were observed west of Kingittoq by the present authors. The freshwater bivalve *Unio* sp. occurs in the upper, sandy part of the Assoq Member (Koch 1959). Fish scales and bones are preserved in a concretion from Akuliarusinguaq (c. 4 km north of Gieseckes Monument; Fig. 2).

The spores and pollen in the Assoq Member were described by Hjortkjær (1991) and differ little from those in the older members of the Atanikerluk Formation. Piasecki *et al.* (1992) reported finds of marine dinocysts in a few samples from the Assoq Member in southern and eastern Disko. In the inner part of Kvandalen (Fig. 124), the mudstones are found to contain rare bivalves (protobranchs?) and rare dinocysts (Piasecki *et al.* 1992). A few marine dinocysts were found at Tuapaat Qaqqaat at the top of the Assoq Member just below the basalt conglomerate (Fig. 140).

Fig. 139. Type section of the Assoq Member at Assoq on the south coast of Disko (for location, see Fig. 124). The lacustrine mudstones contain numerous millimetre-thick tuff beds. For legend, see Plate 1.



*Depositional environment.* At Skarvefjeld (Fig. 2), the lower, shaly part of the Assoq Member is interbedded with hyaloclastite breccias that are traced laterally into the lower Rinks Dal Member (Heinesen 1987; L.M. Larsen & Pedersen 1990). Water depths of 80–100 m are calculated from the height of the foresets of the hyaloclastite breccias. Similar interbedding of Assoq Member mudstones and hyaloclastite breccias is also known from Sorte Hak on central Disko, slightly east of the Disko Gneiss Ridge (Fig. 124). The Assoq Member is interpreted as lacustrine in origin, deposited within the ‘Assoq lake’. At present it is not possible to demonstrate whether this was one huge lake or several smaller lakes. Scarce marine dinocysts indicate that the Assoq lake was subject to marine inundations. The dinocysts were found in samples from eastern and south-eastern Disko, but were not recorded from Nuussuaq. This distribution, coupled with a south-eastward tilting of an originally nearly horizontal magmatic boundary (L.M. Larsen & Pedersen 1992) suggests that the marine inundations were from the south. The upward transition from mudstones to sandstones reflects shallowing and gradual fill of the lake. During a break in clastic sediment input, peat accumulated in a large swamp in eastern Disko, and resulted in a thick coal bed (Fig. 141).

*Boundaries.* The lower boundary of the Assoq Member is placed at the base of the mudstone succession, and is interpreted as a lacustrine drowning surface (Figs 128, 137). On north-east Disko, the lower boundary overlies a coal bed. The upper boundary is placed where the sediments are overlain by subaerial lava flows of the Rinks Dal Member. Note that locally thin tongues of sediment within the lower Rinks Dal Member are assigned to the Assoq Member; such sediment wedges are bounded abruptly beneath and above by volcanic strata. At Tuapaat Qaqqaat, the uppermost bed in the Assoq Member is a conglomerate with clasts of basaltic rocks derived from lava flows of the Akuarut unit of the Rinks Dal Member (Fig. 140; L.M. Larsen & Pedersen 1990, 2009).

Fig. 140. Composite reference section of the Assoq Member at Tuapaat Qaqqaat, south-eastern Disko (for location, see Fig. 124). Note the occurrence of marine dinocysts at the top of the lacustrine section, indicating a brief marine inundation. Colour coding of volcanic rocks follows Fig. 131. For legend, see Plate 1.

Fig. 141. Upper part of the Assoq Member including a 5.1 m thick coal bed. South side of Blåbærdalen, eastern Disko (for location, see Fig. 124). Correlative coal beds are seen at several widely spaced outcrops indicating the development of large swamps. The sediments are overlain by subaerial lava flows of the volcanic Rinks Dal Member (see Fig. 131).



*Geological age.* The age of the Assoq Member lies within the age range of the Atanikerluk Formation (i.e. early to mid-Paleocene, see p. 146).

*Correlation.* On southern Disko, the lower, shaly, part of the Assoq Member is interbedded with subaqueous lava flows and hyaloclastite breccias, which continue westwards into the Skarvefjeld unit (formerly Pahoehoe unit) of the lower Rinks Dal Member (Fig. 131; Heinesen 1987; L.M. Larsen & Pedersen 1990, 2009; A.K. Pedersen *et al.* 2003; L.M. Larsen *et al.* 2006). On north-eastern Disko (Akunneq and Pingu), the earliest volcanic rocks are thick invasive lava flows with columnar jointing, which invaded the uppermost part of the Umiussat Member and the Assoq Member. The composition of these volcanic rocks tie them to the uppermost lower Rinks Dal Member and the Akuarut unit (formerly FeTi unit) (Fig. 131; A.K. Pedersen *et al.* 2005; L.M. Larsen *et al.* 2006; L.M. Larsen & Pedersen 2009).

On Nuussuaq, lava flows of the Akuarut unit invaded mudstones of the Assoq Member and increased markedly in thickness due to ponding of the lavas in the 'Assoq lake'. Throughout eastern Disko and southern Nuussuaq the Assoq Member is thus interbedded with invasive flows of the Rinks Dal Member, and the various volcanic facies (breccias, invasive lavas or ponded subaerial lava flows) are thought to reflect different extrusion rates. In most of its area of distribution, the Assoq Member is overlain by subaerial lava flows of the upper Rinks Dal Member (Fig. 131). It is concluded that the Assoq Member gen-

erally correlates with the Rinks Dal Member. On easternmost central Nuussuaq, however, an outcrop of mudstones interbedded with invasive lava flows of the younger Niaqussat Member is also referred to the Assoq Member (A.K. Pedersen *et al.* 2002).

## Acknowledgements

The work reported on in this publication was carried out with considerable financial support from the Danish Energy Research Programme (EFP), the Danish Natural Science Research Council (SNF), the Bureau of Minerals and Petroleum, Government of Greenland, the Carlsberg Foundation and the Arktisk Station, University of Copenhagen. Their support is gratefully acknowledged.

The authors are greatly indebted to the three referees: Dr. T. Christopher R. Pulvertaft, now retired from GEUS, has taken a keen interest in the manuscript from its early stages and has encouraged the authors throughout. He has corrected the English language and has used his great knowledge of the area to ensure that details in descriptions and illustrations are correct. Dr. J. Christopher Harrison of the Geological Survey of Canada and Dr. Robert Knox of the British Geological Survey have read the manuscript very carefully and offered a large number of helpful suggestions for the improvement of text and figures. With few exceptions, the illustrations have been prepared by Jette Halskov, GEUS, without whom the manuscript would not have been completed.