Correlation. The Upernivik Næs flora was suggested to be coeval with the Ravn Kløft flora by Boyd (1998a). This suggests a correlation between the Upernivik Næs Formation and the Ravn Kløft Member of the Atane Formation (Figs 13, 16).

Atane Formation

redefined formation

History. Nordenskiöld (1871) erected the Atane Formation (Atanelagren), naming it after the now-abandoned settlement of Atane (now Ataa, Figs 3, 40). He described the unit to be more shaly than both the underlying Kome Formation and the overlying Upper Atanikerdluk Formation, and interpreted the Atane Formation as freshwater deposits. He referred the formation to the Upper Cretaceous, following Heer (1868), with a distribution on southern Nuussuaq (between Atanikerluk and Ataa), northern Disko (at Qullissat) and at Kuuk on northern Nuussuaq (at altitudes above 250–300 m). Outcrops with coal seams were visited by Steenstrup (1874), who noted the occurrence of marine invertebrates in mudstones between the coal seams at Paatuut and Nuuk Qiterleq.

The Atane Formation normally appears as a striped white, grey and black sandy and shaly unit rich in coalified plant fossils (Fig. 41) that formed the basis of the classic studies by Heer (1868, 1870, 1874a, b, 1880, 1883a, b). However, self-combustion of the mudstones has locally produced brick-red, hard and fissile burnt slabs (Fig. 42) in which fossils are excellently preserved as impressions. Burnt mudstones are fairly common in the Paatuut (formerly spelled Patoot, Pâtût or Pautût) and Kingittoq areas, and they were included in the regional collection that Steenstrup sent to O. Heer (Steenstrup 1883a, b). Based on their colour, Heer treated the samples of burnt mudstones from Paatuut as lithostratigraphically different from those containing the Atane flora. Thereby a Patoot Formation (i.e. the sediments comprising the Patoot flora) was introduced and subsequently treated as a formal unit (Troelsen 1956). Steenstrup (1883c) objected to Heer's interpretation of a stratigraphic boundary between the unburnt and the burnt mudstones from Paatuut since he had observed that the burnt mudstones are laterally equivalent to the normal, unburnt sediments.

Steenstrup (1883a) suggested that all the Cretaceous sediments from Svartenhuk Halvø to Disko should be enclosed in one lithostratigraphic unit. He envisaged the depositional environment of the horizontally bedded mudstones and sandstones as shallow marine on account of his collections of invertebrates (bivalves and echinoids), although the well-preserved plant remains indicated deposition close to vegetated areas (Steenstrup 1883a p. 48).

The Early Cretaceous to Miocene age proposed by Heer for the coal-bearing deposits in West Greenland was discussed by A. Heim and J.P.J. Ravn, who both suggested that Heer's interpretation spans too long a period. Instead they interpreted all the sediments as Upper Cretaceous to Eocene (Heim 1910), more specifically the Kome flora as Albian, the Atane flora as Cenomanian, the Patoot flora as Senonian and the Atanikerdluk flora as Eocene (Ravn 1918 p. 320). Ravn (1918) envisaged the plant bearing sediments as having been deposited in a fresh- to brackish-water environment, in which the rate of deposition equalled the rate of subsidence. The inoceramids provided evidence of marine conditions and Ravn therefore concluded that at times subsidence exceeded deposition and marine environments were established. Furthermore, he observed no changes in the style of sedimentation during the Cretaceous and inferred that deposition had occurred continuously, presumably within a restricted period and consequently at relatively high rates of sediment accumulation.

Troelsen (1956) maintained the distinction between the Kome, Atane and Patoot Formations, quoting descriptions by Nordenskiöld (1871) and Heer (1883b). These authors suggested that the Kome and Atane Formations are separated by a slight angular unconformity (Troelsen 1956).

Koch (1964) regarded the Pautût Formation (*sensu* Heer 1883b) as an artificial unit. Henderson *et al.* (1976 fig. 303) quoted the lithostratigraphy of Troelsen (1956), but stressed that the Kome, Atane and Pautût formations lacked formal stratigraphic definition and referred all the fluvial and deltaic Cretaceous sediments on Disko and southern to central Nuussuaq to the Atane Formation. Ehman *et al.* (1976) used the term Atane Formation informally for the Cretaceous non-marine deposits and found that the sediments range in age from Albian through Santonian.

G.K. Pedersen & Pulvertaft (1992) referred all non-marine Cretaceous sediments on Disko and Nuussuaq to the Atane Formation. They claimed (p. 263) that the term Atane Formation "had outlived the other formation names that have been used in the past for the different isolated outcrops of Cretaceous non-marine strata in West Greenland". Based on the data available at that time, G.K. Pedersen & Pulvertaft (1992 p. 263) interpreted these strata as "belonging to the same deposi-

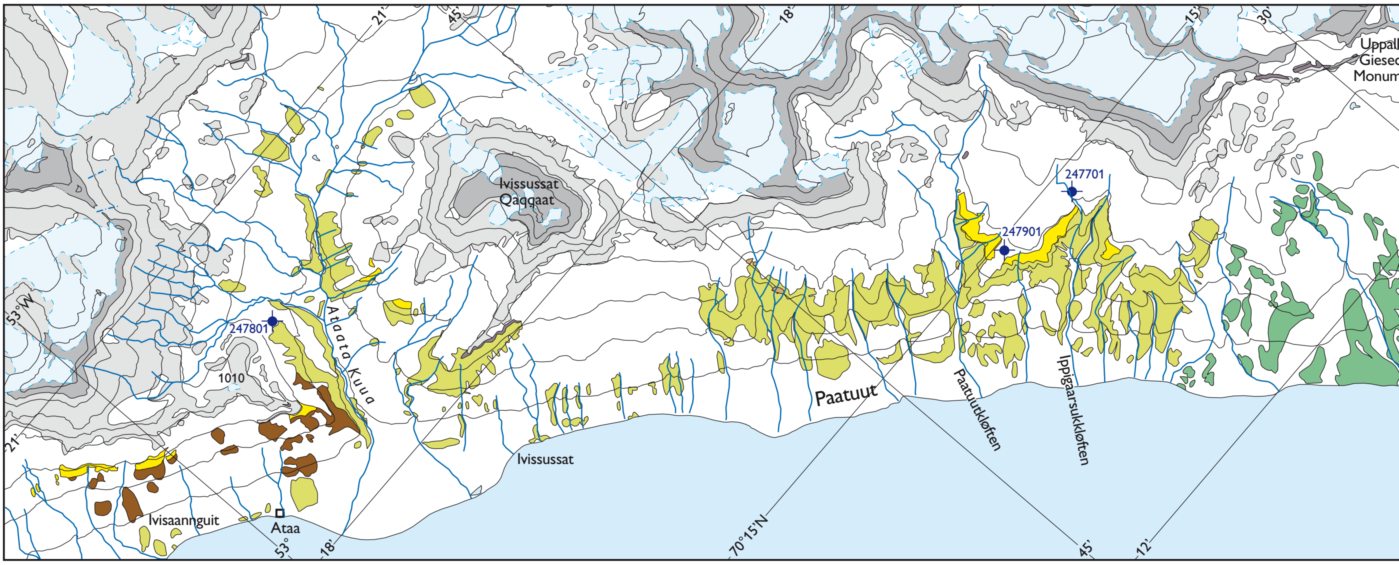
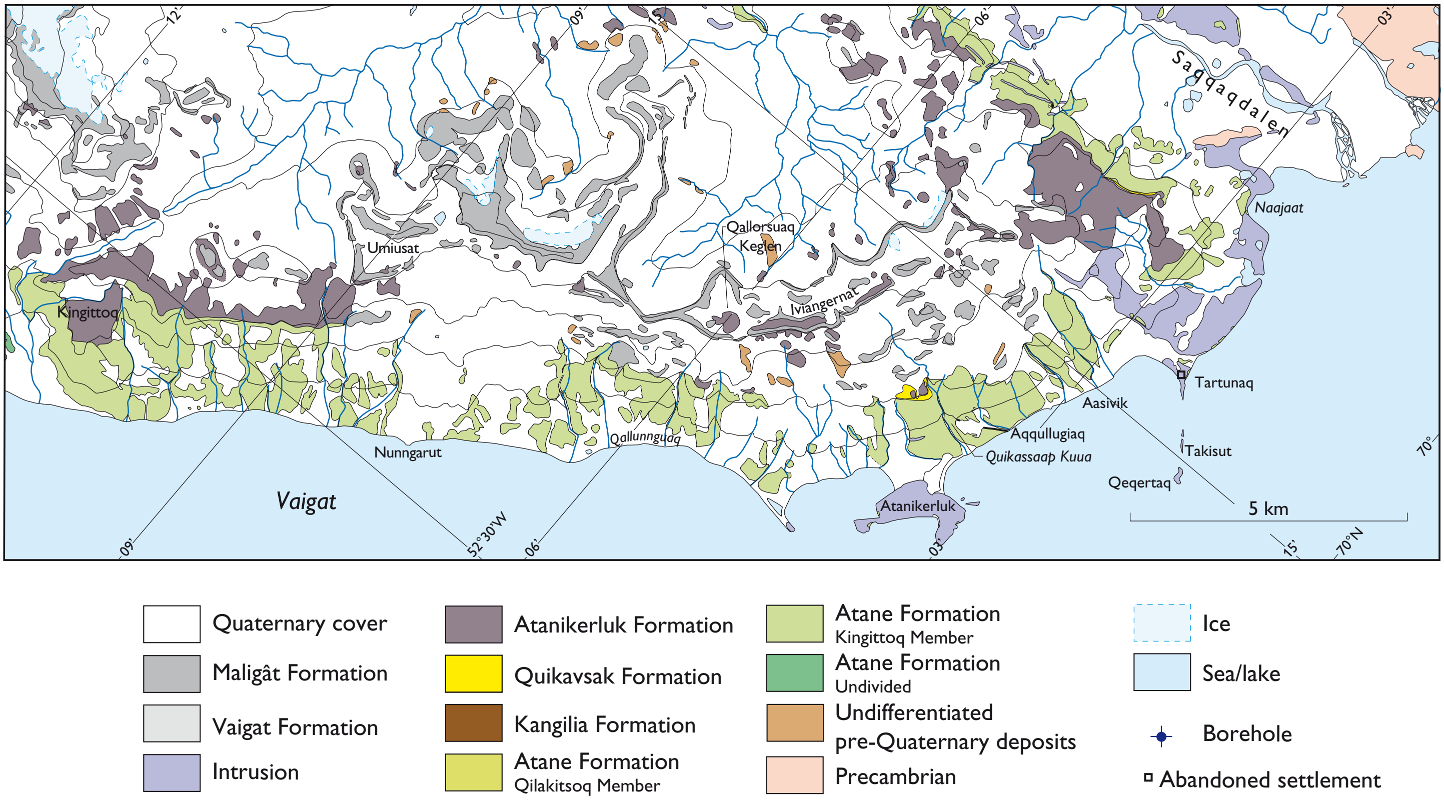


Fig. 40. Geological map of the south coast of Nuussuaq from Saqqaqdalen to Ivisaannguit, simplified from A.K. Pedersen *et al.* (2007b). The type localities of the Atane, Quikavsak and Atanikerluk Formations are all found within this area. The wells GGU 247701, GGU 247801 and GGU 247901 indicated on the map were drilled to obtain technical information on the coal-bearing strata of the Atane Formation. Contour interval is 200 m; for location, see Fig. 2.

Fig. 41. Typical outcrop of the Atane Formation at Paatuut on southern Nuussuaq. Note the prominent cyclic alternation of lithologies. For location, see Fig. 40. **Q**, Quikavsak Formation; compare with Fig. 14.



tional system and the same age interval, so that no more than one formation name seems at present to be required for the entire non-marine Cretaceous of the area". Later, from sedimentological studies, Midtgaard (1996b) argued for the continued distinction between the Atane, Kome and Upernivik Næs Formations, as well as for the new Slibestensfjeldet Formation. Boyd (1993) considered, mostly on floral evidence, that the sediments at Paatuut should not be included in the Atane Formation. He therefore retained the Pautût flora and the Pautût Formation (Boyd 1993 p. 253). There are, however, no lithological or sedimentological arguments for retaining the Pautût Formation of Troelsen (1956) or Boyd (1993), and we therefore recommend that it be abandoned and included in the Atane Formation.

Name. From a former settlement Ataa (old spellings Atane, Atâ) on the south coast of Nuussuaq immediately west of Ataata Kuua (Figs 2, 3, 40; Nordenskiöld 1871 plate XXI). Today only ruins of a few turf houses are seen at Ataa.

Distribution. The Atane Formation is restricted to Disko and Nuussuaq. It comprises the lowermost exposed deposits on eastern Disko and southern and central Nuussuaq. Marginally marine successions of Albian–Cenomanian age in the northern parts of the Nuussuaq Basin are referred to the Upernivik Næs Formation.

Exposures of the Atane Formation are found east of the Disko Gneiss Ridge and east of the Kuugannguaq–Qunnilik Fault (Fig. 10; Chalmers *et al.* 1999). On northern Nuussuaq, the Atane Formation is present east of the Ikorfat fault zone where it overlies the Slibestensfjeldet Formation (Fig. 22; Midtgaard 1996b).

The distribution of the Atane Formation west of the outcrop area is little known. There are, however, no sedimentological data from the Atane Formation to indicate that the Disko Gneiss Ridge formed a morphological element during deposition of the formation. Finds of sandstone xenoliths with chert pebbles in lava flows on western Disko have been suggested to be derived from the Atane Formation (Chalmers *et al.* 1999). The xenoliths could, however, also have been derived from the Itilli Formation, which occurs on western Nuussuaq.

Type section. The type section of the formation is the cored well GGU 247801 (70°19.87′N, 52°55.18′W) in the gorge of the Ataata Kuua river (Figs 14, 40) where these sediments were first described by Nordenskiöld (1871). The next geologist on the site was K.J.V. Steenstrup. He noted in 1872 that the description given by Nordenskiöld did not match the outcrop and that the

Fig. 42. Well-exposed outcrop at Paatuut showing the self-combusted burnt shales (red) that grade into the typical black-and-white unburnt sediments of the Atane Formation (Qilakitsoq Member). Height of section is approximately 50 m. For location, see Fig. 40.

geographical position was inaccurate (Steenstrup 1874). He suggested that Nordenskiöld had measured the type section of the Atane Formation south-east of the Ataa river, at "the northern end of the Patoot gorges" (Steenstrup 1883b p. 64). Later Rosenkrantz (1970 p. 422) stated that: "... the type locality Atâ, 14 km south-east of the old village Atâ on the south coast of Nûgssuaq, is rather close to Pautût..", but in Henderson *et al.* (1976) the type locality of the Atane Formation was again given at Atâ (Ataata Kuua). The exposures along the western and eastern slopes of the Ataata Kuua gorge constitute a long, well-exposed section through the Atane Formation, and this has been measured photogrammetrically (Fig. 15; A.K. Pedersen *et al.* 2007b). The sedimentological log representing the type section (Fig. 43) was measured in the continuously cored borehole GGU 247801, which reached a depth of 566 m below terrain (76 m below sea level).

Reference sections. Skansen, J.P.J. Ravn Kløft, Kingittoq and Qilakitsoq provide well-exposed reference sections for the Atane Formation (Figs 48, 51, 53, 60). The two continuously cored boreholes GGU 247701 and GGU 247901, both from the Paatuut area, are reference boreholes for the Atane Formation. They comprise strata from the Qilakitsoq Member and have been described in detail by Ambirk (2000).

Thickness. The Atane Formation occurs in a number of fault blocks (J.M. Hansen 1980b; Chalmers *et al.* 1999; Marcussen *et al.* 2001, 2002). The faults are, however, rarely exposed and although they have been recognised on seismic profiles acquired in Vaigat and Uummannaq Fjord (Marcussen *et al.* 2002), it has not been possible to determine their throw. Furthermore the lower boundary of the formation is very rarely exposed. Therefore the thickness of the Atane Formation can only be given as an estimate.

The thickest exposed sections occur at Ivissussat on the south coast of Nuussuaq (700 m) and at Qilakitsoq on central Nuussuaq (800 m). Seismic data from the south coast of Nuussuaq show an unconformity at a depth of 1.5–2 km that has been suggested to represent the base of the Atane Formation (Christiansen *et al.* 1995; Chalmers *et al.* 1999). A seismic line across Vaigat indicates a minimum thickness of 3000 m for the Atane Formation (Fig. 44; Marcussen *et al.* 2001, 2002).

Lithology. The Atane Formation comprises mudstones, heteroliths, sandstones and coal beds; the relative proportion of the lithologies varies regionally. The formation is characterised by aggradation of 10–40 m thick depositional cycles, which often coarsen upwards (Fig. 45).

The sandstones are typically fine- to medium-grained, well sorted or heterolithic, with various types of cross-

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Fig. 43. Type section of the Atane Formation (and reference section for the Qilakitsoq Member) from Ataata Kuua, borehole GGU 247801. This core documents the stratigraphic interval known from the well-exposed section in the Ataata Kuua river gorge and extends this section down to 76 m below sea level. **Tr**, transgressive sandstones. For legend see Plate 1; for location, see Fig. 40.

GGU 247801
m
0
50
100
150
200
250
300
350
400
450
500
550
Tr
clay
silt
vf
f
m
c
vc
sand
pebbles

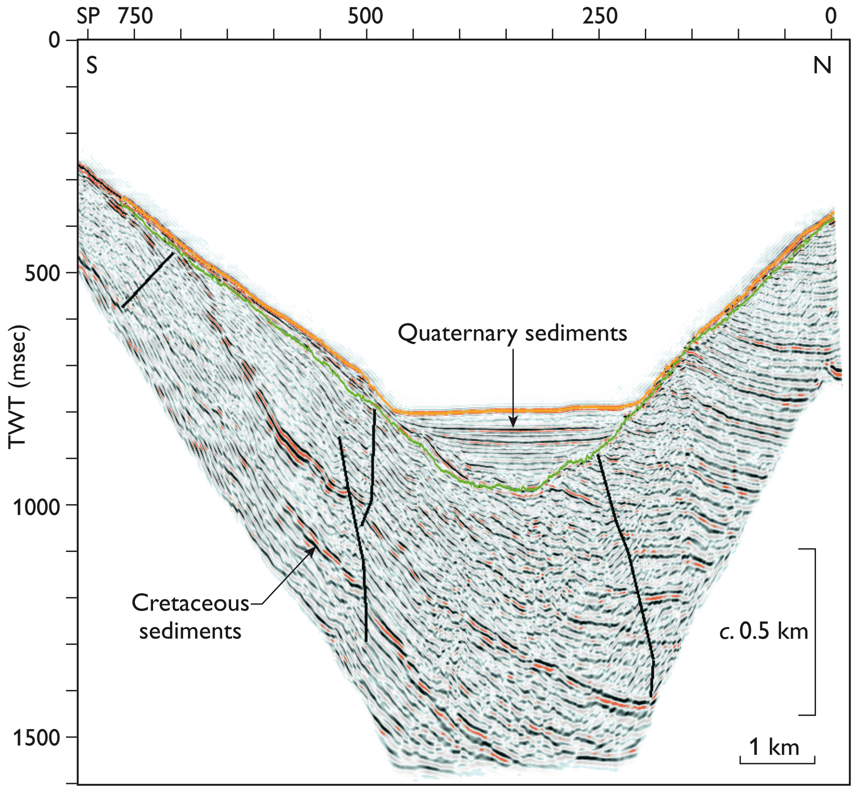


Fig. 44. Seismic section across the Vaigat (for location, see Fig. 2; sea level is at TWT=0). The submarine section continues into exposures of the formation up to 200–400 m a.s.l. on both sides of Vaigat indicating a minimum thickness of the Atane Formation of 3000 m (from Marcussen *et al.* 2002). **SP**, seismic shot points.

bedding, numerous soft-sediment deformation structures and local bioturbation. The sandstones consist of quartz, variably kaolinised feldspars, fragments of older quartz-rich sedimentary rocks, and small amounts of mica and other detrital minerals together with comminuted plant debris. Trace fossils are locally abundant. The sandstones are cemented by carbonate or clay minerals but are generally friable. Pervasive cementation is only patchily developed. The sandstones have sheet or ribbon geometries.

The mudstones are weakly laminated, typically silty, with kaolinite as the dominant clay mineral accompanied by a little mica. The mudstones fall into two groups: (1) mudstones ranging from silt-streaked mudstone to

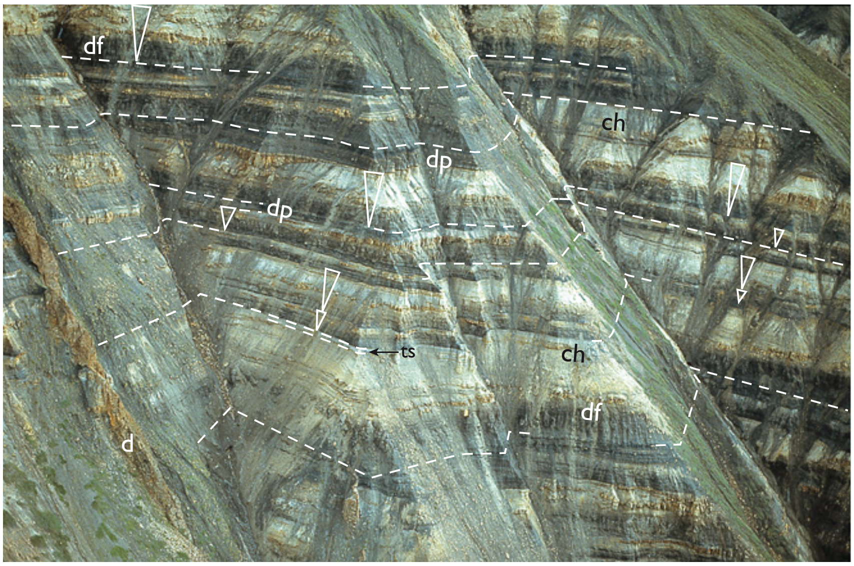


Fig. 45. Outcrop of the Atane Formation in the Paatuut area showing the four depositional environments characterising the Atane Formation: delta front (**df**), delta plain (**dp**), fluvial or distributary channel (**ch**) and transgressive shoreface deposits (**ts**). The delta front deposits form coarsening-upward units, indicated by triangular symbols. The dashed lines trace the bases of delta front mudstones. The sedimentary succession is cut by a dyke (**d**). The thickness of the section is *c.* 120 m; for location, see Fig. 40.

wave-rippled sand streaked mudstone to heterolithic sandstone, and (2) mudstones with plant debris, ranging from carbonaceous mudstone to clayey coal.

The coal beds are interbedded with carbonaceous mudstones, sand-streaked mudstones and heterolithic cross-laminated sandstones with local root horizons. The coal beds are typically less than 0.8 m thick. In several horizons, coal balls are observed, and silicified wood fragments are common. The coals belong to the 'banded coal' type dominated by the lithotypes vitrain and clarain. Macerals of the vitrinite group are often well preserved owing to the prevailing low rank of the coal. Detailed study of the organic particles and their geochemistry permit a distinction between fresh- and brackish-water environments of coal deposition (Shekhar *et al.* 1982; Bojesen-Koefoed *et al.* 2001; G.K. Pedersen *et al.* 2006).

The Atane Formation is characterised by depositional cycles that are typically 10–40 m thick (Figs 41, 46). The simplest cycles are seen on eastern Disko where they consist of 10–30 m thick sandstone sheets separated by *c.* 5 m thick units of mudstone and coal beds. On southern and central Nuussuaq, the cycles range in thickness from 5–15 m up to 40 m. They include coarsening-upward units beginning with mudstones at the base passing up into heterolithic mudstones, then heterolithic sandstones with hummocky cross-stratification and ripple cross-lamination and finally into cross-bedded sandstones, often with coal debris. The typical coarsening-upward cycle is capped by carbonaceous mudstones with thin sandstone or coal beds (Pedersen & Pulvertaft 1992 fig. 5). Bioturbated sandstones form part of many cycles. In the Paatuut area, 32 such cycles have been identified (Olsen 1991; Dueholm & Olsen 1993).

Fossils. The fossils of the Atane Formation comprise macroflora, spores and pollen, dinocysts, and invertebrate fossils (Heer 1868, 1870, 1874a, b, 1880, 1883a, b; Ravn 1918; Koch 1964; Birkelund 1965; Ehman *et al.* 1976; Croxton 1978a, b; Boyd 1990, 1992, 1993, 1994, 1998a, b; Olsen & Pedersen 1991; Koppelhus & Pedersen 1993; McIntyre 1994a, b, c; Nøhr-Hansen 1996; Lanstorp 1999; Dam *et al.* 2000).

Macrofossil plants from the Atane Formation are referred to three floras. The Ravn Kløft flora is characterised by angiosperms and conifers, and has few species in common with the Atane flora (Boyd 1998a, b). The Atane flora is a mixture of older Cretaceous species together with well-differentiated angiosperm species representative of many families (Koch 1964; K.R. Pedersen 1976). The Paatuut flora is dominated by conifer and angiosperm leaf species, and has many species in common with the Atane flora as well as numerous endemic species (Koch 1964; Boyd 1992, 1993, 1994).

Spores and pollen occur in most mudstone samples from the Atane Formation, although often the preservation is poor or the number of identifiable specimens is low. Regional studies of the spore and pollen assemblages have been carried out by Ehman *et al.* (1976) and Croxton (1976, 1978a, b). The latter distinguished two stratigraphically important assemblages, the first without angiospermous (tricolpate) grains (supposed to be Cenomanian or older), the second with angiospermous grains but lacking both *Aquilapollenites* and complex triporate grains. The second assemblage was proposed to be older than Late Campanian (Croxton 1978a p. 76). A large number of samples from the Cretaceous were examined on a reconnaissance basis by McIntyre (1994a, b, c, personal communication 1997) whereas Koppelhus & Pedersen (1993) and Lanstorp (1999) studied fewer sections in greater detail.

Marine dinocysts were described from central Nuussuaq (Ilugissoq, Qilakitsoq, Tunoqqu, southern part of Agatdalen) and from southern Nuussuaq (Paatuut, Ataata Kuua, Nuuk Qiterleq and Nuuk Killeq) by Nøhr-Hansen (1996), Croxton (1978a, b), McIntyre (1994a, b, c, personal communication 1997) and Dam *et al.* (2000). Brackish-water dinocysts of Late Albian to Cenomanian age have been described from northern Nuussuaq (Figs 29, 30; Nøhr-Hansen in Sønderholm *et al.* (2003), Asuk and in the F93-3-1 core from Kuugannguaq, northern Disko.

A sparse fauna of marine invertebrates (echinoids and bivalves) is known from southern and central Nuussuaq including *Sphenoceramus patootensis, Sphenoceramus pinniformis*, and *Oxytoma tenuicostata* (Ravn 1918; Olsen & Pedersen 1991). Ammonites from a single horizon at Alianaatsunnguaq were referred to the *Scaphites ventricosus – Inoceramus involutus* Zone by Birkelund (1965); the Atane Formation in Agatdalen has yielded *Baculites codyensis* (Reeside) and radially ribbed inoceramids of the *steenstrupi* species-group, an assemblage referred to the *Clioscaphites montanensis* Zone (Birkelund 1965; Dam *et al.* 2000). Ammonites from the Atane Formation occur as redeposited fossils in the Itilli Formation on central Nuussuaq (Dam *et al.* 2000). *Clioscaphites saxitonianus septentrionalis* (Birkelund) has been described from Ilugissoq, and at Tunoqqo *Clioscaphites* sp. aff. *saxitonianus* (McLearn) occurs together with a single *Scaphites* cf. *Svartenhukensis* (Birkelund 1965; Dam *et al.* 2000).

Although Koch (1964) suggested that the marine fossils are restricted to a few horizons, Olsen & Pedersen (1991) reported that the marine fossils recur through

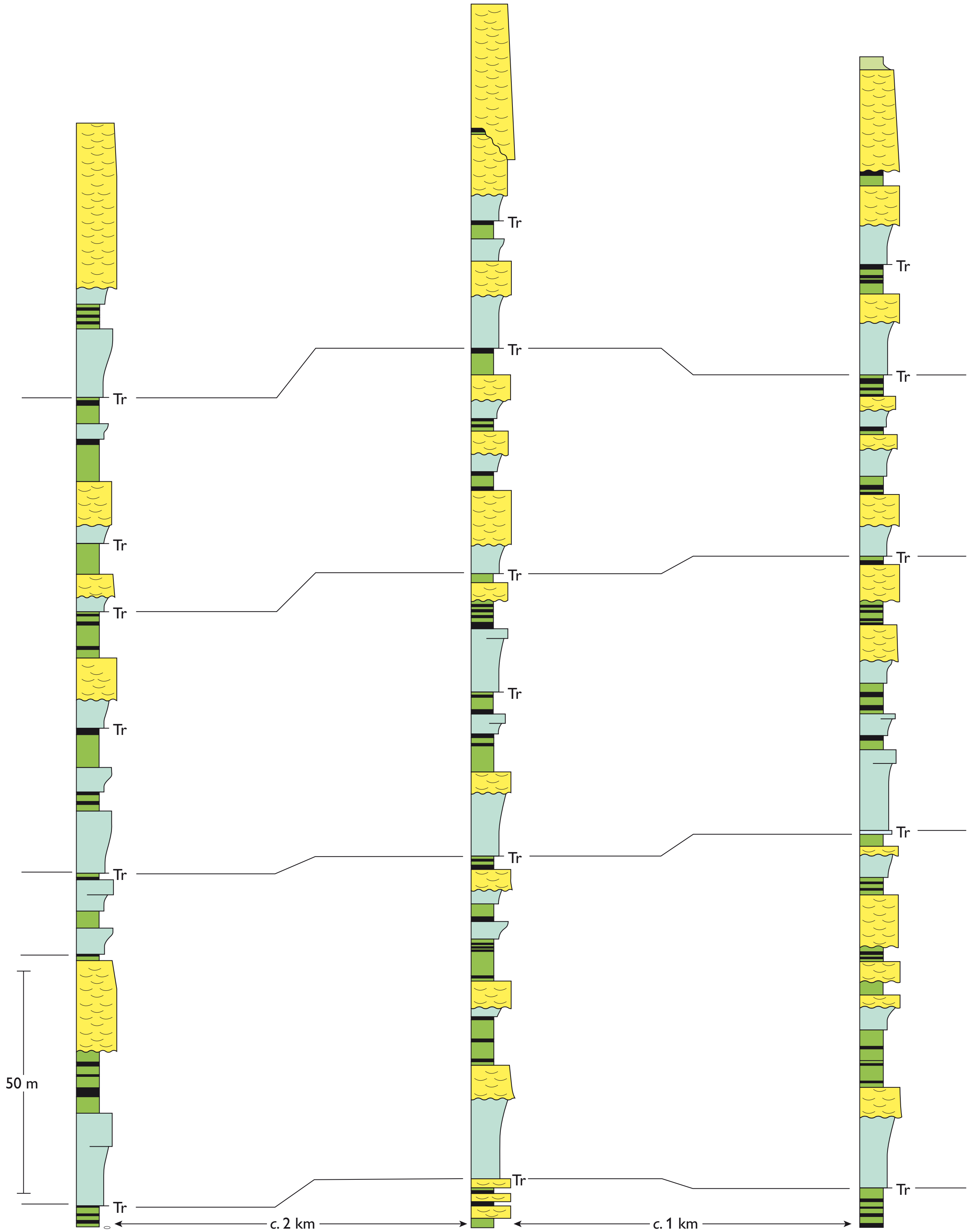


Fig. 46. Simplified sedimentological logs from the Ivissussat–Paatuut area; colours depict depositional environments, see Plate 1. The logs document the cyclic depositional pattern and local variations in thickness and lateral changes of facies. Individual phases of delta progradation may be correlated over short distances between neighbouring sections. The resulting high-resolution lithostratigraphy has only local significance. For legend, see Plate 1; **Tr**, Transgressive sand. For location, see Fig. 40.

the formation in the marine mudstones at the base of the delta front cycles. Boyd (1993) also reported marine invertebrates from several stratigraphic horizons.

Trace fossils are locally abundant and include *Dactyoloidites ottoi, Ophiomorpha nodosa, O. irregulaire, Taenidium serpentinum, Planolites* isp., *Teichichnus* isp., *Thalassinoides* isp., *Diplocraterion* isp., *Skolithos* isp. (Fürsich & Bromley 1985; G.K. Pedersen & Rasmussen 1989; Bojesen-Koefoed *et al.* 2001; G.K. Pedersen & Bromley 2006, Bromley & G.K. Pedersen 2008).

Depositional environment. The Atane Formation is interpreted as having been deposited in a major delta system, and four depositional environments are distinguished: the prograding marine delta front, fluvial or distributary channels of the delta plain, lakes and swamps of the delta plain, and the marine shoreface.

The coarsening-upward successions of mudstones, heteroliths and fine-grained sandstones are interpreted as delta front deposits. In some successions, they include interdistributary bay deposits (J.M.Hansen 1976; Midtgaard & Olsen, 1989; Midtgaard 1991; Olsen 1991; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; Dueholm & Olsen 1993, Nielsen 2003) (Figs 45, 46). They are interpreted to have resulted from progradation of shelf deltas *sensu* Elliott (1989). Olsen (1993) described channel mouth complexes from the uppermost part of many delta front cycles at Paatuut.

The fluvial sandstone sheets on eastern Disko are interpreted as sandy braided river deposits (Johannessen & Nielsen 1982; Koppelhus & Pedersen 1993; Bruun 2006). These may constitute the multi-storey fill of fluvial valleys on south-east Nuussuaq (Jensen 2000; Jensen & Pedersen in press). Fluvial sandstones with ribbon geometry are interpreted as slightly sinuous distributary channel deposits (Olsen 1991, 1993). The carbonaceous mudstones, sandstones and coal seams are interpreted as freshwater lake or swamp deposits on the delta plain (Midtgaard 1991; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; Koppelhus & Pedersen 1993; Nielsen 2003; Møller 2006; G.K. Pedersen *et al.* 2006). This facies association is interpreted as representing the vertical aggradation of a subaerial to shallow limnic, upper and lower delta plain. The thin beds of sand with marine trace fossils are interpreted as transgressive sand sheets, the erosional base of which constitutes a ravinement surface (Midtgaard 1991; Olsen & Pedersen 1991; G.K. Pedersen & Rasmussen 1989).

Olsen (1991) and Dueholm & Olsen (1993) documented 32 cycles of delta progradation in the Paatuut area and comparable numbers of delta cycles are known from the Qilakitsoq area. J.M. Hansen (1976) observed that the deltaic cycles in a vertical section at any locality show a remarkable similarity, indicating an aggradational stacking pattern. Correlation of individual deltaic cycles is only possible between closely spaced outcrops (Fig. 46), but lateral changes in depositional environment within the Atane Formation may be demonstrated on a larger scale (Fig. 16).

Boundaries. On Disko, the Atane Formation overlies a basement high in the FP-93-3-1 well (Fig. 19). On Nuussuaq, the base of the Atane Formation is exposed along the north coast where the formation erosively overlies the Slibestensfjeldet Formation between Ikorfat and Vesterfjeld (Figs 30, 32). The boundary has been interpreted either as a minor angular unconformity (Gry 1940; Koch 1964) or as a conformable, erosional base of a channel (Ehman *et al.* 1976; Schiener 1977; Croxton 1978a, b; Midtgaard 1996b). Midtgaard (1996b) interpreted the unconformity as a sequence boundary (Fig. 32).

The upper boundary of the Atane Formation is a marked erosional unconformity (see Fig. 16). On eastern Disko and Nuussuaq, it is overlain by fluvial and lacustrine Paleocene deposits of the Atanikerluk Formation. On northern Disko, the Atane Formation is erosively truncated by the Itilli Formation at Kussinerujuk and Asuk and by the volcanic Vaigat Formation at Naajannguit (Hald & Pedersen 1975; A.K. Pedersen 1985). Along the south coast of Nuussuaq, the Atane Formation is unconformably overlain by the marine Kangilia Formation (Dam *et al.* 2000), by incised valley fills of the Quikavsak Formation (Dam *et al.* 1998a; Dam & Sønderholm 1998; Dam *et al.* 2000; Dam 2002), and by the Eqalulik Formation. In the Aaffarsuaq valley the Atane Formation is unconformably overlain by the Itilli Formation (Dam *et al.* 2000) with rare ammonites (Birkelund 1965). West of Ilugissoq (central Nuussuaq), the upper boundary of the Atane Formation is not exposed.

On northern Nuussuaq, the upper boundary of the formation can only be seen between Vesterfjeld and Ikorfat but is generally poorly exposed. Directly east of the Ikorfat fault zone, the Atane Formation is overlain by mudstones with Late Campanian to Maastrichtian ammonites (Birkelund 1965), referred to the Itilli Formation. Between Vesterfjeld and Ikorfat, the Atane Formation is overlain by the Eqalulik Formation or by volcanic rocks of the Vaigat Formation (Figs. 22, 29; A.K. Pedersen *et al.* 1996, 2006b).

Geological age. The scarcity of marine fossils combined with the long range of many terrestrial plants, spores and pollen makes it difficult to determine the age of the Atane Formation with precision; for this purpose not only the presence but also the abundance of palynomorphs is important. The age of the formation is bracketed by the palynomorphs or plant macrofossils in the underlying Kome and Slibestensfjeldet Formations and by dinocysts and ammonites in the overlying Itilli Formation on central and northern Nuussuaq (Fig. 16).

The oldest parts of the Atane Formation are Albian–Cenomanian and Early Turonian and occur on Disko, on southern Nuussuaq at Kingittoq and eastwards, and on northern Nuussuaq around J.P.J. Ravn Kløft (Croxton 1978a, b; Koppelhus & Pedersen 1993; McIntyre 1994a, b, c, personal communication 1997; Boyd 1998a, b; Lanstorp 1999; this study). Sediments of Albian–Cenomanian to Turonian age have been reported from Asuk, and at Kussinerujuk the Atane Formation is overlain by the Cenomanian Kussinerujuk Member of the Itilli Formation (McIntyre 1994a, b; Bojesen-Koefoed *et al.* 2007). The presence of Coniacian deposits is based on the occurrence of *Scaphites ventricosus* at Alianaatsunnguaq (Birkelund 1965). The youngest parts of the formation are of Late Santonian to earliest Campanian age and occur on southern and central Nuussuaq (Paatuut, Qilakitsoq, Agatdalen; Olsen & Pedersen 1991; Boyd 1992, 1993, 1994; Nøhr-Hansen 1996; D.J. McIntyre, personal communication 1997; Dam *et al.* 2000). These sediments are dated from ammonites (*Clioscaphites montanensis* Zone), dinocysts and macroplant fossils (Birkelund 1965; Boyd 1992, 1993, 1994; Nøhr-Hansen 1996; Dam *et al.* 2000). Coniacian to Early Santonian ammonites in the Itilli Formation on central Nuussuaq overlying the Atane Formation indicate that the latter is Santonian or older in this area (Birkelund 1965; Dam *et al.* 2000).

Correlation. The Atane Formation is in part coeval with the marginally marine Upernivik Næs Formation north of Nuussuaq, and with the lower part of the deep marine Itilli Formation on Nuussuaq (west of the Kuugannguaq–Qunnilik Fault) and on Svartenhuk Halvø (Figs 13, 16).

Subdivision. The Atane Formation is divided into four members: the Albian–Cenomanian Skansen Member and Ravn Kløft Member, the Albian to Lower Turonian Kingittoq Member, and the Upper Turonian to Santonian – lowermost Campanian Qilakitsoq Member, which includes the ?lower Campanian Itivnera Bed.

Skansen Member

new member

History. The Skansen Member includes the sediments referred to the Atane Formation on southern and eastern Disko. The coal beds at Skansen were visited by Giesecke in 1807 and 1811 (in: Steenstrup 1910). He described the alternation between sandstones and coal beds, and noted that spherical concretions (Kieskugeln) are frequent in the sandstones. The history of coal mining at Skansen was summarised by K.J.V. Steenstrup, who also measured a geological profile of the coastal cliff at Skansen (Steenstrup 1874 plate VIII).

Name. The name is taken from the former settlement Skansen (old spelling Skandsen) or Aamaruutissat, on the south coast of Disko (Fig. 124). The name 'Skansen' (meaning rampart or palisade) originates from a thick and very prominent sill of columnar jointed basalt, named Innaarsuit in Greenlandic.

Distribution. The Skansen Member crops out on southern and eastern Disko (Figs 124, 132; A.K. Pedersen *et al.* 2000, 2001, 2003). The sediments are exposed in stream sections along the coast and in the inland valleys such as Kvandalen and Laksedalen. The Skansen Member is not known from wells and its distribution outside the area of outcrop is unknown. The Cretaceous sediments recorded in seismic sections in Disko Bugt south and east of Disko (Chalmers *et al.* 1999) presumably in part belong to the Skansen Member.

Type section. The type section of the Skansen Member is on the south-facing slope behind the settlement of Skansen (Figs 47, 48, 124). The sedimentology and palynology of this section have been studied in some detail (Koppelhus & Pedersen 1993; Bruun 2006; Møller 2006a, b). The base of the type section is located at 69°26.40´N, 52°26.32´W.

Reference sections. Reference sections are found at Illunnguaq (Koppelhus & Pedersen 1993) and Pingu (Fig. 132).

Thickness. Only the upper 470 m of the Skansen Member are exposed. However, geophysical data indicate that sediments with a thickness of *c.* 2 km are present east of Disko (Chalmers *et al.* 1999), suggesting that the Skansen Member may reach a considerable thickness in the subsurface.

Fig. 47. Type locality of the Skansen Member of the Atane Formation at Skansen, southern Disko (for location, see Fig. 124). The Skansen Member is dominated by fluvial sandstones, interbedded with fine-grained floodplain deposits and thin coal seams. The peak is at 470 m a.s.l. and the sediments are cut by several dykes (**d**).

Lithology. The Skansen Member is dominated by white to yellow sandstones with sheet geometry, intercalated with coal seams, mudstones and heteroliths rich in plant debris arranged in a cyclic depositional pattern (Figs 47, 49). Sixteen cycles are recognised, typically 20–30 m thick (Bruun 2006). The sandstones consist of quartz, more or less kaolinised feldspars, fragments of older quartz-rich sedimentary rocks, and small amounts of mica and other detrital minerals together with comminuted plant debris. The sandstones are generally friable, since carbonate or clay mineral cement is only locally developed. The sandstones are medium- to coarse-grained, in places with pebbly channel lags of intraformational mudstones, coal clasts or pebbles of chert and Ordovician limestone (A.K. Pedersen & Peel 1985). They are dominantly cross bedded or structureless (Fig. 49), but commonly show soft-sediment deformation structures. Sandstone sheets with a width: thickness ratio in excess of 15 are characteristic. The interbedded fine-grained sediments are dark grey to black due to the ubiquitous presence of comminuted plant debris. Facies vary rapidly both vertically and laterally between heterolithic, cross laminated sand, mudstone with plant debris, massive brownish mudstone and coal beds, most of which are less than 1 m thick. Locally, root horizons or rare tree stumps are present. The coal beds are *c.* 0.5 m thick, and the coals are subbituminous, with up to 20% siliciclastic particles and very little pyrite. The coals are dominated by huminite which originates from wood and plant tissue rich in cellulose (Møller 2006a, b).

Fossils. Macroflora, spores and pollen are known from the Skansen Member (Heer 1883a, b; Seward 1926; Miner 1932a, b, 1935; Ehman *et al.* 1976; Croxton 1978a, b; Koppelhus & Pedersen 1993). The plant fossils from six localities (Innanguit, Killusat, Skansen, Pingu, Ujarasussuk, Illukunnguaq) were referred to the Atane flora by Heer (1883b p. 93). Assemblages of palynomorphs

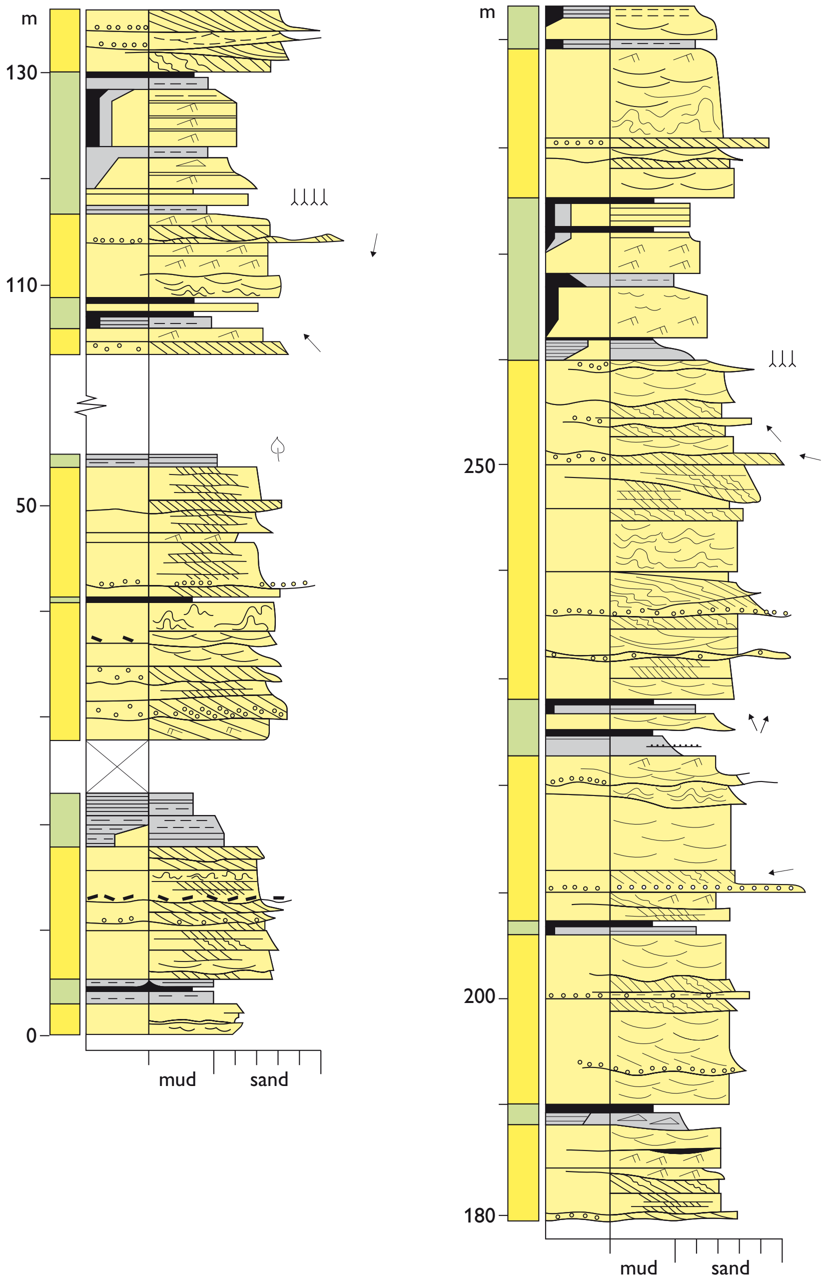


Fig. 48. Type section of the Skansen Member; note the dominance of fluvial channel deposits, (see also Figs 47 and 49). Base of section is at *c*. 120 m a.s.l. For legend, see Plate 1.

have been studied at reconnaissance level at Marraat (southern Disko) and Skansen (Ehman *et al.* 1976), at Kuuk Quamasoq and Pingu (Croxton 1978a, b; D.J. McIntyre, personal communication 2003) and in more detail at Skansen and Illunnguaq (Koppelhus & Pedersen 1993) (Fig. 124).

Depositional environment. The sandstone sheets in the Skansen Member are interpreted as sandy braided river deposits. The sediment transport directions on eastern Disko vary from north-north-west at Pingu to south-west at Gule Ryg and Skansen (G.K. Pedersen & Pulvertaft 1992 fig. 6), suggesting the presence of a huge alluvial cone with its apex east of Disko. Apparently, the Disko Gneiss Ridge did not affect the depositional pattern of the Skansen Member (Johannessen & Nielsen 1982; G.K. Pedersen & Jeppesen 1988; Koppelhus & Pedersen 1993; Bruun 2006).

The carbonaceous mudstones, sandstones and coal seams are interpreted as freshwater lake or swamp deposits representing the vertical aggradation of a subaerial to shallow, limnic floodplain to upper delta plain. The

Fig. 49. Cross-bedded medium- to coarse-grained fluvial sandstones of the Skansen Member at Skansen. Note the intraformational conglomerate (**C**) composed of mudstone and coal clasts (lower part of photo), and the thin interval of carbonaceous mudstone (floodplain deposits; **fp**) in the upper part.

spores and pollen represent vegetation dominated by conifers and ferns; there are no indications – neither palynological evidence nor the presence of pyrite – to suggest marine or brackish-water conditions (G.K. Pedersen & Pulvertaft 1992; Koppelhus & Pedersen 1993; Møller 2006).

Boundaries. The lower boundary of the Skansen Member is not exposed. The upper boundary is an erosional unconformity overlain by the Paleocene Atanikerluk Formation. At Pingu, the Skansen Member is overlain by fluvial sand of the Akunneq Member (Figs 16, 132), while it is overlain by lacustrine mudstones of the Assoq Member at Tuapaat on southern Disko. The presence of late Cenomanian or Turonian strata at the top of the Illunnguaq section was suggested by Koppelhus & Pedersen (1993), but was not confirmed by examination of additional samples. The upper boundary of the Skansen Member corresponds to the upper boundary of the Atane Formation in the area where the Skansen Member occurs.

Geological age. The Skansen Member is dated on the basis of spores and pollen. At its type locality, a mid-Cenomanian age seems most likely, with a maximum age range of Late Albian to Cenomanian for the palynomorph assemblages from this member (Croxton 1978a, b; Ehman *et al.* 1976; Koppelhus & Pedersen 1993).

Correlation. The fluvial Skansen Member is laterally equivalent to the deltaic Kingittoq Member on northern Disko (between Qullissat and Kussinerujuk), and on southern Nuussuaq (between Atanikerluk and Kingittoq) (Fig. 16). The Skansen Member also correlates with the fluviodeltaic Ravn Kløft Member on north-eastern Nuussuaq and in part at least with the Upernivik Næs Formation on Upernivik Ø. Palynomorphs are not preserved in the lower part of the Itilli Formation on Svartenhuk Halvø and on western Nuussuaq, which precludes firm correlation between the Skansen Member and the Itilli Formation (Figs 13, 16).

Ravn Kløft Member

new member

History. The Ravn Kløft Member is part of the Cretaceous succession overlying the Slibestensfjeldet Formation on north-eastern Nuussuaq. These sediments have previously been referred to the Atane Formation (Nordenskiöld 1871; Gry 1942; Midtgaard 1996b) or to the Upernivik Næs Formation (Rosenkrantz 1970; Henderson *et al.* 1976).

Name. The member is named after the gorge J.P.J. Ravn Kløft where it forms impressive outcrops (Fig. 50A, B). J.P.J. Ravn studied the geology of the Nuussuaq Basin in 1909, with focus on the marine invertebrates from the region (Ravn 1918).

Distribution. The Ravn Kløft Member is known from outcrops along the north coast of Nuussuaq between Ikorfat

Fig. 50. **A**: Type locality of the Ravn Kløft Member on the west-facing slopes of the J.P.J. Ravn Kløft gorge on Slibestensfjeldet. Note the very thick fluvial sandstone bodies at the top of the Ravn Kløft Member that can be traced westwards to Ikorfat. The Ravn Kløft Member is overlain by the Kingittoq Member (Atane Formation). For location, see Fig. 22. **B**: Large-scale cross-bedding in sandstones of the thick, amalgamated fluvial channel deposits at the top of the Ravn Kløft Member at Ravn Kløft (*c*. 395 m in Fig. 51A). The height of the exposure is *c*. 3 m.

and Qaarsut (Fig. 22). Its wider distribution is not known due to lack of exposures.

Type section. The eastern slope of J.P.J. Ravn Kløft constitutes the type section (Figs 22, 51A). The base of the type section is located at 70°45.18´N, 52°55.08´W.

Reference sections. Reference sections are found in stream exposures just east of Ikorfat, at Slibestensfjeldet and at Vesterfjeld (Figs 22, 51B, 52).

Thickness. The thickness of the Ravn Kløft Member is about 450 m in the type section, thinning both towards the east and the west (Midtgaard 1996b). The basal pebbly sandstone varies in thickness from less than 2 m to a maximum of 56 m. The overlying deposits are *c*. 400 m thick in J.P.J. Ravn Kløft.

Lithology. A variety of lithologies and sedimentary facies are present in the Ravn Kløft Member. The member is tripartite, comprising a lower pebbly sandstone unit, a middle unit of mudstones, heteroliths and fine-grained sandstones with coarsening-upward or fining-upward depositional patterns, and an upper unit of thick-bedded medium- to coarse-grained sandstones interbedded with mudstones and heteroliths (Fig. 50B; Midtgaard 1996b). The lower unit (*c*. 35–62 m on Fig. 51A) includes a *c*. 3 m thick conglomeratic sandstone with rounded pebbles and large clasts of coaly mudstone, fossil wood and mudstone, interpreted as a channel lag. This is overlain by pebbly coarse-grained sandstones with large-scale cross-bedding, followed by coal-bearing mudstones with beds consisting of small *Scaidopityoides* leaves (Midtgaard 1996b). The cross-bedding indicates unidirectional northward sediment transport.

The middle unit (*c*. 62–340 m on Fig. 51A) comprises a variety of facies. Coarsening-upward successions comprise laminated mudstones, heterolithic sandstones and hummocky cross-stratified sandstones, which locally are capped by trough cross-bedded sandstones, mudstones with root horizons and thin coal beds. Wave-ripple crests are oriented ESE–WNW. Comminuted carbonaceous debris is abundant. Fining-upward successions comprise medium- to coarse-grained, well-sorted sandstones with cross-bedding, double mud-drapes, and abundant reactivation surfaces. They are overlain by heteroliths with current and wave ripple cross-lamination followed by black, laminated mudstones. Synaeresis cracks are common.

The upper unit (*c*. 340–400 m on Fig. 51A) of the Ravn Kløft Member consists of thick, erosively based bodies of greyish sandstone alternating with dark heterolithic mudstone. The sandstones are fine- to coarse-grained or conglomeratic, and dominantly cross-bedded. Foresets are often oversteepened and large-scale soft-sediment deformation structures are very common (Fig. 52). Composite sandstone bodies may be up to 60 m thick (Fig. 50), and may extend laterally for at least 8 km. The cross-bedding indicates sediment transport to the NE–N–NW. The sandstone bodies alternate with thinly interbedded rippled sandstones, laminated mudstones and heteroliths containing abundant rootlets and plant fossils, thin coal beds and palaeosols at certain levels.

Fossils. A brackish-water dinocyst assemblage dominated by *Nyktericysta davisii* has been identified in a number of the mudstone beds. The pollen *Rugubivesiculites rugosus* has its first stratigraphical occurrence within the member (Fig. 29).

Depositional environment. The lower unit of the Ravn Kløft Member is interpreted as a basal fluvial valley-fill conglomerate overlain by fluvial sandstones deposited by unidirectional northward-flowing currents. The middle units are interpreted as interbedded deltaic and tidal estuarine deposits, and wave-ripple crestlines suggest an ESE–WNW-oriented coastline. The overlying single to multi-storey sandstone bodies represent a variety of fluvial styles from slightly sinuous single channels to braided rivers with multiple channels and northward palaeocurrents. The presence of rootlets, vitrinite lenses and local coal beds in the floodplain sandstones and mudstones indicates the existence of a range of sub-environments from subaerial floodplain to shallow-water swamps or ponds adjacent to the fluvial channels. The fluvial sandstones show an increasing tendency up-section to amalgamate and form thick, multi-storey sandstone sheets (Midtgaard 1996b).

Boundaries. The lower boundary of the Ravn Kløft Member is the same as for the Atane Formation. The thickness variation of the lower fluvial sandstones of the Ravn Kløft Member suggests that the base had a relief of nearly 55 m on a regional scale (Midtgaard 1996b).

The upper boundary is placed at the top of a *c*. 60 m thick, amalgamated multi-storey fluvial sandstone sheet which is abruptly overlain by a succession of interbedded mudstones, heteroliths, sandstones and thin coal seams referred to the Kingittoq Member (Fig. 50).

Geological age. Based on the palynomorphs, the Ravn Kløft Member is assigned a Late Albian – Early Ceno-

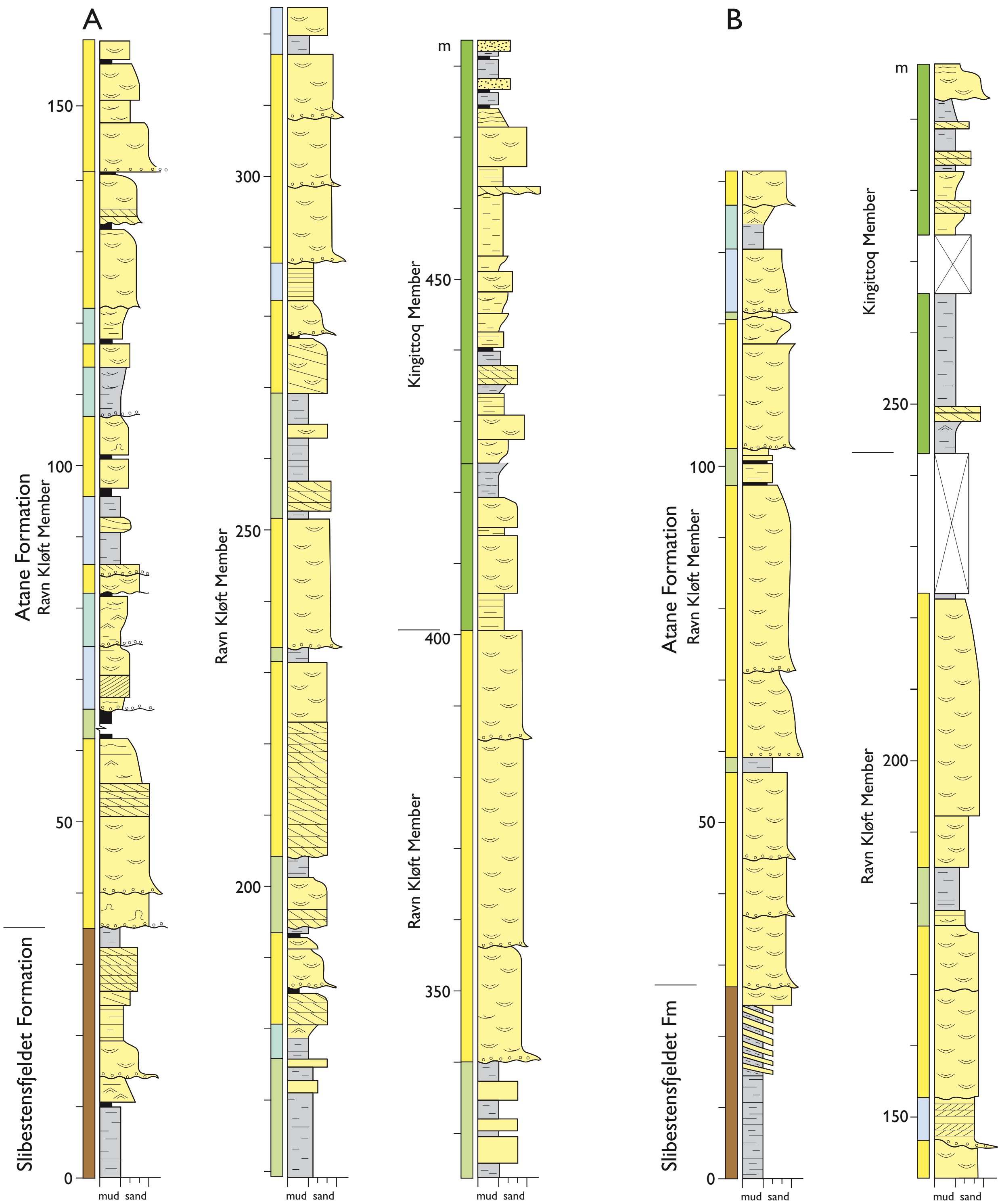


Fig. 51. **A**: Type section of the Ravn Kløft Member at J.P.J. Ravn Kløft. **B**: Reference section at Ikorfat. The thick sandstone beds at the top of the member are overlain by the Kingittoq Member. For legend, see Plate 1; for location, see Fig. 22.

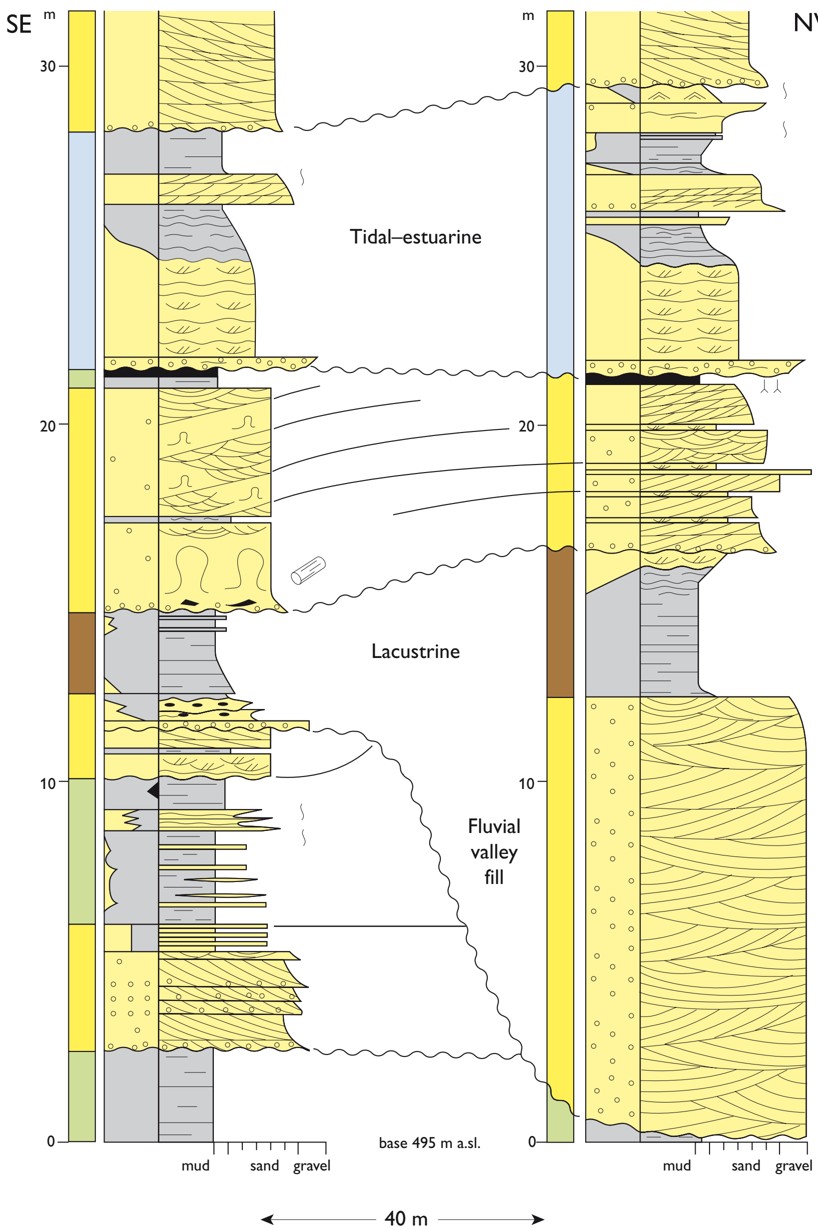


Fig. 52. Two closely spaced sections through the Ravn Kløft Member showing the rapid lateral facies changes especially of the fluvial channel deposits. The sections correspond approximately to the interval 255–285 m in Fig. 51A. For legend, see Plate 1; for location, see Fig. 22.

manian age (Ehman *et al.* 1976; Croxton 1978a, b; this study). A distinct macroflora (the Ravn Kløft flora) of Middle Albian to Early Cenomanian age was established by Boyd (1998a, b, c, 2000); this flora was broadly contemporaneous with the Upernivik Næs flora of Rosenkrantz (1970).

Correlation. The Ravn Kløft Member is laterally equivalent to the Skansen Member in southern and eastern Disko and the older parts of the Kingittoq Member on central and southern Nuussuaq and northern Disko. The Ravn Kløft Member is possibly coeval with the lower part of the Itilli Formation on western Nuussuaq and Svartenhuk Halvø and with parts of the Upernivik Næs Formation on Upernivik Ø (Fig. 16).

Kingittoq Member

new member

History. The Kingittoq Member includes the sediments referred to the Atane Formation on northern Disko, south-eastern Nuussuaq, as well as some of those on northern Nuussuaq.

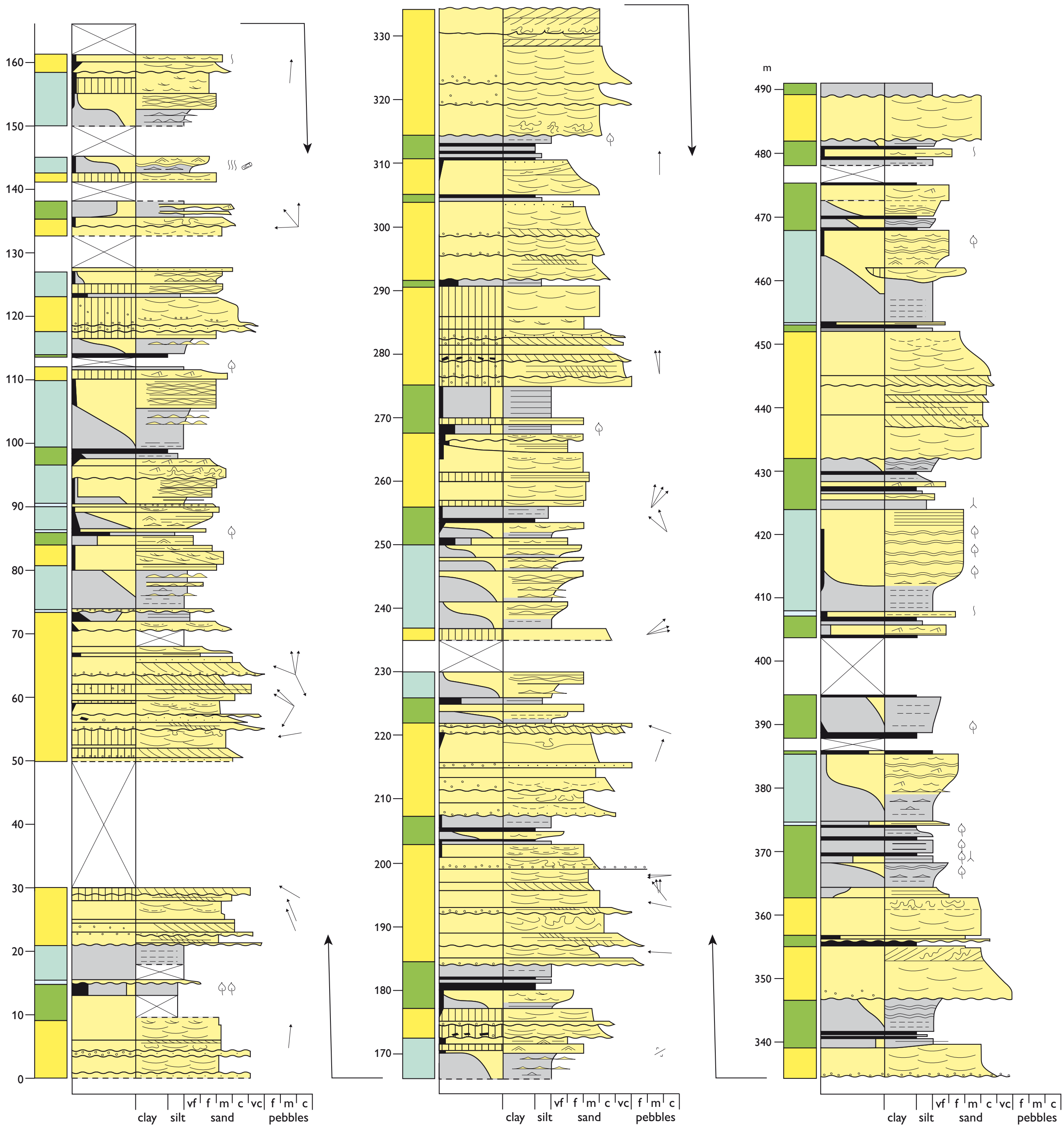


Fig. 53. Type section of the Kingittoq Member of the Atane Formation at Kingittoq, south coast of Nuussuaq (for location, see Fig. 40). Note the higher proportion of delta channel deposits compared to the Qilakitsoq Member (Fig. 60). Compare with Figs 54 and 55 to appreciate the facies variations within the member. Marine dinocysts are only found in a few of the delta front units. For legend, see Plate 1.

Name. The member is named from the coastal slopes at Kingittoq on the south coast of Nuussuaq, where it is well exposed (Fig. 40).

Distribution. The Kingittoq Member is known from outcrops on southern Nuussuaq from Saqqaqdalen to Kingittoq, on northern Disko from Qullissat to Kussinerujuk, and on northern Nuussuaq from Vesterfjeld to Ikorfat (Figs 2, 22, 40, 50A).

Type section. The type section of the Kingittoq Member is exposed in the slopes at Kingittoq on southern Nuussuaq (Figs 40, 53, 59). The base of the type section is located at 70°09.77′N, 52°31.38′W.

Reference sections. Reference sections are found in the upper reaches of J.P.J. Ravn Kløft and at Asuk (Figs 54, 55).

Thickness. The thickness of the Kingittoq Member is not known, but it probably exceeds 1 km. In the area of the type section, more than 600 m are exposed (A.K. Pedersen *et al.* 2007a), *c.* 450 m are exposed at Kuussinerujuk and up to 150 m are exposed above the Ravn Kløft Member on northern Nuussuaq.

Lithology. On southern Nuussuaq, the Kingittoq Member is characterised by 10–25 m thick depositional cycles, which comprise coarsening-upward successions of mudstones, heteroliths and well-sorted sandstones (Figs 53–58). Complex sandstone sheets, up to 40 m thick, are often overlain by carbonaceous heterolithic mudstones with thin coal beds and constitute fining-upward successions (Figs 53, 59). In the Atanikerluk area, the complex sandstone sheets constitute *c.* 40% of the section (Nielsen 2003) whereas their proportion is higher in Saqqaqdalen (Shekhar *et al.* 1982) and at Kussinerujuk (Pulvertaft & Chalmers 1990). The member is characterised by aggradational stacking of the depositional cycles (Figs 57, 58).

The sandstones are pale, friable, medium- to coarse-grained, in places with pebbly channel lags of intraformational mudstone or coal clasts, and are either cross-bedded or structureless, commonly with soft-sediment deformation structures (Midtgaard 1991; Olsen 1991; G.K. Pedersen & Pulvertaft 1992; Jensen 2000; Nielsen 2003; G.K. Pedersen *et al.* 2006). The mudstones are grey, silty, carbonaceous, at several localities with high C/S ratios, and are weakly laminated (Nielsen 2003). The mineralogy is similar to that in the rest of the Atane Formation. The coal beds are interbedded with mudstones with plant debris, sand streaked mudstones and cross laminated sand. Root horizons are seen locally, but preserved tree stumps are rare. A few of the coal beds have been studied in detail (Shekhar *et al.* 1982; Bojesen-Koefoed *et al.* 2001; G.K. Pedersen *et al.* 2006). Coarsening-upward successions of grey mudstones, wave-rippled heterolithic sandstones and fine-grained sandstones with swaley and hummocky cross stratification are especially well developed at Asuk (Fig. 56). The sedimentary structures are enhanced by drapes of comminuted plant (coal)

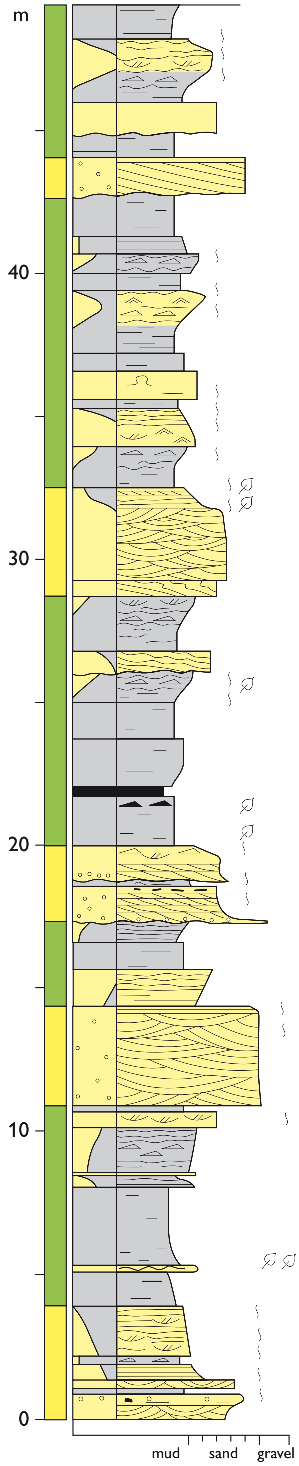
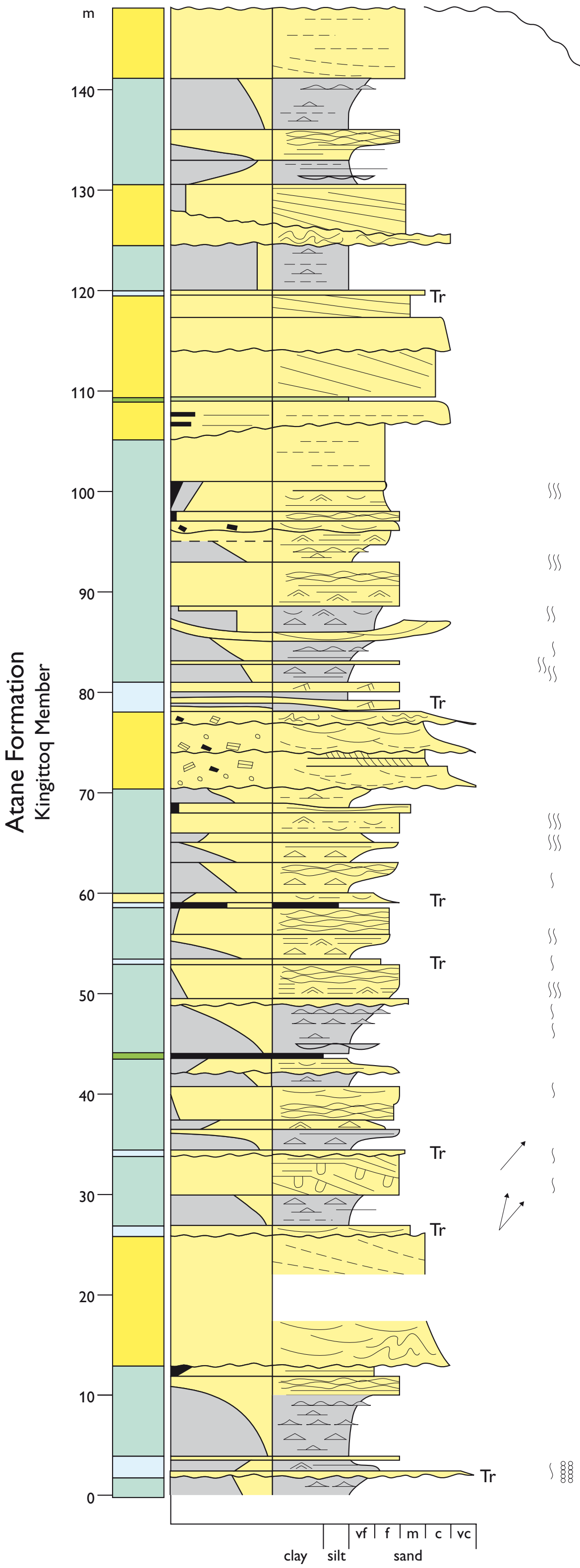


Fig. 54. Reference section of the Kingitoq Member at J.P.J. Ravn Kløft (for location, see Fig. 22). Note the predominance of delta plain facies deposited in shallow lakes, small channels and interdistributary bays. See also Fig. 51A. Base of section at *c.* 650 m a.s.l. For legend, see Plate 1.



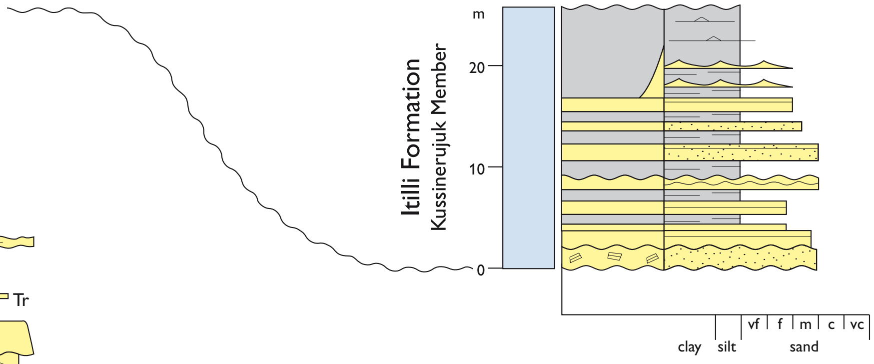


Fig. 55. Reference section of the Kingittoq Member at Asuk, north coast of Disko (for location, see Fig. 2). The section is dominated by stacked delta front deposits and intervals assigned to the delta plain facies association are thin. Note that only one thin coal seam is present (44 m). See also Figs 56, 57 and 80. At this locality, the member is clearly more influenced by marine deposition than at Kingittoq (Fig. 53). **Tr**, transgressive sandstones. For legend, see Plate 1.

debris. Marine fossils are found locally and bioturbation is generally slight. Thin beds of well-sorted, structureless sandstone are seen at Kingittoq, whereas similar beds at Asuk show erosional bases and contain numerous trace fossils, of which *Ophiomorpha nodosa* is prominent (Fig. 55).

Fossils. Plant macrofossils, spores and pollen are known from the Kingittoq Member (Heer 1883a, b; Seward 1926; Ehman *et al.* 1976; Croxton 1978a, b; Lanstorp 1999). Heer (1883b) described plant fossils collected from four outcrops of the Kingittoq Member (Qullissat, Asuk, Qallunnguaq, and Atanikerluk) and referred these to the Atane flora and the Patoot flora.

Marine dinocysts are known from the Kingittoq Member (D.J. McIntyre, personal communication 1997) and finds of rare individuals of three marine invertebrates, *Nucula cancellata*, *Nucula* sp., and *Lucina occidentalis*, were reported from Kingittoq (Ravn 1918). The trace fossils *Ophiomorpha nodosa, Taenidium serpentinum, Teichichnus rectus, Thalassinoides* isp. occur locally in the Kingittoq Member.

Fig. 56. Delta front succession of the Kingittoq Member at Asuk (27–35 m in Fig. 55). Note the upward increase in frequency and thickness of sandstone beds. The well-sorted sandstones with hummocky and swaley cross-stratification (**S**) are indicative of a high-energy depositional environment. The mudstone (**M**) at the top of the section is interpreted as an interdistributary bay deposit. For location, see Fig. 2.

Depositional environment. The Kingittoq Member is interpreted to represent fluvial to deltaic deposits and is referred to four facies associations: the channel and delta plain associations (dominant), the delta front or mouth bar association (subordinate) and the transgressive sand sheet association (rare) (Midtgaard 1991; G.K. Pedersen & Pulvertaft 1992; Dam *et al.* 2000; Jensen 2000; Nielsen 2003; G.K. Pedersen *et al.* 2006). The cross-bedded, medium- to coarse-grained sandstones are interpreted as fluvial channel deposits. The sedimentary structures frequently indicate downstream accretion on bars and rare development of point bars, indicating that the fluvial channels were mostly braided. The complex sheets of coarse-grained sandstones are interpreted as having been deposited as the multi-storey fill of fluvial valleys (Jensen 2000; Jensen & Pedersen in press).

The carbonaceous mudstones, sandstones and coal beds are interpreted to represent the vertical aggradation of subaerial to freshwater lacustrine or swamp deposits. The high C/S ratios indicate that deposition occurred in freshwater environments on the upper delta plain (G.K. Pedersen & Pulvertaft 1992; Nielsen 2003). The coal beds are interpreted as the *in situ* accumulations of plant remains in freshwater environments (Bojesen-Koefoed *et al.* 2001; G.K. Pedersen *et al.* 2006). This facies association is subordinate at Asuk.

The coarsening-upward heteroliths are interpreted as delta front or mouth bar deposits formed during progradation of shelf deltas (G.K. Pedersen & Pulvertaft 1992; Bojesen-Koefoed *et al.* 2001; Nielsen 2003; G.K. Pedersen *et al.* 2006). This facies association is dominant at Asuk. The thin beds of sand with marine trace fossils are interpreted as transgressive sand sheets (Midtgaard 1991). The erosive base constitutes a ravinement surface. In the Kingittoq Member, the transgressive sand sheets are best developed at Asuk. The Kingittoq Member is dominated by stacked upper delta plain deposits in the Atanikerluk area and at Qullissat, and by lower delta plain and stacked delta front deposits at Asuk.

Boundaries. The lower boundary of the Kingittoq Member is exposed on northern Nuussuaq where the Kingittoq Member overlies the Ravn Kløft Member (Fig. 50). Here the boundary is a drowning surface which separates the fluvial sandstones from the overlying delta plain deposits. In the rest of the Nuussuaq Basin, the lower boundary is not exposed.

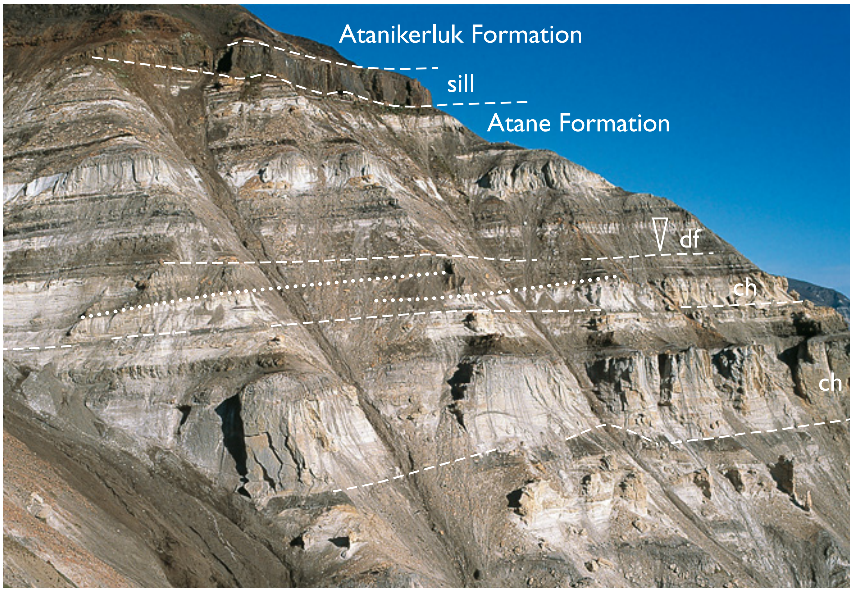
The upper boundary, corresponding generally to the upper boundary of the Atane Formation in the outcrop area of the member, is everywhere an erosional unconformity overlain by the Itilli, Quikavsak, Atanikerluk and Vaigat Formations (Fig. 16). On the north coast of

Fig. 57. The Kingittoq Member at Asuk showing thick fluvial channel deposits overlying coarsening-upward delta front successions capped by transgressive shoreface sandstones (**ts**). For location, see Fig. 2 and Fig. 55: 44–83 m.

Nuussuaq, the upper boundary of the Kingittoq Member is generally poorly exposed due to landslides and rock glaciers, but east of Ikorfat it is overlain by small outcrops of Campanian–Maastrichtian mudstone (the Itilli Formation) and Paleocene tuffaceous mudstone (the Eqalulik Formation) (Birkelund 1965; A.K. Pedersen *et al.* 2006b) (Fig. 22).

Fig 58. Outcrop of the Kingittoq Member on the eastern slope of the Qallunnguaq valley (for location, see Fig. 40). Delta plain facies constitute a large proportion of the succession and delta front deposits are thin and fine-grained suggesting low-energy depositional environments (lower delta plain with swamps, shallow lakes and interdistributary bays (Nielsen 2003)). The channel sandstone at the top of the photograph is the lowermost fluvial unit in a multi-storey sandstone body studied by Jensen (2000) and Jensen & Pedersen (in press).

Fig. 59. The Kingittoq Member at Kingittoq, see 310–465 m in Fig. 53. Most fluvial channels are braided, but a point bar succession is seen in the centre of the photo with inclined accretionary surfaces (indicated by dotted line); **ch**, fluvial channel; **df**, delta front. For location, see Fig 40.



Geological age. The geological age of the Kingittoq Member ranges from Albian (Tartunaq) to Cenomanian (Atanikerluk, Saqqaqdalen, Kingittoq, Kussinerujuk, Asuk and Ravn Kløft) and into Early Turonian (Saqqaqdalen, Kingittoq and Asuk). The deposits are dated on the basis of spores, pollen and marine dinocysts (Croxton 1978a, b; Lanstorp 1999; McIntyre 1994a, personal communication 1997; this study).

Correlation. The Kingittoq Member is coeval with the Skansen Member (eastern Disko); the Kingittoq Member of southern Nuussuaq may be equivalent the Ravn Kløft Member on northern Nuussuaq (Fig. 16). The Kingittoq Member correlates with the Upernivik Næs Formation on Upernivik Ø, and possibly to the lower part of the Itilli Formation of western Nuussuaq and Svartenhuk Halvø.

Qilakitsoq Member

new member

History. The Qilakitsoq Member includes sediments referred to the Atane Formation on southern and central Nuussuaq, and sediments formerly referred to the now abandoned Pautût (or Patoot) Formation (see above under history of the Atane Formation).

Name. The name is derived from the Qilakitsoq stream, a tributary to the Kuussuaq river which flows through the Aaffarsuaq valley on central Nuussuaq (Fig. 82).

Distribution. The Qilakitsoq Member is the sole representative of the Atane Formation in central Nuussuaq and parts of southern Nuussuaq. Outcrops are found from Agatdalen to Ilugissoq along the north slope of the Aaffarsuaq Valley and along the south coast from Paatuut to Alianaatsunnguaq (Figs 2, 40, 82).

Type section. The type section of the Qilakitsoq Member is along the Qilakitsoq stream on central Nuussuaq (Figs 60, 82). The base of the type section is located at 70°27.97′N, 53°27.13′W.

Reference sections. Reference sections are found at Nuuk Killeq and Ataata Kuua (type section of the Atane Formation; Fig. 43). Two continuously cored boreholes from the Paatuut area (GGU 247701 and GGU 247901) provide reference sections of the Qilakitsoq Member and have been described in detail by Ambirk (2000).

Thickness. The type section documents a minimum thickness of 480 m, but correlation with nearby sections shows that at least 820 m are exposed in the Qilakitsoq area, and *c*. 600 m are known from the well at Ataata Kuua together with nearby outcrops (Fig. 43; A.K. Pedersen *et al.* 2007b).

Lithology. The Qilakitsoq Member is characteristically cyclic, individual cycles typically passing up from mudstones through heteroliths, well-sorted sandstones, coarser grained sandstones with ribbon geometry, and finally into carbonaceous mudstones with coal beds overlain by thin sheets of bioturbated sandstone (Fig. 60; Midtgaard

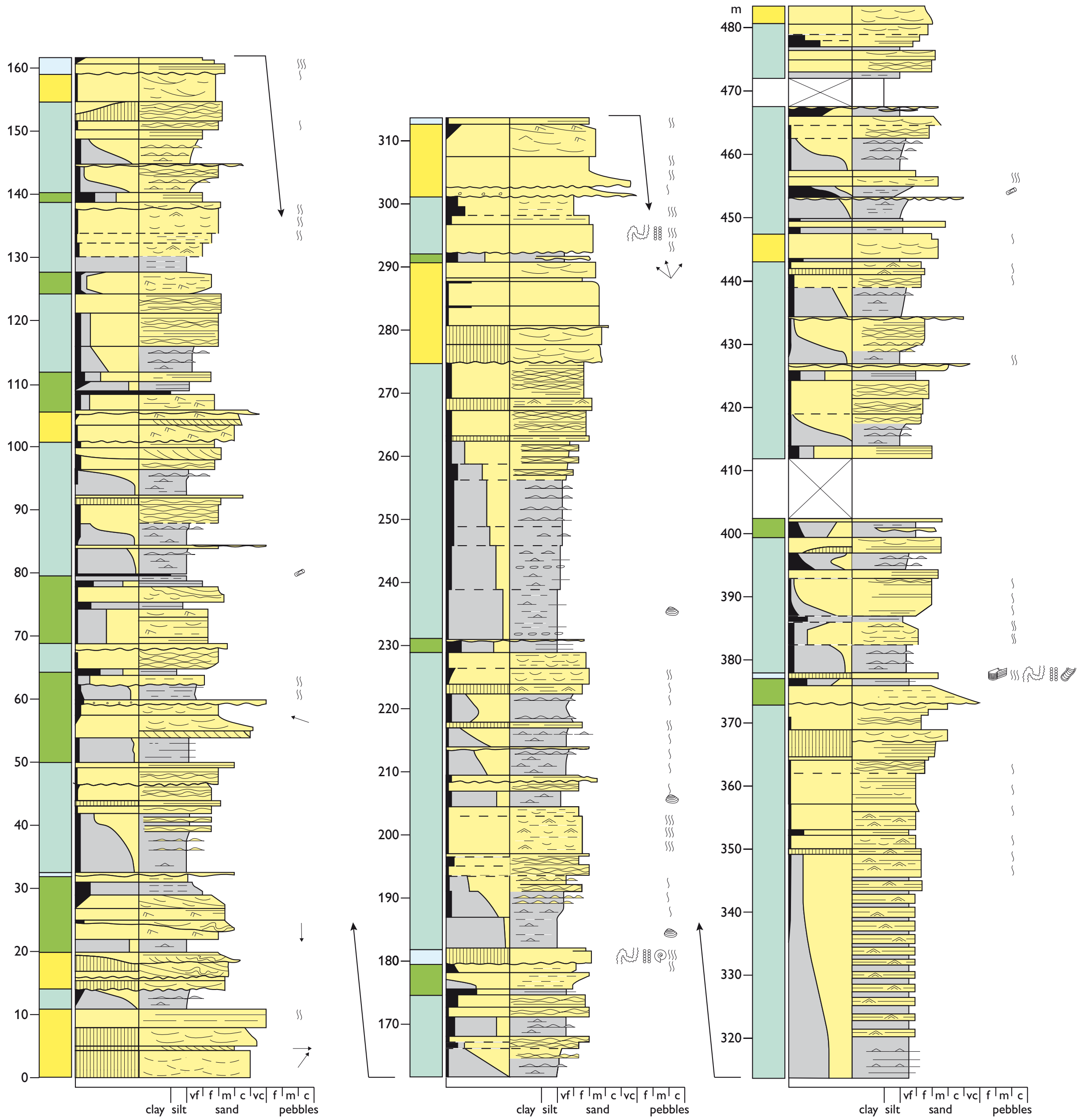


Fig. 60. Type section of the Qilakitsoq Member (Atane Formation) on the western side of the Qilakitsoq stream, central Nuussuaq. Note the higher proportion of delta front deposits compared to the Kingittoq Member (Fig. 53). For location, see Fig. 82; for legend, see Plate 1.

1991; Olsen 1991, 1993; G.K. Pedersen & Pulvertaft 1992; Boyd 1993; Dueholm & Olsen 1993; Ambirk 2000; Dam *et al.* 2000). The coarsening-upward successions are typically 5–25 m thick but may reach up to *c.* 70 m (Fig. 61). They can be traced laterally through closely spaced outcrops for up to 8 km in the Paatuut area (Fig. 46; Olsen 1991, 1993; Dueholm & Olsen1993) and also in the Qilakitsoq area.

The mudstones at the base of the coarsening-upward units are dark grey, silty and weakly laminated, and may contain marine fossils (Olsen & Pedersen 1991; Nøhr-Hansen 1996). These grade up into sand streaked mudstones and heterolithic sandstones, where wave-ripples and swaley- and hummocky cross-stratification are enhanced by drapes of comminuted plant debris (Fig. 60, 33–50 m). The successions are frequently topped by medium-grained, trough cross-bedded sandstones (Fig. 60, 145-158 m). Bioturbation may locally be very intense and totally obscure primary structures.

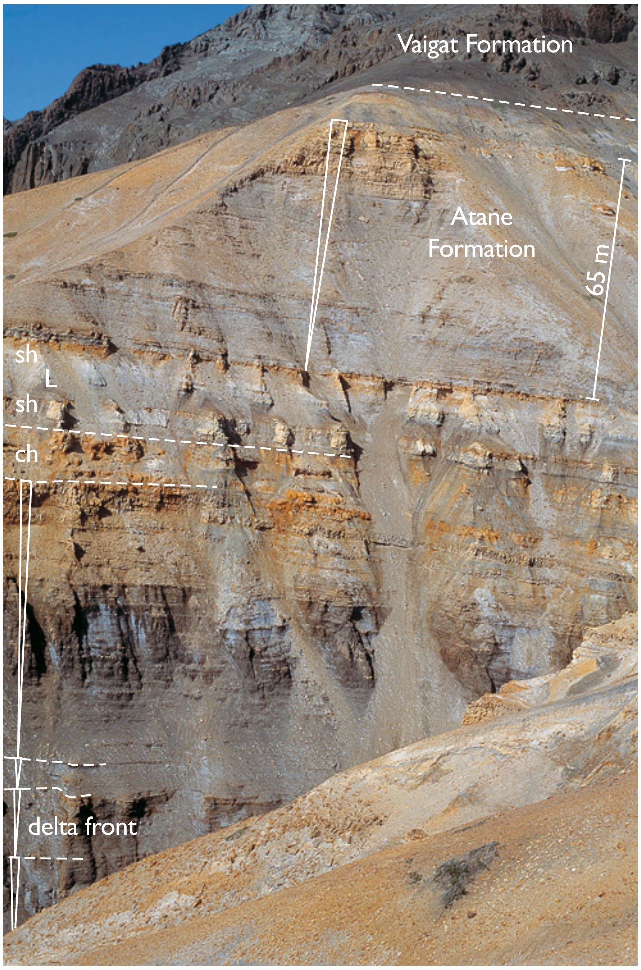


Fig. 61. Outcrop of the Qilakitsoq Member on the western slope of gully immediately west of Qilakitsoq. The member is dominated by stacked delta front successions. The outcrop corresponds to the interval 200–380 m in Fig. 60; **ch**, channel; **L**, lagoon; **sh**, shoreface. Note that the uppermost delta front succession is abnormally thick at this locality. For location, see Fig. 82.

Other sandstones are pale, friable, medium- to coarse-grained, in places with channel lags of pebbles or intraformational clasts of mudstone and coal. These sandstones are cross bedded or structureless, commonly with soft-sediment deformation structures. They form single-storey sandstone ribbons with a width:thickness ratio as low as 6 and a sinuosity of 1.2 (Olsen 1993) (Fig. 60: 0–11 m).

Successions of carbonaceous heteroliths interbedded with cross laminated sand, sand streaked mudstones, mudstones with plant debris and coal seams occur in all outcrops of the Qilakitsoq Member. Their dark grey to black colour reflects the abundance of comminuted plant debris. Locally, root horizons or rare tree stumps are present. Numerous coal beds at Paatuut and Ataa are more than 0.8 m thick. Concretions and 'coal balls' are observed in several horizons, as well as silicified wood. Dirt bands in coal beds are common, mainly consisting of carbonaceous mudstones (Fig. 60: 20–32 m).

Sheets of structureless or strongly bioturbated sandstone with an erosional base occur in most outcrops of the Qilakitsoq Member. They range from thin (*c*. 0.05 m) fine-grained sandstones to thick (*c*. 3 m) medium- to coarse-grained sandstones. Upwards, these sandstones may pass gradually into mudstones (Fig. 60, 180–182 m).

Fossils. Plant macrofossils, spores and pollen are known from the Qilakitsoq Member (Heer 1883a, b; Seward 1926; Ehman *et al*. 1976; Croxton 1978a, b; Boyd 1990, 1992, 1993, 1994). Heer (1883b) described plant fossils collected from three outcrops of the Qilakitsoq Member (Alianaatsunnguaq, Ataa, and Paatuut) and referred these to the Atane and Patoot floras. Boyd (1992, 1993) recognised three or more floral communities (nearshore lacustrine, backswamp, levee and riparian vegetation) in the fossil flora from the Paatuut area (the Paatuut flora).

Marine dinocysts have been identified in samples from the Qilakitsoq Member (D.J. McIntyre, personal communications 1997, 1999; Nøhr-Hansen 1996). The sparse marine invertebrates include ammonites (*Clioscaphites saxitonianus septentrionalis* (Birkelund), *Clioscaphites* sp. aff. *saxitonianus* (McLearn), *Scaphites ventricosus, Scaphites* cf. *Svartenhukensis*, and *Baculites codyensis* (Reeside)) (Birkelund 1965; Dam *et al*. 2000); bivalves (*Sphenoceramus patootensis, S. pinniformis, Oxytoma tenuicostata*) and echinoderms (Ravn 1918; Olsen & Pedersen 1991; Boyd 1993).

Trace fossils are common in the Qilakitsoq and Nuuk Killeq areas. Burrows such as *Planolites* isp., *Teichichnus* isp., *Dactyolidites ottoi*, and *Helminthopsis horizontalis* occur in the coarsening-upward successions, whereas *Ophiomorpha nodosa* and *O. irregulaire* are seen in the sandstone sheets (Fig. 62; G.K. Pedersen & Rasmussen 1989; Dam *et al*. 2000; G.K. Pedersen & Bromley 2006). The trace fossil assemblages indicate the presence of both suspension and deposit feeders.

Depositional environment. The Qilakitsoq Member is interpreted as being constructed of aggradational deltaic deposits referred to four facies associations: the marine delta front association, the distributary channel association, the delta plain association and the transgressive sand sheet association (Midtgaard 1991; Olsen 1991, 1993; G.K. Pedersen & Pulvertaft 1992; Dueholm & Olsen 1993; Dam *et al*. 2000).

Fig. 62. The trace fossil *Ophiomorpha irregulare* is characteristic of transgressive shoreface sandstones in the Qilakitsoq Member, especially at Qilakitsoq and Nuuk Killeq. For location, see Fig. 2.

The marine delta front association comprises coarsening-upward units where mudstones with marine fossils deposited below storm-wave base are overlain by heterolithic mudstones and sandstones which pass up into shallower water facies. These units are interpreted as the result of delta front progradation of shelf deltas.

The distributary channel association consists of cross-bedded, medium- to coarse-grained sandstones, which are interpreted as having been deposited within almost straight to slightly sinuous fluvial channels (Olsen 1991, 1993). Small fluvial channels are included in the delta plain association, which is characterised by carbonaceous mudstones, sandstones and coal beds, interpreted as having formed through vertical aggradation of subaerial to freshwater lacustrine or swamp deposits on the lower and upper delta plain. The coal beds are interpreted as the *in situ* accumulations of plant remains in both fresh- and brackish-water environments. The transgressive sand sheet association includes thin beds of sand with erosive bases and often with numerous marine trace fossils, indicating deposition on a marine shoreface (G.K. Pedersen & Rasmussen 1989; Midtgaard 1991; Olsen 1991; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; G.K. Pedersen & Bromley 2006). The erosional bases represent ravinement surfaces.

Boundaries. The lower boundary of the Qilakitsoq Member is not exposed. The upper boundary, which corresponds to the upper boundary of the Atane Formation, is everywhere an erosional unconformity. Different units overlie the member throughout the region; these include the Itilli, Kangilia, Quikavsak and Atanikerluk Formations as well as volcanic rocks of the Vaigat Formation (Fig. 16).

Geological age. The geological age of the Qilakitsoq Member is Middle Turonian to Santonian at Ataata Kuua, Coniacian at Alianaatsunnguaq (Birkelund 1965), Santonian – earliest Campanian at Paatuut, Nuuk Killeq and on central Nuussuaq (Koch 1964; Boyd 1990, 1992; Olsen & Pedersen 1991; G.K. Pedersen & Pulvertaft 1992; Nøhr-Hansen 1996; D.J. McIntyre, personal communication 1997). Stable carbon isotopes in wood fragments suggest a Middle to Late Santonian age (Ambirk 2000).

Correlation. The Qilakitsoq Member correlates with part of the Itilli Formation (western Nuussuaq and Svartenhuk Halvø).

Subdivision. The Qilakitsoq Member includes the Itivnera Bed in the Aaffarsuaq valley near Tunoqqu.

Itivnera Bed

revised bed

History. The Itivnera beds were described by Dam *et al.* (2000) as fluvial sandstones incised into the top of the Qilakitsoq Member (Atane Formation) at two widely separated localities: Itivnera and Ataata Kuua (Figs 40, 82). The erosional, lower boundary was interpreted as a sequence boundary. At Itivnera, the fluvial deposits are

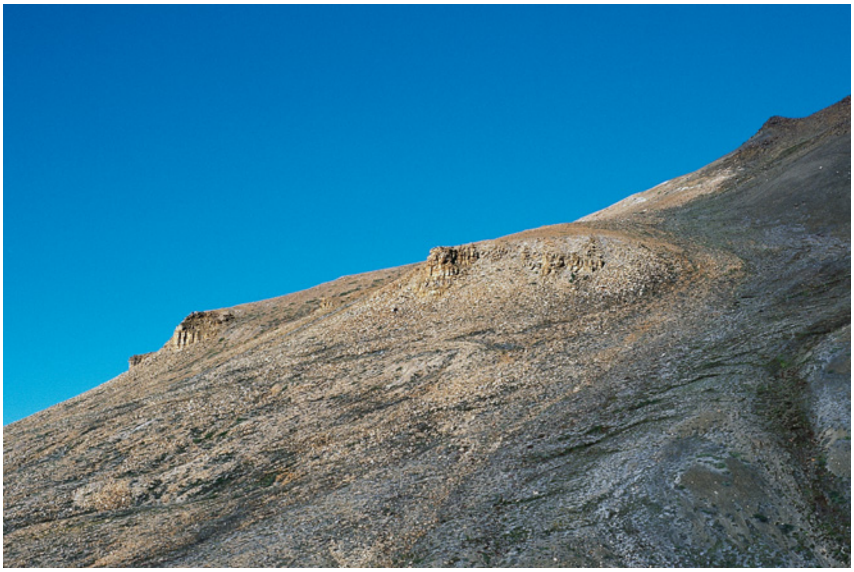


Fig. 63. Type locality of the Itivnera Bed in central Nuussuaq (for location, see Fig. 82). The bed comprises three channellised sandstone units up to 38 m thick that cut down into Santonian deltaic deposits of the Qilakitsoq Member (Atane Formation). The Itivnera Bed is overlain by submarine fan deposits of the Itilli Formation (Aaffarsuaq Member). The sandstone cliffs are about 16 m high and the spacing between the valleys is less than 100 m (see Dam *et al.* 2000).

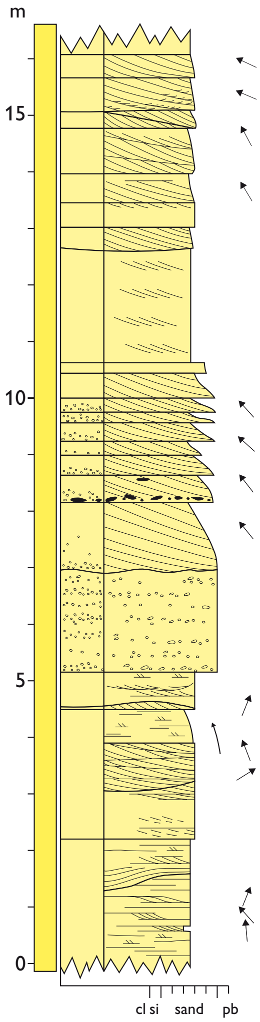


Fig. 64. Type section of the Itivnera Bed. Neither the base nor the top of the fluvial sandstone unit is exposed (from Dam *et al.* 2000). For legend, see Plate 1; for location, see Fig. 82.

overlain by deep marine deposits belonging to the Aaffarsuaq Member of the Itilli Formation. At Ataata Kuua, a valley incised into the Atane Formation is filled by turbidite mudstones, sandstones and conglomerates referred to the late Maastrichtian to earliest Paleocene Kangilia Formation; the Itilli Formation is not present at Ataata Kuua (Figs 14, 15, 16). The Qilakitsoq Member here is of Turonian–Santonian age. Fine-grained organic-rich sediments preserved in the top of a small fluvial channel contain palynomorphs indicating a Coniacian age.

The fluvial channel deposits at Ataata Kuua that were previously referred to as Itivnera beds are now assigned to the Qilakitsoq Member on the basis of photogrammetric mapping (A.K. Pedersen *et al.* 2007b) and dating of the fine-grained channel fill, which lies within the age range of the Qilakitsoq Member at this locality. The presence of Early Campanian fluvial deposits at Ataata Kuua cannot be demonstrated.

The Itivnera beds sensu Dam *et al.* (2000) constituted the basal part of the Itilli Formation. In the present paper, this unit is restricted to the cemented channel sandstones at Itivnera which are defined here as the Itivnera Bed of the Qilakitsoq Member.

Name. The strata are named after the saddle feature named Itivnera between Nalluarissat and Tunoqqu (Fig. 82). The name was derived from a nearby locality shown on the geodetic map from 1966 (Geodætisk Institut 1966); the spelling has not been changed to modern Greenlandic orthography because the locality is not shown on later geodetic maps.

Type section. The strata exposed on the south-facing slope of Nalluarissat between Aaffarsuaq and Kangersooq, just west of Itivnera, are designated as the type section (Figs 63, 64). The type section is located at 70°29.50′N, 53°08.87′W.

Distribution. The bed has only been recognised on the south-facing slope of Nalluarissat between Aaffarsuaq and Kangersooq (Fig. 82).

Thickness. The bed is up to 38 m thick and confined to lensoid bodies up to 100 m wide.

Lithology. The bed consists of cross-bedded coarse-grained sandstones, arranged in fining-upward successions form lensoid bodies arranged like pearls on a string (Figs 63, 64). Basement pebble conglomerates are locally present. The sediments between the cemented sandstone bodies are covered by scree (Dam *et al.* 2000).

Fossils. Macrofossils have not been found.

Depositional environment. The sandstones of the Itivnera Bed were deposited in fluvial channels (Dam *et al.* 2000).

Boundaries. The Itivnera Bed erosively overlies deltaic deposits of the Qilakitsoq Member (Atane Formation). In the type section, the fluvial sandstones are succeeded by turbiditic mudstones and sandstones of the Aaffarsuaq Member (Itilli Formation). The lower boundary is no longer interpreted as a sequence boundary because there is insufficient evidence that a sea-level fall preceded the rise in sea level that marks the transition to the deep-water deposits of the Aaffarsuaq Member.

Geological age. At Nalluarissat, just west of Itivnera, the Qilakitsoq Member is Late Santonian in age, and at Tunoqqu, immediately east of Itivnera, the Aaffarsuaq Member is of Early to Middle Campanian age (Nøhr-Hansen 1996). Deposition of the fluvial sandstone bodies at Itivnera is therefore well constrained to the Early Campanian.

Itilli Formation

new formation

History. The strata exposed in river sections in the Itilli valley on western Nuussuaq were informally assigned to the Itilli formation by J.M. Hansen (1980b). The Itilli Formation is here extended to include the unnamed Upper Turonian to Campanian marine strata on Svartenhuk Halvø and Nuussuaq (cf. Birkelund 1965; Henderson *et al.* 1976; J.G. Larsen & Pulvertaft 2000). Furthermore, on northern Disko at Kussinerujuk and Asuk, outcrops previously correlated with the Paleocene Kangilia Formation (J.M. Hansen 1980b; Pulvertaft & Chalmers 1990) are here assigned to the Itilli Formation (see below). The Itivnera beds of the Itilli Formation (Dam *et al.* 2000) are, however, now redefined as the Itivnera Bed of the Qilakitsoq Member (Atane Formation).

On Itsaku (Svartenhuk Halvø), the ?Upper Campanian/Maastrichtian to Paleocene succession has been suggested to be equivalent either to both the Itilli and Kangilia Formations (i.e. Campanian to Paleocene) or to the Kangilia Formation alone (i.e. upper Maastrichtian to Paleocene), based on correlation of two major conglomerate horizons with tectonic events recognised on Nuussuaq (J.G. Larsen & Pulvertaft 2000). Based on zircon provenance data, this succession is here assigned to the Kangilia Formation (see below).

Name. After Itilli, a major valley transecting Nuussuaq from north-west of Marraat on the south coast to west of Niaqornat on the north coast (Figs 2, 65).

Distribution. The Itilli Formation is exposed in the Itilli valley (Fig. 65) and on the north coast of Nuussuaq in the ravines between Ikorfat and Niaqornat (Fig. 74) where it has been drilled in the shallow wells GGU 400705, GGU 400706, and GGU 400407 (Christiansen *et al.* 1994a), and the formation is probably also present in the FP94-11-02, FP94-11-04 and FP94-11-05 wells (Dam & Nøhr-Hansen 1995). It is also well exposed on central Nuussuaq along the slopes of the valley of Aaffarsuaq between Qilakitsoq and Tunoqqu, along the slopes of the valley Kangersooq (Fig. 82), and in the valley of Agatdalen including the shallow well GGU 400702 (Fig. 113; Nøhr-Hansen 1996; Dam *et al.* 2000). On Disko, the formation is exposed at Asuk and Kussinerujuk.

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Fig. 65. Map of the southern part of the Itilli valley showing outcrops of the Itilli Formation (Anariartorfik Member) and the Eqalulik Formation and location of the wells Marraat-1, GANW#1, GANE#1, GANK#1 GRO#3 and FP94-9-01. Based on Rosenkrantz *et al.* (1974) and Hald (1976). Contour interval 200 m. For location, see Fig. 2.