Mantle plumes and sequence stratigraphy; Late Maastrichtian-Early Paleocene of West Greenland

GREGERS DAM & HENRIK NØHR-HANSEN

Dam, G. & Nøhr-Hansen, H. 2001–11–24: Mantle plumes and sequence stratigraphy; Late Maastrichtian-Early Paleocene of West Greenland. *Bulletin of the Geological Society of Denmark*, Vol. 48, pp. 189–207. Copenhagen. https://doi.org/10.37570/bgsd-2001-48-11

The sedimentary history of the upper Maastrichtian–Paleocene succession underneath the extensive Paleocene flood basalts in central West Greenland supports models for the generation of flood basalt provinces in response to rising, hot mantle plumes. The rise of the North Atlantic mantle plume was associated with deposition of at least three sedimentary sequences; each associated with incision of submarine canyons and valleys. Relative sea-level changes were caused by plume-related tectonics and generation of sequence boundaries was in general associated with catastrophic sedimentation and very rapid development of sequences. As such the late Maastrichtian–early Paleocene sequences record a spectacular and significant but rare geological event.

Key words: Mantle plumes, sequence stratigraphy, Late Maastrichtian-Early Paleocene, West Greenland.

Gregers Dam, Geological Survey of Denmark and Grenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark. Present address: DONG E & P, Agern Alle 24–26, DK-2970 Hørsholm, Denmark. Henrik Nøhr-Hansen, Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 NV, Denmark. 1 May 2001.

Recent studies of the Upper Cretaceous–Paleocene sedimentary successions in East and West Greenland and in the offshore areas of between West Greenland and Canada indicate major uplift prior to generation of flood basalt provinces in response to rising, hot mantle plumes (Dam et al. 1998a; Nøhr-Hansen et al. 1999). In particular, the studies in the Nuussuaq Basin, West Greenland, have shown that the rise of the North Atlantic plume had a major impact on development of depositional systems and formation of major sequence boundaries (Dam & Sønderholm 1998; Dam, in press). The paper by Dam et al. (1998) only dealt with the uppermost sequence, reflecting the culmination of the impact of the plume, whereas the present paper include all three sequences that are believed to have been formed as the result of the rise of the North Atlantic mantle plume. Sequences related to the rise of mantle plumes have not yet been described from other regions, however, White & Lovell (1997) related the Paleocene submarine fan deposition in the North Sea to pulses of magmatic underplating associated with mantle plume activity. As with the pulses in the North Sea, the three major late Maastrichtian–early Paleocene sequences present in the Nuussuaq Basin are believed to reflect major phases of plume activity during the rise of the North Atlantic mantle plume. The recent studies suggest that such sequences are characterised by very fast development of submarine canyons and valleys and catastrophic deposition.

The aim of the present paper is to place the sediments deposited in the Nuussuaq Basin during the rise of the North Atlantic mantle plume within a sequence stratigraphic framework and to provide a description of the effects of the North Atlantic mantle plume on associated sequence development. An estimate of the time range of sequence development will be discussed.

Geological setting

The continental margin of West Greenland was formed during extensional opening of the Labrador Sea in Late Mesozoic–Early Cenozoic time. A complex of linked basins stretches from the Labrador Sea in the south to northern Baffin Bay (e.g. Rolle 1985; Chalmers et al. 1993, 1999). Cretaceous–Paleocene sediments outcrop onshore on Cape Dyer on Baffin Island, Canada and in the Nuussuaq Basin in the Disko–Svartenhuk Halvø region, West Greenland

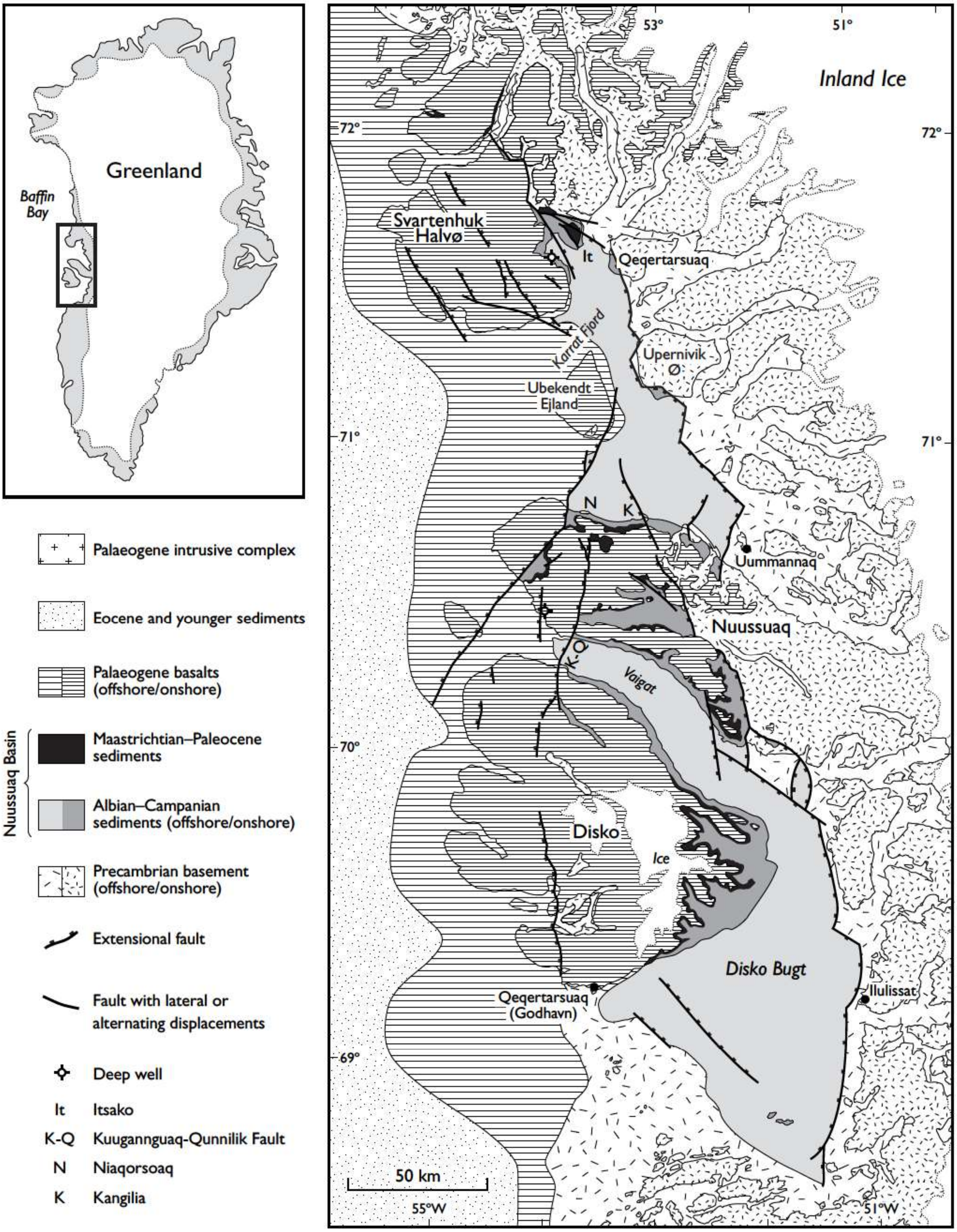

Fig. 1. Geological map of the Nuussuaq Basin, West Greenland, showing localities mentioned in the text. Based on Chalmers et al. (1999).

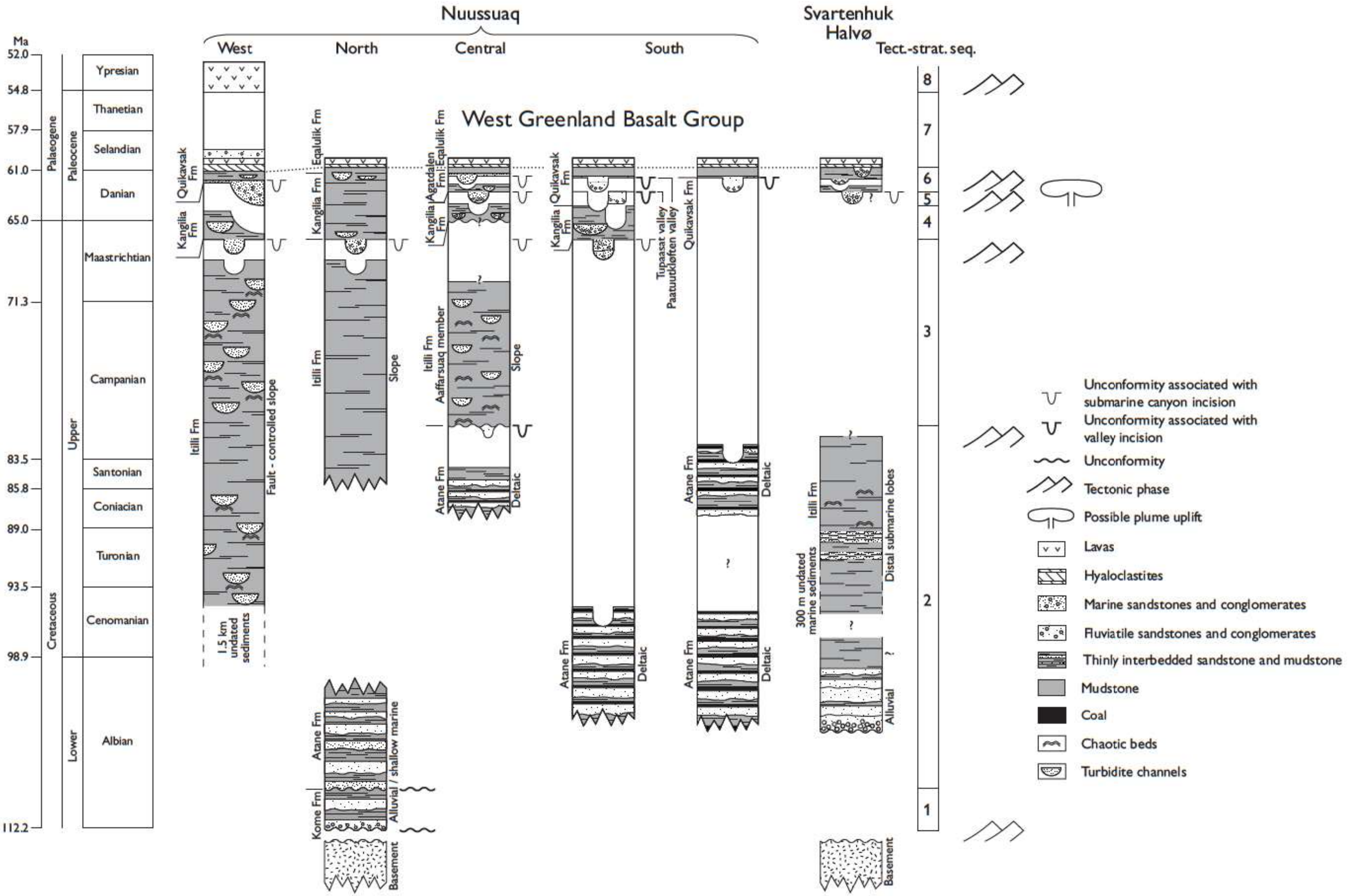

Fig. 2. Generalised stratigraphy of the Cretaceous – Paleogene sediments on Nuussuaq and Svartenhuk Halvø, West Greenland. Note that the heights of the stratigraphic columns relate to the chronostratigraphic divisions on the left and not to thicknesses of sedimentary successions. From Dam et al. (2000).

(69°–72°N); in both areas the sediments are overlain by Palaeogene basalts (Fig. 1; Clarke & Pedersen 1976; Henderson 1976; Burden & Langille, 1990). Although now bounded to the east by an extensional fault system, the sediments in the Nuussuaq Basin may originally have extended both east and south of their present area of outcrop (Chalmers et al. 1999). The maximum thickness of the sediments in the basin exceeds 8 km (Christiansen et al. 1995; Chalmers et al. 1999) but the age and the character of the deepest sediments are not known.

The exposed part of the succession can be divided into eight tectono-stratigraphic sequences (tss) mainly related to the tectonic events that controlled a series of discrete basin-fill phases (Fig. 2). The oldest sediments of tss 1 represent a Late Albian syn-rift phase. These sediments onlap the basement on the north coast of Nuussuaq, on Disko (well FP93-3-1) and on Itsaku (Figs 1, 2). The basal sediments consist of basement-derived conglomerates deposited from subaerial and subaqueous debris flows in a fan-delta environment; these are succeeded by sandstones, heteroliths, mudstones and thin discontinuous coal beds deposited in shallow marine and fluvio-deltaic environments. These sediments constitute the Kome Formation (Figs 1, 2; see Pulvertaft 1979; Midtgaard 1996a, 1996b; Larsen & Pulvertaft 2000).

Tss 1 is separated from tss 2 by a small angular unconformity. Tss 2 represents a long period of thermal subsidence that spans the Late Albian–earliest Campanian time interval. It is dominated by fluvio-deltaic deposits (Atane Formation; Johannessen & Nielsen 1982; Midtgaard 1991; Pedersen & Pulvertaft 1992; Olsen 1993). The Atane delta fanned out to the west and north-west from a point east of Disko island (Schiener 1975; Pedersen & Pulvertaft 1992), reaching into deeper-water turbidite environments west of the Kuugannguaq-Qunnilik Fault (Figs 1, 2; Dam & Sønderholm 1994; Dam 1997; Kristensen & Dam 1997). The sediments deposited in the deep-water environment are referred to as the Itilli Formation (Fig. 2). In the northern part of the basin Late Albian–early Cenomanian fluvial deposits outcrop on Qeqertarsuaq and also on Itsaku where they grade into fluvio-deltaic deposits (Larsen & Pulvertaft 2000). Turonian–early Campanian distal marine slope mudstones and heteroliths are exposed in the eastern part of Svartenhuk Halvø and were drilled in the Umiivik-1 well (Fig. 1; Dam et al. 1998b; Larsen & Pulvertaft 2000). There is evidence of increased Late Santonian subsidence in central Nuussuaq, possibly due to tensional sagging preceding a new rift phase that took place in early Campanian time (Fig. 2; Dam et al. 2000).

In the earliest Campanian a new tectonic phase gave rise to catastrophic deposition in a footwall fan environment along N–S trending faults. The resulting syn-rift deposits are referred to as tss 3 (Fig. 2; Aaffarsuaq Member). Sediments of this sequence were deposited from gravity flows in a fully marine environment.

In late Maastrichtian time the stress system in the region changed and extension took place along NW–SE trending faults. In latest Maastrichtian–earliest Paleocene time three major tectonic phases are recognised, each associated with incision of valleys and submarine canyons (Fig. 2). The first phase (latest Maastrichtian represented by tss 4; Kangilia Formation) gave rise to uplift followed by down-cutting and filling of two major NW–SE trending submarine canyons. The second phase (tss 5; Quikavsak Formation, Tupaasat and Nuuk Qiterleq Members) took place in the earliest Paleocene and was associated with major uplift of the basin and valley incision into early Paleocene fault scars (Dam, in press). This phase was characterised by catastrophic deposition. The third phase was associated with renewed uplift, and valleys up to 200 m deep and 2 km wide were incised into the previous valley fill deposits and filled with fluvial and estuarine deposits (tss 6; Quikavsak Formation, Paatuutkløften Member; Dam & Sønderholm 1998; Dam, in press). This phase was followed by very rapid subsidence shortly before extrusion of picritic hyaloclastite breccias. This sequence of events (tss 4–6) is interpreted as an expression of the arrival of the North Atlantic mantle plume (Fig. 2).

Extrusion of the volcanic succession can be divided into two phases and is related to continental break-up (Chalmers et al. 1999). The first phase (tss 7) was dominated by extrusion of olivine-rich basalts and picrites (Vaigat Formation) followed by more evolved, plagioclase-phyric basalts (Fig. 2; Maligât Formation; Pedersen 1985). As the volcanic front moved towards east, large lakes were established between the front in the west and the basement in the east, giving rise to syn-volcanic lacustrine deposits (Atanikerluk Formation; Pedersen et al. 1996). Magmatic activity in the Nuussuaq Basin resumed in the early Eocene with an episode of intrusion of dyke swarms and extrusion of basalts and sparse comendite tuffs (tss 8; Chalmers et al. 1999).

Rise of mantle plume

In recent years the Tertiary volcanic provinces of the North Atlantic region and their relationship to the arrival of the North Atlantic Plume have been discussed. Although aspects such as the size and dynamics of such plumes are still discussed, the involvement

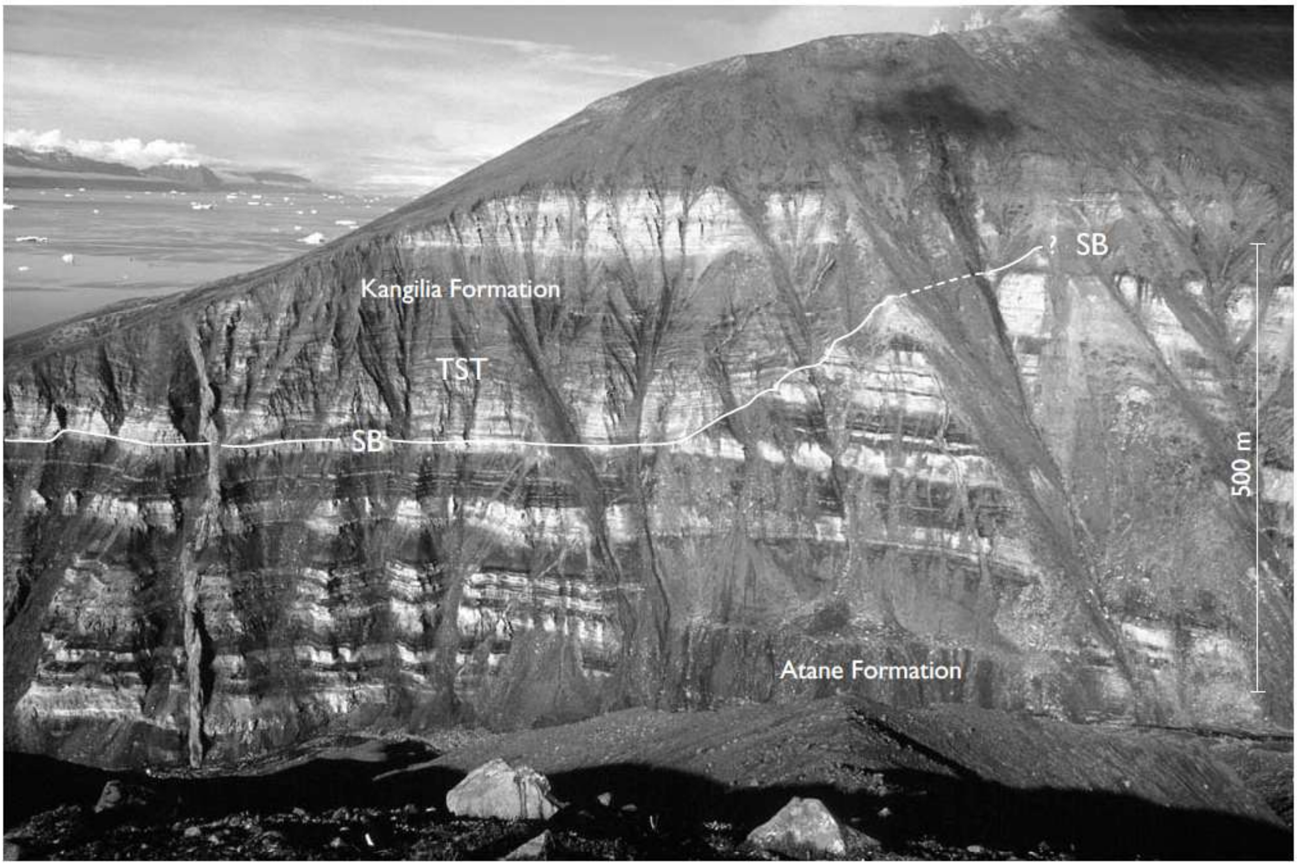

Fig. 3. Late Maastrichtian submarine canyon at Ataata Kuua. The canyon is incised into mid-Cretaceous deltaic deposits of the Atane Formation. The cliff face is perpendicular to the canyon axis. SB: sequence boundary at the base of the submarine canyon; TST: transgressive systems tract.

of mantle plumes in the generation of widespread flood basalts is now widely accepted (e.g. Brooks 1973; Chalmers et al. 1995; Clift 1996; Clift et al. 1998; Gill et al. 1992; Holm et al. 1992; Lawver & Müller, 1994; Marty et al. 1998; Schaefer et al. 2000). In West Greenland some of the most important evidence for the relationship between the flood basalts and the involvement of a mantle plume is the presence of the unusually high proportion of magnesian picritic lavas and hyaloclastites, indicating abnormally high mantle temperatures (e.g. Gill et al. 1992). Seaward-dipping reflectors and a landward facing volcanic escarpment, indicating that sub-aerial sea-floor spreading took place is also interpreted as evidence for abnormally high mantle temperatures (Chalmers et al. 1995). Other evidences include osmium isotope signature (Schaefer et al. 2000) and the erosional and uplift history of north-east Atlantic passive margins (Clift et al. 1998; Dam et al. 1999). Depending on the size of the thermal anomaly, the dynamic and thermal effects of the rise of hot mantle material may produce significant surface uplift, possibly as much as 3 km (Campbell & Griffiths 1990; White & McKenzie 1995). This uplift is widely recognised in the volcanic successions exposed along most volcanic margins and also accounts for the fact that basalts forming seaward dipping reflectors in the adjacent oceanic area are subaerial (e.g. Larsen et al. 1994). It is believed that the uplift recorded in the sediments just underneath the Paleocene volcanics in East and West Greenland reflects this significant surface uplift (Dam et al. 1998).

The plume-associated sequences

Tectono-stratigraphic sequences 4–6 in the Nuussuaq Basin are associated with the rift event associated with the rise of the North Atlantic mantle plume. At least three tectonic phases have been recognised (Fig. 2), each associated with substantial uplift and repeated erosion and filling of incised subaerial valleys and submarine canyons resulting in basin-wide unconformities/sequence boundaries. These events are dealt with in detail in the following part.

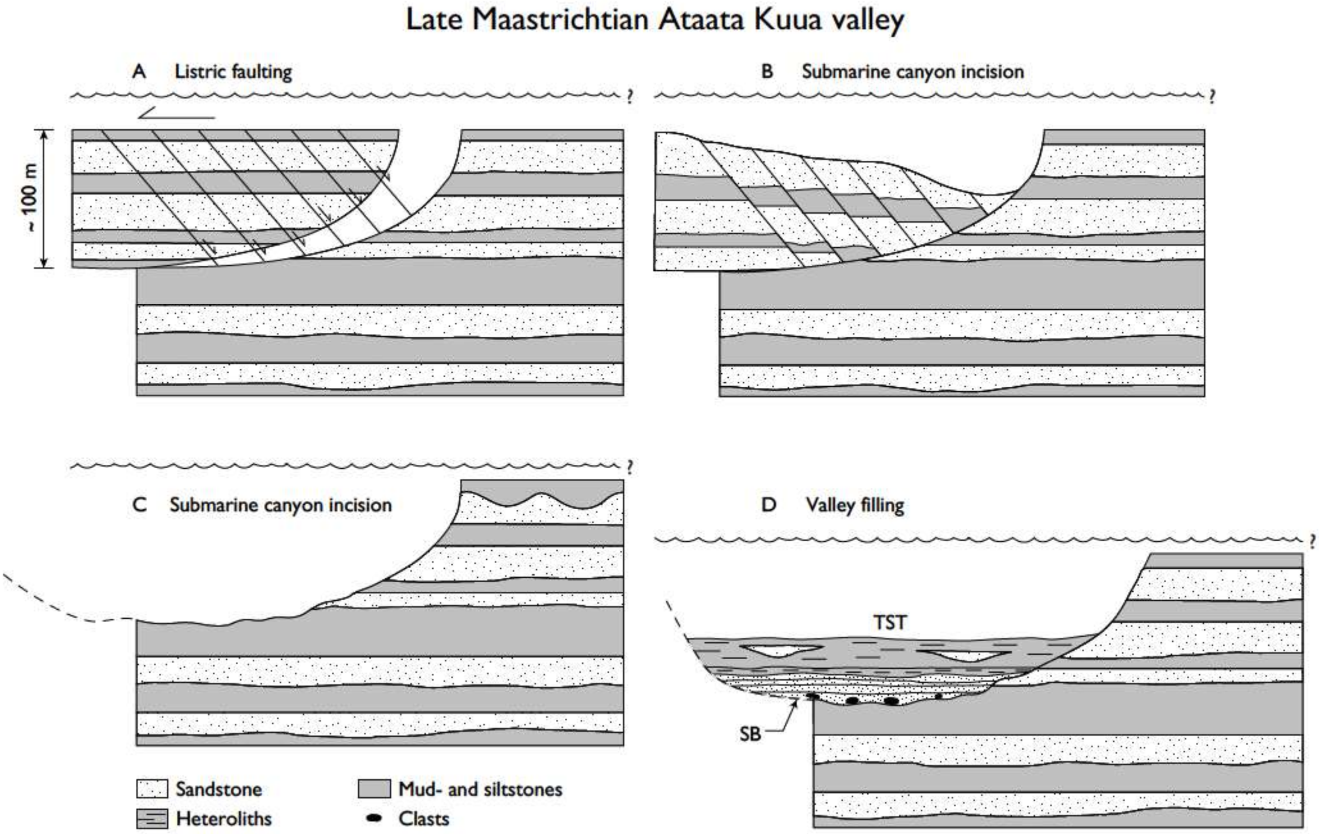

Fig. 4. Conceptual model showing the development of the Ataata Kuua submarine canyon. A: The canyon formed in association with listric faulting. B: The canyon was established in the accomodation space produced by detachment and collapse of the hanging wall. C: The steeply dipping part of the detachment surface of the footwall acted as canyon wall and seems not to have been eroded in appreciable extent, whereas the gently dipping part of the detachment surface formed due to canyon incision. D: The canyon was subsequently filled with transgressive systems tract turbidite deposits.

Tectono-stratigraphic sequence 4

Initiation of plume-related uplift resulted in a late Maastrichtian erosional unconformity present throughout most of Nuussuaq. It can be traced from the north-east, where the upper Maastrichtian–early Paleocene Kangilia Formation rests unconformably on upper Campanian slope mudstones of the Itilli Formation, to the south coast of Nuussuaq where the Kangilia Formation rests with an erosional unconformity upon the deltaic deposits of the Albian–Cenomanian Atane Formation (Fig. 2). At Ataata Kuua and in the Annertuneq area on the north coast of Nuussuaq the unconformity is associated with submarine canyon incision.

Ataata Kuua

Sequence boundary. The northern side of a submarine canyon exposed in cross-section (Fig. 3) defines tectono-stratigraphic sequence 4 boundary at Ataata Kuua. The canyon appears to have a broad U-shaped geometry, with a flat bottom and very steep walls. The width of the canyon is unknown, but it is up to 105 m deep. Flutes and channel-shaped scours are common along the base of the canyon. The relatively flat erosional canyon floor grades into a steep canyon wall that dips up to 80°, along which the fill (Kangilia Formation) abuts against the Atane Formation. The canyon wall strikes 125°–305°. The very steep, almost vertical, wall of the canyon was interpreted as a fault by Hansen (1980) and as a listric fault by Pulvertaft & Chalmers (1990). The latter was confirmed by Dam et al. (1996) who suggested that the canyon was established in the accommodation space produced by detachment of the hanging wall. The vertical and steeply dipping part of the detachment surface of the footwall acted as the canyon wall and seems not to have been eroded significantly, whereas the gently dipping part of the detachment surface was eroded during canyon incision (Fig. 4).

Transgressive systems tract. The fill of the Ataata Kuua

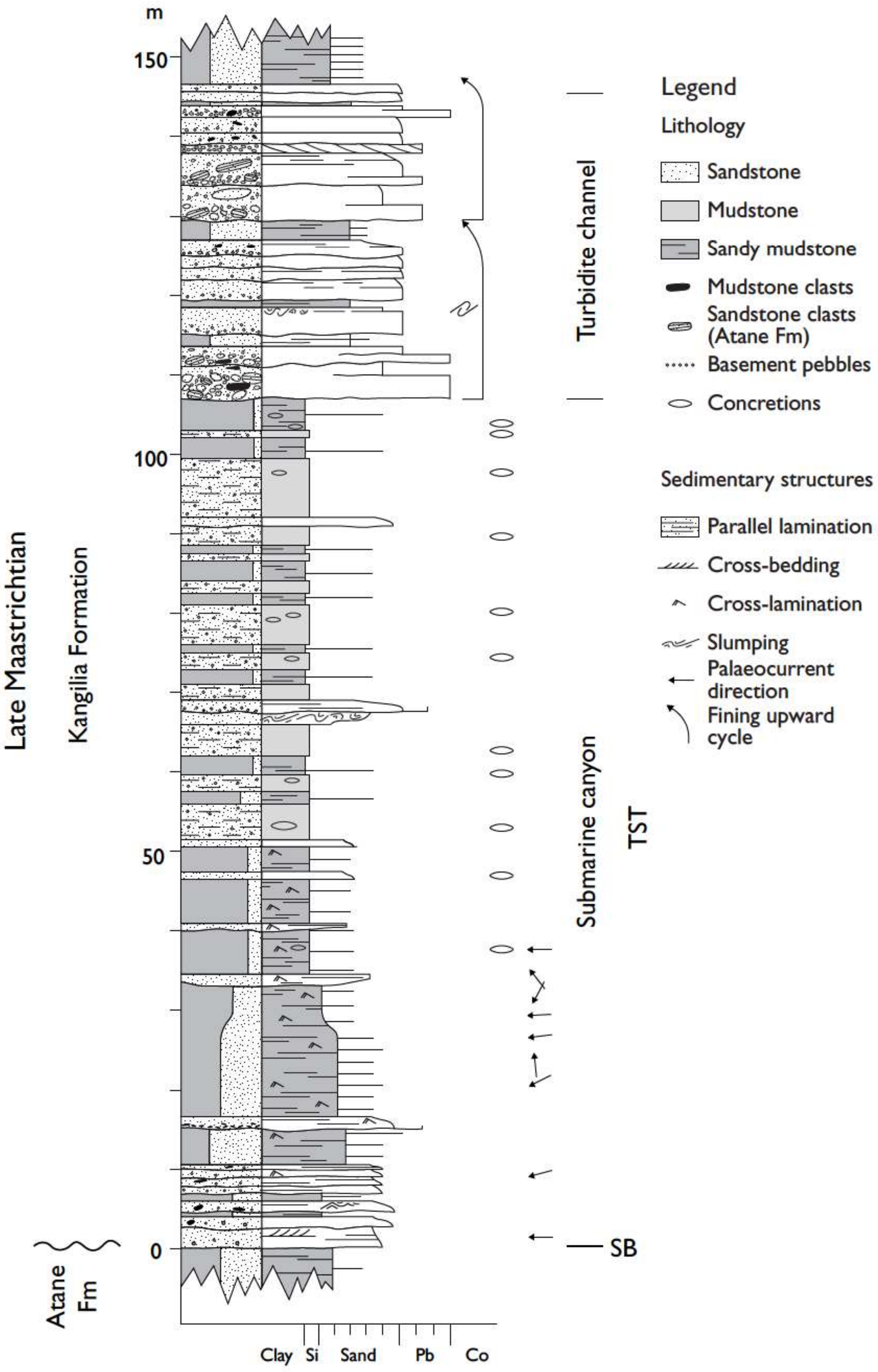

Fig. 5. Generalised sedimentological log of the upper Maastrichtian Ataata Kuua canyon fill. SB: sequence boundary; TST: transgressive systems tract. See also Figure 4.

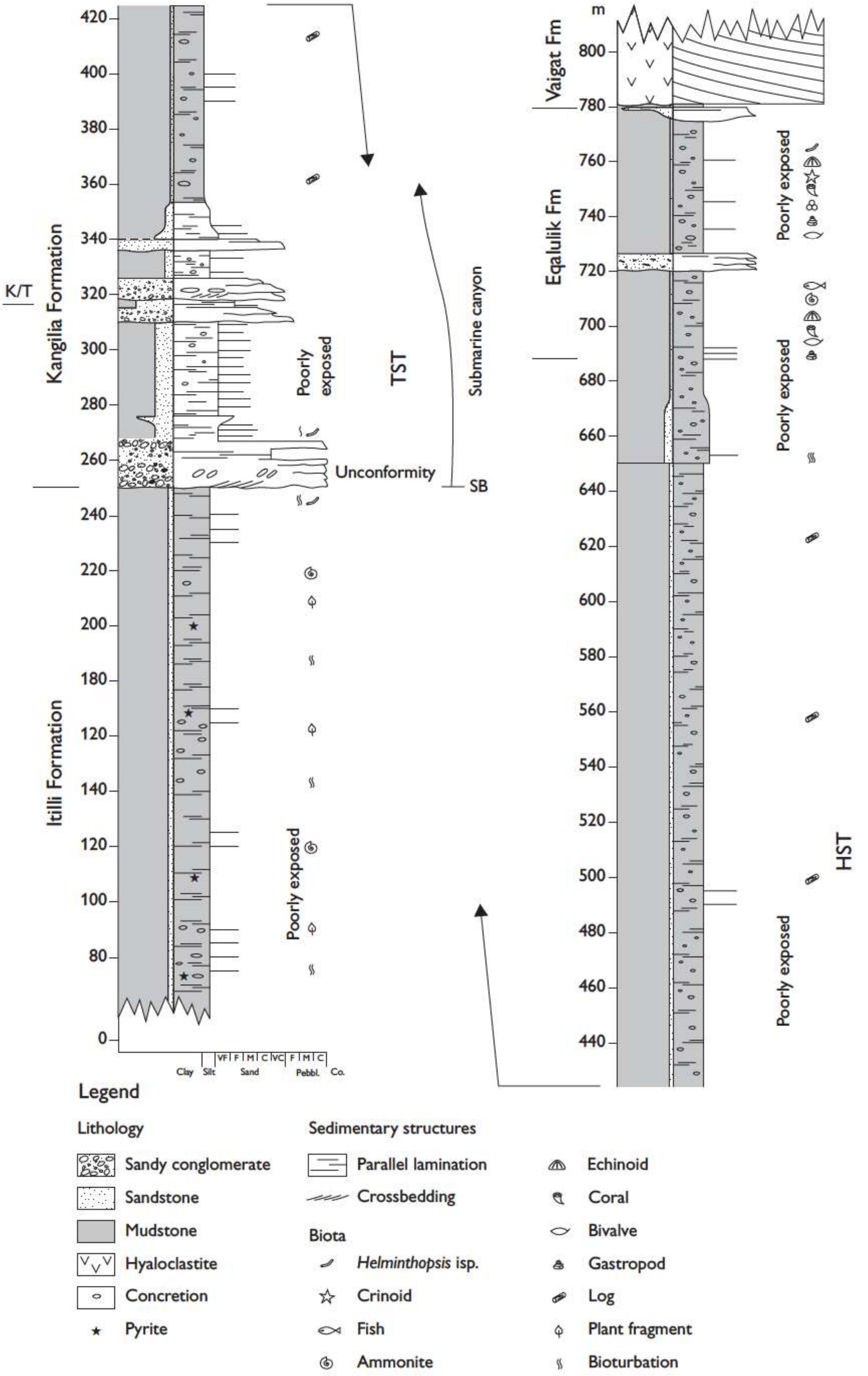

Fig. 6. Generalised sedimentological log of the upper Paleocene Annertuneq canyon fill. SB: sequence boundary; TST: Transgressive systems tract; HST: highstand systems tract.

Fig. 7. Late Maastrichtian Annertuneq submarine canyon on the north coast of Nuussuaq. The canyon is incised into the Campanian slope deposits of the Itilli Formation. The coast is parallel to the canyon axis.

canyon constitutes an overall fining-upward succession interpreted as representing the transgressive systems tract (Fig. 5). In places transported outsized concretions with a diameter up to 1.5 m occur just above the sequence boundary. They are overlain by composite sandstone bedsets composed of graded, massive, coarse-grained pebbly sandstones deposited from sandy high-density turbidity currents, grading upward into coarse- to fine fine-grained, parallel-sided sandstones deposited from low-density turbidity currents.

The composite sandstone bedsets are succeeded by lenticular bodies a few tens of metres wide and up to 2 m thick. They are composed of interbedded sandstone and mudstone arranged in fining-upward cycles. The interbedded sandstones and mudstones were deposited from low-density turbidity currents in small submarine channels confined to the canyon. The uppermost 56 m of the canyon fill is dominated by massive mudstones containing scattered sand grains and few pebble and cobble sized basement clasts deposited from debris flows.

Highstand systems tract. The canyon deposits are overlain by slope deposits composed of mudstones and thinly interbedded sandstones and mudstones several hundreds of metres thick, tentatively interpreted as highstand systems tract deposits. Occasionally, these deposits are interbedded with turbidite channel deposits consisting of conglomerates and sandstones showing the same facies as the sandstones and conglomerates of the Annertuneq canyon (see below).

Annertuneq

Sequence boundary. On the north coast of Nuussuaq, between Niaqorsuaq and Kangilia, the sequence boundary between the Kangilia and Itilli Formations is an erosional unconformity, here separating upper Campanian marine slope mudstones from upper Maastrichtian submarine canyon conglomerates and sandstones (Figs 6, 7; Nøhr-Hansen & Dam, 1997). The unconformity is interpreted as a sequence boundary and crosscuts minor syn-sedimentary faults within the mudstones below. The sequence boundary is the northern flank of a submarine canyon in a section parallel to the canyon axis. At the north coast the canyon deposits are up to 100 m thick, and it increases in thickness to approximately 150 m in the GANT#1 well situated 6 km SSE of Kangilia (Fig. 1). The width of the canyon is unknown, but exceeds 6 km, which is the distance between the Annertuneq section and the GANT#1 well, perpendicular to the canyon axis.

Transgressive systems tract. The canyon fill consists of amalgamated conglomerates and sandstones arranged in one or two overall fining-upward successions (Fig. 6) and are interpreted as deposits of the transgressive systems tract. The conglomerates occur in beds up to 8 m thick composed of poorly sorted, matrix or clast-supported and contain a matrix of either medium- to very coarse-grained sandstone or sandy mudstone. Both matrix- and clast-supported beds occur. The clasts consist of basement lithologies, sandstone, transported intraformational mudstones and concretions, and rarely Ordovician cherty ooidstones. The conglomerates were deposited from debris flows

Fig. 8. Tupaasat valley incised into mid-Cretaceous deltaic deposits of the Atane Formation along a NW trending fault and filled with lower Paleocene sandy conglomerates. SB: sequence boundary.

and high-density turbidity currents. Occasionally, deposition of conglomerates from high-density turbidity currents was succeeded by deposition of well-developed parallel-laminated and cross-laminated sandstones deposited from late-stage, low-density residual currents after deposition of the more coarse-grained suspended-sediment load.

The amalgamated sandstones are made up of graded beds deposited from high-density turbidity currents. In vertical section the beds show a general thinning- and fining-upward trend. In the upper part the sandstones are commonly separated by thinly interbedded sandstone and mudstone. These heterolithes were deposited from low-density turbidity currents.

Highstand systems tract. As on the south coast of Nuussuaq, the canyon deposits are overlain by a slope succession composed of mudstones and thinly interbedded sandstones and mudstones several hundreds of metres thick; these are interpreted as highstand systems tract deposits (Fig. 6). Occasionally these deposits are interbedded with turbidite channel deposits composed of conglomerates and sandstones showing the same facies as the sandstones and conglomerates of the Annertuneq canyon (see above).

Tectono-stratigraphic sequence 5

A major tectonic phase took place during the early Paleocene, probably sometime during nannoplankton zone NP2–NP4 times (Fig. 2; Dam, in press; Nøhr-Hansen et al. in press). Extensional faulting took place along NW–SE striking normal faults, some of which are exposed along the south coast of Nuussuaq (Dam, in press) and in central Nuussuaq (Dam et al. 2000). Along Vaigat these faults show a down-throw of at least 300 m to the north-east (Fig. 8). Early Paleocene faulting was associated with major uplift of the basin, erosion of more that 1 km of sediment in the crestal areas of footwall blocks, and incision of valleys along the NW-trending normal faults, clearly showing that the trend and the relief of the valleys were structurally controlled (Dam et al. 1998a; Dam & Sønderholm 1998; Dam, in press). In western Nuussuaq the incised valleys pass seawards into a submarine canyon system as they cross a fault-controlled slope along the Kuugannguaq-Qunnilik Fault (Figs 1, 2).

Sequence boundary. The outline of the Tupaasat valley is not very well defined. In cross-sections it is marked by a major erosional unconformity outlining a broad U-shaped valley (Fig. 8).

Lowstand systems tract. A succession, up to 115 m thick and composed of pebbly sandstones and conglomerates fills in large depressions in the Tupaasat valley system. As these sediments are thought to have been deposited in large depressions during uplift from catastrophic outburst floods, they are tentatively assigned to lowstand deposits (Figs 8–10). Alternatively, they can be interpreted as early transgressive systems tract deposits. The lower part consists of giant-scale, low-angle cross-bedded pebbly sandstones, conglomerates

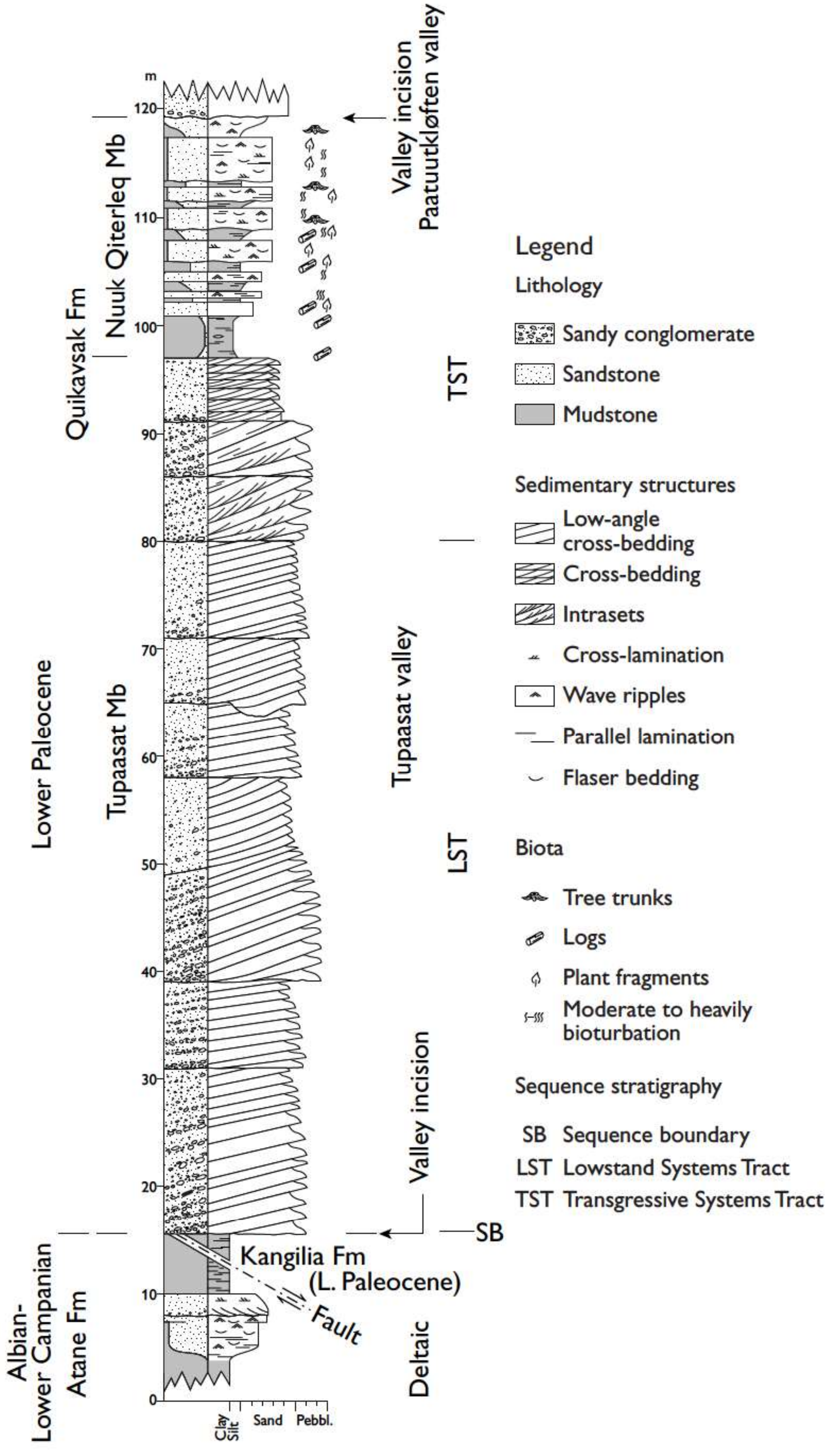

Fig. 9. Generalised sedimentary log of the Danian-Paleocene Tupaasat valley fill. See also Fig. 10.

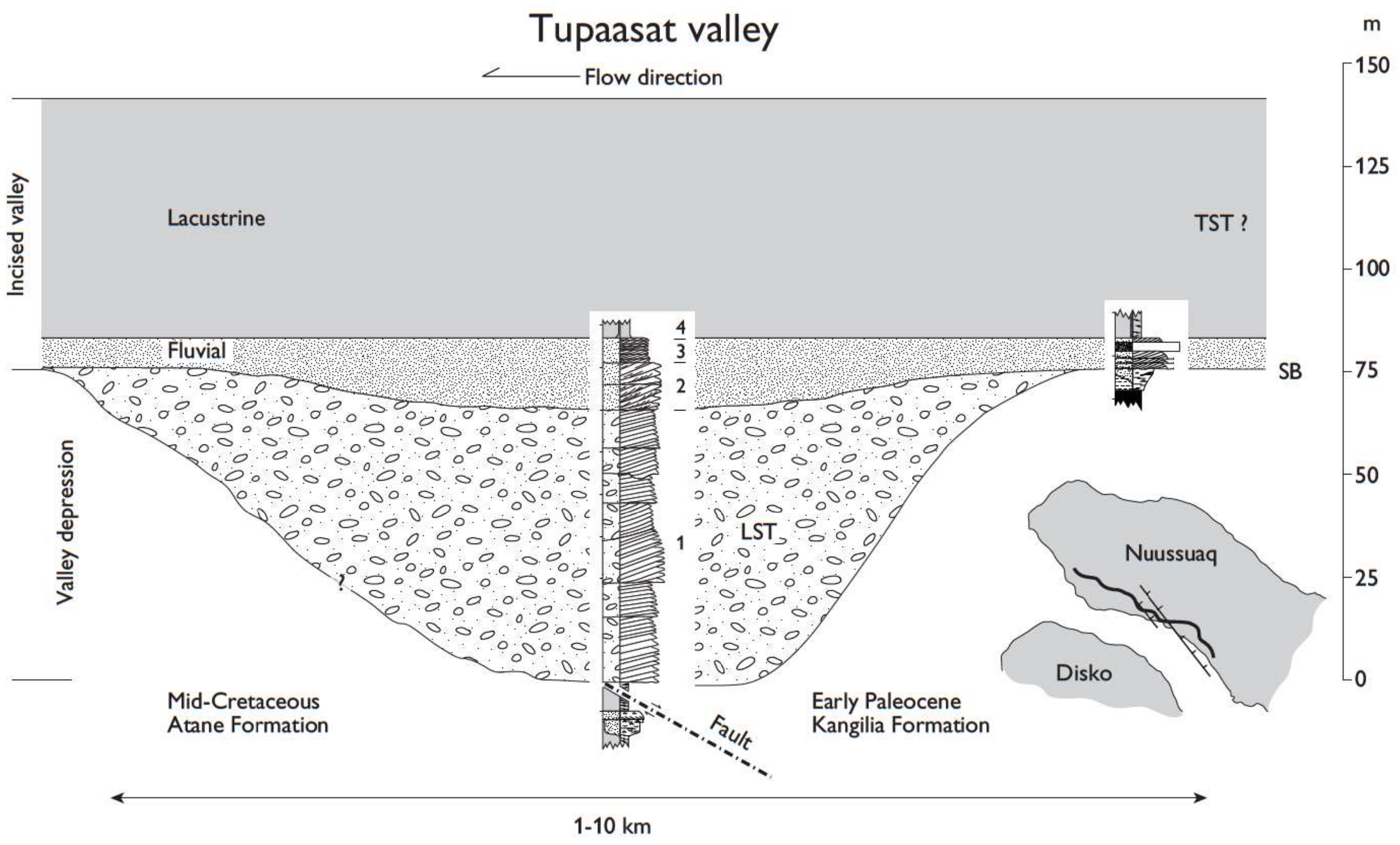

Fig. 10. Schematic cross-section of the Tupaasat valley fill showing the lowstand conglomeratic sandstones deposited in depressions formed in areas where the valley cut down into and along the NW-trending faults. The lowstand deposits are overlain by fluvial and lacustrine transgressive systems tract deposits. SB: sequence boundary; LST: lowstand systems tract; TST: transgressive systems tract.

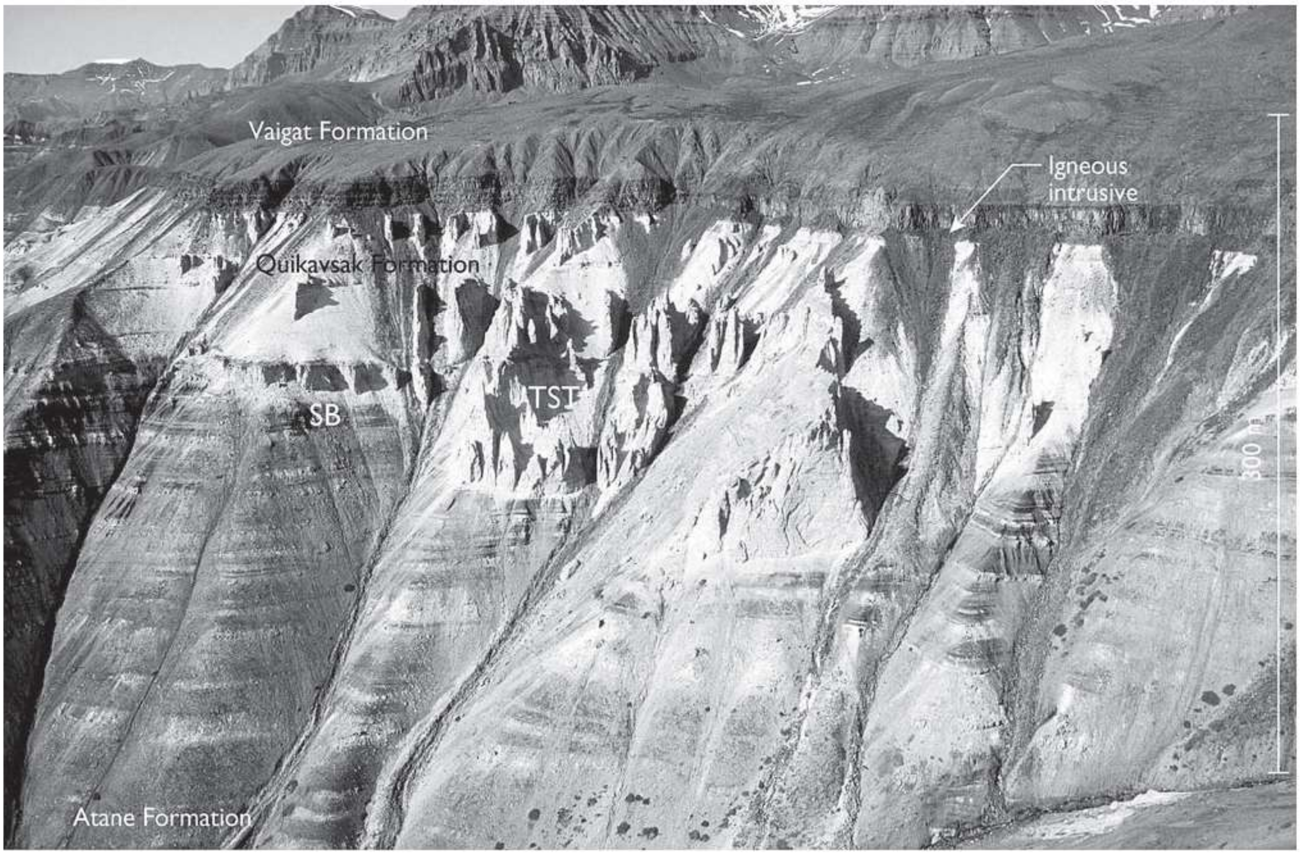

Fig. 11. Early Paleocene sedimentary fill of the Paatuutkløften valley. The valley is incised into Danian sedimentary fill of the Tupaasat valley and mid-Cretaceous deltaic deposits of the Atane Formation. SB: Sequence boundary.

and horizontal to gently inclined pebbly sandstones and cross-bedded sandstones forming in an overall fining-upward succession. The lower cross-bedded sets are up to 30 m thick and the foresets dip less than 15° which is well below the angle of repose. In other areas they form large spoon-shaped sets. Individual foresets are up to 3.5 m thick and consists of sharply-based, graded pebbly sandstones and conglomerates. The giant-scale cross-bedded sandy conglomerates are succeeded by amalgamated horizontal to gently inclined graded pebbly sandstone beds.

The cross-bedded sandstones and conglomerates form an intriguing facies. They could be interpreted as avalanche deposits, however, that does not explain the very thick foresets, the interbedding with graded sheet sands most likely deposited from flows characterised by very high concentrations of suspended coarse-grained sediment load and the general low foreset dips. They are most likely clinoforms formed by migration of attached bars in the valley depressions. They may have formed due to a hydrolic jump that possibly was created when the flows passed the depressions. The large spoon-shaped sets, may represent large scour-and-fill structures formed during fluctuations in the flow (Dam, in press). It is difficult to divide the succession into more than one or two units, and these lowstand or early transgressive sediments were deposited during a single or a few catastrophic, powerful outburst-generated floods in the large depressions of the valley.

Transgressive systems tract. Cross-bedded fluvial sandstones and lacustrine heteroliths, up to 56 m thick succeed the lowstand deposits. They constitute the upper part of the valley fill (Fig. 10; Dam, in press). Above the valley depressions these sediments are separated from the pebbly sandstones and conglomerates by a sharp boundary (Figs 9, 10). The fluvial sandstones are medium- to coarse-grained, up to 16 m thick, and are dominantly planar cross-bedded. In places the cross-beds are separated by low-angle inclined set boundaries, delineating co-sets 5 to 6 m thick. The cross-bedded sandstones represent fields of subaqueous low-sinuosity dunes migrating along the valley floor, whereas the composite sets are interpreted as deposits of channel bars (Dam, in press).

The fluvial sandstones are overlain by heterolithic lacustrine sediments composed of silt and sand streaked mudstones overlain by fine- to medium-grained sandstones, together forming coarsening-upward cycles up to 6 m thick (Fig. 9). Disintegrated plant material, leaf fossils and *in situ* vertical and drifted coalified tree trunks are abundant. The fluvial and lacustrine deposits were deposited in the incised valleys during a period of tectonic quiescence. The stacked coarsening-upward cycles were formed by repeated shoreface or bayhead delta progradation into a lacustrine environment.

Tectono-stratigraphic sequence 6

Following a period of tectonic quiescence, a period of renewed faulting, uplift and valley incision took place in late early Paleocene, reflected in the incision and subsequent filling of the Paatuutkløften valley and deposition of the overlying hyaloclastites.

Sequence boundary. The Paatuutkløften valley was cut into the Tupaasat valley fill, which in many places were completely or nearly completely eroded away, creating a new sequence boundary. The valley is up to 190 m deep and 1–2 km wide and consists of fluvial and estuarine deposits (Fig. 11). Offshore marine mudstone and hyaloclastites overlie the valley fill. The valley-fill deposits comprise a uniform succession of fluvial and estuarine sandstones.

Lowstand systems tract. The only lowstand deposits comprise paraconglomerates composed of rounded gneiss pebbles and boulders, which were concentrated as a basal lag on the valley floor as the finer grained sediments were flushed through the valley system (Fig. 12; Dam & Sønderholm 1998).

Transgressive systems tract. The succeeding phase of fluvial sandstone deposition resulted in a monotonous aggradational succession of cross-bedded fluvial sandstones, 65–120 m thick (Fig. 12; Dam & Sønderholm 1998). Convolute bedding is common. From a distance it seems that the lower fluvial sandstone in particular forms major composite bedsets in which the set boundaries dip a few degrees in a downstream direction and downlap onto the valley floor (Dam, in press). Intriguing characteristics of the fluvial fill are the absence of repetitive genetic units such as stacked fining-upward successions and the gently dipping downlap surfaces along the valley floor and sides. The only vertical trend is an overall upward decrease in grain size, clast size and set thickness. The overall uniform composition and the absence of stacked channel units suggest that a single flow occupied the full width of the valley without segregation into multiple channels. Moreover these features are suggesting very rapid vertical aggradation caused by an oversupply of sand during a period of rapid relative sea-level rise. The gently dipping downlapping surfaces seen in downstream sections and the very homogeneous nature of the cross-bedded sets suggest that the sandstones represent major downstream accretion elements that covered the full width of the valley (Dam, in press).

A mudstone unit separating the fluvial sandstones from the overlying tidal estuarine sandstones was deposited in a mid-estuary funnel environment (Fig. 12; Dam & Sønderholm 1998). A sharp boundary between the mid-estuary funnel mudstone and the estuary-mouth sandstones is probably a tidal ravinement surface formed as the ebb tidal delta retreated into the estuary (Fig. 12; Dam & Sønderholm 1998). The estuarine sandstones are cross-bedded showing typical features of tidal activity (Dam & Sønderholm 1998). Marine molluscs are rarely present, while the trace fossils *Ophiomorpha nodosa*, *Ophiomorpha* isp., *Thalassinoides* isp., *Diplocraterion parallelum* and *Planolites* isp. as well as plant debris are common. At some localities the valley fill sandstones are overlain by two coarsening-upward shoreface successions, both composed of silt- and sand-streaked mudstones grading upward into bioturbated interbedded siltstones and sandstones. Wave and current ripple cross-lamination are common. The lenticular beds are succeeded by heavily bioturbated medium-grained sandstones showing abundant *Ophiomorpha nodosa*, *Ophiomorpha* isp. and *Thalassinoides* isp. A sharp boundary between the estuarine valley fill sandstones and the shoreface deposits is occasionally present and is interpreted as a shoreface wave ravinement surface (Fig. 12).

The valley fill and shoreface sandstones are abruptly overlain by offshore mudstones up to 44 m thick, deposited shortly before and during initial extrusion of a thick hyaloclastite successions (Fig. 12). The maximum flooding surface is tentatively placed at the base of the hyaloclastites (Fig. 13).

The Paatuutkløften valley fill is attributed to a very rapid rise in relative sea-level just prior to or contemporaneously with extensive volcanism. The fill and the offshore mudstones have an NP4–(?)NP5 age (Nøhr-Hansen et al. in press).

Highstand systems tract. Faulting took place immediately prior to eruption of the Vaigat Formation hyaloclastite breccias, as indicated by abrupt steps in the sub-hyaloclastite surface along some of the N–S trending extensional faults. At these localities the base of the hyaloclastite breccia rises abruptly eastwards by 400–500 m (Chalmers et al. 1999). The thickness of

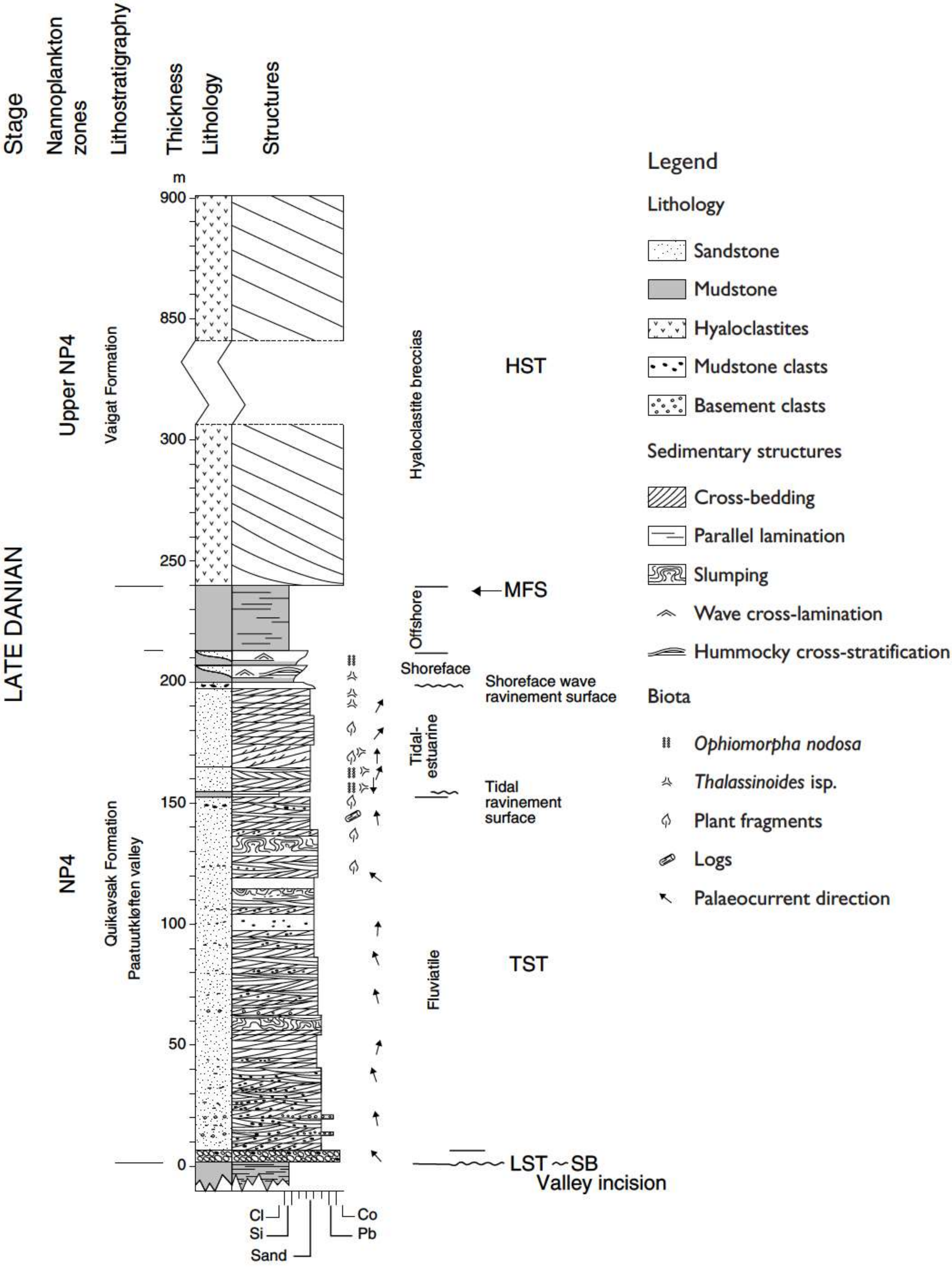

Fig. 12. Generalised sedimentary log of the Paatuutkløften valley fill. SB: Sequence boundary; LST: lowstand systems tract; TST: Transgressive systems tract; HST: Highstand systems tract; MFS: maximum flooding surface.

Fig. 13. Hyaloclastites and lavas of the Lower Palaeogene Vaigat and Maligat Formations overlying Cretaceous-Lower Palaeogene sediments of the Nuussuaq Group. Note the giant-scale foresets of the hyaloclastites indicating water depths of up to 700 m. HST: highstand systems tract; MFS: maximum flooding surface. Photo by A.K. Pedersen.

cross-bedded hyaloclastite sets indicates that the water depth in places exceeded 700 m during the early phase of volcanism; but the thickness of the sets varies considerably between fault blocks (Fig. 13; Pedersen 1993). The hyaloclastites were deposited during highstand conditions. The very rapid rise in relative sea-level immediately prior to volcanism is regarded as the result of major subsidence due to magma escaping from the mantle and extrusion of volcanics in the offshore areas. The steps in the sub-hyaloclastite surfaces are regarded as expressions of fault scarps created during the very rapid subsidence that preceded the extrusion of the breccias (Chalmers et al. 1999).

Onset of volcanism in the Nuussuaq Basin started at c. 61 Ma and the main part of the volcanic succession on Disko and Nuussuaq was erupted within 1 Ma or less (Storey et al. 1998). It is possible to correlate the uppermost pre-volcanic marine mudstone succession, of latest Danian age (late NP4; Nøhr-Hansen et al., in press) with the overlying and partly time equivalent volcanics of the normally magnetised chron 27. These volcanics underlie reverse magnetised volcanics of chron 26 (Riisager & Abrahamsen 1999), which gives $^{40}Ar/^{39}Ar$ ages of 60.9 and 61.3 Ma (Storey et al. 1998).

Discussion of timing of sequence development and conclusions

The late Maastrichtian–Danian succession in the Nuussuaq Basin, West Greenland reflects the geological evolution during the rise of the North Atlantic mantle plume. The succession indicates that significant uplift began approximately 5 Ma before onset of volcanism and that three sequences, each associated with submarine canyon and valley incision, were formed during this event. Each of the sequences was associated with tectonic phases and was followed by a period of catastrophic deposition. It has not been possible to precisely estimate the amount of uplift, but it has resulted in local erosion of up to 1.3 km of sediments on the footwall block (Dam et al. 1998a). Just prior to volcanism the basin experienced a significant rise in relative sea-level due to subsidence. Deposition of the last valley fill and the overlying mudstones and hyaloclastites (the latter indicating water depths of up to 700 m) took place within less time than is represented by one nannoplankton zone (~ 1 Ma; Nøhr-Hansen et al., in press). This geological scenario is in accordance with the fluid dynamical model for mantle plumes of Campbell & Griffiths (1990). In their model, the increased temperatures in the upper mantle cause elevation of the lithosphere by about 1 km. Campbell & Griffiths (1990) predicted (1) a period of subsidence due to lateral spreading of the plume head before the onset of the main period of volcanism, and (2) a later period of subsidence after the uplift phase enhanced by the combined effects of magma escaping from the mantle and the subsequent loading.

Early applications of the sequence stratigraphic concept were based on the assumption that eustasy were the most important control on sequence development in the rock record. Later research has demonstrated that changes in relative sea-level caused by tectonic events may be of equal or even greater importance (e.g. Ethridge et al. 1998). The present study indicates that in areas influenced by rising mantle plumes, plume-related tectonics may be the most important or even the only factor controlling the relative sea-level. In this situation changes may be very dramatic, with changes of several hundreds of metres taking place in less than 1 Ma.

In addition, the present study indicates that the valleys formed during uplift of the Nuussuaq Basin are very special cases of incised valleys. A major difference between the Tupaasat valley fill and other published examples of valley fills is that most of the fill of the Tupaasat valley most likely represents lowstand deposits, whereas in other published examples most of the fills are placed in the transgressive systems tract. Taking the time factor into account, both the Tupaasat and Paatuutkløften valleys were incised and filled within a very short time; this is especially the case for the Tupaasat valley that was eroded and partly filled in during a single drainage event. Thus the sequences in the Nuussuaq Basin related to the rise of the North Atlantic mantle plume are a record of a spectacular and significant but rare geological event.

Acknowledgements

This study was generously supported by the Carlsberg Foundation. Thanks to L. Clemmensen, T.C.R. Pulvertaft, and F. Surlyk for constructive criticism and many helpful suggestions to the manuscript and colleagues from GEUS, University of Copenhagen and the Geological Museum for many discussions. J. Halskov are thanked for drafting and J. Lautrup for darkroom work. The paper is published with permission of the Geological Survey of Denmark and Greenland.

References

Brooks, C.K. 1973: Rifting & doming in southern East Greenland. Nature 244, 23–25.

Burden, E.T. & Langille, A.B. 1990: Stratigraphy and sedimentology of Cretaceous and Paleocene strata in half-grabens on the southeast coast of Baffin Island, Northwest Territories. Bulletin of Canadian Petroleum Geology 38, 185–195.

Campbell, I.H. & Griffiths, R.W. 1990: Implications of mantle plume structure for the evolution of flood basalts. Earth and Planetary Science Letters 99, 79–93.

Chalmers, J.A., Larsen, L.M. & Pedersen, A.K. 1995: Widespread Palaeocene volcanism around the northern North Atlantic and Labrador Sea: Evidence for a large, hot, early plume head. Geological Society London Journal 152, 965–969.

Chalmers, J.A., Pulvertaft, T.C.R., Christiansen, F.G., Larsen, H.C., Laursen, K.H. & Ottesen, T.G. 1993: The southern West Greenland continental margin: rifting history, basin development and petroleum potential. In Parker, J.R (ed.) Petroleum geology of northwest Europe: proceedings of the 4th conference, 915–931. The Geological Society, London.

Chalmers, J.A., Pulvertaft, T.C.R., Marcussen, C. & Pedersen, A.K. 1999: New insight into the structure of the Nuussuaq Basin, central West Greenland. Marine and Petroleum Geology 16, 197–224.

Christiansen, F.G., Marcussen, C. & Chalmers, J.A. 1995: Geophysical and petroleum geological activities in the Nuussuaq – Svartenhuk Halvø area 1994: promising results for onshore exploration potential. Rapport Grønlands Geologiske Undersøgelse 165, 30–39.

Clarke, D.B. and Pedersen, A.K. 1976: Tertiary volcanic province of West Greenland. In Escher, A. and Watt, W.S. (eds) Geology of Greenland, 365–387. The Geological Survey of Greenland.

Clift, P.D. 1996: Plume tectonics as a cause of mass wasting on the southeast Greenland continental margin. Marine and Petroleum Geology 13, 771–780.

Clift, P.D., Carter, A. & Hurford, A.J. 1998: The erosional and uplift history of NE Atlantic passive margins: constraints on a passing plume. Journal of the Geological Society, London 155, 787–800.

Dam, G. 1997: Sedimentology of the Umiivik-1 core, Svartenhuk Halvø, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/136, 15 pp., 1 figure, 1 table, 1 enclosure.

Dam, G. in press: Sedimentology of magmatically and structurally controlled outburst valleys along rifted volcanic margins; examples from the Nuussuaq Basin, West Greenland. Sedimentology.

Dam, G., Larsen, M., Nøhr-Hansen, H. & Pulvertaft, T.C.R. 1999: Discussion on the erosional and uplift history of NE Atlantic passive margins: constraints on a passing plume. Journal of the Geological Society, London 156, 653–656.

Dam, G., Larsen, L.M. & Sønderholm, M., Pedersen, A.K. 1996: Valley incision in a tectonically active basin, onshore West Greenland (abstract). In: AAPG Annual Meeting, San Diego, USA.

Dam, G., Larsen, M. & Sønderholm, M. 1998a: Sedimentary response to mantle plumes: Implications from Paleocene onshore successions, West and East Greenland. Geology 26, 207–210.

Dam, G., Nøhr-Hansen, H., Christiansen, F.G., Bojesen-Kofoed, J.A. & Laier, T. 1998b: The oldest marine Cretaceous sediments in West Greenland (Umiivik-1 borehole) – record of the Cenomanian-Turonian Anoxic Event? Geology of Greenland Survey Bulletin 180, 128–137.

Dam, G., Nøhr-Hansen, H., Pedersen, G.K. & Sønderholm, M. 2000: Sedimentary and structural evidence of a new early Campanian rift phase in the Nuussuaq Basin, West Greenland. Cretaceous Research 21, 127–154.

Dam, G. & Sønderholm, M. 1994: Lowstand slope channels of the Itilli succession (Maastrichtian-Lower Paleocene), Nuussuaq, West Greenland. Sedimentary Geology 94, 47–71.

Dam, G. & Sønderholm, M. 1998: Sedimentological evolution of a fault-controlled Early Paleocene incised-valley system, Nuussuaq Basin, West Greenland. In Shanley, K.W. & McCabe, P.J. (eds) Relative role of eustasy, climate, and tectonism in continental rocks. Society of Economic Paleontologists and Mineralogists Special Publication 59, 109–121.

Ethridge, F.G., Wood, L.J. & Schumm, S.A. 1998: Cyclic variables controlling fluvial sequence development: Problems and perspectives. In Shanley, K.W. & McCabe, P.J. (eds) Relative role of eustasy, climate, and tectonism in continental rocks. Society of Economic Paleontologists and Mineralogists Special Publication 59, 17–29.

Gill, R.C.O., Pedersen, A.K. & Larsen, J.G. 1992: Tertiary picrites in West Greenland: Melting at the periphery of a plume? In Storey, B.C. Alabaster, T. & Pankhurst, R.J. (eds) Magmatism and the causes of continental break-up. Geological Society Special Publication, London 68, 335–348

Hansen, J.M. 1980: Stratigraphy and structure of the Paleocene in central West Greenland and Denmark. University of Copenhagen, unpublished lic. scient. thesis, 256 pp.

Henderson, G. 1976: Petroleum geology. In Escher, A. & Watt, W.S. (eds) Geology of Greenland, 488–505. Geological Survey of Greenland, Copenhagen.

Holm, P.M., Hald, N. & Nielsen, T.F.D. 1992, Contrasts in composition and evolution of Tertiary CFBs between West and East Greenland and their reltions to the establishment of the Icelandic mantle plume. In Storey, B.C., Alabaster, T. & Pankhurst, R.J. (eds) Magmatism and the causes of continental break-up. Geological Society Special Publication, London 68, 349–362.

Johannessen, P. & Nielsen, L.H. 1982: Aflejringer fra flettede floder, Atane Formation, Øvre Kridt, Pingo, Øst Disko. Dansk Geologisk Forening Årsskrift 1981, 13–27.

Kristensen, L. & Dam, G. 1997: Lithological and petrophysical evaluation of the GRO#3 well, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/136.

Larsen, H.C., Saunders, A.D., Clift, P.D. & Party 1994: Ocean Drilling Program, College Station, Texas, 977 pp.

Larsen, J.G. & Pulvertaft, T.C.R. 2000: The structure of the Cretaceous-Paleogene sedimentary-volcanic area of Svartenhuk Halvø, central West Greenland. Geology of Greenland Survey Bulletin 188, 40 pp.

Lawver, L.A. & Müller, R.D. 1994: Iceland hotspot track. Geology 22, 311–314.

Marty, B., Upton, B.G.J. & Ellam, R.M. 1998: Helium isotopes in early Tertiary basalts, northeast Greenland: Evidence for 58 Ma plume activity in the North Atlantic-Iceland volcanic province. Geology 26, 407–410.

Midtgaard, H.H. 1991: Vertikal og regional facies fordeling i delta cykler fra Atane Formationen, Øvre Kridt, Vestgrønland – et tidsmæssigt perspektiv. Unpublished M.Sc. thesis, University of Copenhagen.

Midtgaard, H. 1996a: Inner-shelf to lower-shoreface hummocky sandstone bodies with evidence for geostrophic influenced combined flow, Lower Cretaceous, West Greenland. Journal of Sedimentary Research 66, 343–353.

Midtgaard, H. 1996b: Sedimentology and sequence stratigraphy of coalbearing synrift sediments on Nuussuaq and Upernivik Ø (U. Albian–L. Cenomanian), Central West Greenland. Unpublished Ph.D. thesis, University of Copenhagen.

Nøhr-Hansen, H. & Dam, G. 1997: Palynology and sedimentology across a new marine Cretaceous-Tertiary boundary section on Nuussuaq, West Greenland. Geology, 25, 851–854.

Nøhr-Hansen, H., Dam, G. & Chalmers, J.A. 1999: New evidence for regional pre-volcanic uplift in West Greenland. In Jolley, D. & Bell, B. (eds) The North Atlantic Igneous Province: Magmatic controls on sedimentation. Geological Society, Geological Society, Burlington House, London, U.K. (Abstract)

Nøhr-Hansen, H., Sheldon, E. & Dam, G. In press: Biostratigraphic dating and sedimentary evolution preluding the early Paleocene volcanism in central West Greenland. In Jolley, D. & Bell, B. (eds) The North Atlantic Igneous Province: Stratigraphy, tectonics, volcanic and magmatic processes. Geological Society Special Publications, London.

Olsen, T. 1993: Large fluvial systems: the Atane Formation, a fluvio-deltaic example from the Upper Cretaceous of central West Greenland. Sedimentary Geology 85, 457–473.

Pedersen, A.K. 1985: Lithostratigraphy of the Tertiary Vaigat Formation on Disko, central West Greenland. Rapport Grønlands Geologiske Undersøgelse 124, 30 pp.

Pedersen, A.K. 1993: Geological section along the south coast of Nuussuaq, central West Greenland. Geological Survey of Greenland, Copenhagen.

Pedersen, A.K., Larsen, L.M., Pedersen, G.K. & Dueholm, K.S. 1996: Filling and plugging of a marine basin by volcanic rocks: the Tunoqqu Member of the Lower Tertiary Vaigat Formation on Nuussuaq, central West Greenland. Bulletin Grønlands Geologiske Undersøgelse 171, 5–28.

Pedersen, G.K. & Pulvertaft, T.C.R. 1992: The non-marine Cretaceous of the West Greenland Basin, onshore West Greenland. Cretaceous Research 13, 263–272.

Pulvertaft, T.C.R. 1979: Lower Cretaceous fluvial-deltaic sediments at Kuk, Nûgssuaq, West Greenland. Bulletin of the geological Society of Denmark 28, 57–72.

Pulvertaft, T.C.R. & Chalmers, J.A. 1990: Are there Late Cretaceous unconformities in the onshore outcrops of the West Greenland Basin? Rapport Grønlands Geologiske Undersøgelse 148, 75–82.

Riisager, P. & Abrahamsen, N. 1999: Magnetostratigraphy of

Palaeocene basalts from the Vaigat Formation of West Greenland. Geophysical Journal International 137, 774–782.

Rolle, F. 1985: Late Cretaceous–Tertiary sediments offshore central West Greenland: Lithostratigraphy, sedimentary evolution, and petroleum potential. Canadian Journal of Earth Sciences 22, 1001–1019.

Schaefer, B.F., Parkinson, I.J. & Hawkesworth, C.J. 2000: Deep mantle plume osmium isotope signature from West Greenland Tertiary Picrites. Earth and Planetary Science Letters 175, 105–118.

Schiener, E.J. 1975: Basin study: central West Greenland onshore Cretaceous-Tertiary sediments. IXme Congrès international de Sedimentologie, Vol. 2, Theme 5, 379–385, Nice 1975.

Storey, M., Duncan, R.A., Pedersen, A.K., Larsen, L.M. & Larsen, H.C. 1998: ^{40}Ar/^{39}Ar geochronology of the West Greenland Tertiary volcanic province. Earth and Planetary Science Letters 160, 569–586.

White, N. & Lovell, B. 1997: Measuring the pulse of a plume with the sedimentary record. Nature 387, 888–891.

White, R. & McKenzie, D. 1995: Mantle plumes and flood basalts. Journal of Geophysical Research 100, 17543–17585.