Aspects of the structure on the coast of the West Greenland volcanic province revealed in seismic data

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The coastal structure in central West Greenland is expressed by Palaeogene basalts which show pronounced seaward dip. Traced along strike the tilted basalts occur in two segments, separated by an area in which dips are low. Within these segments the lavas have been displaced by extensional faults with strike parallel to the strike of the lavas and dip and downthrow to the landward side. This structural pattern bears many similarities to regional structural features in volcanic rifted margins in other parts of the world, although in West Greenland the continent-ocean boundary is situated more than 100 km west of the coast. The structure has previously been studied onshore and has now been studied in high-resolution seismic data acquired both west of the coast and in the sounds between the Nuussuaq and Svartenhuk peninsulas. From the offshore data it can be seen that within the sections correlated with mid-Paleocene volcanic rocks onshore, the tilting of the lavas took place almost entirely after eruption, as there is little or no indication of any increase of dip towards the faults or of fan-shaped geometry in cross-section. However, southwest of Ubekendt Ejland and stratigraphically within Early Eocene lavas, dips can be seen to increase with depth in several fault blocks, indicating that tilting was active during eruption of these lavas. It is therefore concluded that tilting of the volcanic rocks in the coastal zone took place largely in the Eocene. This conclusion is corroborated by the following onshore evidence: Firstly, the angle of discordance between seaward-dipping Eocene lavas and the underlying tilted Paleocene lavas is small, where observed at all, so the mid-Paleocene lavas must owe their seaward dip largely to tilting during the Eocene. Secondly, Early Eocene ages have been obtained from sequentially tilted dykes onshore. This tilting and concomitant extensional faulting was contemporaneous with the second phase of seafloor spreading in the Labrador Sea which took place during the Eocene. The first phase of seafloor spreading in this sea took place between magnetochrons 27r and 24r and was not accompanied by significant rifting of lavas in central West Greenland.

It can also be seen from the seismic data that the tilted lavas level out less than 25 km from the coast. West of this, the volcanics generally show very low dips and thin gradually towards the continent-ocean boundary.

Key words: West Greenland, coastal tilting, extensional faulting, Palaeogene basalts.

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In the coastal zone of central West Greenland between 69°45´ and 71°50´N, Palaeogene basalts of the West Greenland volcanic province have been tilted seawards by angles up to 45°, locally even steeper. The tilted lavas are displaced by extensional faults with strike normal to the dip direction of the lavas and downthrow on the landward side (Fig. 4). Seawards, the structure levels out less than 25 km from the coast in a narrow zone of fault blocks with decreasing tilt westwards. Following earlier workers on the similar structure on the coast of the East Greenland volcanic province (Wager & Deer 1938; Nielsen & Brooks 1981), Geoffroy *et al.* (1998) applied the term coastal flexure to the coastal structure of central West Greenland. However, in neither situation is the term appropriate, as the structural pattern in both situations is an expression of extensional tectonics and not an elastic bending of the volcanic piles or the underlying continental crust. Nowadays the southern East Greenland coast is described as a volcanic rifted

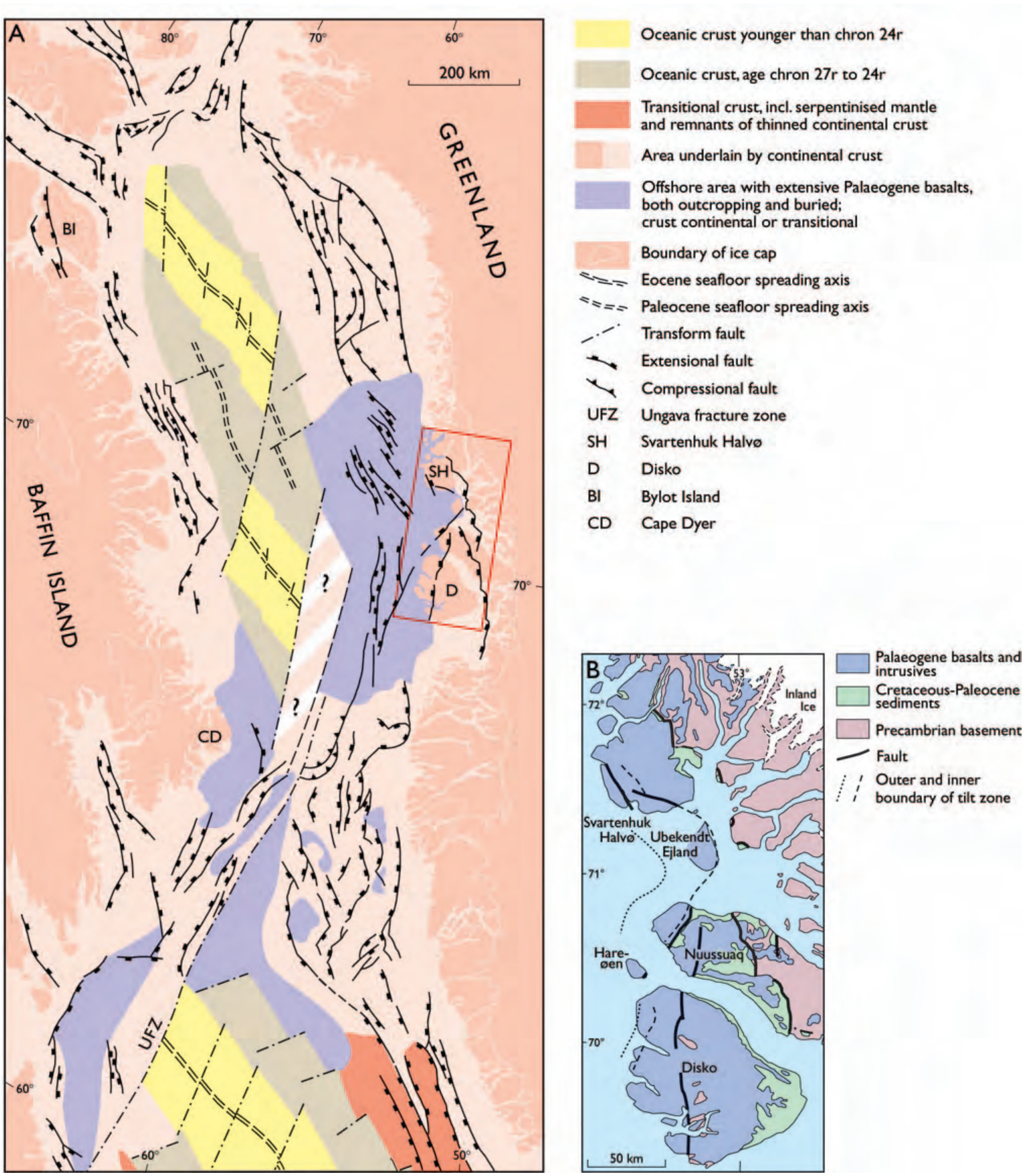

Fig. 1. A) Map of the Labrador Sea-Davis Strait-Baffin Bay region showing the distribution of crustal types and Palaeogene volcanic rocks offshore according to Oakey (2005, p. 212), and main faults. Frame outlines the area shown in (B). B) Simplified map of the Disko–Svartenhuk area, central West Greenland, showing the main structures and the position of the coastal tilt zone.

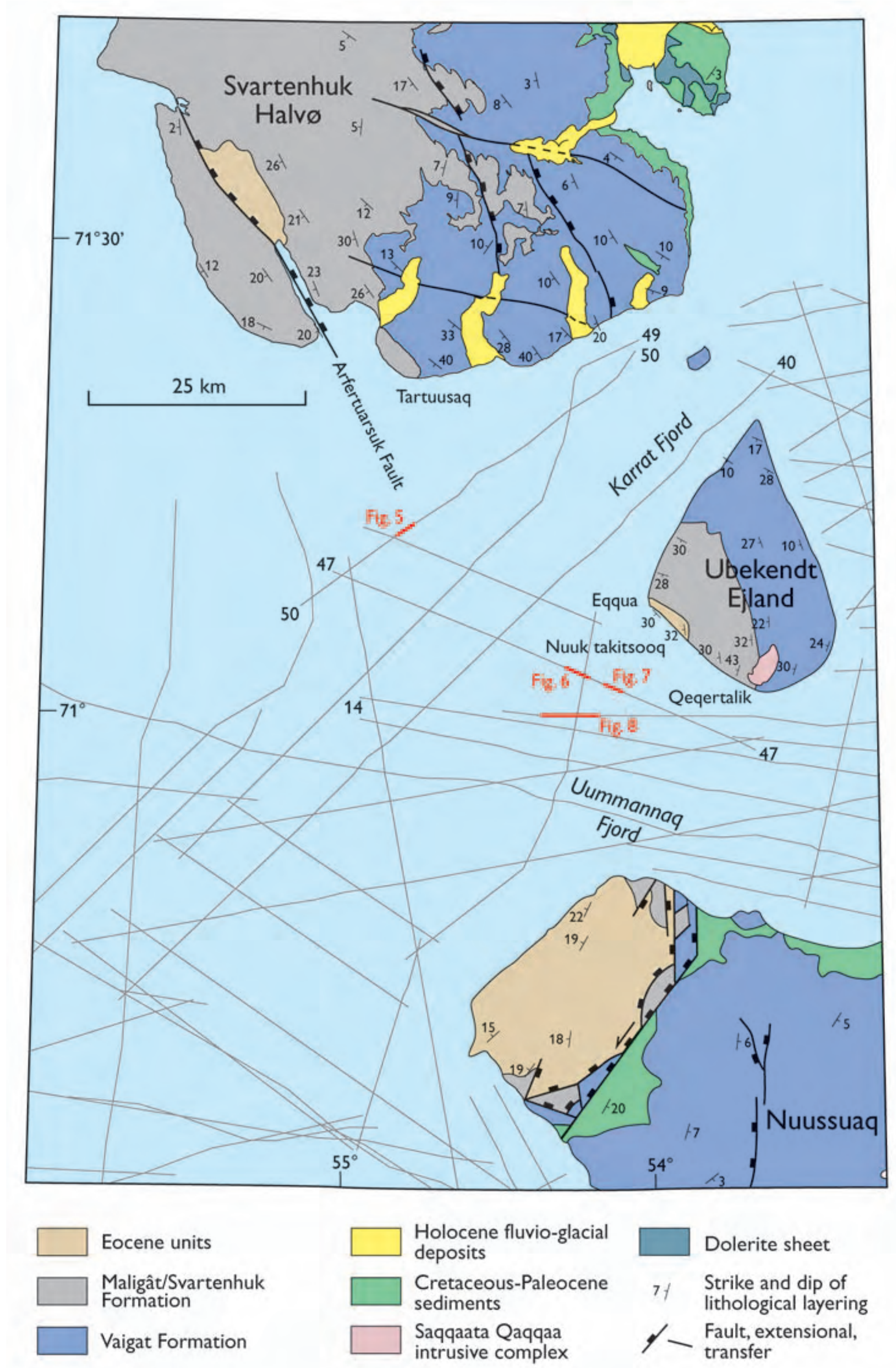

Fig. 2. Map of southern Svartenhuk Halvø, Ubekendt Ejland and northern Nuussuaq, showing the outcrop of the main stratigraphic units and the position of the seismic lines acquired in the area. Note that the authorised spellings of Greenlandic place names have been changed since the stratigraphic units were named.

margin (Karson & Brooks 1999), but this term is not suitable for the West Greenland structure, as continental crust extends more than 100 km to the west of the West Greenland coast (Fig. 1; Chalmers & Pulvertaft 2001; Skaarup 2002). Consequently, the term tilt zone will be applied to the structure on the coast of the West Greenland volcanic province.

Traced laterally the tilt zone consists of two segments, three if northwest Nuussuaq is considered as a separate segment (*cf.* Geoffroy *et al.* 2001). The northern segment has an arcuate course, striking NW–SE in southern Svartenhuk Halvø and northern Ubekendt Ejland, turning to NNE–SSW in southern Ubekendt Ejland and continuing in a SW direction into northwestern Nuussuaq (Figs 1, 2). The southern segment is situated in western Disko; here the trend is N–S. There is no expression of the structure in northernmost Disko or in the sound to the northwest. Seaward dips of the lavas are steepest in southern Svartenhuk Halvø and on Ubekendt Ejland, locally exceeding 45°. Numerous dykes cut the lavas (see e.g. Larsen & Pulvertaft 2000, figs 4, 5). Although many dykes strike parallel to the strike of the dipping lavas, there is no dense coast-parallel swarm such as that in East Greenland.

The timing of the various phases of volcanic eruption, dyke emplacement, and block faulting relative to one another is still being discussed. Geoffroy *et al.* (1998) presented detailed structural evidence suggesting that faulting and dyke intrusion on Disko took place during tilting. They also suggested that eruption of the entire lava succession on Disko was syn-tectonic, and they interpreted the overall structure as a series of syn-volcanic half-grabens that developed along a landward-dipping major listric growth fault (Geoffroy *et al.* 1998, fig. 9; 1999, fig. 5).

Geoffroy *et al.* (1997, 2001) have also examined the structures in the tilted and block-faulted lavas on the south coast of Svartenhuk Halvø. Here, they demonstrated that dykes striking parallel to the axis of tilting were injected vertically during incremental steps of tilting, so that the earliest dykes dip landwards at 90°-minus-tilt of the lavas, while the youngest dykes are approximately vertical. Although Larsen & Pulvertaft (2000) in a regional study showed that the dyke pattern is more complex than Geoffroy *et al.* (2001) indicated, they agree that dykes striking parallel to the axis of tilting can dip landwards at any angle between 90°-minus-lava tilt and 90°. In one area of tilted Vaigat Formation lavas a plot of dyke orientations shows a maximum in 143/74°NE, while the surrounding lavas dip SW at around 27°; this indicates a *c.* 10° tilt of the lavas prior to maximum dyke intrusion (Larsen & Pulvertaft 2000, fig. 5). This early tilting, however, need not have been syn-volcanic with respect to the eruption of the basalt flows.

Because dykes parallel to the coastal tilt zone were injected during its evolution, dating of these dykes provides a way of dating the tilting itself. For this reason Geoffroy *et al.* (2001) submitted samples of five dykes from southern Svartenhuk Halvø for K-Ar age determination, including three with NW–SE trend and landward dips between 66 and 78°. The ages obtained cluster around 54.6±0.6 Ma. This means that "most of the crustal flexuring postdates these ages, that is, is of Eocene age" (Geoffroy *et al.* 2001, p. 579). What Geoffroy *et al.* seem not to have realised is that their Eocene age for "crustal flexuring" contradicts their earlier conclusion that the volcanic section in western Disko is syn-flexuring (Geoffroy *et al.* 1998, 1999). The important fact that was overlooked by Geoffroy *et al.* (1998, 2001) is that the lavas in western Disko that they interpreted as having been extruded syn-tectonically into active half-grabens are of *middle Paleocene* age, i.e. *pre*-Eocene tilting. The uppermost tilted lavas in western Disko include the Nordfjord and Niaqussat Members of the Maligât Formation (Pedersen 1975) which were extruded between 60.7±0.4 and 59.8±0.5 Ma (Fig. 3; Storey *et al.* 1998), i.e. in mid-Paleocene. The lavas that dominate the south coast of Svartenhuk Halvø and the eastern half of Ubekendt Ejland belong to the Vaigat Formation (Figs 2, 4), i.e. are also mid-Paleocene (see next section).

Regarding the structure of the basalt lava succession, Geoffroy *et al.* (2001) state that in the studied profiles the dips of the tilted lavas decrease upwards, and that both in southern Svartenhuk Halvø and on Ubekendt Ejland there are low-angle unconformities in the lavas, all of which open seawards (Geoffroy *et al.* 1997). These features suggest fan-like geometries, with extrusion of the lavas into active half-grabens bounded seawards by landward-dipping extensional faults. However, Geoffroy *et al.* do not illustrate this feature, and not all Geoffroy *et al.*'s observations were corroborated by Larsen & Pulvertaft (2000).

In the following we present examples of seismic data acquired in the sound between Svartenhuk Halvø and Ubekendt Ejland and southwest of Ubekendt Ejland which improve the basis for interpretation of the structural development of the coastal zone. We also present a seismic example showing how the tilted lavas level out under the sea.

Summary of basalt stratigraphy

The extrusive rocks in the West Greenland volcanic province have been divided into a number of forma-

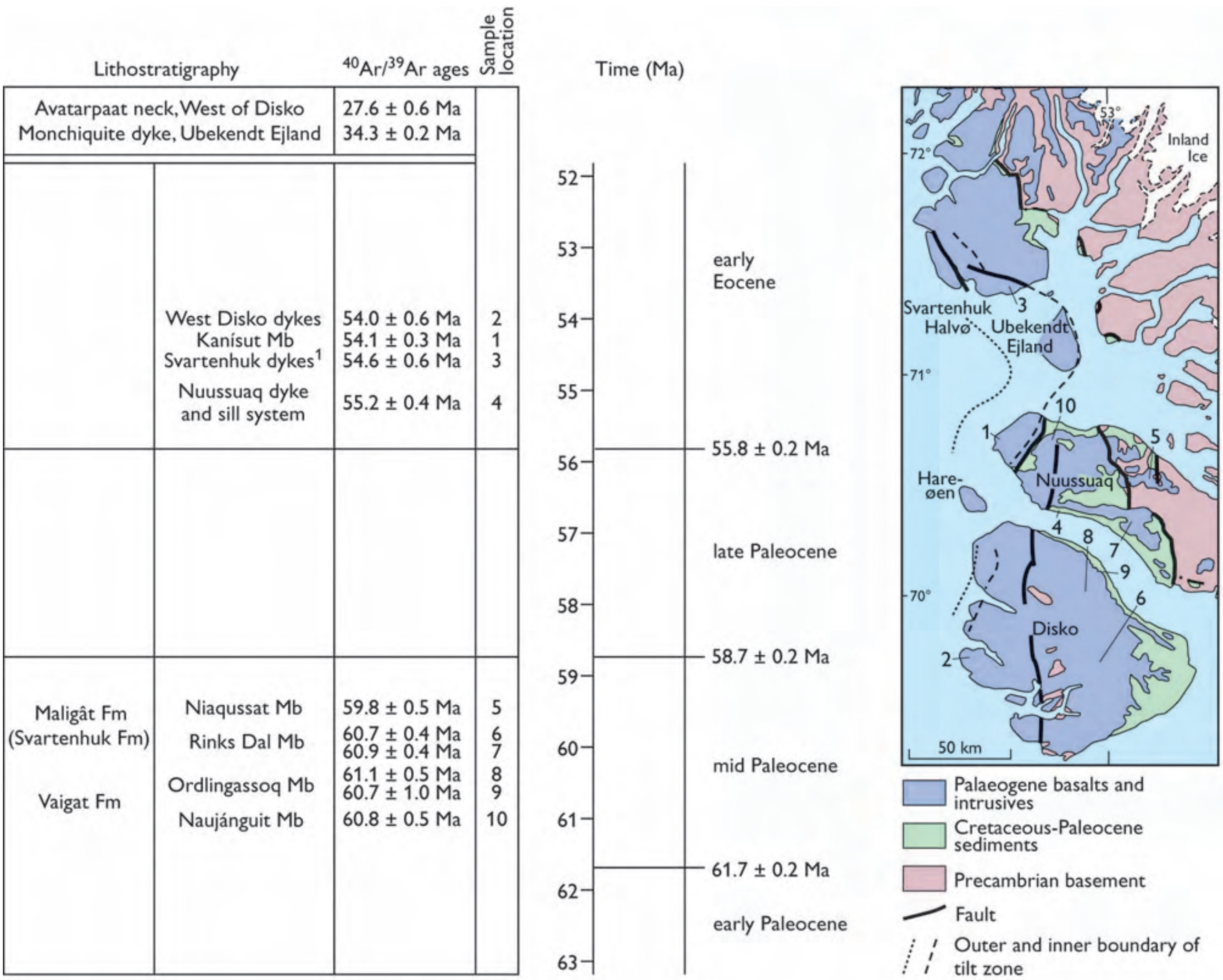

Fig. 3. Lithostratigraphy and $^{40}Ar/^{39}Ar$ ages of the West Greenland volcanic province. From Hald (1977), Pedersen (1985), Geoffroy *et al.* (2001), Storey *et al.* (1998) and Larsen & Pulvertaft (2000). The division of the epochs is from Gradstein *et al.* (2004). Lynne Chambers from NERC is thanked for the corrected $^{40}Ar/^{39}Ar$ ages of the dates published in Storey *et al.* (1998). The new ages are calculated by using the new age for the Fish Canyon Tuff standard (28.03 Ma), whereas the ages published in Storey *et al.* (1998) are calculated from the old age for the standard (27.84 Ma).

tions and members (Fig. 3; Hald & Pedersen 1975; Larsen 1977b; Pedersen 1985). The lowest formation is the *Vaigat Formation*. This consists almost entirely of tholeiitic picrites and olivine-phyric to aphyric magnesian basalts. The lowermost rocks in the formation are hyaloclastic breccias that were erupted in a marine environment; as soon as the basin filled up subaerial conditions were established so that the remainder of the fo0rmation consists mainly of pahoehoe flows. $^{40}Ar/^{39}Ar$ ages obtained from this formation on Disko and Nuussuaq lie between 61.1±0.5 and 60.7±1.0 Ma (Storey *et al.* 1998)[1].

1. The ages quoted here are the ages published by Storey *et al.* corrected using the new age for the Fish Canyon Tuff standard (28.03 Ma); the ages published by Storey *et al.* were calculated using the old age for the standard (27.84 Ma).

The Vaigat Formation is overlain by the *Maligât Formation* which is dominated by tholeiitic plagioclase-porphyritic basalts. Three $^{40}Ar/^{39}Ar$ ages from lavas in this formation lie between 60.9±0.4 and 59.8±0.5 Ma. However, the uppermost unit of the Maligât Formation on Nuussuaq, previously termed the Kanísut 'Member' (Hald 1976), has turned out to be of Eocene age, yielding an $^{40}Ar/^{39}Ar$ age of 54.14 ± 0.29 Ma (Lara Heisler, unpublished data 2001). This uppermost unit consists mainly of plagioclase-porphyritic tholeiitic lavas; acid lavas and tuffs occur in subordinate amounts (Hald 1977). Between the Kanísut 'Member' and the underlying lavas of the Maligât Formation there is a sedimentary unit dominated by a coarse breccia with angular fragments of basalt; in addition there is sandstone, tuff, clay-ironstone and coal. Hald (1973) reported that there is an angular unconformity between these sediments and the underlying lavas, but no discordance is shown in his cross-section (Hald 1973, fig. 3). Dips recorded on the 1:100 000 map sheet (Rosenkrantz *et al.* 1974) indicate that the angle of discordance is not greater than 5°. The lavas of the Kanísut 'Member' cover these sediments concordantly or with only a minor angular unconformity (Hald 1977). Since isotopic dating has shown that the Kanísut 'Member' is more than 5 Ma younger than the remainder of the Maligât Formation, its status as a member of this formation requires revision.

Thick picritic lava successions that can be correlated with the Vaigat Formation make up the entire eastern part of Ubekendt Ejland and continue into the southern and eastern part of Svartenhuk Halvø (Fig. 2; Larsen 1977a; Larsen & Pulvertaft 2000). In both areas the picritic basalts are overlain by units corresponding to the Maligât Formation on Nuussuaq and Disko. However, there is a much greater variety of volcanic rocks in the upper part of the Maligât Formation on Ubekendt Ejland, warranting a division into members. Three members have been distinguished: the Qeqertalik Member (lowest), the Tuperssuartâta kûa Member and the Nûk takisôq Member (Larsen 1977b).

The Qeqertalik Member consists of a thick sequence of mainly olivine-porphyritic and olivine-plagioclase-porphyritic basaltic lavas. The thickness of the member is difficult to assess because of poor outcrop and because of the lack of a well-defined lower border to the Vaigat Formation, but Larsen (1977b) set it to 3–3.5 km. There is an angular unconformity within the lower part of the member.

The Tuperssuartâta kûa Member is a pyroclastic unit with strongly altered tuffs. The member is between 500 and 750 m thick (Larsen 1977b) and overlies the Qeqertalik Member conformably.

The uppermost member of the Maligât Formation on Ubekendt Ejland is the Nûk takisôq Member. This is approximately a kilometre thick and consists of a sequence of plagioclase-phyric basaltic flows, followed by rhyolitic ignimbrites, and at the top plagioclase-phyric and aphyric basaltic lavas (Larsen 1977b). There is a low-angle unconformity between this member and the underlying Tuperssuartâta kûa Member.

The volcanic sequence on Ubekendt Ejland terminates with a 150 m thick series of mildly alkaline basaltic lavas, the Erqua Formation (Larsen 1977b), exposed only at the westernmost corner of Ubekendt Ejland.

Results of a recent $^{40}Ar/^{39}Ar$ dating programme have confirmed the correlation of the picritic lavas in eastern and southernmost Ubekendt Ejland with the Vaigat Formation in its type area and have revealed that the youngest eruptives on the island (the Nûk takisôq Member and the Erqua Formation) are of Early Eocene age, i.e. are approximate correlatives of the Kanísut 'Member' in northwest Nuussuaq (Christian Tegner, personal communication 2005).

The stratigraphy of the volcanic rocks on Svartenhuk peninsula is broadly similar to that on Disko and Nuussuaq (Larsen & Pulvertaft 2000). There is the same two-fold division into a lower formation, the Vaigat Formation, dominated by greyish-weathering picrites, and an upper formation, here named the Svartenhuk Formation, dominated by brownish-weathering, plagioclase-porphyritic or aphyric tholeiitic basalts. In the uppermost part of the Svartenhuk Formation there is a conspicuous anorthosite-porphyritic trachyte, the Arfertuarsuk trachyte (Larsen & Pulvertaft 2000, p. 15, Plate 1). This has recently been dated and shown to be of earliest Eocene age (L.M. Larsen, personal communication 2006). This means that the uppermost lavas of the Svartenhuk Formation are of Early Eocene age and are approximately equivalent to the Kanísut 'Member' of the Maligât Formation on Nuussuaq.

Structure of the onshore area

The seismic survey carried out in 2000 in central West Greenland waters included several lines in the sounds between the Nuussuaq and Svartenhuk peninsulas and Ubekendt Ejland (Fig. 2). Since the interpretation of these lines draws on knowledge of the adjacent onshore areas, a short summary of the structure of these areas is provided in the following.

Nuussuaq

The Nuussuaq peninsula is divided into three main blocks by two major faults (Fig. 1). The eastern block consists of Precambrian basement overlain in part by virtually horizontal Paleocene basalts belonging to the Maligât Formation. In the central block faulted and tilted early Campanian and older sediments are overlain unconformably by horizontal or gently dipping middle–late Campanian–middle Paleocene sediments that are overlain in turn by hyaloclastites and lavas of the Vaigat and Maligât Formations. The Cretaceous sediments have been downfaulted against the Precambrian basement to the east by the Cretaceous Boundary Fault (Chalmers *et al.* 1999).

The northwestern block is separated from the central block by the Itilli Fault. This fault strikes 37°.

Fig. 4. View of part of the south coast of Svartenhuk Halvø, 3.5 km east of Tartuusaq, showing lavas dipping southwest (oceanwards) cut by dykes and faults dipping northeast. The height of the mountain on the right is 544 m (Larsen & Pulvertaft 2000, frontispiece).

The general displacement of the Itilli fault is a downthrow to the northwest, but there is also a small component of left-lateral displacement (Chalmers *et al.* 1999, p. 203). The northwestern block is dominated by lavas of the Maligât Formation including the Early Eocene Kanísut 'Member'. Structurally the northwestern block differs strongly from the central and eastern blocks in that the lavas in the northwest, including those of the Kanísut 'Member', dip WNW at angles between 12 and 24°. Furthermore, locally the tilted lavas in the northwestern block are disrupted by a set of extensional faults with dip and downthrow to the east (Hald 1973, fig. 3). As already described, there is an angular unconformity of maximum 5° between the Kanísut 'Member', including the underlying sediments, and the lavas below of the Maligât Formation.

Ubekendt Ejland

The eastern and southernmost part of Ubekendt Ejland consists of thick sequences of picrites, mainly pahoehoe flows, olivine-phyric and aphyric basaltic lavas and hyaloclastites belonging to the Vaigat Formation (Larsen 1977a). The lavas dip in a general westerly direction at angles between 10 and 44°, in the south locally up to 60°; the strike swings from NW–SE in the north through N–S to NNE–SSW in the south (Larsen 1983).

Overlying the Vaigat Formation is the Maligât Formation covering most of the southwestern part of the island (Fig. 2). As already described, the formation is divided into three parts; the Qeqertalik Member (lowest), the Tuperssuartâta kûa Member and the Nûk takisôq Member.

The Qeqertalik Member shows the same swing in strike as the Vaigat Formation, from NW–SE on the northwest coast to N–S or NNE–SSW on the southwest coast; dips are to the southwest or west at angles between 30 and 44°.

The eruptive rocks of the Nûk takisôq Member strike between 141° on the northwest coast and 172° on the southwest coast and dip between 26 and 32° to the west (Larsen 1983).

The volcanic sequence on Ubekendt Ejland terminates with the Erqua Formation (Larsen 1977b), exposed only at the westernmost corner of Ubekendt Ejland. The Erqua Formation basalts strike 135° and dip 30° to the southwest (Stefan Bernstein, personal communication 2005).

Svartenhuk Halvø

The structure of the Svartenhuk peninsula has been described by Larsen & Pulvertaft (2000). The structural style changes dramatically from southeast to northwest across the peninsula, the change taking place at a number of *c.* E–W/ESE–WNW transfer faults. In the southern part of the peninsula the basalts dip SW at angles between 20 and 40° and are displaced by a number of NW–SE-trending faults with downthrow to NE (see Fig. 4 and Larsen & Pulvertaft 2000, frontispiece, for illustrations). The largest of these faults is the Arfertuarsuk fault in the southwest which has a downthrow of at least 2 km at its southeastern end. The overall structure of southern Svartenhuk can be interpreted as a complex rollover into the Arfertuarsuk fault (Geoffroy *et al.* 1999, 2001; Larsen & Pulvertaft 2000). In contrast, in the north, dips in the basalts are generally less than 10° to SW, except close to narrow NW–SE-trending flexure zones or near faults.

No angular unconformities have yet been recorded in the uppermost lavas of the Svartenhuk Formation. Dips in the Arfertuarsuk trachyte and overlying Eocene lavas are mostly between 15 and 20° to the southwest, but locally exceed 30° approaching the Arfertuarsuk fault (Larsen & Grocott 1992).

Structure as seen in seismic data

Seismic data acquired in 2000 in the sounds between southern Svartenhuk Halvø and Nuussuaq provide an important supplement to onshore observations on the structure of the central West Greenland coastal tilt zone (GEUS00 survey). A few lines traversing the same area were acquired in 1995; part of one of these is shown in Figure 8.

The GEUS00 survey was carried out using a relatively short streamer (96-groups, 594 m long), because experience gained during seismic acquisition in 1995 in the same waters had shown that use of a long streamer (e.g. 3000 m) is likely to be impeded by the large numbers of icebergs often present here. Use of a shorter streamer in these waters greatly increases the flexibility of the operation. Although use of a short streamer makes it impossible to remove seabed multiples by traditional methods (e.g. F/K filtering), experience from earlier surveys had shown that there is little to be gained by using a 3000 m streamer in these waters, given the strength of the multiples generated by the hard, glaciated seabed. Furthermore, where water depths exceed 300 m, it is possible to see more than 900 m of the basalt section before the first seabed multiple obscures deeper reflections. With these considerations in mind, it was decided to accept the limitations of a short streamer and use high-resolution seismic equipment with a considerably smaller source but better resolution than conventional maritime seismic equipment. Technical details concerning acquisition and processing can be found in Marcussen *et al.* (2002).

Four of the GEUS00 lines were selected for study in the present project. The positions of these lines are shown in Figure 2. All four lines run approximately normal to the strike of the tilted lavas onshore, with the exception of a portion of line GEUS00-49 where the seismic vessel had to be diverted to avoid a concentration of icebergs. The GEUS00 lines selected for study were GEUS00-40, -47, -49 and -50. Line GEUS00-14 was inspected, but it did not seem that this line contributes information that could not be seen better on the other four lines. One line from an earlier survey, GGU/95-19, was also studied; this line provides a good example of how the tilting dies out seawards.

All five lines show distinct dipping reflectors. The approximate dips in the direction of the line were calculated using an interval velocity of 4.5 km/sec for the <1500 m of basalt section above the first seabed multiple. (The seismic data indicate no lateral differences in overburden, thus a homogeneous distribution of the velocity of the volcanic rocks is assumed.) The figures obtained were mostly between 20 and 35°, with occasional values over 40° (all dips calculated from seismic lines are apparent dips in the direction of the line of section). These figures are within the same range as the dips recorded in the tilted lavas on Ubekendt Ejland and Svartenhuk Halvø (Larsen 1983; Larsen & Pulvertaft 2000), indicating that the reflections seen on the seismic sections represent reflections from genuine layer boundaries in the basalts. The most unequivocal information regarding syn- contra post-volcanic tilting is to be found on two lines – GEUS00-47 and -50.

There are no age determinations of any of the offshore volcanic rocks in the area, thus the offshore

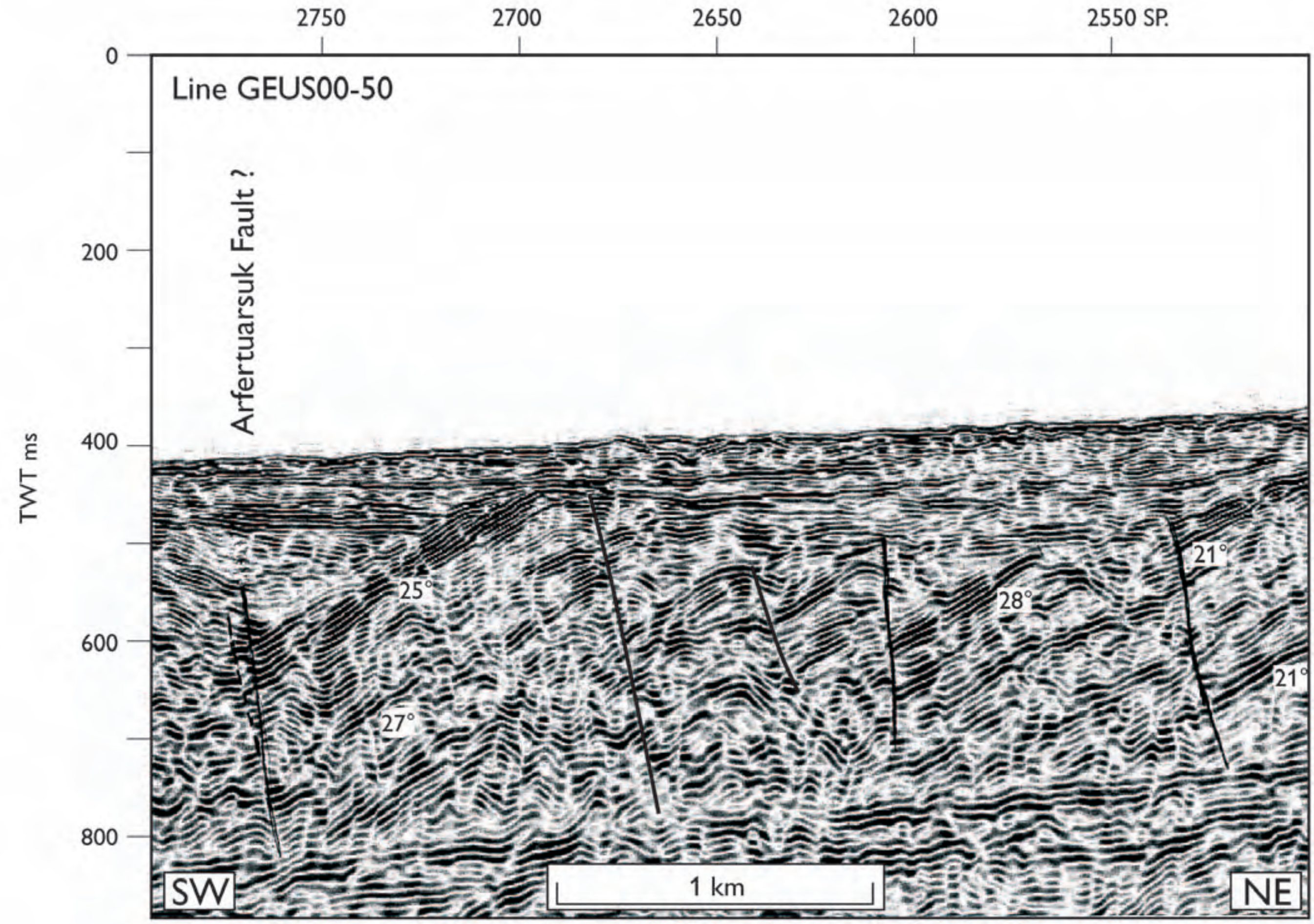

Fig. 5. Part of seismic line GEUS00-50 (striking 54°) in the sound between Svartenhuk Halvø and Ubekendt Ejland, central West Greenland. For location see Fig. 2. At s.p. 2530 two groups of dipping reflections can be seen both dipping 21°, at s.p. 2575 an upper group can be seen dipping 28°, and at s.p. 2740 two groups can be seen where the upper group dips 25° and the lower group dips 27°. Note the anticlines at s.p. 2645 and s.p. 2580, both at *c.* 530 ms depth; these could be an expression of the late compression that gave rise to inversion in northwest Svartenhuk Halvø (Larsen & Pulvertaft 2000, p. 22).

volcanic rocks can only be tentatively correlated with the onshore volcanic formations. Due to the rather long distances between the seismic lines and the coasts of Svartenhuk Halvø and Ubekendt Ejland respectively, the correlation is rather uncertain.

Line GEUS00-50 trends *c.* 54° off southern Svartenhuk Halvø (Fig. 2). This is almost at right angles to the strike of the lavas and faults along the south coast of the peninsula, so the volcanic rocks along this coast may be used for correlation of the seismic line. On this coast the Vaigat Formation strikes between 130° and 150° and dips 28 to 42° to the southwest (Fig. 2). The overlying Svartenhuk Formation is at least 2800 m thick and strikes between 146° and 160° with dips between 13° and 26° to the southwest. It is assumed that both formations extend to the area crossed by this seismic line, and that the reflectors seen in the portion of line GEUS00-50 shown in Figure 5 are from lavas of the Paleocene Svartenhuk Formation.

On Figure 5 it can be seen that packets with dipping reflectors underlie flat-lying reflectors that presumably arise from glacial and post-glacial sediments. The maximum thickness of the dipping packets seen on this figure is 350 ms (*c.* 790 m) before the seabed multiple destroys the seismic image.

Between s.p. 2490 and 2540 there are two groups of reflections coming from depths of *c.* 500 ms and 650 ms respectively that dip 21° SW (Fig. 5). These reflections appear to be cut off to the southwest by a NE-dipping fault that reaches the sub-Quaternary surface at s.p. 2545. As seen on Figure 2, this part of the section is due south of Tartuusaq on the south coast of Svartenhuk Halvø. (Note that in the following the positions given for faults all refer to where the fault reaches the sub-Quaternary surface).

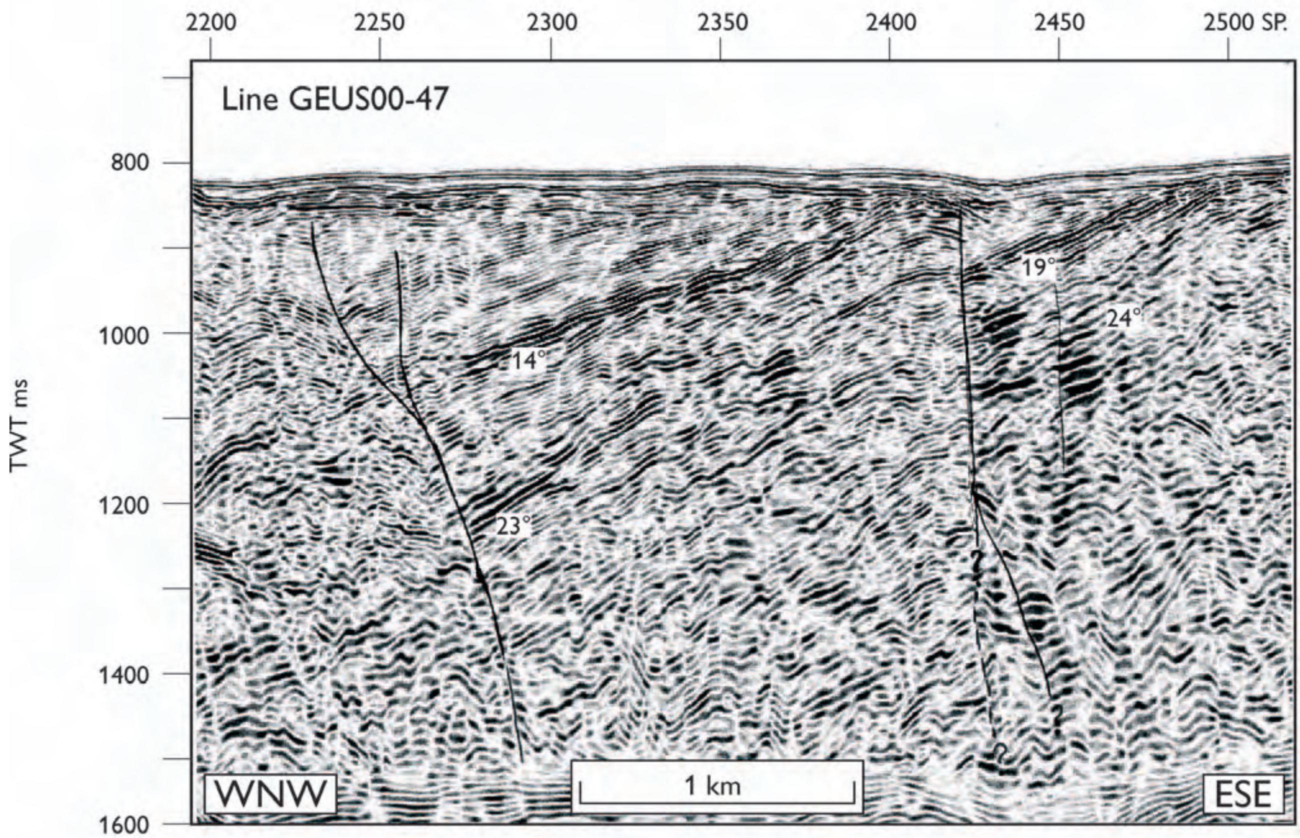

Fig. 6. Part of seismic line GEUS00-47 (striking 113°), s.p. 2200–2500, in the sound between Ubekendt Ejland and Nuussuaq, central West Greenland. For location see Fig. 2. At s.p. 2280 two groups of dipping reflections can be seen, where the upper dips 14° and the lower 23°. At s.p. 2450 two groups of dipping reflections can be seen, the upper group dipping 19° and the lower dipping 24°.

A very steep NE-dipping fault is interpreted at s.p. 2610. Reflectors at a depth of *c.* 550 ms dip into this at 28°.

Between s.p. 2700 and s.p. 2770 there are distinct sets of reflectors dipping 25° (upper set) and 27° (lower set). These terminate southwestwards at a NE-dipping fault at s.p. 2770.

Indications of compression can occasionally be seen in the seismic data, for example between s.p. 2610 and s.p. 2660 on line GEUS00-50. This is scarcely surprising, considering that Larsen & Pulvertaft (2000, p. 22) have documented a striking example of inversion along the Cretaceous Boundary Fault in northwest Svartenhuk Halvø.

Summarising: in two fault blocks there are no indications of steepening of the dips of the reflectors with depth, while in the southwesternmost fault block shown in Figure 5 there is a mere 2° increase in dip within *c.* 325 m of the basalt section. Faulting and tilting of the presumably mid-Paleocene basalt lavas shown in Figure 5 appears to have taken place almost entirely after the eruption of the basalts.

Line GEUS00-47 strikes WNW–ESE (113°) off the southwest coast of Ubekendt Ejland (Fig. 2). For this line the volcanic rocks seen on the southwestern coast of Ubekendt Ejland (Fig. 2) are the most likely correlatives of the volcanic rocks seen on the seismic data. Passing southeastwards along the coast from Eqqua the units encountered are the Erqua Formation and the Nûk takisôq Member of the Maligât Formation, both of Early Eocene age (Christian Tegner, personal communication 2005), and Tuperssuartâta kûa and Qeqertalik Members of the Maligât Formation. Neither of the latter has been dated, but it is assumed that they are correlatives of the lower, mid-Paleocene members of the Maligât Formation on Nuussuaq and Disko. The uppermost unit, the Erqua Formation, strikes 135° and dips 30° to the southwest. The Nûk takisôq Member strikes 141–172° and dips 30–32° to the west-southwest, the Tuperssuartâta kûa Member strikes 162–170° and dips 22 to 32°, locally 50°, to the west, while the strike of the lavas in the Qeqertalik Member swings from 156° through N–S to 29° at the southern end of the island, the dips

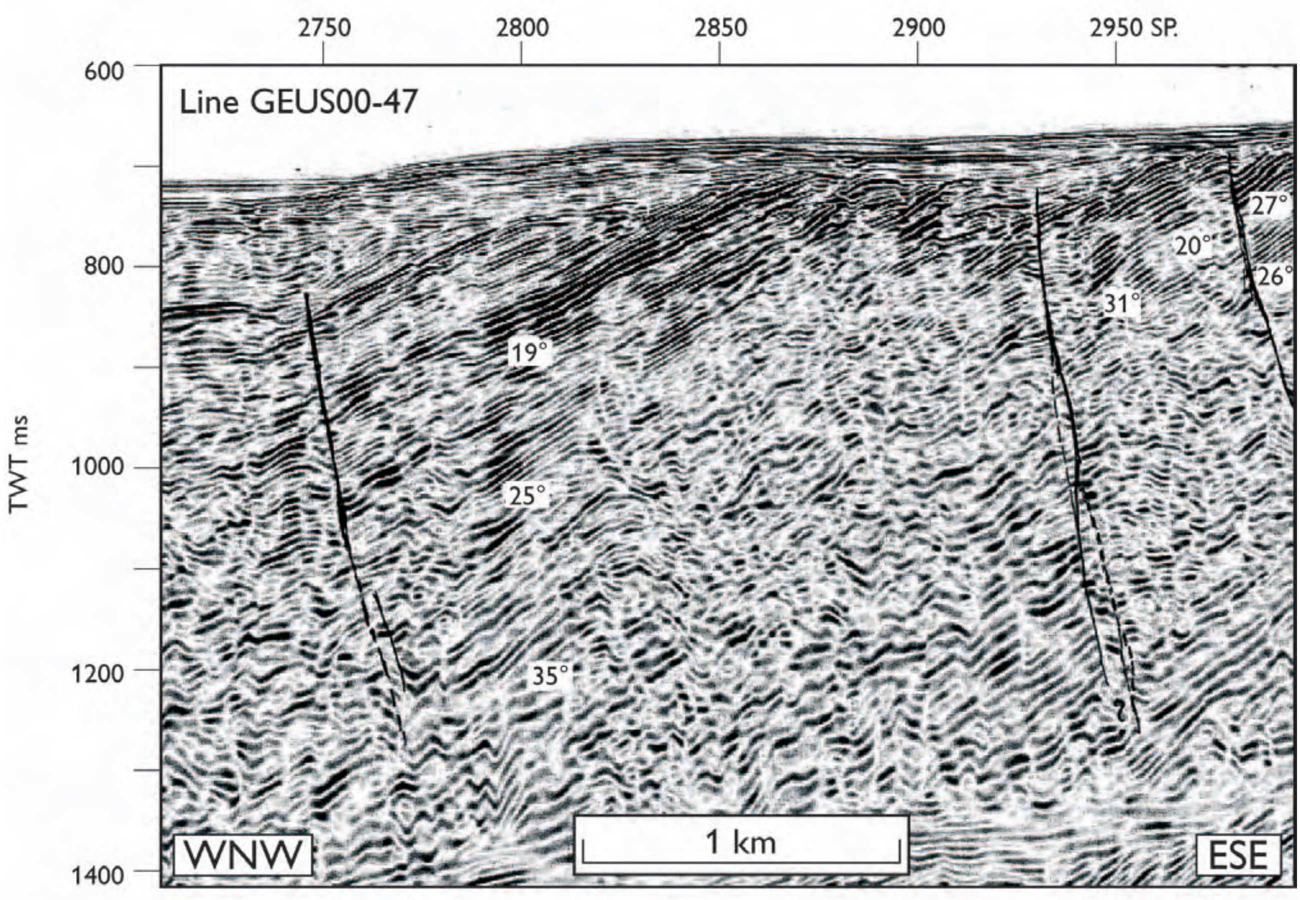

Fig. 7. Part of seismic line GEUS00-47 (striking 113°), s.p. 2700–3000, in the sound between Ubekendt Ejland and Nuussuaq, central West Greenland. For location see Fig. 2. At s.p. 2800 three groups of dipping reflections can be seen, where the upper dips 19°, the middle 25° and the lower group 35°. Between s.p. 2970 and 2940 there appears to be a down-dip steepening of the reflectors, from a dip of 20° at s.p. 2970 to a dip of 31° at s.p. 2945.

to the west being from 30 to 44° (Larsen 1983). Allowing for the swing in strike, the most likely units to be seen in the seismic examples shown (Figs 6, 7) are the Erqua Formation and whatever overlies it, and the uppermost members of the Maligât Formation. Again allowing for the swing in strike, the general westerly dip of the units should be visible on the seismic data, as indeed it is.

In the central fault block shown in Figure 6, between s.p. 2250 and 2300, there are two groups of dipping reflectors, at depths of *c.* 1000 ms and 1200 ms, which dip 14° and 23° respectively. In the fault block to the east, between s.p. 2425 and 2480, two groups of dipping reflectors can be seen at depths of 930 and 1030 ms; the upper group dips 19° and the lower group 24°.

In the main fault block shown in Figure 7, between s.p. 2780 and 2830, three groups of reflectors can be recognised. The upper group dips 19°, the middle group dips 25°, and the lower group dips 35°. In the narrower fault block to the east, between s.p. 2970 and 2940, there appears to be a down-dip steepening of reflectors, from 20° at s.p. 2970 to 31° at s.p. 2945.

Summarising, examples of increasing dip of reflectors with depth can be seen in a number of tilted fault blocks shown in the parts of line GEUS00-47 illustrated in Figures 6 and 7. This suggests activity on the faults and increasing tilting of the lavas during eruption.

GGU/95-19 : The example selected to show how the tilting dies out seawards is from line 19 from the 1995 survey (Fig. 8). This line runs approximately E–W, south of Ubekendt Ejland. The reflector pattern in the eastern part of the line resembles somewhat that seen in line GEUS00-47 (Figs 6, 7), and probably stems from the same units in the volcanic succession. East of a steep fault system at s.p. 2650 reflectors immediately below the Quaternary deposits dip into the fault at 20°, while a little lower down the dip is 24°. Two eastward-dipping faults are interpreted at s.p.

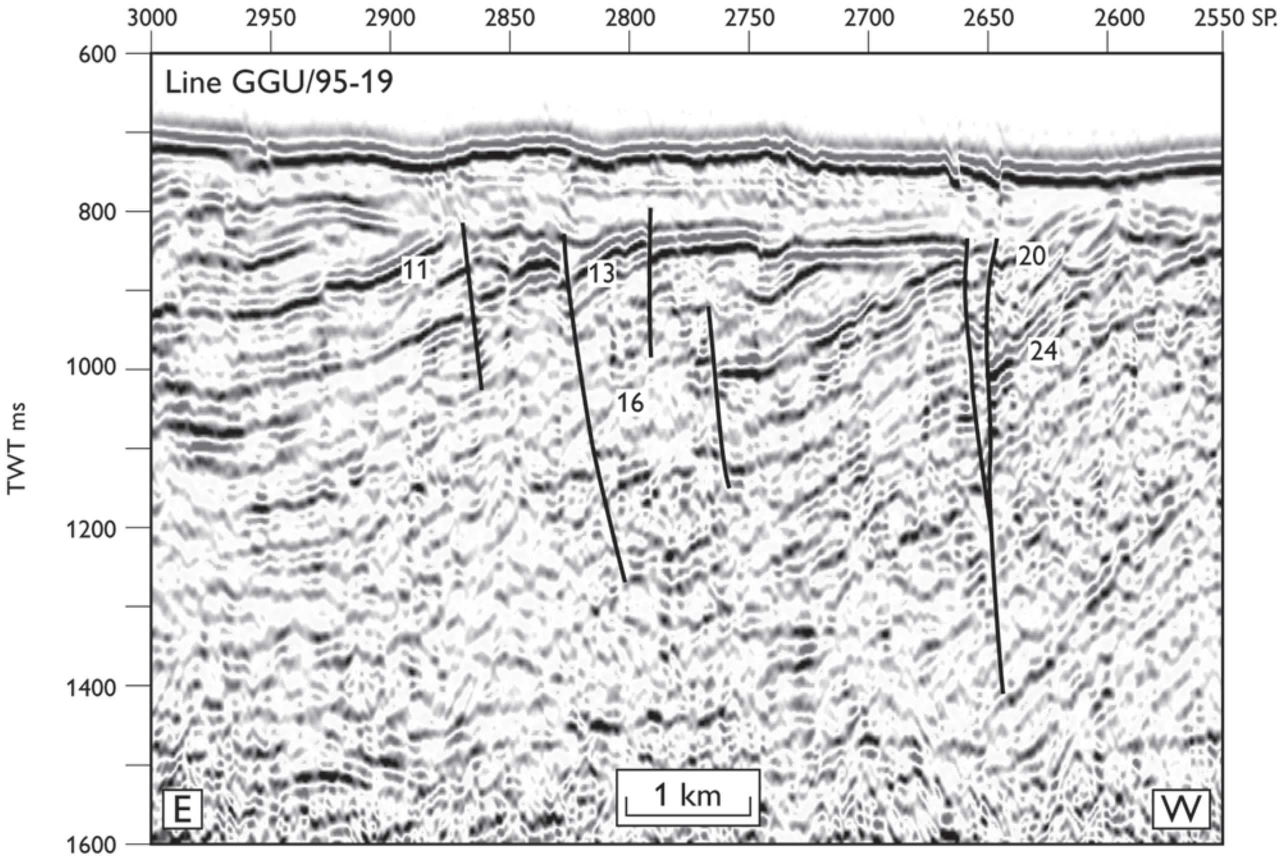

Fig. 8. Part of seismic line GGU/95-19 (striking E–W), s.p. 2550–3000, southwest of Ubekendt Ejland. For location see Fig. 2. Numbers indicate dip of the seismic reflectors. The line provides an example of how the central West Greenland coastal flexure dies out abruptly on its seaward side. See text for further comments.

2830 and 2870 respectively. East of the fault at s.p. 2830 reflectors show an apparent dip into the fault at *c.* 13° immediately below the Quaternary deposits, steepening to *c.* 16° at depth. These examples of steepening of dip with depth indicates active tilting during eruption of the lavas, although not as marked as seen in the examples from line GEUS00-47. However, west of the fault at s.p. 2870 reflectors dip *c.* 11° to the west and level out to horizontal at s.p. 2960. Apparent dip of the reflectors continues to be very low beyond s.p. 3000 as far as the western end of the line.

Discussion

From their studies of the coastal structure onshore, Geoffroy *et al.* (1998, 1999, 2001) proposed not only syn-tectonic dyke injection but also the eruption of all but the earliest lavas into actively subsiding half-grabens bounded seawards by landward-dipping extensional faults. Two of the features that were reported in support of this interpretation were that the dips of the tilted lavas decrease upwards, and the occurrence of low-angle unconformities in the lavas, all opening seawards.

These features cannot be seen in the seismic profile south of Svartenhuk Halvø (Fig. 5). There are no or almost no indications of syn-volcanic movements in the presumably Svartenhuk Formation lavas seen in this profile. The dipping packages are tilted blocks of more or less parallel-bedded lavas and not fan-shaped sequences opening seawards.

On the other hand, southwest of Ubekendt Ejland, in parts of the section on lines GEUS00-47 and GGU/95-19 (Figs 6, 7, 8) progressive tilting of the lavas during eruption is indeed indicated. As already pointed out, the progressively tilted successions seen in the seismic examples shown (Figs 6, 7, 8) most likely belong to be the Erqua Formation and whatever overlies it, and the uppermost members of the Maligât Formation – the Nûk takisôq and Tupersuartâta kûa Members. The Erqua Formation and the

Nûk takisôq Member have been dated at Early Eocene (Christian Tegner, personal communication 2005). The uppermost unit in the Maligât Formation exposed onshore Nuussuaq is the Kanísut 'Member'; both this unit and the uppermost lavas on Svartenhuk Halvø are also Early Eocene in age (Lara Heisler, unpublished data 2001; L.M. Larsen, personal communication 2006). All these Eocene units onshore show dips up to 32° in directions between WNW and SW. The angles of unconformity observed onshore between these Eocene units and the underlying, dipping mid-Paleocene lavas are at most 5°, proving that the greater part of the tilting of all the lavas in the exposed part of the West Greenland coastal tilt zone took place during or after the Eocene. It is therefore completely consistent to suggest that the syn-tectonic lavas seen in the seismic examples shown in Figures 6, 7 and 8 are Eocene and that most of the tilt in the West Greenland coastal region is a syn-volcanic feature that developed during the later, Eocene, phase of volcanism in the region. Note, however, that up to 5° of the tilting on the Kanísut 'Member' in northwest Nuussuaq may well be the result of Neogene uplift of the peninsula (Japsen *et al.* 2006).

Geoffroy *et al.* (1998) suggested not only that dyke injection in western Disko took place during tilting, but also that the eruption of lavas there was syn-tectonic. The lavas in western Disko are of mid-Paleocene age (Storey *et al.* 1998). However, the dykes that have been dated from Disko are of another chemical composition than the lavas (Pedersen 1977) and have yielded an Early Eocene age (Fig. 3; Storey *et al.* 1998). Syn-volcanic dykes of the same chemical composition as the lavas have not yet been dated. Thus it cannot be argued that because the dykes are syn-tectonic, the lavas must also be syn-tectonic.

In 2001 Geoffroy *et al.* suggested the same development on Svartenhuk Halvø as on Disko, and hoped to verify their interpretation with age measurements of syn-tectonic, tilted dykes cutting the Vaigat Formation on the southeastern coast of the peninsula. The ages obtained for the dykes are clearly Early Eocene, 54.6±0.6 Ma, while, as already pointed out, the Vaigat Formation is mid-Paleocene in age (Fig. 3; Storey *et al.* 1998). These results provided no support for the interpretation of the Vaigat Formation or lower part of the Svartenhuk Formation lavas as syn-tilting and as having been erupted into actively developing half-grabens. On the contrary, accepting that the dykes dated were injected vertically during incremental steps of tilting means that tilting took place in the Eocene. Eruption of the *Paleocene* lavas was therefore pre-tectonic with respect to tilting, which is also the conclusion drawn from both the relations exposed onshore and the seismic data.

Origin of the tilt zone

The structure along the south coast of Svartenhuk Halvø has been interpreted by both Geoffroy *et al.* 1998, fig. 9; 1999, fig. 5; 2001, p. 575) and Larsen & Pulvertaft (2000, p. 25) as a roll-over into a major, NE-dipping, listric fault, the Arfertuarsuk Fault. Offshore it can be seen from seismic data that a transition from relatively steeply dipping lavas to gently dipping lavas takes place in a narrow zone of tilted fault blocks (Fig. 8), usually with dips within the blocks dimishing westwards. Since no detail can be seen in the seismic data below the first seabed multiple, it is not known if the final fault to the west is a major listric fault or just another domino fault.

The western margin of the southern segment of the tilt zone lies onshore or close to the coast offshore. In western Disko lavas the transition from lavas dipping west at 27° to lavas dipping west at only 5–10° takes place under a kilometre-wide coastal plain devoid of outcrops. Farther south, basalts dipping 37° west outcrop less than a kilometre from the coast, while seismic data offshore show gently dipping lavas to within 10 km of the coast, indicating that here also the levelling-out of the tilted lavas takes places abruptly.

It is at present not clear what fundamental processes governed the localisation of the zone of tilting and extensional faulting. It may be significant that the tilt zone is confined to the area where the thickest sections of Palaeogene basalts meet the coast; there is no suggestion of similar tilting along the remainder of the West Greenland coast where the Precambrian basement meets the sea. The tilt zone consists of separate segments. Seawards it levels out less than 25 km from the coast, which is still at least 100 km inland of the continent-ocean boundary.

According to Menzies *et al.* (2002, p. 3), lithospheric thinning is an uncontested requirement for volcanic rifted margin formation. In the Disko–Svartenhuk region of West Greenland the only indications of lithospheric thickness are based on modelling of gravity data. This modelling suggests that the continental crust in central West Greenland thins in two steps, from *c.* 35 km east of 54°W to 25 km at the coast (Chalmers 1998) and from *c.* 22 km at the landward limit of the seismic lines west of Disko to 10.5 km about 37 km west of the coast (Skaarup 2002). Neither zone of thinning coincides closely with the position of the zone of tilting, but it does seem that thinning has taken place under the central West Greenland volcanic province. However, much of this thinning is likely to have taken places during Late Cretaceous and Early Paleocene rifting, so it is unknown how much influence it can have had on the development of the coastal tilt zone. Another factor that can have played a part in West Greenland is the presence of thick sediments under the volcanic cover (Whittaker 1996; Skaarup 2002). This could provide a suitable location for detachment at the base of one or more major listric faults.

Comparison with other 'flexures'

The central West Greenland coastal zone does not seem to present an onshore analogue of seaward-dipping reflectors in maritime areas (*cf.* Geoffroy *et al.* 1998). In the first place the setting is intracontinental, far from the continent-ocean boundary. In the second place tilting is much stronger than anything recorded in seaward-dipping reflector sequences offshore, with dips exceeding 45° in places.

Hitherto the only other coastal structure with which the West Greenland 'flexure' has been compared is the East Greenland 'flexure' (Geoffroy *et al.* 1998, 2001). Features in common with the East Greenland coastal zone are degree of tilting, disruption by landward-dipping extensional faults, and syn-tilting, sequential intrusion of coast-parallel dykes (Nielsen & Brooks 1981; Karson & Brooks 1999; Klausen & Larsen 2002). Differences include density of the dyke swarm parallel to the axis of tilting, and in particular the setting of the West Greenland and East Greenland structures. The East Greenland tilt zone is situated at the margin of the continental crust, the intense dyke swarm marking the transition to oceanic crust, while the West Greenland coastal zone of tilting is an intracontinental feature, far from the continent-ocean boundary which lies more than 100 km to the west (Fig. 1; Chalmers & Pulvertaft 2001; Skaarup 2002).

More obvious comparisons to draw are with the Panvel 'flexure' on the west coast of India (Dessai & Bertrand 1995; Sheth 1998) and, possibly, the Lembobo monocline at the eastern edge of the Kaapvaal craton in southern Africa (du Toit 1929; Eales *et al.* 1984; Watkeys 2002).

In the Panvel flexure Deccan Trap lavas start to dip seawards, i.e. to the west, along an axis lying about 30 km inland from the coast. Seaward dips increase gradually westwards to 25°, locally 40°, at the coast. The tilted lavas are cut by faults with strike parallel to the axis of tilting and dip and downthrow to the east. Offshore, seismic surveys and drilling for oil have revealed that the Deccan volcanics on the shelf thin westwards and are interrupted by NNW–SSE-trending horsts of Precambrian basement. The continent-ocean boundary is shown by Sheth (1998, p. 144) to lie 100–180 km west of the coast. Thus, like the West Greenland tilt zone, the Panvel 'flexure' is an intracontinental feature. Sheth (1998, p. 146) believed that the formation of the structure "requires" control by a major, landward-dipping listric fault, the flexure being a roll-over into this fault.

From the description of du Toit (1929) it would appear that, in spite of its relatively short course and segmented nature, the central West Greenland coastal structure has much in common with the Lembobo monocline in southeast Africa. This monocline fringes the eastern edge of the Kaapvaal craton. The rocks in the structure are basalts and rhyolites belonging to the Karoo Province (Jurassic). These are cut by numerous basic and acid dykes running approximately parallel to the axis of the monocline; many of these are believed to have been feeders to the Karoo lava flows. In the west the eruptive rocks have low dips. Passing eastwards the dips increase to more than 30°, locally exceeding 60°, to the east before levelling out to less than 5° as the volcanics pass under the Cretaceous and younger sediments of the Mozambique lowlands. The dykes show dips to the west at angles between vertical and 65° (du Toit 1929; Eales *et al.* 1984, p. 14). The fact that the dykes are seldom vertical and intersect the lavas at angles as low as 60° led du Toit (1929, p. 209) and Bristow (1982, p. 176) to conclude that the Lembobo monocline came into being during eruption of the lavas.

The Lembobo monocline is cut by faults with strike parallel to the axis of the structure and dip and downthrow to the west, but displacement on individual faults is believed to be small.

Whether the fundamental cause of the formation of the central West Greenland and Lembobo 'flexures' could be the same depends on the crustal situation of the Lembobo monocline. Today it lies up to 400 kilometres from the coast from which it is separated by the Mozambique lowlands. What underlies the Cretaceous–Cenozoic sediments in this lowland area is not known. "It might be oceanic ...., it might be stretched pre-existing continental crust, or it might represent a mixture of the two" (Cox 1992, p. 144). Watkeys (2002, p. 41) states that it is probably continental, but highly extended. According to Watkeys (2002), extension of the crust here took place before the opening of the Indian Ocean and South Atlantic.

Conclusion

Seismic data indicate that the older basalt formations in the central West Greenland coastal zone of tilting were erupted prior to the main episode of faulting and tilting. These formations are between 61.6 Ma and 59.3 Ma old, i.e. are mid-Paleocene in age. Where fan-shaped geometry indicating eruption into active half-grabens can be seen in dipping reflectors, the lavas involved are almost certainly of Eocene age. This is consistent with the ages obtained on tilted dykes that were injected vertically during incremental steps of tilting. All these dykes yielded Eocene ages (Geoffroy *et al.* 2001), showing that the main phase of tilting of lavas in coastal central West Greenland took place during the Eocene.

The central West Greenland coastal tilt zone dies out seawards within 25 km from the coast; in most places dips level out within a <5 km wide zone of fault blocks. This is far from the continent-ocean boundary which lies more than 100 km west of the coast.

Events in the coastal area of central West Greenland during the Palaeogene can be expected to be related in some way to the opening of the Labrador Sea and Davis Strait. In the Labrador Sea, seafloor spreading started during magnetochron 27r (late Danian) and took place in a NE–SW direction (Chalmers & Pulvertaft 2001; Oakey 2005) until magnetochron 24r (Early Eocene). At this time the spreading direction changed to NNE–SSW (Srivastava 1978; Chalmers & Pulvertaft 2001; Oakey 2005; Fig. 1) and continued in this direction until approximately the end of the Eocene when spreading died out. Onshore central West Greenland the first phase of volcanism took place at the time seafloor spreading started in the Labrador Sea, and the second phase started when spreading changed direction in this region. It appears from the results presented in this paper that while there was some tectonic activity onshore central West Greenland during the first phase of Palaeogene volcanism in the region, the main extension and tilting seen in the region took place contemporaneously with the second phase of seafloor spreading in the Labrador Sea.

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References

Bristow, J.W. 1982: Geology and structure of the Karoo volcanic and sedimentary rocks of the northern and central Lembobo. Transactions of the Geological Soceity of South Africa 85, 167–178.

Chalmers, J.A. 1998: Gravity models in the Disko-Nuussuaq area of central West Greenland. Danmarks og Grønlands Geologiske Undersøgelse 1998/21, 32 pp. plus 23 figures.

Chalmers, J.A. & Pulvertaft, T.C.R. 2001: Development of the continental margins of the Labrador Sea: a review. In: Wilson, R.C.L., Whitmarsh, R.B., Taylor, B & Froitzheim, N. (eds): Non-volcanic rifting of continental margins: a comparison of evidence from land and sea. Geological Society, London, Special Publication 187, 77–105.

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.

Cox, K.G. 1992: Karoo igneous activity, and the early stages of the break-up of Gondwanaland. In: Storey, B.C., Alabaster, T. & Pankurst, R.J. (eds): Magmatism and the causes of continental break-up. Geological Society, London, Special Publication 68, 137–148.

Desai, A.G. & Bertrand, H. 1995: The "Panvel Flexure" along the western Indian continental margin: an extensional fault structure related to Deccan magmatism. Tectonophysics 241, 165–178.

Du Toit, A.L. 1929; The volcanic belt of the Lembobo – a region of tension. Transactions of the Royal Society of South Africa 18, 189–218.

Eales, H.V., Marsh, J.S. & Cox, K.G. 1984: The Karoo igneous province: an introduction. In: Erlank, A.J. (ed.): Petrogenesis of the volcanic rocks of the Karroo Province. Geological Society of South Africa, Special Publication 13, 1–26.

Geoffroy, L., Gélard, J.-P. & Angelier, J. 1997: The structure and origin of flexured volcanic margins: some key field-observations in the Svartenhuk/Ubekendt-Ejland area (NW Greenland). Terra Nova 9, Abstract Symposium No.1, 525 only.

Geoffroy, L., Gélard, J.P., Lepvrier, C. & Olivier, P. 1998: The coastal flexure of Disko (West Greenland), onshore expression of the 'oblique reflectors'. Journal of the Geological Society, London, 155, 463–473.

Geoffroy, L., Skuse, A.G., Angelier, J. Gélard, J.P., Lepvrier, C. & Olivier, P. 1999: Reply in discussion on the coastal flexure of Disko (West Greenland), onshore expression of the 'oblique reflectors'. Journal of the Geological Society, London, 156, 1052–1055.

Geoffroy, L., Callot, J.-P., Scaillet, S., Skuce, A.[G.], Gélard, J.P., Ravilly, M., Angelier, J., Bonin, B., Cayet, C., Perrot, K. & Lepvrier, C. 2001: Southeast Baffin volcanic margin and the North American-Greenland plate separation. Tectonics 20, 566–584.

Gradstein, F.M., Ogg, J.G. & Smith, A.G. 2004: A geological time scale. Cambridge University Press.

Hald, N. 1973: Preliminary results of the mapping of the Tertiary basalts in western Greenland. Rapport Grønlands Geologiske Undersøgelse 53, 11–19.

Hald, N. 1976: Early Tertiary flood basalts from Hareøen and western Nûgssuaq, West Greenland. Bulletin Grønlands Geologiske Undersøgelse 120, 36 pp.

Hald, N. 1977: Lithostratigraphy of the Maligât and Hareøen Formations, West Greenland Basalt Group, on Hareøen and western Nûgssuaq. Rapport Grønlands Geologiske Undersøgelse 79, 9–16.

Hald, N. & Pedersen, A.K. 1975: Lithostratigraphy of the Early Tertiary volcanic rocks of central West Greenland. Rapport Grønlands Geologiske Undersøgelse 69, 17–24.

Japsen, P., Bonow, J.M., Green, P.F., Chalmers, J.A. & Lidmar-Bergström, K. 2006: Elevated, passive continental margins: Long-term highs or Neogene uplifts? New evidence from West Greenland. Earth and Planetary Science Letters 248, 315–324.

Karson, J.A. & Brooks, C.K. 1999: Structural and magmatic segmentation of the Tertiary East Greenland volcanic rifted margin. In: MacNiocaill, C. & Ryan, P.D. (eds): Continental tectonics. Geological Society, London, Special Publication 164, 313–338.

Klausen, M.B. & Larsen, H.C. 2002: East Greenland coast-parallel dyke swarm and its role in continental breakup. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J. & Baker, J. (eds): Volcanic rifted margins. Geological Society of America, Special Paper 362, 133–158.

Larsen, J.G. 1977a: Fieldwork on Ubekendt Ejland in the Tertiary basalt province of West Greenland in 1971 and 1973. Rapport Grønlands Geologiske Undersøgelse 79, 35–44.

Larsen, J.G. 1977b: Transition from low potassium olivine tholeiites to alkali basalts on Ubekendt Ejland. The Tertiary volcanic province of West Greenland. Meddelelser om Grønland 200(1), 42 pp.

Larsen, J.G. 1983: Geological map of Greenland, 1:100 000, Igdlorssuit 71 V.1 syd. Copenhagen: Geolocical Survey of Greenland.

Larsen, J.G. & Grocott, J. 1992: Geological map of Greenland, 1:100 000, Svartenhuk 71 V.1 nord. Copenhagen: Geological Survey of Greenland.

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

Marcussen, C., Skaarup, N. & Chalmers, J.A. 2002: EFP Project NuussuaqSeis 2000 – final report. Structure and hydrocarbon potential of the Nuussuaq Basin: acquisition and interpretation of high-resolution multichannel seismic data. Geological Survey of Denmark and Greenland, Report 2002/33, 63 pp., 6 enclosures.

Menzies, M.A., Klemperer, S.L., Ebinger, C.J. & Baker, J. 2002: Characteristics of volcanic rifted margins. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J. & Baker, J. (eds): Volcanic rifted margins. Geological Society of America, Special Paper 362, 1–14.

Nielsen, T.F.D. & Brooks, C.K. 1981: The East Greenland continental margin: an examination of the coastal flexure. Journal of the Geological Society, London, 138, 559–568.

Oakey, G.N. 2005: Cenozoic evolution and lithosphere dynamics of the Baffin Bay – Nares Strait region of Arctic Canada and Greenland. Unpublished doctorate thesis, Vrije Universiteit Amsterdam, 233 pp.

Pedersen, A.K. 1975: New mapping in northwestern Disko 1972. Rapport Grønlands Geologiske Undersøgelse 69, 25–32.

Pedersen, A.K. 1977: Dyke intrusions along the south coast of Disko. Rapport Grønlands Geologiske Undersøgelse 81, 57–67

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

Rosenkrantz, A, Münther, V. & Henderson, G. 1974: Geological map of Greenland, 1:100 000, Agatdal 70 V.1 nord. Copenhagen: Geological Survey of Greenland.

Skaarup, N. 2002: Evidence for continental crust in the offshore Palaeogene volcanic province, central West Greenland. Geology of Greenland, Survey Bulletin 191, 97–102.

Sheth, H.C. 1998: A reappraisal of the coastal Panvel flexure, Deccan Traps, as a listric-fault-controlled reverse drag structure. Tectonophysics 294, 143–149.

Srivastava, S.P. 1978: Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic. Geophysical Journal of the Royal Astronomical Society 52, 313–357.

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.

Wager, L.R. & Deer, W.A. 1938: A dyke swarm and crustal flexure in East Greenland. Geological Magazine 75, 49–56.

Watkeys, M.K. 2002: Development of the Lembobo rifted volcanic margin of southeast Africa. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J. & Baker, J. (eds): Volcanic rifted margins. Geological Society of America, Special Paper 362, 27–46.

Whittaker, R.C. 1996: A preliminary seismic interpretation of an area with extensive Tertiary basalts offshore central West Greenland. Bulletin Grønlands Geologiske Undersøgelse 172, 28–31.