Basin development and the Cretaceous boundary fault system

Most of the faulting seen on Svartenhuk Halvø took place after eruption of the Svartenhuk Formation lavas. However, the Cretaceous boundary fault system has a much longer and more complex history, as have also the faults on Itsaku.

Unlike the younger faults on Svartenhuk Halvø, the Cretaceous boundary fault system has an irregular course across the peninsula, just as it has in its continuation to the south-south-east (Fig. 1; Chalmers *et al.* 1998, 1999). Nothing is known about its course in the Innerit area north-west of Umiiarfik fjord. South-east of Umiiarfik the fault system runs south-east along the Simiuttap Kuua valley. In the inner part of this valley the fault turns abruptly to slightly north of east before turning again to follow a north–south valley until reaching the Qorlortup Kuua valley where it strikes NW–SE. In the outer part of the Qorlortup Kuua valley the position of the fault system is speculative because of the very extensive cover of fluvio-glacial sediments. It appears to split into four branches. One branch strikes approximately E–W and runs into the bay Kangiusap Imaa; this marks the northern boundary of outcrops of Cretaceous sediments and is the boundary fault proper. Two branches cross Itsaku, and another branch runs in 147° into Umiiviup Kangerlua. Not only do fluvio-glacial deposits conceal the fault system here but also extensive dolerite sheets (Siuteqqut intrusions) obscure the faults in this area. Cross-sections across the Cretaceous boundary fault system are shown in Plate 1.

Rifting in the Cretaceous basin probably started in Albian or earlier time (Chalmers *et al.* 1998, 1999), but it is not known whether the boundary fault system on Svartenhuk Halvø was initiated at this time or later. The Upper Albian – Lower Cenomanian deltaic deposits on the north side of Itsaku could be syn-rift sediments deposited by deltas prograding parallel to the boundary fault, but they could also represent part of a pre-rift delta complex that extended over the area north of the fault.

The Turonian – lower Campanian marine mudstones and distal turbidites were deposited in a completely different environment, far from fluvial influence. At this time the depositional area almost certainly extended north-east of the fault zone (see p. 10), and it is suggested that these sediments were deposited during a marine transgression that accompanied a phase of thermal subsidence.

Following Turonian–Campanian marine sedimentation there was a phase of uplift and erosion. If a parallel is drawn to developments on Nuussuaq (Dam & Sønderholm 1994; Dam *et al.* 1998a, 2000), this uplift could have taken place either during the Campanian or Maastrichtian, or perhaps not until early Paleocene. During this phase most if not all Cretaceous sediments were eroded off the basement area to the north-east, while conglomerates and other clastic sediments were deposited in erosional lows in the basin area (Fig. 7). Following this there was renewed uplift and erosion, so that any ?upper Campanian – Maastrichtian and lowermost Paleocene sediments that were present were removed everywhere except in the Itsaku block which must have remained a depressed fault block at this time. During this phase of erosion any surviving outliers of Cretaceous sediments in the basement area were also removed, and there was probably further removal of Upper Cretaceous sediments in the basin area.

In mid-Paleocene time the tectonic regime changed to one of subsidence of the basin area along the boundary fault system. Following erosion of the fault plane, mudstones and very coarse conglomerates were deposited and the foot of the bevelled fault scarp. Subsidence was followed rapidly by the eruption of contaminated and picritic basalts of the Vaigat Formation in a subaqueous environment. While hyaloclastite breccias encroached into the area from the south and south-west, mudstones and siltstones, the time-equivalents of the lower hyaloclastites to the south-west and west, were deposited close to the scarp. As the basin became filled up with basalts and subsidence waned, the basalt pile periodically emerged above water level, so that in the south-east there is an interval of alternating subaerial lavas and hyaloclastite breccias. In due course the hyaloclastites and subaerial lavas overstepped the boundary fault zone to lie directly on the basement to the north-east (Fig. 2). The uppermost basalts of the Vaigat Formation are entirely subaerial, with strongly reduced thicknesses in the north and on Innerit.

Evidence of continued tectonic activity prior to the eruption of the Svartenhuk Formation is provided by

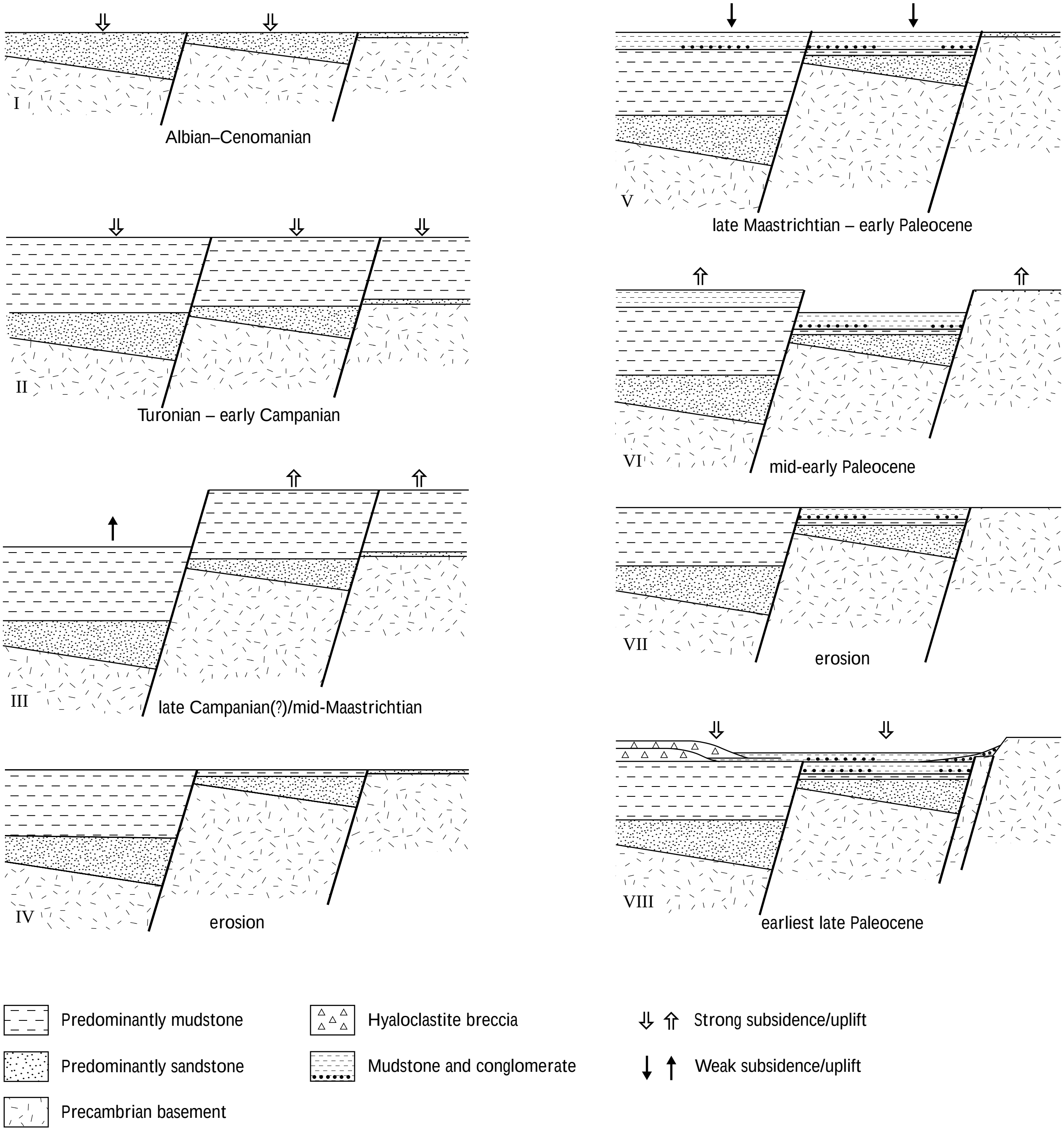

Fig. 7. Diagrammatic representation of the evolution of the Firefjeld–Itsaku area in Late Cretaceous – early Paleocene time.

the angular unconformity locally seen between lavas of the Svartenhuk and Vaigat Formations in the east central part of the peninsula. In the south-west, however, there was no significant break between eruption of Vaigat Formation and Svartenhuk Formation lavas. In contrast, northern Svartenhuk Halvø lay at the fringe of volcanic influence at this time, and here a fluvial plain with lakes developed which straddled the boundary fault and extended some way to the north. The earliest Svartenhuk Formation lavas here flowed into these lakes and developed as hyaloclastite breccias and pillow lava. Stable conditions followed as lavas of the Svartenhuk Formation spread over the basement far to the east and north-east.

The final movement along the Cretaceous boundary fault system on Svartenhuk Halvø took place at some time after the extrusion of the Svartenhuk Formation, and is the best documented; its net effect can

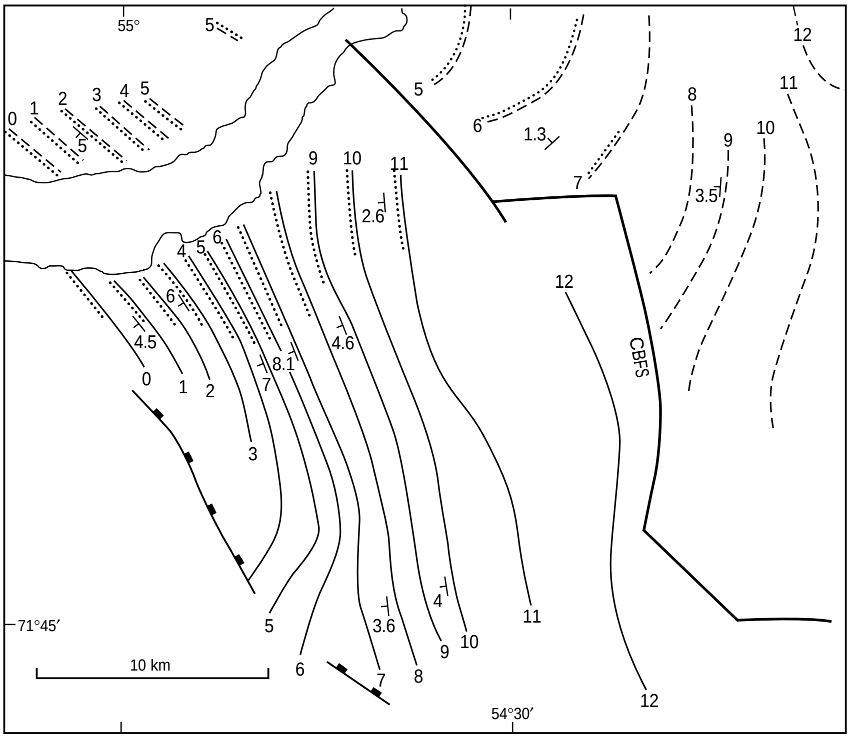

Fig. 8. Structural contour map of the base of Svartenhuk Formation in the north-western part of Svartenhuk Halvø. Contour interval 100 m. Dots along contours indicate where the Svartenhuk Formation overlies intrabasaltic sediments. **CBFS**: Cretaceous boundary fault system.

be seen in the structural contour map of the base of this formation (Fig. 8). This shows uplift of the basin area south-west of the boundary fault relative to the area to the north-east, i.e. *inversion* (cf. Rosenkrantz & Pulvertaft 1969; Münther 1973). Furthermore, the differential post-Svartenhuk Formation displacement increases from 200 m in the east to 600 m in the west (Fig. 8). The outer part of the Innerit area is also depressed relative to the area south-east of Umiiarfik, indicating the presence of a fault along this fjord.

Although evidence of inversion along the northern part of the Cretaceous boundary fault system is unequivocal, no definite signs of inversion have been observed in faults in the basin area. However, the stratigraphic control of complex fault displacements in the flexure zones south of Usuit Kuussuat is poor (see p. 27), and it is here in particular that further evidence for inversion should be sought during future field work in the area. Unfortunately, no information is available that could throw light on the timing and cause of the inversion. Inversion structures have been identified offshore west of Disko and in north-east Baffin Bay. Offshore west Disko open anticlines expressed by the top-basalt surface were attributed by Whittaker (1996) to transpression along a N–S-trending transfer fracture system (see p. 33). In the offshore sedimentary basins in north-east Baffin Bay sediments were folded into anticlines at about the same time as the Eurekan orogeny led to uplift of arches in the Canadian Arctic Islands (Whittaker *et al.* 1997). These examples, however, are far removed from Svartenhuk Halvø and there is as yet no evidence to justify relating inversion on Svartenhuk Halvø to either of them.

The maximum present-day height of hyaloclastite breccias recorded in the basin area is 950 m on Itsaku and 900 m on Firefjeld; these figures provide a measure of the minimum post-Paleocene uplift in this area. In the basement area to the north-east hyaloclastite breccias have been observed in the Svartenhuk Formation up to 1350 m above sea level; if these breccias were extruded in a marine and not a freshwater lake environment, post-Paleocene uplift of this area was at least of this order. This uplift is thought to have taken place in the Neogene (Japsen & Chalmers 2000; Chalmers 2000), although in inner Svartenhuk Halvø of the order of 100 m of the post-Paleocene uplift can be attributed to post-glacial (Holocene) isostatic rebound (Weidick 1976). No satisfactory mechanism has yet been proposed to account for the Neogene uplift that has taken place not only in West Greenland but also all around the North Atlantic (Japsen & Chalmers 2000).

Structures within the basin area

Dips

A striking and significant feature of Svartenhuk Halvø is the way in which it is divided into dip domains with contrasting values of dip (Fig. 9), whereas the strike is consistently between 135° and 155° throughout most of the area. Sailing along the south coast of the peninsula from Ulissat to Kap Cranstown one sees lavas with dips consistently to the south-west at angles up to 40°; these belong to the Tartuusaq dip domain. In contract, along the coast of Umiiarfik which is along strike from the steeply dipping lavas of the south coast, one sees lavas that for the most part dip south-west at angles less than 10°. In the extreme west of the peninsula the lavas are horizontal or dip at very low angles towards both north-east and west. North-east of a line extending roughly from Qooroq to Ulissat dips are generally low, less than 6°, and there are few faults. This line corresponds to the position of a series of flexure zones with offsets at transfer faults (see p. 25). North-east of the boundary fault system the lavas are virtually horizontal, although the contours of the base of the Svartenhuk Formation show a very gentle dip to the west.

As can be seen from the map Fig. 2, the strike of the lavas in the basin area is everywhere parallel or nearly parallel to the extensional faults and 'flexure zones' described in the following sections, the only deviations from the dominant 135–155° strike being westerly dips close to the few N–S extensional faults and anomalous southerly or south-easterly dips in the Vaigat Formation in an area south of Usuit Kuussuat. Thus it can be concluded that the dip of the lavas is due to tilting of fault blocks. It can also be read from Figs 2 and 9 that increase in dip from north-west to south-east takes place mainly at well-defined boundaries between dip domains and not by gradual twisting of the lava pile. The best-defined boundaries are either flexure zones, extensional faults or transfer faults (see p. 29).

Extensional faults

Extensional faults are a prominent feature of the basin area, apart from those parts of the area lying north-east of Qooroq and Qiterlikassak and in the extreme west where only minor faults have been observed. In contrast, Innerit and the basement area to the north-east and east of the Cretaceous boundary fault system have not been affected by faults of any significance (Henderson & Pulvertaft 1987). The most important fault of all in the area is the boundary fault system itself, the complex history of which has already been described.

Extensional faults occur in four main directions. By far the greatest number of faults trend between 145° and 150°. In eastern Svartenhuk Halvø there are several faults trending *c.* 125° and at Kap Cranstown there are extensional faults trending between 100° and 115°, while in the central part of the peninsula a few faults trend N–S. In southern and central Svartenhuk Halvø there are several faults and fractures trending *c.* 100°; these are faults with both lateral and vertical displacements, the latter usually being a downthrow to the north. These are transfer faults and are described in a later section (see p. 29).

Faults trending between 145° and 150° show a distinct concentration in zones; in the areas in between faults are fewer and also show less displacement. Most of these faults show downthrow to the north-east, but their dip is often difficult or impossible to estimate, especially in the case of faults running along valleys. Dips recorded are between 45° and 85° to north-east.

One prominent 145–150° zone extends across the peninsula from the coast of Umiiarfik between Nuuit and Qooroq in the north-west to Saviit in the south-east, with a left-lateral shift on the Qiterlikassak transfer fault (see p. 30). The degree of faulting increases south-eastwards. North and south of the Usuit Kuussuat valley the faults are easily recognised due to displacement of the base of the Svartenhuk Formation. Between Qiterlikassak and Usuit Kuussuat the fault blocks are tilted 13–16° towards south-west (Plate 1). The added vertical displacement of five faults across a 3.7 km wide zone here is *c.* 900 m; the net extension across this zone is not known accurately because of uncertainty concerning the dips of the fault, but must lie between 6 and 12%. Between Usuit Kuussuat and the Saviit–Qinerfik transfer fault (see p. 30) both the fault zone and the spacing between faults are wider, and tilting of fault blocks lessens; the largest vertical displacement recorded on a single fault here is 400 m down to north-east.

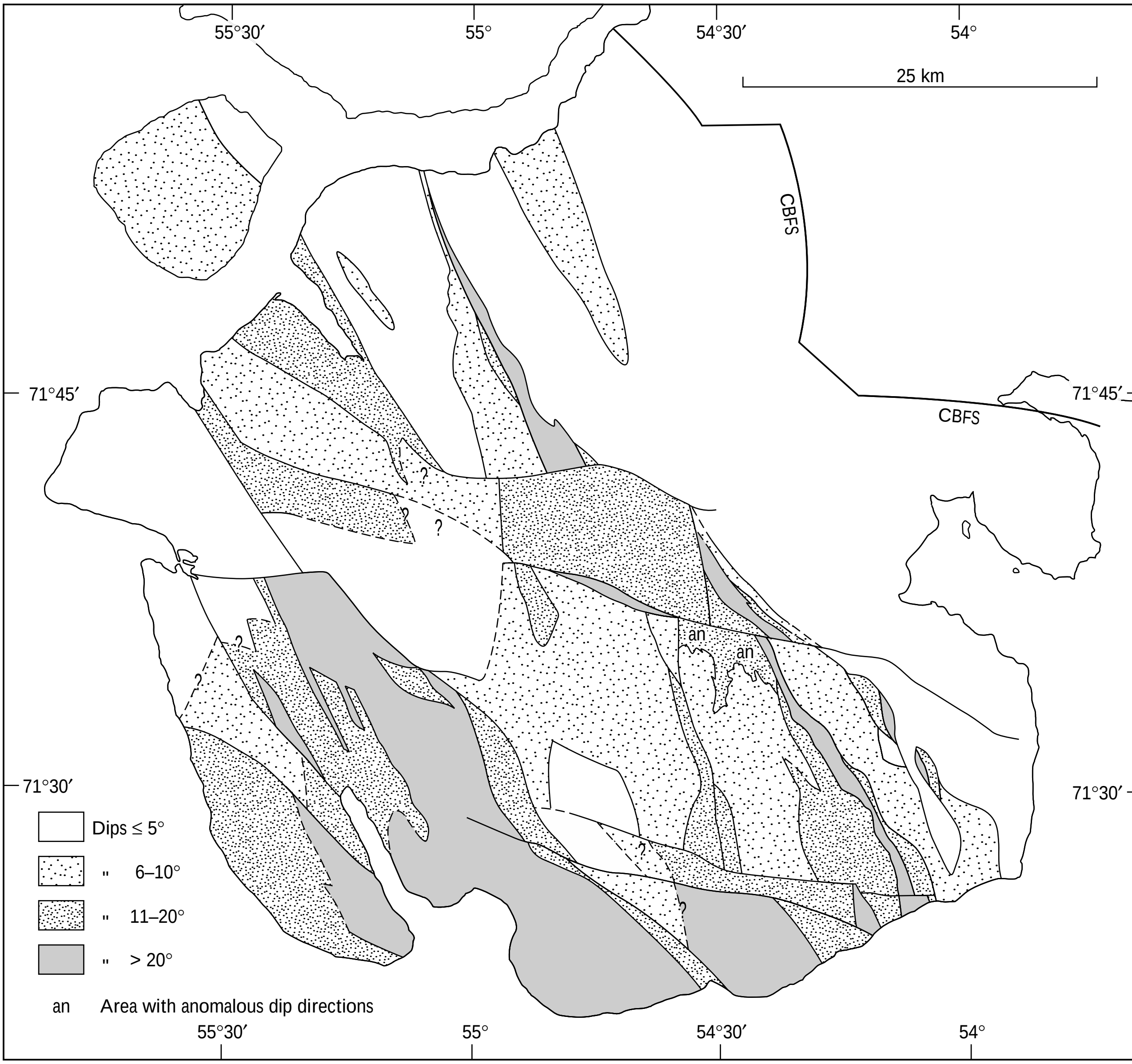

Fig. 9. Map of dip domains on Svartenhuk Halvø. Note that isolated, aberrant dips occur within some of the domains. **CBFS**: Cretaceous boundary fault system.

As has been discussed in an earlier section (p. 14), the apparent thickness of the Vaigat Formation in southern Svartenhuk Halvø is unlikely to be the true thickness. Stratal shingling, extensional faults with downthrow to the north-east, and a combination of these factors, could all account for this exaggerated apparent thickness of the formation. Several NW–SE-trending faults with downthrow to the north-east have been observed in southern Svartenhuk Halvø, but fault displacements can seldom be determined because the lack of distinctive marker horizons in the Vaigat Formation. *If* faults alone account for the excess thickness, the cumulative vertical displacement of these faults would have to be of the order of 4 km, and the cumulative extension *c.* 2 km or *c.* 15%. This question will be taken up in the final section of this paper (see p. 34).

An important fault zone trending between 145° and 150° runs north-westwards from Arfertuarsuk. The fault in Arfertuarsuk fjord itself has the largest displacement of any of the faults in this direction, the reappearance of the Vaigat Formation on the south-west side of the fjord and dip of the lavas requiring a downthrow of more than 2 km on the north-east side of the fault. The displacement of the Arfertuarsuk fault diminishes to the north-west, and the fault terminates at the E–W transfer fault through Svartenhavn. A fault running south-east from Milloofik has a maximum downthrow of 400 m to the north-east.

The overall structure seen between Maligissap Kuua and Tasiusaq can be described as an irregular, faulted roll-over into the Arfertuarsuk fault (Plate 1), assuming that this is a listric fault, and the nearby faults in 145–150° are synthetic faults with regard to this structure. This is also how the Arfertuarsuk fault has been described by Geoffroy *et al.* (1999). Without accurate information on the dip of the Arfertuarsuk fault, one cannot calculate where the fault levels out into a detachment zone, but it is suggested that that the detachment could be at or near the base of the sediments that underlie the basalts.

A suite of faults trending 146° crosses Skalø and continues into the mainland to the south-east. Displacements on the faults in this zone are relatively small, less than 150 m, with one exception that has a downthrow of 225 m to north-east.

Extensional faults trending *c.* 125° occur in eastern Svartenhuk Halvø between Umiiviup Kangerlua and Maniiseqqut. Most of these faults downthrow to the north, the largest downthrow on a single fault being 160 m. These faults were active during eruption of hyaloclastites in the Vaigat Formation, giving rise to the fault scarps already described. Some of these faults are splays at the termination of the strike-slip/transfer fault in the Usuit Kuussuat valley (see p. 31).

The faults at Kap Cranstown with trends between 100° and 115° all have downthrow to the north. The largest of these faults has a vertical displacement of 360 m.

North–south faults have only been recorded in the central part of the peninsula. Downthrows both to the east and to the west have been observed. In the vicinity of these faults the lavas strike N–S, which is abnormal for the area as a whole.

‘Flexure zones’; narrow half-grabens

A number of zones with abnormally steep dips cross Svartenhuk Halvø in directions between 133° and 154°, i.e. approximately parallel to the main extensional faults. Superficially many of these zones resemble monoclines, in that when crossing the zones from north-east to south-west one passes from an area with dips less than 12° to south-west through a zone with much steeper south-westerly dips and back into an area with south-westerly dips lower than 15°. These zones have therefore been referred to as flexure zones, but on closer examination it can be seen that they are really a special type of fault zone. The term ‘flexure zone’ is nevertheless retained to distinguish these zones from other structures in the area. In most cases, unfortunately, the displacement on the faults in the flexure zones is not known due to lack of stratigraphic control, and furthermore the dips of the fault planes are seldom evident and even the dip direction of faults may be uncertain.

The simplest flexure zone and that most resembling a monocline is that at Nuuit. Here, passing south-westwards, the south-westerly dip of the basalts increases abruptly from 3–6° to more than 15°. The change takes place at a nick-point without any apparent faulting. To the south-west one crosses a number of faults with downthrow to the north-east before the dip levels out to less than 10°.

The ‘flexure zone’ in the Qooroq valley is the only one where displacements on some of the related faults are known (Fig. 10a). The increase in south-westerly dip here takes place abruptly at a fault. Where the cross-section has been drawn the flexure zone is *c.* 2 km wide. The net displacement across the flexure zone here is a drop of the south-west side of about 600 m relative to the north-east side. The zone of steep dips, however, is downthrown in relation to both sides of the zone, i.e. the zone is a narrow half-graben. The steeply dipping basalts have been displaced by at least four small faults, each with downthrow to the north-east. While the north-east dips of the minor faults within the graben are distinct, it has not been possible to measure the dip of the major faults, although the impression is that they are steep.

The Qooroq flexure zone is also seen at Oqaasaq where, however, the south-western side of the zone is concealed by fluvio-glacial deposits. At Oqaasaq the net down-to-south-west displacement caused by faulting and flexuring across the zone is estimated to be 550 m. The abrupt steepening of the south-westerly dip of the basalts takes place at a steep fault. This fault is offset 600 m left-laterally at a fault trending almost N–S, with dip and downthrow to the east; a dyke has been emplaced along this fault. Within the flexure zone the basalts dip up to 26° to south-west and have been displaced by numerous faults, each with dip and downthrow to the north-east. Within the wedge between the major NW–SE fault and the *c.* N–S fault the strike of the tilted fault blocks is intermediate between that of the major NW–SE fault and the N–S fault, suggest-

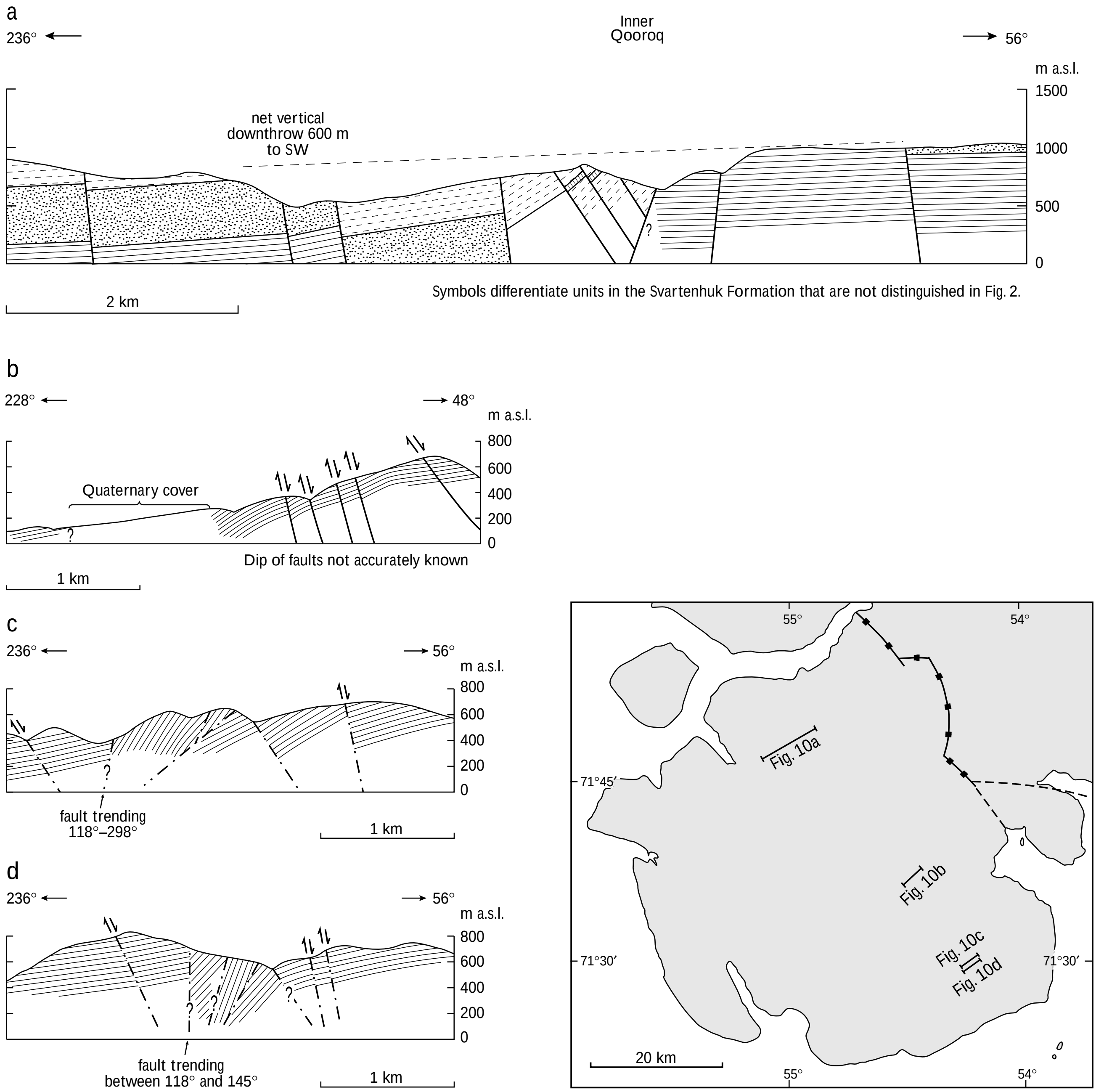

Fig. 10. Cross-sections of 'flexure zones' on Svartenhuk Halvø. **a**: Qooroq; **b**: between Qiterlikassak and Usuit Kuussuat; **c** and **d**: mountains between Usuit Kuussuat and Ulissat. For further explanation, see text.

ing that these two faults were active simultaneously. The transition from steep to gentle south-westerly dips on the south-west side of the zone is not exposed, but it is expected that it takes place at a fault. Close to the expected position of this fault the basalts locally dip 40° towards south-west.

The flexure zone between Qiterlikassak and Usuit Kuussuat has some of the characteristics of a true monocline in that the increase in dip from north-east to south-west starts gradually as a genuine flexure (Fig. 10b). However, as the dip increases, the basalts become displaced and tilted by several small faults with dip and downthrow to the north-east. South-westerly dips as steep as 43° have been recorded in this zone. Unfortunately, as at Oqaasaq, due to poor exposure it cannot be seen how the change from the zone of steep

Fig. 11. South-west margin of flexure zone 10 km south of Usuit Kuussuat, viewed from the south-east. The width of the area shown is *c.* 350 m. For location, see Fig. 2.

dips to the area with lower dips to the south-west takes place.

The most spectacular and complex flexure zone is that running from the Usuit Kuussuat valley to the south coast of Svartenhuk Halvø between Ulissat and Saviit. This zone is entirely within rather monotonous lavas of the Vaigat Formation in which there are very few marker horizons, so rarely can one observe the displacement on the faults in the flexure zone. Furthermore, it has not been possible to demonstrate a net relative down-to-south-west displacement across this flexure zone as could be recorded along the Qooroq–Oqaasaq flexure zone.

Ten kilometres south of Usuit Kuussuat the south-west flank of the flexure zone is well exposed at one locality. This is shown in Fig. 11. The fault itself is vertical or dips steeply to the north-east. Between this fault and the fault to the north-east (right) there is a wedge of near-vertical flows, while the lavas on the north-east side of the faults dip up to 58° to the south-west. It seems that a set of flows outcropping at the top of this wedge has been downthrown about 90 m to the south-west on the vertical fault. Several other extensional faults occur north-east of this and some can be seen in the background in Figs 11 and 12. These faults all dip and have obvious downthrow to the north-

Fig. 12. Panorama of the flexure zone in the mountains between Usuit Kuussuat and Ulissat, seen from the south-east; the cross-section Fig. 10d illustrates the same part of the flexure zone and gives the scale. Note the dyke standing out as a ridge and trending 40° that crosses the flexure zone with small right-lateral offsets at faults. For location, see Fig. 2.

east; the basalts between these faults have been tilted up as much as 48° to the south-west.

Figure 10c and d are cross-sections of the Ulissat – Usuit Kuussuat flexure zone 9.5 km north-west of Ulissat, and Fig. 12 shows the same part of the flexure zone as shown in Fig. 10d. Approaching from the north-east the increase in south-westerly dip starts at an extensional fault with dip and small downthrow to the north-east. Where the dip steepens abruptly, more faults are found. Finally, the dip steepens to more than 45° to south-west and at one locality is steeper than one of the faults. On its south-west side the flexure ends abruptly at a steep oblique fault trending 118°, south-west of which dips in the lavas are much lower than within the flexure zone. A lesser fault with dip and downthrow to the north-east occurs a short distance to the south-west (Fig. 10c, d).

The behaviour of dykes in the Ulissat – Usuit Kuussuat flexure zone is puzzling. One dyke with trend 40° and steep south-easterly dip shows right-lateral offset at four faults in the flexure zone (Fig. 12); the cumulative right-lateral offset is 200 m. In contrast, vertical dykes trending E–W or WNW–ESE show small left-lateral offsets at faults in the flexure zone. Other dykes cross the flexure zone without any offset. As already pointed out, offset of a dyke at a fault as observed on aerial photographs is not proof of fault movement later than dyke emplacement, as dykes often side-step at discordant surfaces; observations made on the ground are needed in this area. It may be significant that within the flexure zones there are only very few dykes parallel to the zones.

On the south coast the Ulissat – Usuit Kuussuat flexure zone is about 2¼ km wide. When viewed from the sea the impression gained is that of increasing south-westwards dip of the basalts taking place stepwise at extensional faults with dip and downthrow to the north-east. However, this impression is an oversimplification because faulting associated with the WNW–ESE-trending Saviit–Qinerfik transfer zone (see p. 30) interferes with the flexure zone here.

Interpretation of the mechanism(s) that gave rise to the flexure zones on Svartenhuk Halvø is hampered by the fact that only limited quantitative information is available concerning displacement and dip of the associated faults. We do know, however, that the Qooroq–Oqaasaq flexure zone is associated with a net relative downthrow of the block to the south-west. We also know that the basalts involved in these structures form a competent layered formation that overlies a substantial thickness of sediments dominated at least in their upper part by incompetent mudstones, and that these sediments lie on a massive, brittle basement. Furthermore, we know from Nuussuaq to the south that extensional faults were established in the basement before eruption of the basalts (Chalmers *et al.* 1999). With this in mind we suggest two possible mechanisms that could have given rise to the flexure zones and associated faults.

The most likely explanation is that the typical narrow flexure zones were developed above faults in the underlying basement that were reactivated after eruption of the basalts. In the situation on Svartenhuk Halvø where an incompetent formation separates the competent basalts from the massive basement, the resulting structures in the basalt cover will not be a simple upwards projection of the basement fault. On the contrary, results of model experiments involving reactivation of a fault in a massive 'basement' overlain by an incompetent layer that is overlain in turn by a competent cover have shown that reactivation of a fault in the basement can lead to a variety of structures in the cover including monoclinal folds, grabens and even reverse faults and thrusts (Mandl 1988, fig. I.2-37; Oudmayer & de Jager 1993, figs 7, 8; Vendeville *et al.* 1995, fig. 6). Pascoe *et al.* (1999) have forward-modelled the structures generated in experiments by Vendeville *et al.* (1995), producing the result shown in Fig. 13a. This structure shows a striking resemblance to the structure in the Qooroq flexure zone/half-graben shown in Fig. 10a, but it should be borne in mind that the relative thickness of the incompetent layer (i.e. mudstones) underlying the basalts at Qooroq is probably much greater than the incompetent layer in Pascoe *et al.*'s forward model. Furthermore it is not known whether the structures on Svartenhuk Halvø ever became overlain by syn- and post-rift sediments as shown in Pascoe *et al.*'s forward modelling.

An alternative explanation is suggested by analogue models of extensional fault geometries reported by Cloos (1968) and McClay & Ellis (1987) and could apply to the flexure zones south-east of Qiterlikassak. The asymmetric graben produced experimentally by Cloos (1968) shows features in common with the flexure zone between Qiterlikassak and Usuit Kuussuat, in particular the way in which steepening of dip of layers in the flexure is accompanied by development of numerous minor faults dipping in the opposite direction (Fig. 13b). Fig. 13c shows the structure generated by McClay & Ellis above a listric detachment fault where the listric fault is almost vertical near the surface. Extension on this fault resulted in a well developed faulted

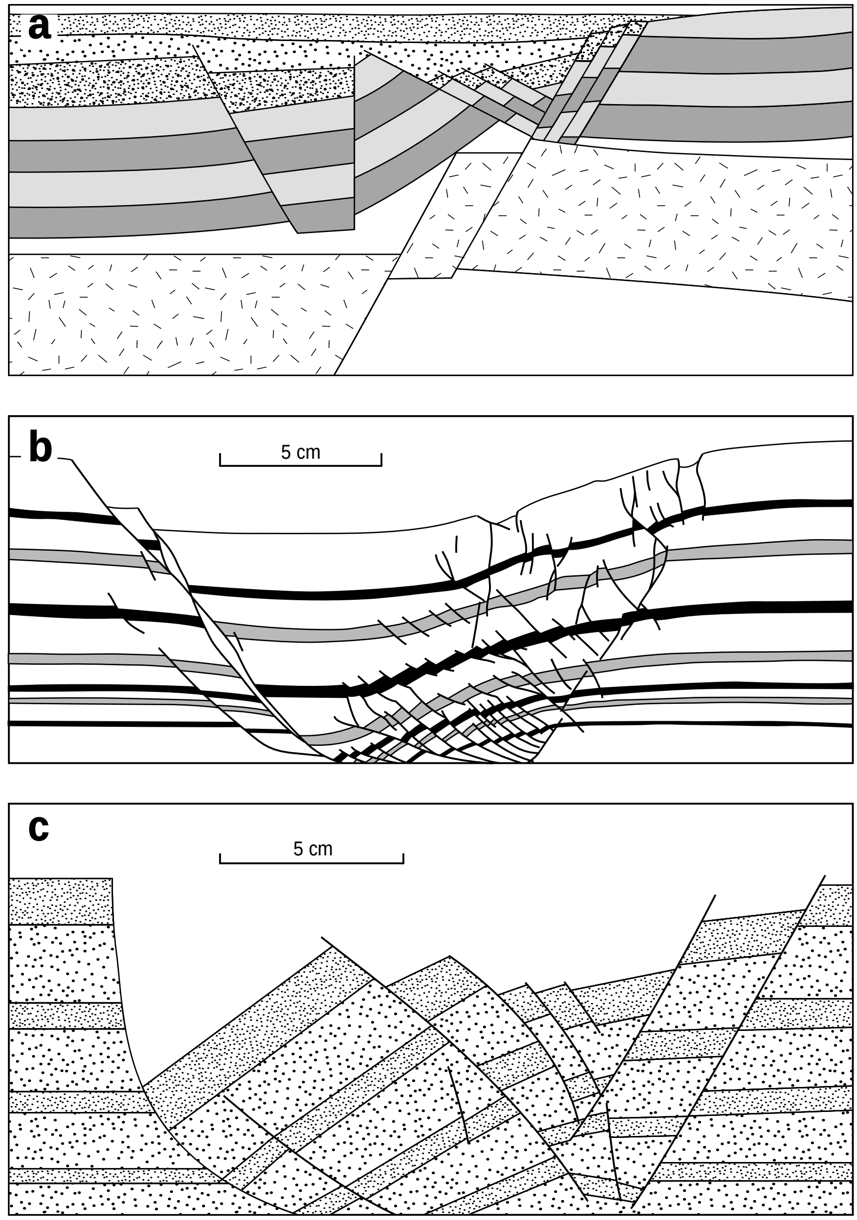

Fig. 13. Examples of fault and flexure patterns produced in analogue model experiments and forward models. **a**: forward model of the structure developed by reactivation of a basement fault where a competent cover is separated from the basement by a ductile layer (Pascoe *et al.* 1999, fig. 6d); **b**: asymmetric graben produced in a clay model (drawn from Cloos 1968, fig. 16, in mirror image); **c**: structure formed by 33% extension on a listric fault (McClay & Ellis 1987, fig. 5b in mirror image).

roll-over with highly rotated (up to 35°) layering; the steepest dip is seen in the segment closest to the listric fault. This modelled structure suggests that the flexure zone south of Usuit Kuussuat might have formed above listric faults that levelled out in detachment zones in the sediments below.

Transfer faults; strike-slip faults

In the southern and central parts of Svartenhuk Halvø there are several faults and fractures trending between 90° and 115°. The four most important of these are the Saviit–Qinerfik fault, the Svartenhavn fault, the Usuit Kuussuat fault and the Qiterlikassak fault. It is tempting to connect the Svartenhavn and Usuit Kuussuat faults, but we have no evidence for movements in the inner part of the Maligissap Kuua valley, nor has any significant change in dip been detected across this part of the valley as there is across the Svartenhavn, Qiterlikassak and Saviit–Qinerfik faults.

The Saviit–Qinerfik, Svartenhavn and Qiterlikassak faults are typical transfer faults as defined by Gibbs (1984, 1989) and Lister *et al.* (1986). Transfer faults allow extension to be transferred laterally along the strike of the fault and divide extensional terrains into segments. Characteristically the degree of extension changes abruptly across transfer faults, and in many cases – but not on Svartenhuk Halvø – the polarity of extensional faults also changes across transfer faults. Transfer faults are analogous to transform faults in spreading oceans, in that the slip on transfer faults is opposite to the sense of mapped offset of the zone of extensional faulting.

On Svartenhuk Halvø the sense of mapped offset of dip domains and extensional zones on the Qiterlikassak, Svartenhavn and Saviit–Qinerfik faults is left-lateral, whereas there is evidence of right-lateral movement on these faults.

The Svartenhavn fault is entirely concealed by alluvium or the sea. Its presence is indicated by an abrupt change in dip values from very low on the north side of the fault to more than 20° south of the fault. With a left-lateral offset this domain of relatively steep dips can be predicted to reappear on the north side of the fault in the offshore area. North of the fault there is an outcrop of the Arfertuarsuk trachyte that is displaced dextrally relative to the outcrops south of the fault. This can be taken as evidence of right-lateral displacement along the Svartenhavn fault, but it could also be the consequence of purely vertical displacements along the Svartenhavn and Milloofik faults. The lavas here have low dips, so the vertical displacement required to cause the repetition is not large.

The Saviit–Qinerfik fault extends from Saviit to Qinerfik, north of Tasiusaq. The fault separates a dip domain to the north with south-westerly dips less than 16° from the Tartuusaq dip domain to the south where dips generally are more than 25° and locally as much as 40° to south-west. Along this fault the dip domain boundary is offset 17 km in a left-lateral direction, whereas outcrops of the Kakilisaat Member at Ulissat are separated right-laterally by 10 km from the large outcrop of this member west of Saviit. If there were no other faults in the area, this separation would imply either a 10 km strike-slip displacement on the Saviit–Qinerfik fault or a *c.* 3 km downthrow to the north or oblique slip combining substantial lateral and vertical movements. However, a lateral displacement of 10 km is not plausible. At Qinerfik, a mere 25 km west of Saviit, the lateral displacement on the fault is at most 250 m. A 10 km lateral displacement could hardly be reduced to a few hundred metres within 25 km. Some right-lateral slip, however, is required, and in the southern part of the area there are examples of smaller faults trending *c.* 100° that displace vertical dykes in a right-lateral direction, proving that such displacements have taken place in this part of the area. There are at least two possible explanations of the situation described.

One explanation is that a new phase of eruption of lavas with Kakilisaat Member chemistry gave rise to the contaminated lavas west of Saviit, so that these form a younger unit than the Kakilisaat Member. This explanation is not favoured. As already mentioned, over a large area of south-east Svartenhuk Halvø, both north and south of the Saviit–Qinerfik fault, the contaminated lavas are overlain by a characteristic massive picrite flow with large olivine phenocrysts. This suggests that all contaminated lavas in this area belong to the same stratigraphic unit – the Kakilisaat Member.

The other explanation of the large apparent lateral displacement of the Kakilisaat Member is that faults trending between 145° and 150° have caused a repeated, stepwise relative uplift of the Kakilisaat Member to the south-west, without bringing it to the surface, so that north of the Saviit–Qinerfik fault this member is not far below sea level, while south of the fault its repetition is seen just west of Saviit. If this is the case, only a modest lateral slip on the Saviit–Qinerfik fault accompanied by a downthrow to the north is required to account for the present-day map pattern.

Other ESE faults and fractures occur in a 1.5–3 km wide zone north of the Saviit–Qinerfik fault. West of Ulissat some of these faults can be seen to have downthrow to the north or equivalent right lateral displacements. Dykes occur both within and parallel to these faults. These structures may be the result of transtension along the Saviit–Qinerfik fault.

The eastwards extension of the Saviit–Qinerfik fault under Karrat Fjord is not known. Chalmers *et al.* (1998) have shown it running south of Schade Øer, because these islands consist of rocks belonging to the Kakilisaat Member which can be linked to the outcrops at Maniiseqqut without introducing lateral displacements.

As already pointed out, the Saviit–Qinerfik fault dies out westwards at Qinerfik where it links into the extensional fault system. The Tartuusaq dip domain continues north-west to the Svartenhavn transfer fault.

Along the Qiterlikassak fault the sense of mapped offset is left-lateral, but no evidence of right-lateral slip on this fault has been recorded. In the valley here there are no proper exposures, but there are ridges in the terrain that run parallel to the fault. These appear to reflect the strike of steeply-dipping lavas under the Quaternary debris. The existence of a narrow zone of steeply-dipping lavas striking parallel to the fault can be explained by transtension along the fault.

In the Usuit Kuussuat valley the sense of mapped offset of flexure zones appears to be right-lateral, although a correlation of flexures zones involving a left-lateral offset across the valley could also be made. The existence of a right-lateral fault in this valley is strongly suggested by a small downthrown lens of steeply-dipping Svartenhuk Formation lavas in the inner part of the valley. The shape and orientation of this lens is like that of a small pull-apart basin resulting from transtensional displacement on a right-lateral fault trending 105° along the valley floor.

The Usuit Kuussuat fault dies out at both ends in extensional horsetail splays, best seen at the east-south-east end where the splay faults show downthrow to the north-east.

Origin of the structural pattern

It remains to be discussed whether and how dip directions and values, extensional faults, flexure zones, and transfer and strike-slip faults are related to one another and to the regional structural development and plate-tectonic setting of central West Greenland.

The Cretaceous boundary fault system is a segmented extensional fault system that extends from Svartenhuk Halvø in the north to the south-east corner of Disko Bugt in the south (Fig. 1). The fault system has been described in several papers, most recently by Chalmers *et al.* (1999) who interpreted its zig-zag course as partially controlled by pre-existing fractures in the Precambrian basement and also drew attention to its similarity to the course of the Suez rift (Patton *et al.* 1994). The fault appears to have been active in the Late Albian – Early Cenomanian on Qeqertarsuaq and Upernivik Ø (Chalmers *et al.* 1999), whereas on Nuussuaq the fault system truncates Albian–Cenomanian sediments without any sign that it was active during sedimentation here. Inversion on the Cretaceous boundary fault system has only been observed on Svartenhuk Halvø. Otherwise outcrops on Svartenhuk Halvø add little to what is already known from areas to the south-south-east.

As has already been pointed out, dip directions in the basalts in the basin area are predominantly normal to the strike of extensional faults. Most of these faults strike between 145° and 150°, and dip is largely the consequence of rotation along faults with this trend. The flexure zones are also interpreted as extensional structures that most likely developed as a response to reactivation of faults in the underlying basement with uplift on the north-east side. Alternatively they could have formed in connection with listric faults that levelled out below the base of the basalts. The question to be addressed now is whether the direction of *regional* extension is normal to the numerous extensional faults in 145–150°, because McClay & White (1995) have shown that this need not necessarily be so. In situations where extension in a rift system is oblique to the overall trend of the underlying rift, extensional faults within the rift cover can form parallel or at a low angle to the rift margins rather than at right angles to the direction of extension, even where the direction of extension is at 45° to the rift (McClay & White 1995, fig. 5D). Thus, if the rift system in the sediments and basement underlying Svartenhuk Halvø trends 145–150°, extensional faults in this direction could form in the basalt cover as a consequence of regional extension in any direction between *c.* 55–60° (i.e. normal to the extensional faults) and 100–105°. Now the latter direction, 100–105°, is approximately the trend of transfer faults on Svartenhuk Halvø. Transfer faults are by definition part of the extensional fault system (Gibbs 1984), and ideally they are parallel or nearly parallel to the extension vector. Thus one could suggest that on Svartenhuk Halvø the post-basalt regional extension vector was in 100–105° and that this acted on a deeper NW–SE rift system, giving rise to widespread extensional faults in 145–150°.

Even though approximately E–W extension could account for the extensional structures seen in the basalts on Svartenhuk Halvø and is consistent with the direction of transfer faults in the region, this suggestion is not favoured because it is not compatible with current models for the regional plate-tectonic setting of the region and the – admittedly sparse – information available from adjacent offshore areas.