though 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.

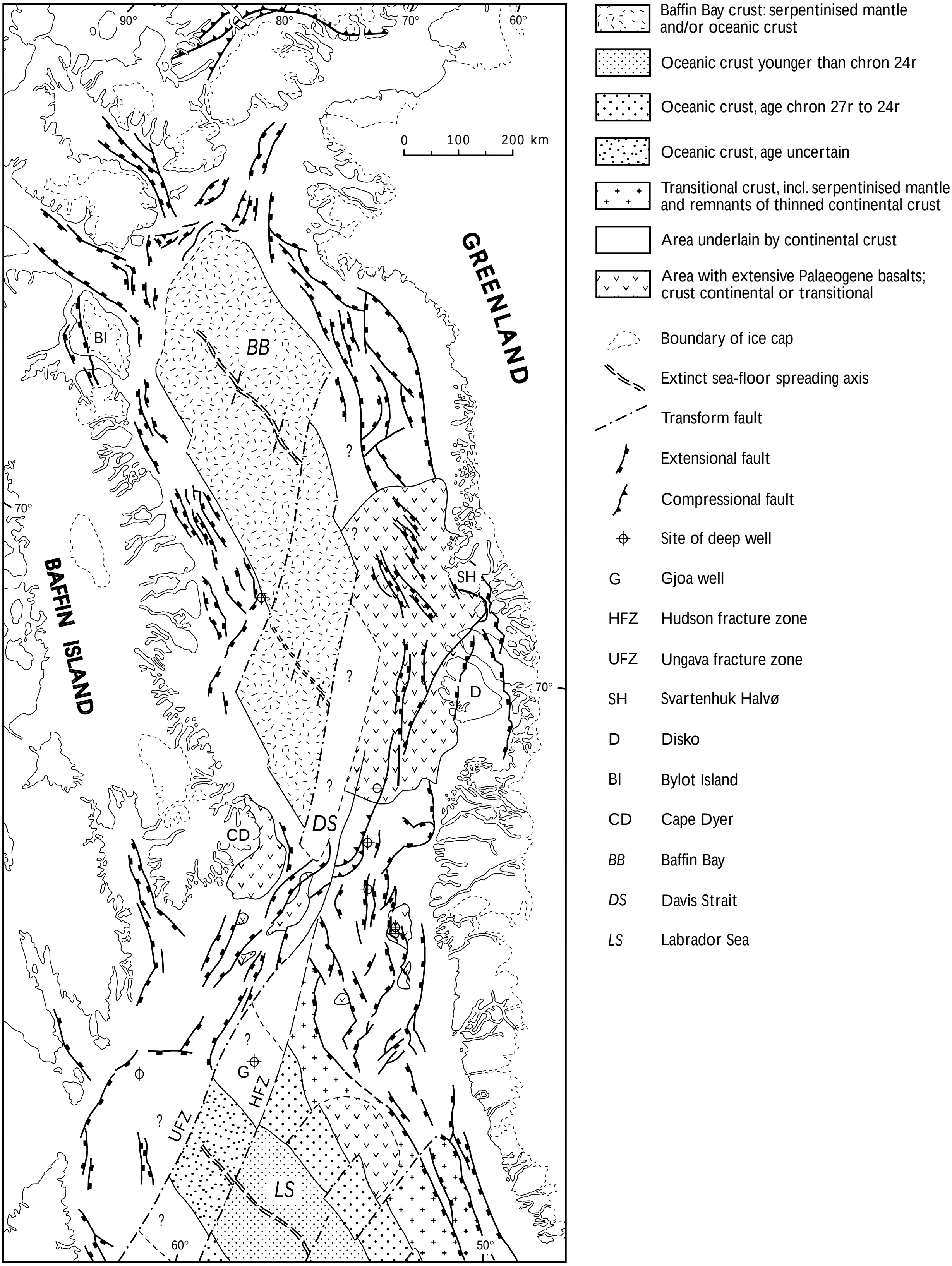

Fig. 14. Map of crustal structure of the northern Labrador Sea – Davis Strait – Baffin Bay region. Principal sources: Keen *et al.* (1974), Balkwill (1987), Jackson *et al.* (1992), Chalmers *et al.* (1995), Whittaker (1996), Reid & Jackson (1997) and Whittaker *et al.* (1997). Compilation by T.C.R. Pulvertaft.

At the time when syn- and post-basalt faulting was taking place on Svartenhuk Halvø, sea-floor spreading was active in the inner Labrador Sea. Spreading in Baffin Bay probably began at the same time or shortly after spreading started in the Labrador Sea, i.e. in the late Paleocene (Chalmers & Pulvertaft in press). Spreading in both regions slowed down after magnetochron 20 (43 Ma; middle Eocene) and had died out altogether by magnetochron 13 (33 Ma; earliest Oligocene) (Srivastava 1978; Chalmers & Pulvertaft in press). The spreading axes in the respective regions were linked by an approximately north–south transform fracture system (Fig. 14), and the area offshore west Disko was adjacent to this active transform system from late Paleocene until the end of the Eocene. Open folding of the top-basalt surface offshore west Disko has been interpreted as due to transpression associated with this transform system, and the N–S-trending extensional faults mapped here from the seismic data could be transtensional rather than simple extensional features (Whittaker 1995, 1996).

At about 70°30′N offshore, and on Ubekendt Ejland onshore, the structural trend changes fairly rapidly from *c.* N–S to NW–SE (Fig. 14). This is approximately where the current model (Chalmers & Pulvertaft in press) requires that the strike-slip influenced area gives way northwards to an extensional regime in which post-basalt faults are parallel to the extinct spreading axis in Baffin Bay. Svartenhuk Halvø belongs to this regime, and the NW–SE-trending extensional faults onshore and offshore are most likely controlled by regional extension normal to the faults and the spreading axis.

Accepting that, in accordance with the regional model, the direction of extension on Svartenhuk Halvø was *c.* 55–60°, the transfer faults on the peninsula are at about 40° oblique to the extension direction. Oblique transfer faults are known from many rift basins, e.g. the Midland Valley of Scotland and the Carlisle Basin, UK (Gibbs 1989), the Suez Rift (Chénet *et al.* 1987; Colletta *et al.* 1988; Moustafa 1997; McClay & Khalil 1998), the East African Rift (Ebinger 1989; Chorowicz & Sorlein 1992), the eastern margin of the Basin and Range province, USA (Henry 1998), the Rocôncavo Graben, Brazil (Milani & Davison 1988), just as transform faults can be oblique to the direction of extension in a spreading oceanic ridge, e.g. the Grimsey Fault in northern Iceland which is at an angle of about 40° to the extensional faults and grabens on either side (Gudmundsson *et al.* 1993). However, if transfer faults are markedly oblique to the direction of extension, there must be an element of extension or compression along the transfer (Gibbs 1989). On Svartenhuk Halvø there is evidence of transtension along the Qiterlikassak and Usuit Kuussuat faults, and there are extensional faults parallel to and associated with the Saviit–Qinerfik fault that can also be attributed to transtension. The numerous dykes parallel to this fault indicate that extensional fractures in this direction existed already during volcanism. However, no evidence of extension has been observed along the Svartenhavn fault, although just north-west of Svartenhavn there are a few dykes parallel to this fault. However, exposures in the Maligissap Kuua valley are very poor and such evidence could have been overlooked.

Of the examples of oblique transfer faults listed in the foregoing paragraph, that described by McClay & Khalil (1998) from the Araba – Abu Durba area on the eastern margin of the Gulf of Suez shows the closest similarity to the structural pattern on Svartenhuk Halvø. To make this similarity clear, a rotated mirror image of McClay & Khalil's map is shown in Fig. 15 side-by-side with a simplified map of the faults on Svartenhuk Halvø. Elements of similarity include the approximate angle between regional extension and the transfer faults, vertical displacement on the transfer faults, horsetail splays at the termination of transfer faults, and the way in which the Durba transfer fault of McClay & Khalil (1998) and the Saviit–Qinerfik transfer fault on Svartenhuk Halvø link into the extensional fault systems in the respective areas.

In rift systems where oblique transfer faults occur, the orientation of these faults is often controlled by older structures in the underlying basement (e.g. Patton *et al.* 1994; Ring 1994; Moustafa 1997). Although no E–W or ESE faults and shear zones have been recorded in the Precambrian basement east of Svartenhuk Halvø (Henderson & Pulvertaft 1987), there are WNW–ESE fractures in the basement north-west of Kangiusap Imaa, and E–W segments of the Cretaceous boundary fault system occur both north of Itsaku and in south-west Upernivik Ø (Figs 1, 2), so weaknesses in the basement in this direction do exist.

For completeness it should be mentioned that if the transfer faults were right-lateral strike-slip faults, the right-lateral couple would generate extensional faults in the direction of the dominant extensional faults on Svartenhuk Halvø. This is believed to be a coincidence and insufficient to counter the evidence against the E–W to 105°–285° faults being major strike-slip faults.

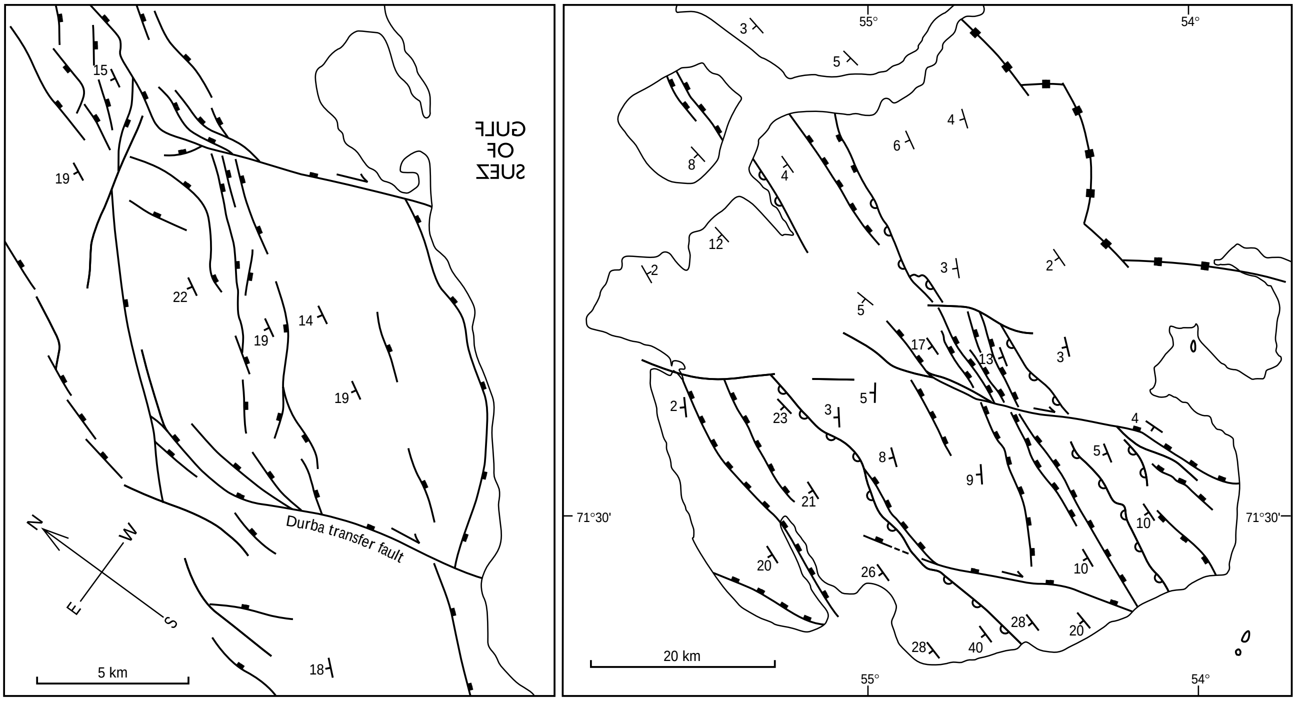

Fig. 15. Simplified, rotated **mirror image** of the map of the Durba and Ekma transfer faults, Araba–Abu Durba area, eastern Gulf of Suez (modified from McClay & Khalil 1998, fig. 1), side-by-side with a simplified map of Svartenhuk Halvø.

The relative roles of extensional faulting, stratal shingling and syn-volcanic tilting in southern Svartenhuk Halvø

It has already been pointed out that the very large apparent thickness of Vaigat Formation lavas in southern Svartenhuk Halvø (*c.* 9 km) presents a problem that has been discussed since early reconnaissance investigations (Noe-Nygaard 1942; Pulvertaft & Clarke 1966; Münther 1973; Larsen 1981b). While repetition by extensional faulting could alone account for this apparent thickness, the number of NW–SE faults actually observed along the south coast of Svartenhuk Halvø seems insufficient to be the only factor involved. However, significant faults may be concealed under the large valleys, and furthermore both the rubbly nature of outcrops in the Vaigat Formation and the uniformity of the formation make faults within the formation hard to recognise.

Stratal shingling (Crowell 1982) is also a feasible mechanism for the development of a lava succession with a stratigraphic thickness that greatly exceeds the real thickness of the succession. However, interpreting the excessive stratigraphic thickness of the Vaigat Formation in southern Svartenhuk Halvø as due to stratal shingling alone meets with difficulties. Essential to the mechanism is a basinward migration of the source accompanied by subsidence of the basin during volcanism, so that the younger lavas are confined to the basinward side of the outcrop. Retreat of lava flows from northern Svartenhuk Halvø did take place at the end of Vaigat Formation time to allow the deposition of the intrabasaltic sediments here, but this was succeeded by eruption of the Svartenhuk Formation which extends farther to the east and north-east than any of the older lavas, disappearing finally under the Inland Ice (Fig. 1). Furthermore, young dykes with lithologies corresponding to the lavas of the Svartenhuk Formation are very numerous throughout the Vaigat Formation in eastern Svartenhuk Halvø, which does not suggest any basinward (south-westerly) retreat of volcanic sources at this time.

Although stratal shingling *sensu stricto* does not appear to have been a major factor in the structural development of Svartenhuk Halvø, some subsidence did take place during eruption of the Vaigat Formation and was accompanied by flexuring and development of down-to-north-east extensional faults. Geoffroy *et al.* (1998) have provided structural data indicating that on Disko island flexuring and down-to-east extensional faulting was syn-volcanic, and the same team (Geoffroy *et al.* 1997, 1999) propose that this is also the case in southern Svartenhuk Halvø and on Ubekendt Ejland. They interpret the overall structure of Svartenhuk Halvø as a syn-volcanic flexure with fan geometry in cross-section, implying that the basalts on Svartenhuk Halvø were erupted into an active half-graben bounded to the south-west by the Arfertuarsuk listric fault. Geoffroy *et al.* (1997) have also observed a progressive seaward-retreating development of unconformities within the pile of lava flows. Our observations also suggest that some of the tilting of the Vaigat Formation lavas was syn-volcanic, as many NW–SE-trending dykes in Area V (Fig. 5) do not appear not to have been tilted together with their host lavas. We do not dispute the existence of very narrow-angle unconformities although we did not observe them during our regional mapping of the basalt stratigraphy. There is clear evidence of active faulting (syn-volcanic fault scarps) and subsidence during eruption of the lower part of the Vaigat Formation, and we have also pointed out that there must be an angular unconformity between the Svartenhuk Formation and the Vaigat Formation south of Usuit Kuussuat, proving that there was tectonic activity, including tilting, during volcanism. However, we believe that much of the tilting that affected the Svartenhuk Formation, and therefore also the underlying Vaigat Formation, is the result of later tectonic activity. In the first place, both young dykes and the youngest basalts (those overlying the Arfertuarsuk trachyte) have been tilted locally more than 25°. Secondly, if Geoffroy *et al.*'s interpretation applies to the Svartenhuk Formation, stratigraphic units in this formation should thicken south-westwards as they approach the NW–SE extensional faults, in particular the Arfertuarsuk fault. However, at least as regards the lowest unit in the formation, there is no systematic thickening from north-east to south-west. This unit is 800 m thick on Innerit and north-east of Qooroq where it dips less than 5° towards south-west (see Plate 1, section C–D), 500 m thick in central Svartenhuk Halvø (see Plate 1, section A–B south-west of Usuit Kuussuat), 700 m thick north-west of Tasiusaq, and 850 m thick south-east of Tasiusaq where the dip is 28° towards south-west. Finally, in north-west Nuussuaq there is a 52.5 Ma old comendite tuff in basalts dipping 15° NW (Storey *et al.* 1998), proving that substantial tilt occurred here about 7 Ma *after* the eruption of the main lava succession.

However this may be, we are reluctant to accept Geoffroy *et al.*'s (1997, 1998, 1999) contention that the seaward-dipping basalt areas of central West Greenland provide a convenient model for seaward-dipping reflectors in offshore areas around the North Atlantic. Both western Disko and Svartenhuk Halvø are underlain by continental crust, and the basalts in these areas and for some tens of kilometres to the west offshore are underlain by thick successions of Paleocene and earlier sediments. Inclusions of mudstones occur in the volcanic rocks in west Disko and south-western Svartenhuk Halvø, and offshore sedimentary basins can be extrapolated from both north and south into the area west of Disko and Svartenhuk (Fig. 14). In this setting extension is likely to lead to development of listric faults that level out into detachment zones in the underlying sediments. No such ductile units underlie for example the seaward-dipping reflector sequences off South-East Greenland (Larsen & Jakobsdóttir 1988). Furthermore, dips in the basalts in southern Svartenhuk Halvø and parts of western Disko are steeper than any recorded in offshore seaward-dipping reflectors, and indeed such steep dips can be difficult to image in reflection seismic data without special processing procedures. It would be much more useful to look to Iceland rather than onshore West Greenland to find onshore analogues of oceanic seaward-dipping reflector sequences (Larsen *et al.* 1994).

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