Journal of the Geological Society, *London*, Vol. **156,** 1999, pp. 1051–1055. Printed in Great Britain.

Discussion on the coastal flexure of Disko (West Greenland), onshore expression of the 'oblique reflectors'

Journal, Vol. 155, 1998, pp. 463–473

J. A. Chalmers, R. C. Whittaker, N. Skaarup & T. C. R. Pulvertaft write: Geoffroy *et al.* (1998) have published an account of field measurements of the structure of the Palaeogene lavas exposed in western Disko, central West Greenland. They show that the lavas generally dip westwards and that the dips increase from low values immediately west of the Disko gneiss ridge to over 30° on parts of the west coast. These dipping lavas are cut by a set of faults that strike N–S and NW–SE and generally have downthrow to the east or ENE. The tectonic analysis suggests that tilting of the lavas was syn-magmatic. The field work and structural analysis described by Geoffroy *et al.* (1998) appears to us to be a good and competent piece of work, on which they are to be congratulated. However, in their discussion section, they develop a model based on their work which makes a forecast about the structure offshore that is contradicted by published data to which Geoffroy *et al.* refer, but choose to ignore.

Geoffroy *et al.* (1998) point out that the pattern of dips and faults within the lavas along the west coast of Disko is similar to the pattern of dips and faults described from the onshore part of the East Greenland flexure by Nielsen & Brooks (1981) and Larsen *et al.* (1995), and they refer also to Fitton *et al.* (1995) who trace the geochemical signature of the continent–ocean transition in the seaward-dipping reflectors close to the East Greenland coast. Geoffroy *et al.* (1998) conclude that the Disko flexure is a conveniently accessible model for seaward-dipping reflectors elsewhere in the North Atlantic domain and imply that a continent to ocean crust transition similar to that off East Greenland exists a short distance west of Disko. Confusingly, they also refer to an old suggestion based on single-channel seismic data (Denham 1974) that there is a basement ridge offshore about 30 km from the west coast of Disko.

Geoffroy *et al.*'s (1998) second hypothesis is that the pattern of dips and faults observed in western Disko suggests the existence of a deep, synthetic, continentward-dipping fault or shear zone over which the lava pile is flexed (their fig. 9, reproduced here as Fig. 1a).

Geoffroy *et al.*'s (1998) hypotheses can be tested by inspection of multichannel seismic data offshore western Disko. Such data exist, and an interpretation of some of these data was presented by Whittaker (1996) to which Geoffroy *et al.* (1998) refer in another context. Examples of the data and more detailed interpretations were published by Whittaker (1995) and referenced in Whittaker (1996). Both of Geoffroy *et al.*'s (1998) hypotheses are contradicted by the seismic data. Seaward-dipping reflectors are not visible on the seismic data close to the coast. No major down-to-the-east fault can be seen in the seismic data; the first major fault west of the coast throws down to the west (Figs 1b and 2).

Figure 1b is an interpretation based on published Survey map sheets, Geoffroy *et al.*'s (1998) observations onshore, known basalt stratigraphy, the gravity modelling described in Chalmers (1998), and interpretation of seismic data offshore. The seismic interpretation has already been published (Whittaker 1995, fig. 6; 1996, fig. 2). Figure 1b is shown below a reproduction of Geoffroy *et al.*'s (1998) fig. 9 for direct comparison. The seismic line on which Fig. 1b is based is shown in Fig. 2. While Geoffroy *et al.* (1998) correctly point out that Whittaker's (1996) conjecture that thick sediments exist offshore under the basalts is speculative, the same cannot be said about Whittaker's (1995, 1996) interpretation of the structure of the top of the lavas, because the reflection from the top of the lavas is distinct on the seismic lines (Fig. 2). From

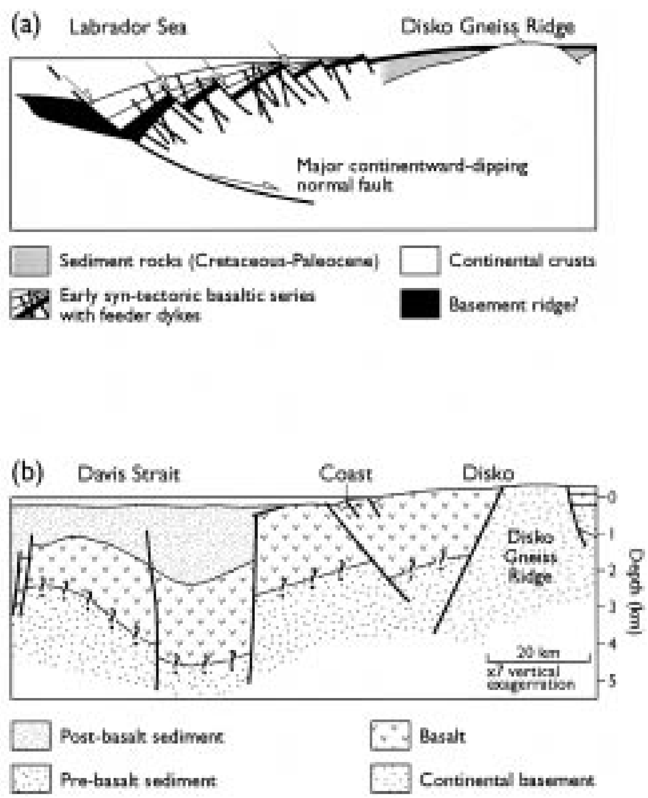

Fig. 1. Geological cross-sections across the Disko gneiss ridge and the area to its west. (**a**) The roll-over hypothesis of the coastal flexure of Disko. Figure is schematic and not to scale (Geoffroy *et al.* 1998, fig. 9). The comparison cross-section in (**b**) has been compiled from Survey 1:100 000 map sheets, Geoffroy *et al.*'s (1998) observations onshore, known basalt stratigraphy, the gravity modelling described in Chalmers (1998) and interpretation of seismic line GGU/90-2 offshore by Whittaker (1995, fig. 6) and Whittaker (1996, fig. 2). While Geoffroy *et al.*'s (1998) figure shown in (a) is not to scale, an approximate horizontal scale can be inferred from the distance between the Disko gneiss ridge and the 'basement ridge' at the left (west) end of (a) which Geoffroy *et al.* (1998) take from Denham (1974). (b) is drawn at approximately the same horizontal scale. No vertical scale is indicated for (a).

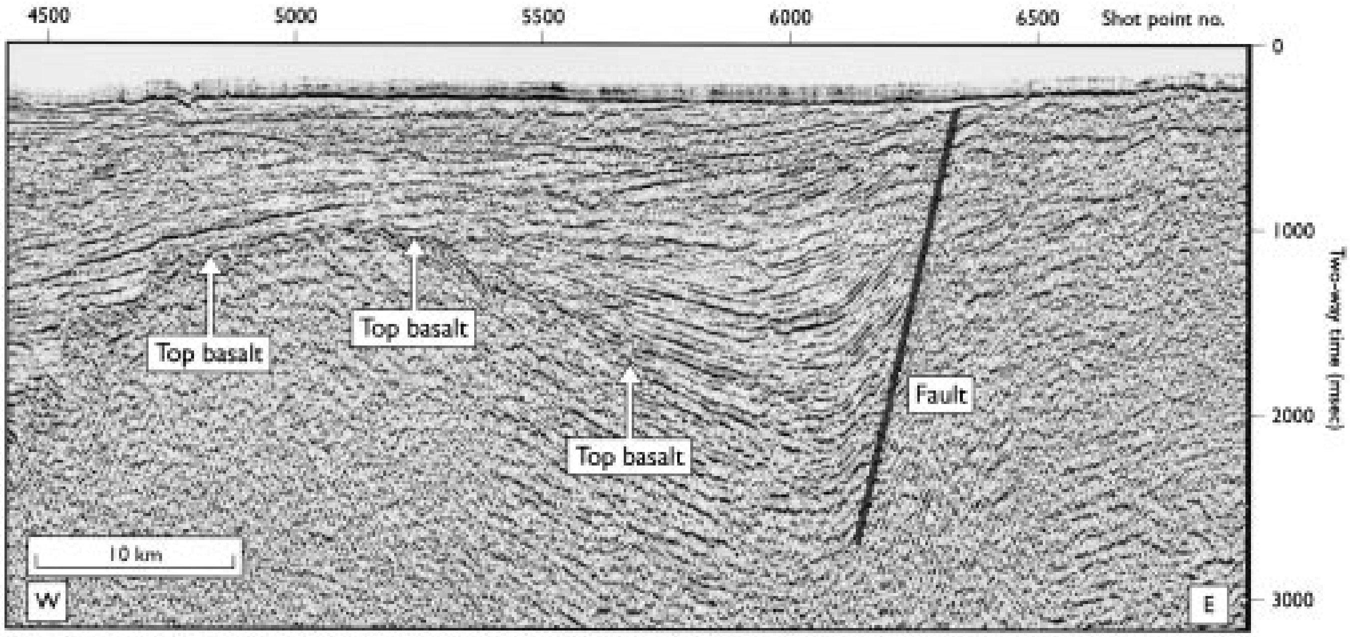

Fig. 2. Part of seismic line GGU/90-2 west of Disko. The basalts are at the seabed southeast of shot-point (S.P.) 6500 and there is a major fault that throws the top of the basalts down to below 2 seconds two-way time (more than 2 km depth) between S.P.s 6200 and 6500. The reflection from the top of the basalts is visible west of the fault.

the seismic data, it can be seen that the top of the basalts are thrown down to the west by a fault and there is no evidence to support the existence of Geoffroy *et al.*'s (1998) hypothesized major down-to-the-east fault. The first major fault west of Disko is probably the southwestern extension of the Itilli fault which is exposed onshore in western Nuussuaq and on Hare Ø, where the basalt stratigraphy indicates that there is a throw in excess of 1 km down to the northwest.

Geoffroy *et al.*'s (1998) first hypothesis implies that seaward-dipping reflections should be observed a short distance west of Disko. The seismic data show no reflection patterns that could be interpreted in this way closer to Disko than 70 km. Farther west, there are patterns on the seismic lines that may indicate seaward-dipping reflections, but other interpretations are also possible, for example intra- and pre-basaltic sediments as suggested by Whittaker (1995, 1996). In the 70 km wide interval, evidence for complex tectonics can be seen on the seismic data, and in places reflections from within the basalts clearly indicate dips to the east. The seismic lines reproduced in Whittaker's (1995) figs 9 and 10 show these various features clearly.

The presence of a monocline that was tectonically active during eruption of the basalts does not necessarily indicate the nearby presence of oceanic crust. Other hypotheses are possible, such as that the monocline marks the boundary between two areas where crustal stretching is different. Such a situation appears to be the case across, e.g. the Lebombo monocline in the Karoo lavas of East Africa (Eales *et al*. 1984). Gravity modelling (Chalmers 1998) suggests that the Moho is shallower and that the total thickness of basalt plus sediment is greater to the west of the Disko gneiss ridge than farther east, indicating that there has been greater extension to the west of the Disko gneiss ridge. Oceanic crust may be found farther west still, but there is no indication on the presently available geophysical data west of Disko that it is present nearer to Disko than 70 km.

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13 August 1998

L. Geoffroy, A. G. Skuce, J. Angelier, J. P. Gelard, C. Lepvrier & P. Olivier reply: We thank Chalmers *et al.* for giving us the opportunity to clarify and present in more detail our interpretation of the West Greenland coastal flexure.

Geoffroy *et al.* (1998) argued that the Disko coastal flexure, as well as the whole exposed Baffin Bay continental margin was accommodated by an array of continentward-dipping normal faults active during the accumulation of the volcanic pile. In the same paper, it was also suggested that a larger syn-magmatic and continentward-dipping fault, located offshore, was responsible for the coastal flexure, thereby interpreting the structure above as a faulted roll-over anticline. Such a conclusion was in accordance with previous geophysical work mainly based on a combined magnetic and geologic approach (Denham 1974). Comparing the structure with that of the West Greenland margin with that of the East Greenland margin, Geoffroy *et al.* (1998) concluded that the East Baffin passive margin was a convenient model for the onshore study of the development and deformation of seaward-dipping volcanic piles.

Using Whittaker's (1995) seismic reflection data, Chalmers *et al.* contend that no seaward-dipping reflectors can be recognized immediately west of Disko. In addition, based on the single seismic line GGU 90-2, they claim that the only major fault that can be recognized west of Disko is an oceanward dipping fault (Fig. 2) that they equate with the onshore Itilli fault. They present a new combined onshore/offshore cross-section (Fig. 1b) in which they suggest that the West Greenland margin comprises 1–2 km in thickness of tabular basalts overlying thick Cretaceous–Palaeocene sediments.

Fig. 3. Seaward-dipping basalts accommodated by continentward-dipping normal faults (here a moderate *c.* 70 m continentward throw) in South Svartenhuk. This pattern constitutes the typical structural grain of the lower basaltic pile in the E-Baffin flexed area. Compare with the tabular stratigraphy (take into account $\times$ 7 vertical exaggeration) proposed in Fig. 1b.

Although we readily acknowledge the usefulness of the offshore survey compiled by Whittaker (1995), we think that it is not possible to assess the crustal structure of the southern Baffin Bay based on the published seismic data that Chalmers *et al.* refer to. Based on the following considerations, we think that the arguments and interpretations put forward by Chalmers *et al.* are not convincing or cannot be used to constrain the development of the East Baffin volcanic margin.

(1) Whittaker (1995, p. 13) appropriately stated that: 'Seismic resolution is not sufficiently high to determine the internal reflection configuration within the volcanics to allow seismic facies interpretation to be carried out'. In addition, Chalmers *et al.* admit that the seismic reflection data provided by Whittaker (1995) correctly constrain the attitude of the top of the lava series only. In other words, the attitude of lava flows inside the volcanic pile is poorly constrained by seismic reflection studies. Therefore, a crucial question concerning the structure of the lava series is: can the top of a volcanic pile, which is an erosion level, be considered an indicator of the internal attitude of the lava beds themselves? Obviously, the answer to this question is negative regarding published seismic data on volcanic margins. Chalmers *et al.* suggest that their non-recognition of seaward-dipping reflectors (SDRS) in the uppermost part of the lava pile west of Disko is a proof of their non-existence. Although such a suggestion is not inconsistent with Geoffroy *et al.*'s (1998) assumptions (see the uppermost part of the lava pile in Geoffroy *et al.* 1998, fig. 9), the failure to image dipping reflectors within the basalts does not constitute proof that seaward-dipping basaltic layers are not present. For example, it has been proved from ODP site 642 that SDRS can exist without being seismically characterized (Eldholm *et al.* 1995).

(2) The existence of an oceanward-dipping fault is extensively reported by Chalmers *et al.* as evidence of the non-validity of Geoffroy *et al.*'s (1998) model. However, the fault reported by Chalmers *et al.* is post-volcanic, a reason why Geoffroy *et al.* did not take it into account in their analysis of syn-volcanic structural development. Thus, this fault should not be compared with the large and early continentward-dipping syn-magmatic fault referred to in Geoffroy *et al.* (1998) which, in any case, is probably located closer to the coast line. In addition, some aspects are unclear concerning the significance of the seaward-dipping fault reported by Chalmers *et al.* First, on GGU profiles 90-3 and 90-1, along strike to the north and south (Whittaker 1995), seaward-dipping faults of the same size are absent, which raises doubt on both the correlation and the regional significance of this fault. Second, and still more important, the anticlinal structure at the west end of Fig. 2 is similar in many aspects to the structure interpreted on line GGU/92-08, 50 km west of the Hellefisk-1 well (Whittaker 1995), some 200 km SW of Disko. The seismically interpretable parts of these structures (post-basalt) are similar in size and geometry (i.e., broad anticlines at top basalt level with Lower Eocene horizons onlapping the flanks and seaward-thickening wedges of Eocene and younger rocks gently draped over the highs). However, the interpretation of the deeper geology is dramatically different, with Whittaker (1995) showing an unusual, very low angle (dip around 7°) and high displacement (greater than 25 km at the basement level) fault, that dips continentward east of the high on line GGU/92-08; such a fault is larger, older and more gently dipping than the continent-ward dipping fault predicted by Geoffroy *et al.* (1998) west of Disko. Similarly, in GGU profile 90-4 located northward relative to the former, Whittaker (1995) proposed the existence of a large continentward-dipping normal fault of Paleogene age with displacement as high as 5 km. In contrast, the poor quality data below the top basalt on line GGU/90-2 is presented by Chalmers *et al.* as evidence for the absence of any such continentward-dipping fault. Because we have not seen the original data from lines GGU/92-08 and 92-04, we certainly cannot further discuss their interpretation. However, we would conclude, on the basis of published seismic data, that, in general, no definitive interpretation can be made concerning the structure below the top basalts.

(3) We disagree with the suggestion of Whittaker (1995) and Chalmers *et al.* that no oceanic crust could exist in the southern Baffin Bay. First, an extinct oceanic axis has been proposed by Rice & Shade (1982) from multichannel seismic data in the southern Baffin area, a Canadian study not referred by Chalmers *et al.* and Whittaker (1995). Secondly, such a suggestion conflicts with the structure proposed by Chalmers *et al.* themselves for the margin, with little tectonic stretching

Fig. 4. Example of the non-tectonic stratigraphic contact between the Palaeocene basalts and the Disko basement ridge in Godhavn (G, Precambrian gneiss; B, basaltic volcanics filling up basement irregularities—arrows).

affecting the Palaeocene–Eocene basalts. Indeed, from the kinematic point of view, more than 250 km of post-C27 opening has to be accommodated immediately north of the Ungava fault zone between Baffin Island and the Disko–Svartenhuk area. Without significant oceanic spreading how could the poor development of faults referred to by Whittaker (1995) and Chalmers *et al.* in Palaeogene basalts accommodate such large tectonic stretching between Cape Dyer and Disko?

(4) The major point concerning Chalmers *et al.*'s comment is that they implicitly deny the existence and the regional significance of the crustal flexure along the East Baffin volcanic margin (Fig. 1b). We cannot accept this interpretation which conflicts with geological evidence on more than 400 000 km^2 of exposed margin.The average accumulated thickness of plume-related Palaeocene–Eocene basalts in Disko and Nuussuaq is certainly twice the one proposed by Chalmers *et al.* (Hald & Pedersen 1975; Storey *et al.* 1998). In the northern part of the margin at least, taking into account strong seaward-dips (Fig. 3), the total thickness of seaward-dipping basalts would be enormous seaward (>8 km) without postulating the existence of large continentward-dipping faults, a regional structural problem recognized a long-time ago. Both these solutions (very thick lava piles or large continentward-dipping faults) conflict with the interpretation in Fig. 1b. In addition, the clear

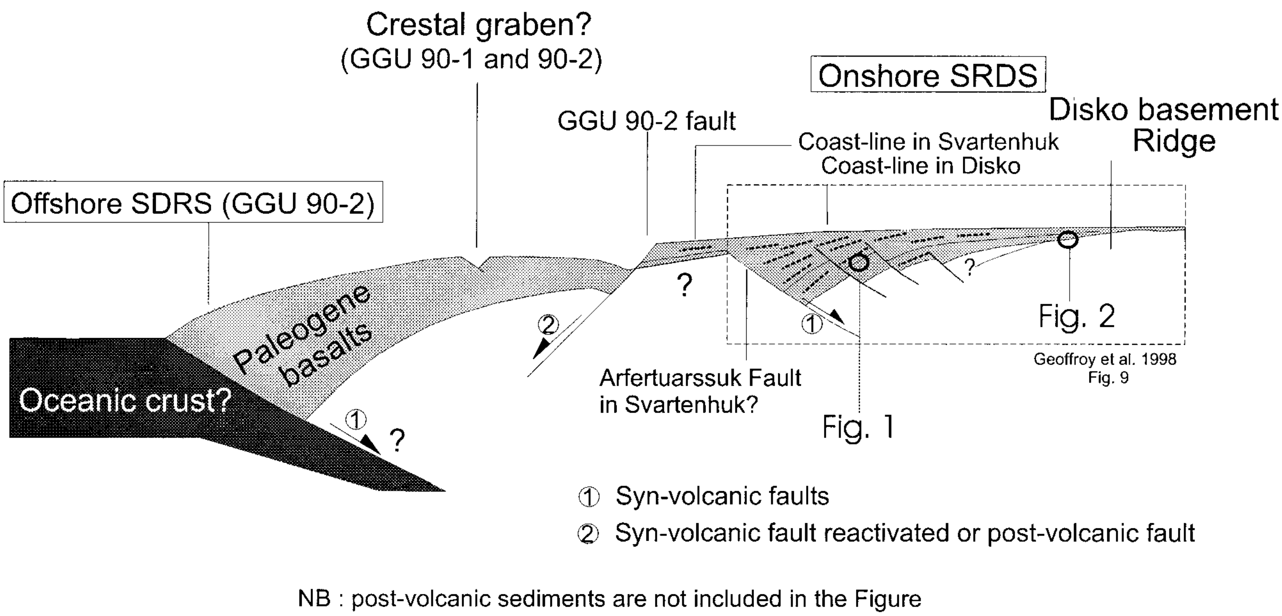

Fig. 5. Hypothetical, synthetical and not-to-scale cross-section of the SE Baffin volcanic margin at the level of northern Disko. This margin is characterized onshore by a thick fan of seaward-dipping basalts (Fig. 3). Note: (a) the upward decrease of the seaward-dip of the basalts in the coastal flexed area on vertical sections, (b) the seaward development of the flexure with time marked by a seaward flexure of the upper basalts, (c) the geometrical need for a crustal-scale continentward-dipping fault close to the coast (see the flexure dip-gradients in Geoffroy *et al.* 1998, fig. 3). The apparent existence of offshore SDRS in the western part of GGU profiles 90-1 and 90-2 is taken into account in the figure, as well as the general Eldholm et al. (1995) suggestion that the SDRS are fault-controlled.

syn-tectonic fan geometry of the exposed lava pile in the flexed area, particularly observable in Svartenhuk, with strong seaward dips in the lower part and gently seaward dips in the upper part is enough by itself to make clear the existence of such a fault (see Geoffroy *et al.* 1998, fig. 9). For Chalmers *et al.*, the necessary thickness increase in the post-basement formations west of the Disko ridge is accommodated by a syn-depositional (?) seaward-dipping normal fault bounding the gneiss ridge (see Fig. 1b). This interpretation is strictly contradicted by the onshore observation of the contact between the Palaeocene basalts and the basement gneiss: it is nowhere a fault, but rather a paleo-ground or a stratigraphic contact as seen, for example, in Fig. 4. Thus, the westward increase in thickness of the basalts should not be attributed to the presence of a fault bounding the western side of the basement ridge, but to a seaward deepening of the roof of the Precambrian basement (Fig. 5). This is a consequence of both the palaeo-topographic pattern and to the clearly observable Palaeogene syn-magmatic and syn-tectonic coastal flexure (Figs 3 and 5).

In summary, we do not think that any of the points discussed by Chalmers *et al.* bring definite argument against the tectonic interpretation proposed by Geoffroy *et al.* (1998), concerning the existence of a fault-controlled SDRS-like basaltic wedge along the SE margin of Baffin Bay. In particular, adopting their interpretation would result in major geometrical difficulty from the kinematic and structural points of view. On the other hand, we acknowledge that there is a need to clarify the preliminary views of Geoffroy *et al.* (1998, fig. 9) at a regional scale. Although it still remains schematic and hypothetical in several aspects, the synthetic Fig. 5 accounts for most of the facts observed by previous authors and by ourselves. It is presented as a hypothetical cross-section at the latitude of Northern Disko but it also integrates information from other segments along the same margin, in Nuussuaq and especially in Svartenhuk. We also include some of the assumptions brought forward by Chalmers *et al.*, although we have very strong doubts about the reliability of the Whittaker (1995) seismic interpretations deeper than the top of the basaltic pile. Note that the resultant figure is very close to the structure proposed elsewhere in other volcanic margins (e.g. Barton & White 1997; Tard *et al.* 1991).

This work is supported by the Institut Français de Recherche et de Technologie Polaire (IFRTP) and by the Institut National des Sciences de l'Univers (CNRS).

27 April 1999

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