Evidence for continental crust in the offshore Palaeogene volcanic province, central West Greenland

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The Palaeogene volcanic province of central West Greenland extends for 550 km from north to south and 200 km from east to west (Henderson 1973; Henderson *et al.* 1981; Whittaker 1996). In a preliminary interpretation of the area offshore Disko and Nuussuaq, based on older seismic data, Whittaker (1996) described a number of large rotated fault blocks containing structural closures at top volcanic level that could indicate leads capable of trapping hydrocarbons. This work, combined with the discovery of oil in the basalts onshore, led the Geological Survey of Denmark and Greenland (GEUS) to acquire 1960 km of multi-channel 2D seismic data in the area between 68°N and 71°N in 1995 (Fig. 1). These seismic data are the primary data source for the interpretation presented in this paper.

By combining the interpretation of the seismic data with modelling of gravity data, the possibility of oceanic crust being present in the volcanic offshore area has been tested. It has been found that the observed gravity field is inconsistent with the presence of oceanic crust, whereas continental crust with sediments below the volcanic section fits the modelling. In the uppermost part of the offshore volcanic rocks, divergent flow directions indicate the presence of an eruption zone (Skaarup 2001). Dating of onshore volcanic rocks, a new date from an offshore well, and the interpretation of seismic units suggest that the volcanic rocks in the offshore area were erupted at the earliest during magnetic chron C26r (60.9–58.4 Ma), and not much later than C24n (53.6–52.4 Ma).

Structures, stratigraphy and thickness of the offshore volcanic rocks

Volcanic rocks have been mapped in the offshore area between 68°N and 71°N (Fig. 1). The top volcanic surface crops out close to the western coast of Nuussuaq and Disko, and dips westwards below sediments of Eocene age and younger. The volcanic rocks are not limited to this area, but continue west of longitude 58°30´W, which is the western limit of the data.

Structures at top volcanic level have been interpreted and mapped. The fault pattern is dominated by steep, normal faults with N–S trends curving towards the northwest north of latitude 70°30´N (Fig. 1). The major faults outline horst and graben structures and complex minor faulting is commonly found within the grabens (Skaarup *et al.* 2000). This structural system is probably associated with transform strike-slip faults arising from seafloor spreading in Labrador Sea and Baffin Bay (Chalmers *et al.* 1993).

The volcanic section can be divided into five mappable seismic units (Figs 1A, 2). The predominant seismic facies in the volcanic rocks is parallel to subparallel, with various degrees of downlap. These parallel-bedded units pass into downlapping units of both oblique and sigmoidal to almost chaotic hummocky clinoforms (Fig. 2). They form a direct equivalent to the onshore exposures where horizontal subaerial volcanic rocks pass into downlapping subaqueous hyaloclastites (Pedersen *et al.* 1993).

On several seismic lines, foresets in the uppermost volcanic unit show divergence eastwards and westwards (Fig. 1B). This indicates the presence of an eruption zone, and the pattern of distribution suggests that it is dissected into several en échelon segments as seen on Iceland at the mid-Atlantic Ridge.

Gravity modelling

It has not been possible to interpret the base of the volcanic rocks from the seismic data alone, mainly because of the transmission loss of the seismic signal within the volcanic rocks. Modelling of the thickness of the volcanic rocks can, however, be carried out by combining gravity data and seismic interpretation.

Onshore western Disko, a monoclinal flexuring of the basaltic succession has been interpreted to represent a seaward-dipping reflector sequence derived from a plume-related plate break-up (Geoffroy *et al.* 1998, 2001). According to this interpretation the ocean–con-

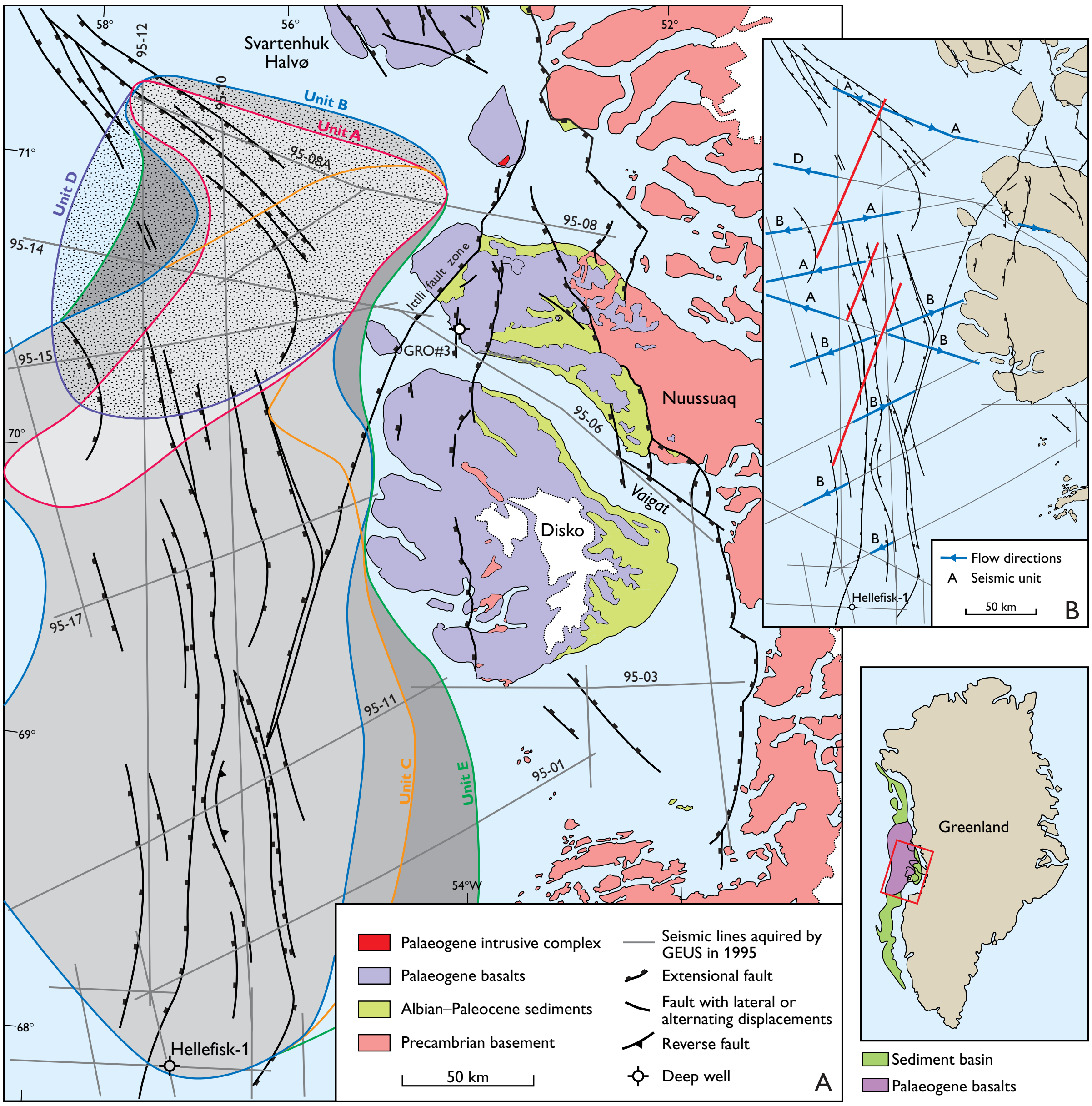


Fig. 1. **A**: Map of the study area showing structures at top volcanic level and the distribution of seismic units A–E. Onshore geology slightly modified from Chalmers *et al.* (1999). White areas are ice. **B**: The eruption zone in the offshore area marked by the en échelon segments interpreted from divergence of the volcanic foreset directions observed in seismic units **A**, **B** and **D** (indicated).

tinent boundary lies close to the west coast of Disko. This hypothesis may be tested by modelling two scenarios of ocean crust offshore Disko: a warm, Icelandic plume type and a cool, normal type. In the 'warm' model, Moho is assumed to lie at a depth of 25 km, and the continental crust has been terminated a short distance offshore. This model results in a difference between the calculated and measured gravity data of 120–160 mGal in the area of assumed oceanic crust. In the 'cool' model, the Moho is assumed to lie at a depth of 12–13 km. This model shows an even greater difference between calculated and measured gravity data amounting to 250–300 mGal. The most likely solution to reducing the excess mass in these models is by incorporating a layer of sediment. Further modelling was carried out assuming continental crust in the offshore

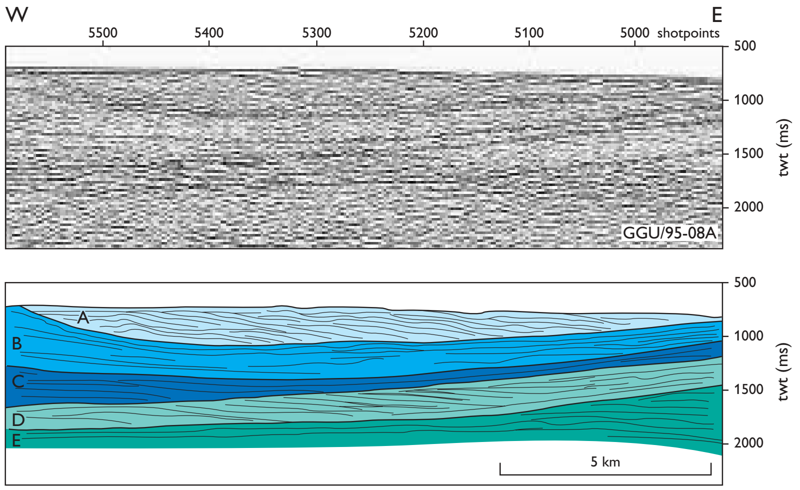


Fig. 2. Part of seismic line GGU/95-08A, just north-west of Nuussuaq. Several basin fill structures can be seen as seismic units **A–E**. In this area seismic unit A has a strongly downlapping appearance where the top reflection passes into eastward prograding facies. The vertical height of the downlapping units is 700–800 m, which is directly equivalent to the 700 m high foresets observed in the Vaigat Formation on the south coast of Nuussuaq (Pedersen *et al.* 1993).

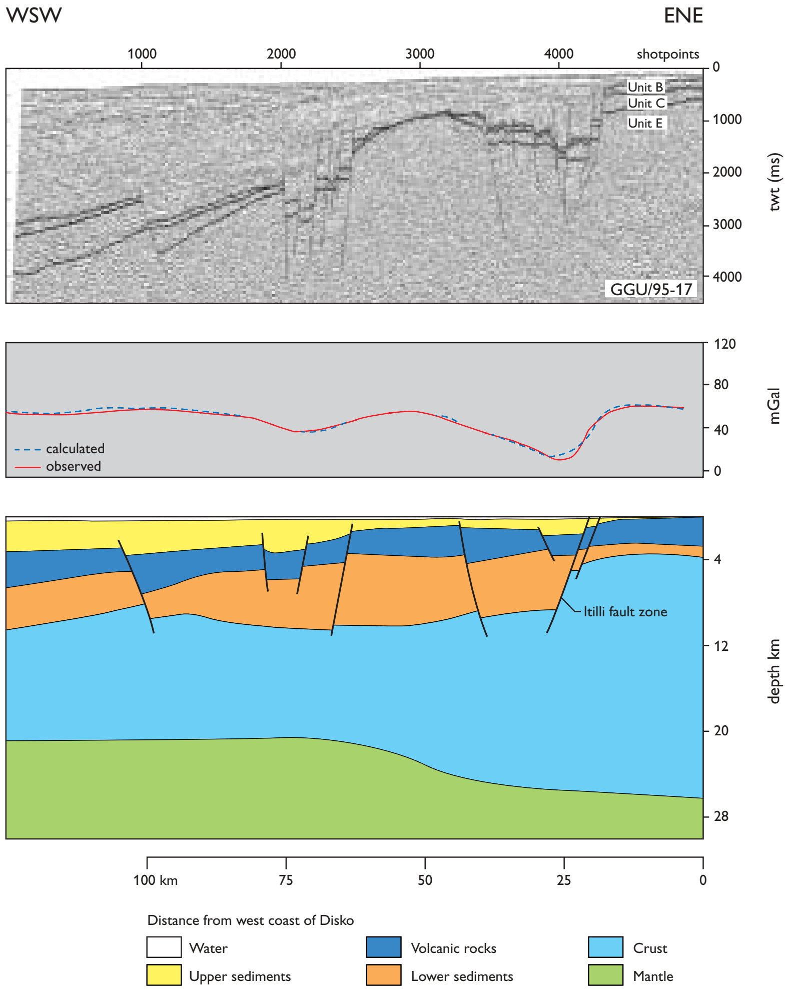


Fig. 3. Geological model of the region west of Disko based on gravity modelling assuming continental crust in the offshore area. Based on onshore geological data, a rather uniform thickness of 2.5–3.5 km has been assigned to the volcanic section. The depression in the gravity signal west of the Itilli fault zone is partly compensated by a postulated abrupt increase in thickness of the pre-volcanic sediments and by a change in the topography of the volcanic surface.

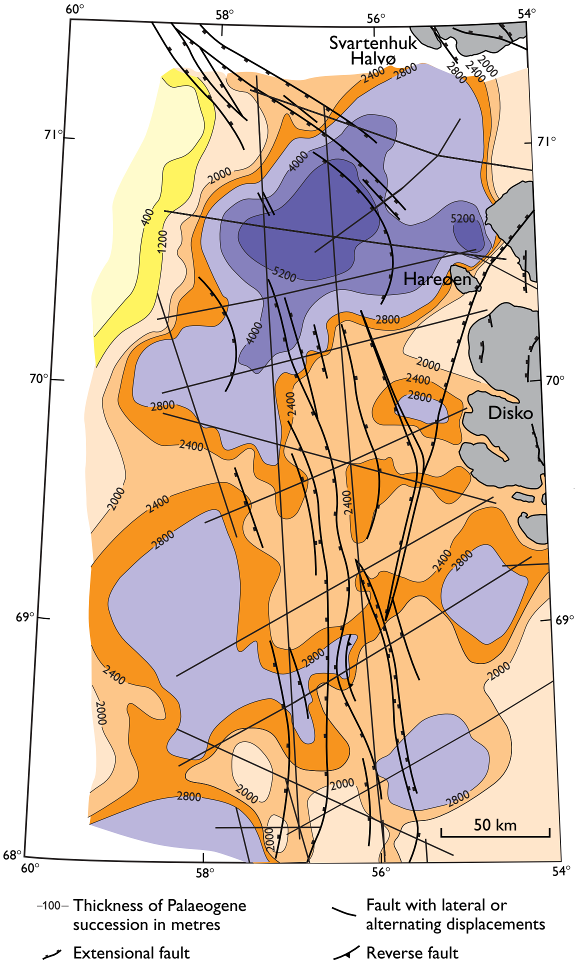


Fig. 4. Isopach map of the Palaeogene volcanic succession, based on the results of the gravity modelling. The isolines showing the thickness of the volcanic section curve around Disko and display thicknesses of 2.5–3.5 km, with a local maximum just west of Hareøen with more than 5 km. The determination of the base of the volcanic section is based only on gravity modelling, since it cannot be seen on the seismic data.

area and sediments between the volcanic rocks and the continental basement.

In order to further constrain the modelling, geological data from onshore Disko and Nuussuaq have been incorporated into the model shown in Fig. 3. The Palaeogene volcanic rocks on western Nuussuaq comprise the Maligât Formation (estimated thickness *c.* 3 km) and the 1–2 km thick Paleocene–Eocene Vaigat Formation (Chalmers *et al.* 1999). On the south coast of Nuussuaq, the GRO#3 well recorded at least 2700 m of Upper Cretaceous sediments below the volcanic rocks (Christiansen *et al.* 1999). Fifteen kilometres to the east of the GRO#3 well (Fig. 1A) a short seismic line shows at least 4.5–6 km, and possibly as much as 7–8 km of sediments below the volcanic section (Christiansen *et al.* 1995; Chalmers *et al.* 1999). Furthermore, the occurrence of sedimentary xenoliths and metallic iron in many volcanic rocks on western Disko, is strongly indicative of the presence of pre-volcanic sediments there (Pedersen 1981).

The resulting model (Fig. 3) shows a good correlation between the observed and calculated gravity data supporting the contention that the region offshore Disko and Nuussuaq is underlain by continental and not oceanic crust.

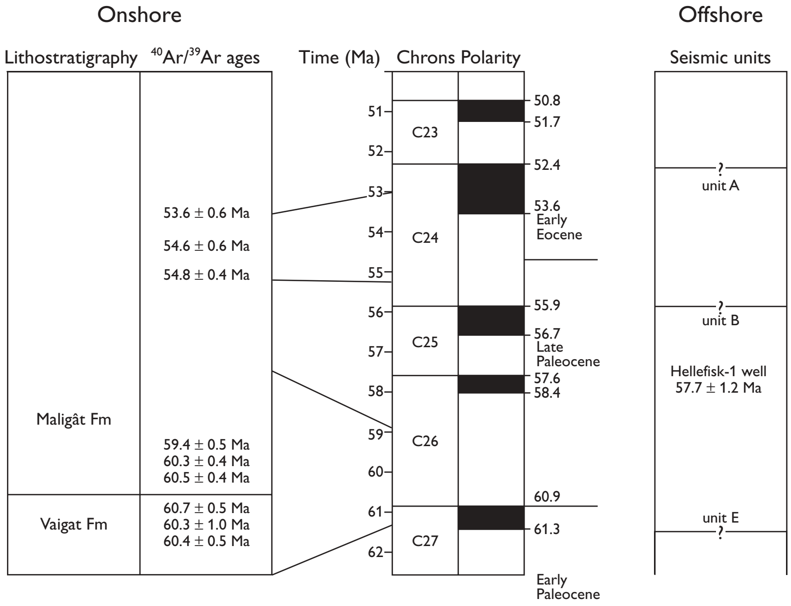
There is, of course, no unique solution to the gravity modelling. It must, however, be based on all available geological data and in the end show a good fit between the observed and calculated gravity data. The offshore volcanic succession thickens towards the west (Fig. 4). The sedimentary section below the volcanic rocks displays more or less the same outline as the volcanic rocks, where the sedimentary basin deepens very rapidly off the coast to attain a maximum thickness of 7–9 km (Fig. 3; Skaarup *et al.* 2000).

Dating of the offshore volcanic rocks

An estimate of the age of the offshore volcanic rocks can be given by comparing the seismic interpretation of the volcanic units in the offshore area with an Ar/Ar age determination from the offshore Hellefisk-1 well and with Ar/Ar and K/Ar age determinations and geomagnetic polarity determinations from onshore exposures.

Onshore, most of the exposed volcanic rocks were erupted in two phases (Storey *et al.* 1998; Riisager & Abrahamsen 1999). The first phase (represented by the Vaigat and Maligât Formations) between 60.7 Ma and 59.4 Ma and the second, mainly represented by dykes, between 54.8 Ma and 53.6 Ma (Fig. 5). Offshore, the uppermost seismic unit (unit A) is normally magnetised (Rasmussen 2002, this volume) and probably overlies the offshore equivalent to the youngest volcanic rocks on western Nuussuaq. The onshore volcanic rocks are reversely magnetised (Riisager *et al.* 1999) and were possibly erupted during magnetic chron C24r. Therefore, seismic unit A could have been erupted during chron C24n. Seismic unit B is interpreted to reach the Hellefisk-1 well, where an Ar/Ar date shows an age of 57.7 ± 1.2 Ma (Williamson *et al.* 2001), and seismic unit B could have been erupted during C25 at the latest, and more probably during C26.

Fig. 5. Overview of the onshore volcanic succession compared to the seismic units in the offshore area. The lithostratigraphy and ^{40}Ar/^{39}Ar ages are from Storey *et al.* (1998), the ^{40}K/^{40}Ar date for the Svartenhuk dykes from Geoffroy *et al.* (2001), the geomagnetic time scale from Cande & Kent (1995), the measurements of the magnetic chrons and reversals in the Vaigat and Maligât Formations from Riisager & Abrahamsen (1999) and Riisager *et al.* (1999) and the ^{40}Ar/^{39}Ar measurement from the Hellefisk-1 well from Williamson *et al.* (2001).



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