New structure maps over the Nuussuaq Basin, central West Greenland

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In 1992 the Geological Survey of Greenland (GGU) discovered bitumen in vugs and vesicles in Upper Paleocene basalts in western Nuussuaq (Christiansen *et al.* 1994). Since then the search for surface oil showings by GGU (from 1995 by the Geological Survey of Denmark and Greenland, GEUS) has resulted in finds over an area extending from northern Disko through Nuussuaq to the south-east corner of Svartenhuk Halvø (Christiansen *et al.* 1997, 1998, this volume). In addition, slim core drilling by GGU and grønArctic Energy Inc., the holder of an exclusive licence in western Nuussuaq, penetrated oil-saturated rocks at four localities (Christiansen *et al.* 1996). Encouraged by these results, grønArctic drilled a conventional exploration well (GRO#3) to 2996 m in 1996 (Christiansen *et al.* 1997), but details about this have not been released. The net effect of these efforts has been to dispel partially the formerly widespread view that the West Greenland area is entirely gas-prone and to promote the Cretaceous–Tertiary Nuussuaq Basin from being a model for what may occur in offshore basins to being a potential petroleum basin in its own right.

Evolving conceptions of the Nuussuaq Basin took a large step forward when GGU in 1994 acquired a 13 km 15-fold seismic line on the south coast of Nuussuaq (Christiansen *et al.* 1995). This showed a sedimentary section 6–8 km thick, much greater than the 2–3 km previously measured from onshore outcrops alone. This showed how little was understood about the structure of the basin, as well as where hydrocarbons might have been generated and where exploration could best be directed.

A first step to rectify this situation was taken in 1995 when multichannel seismic and gravity data were acquired by the Survey in Disko Bugt and the fjords north and south of Nuussuaq, as well as west of Disko (Christiansen *et al.* 1996). The new data have been integrated with older gravity, magnetic and seismic data from both onshore and offshore. This report summarises the results of interpretation of all available geophysical data together with a reappraisal of all available data on faults onshore. Detailed accounts are being published elsewhere (Chalmers 1998; J.A. Chalmers *et al.* unpublished data). Although the open spacing of the seismic lines and the almost total lack of reflections below the first sea-bed multiple on these lines make it impossible to present a definitive structural model at this stage, the structural style in the basin is now apparent and a number of the major structures in the area have been identified with confidence.

Geophysical data

The following geophysical data have been used in the interpretation presented in this report.

1. A 13 km long digital seismic line, GGU/NU94-01, along the south coast of Nuussuaq, acquired by GGU in 1994 using explosives as source and geophone detectors. Processing to stack stage only (Christiansen *et al.* 1995).

2. 711 km multichannel seismic data along eight lines in Disko Bugt, Vaigat and north of Nuussuaq (Fig. 1) acquired by the Survey in 1995 using the adapted high ice-class Danish Navy vessel *Thetis,* under charter to Nunaoil. Funding was provided by the Government of Greenland, Minerals Office (*now* Bureau of Minerals and Petroleum) and the Danish State through the Mineral Resources Administration for Greenland. The four lines in Disko Bugt were acquired using a 3 km digital streamer, but because of ice conditions in Vaigat and north of Nuussuaq only a 1200 m streamer could be deployed in these areas.

3. Single channel analogue seismic data and magnetic data acquired in 1970 by M.S. *Brandal* (Denham

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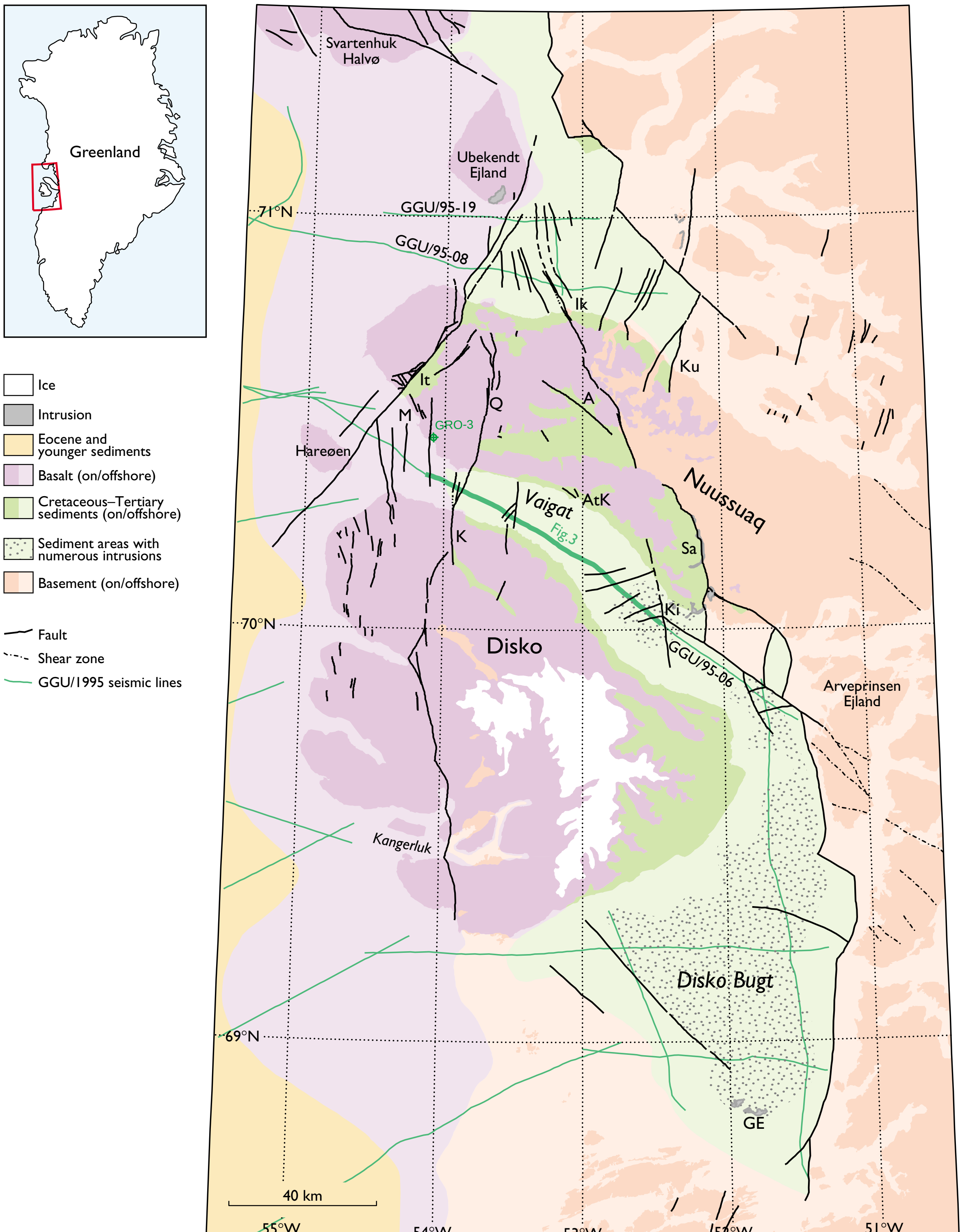

Fig. 1. Geological outcrop map (including outcrop at sea-bed) of the Disko–Nuussuaq area, showing also the position of the seismic lines acquired in 1995 and the GRO#3 well site. Place name abbreviations as follows: Ik: Ikorfat; Ku: Kuuk; It: Itilli; M: Marraat Killiit; Q: Qunnilik; AtK: Ataata Kuua; A: Agatdalen; Sa: Saqqaqdalen; K: Kuugannguaq; Ki: Kingittoq; GE: Grønne Ejland.

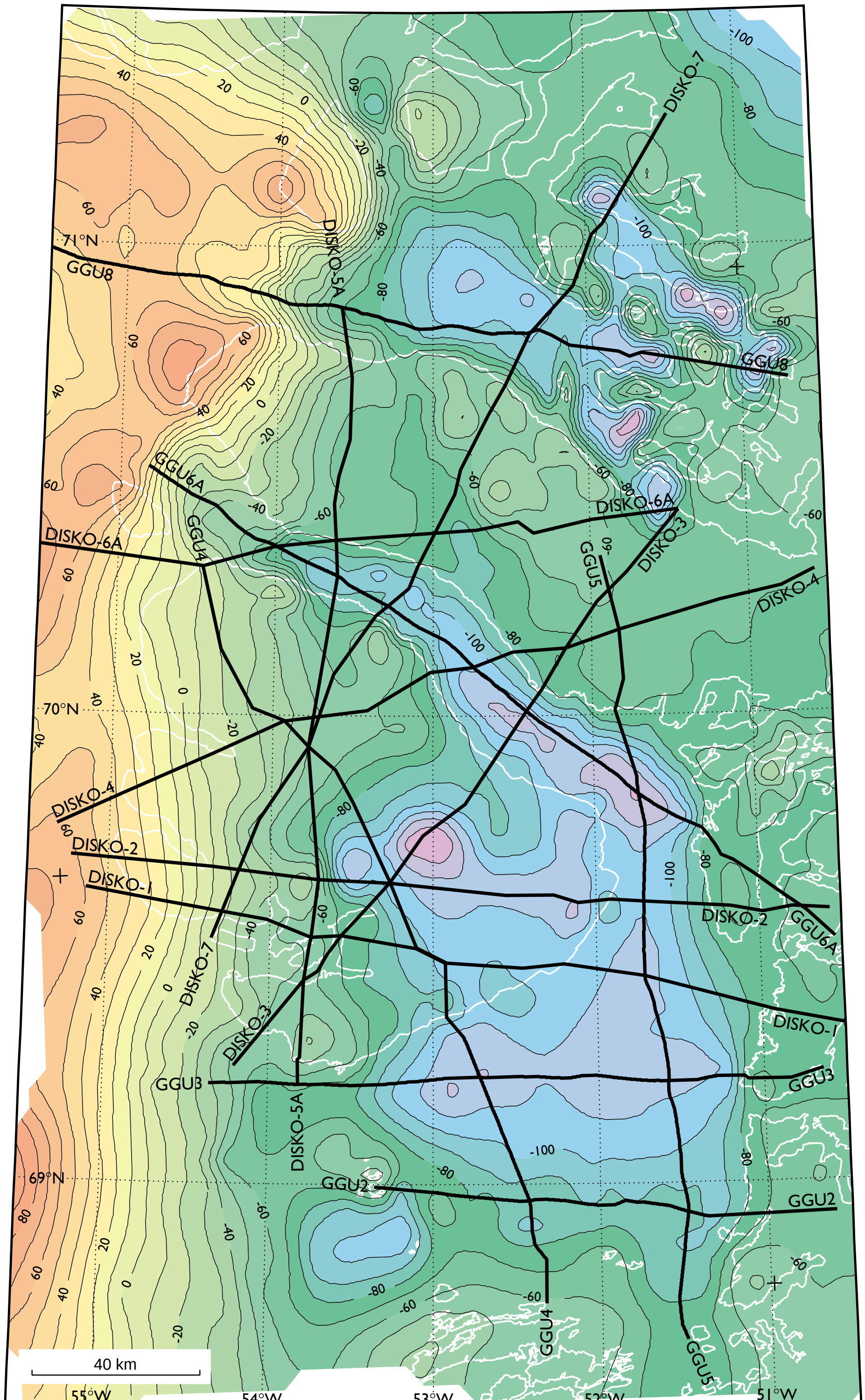

Fig. 2. Gravity anomaly map. Bouguer anomalies are shown onshore and free-air anomalies offshore. The labelled lines show the locations along which modelling was carried out to produce the depth to basement map shown in Figure 4. See Chalmers (1998) for details. Coastline shown by white lines.

1974) and in 1978 by M.V. *Dana* (Brett & Zarudski 1979). Navigation on *Dana* was by Transit satellites and Doppler sonar, but on *Brandal* only by dead reckoning and radar fixes of coastal features. There is thus an uncertainty of up to a few kilometres in the location of the *Brandal* profiles. The maximum depth of reflections that can be seen in the single channel data is about 500 metres.

4. Gravity data. New gravity data were acquired concurrently with the multichannel seismic data on the *Thetis* cruise. These data were integrated with all data in the archive of the Danish National Survey and Cadastre (KMS) to form a single data set (R. Forsberg, personal communication 1997). An anomaly map, shown in Figure 2, was then compiled using Bouguer anomalies onshore and free air anomalies offshore. Forward modelling of the gravity data was carried out along the lines also shown in Figure 2.

Seismic interpretation and mapping

The migrated multichannel data were interpreted on a Landmark work-station. The procedure adopted initially was to survey the profiles in detail by picking reflections without regard for their geological significance. During this procedure it was realised that, on the lines acquired using a 1200 m streamer, only very few real reflections were visible below the first sea-bed multiple. In Disko Bugt, where a 3 km streamer was deployed, many real reflections below the sea-bed multiple can be seen, but no unambiguous top basement reflector could be distinguished. In some areas it was not possible on the seismic data alone to distinguish between basement and basalt outcrops at sea-bed, but on the *Brandal* magnetic data the two areas are distinguished clearly. The basalt flows, and also dolerite sills, are generally reversely magnetised, while the basement gives a positive magnetic signature.

This initial procedure was supplemented by an examination of the single channel seismic data, on which boundaries between areas with outcrop of sediments and areas of crystalline rocks (basalt and basement) at sea-bed could be distinguished. Again, *Brandal* magnetic data were used to distinguish between basalt, basement and sills. With the onshore geological maps as further control, a simple sea-bed outcrop map was then prepared (Fig. 1).

Further interpretation of the multichannel seismic data, especially in areas of sediment, consisted of picking prominent unconformities, faults, dykes and sills, and sufficient sedimentary reflections to give a good image of the structure. The envelope of the deepest visible reflections was also picked to be used in the gravity modelling.

Supplementary examination of the single channel seismic data revealed several faults which could be tied to faults identified on the multichannel data. Furthermore, apparent dips in sediments in intersecting lines could be used to calculate true strike and dip of the beds.

Faults and related structures in the onshore area

An examination of all relevant maps, reports and field notes has been carried out with regard to locating faults in the onshore area. Some of the major faults had already been located, e.g. the Ikorfat–Saqqaqdalen fault (Ik–Sa, Figs 1, 4; Rosenkrantz *et al.* 1974; Pulvertaft 1989); others that appear on older maps (e.g. 1:500 000 sheet Søndre Strømfjord – Nûgssuaq) could not be substantiated. The main improvements in the new fault map arise from accurate field and photogrammetric mapping of the Tunoqqu Member and other distinctive contaminated basalt marker horizons in the Vaigat Formation, the lowest of the Paleocene volcanic formations in the area (Pedersen *et al.* 1996; A.K. Pedersen, manuscript maps). This has revealed a number of approximately N–S faults in western Disko and western Nuussuaq. The most important of these is the Kuugannguaq–Qunnilik fault (K–Q; Figs 1, 4), which has a post-Vaigat Formation downthrow to the west of 380 m in the south, decreasing to 200 m in central Disko, then increasing to 700 m in central Nuussuaq.

Another significant N–S trending fault with downthrow to the west runs just west of the GRO#3 well (Fig. 1); the net post-Vaigat Formation downthrow on this fault plus lesser faults to the west is of the order of 900 m.

In Agatdalen in central Nuussuaq there is a fault trending 125° which downthrows the Tunoqqu Member up to 300 m on the north-east side.

Two faults trending 124° and 161° have been observed on the south side of Nuussuaq west of Ataata Kuua (G. Dam, personal communication 1997). Both faults downthrow Upper Cretaceous sediments about 300 m to the north-east; neither fault displaces the Lower Paleocene Quikavsak Member nor the basalts above.

Another previously unrecorded fault crosses the south coast of Nuussuaq at Kingittoq. This has been drawn in a NNW direction to link with the Ikorfat–Saqqaqdalen fault in central Nuussuaq. The Cretaceous–Tertiary sediments at Kingittoq have been displaced by large landslides, so that the Kingittoq fault cannot be observed in outcrop, but a pre-basalt down-to-west fault is required because east of Kingittoq there are Cenomanian sediments dipping north-east (Croxton 1978), while to the west there are nearly horizontal Santonian – Lower Campanian sediments (Olsen & Pedersen 1991).

The Ikorfat–Saqqaqdalen fault is part of the Cretaceous boundary fault system in central West Greenland, so named because the fault system delineates the eastern margin of present-day outcrops of Cretaceous sediments in the area. At Ikorfat the displacement of the Tunoqqu Member by the fault is 500 m down to the west, while Lower Cretaceous sediments must be downthrown very much more than this.

The Ikorfat–Saqqaqdalen fault is linked to the Kuuk fault to the east by a ramp, in which the basement surface and overlying Upper Albian sediments dip 9–16° towards north and north-east and are overlain unconformably by almost horizontal Maastrichtian mudstones and extensive Paleocene basalts. The Upper Albian sediments were deposited in a succession of environments from fluvial through marine inner shelf and tidal estuarine to lacustrine deltaic, with no indication of a steep fault scarp to the east during sedimentation (Pulvertaft 1979; Midtgaard 1996). This is one of the indications that the area of Cretaceous sediments originally extended east of the boundary fault system. Three N–S to NNE–SSW trending faults, each with a downthrow of 350–400 m to the west, dissect the ramp.

The Itilli fault crossing Hareø and western Nuussuaq is the only major fault in the exposed area with a NE–SW trend. The maximum vertical displacement on the Itilli fault is more than 3000 m down to the north-west, but much of this is uplift confined to the axial zone of an eastward-plunging anticline on the south-east side of the fault. It has been suggested that the Itilli fault is a left-lateral splay of the Ungava Fracture Zone to the west and south-west (Chalmers *et al.* 1993).

Sub-surface structure offshore interpreted from seismic data

East, south and west of Disko

Basement is exposed at sea-bed south of Disko and around the margins of Disko Bugt (Fig. 1). To the south-west and west of Disko, basalts are exposed on the sea floor; farther to the west these become covered by Eocene and younger sediments.

In much of Disko Bugt, two different facies can be seen on the multichannel lines. Locally, units up to a few hundred metres thick contain continuous and strong reflections (facies 1). Over larger areas, there are only weak and discontinuous reflections from within the sediments (facies 2). Both facies are interrupted by numerous faults of no great throw. The Cretaceous Atane Formation, exposed onshore (Pedersen & Pulvertaft 1992), is either dominated by fairly monotonous fluvial sandstones which could give rise to facies 2, or consists of alternating mudstones, sandstones and coals laid down in a fluvio-deltaic environment, which could give rise to facies 1.

In places there are strong discontinuous reflections which are often reversely magnetised and so probably indicate sills and dykes similar to those exposed in Saqqaqdalen on Nuussuaq and on Grønne Ejland in southern Disko Bugt. The areas within which these reflections commonly occur are shown in Figure 1 with an overprint.

Vaigat

Facies 2 is also present at sea-bed in much of the south-eastern third of Vaigat, except at the south-eastern end where a small graben contains over 1500 m of facies 1. No fault that could be an extension of the Saqqaqdalen fault into Vaigat is visible on the seismic lines, so it is shown in Figure 1 as being terminated to the south by a fault that strikes about 120° along eastern Vaigat; this fault is indicated on *Brandal* seismic lines and is also modelled on gravity profiles.

North-west of the south termination of the Saqqaqdalen fault, the structural pattern visible on seismic line GGU/95-06 is different. Sections of facies 1 over 2 km in thickness are visible, dipping eastwards in fault blocks separated by faults with downthrow to the west (Fig. 3). Intersecting single channel lines show the shallowest parts of these reflections in many places and this has enabled several true dips to be calculated, the resulting values being 5°–18° towards north-east and east. The location of the faults that separate the fault blocks can also be seen on the single channel lines, enabling the faults to be mapped. Some of these faults are known onshore.

North-west of shot-point (S.P.) 6350 on seismic line GGU/95-06 (Fig. 3) basalts are exposed at sea-bed. In the GRO#3 well the base of the basalts is 294 m below sea level (Christiansen *et al.* 1997), and approximately offshore Marraat Killiit, where the first discovery of an oil seep was made, the basalts are only about 300–500 metres thick; below the basalts eastwards-dipping reflections can be seen.

North of Nuussuaq

North of Nuussuaq, reflection patterns similar to those visible in Vaigat can been seen. East of the offshore extension of the Itilli fault, fault blocks containing more than 2 km of facies 1 sediments (here most likely marine) are separated by faults that throw down to the west. Basalt is exposed at sea-bed along the west side of the Itilli fault extension. North of seismic line GGU/95-19, basement, sediments and basalt have been mapped on the sea-bed using the single channel seismic and magnetic lines.

Deep structure from gravity interpretation onshore and offshore

Modelling techniques

Modelling of the gravity data proved to be difficult and ambiguous and a detailed description of the techniques used, problems encountered and results obtained is provided by Chalmers (1998). Only a summary is given here.

Attempts at identifying a regional gravity field by interpolating between the observed gravity values over areas of known basement were ambiguous and inconclusive, so models that included the crust–mantle transition were calculated. Where basement is known to be exposed, the only spatial variable is the depth to Moho, which was adjusted until a satisfactory agreement between modelled and observed fields was obtained.

Gravity profiles were constructed along the seismic lines plus extensions for several tens of kilometres into areas where basement is exposed, either onshore or at the sea-bed as in the area south of Disko. Additional profiles were constructed from gravity observations that lie approximately along a straight line. The location of all these profiles is shown on Figure 2. Where possible, profiles were constructed in such a way that they passed over two areas of basement outcrop, in order to be able to interpolate the Moho (regional) profiles. However, there is no unambiguous calibration of the profiles west of the Disko gneiss ridge (Fig. 4), over western Nuussuaq and north of Nuussuaq. In these areas it is necessary to *extrapolate* in some way the regional gravity field (depth to Moho) from where it is constrained. The models in

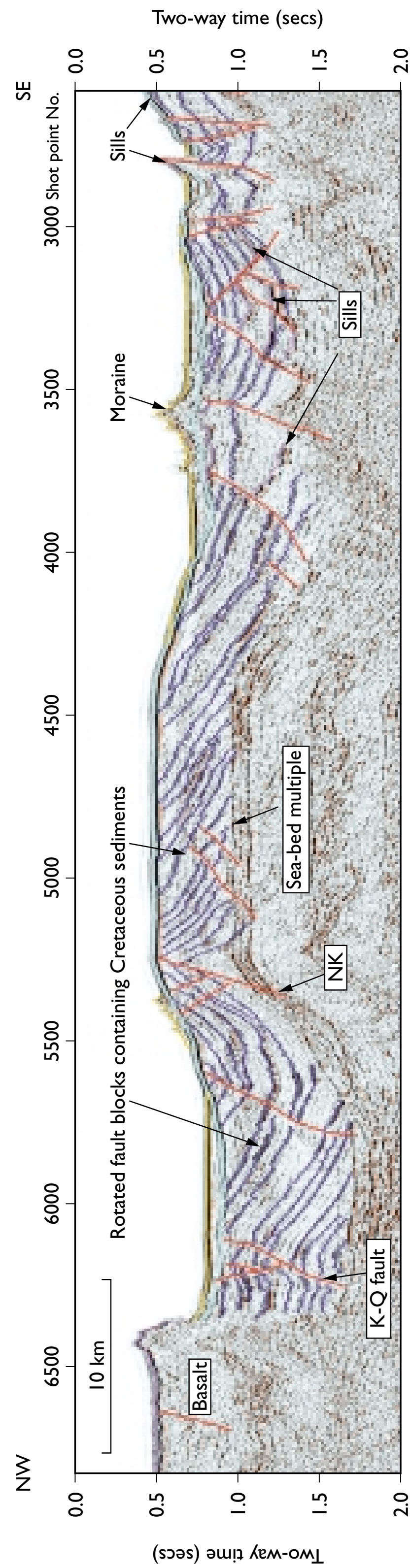

Fig. 3. Part of seismic line GGU/95-06 (outer part of Vaigat; Fig. 1). Facies 1 sediments (see text) can be seen separated into fault blocks, and the seismic response of basalts at sea-bed, a moraine, and sills can also be seen. K–Q: Kuugannguaq–Qunnilik fault; NK: a fault offshore Nuuk Killeq on the south coast of Nuussuaq where the subsurface of the hyaloclastite breccias drops about 400 m to the west in a monoclinal flexure (Pedersen *et al.* 1993). Red lines are faults

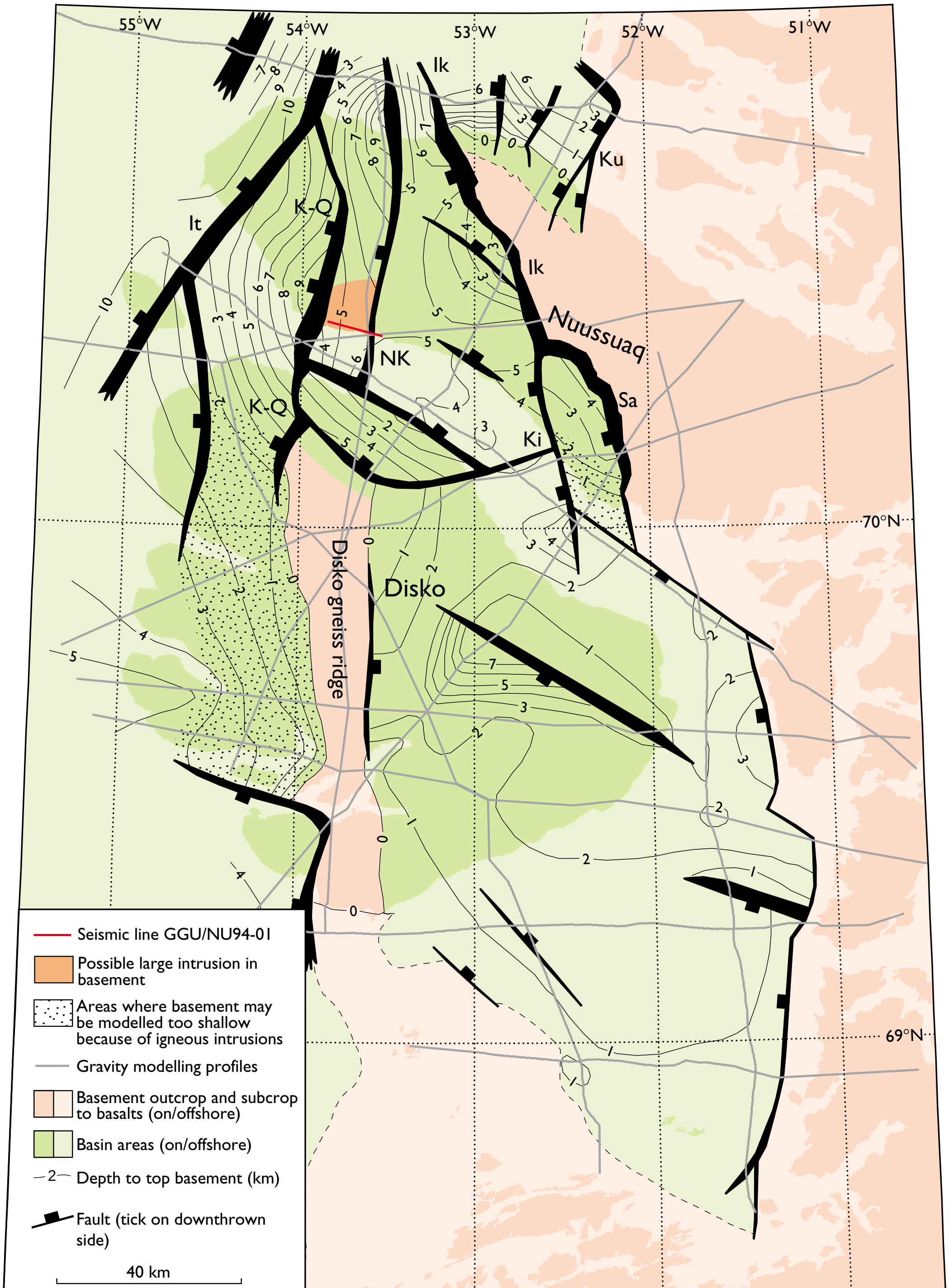

Fig. 4. Map of one interpretation of depth to basement obtained by forward modelling of gravity data along the profiles shown. Alternative interpretations are discussed in Chalmers (1998). Abbreviations on map as follows: It: Itilli fault; K–Q: Kuugannguaq–Qunnilik fault; Ik: Ikorfat fault; Sa: Saqqaqdalen fault; Ku: Kuuk fault; Ki: Kingittoq; NK: Nuuk Killeq, where the base of the hyaloclastite breccias drops 400 m to the west in a monoclinal flexure (Pedersen *et al.* 1993) and where a major fault can be seen on seismic line GGU/95-06 offshore (see Fig. 3). Width of fault symbol on map shows calculated heave.

these areas must therefore be treated circumspectly. Additional constraints on the gravity models are obtained from known outcrop limits of sediments, basement and basalts. A further constraint is the requirement that the modelled profiles should tie at their intersections.

Depth-converted interpretations from the multichannel seismic lines were used as starting points for modelling total sediment thickness, and in places the gravity model showed this to be depth to actual basement. However, in other places, lack of reflectivity in the deeper sedimentary section means that actual basement is deeper than 'acoustic basement'; where necessary, additional thicknesses of sediment were modelled until a satisfactory agreement between modelled and observed fields was obtained. In places, it was found necessary to make adjustments to the interpolated Moho profile in the basin areas.

The only constraint on the models west of the Disko gneiss ridge, over western Nuussuaq and north of Nuussuaq is the 13 km, 15-fold seismic line (GGU/NU94-01) on the south coast of Nuussuaq (Christiansen *et al.* 1995; Fig. 4). However interpretation of depth to basement on this line is ambiguous (Chalmers 1998) which means that two alternative models of depths to basement in north-western Disko, western Vaigat and western Nuussuaq have been produced, only one of which is shown here (Fig. 4).

Interpretation

Eastern Disko and Disko Bugt. Figure 4 shows depths to basement under eastern Disko and Disko Bugt to be generally less than 3 km. Depths to basement greater than 3 km are found only south-west of Arveprinsen Ejland and (possibly as great as over 7 km) under central Disko. However, the terrain in central Disko is alpine and capped with ice, so the somewhat simplified calculations carried out to produce the Bouguer anomalies mean that there may be considerable uncertainty in the accuracy of the gravity anomalies. The details of the modelling in this area are therefore very uncertain. The interpretation shown here implies the existence of a shallow basement ridge that strikes NW–SE under north-eastern Disko.

West of the Disko gneiss ridge. The modelling shows that the Disko gneiss ridge is bounded by faults to its north-west (the Kuugannguaq–Qunnilik fault (K-Q), which is known at outcrop) and south-west. The map in Figure 4 shows top basement dipping to the west at about 6°–10° from the central part of the ridge. It is difficult to reconcile the contours drawn through these lines with those drawn farther south, without either a fault or an area of steep contours, so a fault has been drawn striking 115°–120° under Kangerluk (Figs 1, 3).

Basalt thickness is controlled to within a few hundred metres from outcrop stratigraphy. However, it is possible that there are large numbers of Tertiary intrusions in the basement and sediments west of the Disko gneiss ridge, which would have the effect of raising its average density. In consequence, it is possible that the depths to top of basement west of the Disko gneiss ridge should be deeper than those shown on Figure 4. If so, it is possible that more of the western limit of the Disko gneiss ridge than shown here is formed by faulting, and that the Kuugannguaq–Qunnilik fault may continue southwards along the west margin of the ridge with larger throw at top of basement than is observed at basalt outcrop. In this case, the fault striking 115°–120° in Kangerluk is an artefact of the uncertainty in gravity modelling and has more to do with the intensity of igneous intrusions in the basement than with structure at top of basement. Areas where basement may be modelled too shallow because of igneous intrusions are shown on Figure 4 with an overprint.

Northern Disko, Vaigat, western Nuussuaq and north of Nuussuaq. The map shown in Figure 4 is one of two alternative interpretations of the gravity data. Space does not allow a detailed discussion of the alternatives here, and the interested reader is referred to Chalmers (1998).

Comparison of Figures 1 and 4 shows which faults are known at outcrop and which are modelled entirely from the gravity data. As discussed earlier, the gravity models are not well controlled in this area, and it is likely that many details will have to be revised as exploration proceeds. However, the general pattern of faults shown in Figure 4 is probably a reasonable approximation to the truth. In particular, there must be one or more faults that strike roughly NW–SE near the north-east coast of Disko that throw basement down from the Disko gneiss ridge to where thick sediments are known under Vaigat and Nuussuaq. These faults form a southern limit to an area where the sediments are generally much thicker than they are to the south and east.

Development of structure

The general trend of the fault system that marks the present-day boundary of sedimentary outcrops to the east is NNW–SSE, but components of this fault system also have WNW–ESE and *c.* N–S trends.

Within the basin, three main fault trends are evident. Firstly, a N–S trend is apparent. This especially defines the Disko gneiss ridge and its effect on the basalts shows that faulting with this trend was active at a late stage in basin development.

A second trend lies between WNW–ESE and NW–SE. This is the trend of several shear zones in the Precambrian basement east of Disko Bugt (Fig. 1), suggesting that these old shear zones exerted an influence on later faulting.

The third trend is NE–SW along the Itilli fault in western Nuussuaq that probably connects with the Ungava Fracture Zone farther south-west (Chalmers *et al.* 1993).

At present the sequence of events that created the Nuussuaq Basin is not entirely clear. There appears to be a deep basin under western Disko, western Nuussuaq and Vaigat that extends northwards beyond where it can be delineated by present data. There may also be a deep half-graben under central Disko east of the Disko gneiss ridge. A much more extensive and shallower basin extends over eastern Disko and Disko Bugt.

It is possible that the deep basin in the north-west is a rift basin, a hypothesis supported by the Moho being shallow in this area. In this case the more extensive, shallower basin could represent the thermal subsidence ('steer's head') phase of this rifting episode during which the Atane Formation was deposited.

These basins were then dissected by a new rift phase in the Maastrichtian and Early Paleocene (Rosenkrantz & Pulvertaft 1969; Pulvertaft 1989; Dam & Sønderholm 1998) which created the faults that form the present eastern limit of the basin, and faulted and rotated the facies 1 sediments into the fault blocks visible on line GGU/95-06 in Vaigat and on lines GGU/95-08 and GGU/95-19 north of Nuussuaq as well as onshore Nuussuaq. These faults trend between WNW–ESE and NW–SE, and N–S.

The rift blocks were eroded before being covered by Late Maastrichtian – Early Paleocene sediments and voluminous Late Paleocene basaltic lavas. These were in turn dissected during the Eocene by faults along a N–S (reactivated?) and a new NE–SW (Itilli) trend probably connected to plate tectonic movements of Canada relative to Greenland. This tectonic activity probably subsided during later Palaeogene times and the area appears to have been uplifted by 1–2 km during the Neogene to its present situation.

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