DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/31

Project Fjord Seis:

An evaluation of the structure and petroleum potential of Disko, Nuussuaq and the surrounding fjord areas, central West Greenland

James A. Chalmers and Christian Marcussen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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Introduction

This report is a summary for the Mineral Resources Administration for Greenland and the Government of Greenland, Minerals Office of the results of interpreting seismic and gravity data in order to evaluate the structure and petroleum prospectivity of the sedimentary basins onshore and in the fjord areas of central West Greenland (the Nuussuaq and Disko Bugt Basins).

The background for the report is the series of petroleum activities in the Disko Bugt/-Nuussuaq area that started with the discovery by GGU in 1992 of oil in basalts on the Nuussuaq peninsula (Fig. 1) (Christiansen *et al.*, 1993). The discovery was subsequently extended by GGU both at outcrop and by drilling (Christiansen *et al.*, 1994) and by the exploration work carried out by grønArctic Energy Inc. in their various licences (Christiansen *et al.*, 1996), which included the drilling of 3 slim-hole wells in 1995 and a full-scale exploration well in 1996. The discovery of oil has revised the existing opinion that the whole of the West Greenland area is gas-prone and in particular has promoted the Nuussuaq Basin from being merely a model for what might be found offshore to being an exploration province in its own right.

New aerogravity data (Forsberg & Brozena, 1992) and a single short seismic line acquired by GGU in 1994 on the south coast of Nuussuaq (Christiansen *et al.*, 1995) showed that the sediments in the basin are probably much thicker (6-8 km) than the previously known 2-3 km exposed onshore. In addition, little is known of the sub-surface structure of the basin. Magneto–telluric data and aeromagnetic data acquired by grønArctic in 1995 and 1996 respectively have improved this situation to some extent, but these data are limited to only part of the basin. There were no data that could be used to understand the structure of the basin as a whole and that could point the way to where hydrocarbons may have been generated and where future exploration could best be carried out.

In order to provide such information, in the summer of 1995 GGU acquired 711 km of multichannel seismic and gravity data in Disko Bugt, Vaigat and in the fjord north of Nuussuaq. The data were acquired using the Danish Navy ship 'Thetis' under charter to Nunaoil and acquisition was financed by funds provided by the Government of Greenland, Minerals Office and the Danish State through the Mineral Resources Administration for Greenland. Originally it was planned to acquire seismic data farther north, both east and west of Ubekendt Ejland and east of Svartenhuk Halvø, where the GGU borehole Umiivik-1 was drilled in 1995 (Bate & Christiansen, 1996), but Thetis' captain did not wish to sail in these poorly charted waters. The seismic lines used in this report are shown on Fig. 1.

Interpretation of the multi-channel seismic and gravity data has been supplemented with single-channel seismic data acquired by GGU in 1972 (Denham, 1974) and 1979 (Brett & Zarudzki, 1979), gravity data from KMS and a new evaluation of the fault pattern at onshore outcrop.

Interpretation

Multi-channel seismic data

Thick glaciers once covered what is now the sea-bed in Disko Bugt and the fjords north and south of Nuussuaq. The weight of this ice compressed the sea-bed, making it very hard, so that it is now a very strong reflector of seismic energy. This means that the multiple energy formed by repeated reflections between the sea-bed and sea surface are very strong. It has been possible to attenuate them to some extent in Disko Bugt where a 3 km long streamer was used. Because of the many icebergs in Vaigat and north of Nuussuaq, it was possible to tow a streamer only 1200 metres long, which is too short to attenuate the sea-bed multiples, so in these areas only reflections from shallower than the first multiple are visible. Luckily, the water in these areas is deep, so in many places around a kilometre of sediment is visible on the seismic sections.

The sections were interpreted in the normal way on a "Landmark" work-station. Prominent unconformities, faults and sufficient reflectors between the unconformities to delineate the sedimentary structure were picked.

Disko Bugt. There appear to be two seismic facies with distinctly different internal reflection patterns, termed Facies 1 and Facies 2. In much of Disko Bugt there are only weak and discontinuous reflections from within the sediments. This facies is referred to Facies 2 (Fig. 2). Because of the weak reflections, it is difficult to identify the base of these sediments with any certainty, so it is difficult or impossible to ascertain the thickness of the units containing Facies 2 from the seismic data alone. In places, there are strong, discontinuous reflections (Figs 2 & 3), probably from sills and dykes similar to those exposed in Sarqaqdal (Nuussuaq) and on Grønne Ejland in southern Disko Bugt.

In places in Disko Bugt, Facies 2 is overlain by Facies 1, from which there are much more continuous and strong reflections (Fig. 2). In Disko Bugt, Facies 1 is present only locally and is nowhere thicker than a few hundred metres. Both facies are interrupted by numerous faults of no great throw.

Onshore, Cretaceous sediments exposed in Disko and southern and central Nuussuaq belong to the so-called Atane formation. This occurs in two rather different facies. In eastern Disko, there are thick sequences of fairly monotonous, fluviatile sandstones. These could give rise to Facies 2. In other places, the Atane Formation consists of alternating sandstones and mudstones or coals, laid down in a fluvio-deltaic environment. Such sediments could appear on seismic sections like Facies 1.

Vaigat. Facies 2 is also present at sea-bed in much of the eastern third of Vaigat (seismic line GGU/95-06) except at the eastern end where a small graben contains over 1500 metres thickness of Facies 1 (Fig. 2, seismic line GGU/95-05, S.P.s 5150 to 5700). However, west of shot point 2700 on line GGU/95-06 (Fig. 1) the structural pattern visible on line GGU/-95-06 is different. Sections of Facies 1 over 2 km in thickness (Fig. 3) are visible dipping eastwards in fault-blocks separated by faults that throw down to the west.

Seismic line GGU/NU94-01 was acquired by GGU in 1994 on the southwest coast of Nuussuaq. Line GGU/NU94-01 is roughly parallel to and about 8 km north of line GGU/-

95-06 between approximately S.P.s 5500 to 6200. This is within the region of the fault-blocks (Fig. 3).

In general, line GGU/NU94-01 shows a sedimentary succession with apparent dip 6-16° towards the east (Fig. 4), which agrees with the structural information at the surface where deltaic Cretaceous sediments are exposed. What may be a large fault can be interpreted below 2.5 sec. TWT on the eastern part of the section. The extrapolation of this fault reaches surface at Nuuk Killeq where the top of Cretaceous sediments rises suddenly 400 m to the east (Pedersen *et al.* 1993). Approximately 1.5 km west of the data coverage on the line, a fault is observed at the surface that throws basalts down to the west (Pedersen, *et al.*, 1993), and this may be the same large fault visible on line GGU/95-06 at approx. S.P. 6100. It is therefore likely that line GGU/NU94-01 lies on the rotated fault-block visible on line GGU/95-06 between S.P.s 5300 and 6100.

A marked change in average velocities takes place at the unconformity visible on line GGU/NU94-01 at two-way times (TWT) between 0.7 secs at the west end of the section and 1.1 secs at the east end (Fig. 4) (Christiansen *et al.*, 1995) which corresponds to depths between about 1 and about 2 km. The stratigraphic thickness of the non-marine and marginal marine Cretaceous sediments exposed on Disko and Nuussuaq is only about 2-3 km and older sediments are not known from outcrops. This may indicate that the unconformity marks the base of the Atane Formation.

What lies below the unconformity can only be a matter of speculation. There is another pattern of strong reflections at about 2.5 secs TWT. The sediments between 1 and 2.5 secs TWT could be Cretaceous, perhaps corresponding to the Appat and/or Kitsissut sequences offshore (Chalmers *et al.*, 1993). Alternatively, they could be Ordovician limestones comparable to those exposed in eastern Canada (Bell & Howie, 1990), erosional remnants of which are found in Greenland (Stouge & Peel, 1979). However, geochemical fingerprints in the Tertiary basalts show that they have definitely passed through clastic and organic-rich sediments but there are neither geochemical nor petrographic fingerprints from carbonate sediments (A.K. Pedersen, pers. comm.) It is therefore possible that the sediments are completely unknown, possibly of Mesozoic age.

What lies below 2.5 secs TWT is not clear on the seismic evidence alone. However gravity modelling (see below) suggests that basement is situated at a depth of around 5-6 km, so the deeper reflections visible on line GGU/NU94-01 appear to come from within basement, possibly from a sill or other intrusion.

The evidence from seismic line GGU/NU/94-01 suggests that the easterly-dipping, block-faulted, Facies-1 sediments visible on seismic line GGU/95-06 between approximately S.P.s 3000 and 6400 (Fig. 3) belong to the Atane Formation, but that beneath them lie 3-4 km of unknown sediments.

West of S.P. 6350 on seismic line GGU/95-06 (Fig. 3) basalts are exposed at sea-bed. Between S.P.s 7100 and 7900 the basalts are only about 300-500 metres thick and eastwards-dipping reflections can be seen from below them (Fig. 5). This area is approximately offshore from Maaraat Killit, where the first discovery of an oil seep was made (Christiansen *et al.*, 1994).

North of Nuussuaq. On lines GGU/95-08, GGU/95-18 and GGU/95-19, north of Nuussuaq, reflection patterns similar to those on line GGU/95-06 can be seen (Fig. 6). The eastern parts of the lines show fault-blocks containing thick (> 2 kms) Facies 1 divided by faults that throw down to the west. Basalt is exposed at seabed along the western parts of the lines, but here no sedimentary reflections can be seen from below the basalts.

Gravity interpretation

A gravity map of the area is shown in Fig. 7. Bouguer anomaly data have been used onshore and free air data offshore. Inspection of the map over areas of known basement exposure shows that the regional anomaly in the Disko Bugt area is very low, of the order of -60 mgals. In order to calculate the gravity effect of the sediments, an estimate must first be made of the regional field, and that subtracted from the measured field. In many parts of the world the regional field is fairly simple, linear or changing only slowly with distance. Much time was used to discover that the regional field in Disko Bugt is not simple, so an alternative interpretation technique had to be used.

It was assumed that the low regional values over areas of known basement are due to overthickened continental crust. This implies that the Moho is at a greater depth than would be the case if the area is in isostatic equilibrium. A number of hypotheses have been devised as to why this should be the case, but none of them have yet been tested, so they remain conjectures. At present, this condition is used as an assumption.

A "reference model" consisting of 30 km thick continental crust of density 2700 kg/m^3 overlying mantle of density 3200 kg/m^3 was used. Calculated depths to Moho are all referred to this model, which means that if the assumed Airy isostacy depth to Moho of 30 km is wrong, the calculated depths to Moho will be correspondingly wrong. However they will all be wrong by the same amount, so the regional field calculated from Moho depths will still be correct.

The depths to the Moho were first calculated in the areas where basement is exposed onshore in eastern Disko Bugt. The basement exposure along the so-called "Gneiss Ridge" on Disko (Fig. 9) was found to be a crucial feature, because calculation of depths to Moho under that feature allowed the regional field to be interpolated across the sedimentary basin under Disko Bugt and under eastern Disko.

Another essential calibration point was seismic line GGU/NU94-01 shot by GGU in 1994 on the south coast of Nuussuaq (Fig. 4). It showed two alternative depths to basement, the shallower at about 5-6 km (2-2.5 secs TWT) and the deeper from 7-8 km (3.2-3.6 secs TWT). Calculations of depth to Moho based on these two estimates show that the second is less likely, since it would imply that the Moho under seismic line GGU/NU94-01 is nearly 20 km shallower than that under the Gneiss Ridge only 20 km to the south. The assumption that basement is 5-6 km down under line GGU/NU94-01 implies that the Moho is only 10 km shallower.

The gravity calculations were made along a number of profiles as shown in Fig. 8. The profiles along the seismic lines were extended onshore using data from KMS. Other profiles were constructed by joining KMS gravity stations onshore and points along various measured profiles offshore. Sediment thicknesses observed on the seismic lines also provide control on the models. In particular, it was found that the highest sediment density that was consistent with the observed thicknesses and measured gravity fields is 2200 kg/m^3, and this figure has been adopted for the density of sediment on all the profiles. If real sediment densities are lower, calculated depths to basement are too large, so the map in Fig. 8 shows maximum depth to basement.

All of the profiles over and east of Disko cross exposed basement over at least two different parts of the lines to enable the regional field to be interpolated. Where these profiles extend west of the Gneiss Ridge, the regional field has been extrapolated, a more uncertain procedure, so the modelled profiles west of the Gneiss Ridge are less reliable than those to its east.

Similarly, the profiles running across the Gneiss Ridge and over the area of exposed basement in eastern Nuussuaq enable the regional field in eastern Nuussuaq to be interpolated and the profiles passing through seismic line GGU/NU94-01 are controlled by it.

Additional control is provided because the modelled profiles must be consistent where they intersect.

In this way, a model in three dimensions was calculated over eastern Disko, Disko Bugt, eastern Vaigat and eastern Nuussuaq. It is then possible to extend the model to some extent west of the gneiss ridge and north of Nuussuaq. The farther the extrapolation, the less control there is on the model, and it was felt that seismic line GGU/95-08, north of Nuussuaq was the farthest north that extrapolation could be justified.

Some control of the modelling west of the Gneiss Ridge is provided by the known basalt stratigraphy in this area (A. K. Pedersen, pers. comm.) which provides control on basalt thickness. The geochemistry of the erupted volcanics in this region shows that they have passed through sediments, so some thickness of sediments must exist under the basalts. Control is lost and modelling becomes increasingly unreliable west of the west coast of Disko.

A map of maximum depth to basement resulting from these calculations is shown in Fig. 8. Calculated depths are probably reliable to about ± 15% vertically and the locations of large faults are probably reliable to about ± 5 km horizontally.

Single-channel seismic data

The single-channel seismic data are of fairly poor quality, and a reflected signal is visible only from the uppermost few hundred milliseconds of sediment. However their areal coverage is much more comprehensive than that of the multi-channel data so they are extremely useful in delimiting the fault pattern at sea-bed and the dips and hence shallow structure within the sediments. This has enabled us to extend offshore fault patterns known onshore, and to map the extent at outcrop of sedimentary patterns and faults visible on the multi-channel data. This work is continuing, and will result in a new 1:500 000 scale geological map of Disko, Disko Bugt, Nuussuaq and the area between Nuussuaq and Ubekendt Ejland.

Structure

Fig. 8 shows that faults in the Disko Bugt - Uumaanaq Fjord area trend in three directions. The dominant trend that outlines the boundary of the basin, especially in the east, is northwest-southeast.

Within the basin, a north-south trend is apparent. This especially defines the Disko Gneiss Ridge and its effect on the basalts shows that faulting in this trend was active at a late stage in basin development.

The third trend is northeast-southwest along the Itilli Fault in western Nuussuaq that connects with the major Ungava system farther southwest (Chalmers *et al.*, 1993; Whittaker 1995).

At present the sequence of events that created the Nuussuaq/Disko Bugt Basin is not entirely clear. There appears to be a deep basin under western Disko, western Nuussuaq and Vaigat that extends northwards beyond where present data can delineate it. There appears to be also up to more than 3 km of sediment under central Disko east of the Gneiss Ridge. An areally much larger and shallower basin extends over eastern Disko and Disko Bugt.

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

These basins were then dissected by a new rift phase, probably in the latest Maastrichtian and Early Paleocene (Rosenkrantz & Pulvertaft, 1969; Pulvertaft, 1989; Dam & Sønderholm, in press) which created the faults that form the present eastern limits 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 NW-SE and N-S

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

Petroleum prospectivity

The area can be divided into a number of structural provinces each with implications for prospectivity. The areas are shown on Fig. 9.

Area A

Area A is north-west of the Itilli Fault. Oil seeps at the surface may indicate the presence of mature source rocks within Area A, or they may indicate oil migrating into Area A from areas offshore or from Area B. Because of the known severe thermal alteration along the Itilli Fault Zone, the latter hypothesis is thought less likely. However, in area A, the basalts are probably several (>3) km thick, which means that any potential sedimentary reservoirs are likely to be buried too deeply to be economic targets at this stage of exploration of the basin. If economic quantities of oil are found elsewhere in the basin, exploration of Area A may become worthwhile at a later stage.

Area B

Area B extends SW-NE on the southeast side of the Itilli Fault from northwestern Disko across Vaigat and western Nuussuaq and extends offshore by an unknown amount to the north of Nuussuaq. It also extends along Vaigat and onto northern Disko north and north-east of the Disko Gneiss Ridge. This is the area in which most indications of oil at the surface have so far been found. Total sedimentary thickness is large, over 5 km in places, and the sediments are divided into large, rotated fault-blocks which could provide structural traps. Facies 1 within these fault blocks could indicate the type of alternating sandstone/mudstone lithology that could provide reservoirs and seals.

Oil has been found in surface outcrops of basalt at a large number of locations in western Nuussuaq and at a few locations in western Disko. Chemical analysis shows that these oils are of 5 different types (Christiansen *et al.*, in press). An additional show of petroleum was encountered at Serfat on the north coast of Nuussuaq where a shallow well being drilled to investigate platinum in sills suffered a blow-out of wet gas which must have come from a Cretaceous source rock. The ages, depositional environments and lateral extent of the source rocks responsible for these oils are unknown. It is difficult, therefore, to indicate where in the basin they may be found. However, for them to be mature, they have to be buried to a certain minimum depth, and this implies that they will be not be mature where depths to basement are low. A somewhat arbitrary depth-to-basement of 2 km has been used to divide Area B from area C.

Area C

Beween Area B and the Sarqaq-Ikorfat Fault in eastern Nuussuaq are two segments of Area C which may resemble Area B, but in which the sediments are much thinner (< 2 km). It is unlikely that oil is being generated in this area, but could have migrated in from mature source rocks in area B.

Area D

At the southeastern end of Vaigat is Area D where a graben containing thick Facies 1 sediments is seen on both line GGU/95-05 and line GGU/95-06. This could be an eastern extension of the fault-block structural style seen in Area B and could therefore be interesting. However the area is small, perhaps too small to generate interesting quantities of hydrocarbons. It is also entirely offshore.

Area E

East of the the Disko Gneiss Ridge is the large Area E. Calculated depth to basement over much of the offshore area is less than 2 km and the facies observed on most of the seismic coverage in this area is Facies 2, which is probably very uniform in lithology. If this lithology consists of thick sands like those known at outcrop in eastern Disko, there seems little opportunity for either seals or source rocks. If the uniform lithology consists of mudstones, there seems little room for reservoir rocks. Where depth to basement is less than about 2 km, there is probably insufficient overburden for any potential source rock to be mature.

Under eastern Disko is an area where depth to basement has been calculated to be more than 3 km and where, therefore, source rocks could be mature. Unfortunately much of this area is under alpine mountains and icecaps. Oil generated here could migrate laterally into traps along the eastern flank of the Gneiss Ridge and under eastern Disko. Such traps are likely to be subtle and difficult to find and will certainly require careful exploration using geophysical techniques.

Area F

Area F lies in western Disko, west of the Disko Gneiss Ridge. It is not clear if this area is different from Area B, nor where the border between it and Area B should be placed. The reason for making it into a separate area from Area B is simply that what is known about it is based only on surface observations and gravity modelling, and conclusions are therefore much less reliable than those about Area B.

Gravity modelling suggests that the northwestern (in Area B) and southwestern margins (in Area F) of the Disko Gneiss Ridge are large faults throwing as much as 4 km down to the west (Fig. 8), but that any faulting along the central western margin of the Gneiss Ridge is much smaller. The models show basement dipping westwards at an angle of about 4°-6°, which could indicate a uniform slope or a series of small faults with downthrow to the west. Basement is more than 2 km below sea-level west of about 20 km west of the Gneiss Ridge and reaches more than 4 km below sea-level another 20 km farther west.

Mature source rock, reservoirs, seals and traps could all be present in this area. A negative factor is the intensity of volcanism that has taken place here. This appears to be where many of the eruptions that sourced the Disko basalts took place. There is evidence in the form of native iron in the basalts that there has been considerable interaction between the ascending magmas and the sediments. Any such interaction will have destroyed source rocks and existing hydrocarbon accumulations. It is not clear what proportion of the area has been affected by such volcanic activity and how much potential remains.

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Figures

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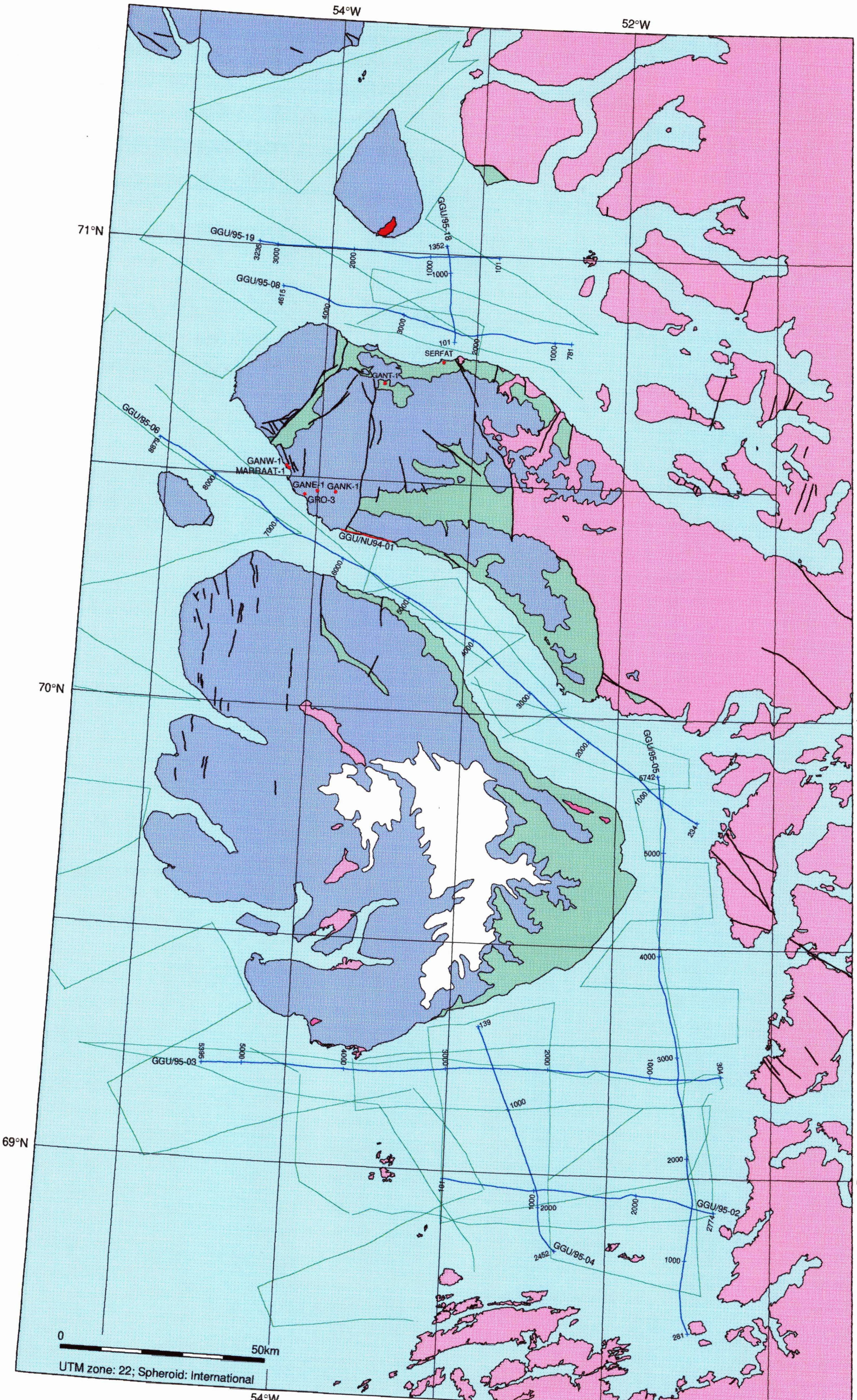

Fig. 1: Simplified geological map showing the position of the multichannel and shallow seismic lines

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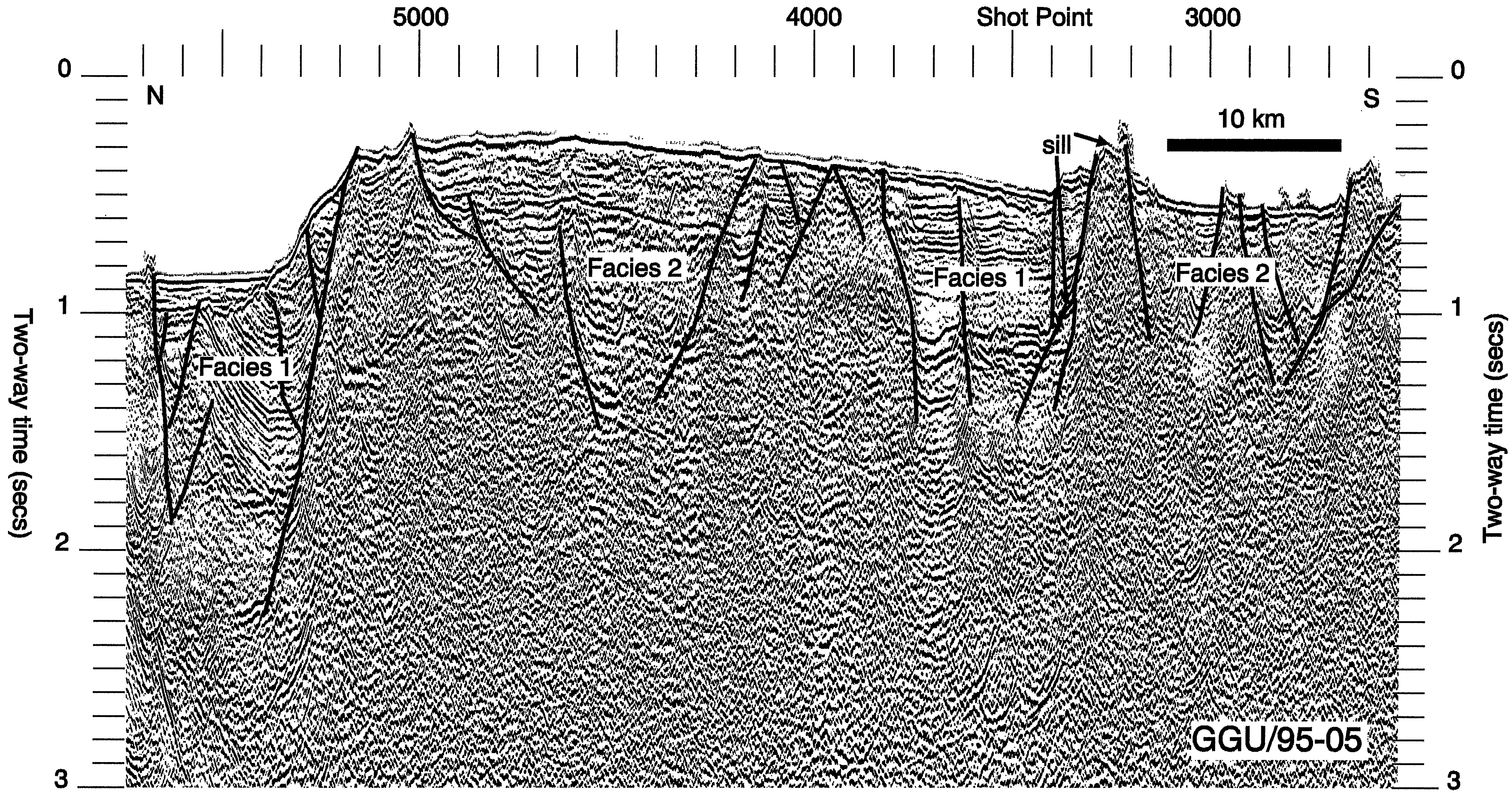

Fig. 2: Part of seismic line GGU/95-05 showing the different character of seismic Facies 1 and Facies 2. The graben containing Facies 1 north (left) of shot point 5200 is the Area D shown on the map in Fig. 9 and discussed in the 'Petroleum Prospectivity' section of the text.

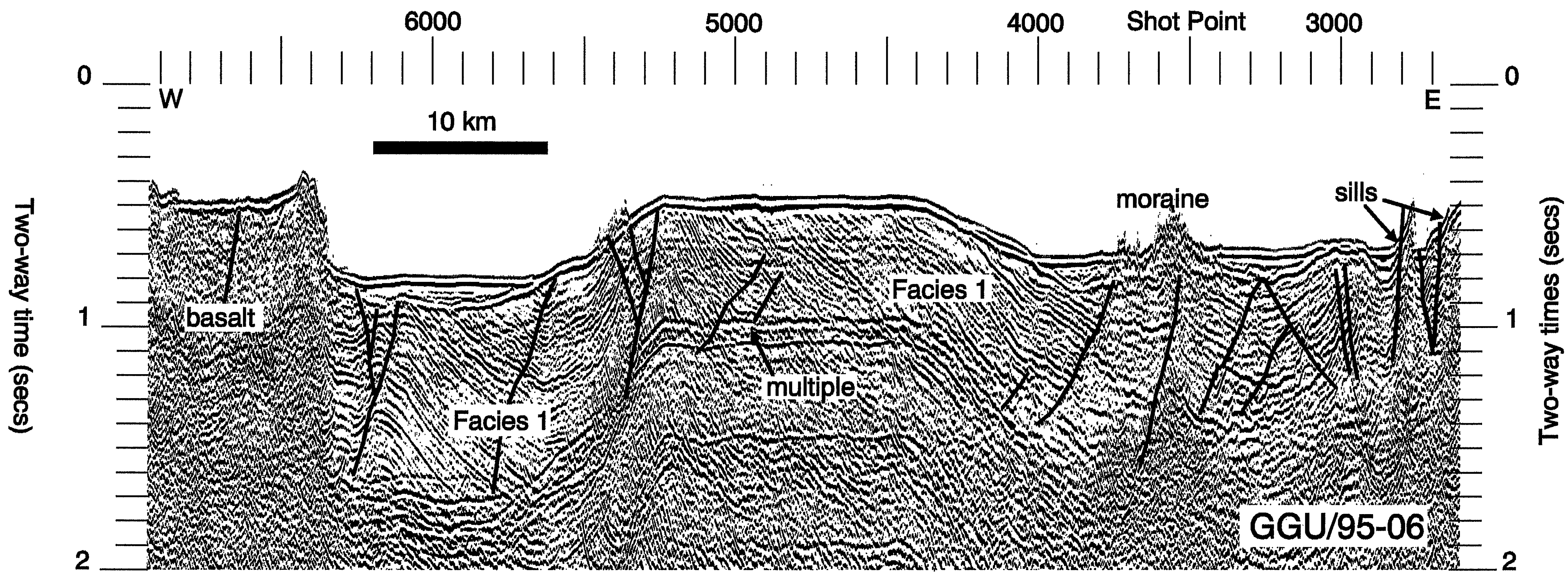

Fig. 3: Part of seismic line GGU/95-06 showing large rotated fault-blocks containing Facies 1 material. The sediments disappear under basalts west (left) of Shot Point 6350. Reflections from the sedimentary section disappear below the strong sea-bed multiple which was impossible to eliminate during processing because the line was acquired with only a 1200-metre long streamer. Interference of the sedimentary reflections because of a large moraine and because of the presence of sills at the sea bed can also be seen.

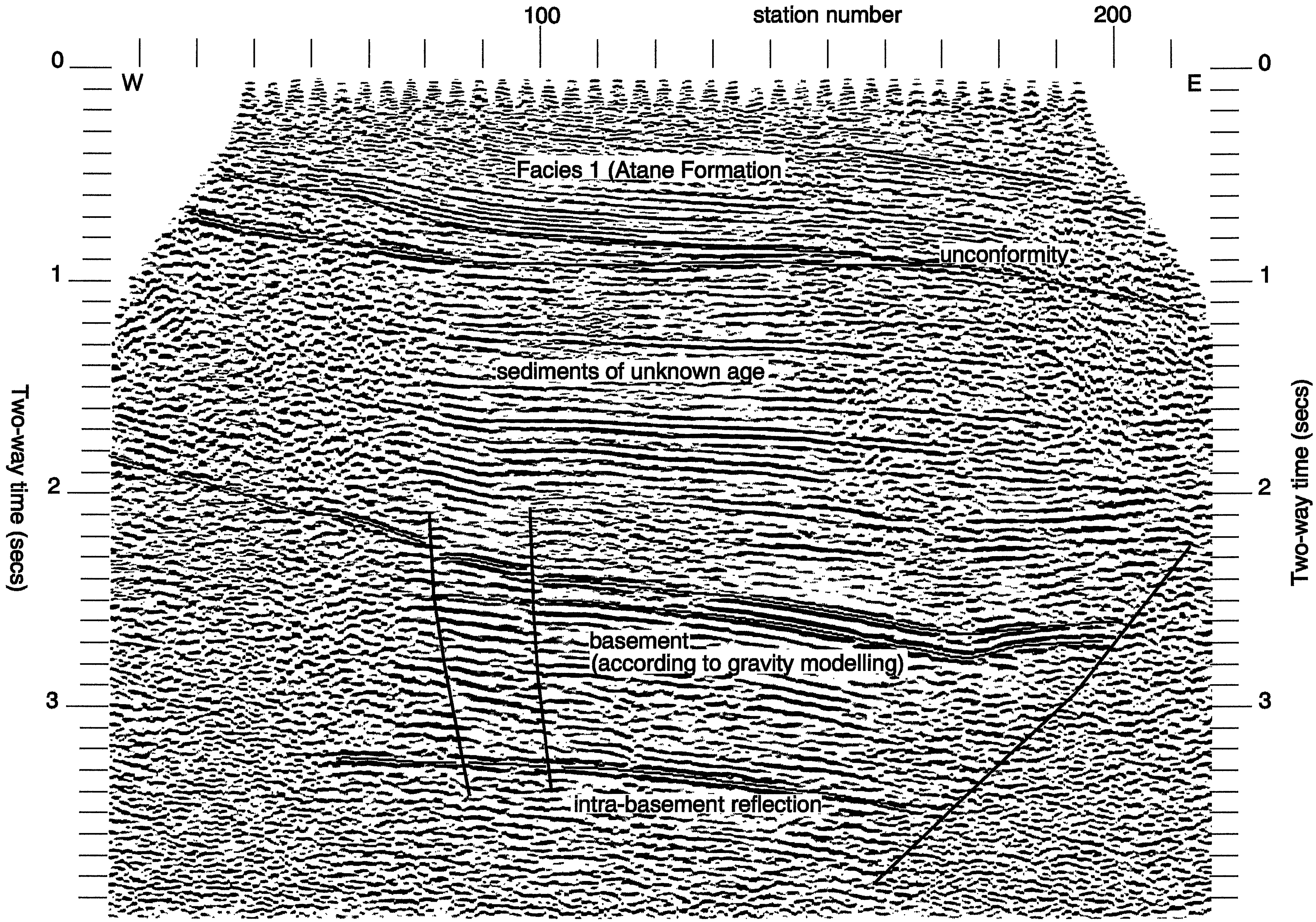

Fig. 4: Seismic section GGU/NU94-01 acquired onshore along the southwest coast of Nuussuaq. Atane Formation sediments exposed where the line was acquired calibrate the sediments above the unconformity at approx. 1 second TWT, but the 1.5 seconds TWT thick sediments below that are unknown. Gravity modelling (see text) suggests that it is more probable that basement is above 3 seconds TWT, so the reflection at approx. 3.3 seconds must come from within the basement.

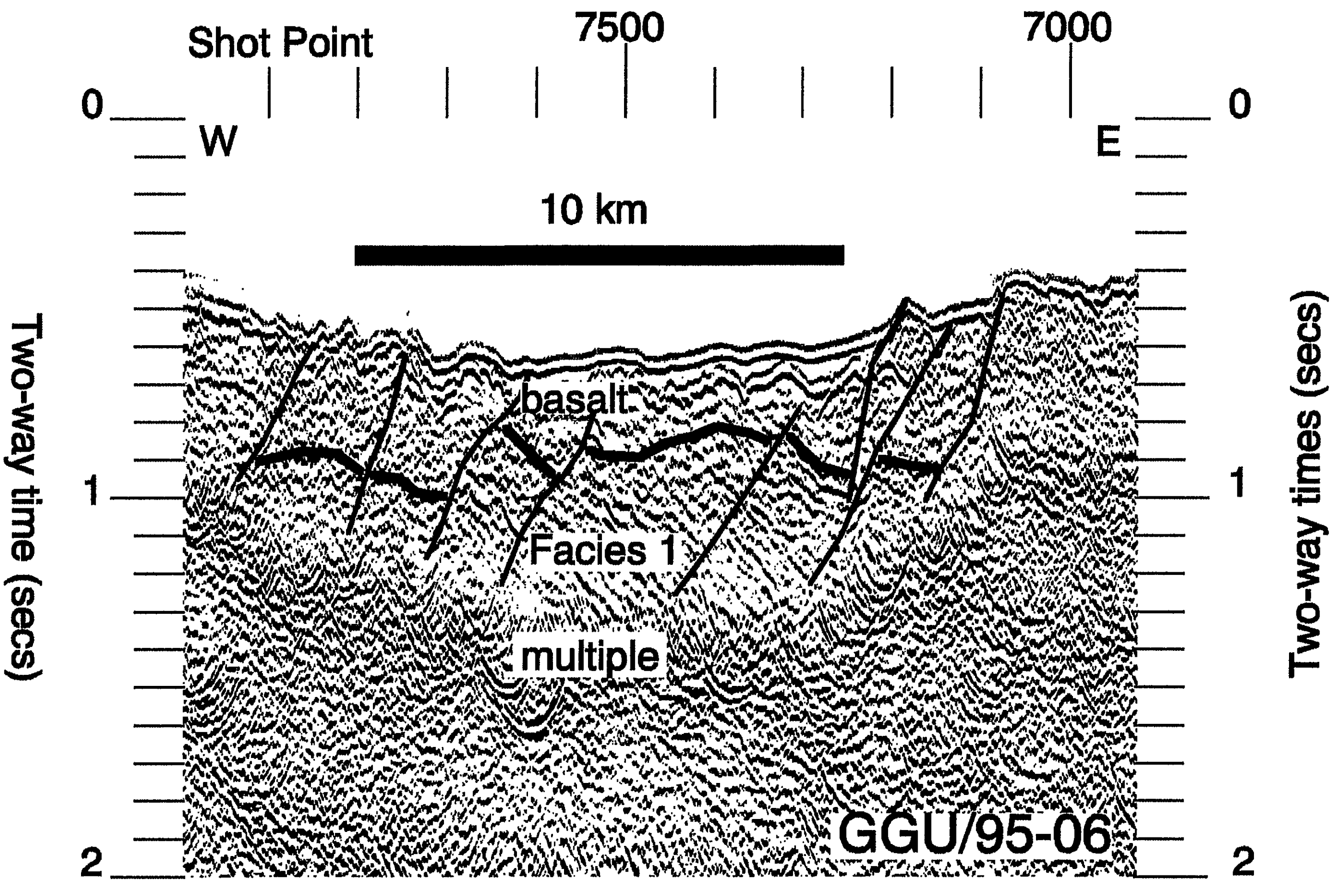

Fig. 5: Part of seismic line GGU/95-06 showing where easterly (rightwards) dipping reflections can be seen under a cover of basalts. This area is approximately offshore Marraat Killit in western Nuussuaq, where extensive seeps of oil have been found at outcrop.

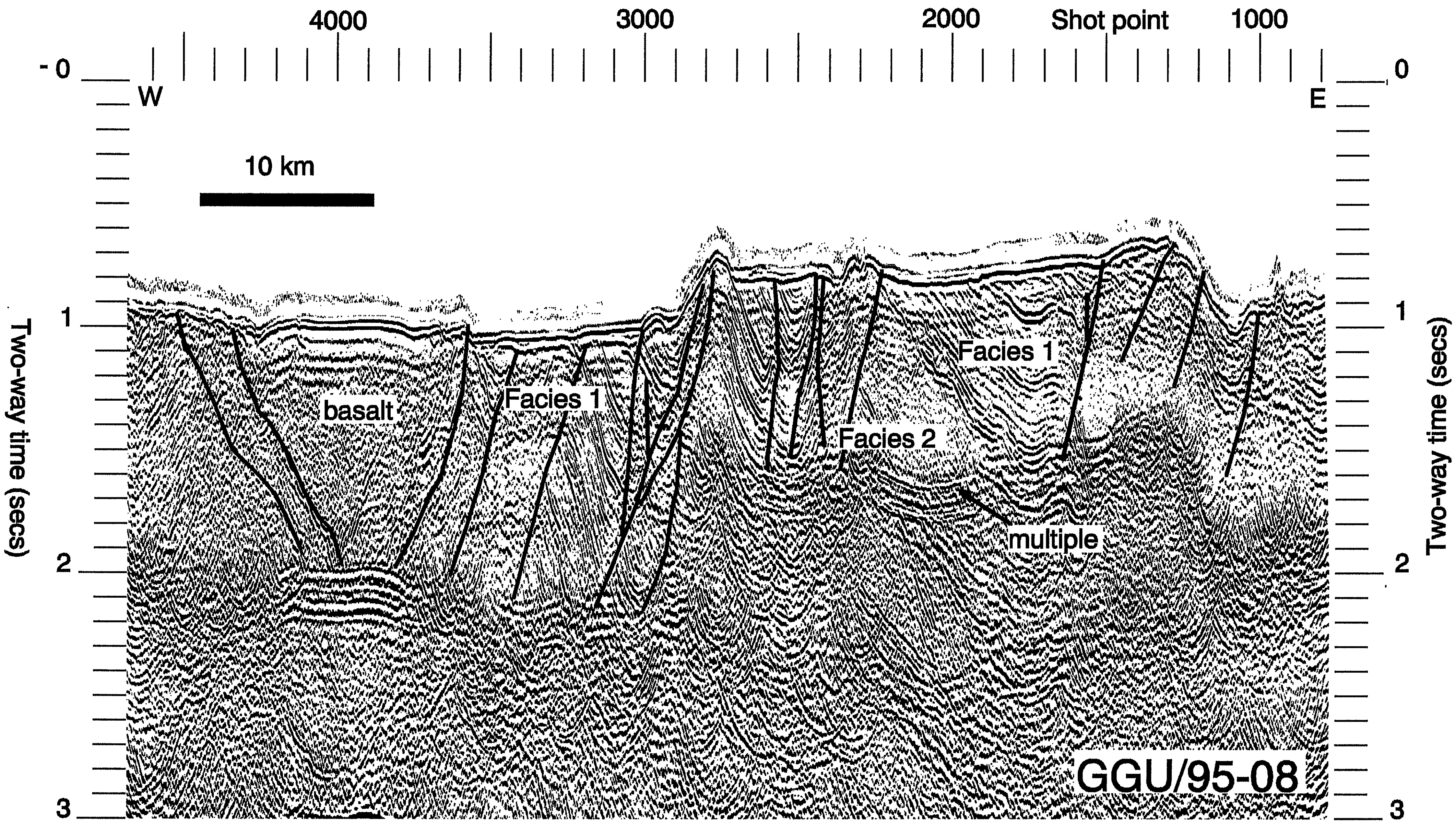

Fig. 6: Part of seismic line GGU/95-08, north of Nuussuaq, showing large, easterly (rightwards) dipping rotated fault-blocks. Mostly Facies 1 can be seen in the sedimentary areas, but between shot points 1800 and 2200, Facies 2 under Facies 1 can be seen. The offshore extension of the Itilli Fault system crosses the line between shot points 2750 and 3550, and west (leftwards) of the latter shot point basalts are exposed at the sea-bed. No reflections that could come from sediments can be discerned beneath the basalts on this line.

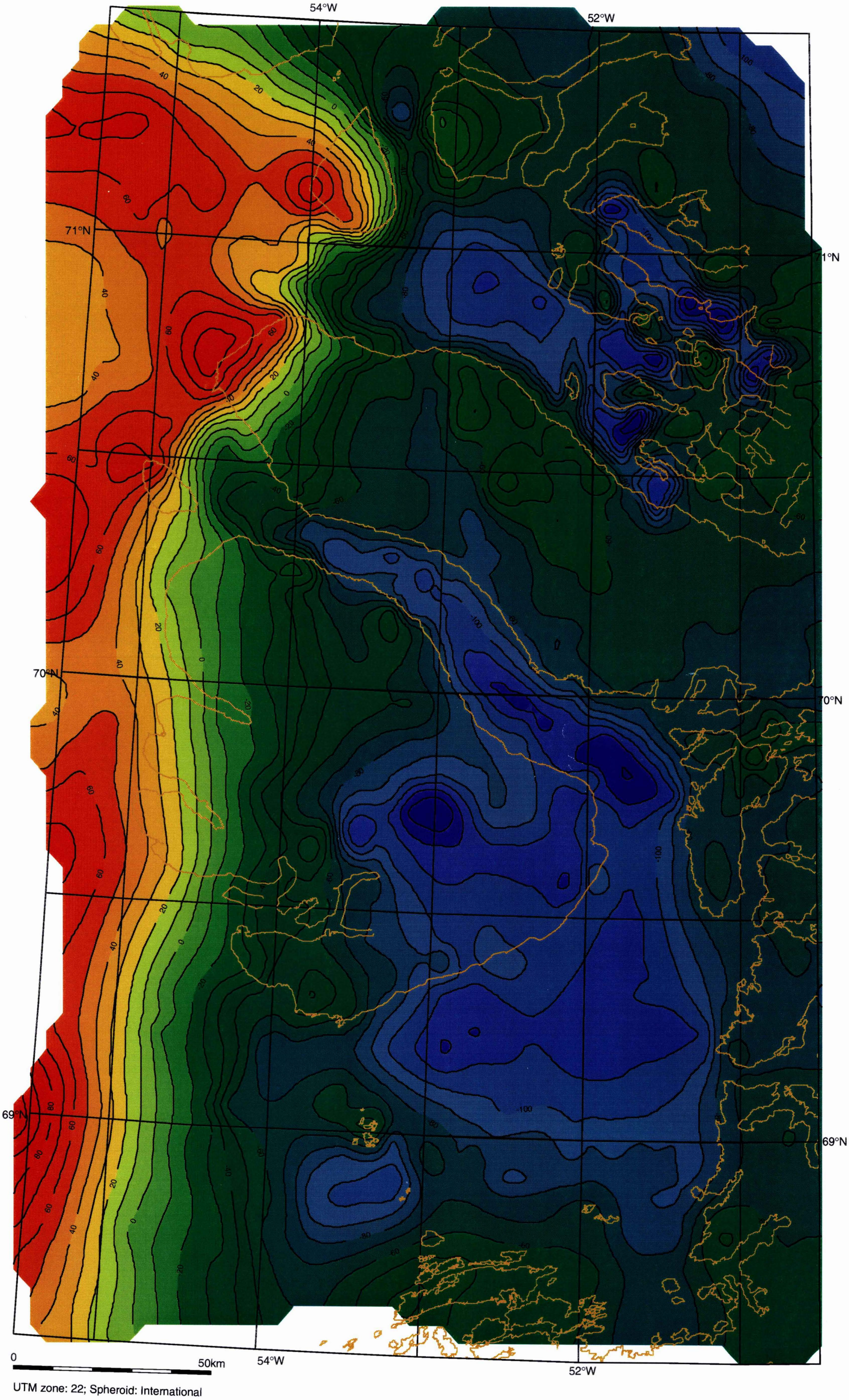

Fig. 7: Gravity anomaly map. Bouguer anomalies onshore, free air anomalies offshore.

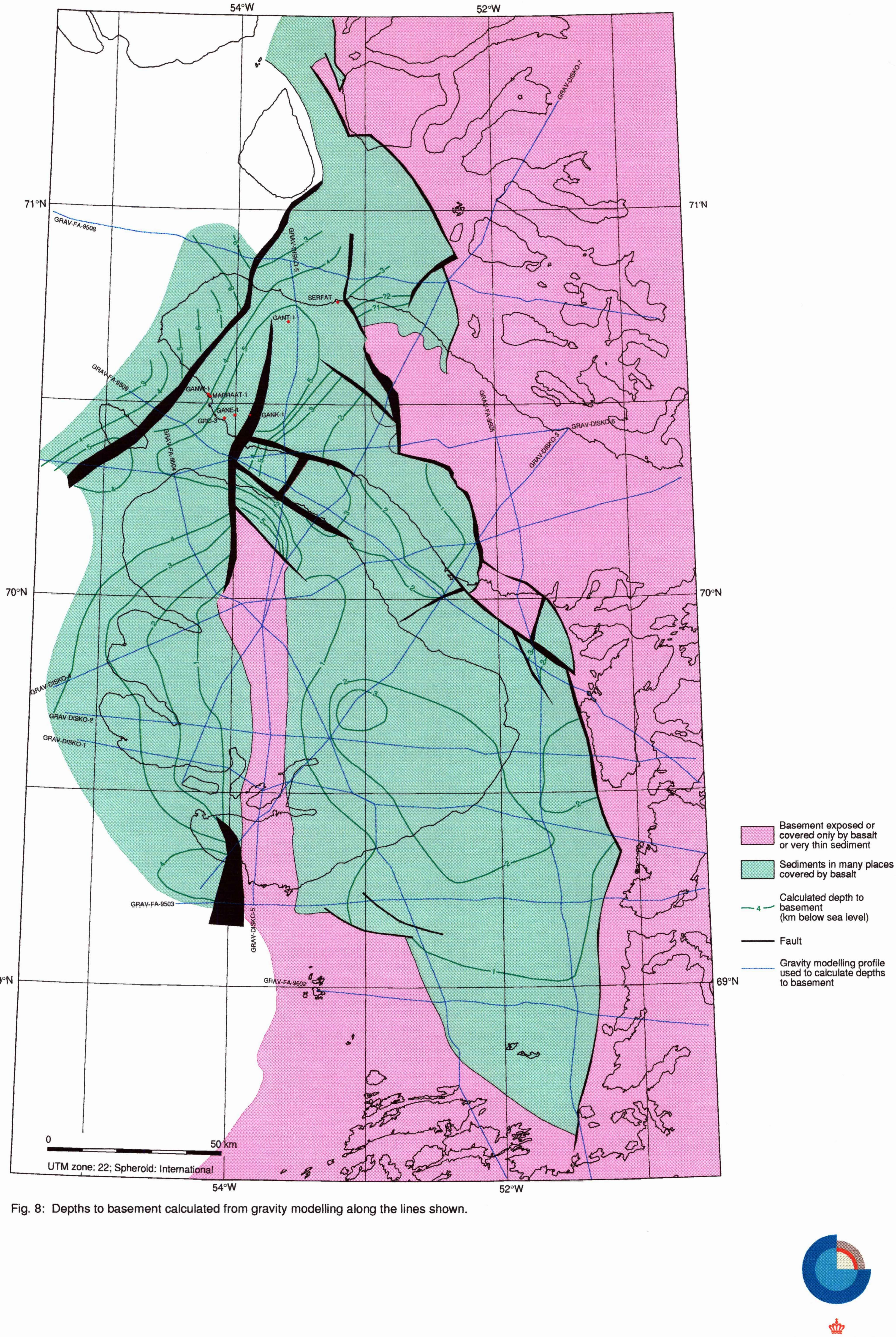

Fig. 8: Depths to basement calculated from gravity modelling along the lines shown.

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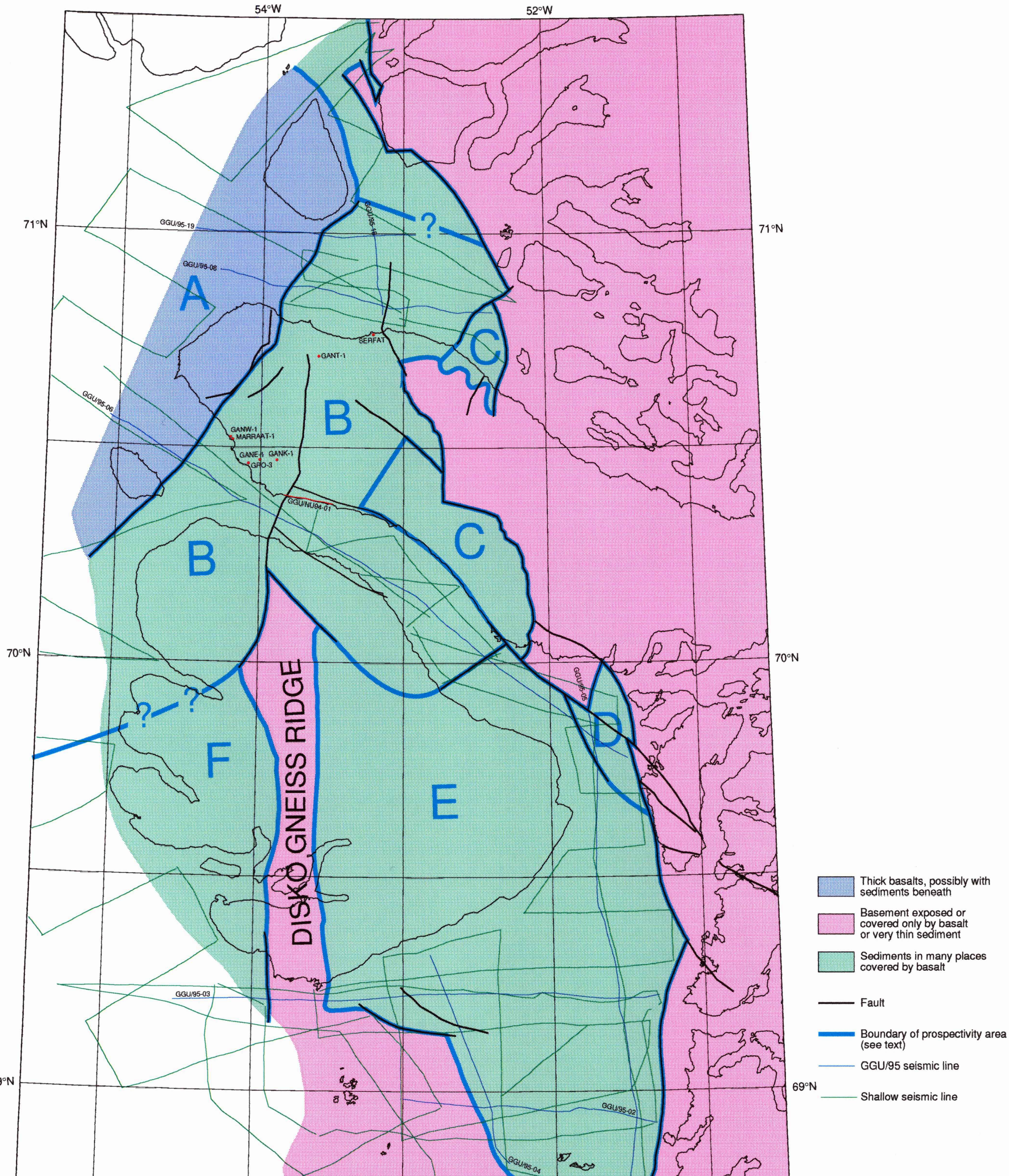

Fig. 9: Areas of different hydrocarbon prospectivity discussed in the text

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