A preliminary assessment of the structure, basin development and petroleum potential offshore central West Greenland

Richard C. Whittaker

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Ujarassiortut Kalaallit Nunaanni Misissuisoqarfiat
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Abstract

The first seismic and geological interpretation of the area covered by Paleocene basalts offshore central West Greenland is presented. The interpretation has incorporated all the existing seismic data in the area, including those lines acquired during the first phase of exploration in the 1970s, and isopach maps have been produced for regionally significant horizons in the Tertiary section. Ties to exploration wells drilled offshore southern West Greenland have lead to a greater understanding of the timing and kinematics of tectonic events during the Tertiary period which are not recorded in the onshore area.

A period of transpression, also seen in the Melville Bay area, is confirmed to have occurred following a period of extension in the Paleocene. The crests of anticlines formed during this time were then eroded at the same time as syn-drift deposition, and transgressive marine sediments infilled a number of restricted basins in the irregular topography. Strike-slip faulting continued to affect the region throughout the Eocene. The formation of north–south transtensional grabens and NW–SE extensional faulting coincided with the opening of Baffin Bay.

It has also been possible, locally, to interpret horizons beneath the Paleocene volcanics, and a thick Cretaceous sedimentary section is inferred to be present. The geological development of the area during this period, however, has had to be extrapolated from geological evidence from nearby areas.

The structure of the area is also illustrated by a number of representative geoseismic cross-sections. Several large structural leads potentially capable of trapping hydrocarbons have been identified by mapping the Top Paleocene Volcanics horizon and are described in detail. The most promising potential plays in the area are sub-basalt Cretaceous and Lower Paleocene plays which are the primary objectives throughout the whole of West Greenland. A possible secondary Tertiary play, identified here above the basalts, may also be present in other parts of West Greenland. The area is considered to have significant exploration potential and warrants additional studies to determine the thickness of basalts covering the area.

CONTENTS

INTRODUCTION

This report presents a seismic and geological interpretation of the area covered by Paleocene basalts offshore central West Greenland. The interpretation is part of a major project involving the interpretation of all the newer seismic data in West Greenland from the Melville Bay area in the north (Whittaker & Hamann, 1995) to the entire continental shelf of southern West Greenland in the south (Chalmers *et al.*, 1995).

The part of the central West Greenland shelf covered in this study extends approximately 600 km from 67°30′ to 73°N and 200 km from east to west. This is a vast underexplored region which is critical to the regional geological understanding and to petroleum exploration of West Greenland. The area is important for correlating the geological data from the five offshore oil exploration wells in southern West Greenland with the Melville Bay region which has outstanding exploration potential (Whittaker & Hamann, 1995). Information gained from this study will also be useful in the interpretation of the adjacent Disko–Nuussuaq–Svartenhuk onshore area where an extensive exploration programme has just begun. The discovery onshore of oil shows in basalts in the Marraat-1 well and surrounding outcrops on the Nuussuaq peninsula have also upgraded the potential for an offshore sub-basalt oil play.

Most of the continental shelf in the area is covered by a water depth of between 100 m and 500 m with a significant proportion being shallower than 200 m (Fig. 1). Physical conditions in the area are however harsh. The sea freezes over in November, and the sea-ice does not break up again until June. Scattered large icebergs derived from glaciers from the Greenland Inland Ice are present all year round. However, experience has shown that geophysical surveys can be carried out in the summer field season with very little down-time, and offshore oil exploration wells were drilled farther south as long ago as 1976.

REGIONAL GEOLOGICAL SETTING

Plate tectonic setting

The area of the continental shelf covered by Paleocene volcanics in central West Greenland lies to the south-east of Baffin Bay, a deep ocean basin. Although there is clear consensus that the deeper part of Baffin Bay is underlain by oceanic crust, the timing, direction and amount of opening are not clearly understood. A summary of the geophysical evidence related to the opening of Baffin Bay is given by Whittaker *et al.* (submitted) who conclude that the oceanic basin formed by oblique north–south sea floor spreading in the Eocene.

Evidence from interpreted magnetic anomalies in the Labrador Sea to the south suggests that opening in this area took place in two phases (Srivastava, 1978; Roest & Srivastava, 1989; Chalmers, 1991; Chalmers & Laursen, 1995). The earlier phase was in a NNE–SSW direction (along a NW–SW axis), roughly parallel to the Ungava transform fault zone linking the Labrador Sea to Baffin Bay. The second phase took place in an almost north–south direction (along a NW–SE axis), starting shortly before anomaly 24 (Early Eocene) and dying out at some time between anomalies 20 and 13 (Late Eocene to Early Oligocene). Judging from the approximate parallelism between the Hudson Fracture Zone and other fracture zones associated with this phase of spreading and the spreading axis generally inferred in Baffin Bay (Jackson *et al.*, 1979; Roest & Srivastava, 1989; Jackson *et al.*, 1992; Whittaker *et al.*, submitted) (Fig. 2), it seems most likely that Baffin Bay opened during this second phase.

Geology of surrounding region

The coastal areas flanking Baffin Bay are dominated by Archaean and Lower Proterozoic igneous and metamorphic rocks. Scattered outcrops of Lower Palaeozoic and Mesozoic rocks, however, provide a basis for speculation on the likely sedimentary fill of the deeper parts of the offshore basins.

In North Greenland, Ellesmere Island, and northern and western Baffin Island there are extensive areas of platform carbonates which range in age from Cambrian–Devonian in the north-west, to Ordovician–Silurian in south-west Baffin Island (Higgins *et al.*, 1991;

Trettin *et al.*, 1991). Ordovician carbonates outcrop at sea bed offshore south-east Baffin Island (MacLean *et al.*, 1977), and further occurrences of Ordovician–Silurian sediments are expected offshore.

Following the deposition of Lower Palaeozoic carbonates there was apparently a period of non-deposition lasting until the Cretaceous. Outcrops of syn-rift Early Cretaceous to Early Tertiary sediments occur in three main areas around the margins of Baffin Bay: (i) the Disko–Nuussuaq–Svartenhuk area, (ii) the Eclipse Trough in Bylot Island, and (iii) Cape Dyer in eastern Baffin Island. Initial non-marine sediments are followed by dark marine mudstones, and at all three localities there are distinct Base Tertiary/Upper Maastrichtian unconformities. In the continental shelves flanking the Labrador Sea well data and seismic interpretation indicate that sedimentation began in the Barremian–Aptian, and that an important unconformity occurs at the base of a Cenomanian/Turonian–Maastrichtian mudstone unit.

In West Greenland and at Cape Dyer the sedimentary sections are overlain by very thick picritic and basaltic lavas. The start of volcanism has been dated in West Greenland as Late Danian, corresponding to sea floor spreading anomaly 27R (Piasecki *et al.*, 1992), which is when the earliest oceanic crust is thought to have been formed in the Labrador Sea (Chalmers, 1991; Chalmers & Laursen, 1995). The youngest basalts known to data are believed to be Late Paleocene, corresponding to anomaly 25N.

A third major regional unconformity in the Lower Oligocene is interpreted in both the Labrador Sea and Baffin Bay, corresponding to the end of sea floor spreading in Baffin Bay and the Labrador Sea (Fig. 3). Seismic interpretation and outcrop evidence also indicate that a late phase of shoulder uplift took place in the Tertiary. Paleocene marine sediments occur today at up to 1000 m above sea level on Nuussuaq peninsula.

DATABASE AND INTERPRETATION METHOD

Seismic database

The seismic data interpreted during this study vary considerably in quality and resolution. Approximately 2500 km of modern multifold reflection seismic data exist in the area from three different surveys (GGU proprietary surveys GGU/90 and GGU/92, and the confidential KANUMAS survey KAN/92). Further information on these surveys is given in Table 1 and a location map of the seismic coverage is shown in Fig. 4.

Over 4000 km of older seismic data, acquired by the oil industry during the first phase of oil exploration in the 1970s, was also interpreted for this study. These data are of generally poor quality but are still useful in defining structural trends and in mapping some of the horizons. Details of these surveys are also given in Table 1.

Table 1. Interpreted seismic surveys

Survey	Vintage	Company	Fold	Processing	km
GGU/90	1990	Geological Survey of Greenland	60	Mig	875
GGU/92	1992	Geological Survey of Greenland	60	Mig	750
KAN/92	1992	Nunaoil A/S	60	Mig	885
CAL/GL	1971	California Oil Company	24	Stk	745
CFP/GL	1970	Compagnie Francaise des Pet.	12	Stk	725
ERA/	1972	Eureka Exploration Ltd./GSI	24	Stk	550
GRX/	1971	Greenland Pet. Expl.(Grepex)	24	Stk	300
TEN/GT–70	1970	Tenneco Oil and Minerals Ltd.	12	Stk	600
TEN/GT–71	1971	Tenneco Oil and Minerals Ltd.	24	Stk	890
OXY/WGC	1970	Occidental of Greenland Inc.	12	Stk	150
BUR/BG	1971	Burmah Oil Trading Ltd.	24	Stk	225

Well data

During the first period of exploration in West Greenland five exploration wells were drilled but only one of these wells is in the study area. This well, Hellefisk-1, drilled in 1977 by ARCO to a total depth of 3201 m (subsea) terminating in Paleocene basalts, provides a tie for the Tertiary succession in the area. A second well, Ikermiut-1, drilled 100 km farther south, is the only well tie for the upper part of the Cretaceous section. This well was terminated in Campanian mudstone at a depth of 3619 m (subsea). The Cretaceous section encountered in the well can be correlated with reasonable confidence to the south-eastern corner of the study area which is outside the area covered by thick Paleocene volcanics.

The Ocean Drilling Program (ODP) well 645E drilled off Baffin Island at a water depth of 2006 m, penetrated 1147 m of Quaternary and Upper Tertiary sediments before terminating in the Lower Miocene (Srivastava *et al.*, 1987). This well, when tied to regional Canadian seismic lines which cross Baffin Bay, can be used to correlate the Quaternary and Neogene sections in the western part of the study area.

The onshore Marraat-1 well in the Nuussuaq area (Christiansen *et al.*, 1994a) cannot be tied directly offshore using the present seismic data base. It is, however, an important data point when assessing the prospectivity of the area.

Gravity data

A preliminary compilation of Bouguer gravity anomaly data covering southern West Greenland and including the study area has been made by the Danish National Survey and Cadastre, KMS (Forsberg, 1995). These data comprise publicly available marine gravity data supplemented by airborne gravity data from the Greenland Aerogeophysics Project (supplied by John Brozena of the U.S. Naval Research Laboratory, 1991–1992) and satellite altimetry data. The derived composite Bouguer anomaly grid was subsequently high-pass filtered to aid geological interpretation. The resultant maps were found to fit very well with the seismic mapping at Top Paleocene Volcanics level. The gravity anomaly maps provide a valuable supplement to the seismic interpretation, indicating trends and features that are not clear on the widely spaced seismic lines.

Magnetic data

Regional magnetic anomaly maps, published by the U.S. Geological Survey (1987) and the Greenland Aerogeophysics Project (1991–1992), cover the central West Greenland area. Magnetic anomaly maps have been useful in helping to interpret fault trends and to define the limits of thick volcanics in the study area.

Magnetic profiles were also acquired along the GGU/90 seismic lines. Some of these data were provisionally interpreted for GGU by Kirsten H. Laursen in 1993, using the magnetic power spectrum analysis method. The aim of that study was to trace the extent of the Paleocene basalts and to determine whether there are sediments below the basalts. The results of this study were generally inconclusive. However, comparison of the depths to magnetic anomalies obtained using the power spectrum analysis method with the depth converted seismic horizons shows a good correlation. Many of the depths to magnetic anomalies correspond to the seismic interpretation of depth to Top Paleocene Volcanics. In the east of the area, deeper magnetic anomalies could correspond to the base of a volcanic section or to the base of a deeper sedimentary section.

Seismic interpretation method

Most of the seismic interpretation was carried out on paper sections because the older data are not available in digital format. Seismic well-ties were made to the relevant offshore wells and the new interpretation was compared to existing interpretations in southern West Greenland (Chalmers *et al.*, 1995) and the KANUMAS area of northern West Greenland (Whittaker & Hamann, 1995). Modifications to these interpretations were made when necessary, particularly to the fault patterns. These changes resulted mainly from the use of the older seismic data which had not been incorporated into the previous interpretations due to time constraints.

A total of eight horizons were picked on the seismic lines and digitised onto the ECHO mapping system. These lines were then depth-converted using regional velocity trends modified from the southern West Greenland mapping project (Chalmers *et al.*, 1995). Each horizon was then computer-contoured in both time and depth using the ECHO system. These structure contour maps identified two main areas of economic interest which were then hand-contoured at a scale of 1:500 000 to make the contouring around fault zones more realistic. These hand contoured maps have been used to assess the structural leads in the area.

Depth conversion

A layer-cake method was used to depth-convert the two-way-time seismic picks. Interval velocities were calculated from the five southern West Greenland wells and then plotted against the two-way-time to the centre of each interval. The interval velocities and time-depth functions used for depth conversion are given in Table 2.

Table 2. Depth conversion velocities

Interval	Velocity (m/s)
Water	1450
Quaternary	2400
Neogene	V int = 1800 + 0.7 T
Palaeogene sediments	2500
Paleocene volcanics	5000
?Cretaceous	3500

SEISMIC INTERPRETATION

This section of the report is a description of the seismic horizons that were picked during the interpretation. The distribution of each horizon is described, together with the internal reflection characteristics of the interval between each horizon and the horizon above. Isopach maps of each of these intervals are shown in Maps 1–3. Evidence for the geological age of the horizons is also given, along with an assessment of the reliability and accuracy of these ages. In general, age determination becomes less reliable farther north in the area, away from the well control. Picks beneath the Top Paleocene Volcanics horizon are more speculative and are based largely on extrapolation of regional geology from outside the area. A structure contour map of the Top Paleocene Volcanics horizon is shown in Map 4.

Base ?Cretaceous

The deeper part of the succession is interpreted to be a thick Cretaceous sedimentary package. Cretaceous sediments encountered in the Ikermiut-1 well can be tied directly, and with fair confidence, into the south-east corner of the study area. Here thick Paleocene plateau lavas, responsible for obscuring the deeper section elsewhere in the area, are thin or absent. The eastern end of seismic line GGU/90-4 (Fig. 5) has a thick (6000 m) sedimentary section below the base of the Tertiary. These sediments have apparently been intruded by igneous bodies. This phenomenon has also been interpreted on seismic data from the southern West Greenland shelf, notably to the west of the Fylla Structural Complex (64°N), where Lower Cretaceous sediments are believed to be intruded by Tertiary sills and dykes (Chalmers *et al.*, 1995).

Evidence of a thick Cretaceous section can be seen in many other parts of the West Greenland continental margin. North of the thick volcanics, over 8000 m of pre-Tertiary sediments are interpreted on seismic data from the deepest part of the Melville Bay Graben (Whittaker & Hamann, 1995). Onshore central West Greenland, a seismic line acquired by GGU in 1994 along the south shore of Nuussuaq indicates that there are at least 6000 m of sediments below the Coniacian sediments exposed here (Christiansen *et al.*, 1995). Added to the exposed sediments, this gives a total thickness of over 7000 m of pre-Tertiary sediments in this onshore part of the West Greenland Basin, immediately to the east of the study area. Very thick Cretaceous and possibly older sections have also been interpreted in southern West Greenland (Chalmers *et al.*, 1995).

Seismic evidence for a thick sedimentary section below the volcanics in central West Greenland is less obvious. However, weak deep reflectors can be seen on most of the newer high fold data. This is particularly true in areas where the top of the volcanics has been eroded, creating a 'window' through which the deeper section can be seen. This may be caused by (i) the presence of a much thinner volcanic section due to erosion or depositional thinning of the lavas over structural highs, and/or (ii) subaerial weathering over the structural highs enabling the seismic energy to penetrate much deeper in the section.

Seismic lines GGU/90-1, 2 and 3 to the west of Disko island clearly show the presence of deep reflectors which are interpreted as Cretaceous sediments up to 5000 m thick (Figs 9 and 10). Estimating the thickness of section in this area is made more difficult by the unknown thickness of Tertiary volcanics overlying the deeper sedimentary section. It seems very unlikely that the section between the top volcanics horizon and the deep reflector could be made up entirely of subaerial lavas. This would require a thickness of around 8500 m of volcanics over much of the offshore area west of Disko. This vast thickness of volcanics seems unlikely particularly in an area where thick Cretaceous sediments are known beneath the volcanics only 20–100 km away in the onshore part of the basin.

Additional evidence for the presence of a deep sedimentary section beneath the volcanics can be seen on the southern lines of the KANUMAS (KAN/92) survey and on some older seismic data. Seismic line ERA/24, a north–south line acquired by GSI in 1972, also shows reflectors with a sedimentary seismic character along the coastal area from south of Disko to north of Svartenhuk Halvø.

Base Paleocene Volcanics

This seismic horizon is the most speculative of the picks but is one of the most important in the economic evaluation of the area. The only relevant well, Hellefisk-1, was terminated before the base of the volcanics was reached, after penetrating 694 m of subaerial lava flows (Fig. 7). The age of the deepest volcanics in this well has not been accurately determined and it is therefore not possible to estimate how close the well was to reaching the base of the volcanic section. The other wells drilled on the Greenland shelf did not penetrate a thick volcanic section and are therefore of no use in identifying this horizon.

Outcrops in the Disko–Nuussuaq–Svartenhuk area are at present the only guide to estimating the thickness of volcanics. The closest outcrops to the offshore seismic grid are on the western coast of Disko where approximately 2000 m of volcanics are known from outcrops. This is only 5 km from the eastern end of two recently acquired seismic lines

(GGU/90-2 and 3). A reflector at about this depth below the Top Paleocene Volcanics horizon can be seen on these seismic lines and is tentatively interpreted as the Base Volcanics horizon. Similar reflectors have been interpreted on other seismic lines in this area, but until a more reliable method can be found to determine the thickness of volcanics this pick will remain speculative. Preliminary estimates indicate that the volcanics could be as thin as 500 m under the eroded crests of some structurally high areas.

Internal reflectors can clearly be seen within the volcanic interval. In several places dipping reflectors can be seen to subcrop the Top Paleocene Volcanics horizon. Seismic resolution is not sufficiently high to determine the internal reflector configuration within the volcanics to allow seismic facies interpretation to be carried out.

Top Paleocene Volcanics

The Top Paleocene Volcanics horizon is the deepest horizon in the study area which can be tied directly to well data. Hellefisk-1 reached the top of the volcanic section at 2493 m (subsea) (Fig. 7) and has been tied to seismic data using a synthetic seismic log. The top of the volcanics produces a characteristic strong reflector which can be traced with relative confidence away from the well tie. The map of this horizon (Map 4), therefore, illustrates the post-volcanics fault pattern in the area.

The Top Paleocene depth map (Map 4) also includes laterally equivalent horizons away from the area of thick volcanics. It is likely that thinner volcanic beds of the same age continue into these areas. The eastern boundary of the contoured area is the outcrop of volcanics at sea bed between 25 km to 100 km west of the coastline. Landward of this line of outcrop, the top of the volcanics is at sea bed where it has been subjected to recent and glacial erosion.

The Top Paleocene Volcanics horizon dips generally west towards Baffin Bay, reaching a depth of 6000 m in the deepest part of the study area. The dominant fault trend changes from north–south and NNE–SSW in the southern half of the area, to NW–SE in the north. This change in fault trends is also seen on geological maps covering the onshore area.

Base Eocene and Intra-Eocene

The Upper Paleocene and Eocene intervals have been sub-divided by three horizons, based on correlation with the Hellefisk-1 well. These horizons are Base Eocene, Intra-Eocene(1), and Intra-Eocene(2).

Sediments overlying the Paleocene volcanics in Hellefisk-1 have been interpreted by Rolle (1985) to be Late Paleocene interbedded sands and silty mudstones deposited in a transgressive shallow shelf environment (Fig. 7). These sediments are overlain by an increasingly coarse grained deltaic section. A distinct unconformity can be seen on seismic data at the Base Eocene horizon and the seismic character below this suggests much more distinct bedding. This seismic character continues north and probably indicates the predominance of finer grained material in the lower part of the Palaeogene section.

The overlying section infills an irregular erosion surface at the top of the volcanics and the basal part of the Eocene section clearly onlaps topographic highs. The unstippled areas on the Eocene Isopach Map (which includes the Upper Paleocene sediments) (Map 3) show areas where the lowermost part of the section are present. These areas have obviously been strongly influenced by the underlying structure. Also apparent from this map is the rapid increase in thickness of this interval immediately north and south of the Paleocene plateau lavas. This increase in thickness is seen on the cross-sections over the southern edge of the plateau basalts (Figs 5 and 7) and on KANUMAS seismic lines which cross the northern edge of the basalts.

The Intra-Eocene(1) horizon marks the base of the dominantly sandy section in the Hellefisk-1 well (Fig. 7) deposited in a shallow shelf and delta front environment (Rolle, 1985). Fault offsets can be seen to decrease higher up in the section and fault throws above the Intra-Eocene(2) horizon diminish almost completely. The internal seismic character of this section becomes less well bedded.

Base Neogene

The base of what is for convenience called the Neogene section in the wells drilled on the southern West Greenland shelf is Oligocene in age. The Neogene section is a predominantly sandy succession of prograding deltaic deposits. Regionally this horizon is known to be a major unconformity with the overlying sediment onlapping towards the east.

A distal shaly section has been inferred in this interval in the Labrador Shelf area but this is unlikely to be the case in this part of West Greenland. The ODP drill site 645E off north-east Baffin Island terminated at 1147 m (subsea), in Early–middle Miocene muddy sandstones. The well failed to reach a regional unconformity recognised on the seismic grid in the area; however, from extrapolation of sedimentation rates, this seismic marker has been placed at the Eocene–Oligocene boundary (Srivastava *et al.*, 1987). This marker is therefore equivalent to the Base Neogene horizon and can be traced, using the same regional seismic grid, into the western margin of the study area.

The Neogene Isopach Map (Map 2) shows that this interval gradually thickens towards Baffin Bay although there is also a marked increase across the shelf edge. The interval reaches a maximum thickness of over 2000 m in the west. The isopachs also show a thinning over the Davis Strait High and thickening across the northern and southern edges of the plateau basalts. These more local changes in thickness are mainly caused by differential compaction, although erosion of the upper part of the section has also played a part.

The eastern limit of the Neogene interval is an erosional surface but the timing and amount of uplift and erosion cannot be precisely determined. What can be determined is that the uplift was regional, that it probably occurred relatively late, and that the amount of uplift was considerable. The western half of the study area, however, does not appear to have been affected by this uplift and is at present at its maximum depth of burial

Base Quaternary

The interval above the Base Quaternary horizon may also include Late Pliocene sediments. This section consists of Pleistocene proglacial gravel and boulder clay in the southern West Greenland wells (Rolle, 1985). The ODP-645 well off north-east Baffin Island also encountered a major regional unconformity at the base of Late Pliocene–Pleistocene 'glacial' deposits (Srivastava *et al.*, 1987).

In some parts of the study area, particularly in the south-east, the base of this interval has been interpreted as deposited on a very irregular surface of deep channels or canyons. The interval generally progrades across the eroded surface of the Neogene. The section reaches a maximum thickness of 1500 m along the shelf edge (Map 1) where a series of prograding wedges was deposited.

GEOLOGICAL DEVELOPMENT

The lack of well data and the generally poor seismic resolution in the area makes the pre-Tertiary geological development difficult to determine. Dating of the deeper geological events is dependent on analogies with better known areas. The Tertiary geological development can be resolved with more confidence.

Pre-rift development

There is no indication of the presence of pre-rift sediments on seismic lines in the study area. Ordovician carbonates similar to those outcropping on western Baffin Island, on the south-east Baffin Island shelf (MacLean *et al.*, 1977), and in a fault breccia in southern West Greenland (Stouge & Peel, 1979) are, however, anticipated.

There is no evidence in the Baffin Bay area for the existence of sediments deposited in the interval Devonian–Jurassic. Palaeogeographic maps showing the development of the Sverdrup Basin in arctic Canada during this time interval indicate that north-west Greenland, eastern Ellesmere Island, Devon Island and northern Baffin Island belonged to an uplifted area throughout this time (Embry, 1991a, b).

Early rift development

Thick Cretaceous rift deposits are interpreted in the study area but poor seismic data quality and the presence of thick Paleocene volcanic rocks mean that details of the early rift development phase cannot be resolved. Instead the geological development of the area during this period has to be inferred from other evidence.

The earliest phase of rifting known in the surrounding areas took place in the Labrador Sea, where fluvio-deltaic and shallow marine sediments of the Barremian–Albian (–earliest Cenomanian) Bjarni Formation were deposited (Balkwill *et al.*, 1990). Equivalent sediments are believed to exist in the southern West Greenland Shelf (Chalmers *et al.*,

1993) and in the Melville Bay area (Whittaker *et al.*, submitted). The earliest known syn-rift sediments onshore belong to the Quqaluit Formation at Cape Dyer (late Neocomian–Cenomanian; Burden & Langille, 1991), the Hassel Formation in the Eclipse Trough, Bylot Island (Albian–Cenomanian; Miall *et al.*, 1980), and the Atane Formation in West Greenland (Albian–Santonian; Pedersen & Pulvertaft, 1992). All these formations are dominated by fluvio-deltaic sandstones and mudstones, with local coal seams.

A mid-Cretaceous pause in rifting is known from the Labrador Sea and southern West Greenland; this pause in rifting probably began at the end of the Cenomanian or in the Early Turonian, when a phase of thermal subsidence was initiated in these areas (Balkwill *et al.*, 1990; Chalmers *et al.*, 1993). Seismic evidence from the Melville Bay area suggests that this event also influenced sedimentation to the north of the study area (Whittaker *et al.*, submitted). During this time a major transgression spread across the region, depositing mudstones of the Kanguq Formation in the Sverdrup Basin in the Canadian Arctic Islands and the Kangeq sequence offshore southern West Greenland.

Late extension, volcanism, and inversion

A later phase of extension is interpreted in southern West Greenland (Chalmers *et al.*, 1993) and in the Melville Bay area (Whittaker *et al.*, submitted). In the nearest outcrops in West Greenland pronounced rifting is reported to have taken place in the Late Maastrichtian and again after the extrusion of the Upper Paleocene basalts (Rosenkrantz & Pulvertaft, 1969; Dam & Sønderholm, 1994), and on the Canadian side of Baffin Bay there are unconformities between the Early Tertiary and underlying Cretaceous both at Cape Dyer (Burden & Langille, 1991) and in the Eclipse Trough (Miall *et al.*, 1980). In the southern West Greenland shelf the second phase of rifting is believed to have taken place largely in the Early Paleocene, whereas in Melville Bay renewed rifting may have begun in the Late Cretaceous.

Towards the end of this period compression and inversion began to affect the area, leading to the development of anticlines in the syn-rift sequences. These movements occurred near the end of the first phase of sea floor spreading in the Labrador Sea (anomaly 24R; Late Paleocene) and followed the extrusion of the West Greenland plateau basalts. Sea floor spreading in Baffin Bay does not appear to have begun until after this period.

The crests of anticlines formed during this phase of inversion were eroded prior to the deposition of post-rift, drift-phase sediments. Folding is localised and difficult to correlate between the widely spaced seismic lines but appears to have ESE–WNW axes. The northern and southern edge of the plateau basalts is fault controlled in a NE–SW direction, the direction of opening of the Labrador Sea during the extrusion of the basalts.

Drift phase

Rifting and volcanism were followed by a relatively quiet period of thermal subsidence, with less active extensional faulting gradually dying out towards the end of this drift phase. This period of faulting was controlled by the opening of the Baffin Bay ocean in the Early Eocene. Steep faults penetrating the drift-phase sediments are probably strike-slip faults related to the oblique spreading of Baffin Bay. The direction of sea floor spreading in Baffin Bay and the Labrador Sea was roughly north–south.

Early Eocene marine and delta front deposits are known to have transgressed the southern part of the area and are described from the Hellefisk-1 well (Rolle, 1985). Deposition following the latest phase of rifting is interpreted from seismic data to have taken place in a series of restricted basins, controlled by extension or strike-slip movements. Evidence for strike-slip movements along faults can be seen on seismic lines north of Hellefisk-1. Here two major but narrow grabens extend north–south and NNE–SSW, the latter continuing into the Itilli fault zone onshore Nuussuaq. Shale diapirs and folds trending NW–SE seen immediately north and south of the plateau basalts were also formed during this period.

Post-drift and late uplift

Sea floor spreading in Baffin Bay is assumed to have ceased at the same time as in the Labrador Sea. Although linear magnetic anomalies younger than anomaly 21 cannot be identified in the Labrador Sea, it is generally assumed that spreading continued until about anomaly 13 time (at about the Oligocene–Eocene boundary; Srivastava, 1978). Following this, sedimentation took place by simple progradation into the Baffin Bay Basin.

Seismic data from the study area indicate that there was a period of late uplift and erosion. The timing of this episode appears to be post-thermal subsidence of the continental shelf. There is also evidence from the Labrador Sea and south-east Baffin Island that a high relief was established in the onshore areas in the Late Oligocene, and that uplift was renewed in the Late Miocene (Trettin, 1991). An indication of the minimum post-Paleocene uplift onshore West Greenland is provided by the occurrence of Early Paleocene marine mudstones at about 1000 m above sea level. The western half of the offshore area, however, does not appear to have been affected by this uplift and is now at the maximum depth of burial.

Erosion of deep troughs in the seabed off central West Greenland (Fig. 1) probably took place during Quaternary glaciation.

PETROLEUM POTENTIAL

Source rocks

Recent work in both the Canadian Arctic Islands and in onshore West Greenland has indicated that there are grounds for expecting that oil-prone source rocks occur at two levels in the central West Greenland area. A third possibility for a source rock in the area is most likely to be gas-prone.

(i) Lower Tertiary

An oil-prone source rock is known to be present in the lowermost part of the Tertiary or Upper Maastrichtian. Oil has been found in vesicles in Paleocene basalts on the Nuussuaq peninsula. In a well drilled in these basalts liquid oil was found in vesicles down to a depth of 86 m (Christiansen *et al.*, 1994a). The geochemistry of the oil indicates that the organic material in the source rock is of terrestrial origin but was deposited in a marine environment (Christiansen *et al.*, 1994b). The geological setting of the Marraat oil suggests that the source is Early Paleocene or older. The source rock is most likely to be of Tertiary age since it has the same geochemical characteristics as oil found in latest

Cretaceous–Tertiary deltas such as the Niger delta, the Mahakam delta in Indonesia, and the Beaufort-Mackenzie delta in northern Canada.

(ii) Mid-Cretaceous

Cenomanian–Turonian oil-prone source rocks occur in the Kanguk Formation of the Sverdrup Basin in Arctic Canada (Núñez-Betulu, 1993; Núñez-Betelu *et al.*, 1993). This formation was deposited during the marine transgression that extended outside the basin, possibly reaching the central West Greenland area. The likelihood of the presence of a mid-Cretaceous source rock is supported by the occurrence of a submarine oil seep in the Scott Trough on the western side of Baffin Bay, which is reported to have come from a Cretaceous source rock (Balkwill *et al.*, 1990). Furthermore a mining company drilling for hard minerals on the north coast of Nuussuaq in 1994, struck wet gas (up to C5) in Upper Cretaceous mudstone.

(iii) Lower Cretaceous

Source rocks within the Lower Cretaceous syn-rift succession could include lacustrine oil-prone source rocks and oil-/gas-prone coals. However, gas-prone source rocks are most likely from this part of the succession and indeed rocks of this age are believed to have been the primary source for the gas discoveries in the Labrador Sea (McWhae *et al.*, 1980)

Maturity

The geothermal gradient in the southern West Greenland wells has been found to be generally low but varies greatly. The Nukik-2 well, drilled on the inner part of the shelf, had a geothermal gradient of 19.3°C/km, whereas Ikermiut-1, close to the continental slope, had a gradient of 28.9°C/km (Rolle, 1985). These variations are influenced by (i) the degree of stretching of the continental crust, (ii) the lithologies encountered in the wells, and (iii) the degree of uplift and inversion.

Problems in determining the maturity of potential source rocks in the area are compounded by uncertainty about the location of these source rocks in the geological section. There is a lack of seismic resolution in the deeper part of the section where these source rocks are likely to be found. The Top Paleocene Volcanics Map (Map 4) can, however, be used as a guide when discussing maturity of the most likely source rocks in the area.

(i) Lower Tertiary

The presence of the oil at or near the surface at Marraat proves that a mature uppermost Cretaceous or Lower Paleocene source rock exists in that area. Locating the kitchen in which this oil was generated, however, is complicated by the unknown thickness of volcanics in the area, the likely presence of a thick Lower Paleocene section, and the fact that there has been a significant amount of late uplift in the onshore area.

Offshore, the source rock responsible for the Marraat oil would most likely be mature at present-day depths of burial as far as 50 km west of Marraat. This is highly dependent on the thickness of the volcanics.

Late Paleocene or Early Eocene source rocks deposited in restricted basins could have significant source potential for an oil play in the deeper parts of the area.

(ii) Mid-Cretaceous

The maturity of mid-Cretaceous source rock is also very difficult to estimate because of the unknown thickness of Paleocene volcanics and Upper Cretaceous–Lower Paleocene sediments. It is likely that source rocks of this age would be within the oil window in the eastern part of the study area. In the west, however, they would almost certainly be within the gas window at present levels of maturity, but may have generated oil in the past.

(iii) Lower Cretaceous

Source rocks of this age are likely to be gas-prone and be in or have been through the gas generation threshold over most of the offshore area.

Reservoirs

Potential reservoirs are predicted throughout the sedimentary succession, but the primary objectives in this area can be confined to three levels (i) Lower Cretaceous deltaic sandstones, (ii) Upper Maastrichtian–Lower Paleocene turbidite sandstones and (iii) Upper Paleocene–Lower Eocene shallow marine and delta-front sandstones.

(i) Lower Cretaceous

Lower Cretaceous syn-rift deposits probably contain good quality fluvio-deltaic reservoir sandstones and are the primary objective in the area. Equivalent Lower Cretaceous Bjarni sandstones are the main reservoir in the Labrador Sea wells. Quality of these reservoirs appears to vary, with porosities ranging from 17% to 24% in the Labrador Sea discovery wells (Bell & Campbell, 1990). The North Bjarni gas field alone contains over 2.2 TCF gas reserves in Lower Cretaceous sandstones. These sandstones have a net pay of 177 m, one of the thickest pay sections of any well drilled in Canada. One nearby well (Herjolf M-92) encountered over 915 m of water-wet Bjarni sandstone.

(ii) Upper Maastrichtian–Lower Paleocene

A thick succession of more than 2500 m of marine turbidite sandstones interlayered with mudstones is exposed in the Itilli valley north-west of Marraat (Dam & Sønderholm, 1994). These turbidite sandstones were deposited in wide channels on the slope below the outlets of valleys excavated in the Cretaceous deltaic sediments following the tectonic movements and relative fall in sea level that took place in the Maastrichtian. In the Itilli valley hydrothermal alteration along a major fault has taken place, so that the turbidite sandstones are well cemented. However, away from this zone of alteration these sandstones are likely to have excellent reservoir properties.

(iii) Upper Paleocene–Lower lower Eocene

Porous Upper Paleocene and Lower Eocene marine and delta front sandstones were encountered in the Hellefisk-1 well. These sandstones appear to be tuffaceous in the lower part of the section but there are approximately 80 m of clean, porous Lower Eocene sandstones.

In the Labrador Sea, the Snorri J-90 well encountered significant volumes of hydrocarbons (gas and condensate) in the Upper Paleocene Gudrid sandstone. This reservoir consists of a fine-grained, well sorted, calcareous sandstone with an average porosity exceeding 20%.

Structural leads

The Top Paleocene Volcanics Map (Map 4) illustrates the structural leads identified in the study. There are five main structural leads and a number of smaller or less well defined leads. The main leads have been labelled A–E and leads B–E have been mapped in more detail on Maps 5 and 6.

The Top Paleocene Volcanics maps give a good indication of structural closures for potential Tertiary plays above the basalts but are also used here to define areas where structural closure for sub-basalt plays are possible although the seismic data does not resolve the detailed structure beneath the volcanics. It has been demonstrated that in other parts of West Greenland the major Cretaceous structural leads *do* correspond to structures at this shallower level. Seals likely to be present in the Lower Paleocene or Upper Cretaceous section may, however, make structural closures more complicated. The structural leads in the Fylla Structural Complex of southern West Greenland and the major leads in the Melville Bay area were formed by the same period of faulting as those identified in the central West Greenland area. Structural closures may also exist in the extensive area where volcanics outcrop at sea bed.

The five main leads are described in detail below:

(i) Lead A

This lead is on the structural high drilled by Hellefisk-1 but there is still significant potential untested by this well. A cross-section through the well (Fig. 7) shows that although the well penetrated Lower Tertiary sandstones, there remains up-dip potential. The part of the lead to the west of the graben may have greater potential as is also true of the potential sub-basalt play. The cross-section (Fig. 7) shows a large untested lead at Cretaceous level to the west of the fault zone. Late faulting, forming a graben through the crest of the structure may, however, have caused the structure to leak and the seal is a major risk for the shallower section.

(ii) Lead B

This structural lead can be split into two parts (Map 5) and is likely to be even more complicated than this. The structural style of the area is shown in the cross-section along seismic line GGU/90-3 (Fig. 5). Two major fault-zones can be seen on the cross-section to be much more complex than shown on the simplified map. The map only shows the major faults which can be correlated between seismic lines. A more detailed seismic grid would certainly therefore show the structure to be much more complicated. Despite the complex structural style in this area, the total area of closure could still be significant. The location of two short NW–SE trending seismic lines in the vicinity of the lead (acquired by Grepex in 1971) indicates that this area was also identified as an area of interest in the first phase of exploration.

(iii) Lead C

Although this structural lead is only crossed by one seismic line (Map 5) it probably has the greatest potential. Filtered Bouguer gravity maps, compiled by KMS for this study, show a corresponding closed gravity high in the same location (Fig. 8), supporting the presence of four-way closure. In cross-section (Fig. 6) the crest of the lead appears to be relatively unfaulted and could be partly dip-closed, reducing the risk of fault leakage. A portion of seismic line GGU/90-2 shown in Fig. 9 contains clear deeper reflectors which indicate that the structure could form a much broader anticline at Cretaceous (sub-basalt) level. The crest of the anticline has been eroded at the top of the Paleocene volcanics, reducing the thickness of volcanic section over the lead, and is cut by later faulting.

(iv) Lead D

This lead is covered by the tightest seismic grid in the area (a total of 6 lines). The older of these seismic lines were acquired by four different oil companies in the 1970s. The seismic coverage over this lead is still, however, very sparse and closure is not well defined to the north and south (Map 5). Fault closure to the east and dip closure to the west are better defined, but still require a much tighter seismic grid.

A cross-section through the seismic line GGU/90-1 (Fig. 6) and the portion of the seismic line in Fig. 10 show the structure to be a fairly simple tilted fault block. Potential closure continues at depth and the volcanics have been thinned by erosion over the crest of the structure.

(v) Lead E

The largest lead identified is in the northern part of the area. The lead was first identified in a confidential report by GGU to the Mineral Resources Administration for Greenland in 1993 as an area of interest which needed more detailed interpretation. Now that the older industry data has been incorporated into the mapping, the possible extent of the structure can be seen more clearly (Map 6). The important NW–SE fault direction which closes the lead to the north-east can only be identified using the old data. This structural trend is confirmed by the new gravity anomaly maps covering the area (Fig. 8).

The lead is a tilted fault block, with dip closure to the south and west. It is covered by four seismic lines including two lines acquired in the 1970s.

Table 3. Structural leads in central West Greenland

Lead	A	B	C	D	E
Potential area of closure (km^2)	325	150	375	500	775
Potential hydrocarbon column (m)	200	200	200	600	800
Depth to Top Paleocene Volcanics (m)	2200	1200	1200	1600	1800
Water depth (m)	180	170	260	180	300

CONCLUSIONS

- Seismic data in central West Greenland between 68° and 72°N were previously considered to be of insufficient quality to produce anything but sketchy regional maps. This interpretation project, however, has shown that it is possible to map several horizons within the Tertiary sedimentary section in moderate detail. This has been achieved by the use all the available seismic data including those lines acquired during the first phase of exploration in the 1970s. Geological models from other parts of West Greenland, with better data quality, have also been useful in interpreting deeper parts of the succession.

- It was generally accepted prior to the start of this study that it was almost impossible to see reflectors beneath a thick Paleocene volcanic section. Closer inspection of the data, however, has shown that it is possible to interpret horizons deeper than Top Paleocene Volcanics.

- There are several important tectonic implications that arise from the results of this new seismic interpretation. The study area is closer to the five exploration wells drilled in southern West Greenland than the Melville Bay area, leading to a more accurate estimate of the timing of Tertiary tectonic events than was possible in Melville Bay. A transpressional phase, also seen in the Melville Bay area, is confirmed to have occurred towards the end of a period of rifting in the Paleocene. The crests of anticlines formed during this time were eroded in a period of Eocene syn-drift deposition, when transgressive marine sediments infilled the irregular topography, forming a number of restricted basins. Strike-slip faulting continued to affect the region throughout the Eocene and the formation of north–south transtensional grabens and NW–SE extensional faulting coincided with the opening of Baffin Bay.

- Several promising structural leads have been mapped using the Top Paleocene Volcanics level. None of the leads is a drillable structure at present because of the wide spacing of the seismic coverage. They are, however, of considerable size and worthy of further exploration.

- The most promising potential plays in the area are sub-basalt Cretaceous and Lower Paleocene plays which are the primary objective throughout the whole of West Greenland. A possible secondary Tertiary play identified above the basalts may also have significant potential and could be present in other parts of West Greenland. The thick basalt section may yet prove fatal to the prospectivity of the area, but the present study gives sufficient encouragement to warrant continued exploration.

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FIGURES

MAPS

5. Detailed Top Paleocene Volcanics depth map (southern area). Location of map shown in Map 4.
6. Detailed Top Paleocene Volcanics depth map (northern area). Location of map shown in Map 4.

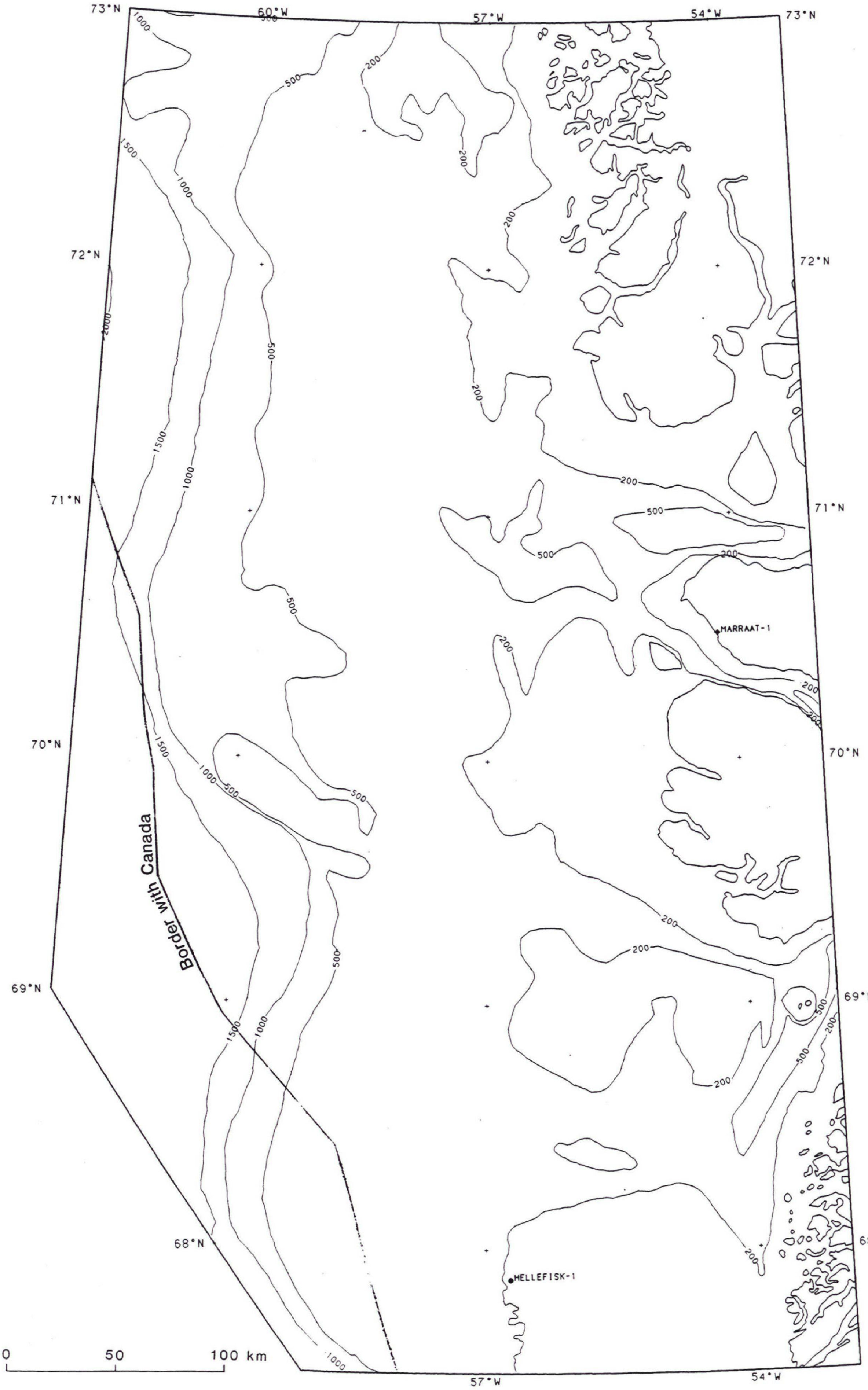


Fig. 1. Bathymetric map of offshore central West Greenland.

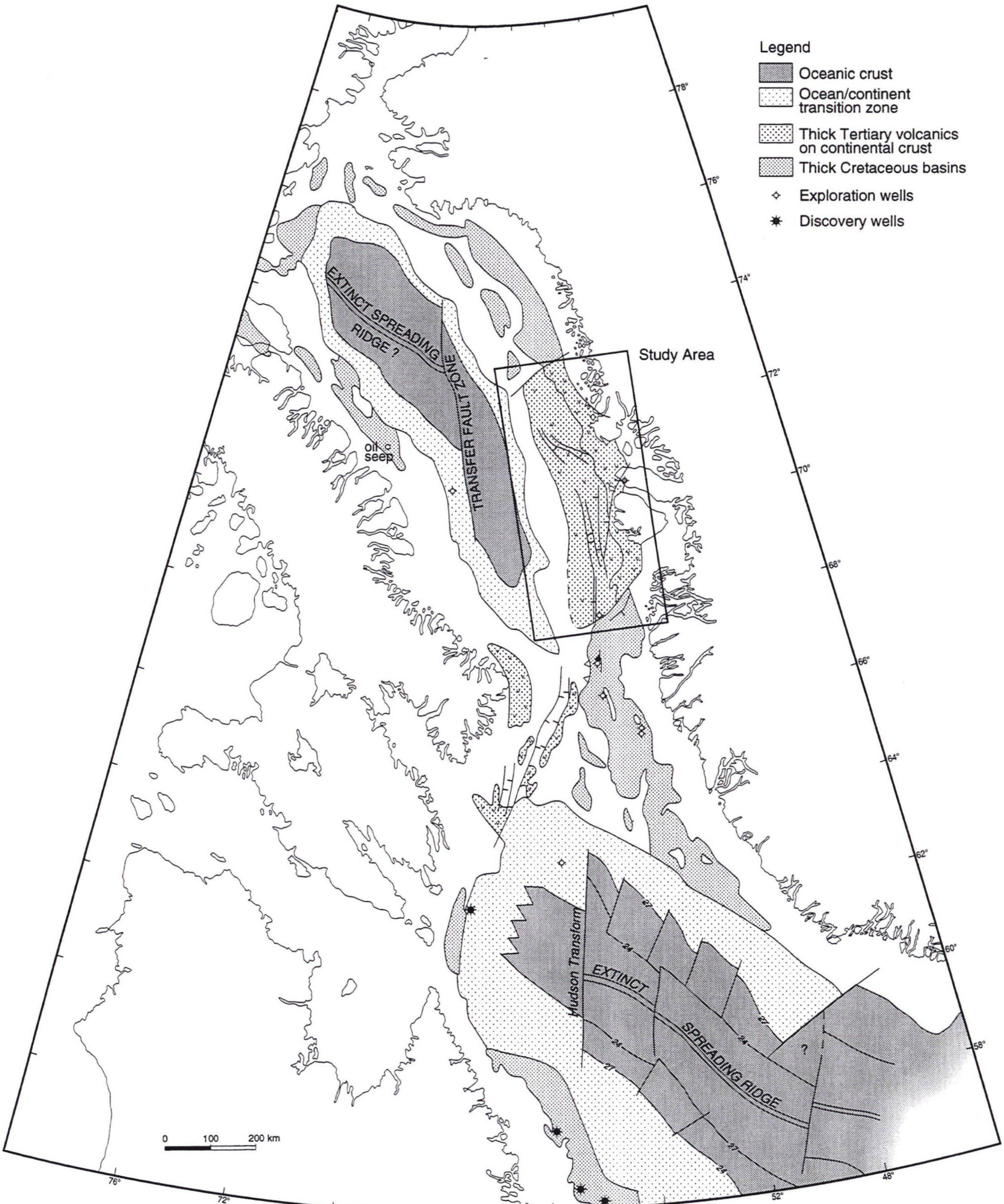


Fig. 2. Tectonic elements of Baffin Bay and the Labrador Sea region.

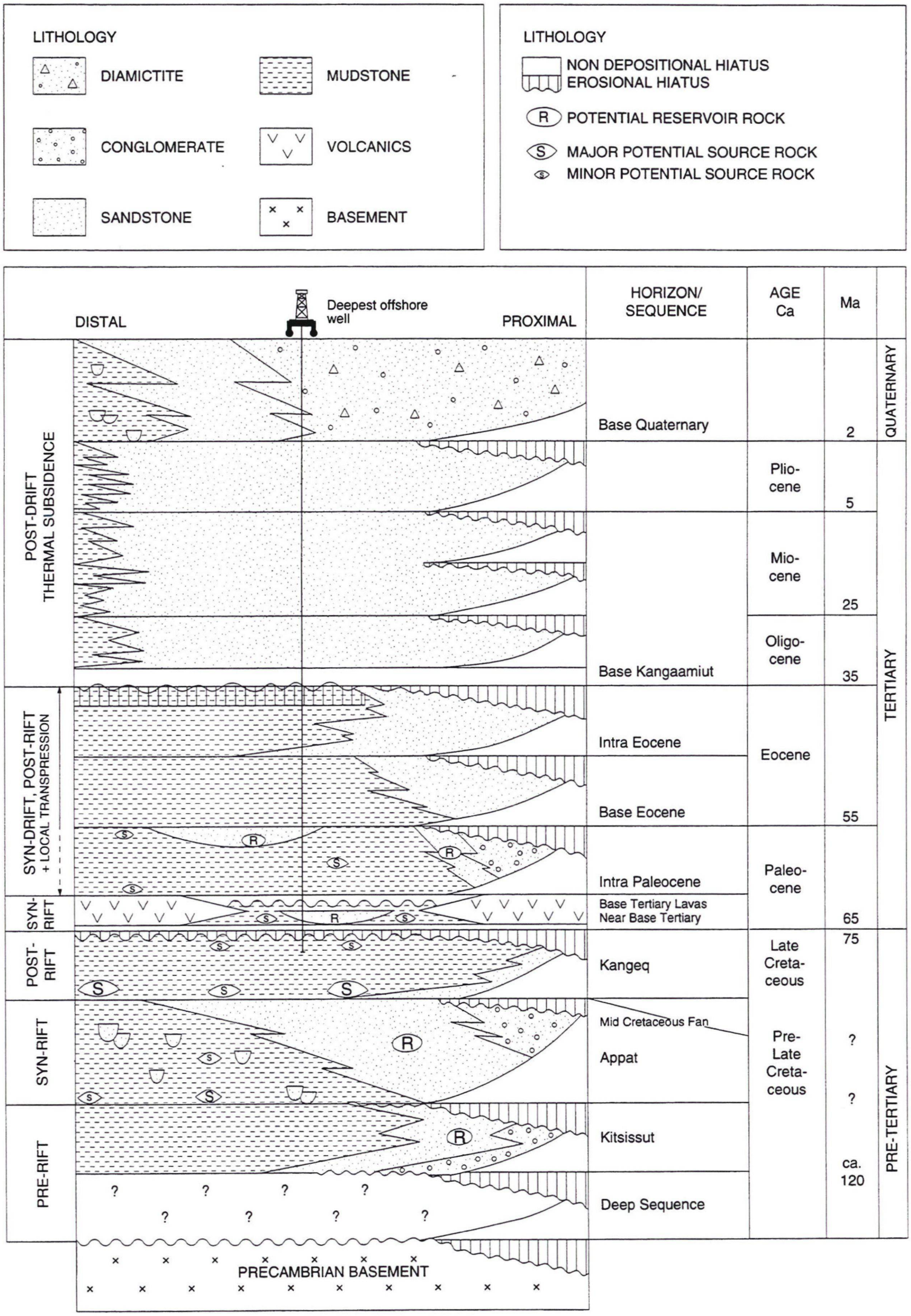


Fig. 3. Summary of the geological succession offshore West Greenland (after Chalmers *et al.*, 1995)

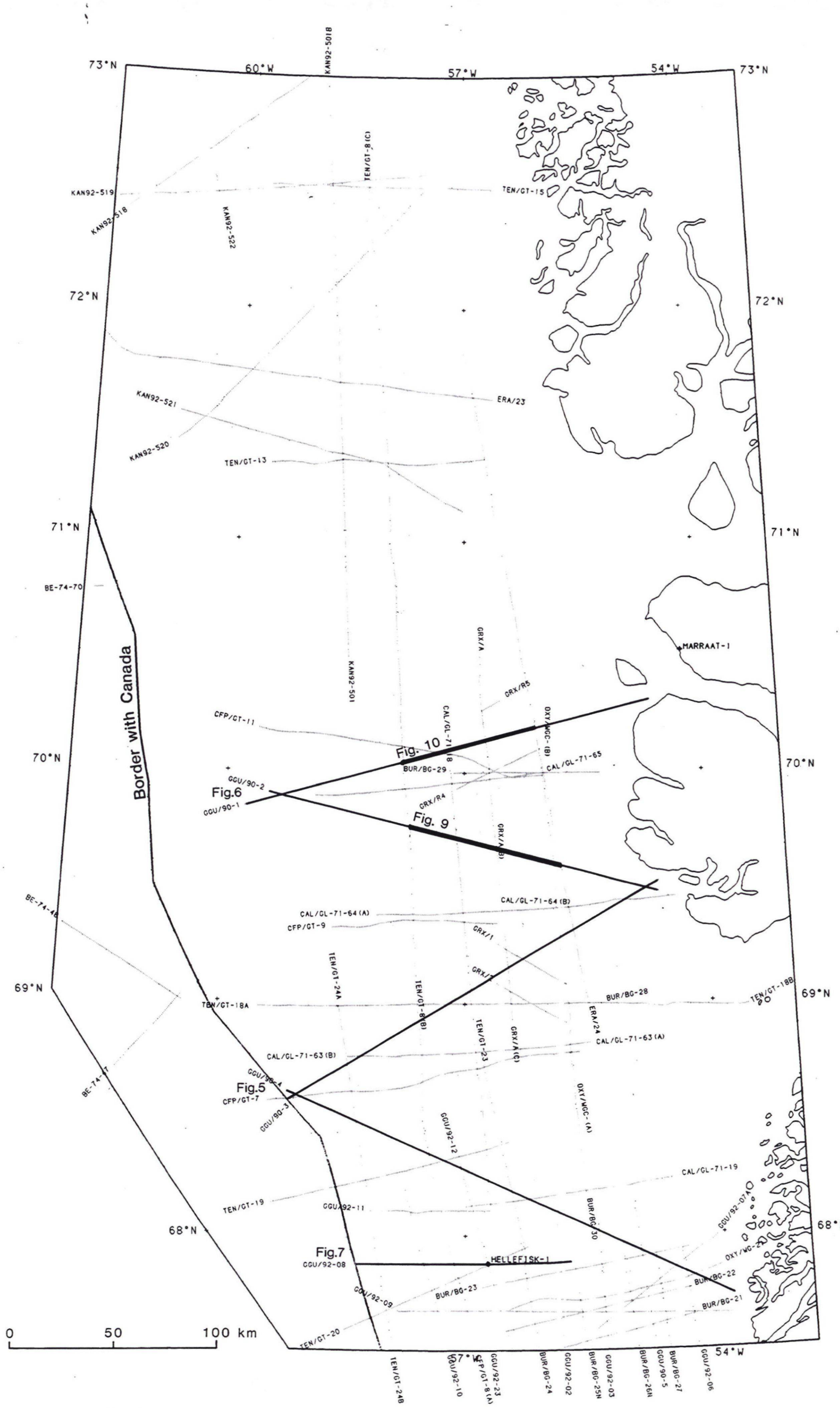


Fig. 4. Total seismic coverage offshore central West Greenland. The lines along wich the cross-sections in Figs 5-7 are drawn and the portions of seismic lines reproduced in Figs 9 and 10 are shown.

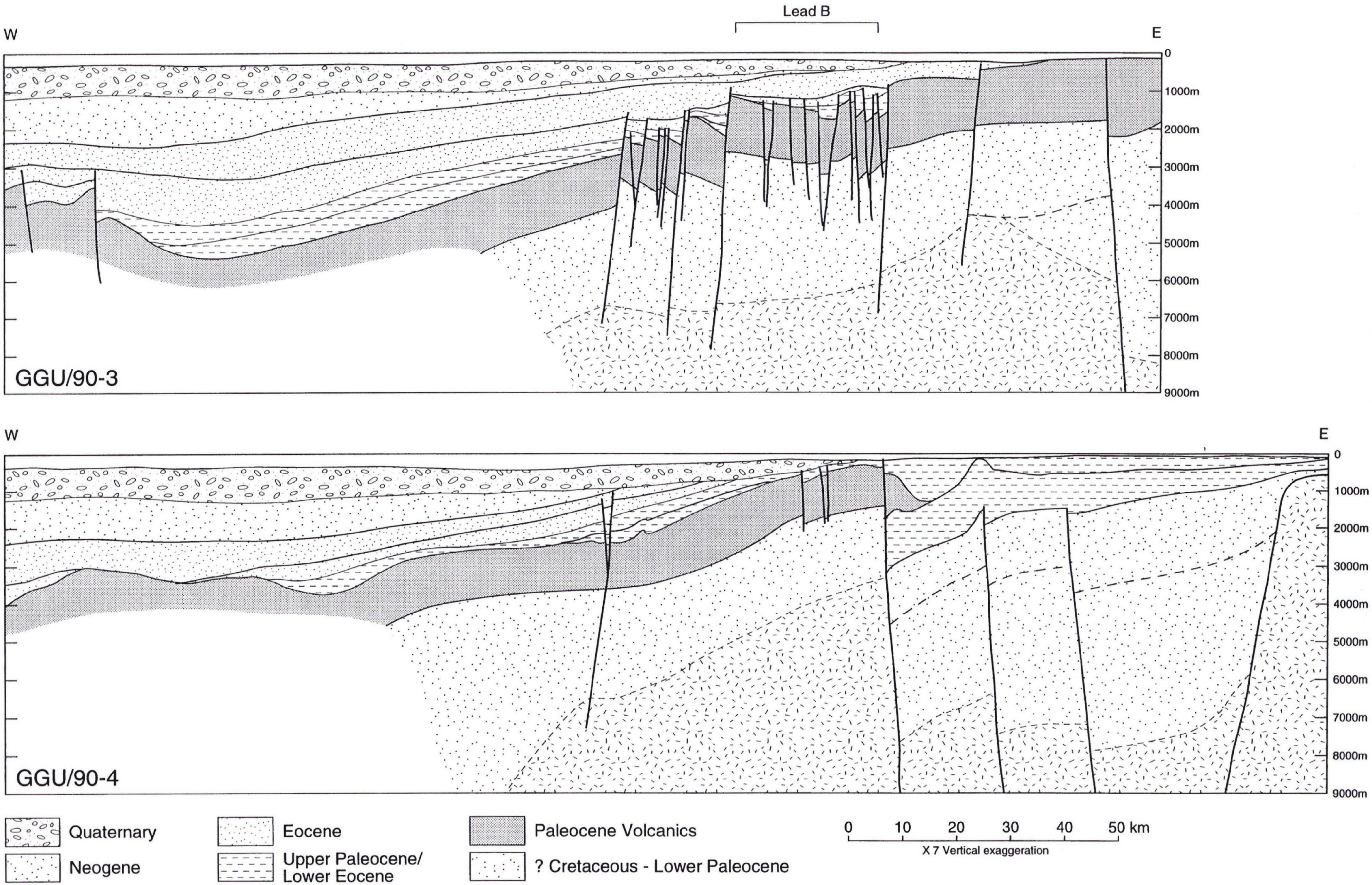


Fig. 5. Cross-sections drawn from depth converted seismic interpretations south-west of Disko, central West Greenland. For locations see Fig. 4.

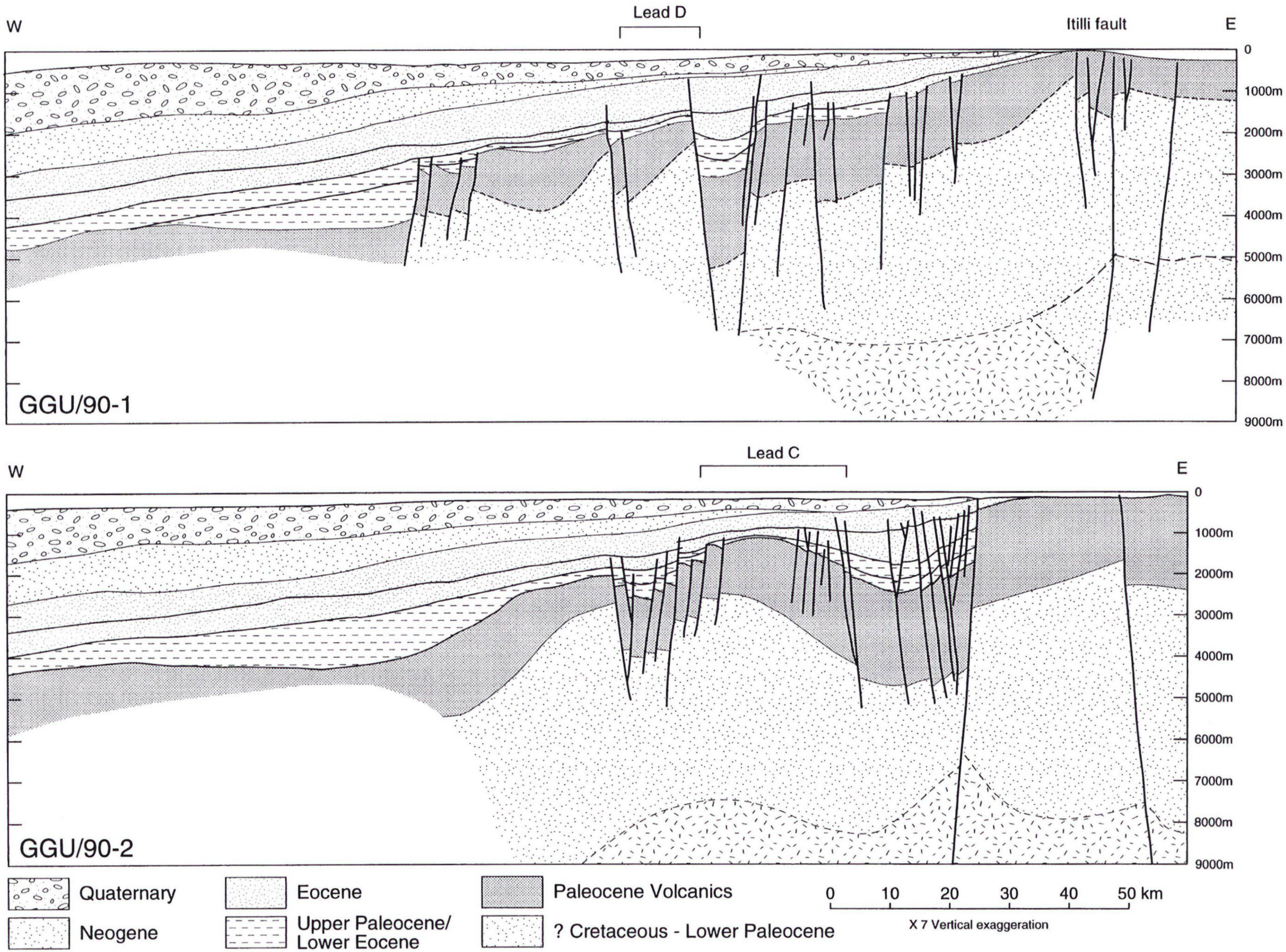


Fig. 6. Cross-sections drawn from depth converted seismic interpretation west of Disko, central West Greenland. For locations see Fig. 4.

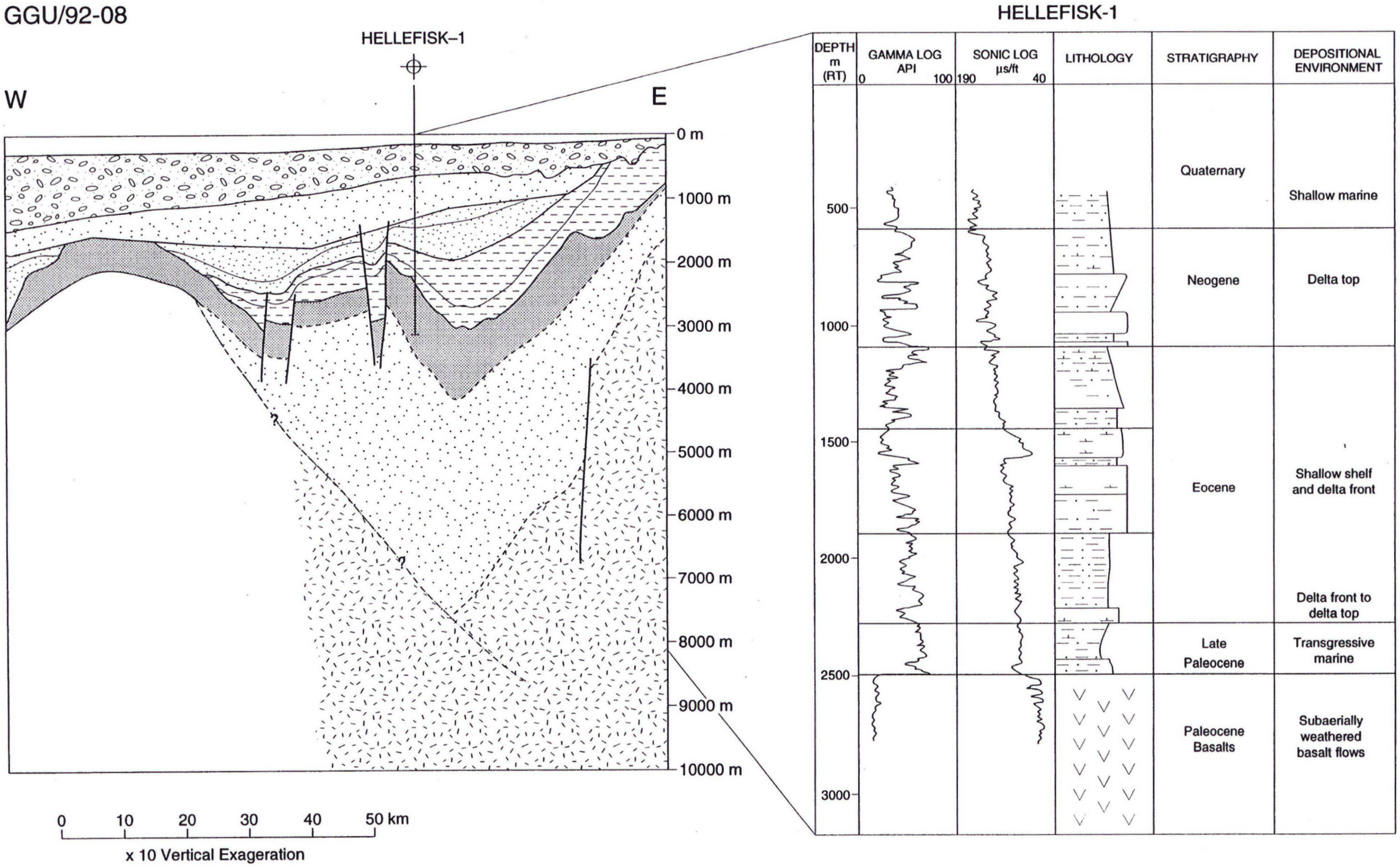


Fig. 7. Cross-section through the Hellefisk-1 well (lithology and depositional environment after Rolle, 1985.)

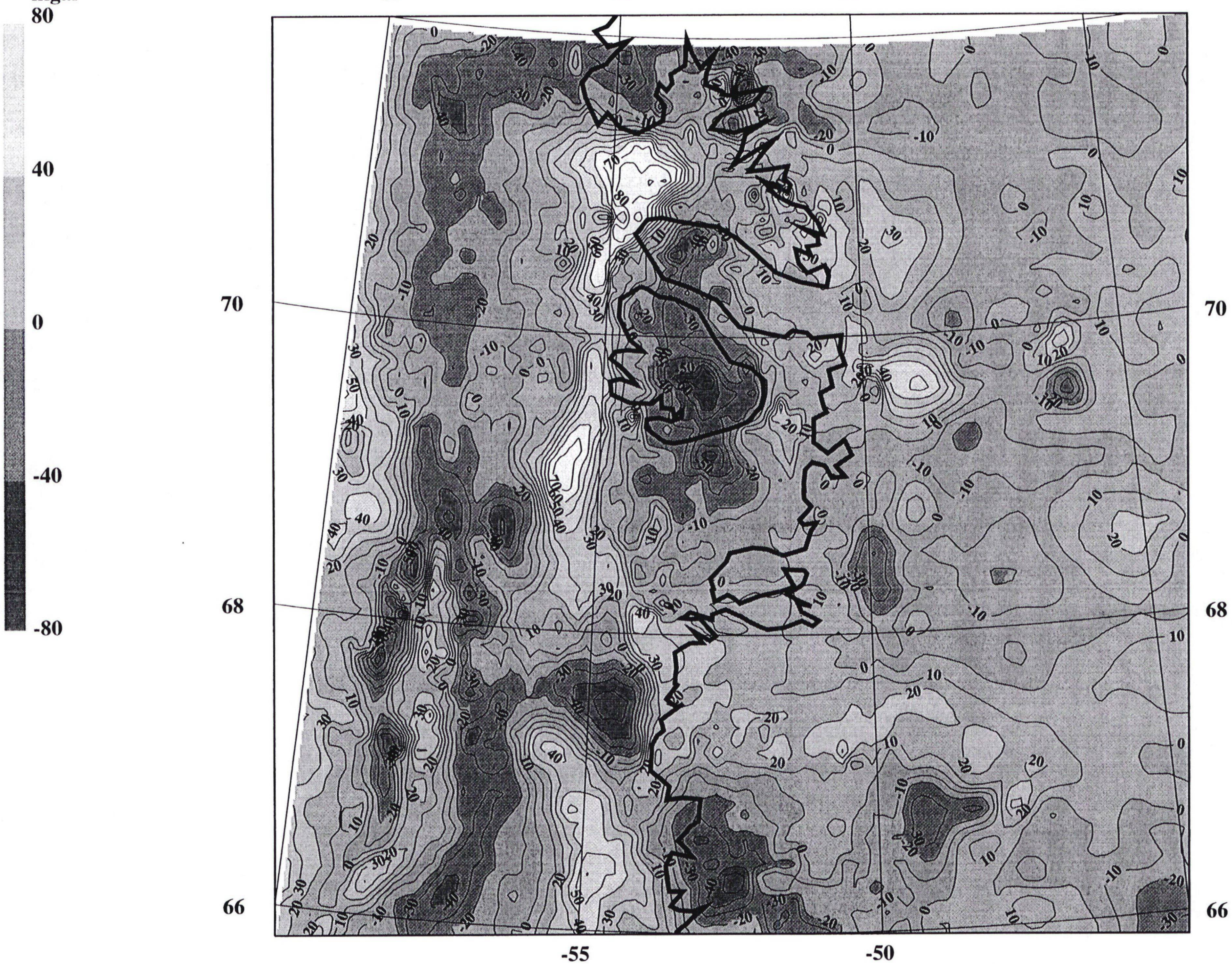


Fig. 8. Filtered Bouguer anomaly map of the central West Greenland area (courtesy of R. Forsberg of the Danish National Survey and Cadastre, KMS).

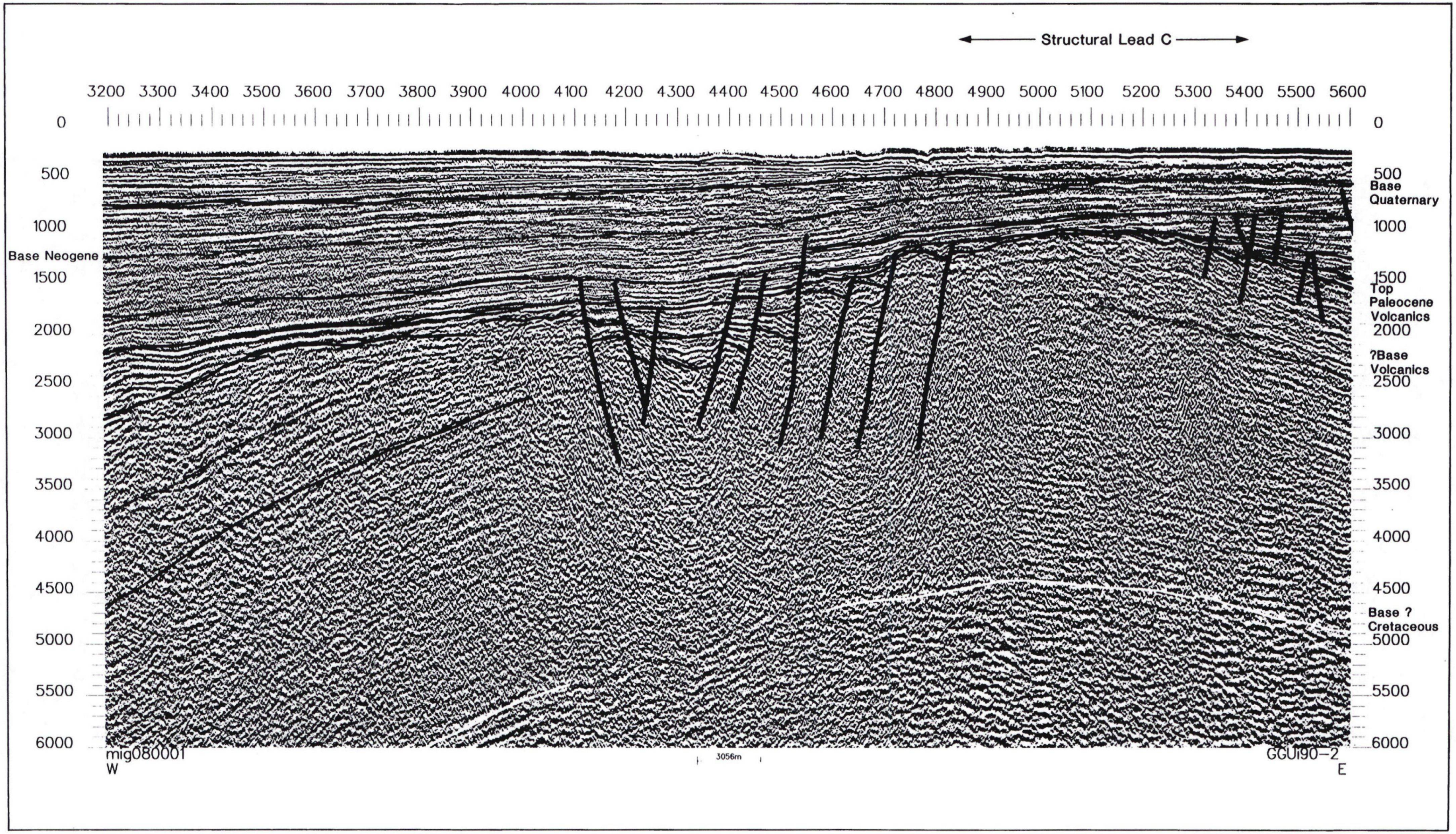


Fig. 9. Seismic line GGU/90-2 showing deep reflectors (5-6 seconds TWT) beneath the partly eroded Paleocene volcanic section. Location of line shown in Fig. 4.

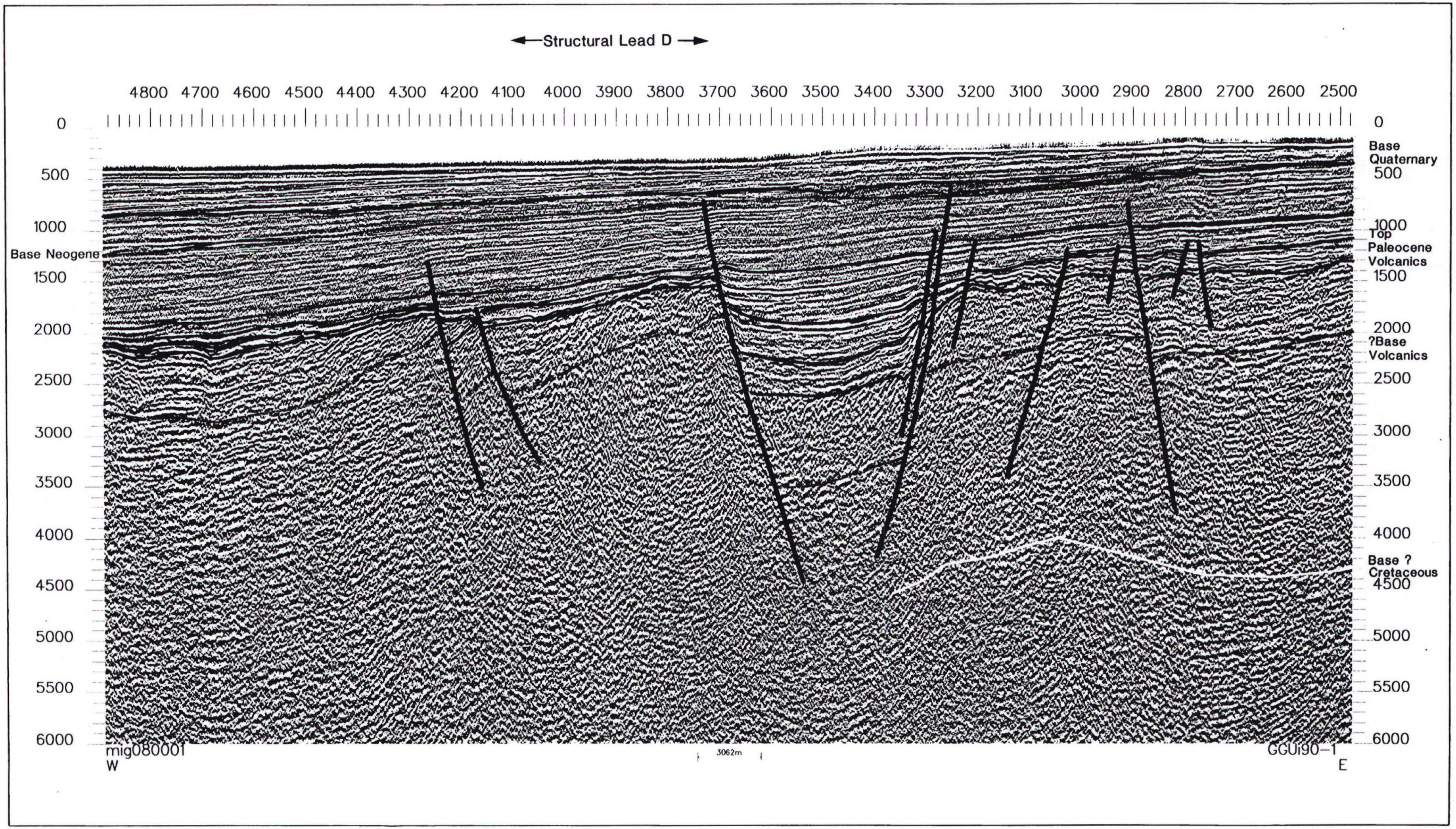
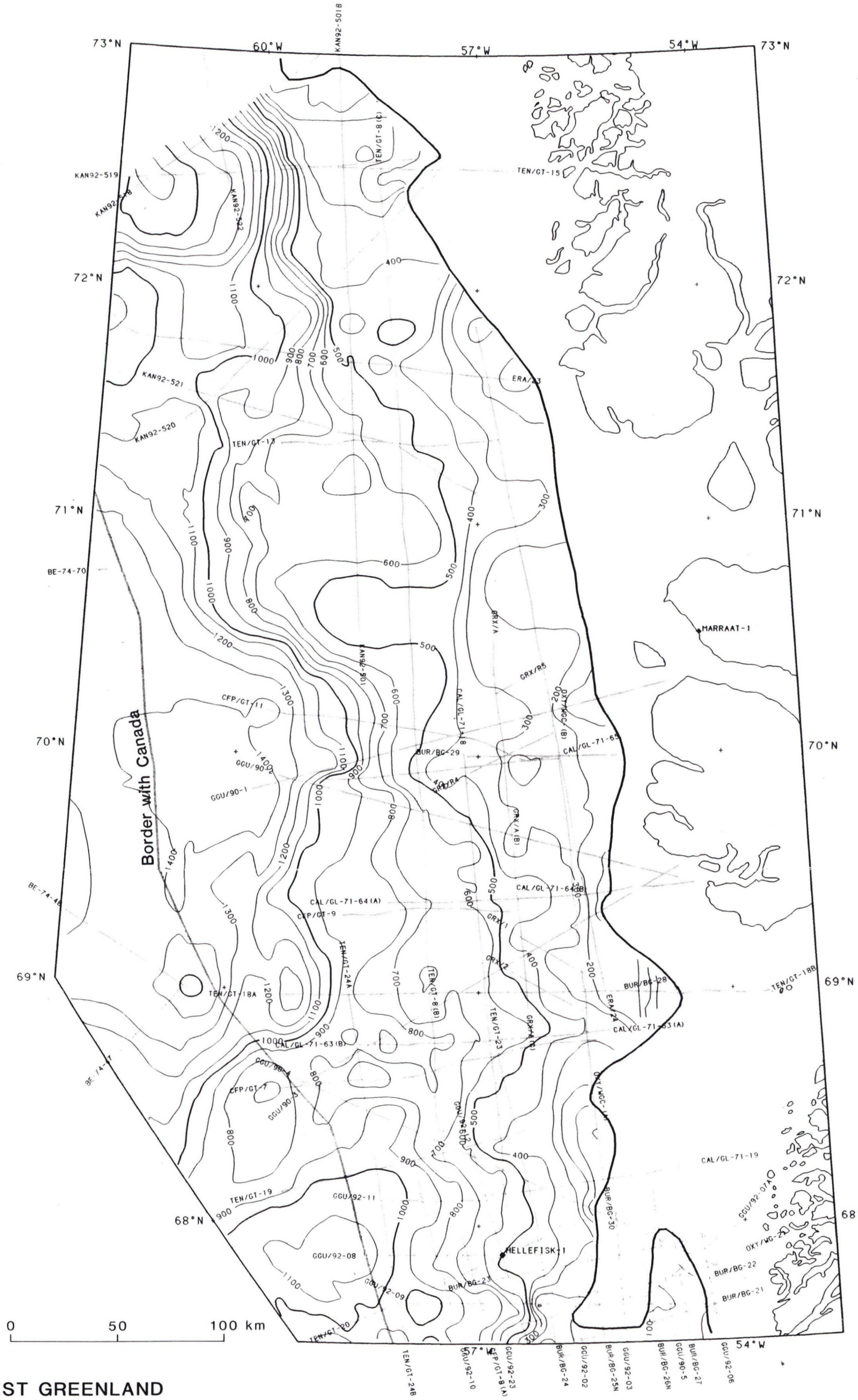
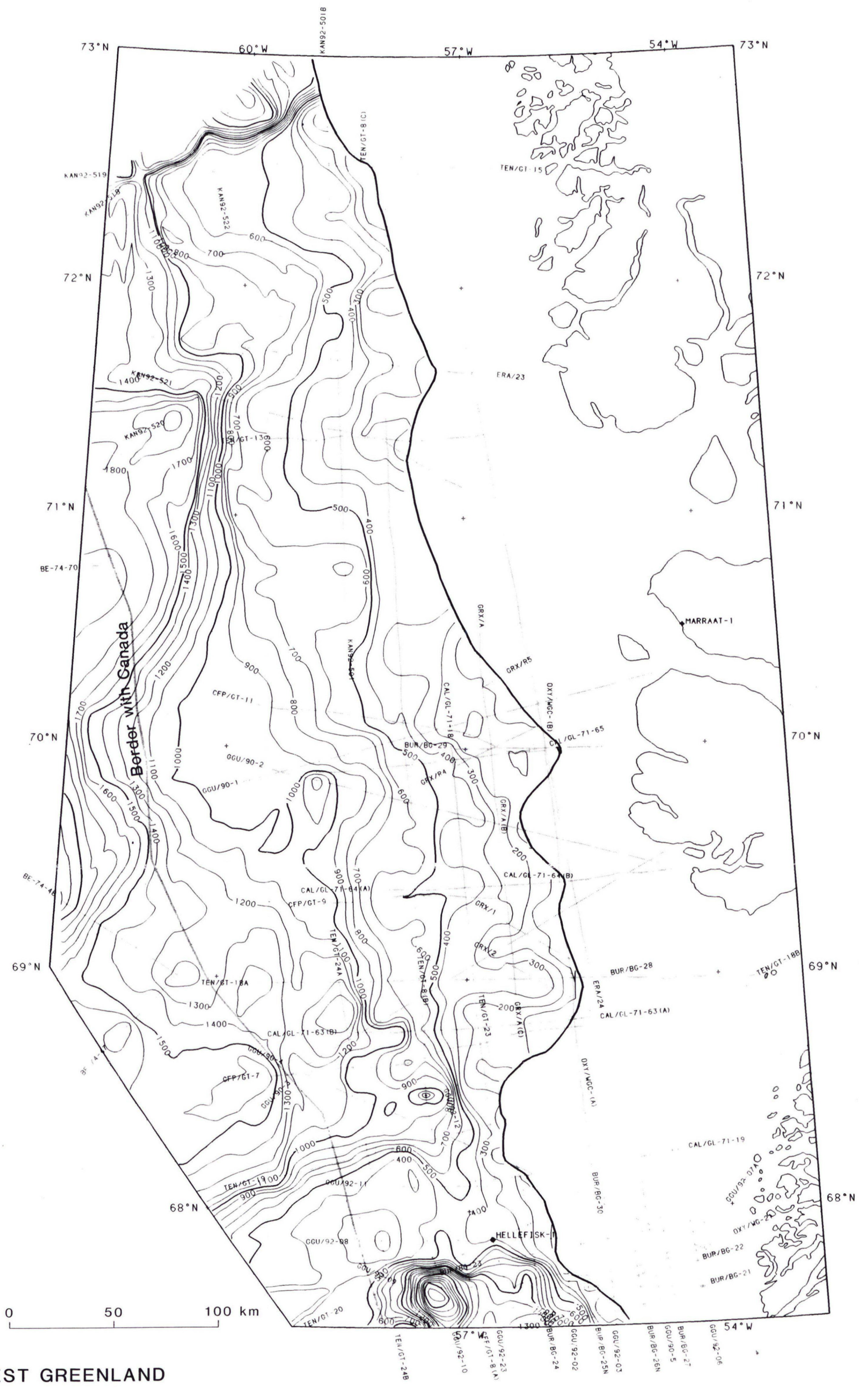


Fig. 10. Seismic line GGU/90-1 showing a narrow graben which has controlled deposition during the Palaeogene. Location of seismic line shown in Fig. 4.



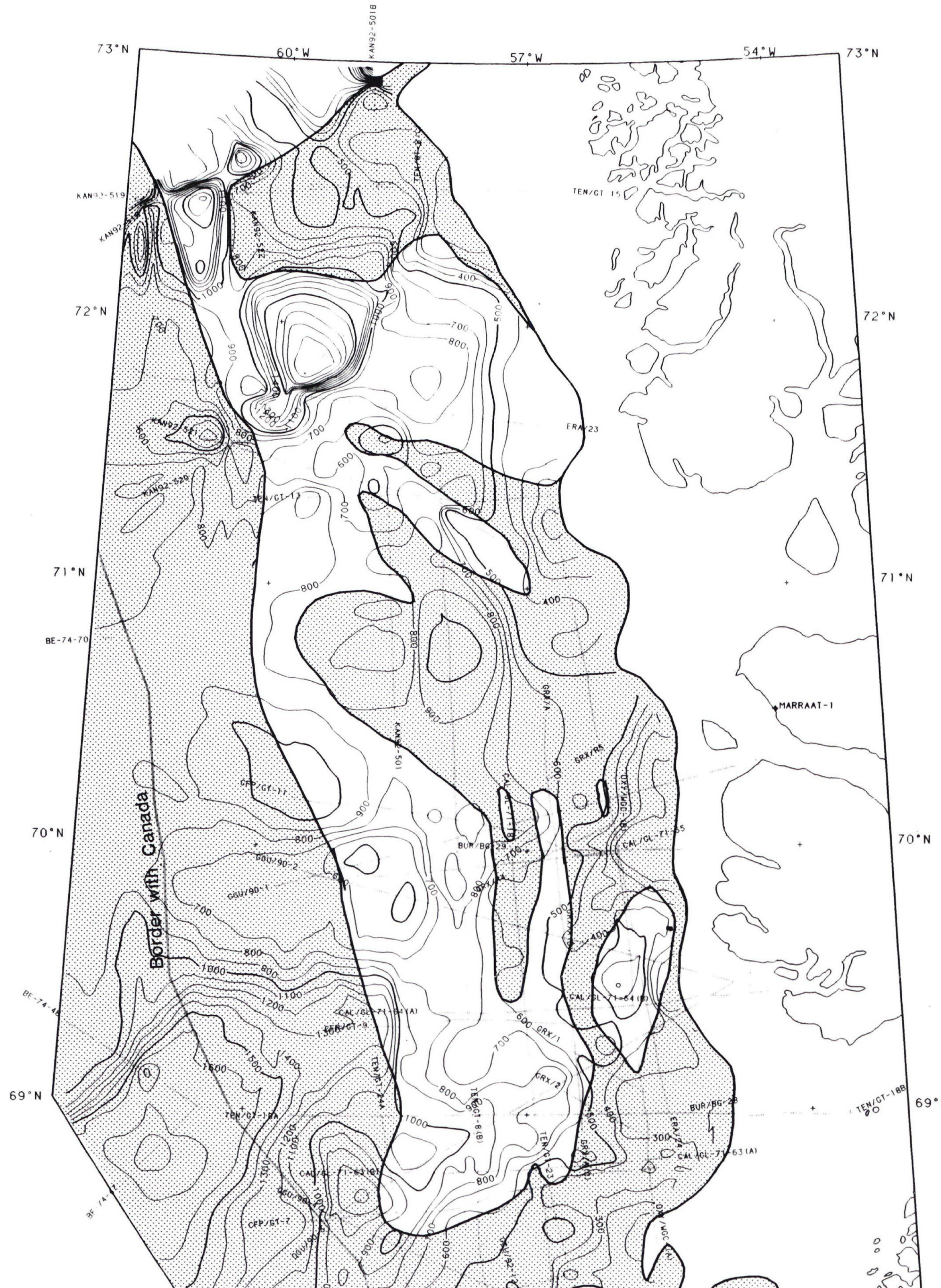
CENTRAL WEST GREENLAND
QUATERNARY
ISOPACH
Contour Interval 100 m

MAP 1



CENTRAL WEST GREENLAND
NEOGENE
ISOPACH
Contour Interval 100 m

MAP 2

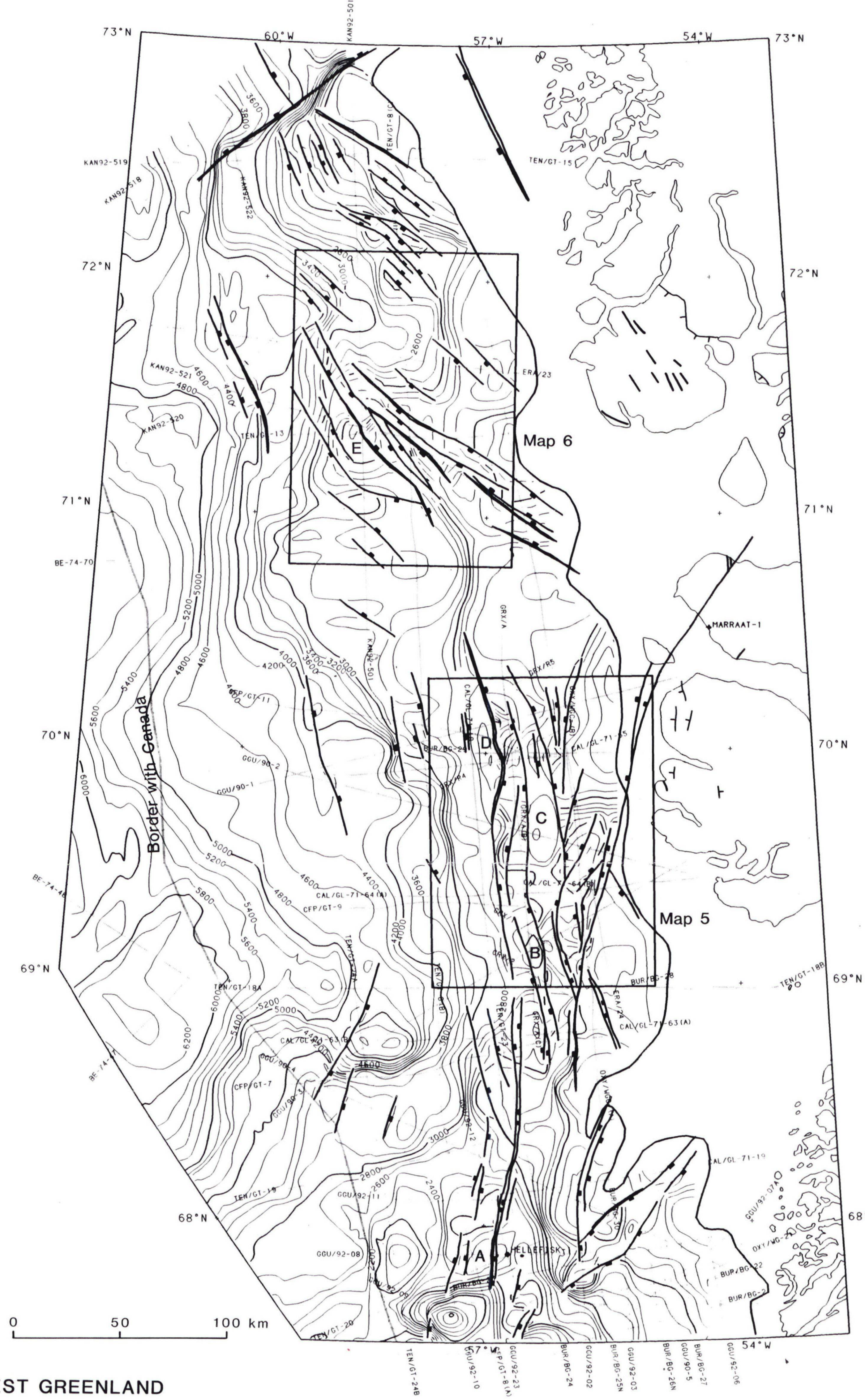


CENTRAL WEST GREENLAND

EOCENE
ISOPACH

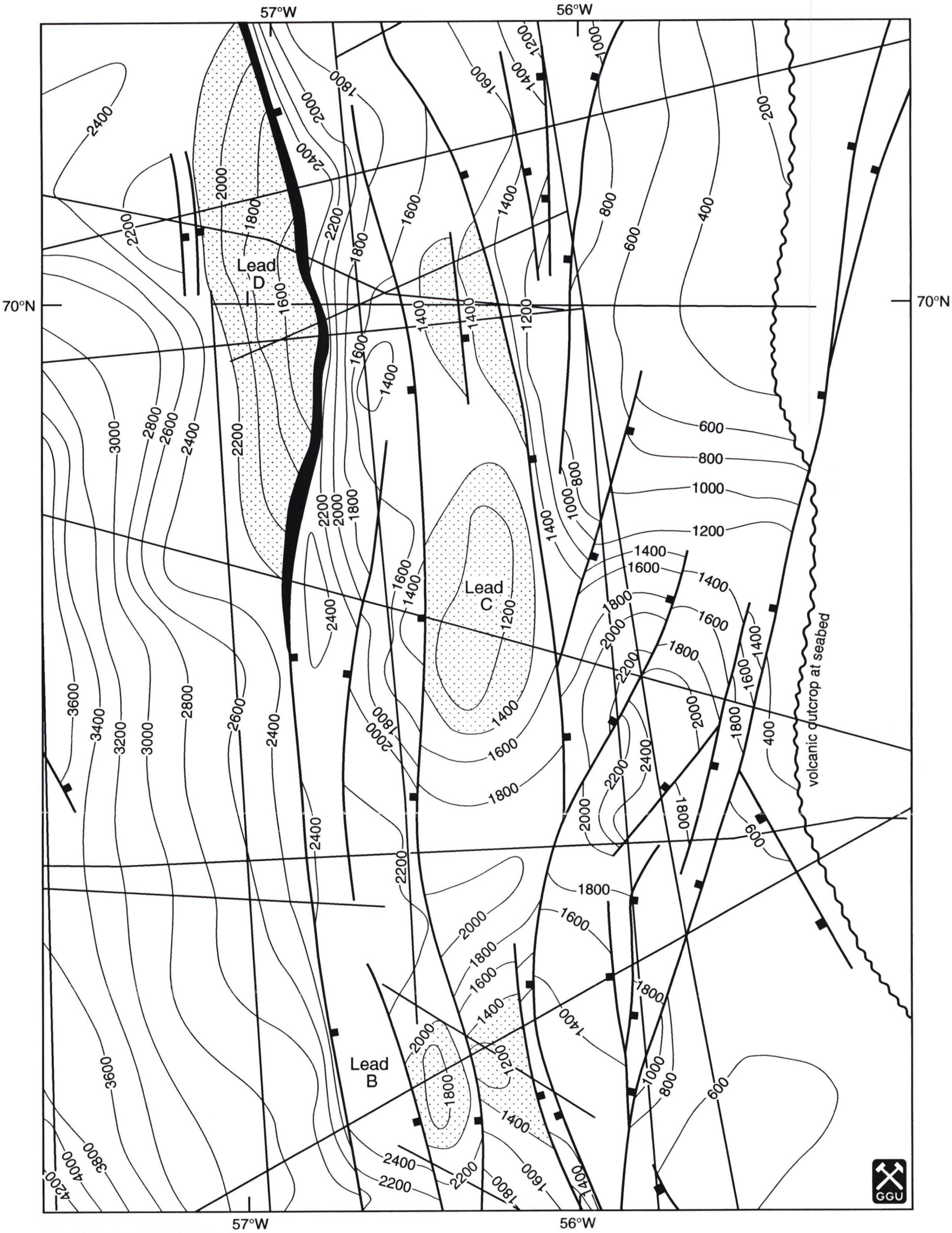
Contour Interval 100 m
(Shaded area: base of section absent)

MAP 3



CENTRAL WEST GREENLAND
TOP PALEOCENE VOLCANICS
DEPTH
Contour Interval 200 m

MAP 4

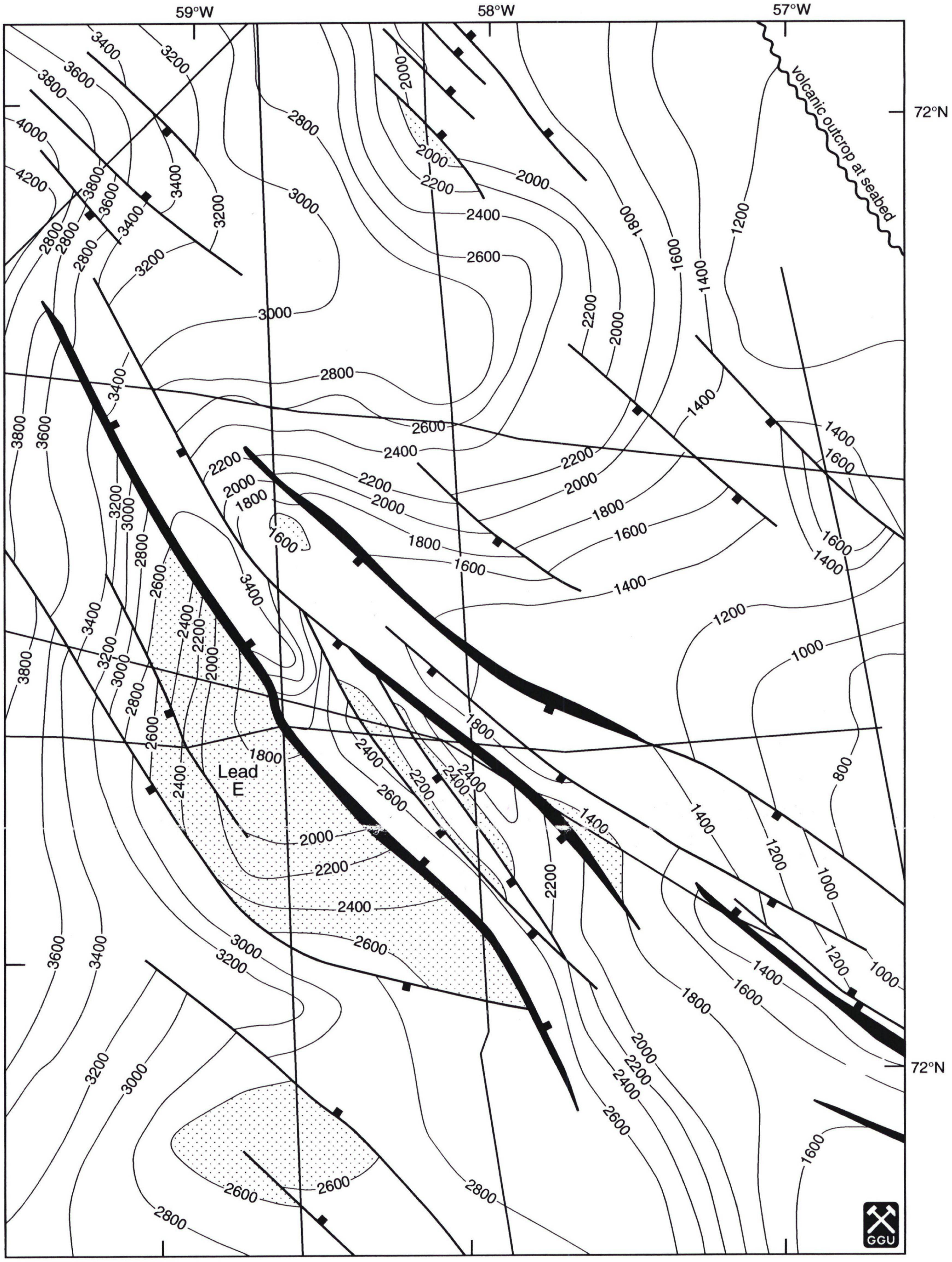


CENTRAL WEST GREENLAND
TOP VOLCANICS DEPTH
Contour Interval 200 m

10 km

Seismic coverage

MAP 5



CENTRAL WEST GREENLAND
TOP VOLCANICS DEPTH
Contour Interval 200 m

10 km

Seismic coverage ————

MAP 6

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