DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2002/33

EFP Project NuussuaqSeis 2000 – Final Report

Structure and hydrocarbon potential of the Nuussuaq Basin: acquisition and interpretation of high-resolution multichannel seismic data

ENS J.nr. 1313/99-0024

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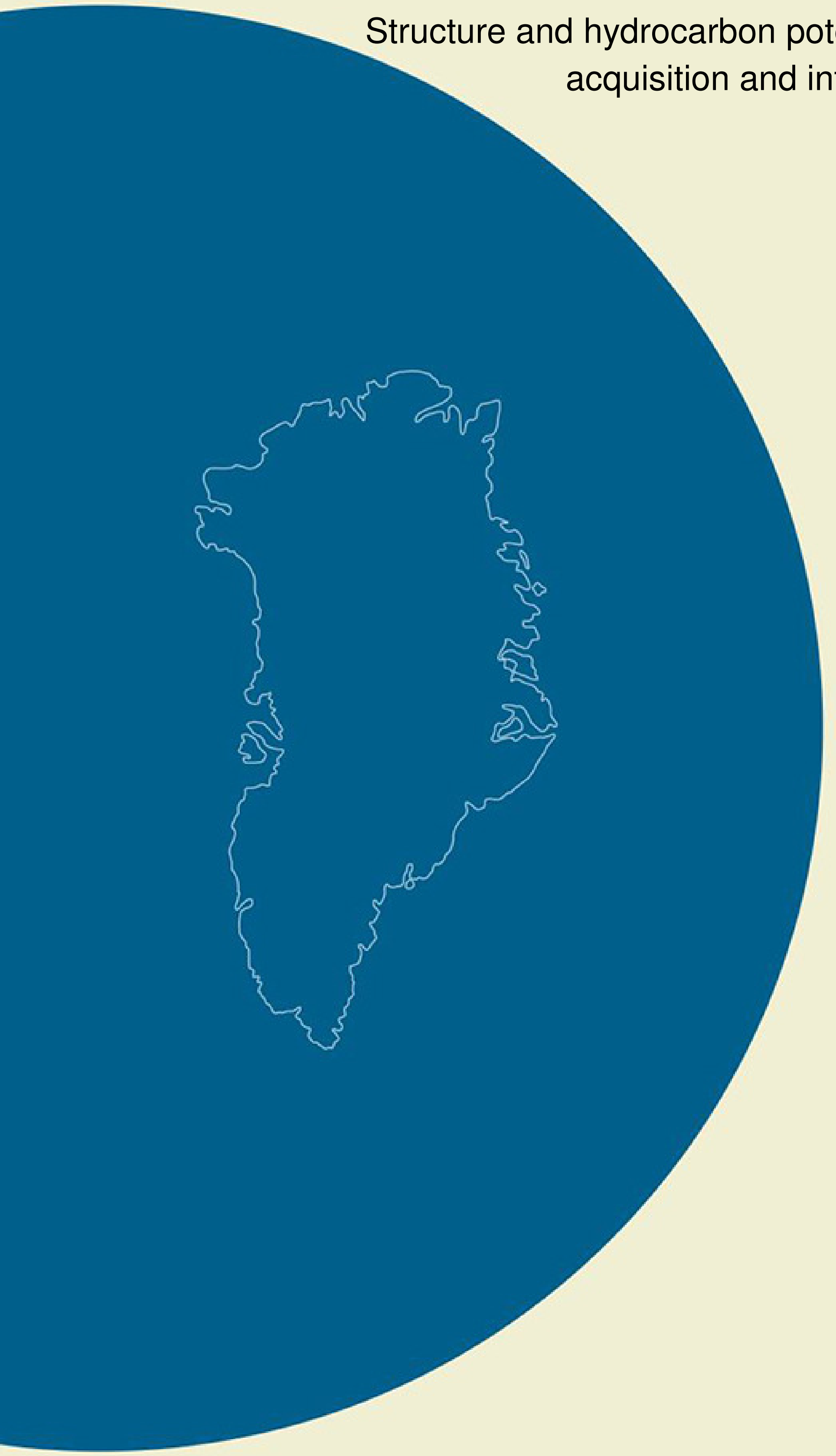

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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1. Introduction

Knowledge of the Nuussuaq Basin in central West Greenland (Fig. 1) has increased significantly since the discovery of extensive oil seeps on western Nuussuaq in 1992 (Christiansen *et al.* 1996; Bojesen-Koefoed *et al.* 1999). A number of geological and geophysical studies have been published and data from slim core drilling and exploration wells are also available. The existence of the oil seeps indicates that the Nuussuaq Basin is a petroleum basin in its own right, and not merely an accessible analogue to potential petroleum basins offshore (Bojesen-Koefoed *et al.* 1999). Seismic data acquired onshore in 1994 (Christiansen *et al.* 1995), followed by a seismic and gravity survey in 1995 in the fjords south and north of Nuussuaq, have greatly improved the general understanding of the structure of the basin (Chalmers *et al.* 1999). Project NuussuaqSeis 2000 – acquisition of high-resolution multichannel seismic data in the waters around Nuussuaq and Ubekendt Ejland – was designed to improve understanding of the shallow structure of the Nuussuaq Basin.

A high-resolution multichannel seismic survey (GEUS2000G - project NuussuaqSeis 2000, Marcussen *et al.* 2001a, b) was carried out from 18 July to 2 August 2000 in the offshore part of the Nuussuaq Basin, central West Greenland using the Danish research vessel *R/V Dana* (Fig. 2) equipped with seismic equipment from the Geological Institute, Aarhus University. Funding for the project was provided by the Danish Energy Research Programme through grant number EFP99-0024, the Bureau of Minerals and Petroleum (BMP), Greenland, the Geological Institute of Aarhus University, Denmark and the Geological Survey of Denmark and Greenland (GEUS).

The seismic cruise in 2000 was a collaboration between the Geological Institute, Aarhus University, the Danish Institute for Fisheries Research (DFU) as owner of *R/V Dana* and GEUS. The following participated in the cruise:

Christian Marcussen, chief scientist, GEUS
Holger Lykke Andersen, co-chief scientist, Aarhus University
James A. Chalmers, senior researcher, GEUS
Rasmus Rasmussen, senior adviser, GEUS
Per Trinhammer, technician, Aarhus University
Egon Hansen, technician, GEUS
Britt Jessen, student, Aarhus University

Peter Østrin, captain of R/V *Dana* and the crew of R/V *Dana*

Processing of the acquired seismic data was undertaken by Rasmus Rasmussen and Trine Dahl-Jensen (Rasmussen & Dahl-Jensen 2001) both from GEUS.

2. The seismic survey

2.1 Planning

Experience during seismic acquisition in earlier years in the same waters has shown that use of a long streamer (e.g. 3000 m) is likely to be impeded by the large numbers of icebergs. While usage of a short streamer makes it impossible to remove seabed multiples by traditional methods (e.g. F/K filtering), the relatively large water depths in the area of interest – between 400 and 800 m – make it possible to see up to 1.5 km of sediments before the first seabed multiple obscures the data. It was therefore decided to accept the limitations of a short streamer, and use high-resolution seismic equipment with a considerably smaller source but better resolution than conventional marine seismic equipment.

Prior to initiation of the survey, all available bathymetric data were compiled and plotted together with the planned lines as overlays to the published charts from the area (Fig. 1). This showed that the bathymetry of parts of the survey area was poorly known. The planned survey consisted of 2013 km of high priority lines in Vaigat and Uummannaq Fjord plus 290 km of lower priority lines over the areas underlain by basalt west of Nuussuaq and Ubekendt Ejland.

2.2 Seismic equipment

The seismic acquisition system used for the survey is owned by the Geological Institute of the University of Aarhus. It included a 96-group, 594 m-long hydrophone streamer with a 6.25 m group interval and two Geometrics R48 recording systems. The source consisted of a 4 x 40 in^3 (cubic inches) sleeve-gun cluster. Navigation was controlled by Navipac software, and positioning was provided by an Ashtec G12 GPS receiver (see Table 1 for further details). A Ramesses quality-control system was integrated in the acquisition system to provide real-time processing and display facilities. Due to technical problems, magnetic data were recorded only from line GEUS00-18.

A ProMax processing system from GEUS was installed on *R/V Dana*; this system was used for test processing of the seismic data and hence gave valuable input for subsequent adjustments of the survey programme.

Table 1: Acquisition parameters

Source:	4 x 40 in^3 TI SG-I sleeve guns	Spacing between individual guns: 50 cm centre to centre
	Pressure: 120 bar	Depth: 3.5 m to centre of cluster
Streamer:	Length: 593.75 m (active section)	Towing cable length: 90 m
	96 groups	6.25 m group interval
	3.125 m group length	Depth: 3 m
Shotpoint interval:	5 sec ≈ 12.5 m	Near offset: 53 m
Recording system:	2 Geometrics R48	Sample rate: 1 msec
	Record length: 3072 msec	Delay: 0 msec
	Filters: Low cut: 10 Hz slope 24 db/oct	Filters: High cut: 300 Hz anti-aliasing
	Data format: SEG-D 8048 revision 0	Output media: IBM 3490 cartridge
Navigation:	GPS	Ashtech G12 receiver
Magnetometer:	Geometrics G866	
Echosounder:	Simrad EK 400	

For further details see Marcussen *et al.* (2001a).

2.3 Data acquisition

A total of 2743 km of data were acquired during the 18 day survey, which was 20% more than planned (Fig. 2) (Marcussen *et al*. 2001a). During the entire cruise, the weather was effectively calm and therefore ideal for seismic acquisition. Icebergs which were expected to be the main obstacles to seismic acquisition, were either relatively sparse, in which case it was possible to acquire data around them without significant problems other than the occasional move slightly off line, or they were packed so densely that some areas were impossible to penetrate. The amount of time lost for equipment downtime was also small, a total of about 10 hours. Maintenance of equipment was mostly undertaken during extended line shifts.

Data were acquired in three areas: (1) the Vaigat area south of Nuussuaq; (2) the area of Uummannaq Fjord and Illorsuit Sund; and (3) the areas west of Ubekendt Ejland and Nuussuaq where basalts are exposed on the seabed.

The first phase of the survey in Vaigat was carried out for the most part on the pre-planned lines. Since the iceberg density was low, the strategically most important data were acquired first over the known area of fault-blocks in western Vaigat. It became apparent during the acquisition of these first lines that the quality of the data was good to excellent in areas without sills, large glacial moraines or post-glacial slumps at the seabed (Fig. 3).

In the area of Uummannaq Fjord and Illorsuit Sund, acquisition started with line GEUS00-13, a long transect from west of Nuussuaq to the basement outcrop west of Appat Ø. On the way into and across Uummannaq Fjord, it became apparent that there was a low density of icebergs in the outer fjord similar to that encountered in Vaigat, but icebergs were tightly packed in the inner part of the fjord around Uummannaq. Of two long transits (GEUS00-14 and -15) across Uummannaq Fjord to the basalt area and back, the eastern end of line GEUS00-15 was terminated early because of dense concentrations of icebergs. Further acquisition of planned lines east of 52º30'W had to be abandoned because of densely packed icebergs, and thus only a few crossings over the eastern margin of the basin were made. New lines were planned in the accessible part of the fjord. After finishing work in the southern part of Uummannaq Fjord, a transit to the north between Ubekendt Ejland and Upernivik Ø (GEUS00-22 and -27) was terminated by large concentrations of icebergs at 71º27'N. It was not possible to proceed farther north, and the entire programme east of Svartenhuk Halvø in the northern part of the basin was abandoned.

Acquisition of lines west of Nuussuaq and Ubekendt Ejland was only of second priority. However, the favourable weather conditions made it possible to expand the acquisition programme considerable in this structurally poorly-known area. Additional lines were thus acquired where basalts are found near seabed, and water depths were large enough to achieve significant penetration of the basalts above the first seabed multiple. Approximately 710 km of data were acquired in a broad grid extending from the mouth of Vaigat in the south to Svartenhuk Halvø in the north during a 3½ day period.

A preliminary interpretation of the data was made onboard as they became available throughout the survey. The primary purposes of the interpretation were to provide information for any necessary alteration of survey plans, to judge the quality of data, to provide input to processing on ProMax, and to develop models for subsequent more detailed interpretation.

2.4 Processing

The seismic data processing was initiated during the survey on selected lines, both to check data quality and to contribute to adjustments in the survey programme. The possibilities of removing the sea bottom multiple were carefully tested, but although it was possible to weaken the seabed multiple substantially, it was still too strong to identify primaries below the multiple except in a few places. This problem was expected because of the small source volume (160 in^3 in total) and in particular the streamer length (600 m). In order to avoid problems in migration, it was therefore decided not to migrate the data below the sea bottom multiple. The relatively time-consuming Kirchoff migration algorithm has been used to ensure optimal migration of the steeply dipping features common in the survey area. The velocity analyses show very high velocities in general, not only in areas covered by basalt, but also in the sediments below the Quaternary cover in most of the survey area, and in particular in Vaigat. See Rasmussen & Dahl-Jensen (2001) for further details.

Table 2: Processing parameters

SEG-D read to final migrated stack:

1. Tape read, noise editing and trace binning (3.125 m CDP distance)
2. Spherical gain correction T**2
3. Resampling from 1 to 2 ms
4. DBS, gap 10 ms, operator length 220 ms, one operator (10/220-1)
5. DMO (Dip Move Out, FK method, 25 m dmo-offset bins)
6. Velocity analyses, every 2 km
7. NMO and trace mute
8. CDP-stack
9. AGC scaling, applied from first order water bottom multiple (robust type, 250 ms windows)
10. Gain correction (T**1.5, applied after water bottom dependent horizon flattening)
11. Kirchoff time migration
12. DIPSCAN (+/- 4 ms/trace, weak TVF applied (from 16-22 to 180-220 Hz at the sea bottom, from 16-22 to 70-90 Hz at the bottom of the data set) in front of the DIPSCAN process)
13. Gain correction (T**0.5 applied after water bottom dependent horizon flattening)
14. AGC scaling (multiple times, window length: 60, 125, 200, 350 and 600 ms, robust type)
15. Trace balancing (robust AGC type, window lengths 2000 ms)
16. TVF (from 19-25 to 180-220 Hz at the sea bottom, from 19-25 to 60-80 Hz at the bottom of the data set)
17. Display and transfer to interpretation

2.5 Magnetic data

Magnetic data are available both as along-line profiles and as aeromagnetic maps from the Aeromag 1997 and 2001 surveys. The aeromagnetic surveys were carried out by flying along a gently-draped surface 300 m above the ground and sea level (Thorning & Stemp, 1998; Rasmussen, in press). Survey lines were aligned in a N–S direction with a separation of 500 m (1000 m in 1997). Orthogonal tie-lines were flown with a separation of 5000 m. Total magnetic field data were recorded with a sampling rate of 0.1 sec, corresponding to 7 m. Data from the two Aeromag surveys have been merged. The magnetic total field has been gridded and is here shown with shaded relief (Enclosure 4). From the gridded data the vertical gradient of the total magnetic field (Enclosure 5) and the analytic signal (represented by the square root of the sum of the squares of the derivatives of the vertical and the two horizontal components of the magnetic total field - Enclosure 6) were produced (Hsu *et al.* 1996).

3. Stratigraphy of the exposed rocks in the Nuussuaq basin

The main outcrops of Cretaceous sediments are in eastern Disko and on Nuussuaq west of the Ikorfat-Saqqaqdalen fault system (Fig. 1). The sediments of Late Albian to early Campanian age were deposited in a fluvial- and wave-dominated delta environment (Pedersen & Pulvertaft, 1992). The delta fanned out to the west and northwest from east of Disko, reaching into deeper waters in the position of present-day northwest Nuussuaq and Svartenhuk Halvø. These sediments are seen as stacked, coarsing-upwards deltaic successions, starting with interdistributary bay mudstones and ending with coal (Olsen, 1993). The non-marine and marginal marine sediments of this delta system has been referred to as the Atane Formation (Pedersen & Pulvertaft, 1992). The Itilli succession, which is exposed on the southeast side of the Itilli valley, consists of mudstones alternating with turbidite channel sandstones, deposited on a submarine slope (Dam & Sønderholm, 1994).

In northern Nuussuaq, west of the Ikorfat fault (Fig. 1), the Cretaceous is mainly represented by dark marine mudstones of Campanian and Maastrichtian age (Dam, 1996; Dam *et al.* 2000; Nøhr-Hansen & Dam, 1997; Birkelund, 1965; Nøhr-Hansen, 1996). East of the Ikorfat fault, Cretaceous sediments form part of a north-northeast dipping ramp linking the Ikorfat and Kuuk faults (Midtgaard, 1996a) (Fig. 1). The succession consists of sandstones, heterolithes and mudstones of fluvial, estuarine, deltaic and lacustrine origin. The base of the succession consists of coarse breccias and conglomerates banked up against fault-controlled basement highs (Chalmers *et al.* 1999). Higher up in the succession a unit mainly consisting of inner shelf marine mudstones (Midtgaard, 1996b) contains brackwater dinoflagelates which shows an age of Late Albian (Nøhr-Hansen, 1992), and thereby might provide the earliest evidence of a marine transgression in the exposed parts of the Nuussuaq Basin. On the southwest corner of Upernivik Ø coarse-grained sediments, deposited in tidal estuarine and coastal plain environments (Midtgaard, 1996a) have approximated dates of Late Albian to Early Cenomanian (Ehman *et al.* 1976; Croxton 1978).

Palaeogene volcanism began in a subaqueous environment, and the earliest lavas formed pillow lavas and hyaloclastite mounds on the sea floor. The volcanics emerged above sea-level so that lavas began to be erupted subaerially, but at the shoreline the lavas entered the sea and formed eastwards-prograding Gilbert-type delta structures, with hyaloclastite sets up to 700 m thick (Pedersen *et al.* 1993). The growing volcanic pile dammed up lakes to the east in which organic-rich lacustrine mudstones were deposited (Pedersen, 1989; Pedersen *et al.* 1998). In southeast Nuussuaq these lacustrine mudstones rest unconformably on tilted fluvio-deltaic sediments of the Atane Formation.

An indication of the presence of sediments below the Palaeogene lavas on eastern Disko is the occurrence of inclusions within the lavas of sandstones with chert pebbles very similar to some of the Atane Formation sandstones. Sediments underlying the volcanic rocks is also witnessed by the presence of contaminated dikes and lavas containing iron, sulphides and numerous inclusions of dark, fissile mudstone that occur throughout western Disko (Pedersen, 1977a, b, c; Ulff-Møller, 1977).

At some time during the Maastrichtian the area became tectonically unstable and on Nuussuaq there is evidence of at least three phases of uplift during the Maastrichtian and early Paleocene (Chalmers *et al.* 1999). Each of the uplift phases were followed by incision of valleys in the underlying sediments, which became filled with conglomerates, turbidites and fluvial sands and estuarine-marine mudstones of late Maastrichtian to middle Paleocene age (Dam & Sønderholm, 1994, 1998; Dam *et al.* 1998). In places there is an angular unconformity between tilted Atane Formation sediments and the overlying sediments of Maastrichtian or early Paleocene age.

4. Faults and related structures in the exposed area

The boundary fault system, defined by the present-day eastern boundary of the Nuussuaq Basin which is marked by a system of faults with an overall NNW–SSE trend that runs from Svartenhuk Halvø in the north through western Upernivik/and central Nuussuaq into Disko Bugt (Fig. 1). In detail the fault system can be seen to be made up of fault segments oriented in directions between NW–SE and NNE–SSW that are linked by transfer faults trending between W–E and WNW–ENE. Downthrow on the boundary faults can exceed 2 km. The fault blocks adjacent to the boundary faults have been rotated up to 20º towards the faults; this rotation has however not affected the Maastrichtian and Paleocene sediments that overlie the tilted blocks on Nuussuaq, providing a constraint on the timing of the tilting (Chalmers *et al.* 1999).

Indications of syn-rift sedimentation are seen on Upernivik Ø. On the northwest corner of the Island, there is a small outcrop of mid-Cretaceous sediments that include conglomerates suggesting the proximity of steep slopes here during sedimentation. However, palaeocurrents in the tidal facies of the succession here flowed in the directions between NNW–NE (Midtgaard, 1996a), which does not suggest that there was a syn-sedimentary fault scarp in the position of the present-day faults. From interpretation of fan-delta deposits on the north side of Nuusssaq it is concluded that the Upper Albian sediments originally extended east of their present-day outcrop in this area and that movement on the fault and associated tilting of the sediments was largely post-Late Albian. Tilting must however have been pre-Maastrichtian because Maastrichtiaan mudstones lie unconformably on the tilted Upper Albian sediments east of Ikorfat.

The relations between Paleocene basalts and the Kuuk fault are also seen in outcrop south of Kuuk. The non-tilted eastwards flowing basalts are exposed in sub-aqueous facies and are seen to have been dammed up against the Kuuk fault scarp (Chalmers *et al.* 1999). There is no erosion indicated at the fault scarp, indicating a very short time lapse between formation of the fault scarp and eruption of the basalts thus suggesting a second post-tilting phase of movement on the Kuuk fault. At Ikorfat the Ikorfat-Saqqaqdalen fault is a combination of an extensional fault and a monocline, where displacement during the pre-Maastrichtian phases of faulting is in the excess of 1275 m (Chalmers *et al.* 1999).

Contaminated lava marker horizons in the volcanic series have provided precise control of the position and displacement of most faults that have been active since the eruption. Faulting that has only affected the pre-volcanic Cretaceous–Paleocene sediments is less well documented. On the south side of Nuussuaq west of Ataata Kuua, two pre-volcanic faults trend 124º and 161º respectively. Both faults downthrow upper Maastrichtian–lower Paleocene valley fill sediments about 300 m to the northeast, and both are truncated by the base of the overlying middle Paleocene valley system (Pulvertaft & Chalmers, 1990). Faulting immediately prior to eruption of the Vaigat Formation hyaloclastite breccias is indicated by abrupt steps in the sub-hyaloclastite surface. The surface on which the hyaloclastite breccias accumulated rises abruptly eastwards by 400-500 m. These steps are regarded as expressions of fault scarps formed during the rapid subsidence that preceeded the extrusion of the breccias. They are not due to younger faulting because they have no influence whatsoever on the lowest subaerial flows above the breccias (Chalmers *et al.* 1999).

Post-volcanic faulting can be seen by several N–S faults displace the basalts in northwest Disko and between Marraat and Qunniliq on Nuussuaq (Chalmers *et al.* 1999). The most important of these is the Kuugannguaq–Qunniliq fault (Fig. 1), which has displacement down to the west, greatest in the north with around 700 m, and least in central Disko where post-volcanic throw is less than 100 m. The Gassø fault, which occurs east of Marraat, shows downthrow in the order of 900 m to the west. In the area around Marraat there are several faults trending about 150º, oblique to the approximately N–S strike of the lavas, which here show easterly dip of up to 25º (Chalmers *et al.* 1999). The cumulative downthrow across the fault zone is in the order of 800 m to the southwest.

The Itilli fault zone trends 37º from the southeast corner of Hareøen to the north coast of Nuussuaq. The general displacement on the fault zone is a downthrow to the northwest. On Hareøen the stratigraphy of the basalts requires a downthrow of more than a kilometre. In the central part of the Itilli valley the upper part of the Itilli succession and the abutted hyaloclastite breccias have been downfaulted out of sight, while on the southeast side of the valley the Itilli succession has been arched up into an eastwards-plunging anticline, where the net vertical displacement is more than 3 km (Chalmers *et al.* 1999). Northwest of where the Itilli emerges on the southwest shore of Nuussuaq there are several extensional faults trending between 120º and 150º. These extensional faults and the compressional anticline are supposed to support the suggestion that the Itilli fault is a splay from the northern extension of the Ungava Fracture Zone (Chalmers *et al.* 1993). The tilting of the basalts northwest of the fault zone is a young feature, since the comendite tuff, dated at 52.5 Ma (Storey *et al.* 1998), is interbedded with basalt lavas showing the same general NW dip as the remainder of the basalts northwest of the fault. Hence the Itilli fault zone is also regarded as a relatively young feature.

The development of rift basins is often influenced by older structures in the underlying basement (Patton *et al.* 1994; Ring 1994). In the basement east of Disko Bugt and in the southeast part of Nuussuaq peninsula faults which strike between 110º and 150º are recognized (Garde, 1994). East of Uummannaq and south of sDisko Bugt there are several faults striking approximately 20º. These are faults with left-lateral displacements up to 1.2 km, sometimes accompanied by a downthrow to the west of up to 100 m (Chalmers *et al.* 1999).

5. Regional structural development

Within the Nuussuaq basin, three trends on the fault system are evident, N–S, WNW–ESE and NE–SW. The N–S trend especially defines the Disko Gneiss ridge, and its effect on the basalts shows that faulting in this trend was active on the western margin of the ridge at a late stage in basin development during the Eocene. Segments of the fault system that marks the present-day boundary of sedimentary outcrops to the east also trend c. N–S and they are offset by segments that trend WNW–ESE, giving an overall NNW–SSE trend to this fault system. The trend between WNW–ESE and NW–SE is the trend of several shear zones in the Precambrian basement east of Disko Bugt, suggesting that these old shear zones in the precambrian zones exerted an influence on later faulting. The third trend is NE–SW along the Itilli fault in western Nuussuaq (Chalmers *et al.* 1999).

The sequence of events that created the Nuussuaq basin is not clear. From modelling of gravity data (Chalmers *et al.* 1999) there appears to be a deep sedimentary basin under western Disko, western Nuussuaq and Vaigat that extends northwards. There may also be a deep halfgraben under central Disko east of the gneiss ridge, and a much smaller basin that extends under eastern Disko and Disko Bugt. The basin that extends under much of eastern Nuussuaq, eastern Disko and Disko Bugt has been exposed to thermal subsidence, followed by faulting in a new phase of rifting during the Maastrichtian and early Paleocene. The rift blocks were eroded before being covered by upper Maastrichtian-lower Paleocene sediments and voluminous middle Paleocene basaltic lavas. These basalts were dissected during the Eocene by faults along the N–S trend and a new (Itilli) trend. This activity probably subsided during later Palaeogene times and the area was lifted by 1-2 km to its present situation probably during the Neogene (Chalmers *et al.* 1999).

The situation of the Nuussuaq basin in its regional setting prior to the start of the sea-floor spreading in the Labrador Sea in the mid-Palaeocene suggests that the basin might be a south-southeasterly extension of the Melville Bay basin (Whittaker *et al.* 1997), however, the structural details of the area between Nuussuaq and Melville Bay are obscured by overlying Palaeogene basalts. The Nuussuaq basin appears not to be directly continuous with the basins off southern West Greenland (Chalmers *et al.* 1999).

Off southern West Greenland the major faults trend N–S as in the Nuussuaq basin (Chalmers *et al.* 1993, 1995; Chalmers & Pulvertaft, 2001). The Melville Bay fault, which forms the eastern limit of the sediments in Melville Bay (Whittaker *et al.* 1997), trends NNW–SSE. This trend is the same as the overall trend of the fault system formed by the Saqqaqdal, Ikorfat and Kuuk faults and their extensions which form the present-day eastern limit of sediments in the Nuussuaq basin (Chalmers *et al.* 1999).

The offshore West Greenland basin system might have been formed in Mesozoic and early Paleocene times, prior to the start of sea-floor spreading in the mid-Paleocene (Chalmers & Laursen, 1995; Chalmers & Pulvertaft, 2001) by crustal extension in an E–W direction in the southern West Greenland and Nuussuaq basins, and WSW–ENE in Melville Bay (Chalmers *et al.* 1999). This extension resulted in normal faults striking N–S and NNW–SSE in Melville Bay. The normal faults appear to be displaced from one another by transfer elements that strike parallel to older structural elements. In the Nuussuaq basin the transfer elements are parallel to NW–SE/WNW–ESE-striking shear zones.

Sea-floor spreading appears to have started in the Labrador Sea in the mid-Paleocene (Chalmers & Laursen, 1995) although there is evidence that there may have been a long period of slow extension between Labrador and Greenland prior to that (Chian *et al.* 1995; Chalmers 1997).

6. Interpretation of the seismic data

6.1 Database

Seismic data from the following survey have been used in the interpretation phase:

- GGU/1990 - deep seismic data acquired in 1990 by GEUS (few lines in the southern part of the survey area off Disko)
- GGU/1995 – deep seismic data acquired in 1995 by GEUS (see Chalmers *et al.* 1999 for details)
- GEUS2000G – high resolution multichannel seismic data acquired under project NuussuaqSeis 2000

The seismic data have been loaded on a Landmark workstation, which was used for interpretation of the data. The ECHO program was used to digitize the interpretation maps, which were finalized in the drawing office. Landmarks Z-Map was used to compile a new bathymetry map from interpretation of the seabed reflector and older bathymetric contours (Enclosure 3).

6.2 Division of the survey area

The survey area has been divided into three areas:

- *Area 1: Vaigat east of Marraat*
- *Area 2: Uummannaq Fjord and Illorsuit Sund*
- *Area 3: Basalt area west of Nuussuaq and Uummannaq Fjord*

6.3 Main purpose of the seismic interpretation

The structural model and seismic interpretation published by Chalmers *et al.* (1999) constitutes the basis for the present interpretation, which has been focused on the following items:

- Detailed mapping of the structural pattern in area 1 and 2
- Mapping of the seabed
- Mapping of Quaternary and Cretaceous sediments
- Adjustments of the sea-bed outcrop map published by Chalmers *et al.* (1999)

The results of the interpretation have been compiled into a map of the structural pattern and the sea-bed geology (Enclosure 1), scale 1:500 000. The interpretation is documented by a number of seismic examples as screen dumps from the Landmark workstation.

6.4 Area 1: Vaigat east of Marraat

Chalmers *et al.* (1999) divided the Vaigat area into three distinct parts. West of about 54ºW, basalt is exposed at the seabed. Between longitudes 54ºW and 53ºW, three large fault blocks with thick, easterly-dipping, Cretaceous sediments can be seen. The centre of the bathymetric channel is partly filled by flat-lying Holocene sediments (Fig. 4). The area east of 53ºW is complex, with both large glacial moraines or post-glacial slumps and sills (Figs 3, 5) at and beneath the seabed.

6.4.1 Fault pattern

There are many more faults visible on the GEUS2000G seismic data than seen onshore (Figs 6, 8). In Vaigat the fault trend shifts from NW–SE in the western part of Vaigat along the landward margin of the volcanic rocks, almost N–S in the middle of the area, whereas the eastern part is dominated by NE–SW-trending faults, and some rather complicated curved faults which follow, or more likely defines, the pronounced sill structures in the easternmost part of Vaigat.

Saqqaqdal fault extension

Across Vaigat there seems to be a line of shallow basement/basement ridges trending southwards or south-southeastwards on the approximate extension of the Saqqaqdal fault (Enclosure 1). Many if not most of the faults have been intruded by sills similar to the onshore exposure of the Saqqaqdal fault plane, and the many sills and their shallow multiples means that it is not easy to pick basement (see Figs 9, 10). Furthermore it is not obvious which of the many faults is the Saqqaqdal fault. The Mesozoic sediments under eastern Disko Bugt are recognised to be within a separate fault-block from those west of the Saqqaqdal fault (Fig. 1). This model is similar to and a mirror image of the structure along the north coast of Nuussuaq, where the sediments around Kuuk are in a fault-block that is east of the extension of the Saqqaqdal fault that crosses the coast at Ikorfat. The zone around fault P (see Fig. 1) between the Itilli and Ikorfat faults on the southcoast of Nuussuaq (Chalmers *et al.* 1999) can be seen on Figure 8 in all its complexity.

6.4.2 Cretaceous and Quaternary basins

Cross sections across Vaigat (Fig. 4) show that the Cretaceous sediments at outcrop on the north coast of Disko must be 2.5–3 km stratigraphically deeper than the sediments at outcrop on the south-west coast of Nuussuaq. At the present stage of the interpretation it has not been possible to tie the interpretation of reflections in the Cretaceous sequence from one fault block to the other.

There is a complex of curiously-shaped little sub-basins in eastern Vaigat, east of the extension of the Saqqaqdal fault (see Enclosure 1). Dips within the basins are steep and there are many sills, many of which are intruded into faults. The eastern and northern marginal faults of these sub-basins are arcuate in plan (see Enclosure 1). The pattern of faulting might indicate that these sub-basins are pull-apart basins formed during NW–SE sinistral shear, possibly along reactivated Proterozoic crush zones that are exposed in the basement onshore. One of these reactivated faults may form the southern (SSW) limit of the basement block whose western margin is the extension of the Saqqaqdal fault.

Quaternary sediments appear in generally in three seismic facies:

- one or more thin layers on top of the Cretaceous sediments (or other underlying rocks) that is probably basal moraine (Fig. 4).
- flat-lying parallel–bedded material lying in troughs that are typically axial to Vaigat (Fig. 4).
- complex mounds in many places especially off the south-west coast of Nuussuaq (Fig. 3). These were interpreted by Chalmers *et al.* (1999) as moraines, but their distribution and especially the event of November 2000[1] strongly suggests that these mounds are the remains of landslides from Nuussuaq's mountains. The mound material interfingers with the flat-lying material. The presence of the mounds destroys the image of the material below them (Fig. 3). In many places it is possible to see that Cretaceous sediments are present, but it is not possible to interpret faults or to see how continuous reflections are.

In Chalmers *et al.* (1999), a small area of Mesozoic sediments was interpreted offshore east of Saqqaq village and just west of the mouth of Torsukattak fjord (Fig. 1). The interpretation was based on two older shallow seismic lines of very poor quality. The new seismic data (Fig. 11) suggest that this little basin in fact consists of Quaternary sediments that fill a deep trench at the mouth of Torsukattak fjord, and that the Quaternary sediments lie directly on basement.

6.4.3 Sills

Southeastern Vaigat is dominated by sills, and Enclosure 1 shows where sills are present at either seabed or at the base of Quaternary sediments. Sills can be seen almost every-

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1 *Land slide at Paatuut on the south coast on Nuussuaq*

In the afternoon November the 21st 2000 the coast at Saqqaq were flooded by a tsunami. Ten boats were destroyed, but no human beings or dogs were affected. Next day the police detected a large land slide in the area around Paatut on the south coast of Nuussuaq (Pedersen et al., 2001). The slide formed a large tongue of dark material reaching out in the water (Fig. 12). The slide was clearly set off against the white snow-covered landscape, and the area along the coast on both sides of the slide were washed clear of snow up to 50 m height. At Qullissat the tsunami had reached 250 m inland and up to a height of 30 m, and destroyed everything within the first 100 m from the coast. The amount of debris which flooded into Vaigat is estimated to c. 30 million m^3. In earlier time several slides have been flooded into Vaigat and Uummannaq Fjord, south and north of Nuussuaq as interpreted on Figures 3 and 19 respectively.

where at various levels within the Cretaceous section in this area, but the map purports to be an outcrop/subcrop base Quaternary.

At outcrop / Quaternary subcrop, the sills form two distinct seismic facies:

- ridges up to several hundred milliseconds high where a (normally westward-dipping) sill, probably much thinner than the height of the ridge, has protected underlying sediment from erosion. A small example of this type of sill is visible on Figure 5 (where it is below top Cretaceous) to 8600 (at outcrop) and a much bigger example from SP 8630 to 9020
- sills with a much more 'mounded' appearance that appear to lie sub-parallel to the top Cretaceous, or even to dip slightly eastwards. An example of this type of sill is on Figure 5 from SP 9230–9800.

The difference between the two facies is more probably due to the difference in response to erosion by ice of sills that present different profiles to the ice, than to any inherent difference in the sills themselves.

Due to the presence of a large numbers of sills the eastern part of Vaigat has a high risk for prospectivity. Furthermore it is difficult to see possible seals in the successions which are in general dominated by sandstones in the neighbouring onshore areas. The aeromagnetic map (Enclosure 4) shows that eastern Disko Bugt is also probably heavily intruded, suggesting little likelihood of prospectivity there either.

6.4.4 Bright spots

The Kuugannguaq-Qunniliq fault is complex and bright spots are visible on the footwall of one of the faults (see Enclosure 1; Figs 6, 7). There are also similar bright spots farther east (see Enclosure 1). The bright spots could be due to hydrocarbons in thin reservoirs in the Atane Formation, or they could be due to thin sills. However they are exclusively parallel to the bedding, and do not appear to cross it anywhere which might be expected if they were due to sills. The bright spots on the seismic lines in western Vaigat dip E or ENE from an area on the north coast of Disko where seeps have been found.

The stacking velocities for the Cretaceous sediments indicate interval velocities over 4 km/sec, similar to those found for the onshore line GGU/NU94-01 on southern Nuussuaq (see Enclosure 1, 2; Christiansen *et al.* 1995) which had much longer offsets. Such high velocities indicate a risk of low porosities within the Cretaceous section.

6.4.5 Magnetic data

The magnetic pattern is dominated by the presence of igneous material. The magnetic total field anomaly map (Enclosure 4) shows that the westernmost part of Nuussuaq, west of the Itilli fault displays a clearly different magnetic signal than the eastern part of Nuussuaq. This difference coincides with the presence of the much younger Kanísut Member on western

Nuussuaq and the Maligât and Vaigat Formations on eastern Nuussuaq and Disko (Storey *et al.* 1998). It is known that most of the Vaigat and Maligât Formations were emplaced during chron 26n, except for the earliest part of the Vaigat Formation, which was erupted during chron 27n. However most of the earliest material is hyaloclastite breccia, which does not give rise to large consistent magnetic anomalies. The negative anomalies above the 'basalt area' (Enclosure 4) are probably due to a significant sub-aerially-erupted component and/or sills.

The Tartunaq sills around Saqqaqdal (Fig. 1) were emplaced during chron 24r, and there is a good correlation offshore between the bodies interpreted as sills on the seismic data and negative magnetic anomalies. In particular the arcuate anomalies in easternmost Vaigat correspond well with the mapped pattern of sill subcrop.

West of the Itilli fault on Nuussuaq the magnetic pattern shifts polarity to strong negative anomalies (Enclosure 4), which coincides with the Kanisút Member (Riisager & Abrahamsen, 1999). Northwest of Nuussuaq, an offshore area with the very positive anomalies northwest of Nuussuaq is recognised as the area of an individual, younger seismic volcanic unit identified from the seismic lines from 1995 (Skaarup, 2001).

6.5 Area 2: Uummannaq Fjord and Illorsuit Sund

The area north of Nuussuaq is characterized by large fault blocks with thick, easterly-dipping, Cretaceous sediments (Chalmers *et al.* 1999). The fault blocks are divided by westdipping normal faults and can be identified as offshore extensions of faults known onshore (Fig. 1). To the east Precambrian basement is exposed, whereas west of the offshore extension of the Itilli fault basalt is exposed at the seabed (Enclosure 1).

Good reflections were obtained on most of the lines acquired and only few areas of moraine or large sills were noted. The area comprises fault blocks, and good images of many of the faults were obtained (Fig. 13). Along the eastern margin of the area, several crossings from Cretaceous sediments to Precambrian basement were achieved (Fig. 13), and many images were also obtained of the margin of the basalts, as well as reflections from below the top of the basalts.

6.5.1 Fault pattern

The overall structural style is characterised by a fault pattern with steep, normal faults trending almost N–S, with slight variations towards NNW–SSE and NNE–SSW.

The two most dominating faults from the onshore are the Itilli and the Ikorfat faults (Fig. 1). The Itilli fault zone trends 37º from the southeast corner of Hareøen to the north coast of Nuussuaq. The general displacement of the fault zone is a downthrow to the northwest varying from approx. 1 km at Hareøen to more than 3 km in the central part of the Itilli valley (Chalmers *et al.* 1999). At Ikorfat the Ikorfat-Saqqaqdalen fault is a combination of an extensional fault and a monocline, where displacement during the pre-Maastrichtian phases of faulting is more than 1275 m (Chalmers *et al.* 1999). A seismic example of the Ikorfat fault zone north of Nuussuaq is shown in Figure 14.

Uummannaq Fjord

The faults in Uummannaq Fjord show a general N–S trend, with a more NNE–SSW'ern trend in the eastern part, west of 53º30'W. The faults are normal faults, with throw up to 100 ms (approx. 125 m), measured where it is possible to recognise specific seismic horizons. The faults can be traced for 20-25 km in areas with line spacing between 4 and 6 km, which is the maximum line spacing for correlating fault from one seismic line to the other with certainty.

Illorsuit Sund

In Illorsuit Sund the offshore extension of the volcanic rocks can be followed between 1.2 and 4 km east of the shoreline of Ubekendt Island. The fault pattern follows the eastern coast of Ubekendt Ejland with a NNW–SSE trend. A westward dipping fault can be followed for ~25 km along the east coast of Ubekendt Ejland, with normal throw in the southern part and reverse throw in the northern part. Other faults in the Illorsuit Sund can be followed for 10–20 km in areas with line spacing between 3 and 7 km. The boundary between the volcanic rocks and the Cretaceous sediments might be marked by a gentle east-dipping fault or the volcanic rocks have simply just stopped flooding upon the sediments. The volcanics are, however, much more resistent to erosion and some of the contacts may have got their present form during glacial erosion. The upper parts of the volcanic and sedimentary sequences are clearly seen to display different reflectivity (Fig. 15). It is not possible from the GEUS2000G seismic data to see if – and at what depth – Cretaceous sediments are present below the volcanic rocks.

Karrat Fjord

In the easternmost part of Karrat Fjord (Fig. 1) the fault pattern seems to continue from Illorsuit Sund with a NNW–SSE trend, but an interpretation of the direct continuation of the faults from the northern part of Illorsuit Sund to Karrat Fjord can not be made with any certainty. The tentative interpretation of the fault pattern in the very northern part of Karrat Fjord close to Svartenhuk Halvø, confirms an offshore extention of the structural interpretation of Larsen and Pulvertaft (2000).

6.5.2 Cretaceous and Quaternary basins

The sedimentary section has been divided into Cretaceous and Quaternary sediments. The Quaternary sediments are mostly seen as thin reflective units of almost horizontally layered sediments, bounded at the base by the very strong reflector from the top Cretaceous (Fig. 16). The Cretaceous sediments are highly reflective and are most often dipping towards the east, and are often erosively truncated at the top.

In Uummannaq Fjord one rotated fault block with Cretaceous sediments can be followed for 25 km N–S and 37 km E–W (Fig. 13). The Cretaceous sediments are at least 800 ms (approx. 1 km) thick. In the easternmost part of the area on line GEUS00-14 (Fig. 17) a marked eastwards dipping unconformity can be seen cutting the Cretaceous sediments.

In the very eastern part of Illorsuit Sund, south of Upernivik Ø, generations of highly reflective, domed units within the Cretaceous sediments can be seen (Fig. 18). This could be interpreted as delta lobes or channels building out from north (or south).

North of Hollænder Bugt (Fig. 1), a 4.5 km broad convex unit of Quaternary sediments overlay Cretaceous sediments (Fig. 19), 2.7 km further north on the next seismic line the convex unit has disppeared. This unit could be interpreted as remains of a landslide from the north coast of Nuussuaq, corresponding to the slides seen in Vaigat. The Quaternary reflectors below the base of the landslide are truncated by erosion.

In Karrat Fjord a deep (200 ms) Quaternary basin can be seen above Cretaceous sediments (Fig. 20). The Cretaceous reflectors are here seen to be truncated by erosion.

Surrounded by Quaternary basins a pronounced high can be seen (Fig. 16) reaching 130 ms up above the Quaternary seabed. As seen in Vaigat (Figs 5, 9) a sill on top of sediments would have prevented erosion of the underlying softer sediments, leaving a high. Compared to the eastern part of Vaigat only few sills are seen in the area north of Nuussuaq, and the sills are seen as small, isolated remnants, and not as larger, complex structures as seen in the eastern part of Vaigat.

6.5.3 Basement

The sedimentary basin north of Nuussuaq is bounded to the east by basement (Fig. 2; Enclosure 1). The boundary between the basement and the sedimentary section is seen as a very sharp increase in seabed topography (Fig. 13), where the seabed rises approx. 400 ms within 1 km. The boundary in this area is clearly defined by a fault.

In the innermost part of Karrat Fjord, north of Upernivik Ø, which mostly consists of gneiss, a less pronounced topographic difference is seen towards the basement boundary, where a very chaotic seabed probably consisting of gneissic basement can be seen (Fig. 21).

6.5.4 Bright spots

At the mouth of Uummannaq Fjord (Enclosure 1) bright reflections following the layering of the Cretaceous sediments can be seen on several lines (Figs 22, 23). The bright reflections stop at the base of the Quaternary sediments (Fig. 22), whereas on line GGU/95-08 (Fig. 23) some of the bright reflections continue all the way to the surface, but display bright reflections at different depths. The bright spots could be due to hydrocarbons in thin reservoirs in the Cretaceous sediments, or they could be due to thin sills.

6.5.5 Magnetic data

A pattern of magnetic anomalies (Rasmussen, in press; enclosure 4) with a very clear boundary between very negative and very positive anomalies seems to follow the boundary between the volcanic rocks and Cretaceous sediments along the east coast of Ubekendt Ejland. However in the northern part the anomaly boundary crosses westwards to coincide with the coast. In Uummannaq Fjord the boundary between the volcanic rocks and the sediments is clearly visible on the magnetic map (Enclosure 4). On the map of the vertical gradient (Enclosure 5) the boundary just north of Nuussuaq, east of the Itilli fault is displaced by 4–6 km towards west. The boundary between volcanic rocks and sediments appear on the map of the analytic signal (Enclosure 6) to coincide with the boundary between the red and green areas. In the eastern part of Uummannaq Fjord a large area with negative anomalies dominates (Enclosure 4), which crosses both fault patterns and deep Cretaceous basins. In general larger areas with positive or negative anomalies seem not to coincide with any specific structure.

North of Nuussuaq (70º50N, 52º30W) a smaller area with highly negative anomalies seems to correspond to similar areas south of Nuussuaq. In Vaigat these areas coincide with complex sill structures, whereas north of Nuussuaq only few sills are found. On line GEUS00-14 (Fig. 24) the area with highly negative magnetic anomalies is seen to coincide with a depression in the seabed topography of 300 ms.

Northwest of Ubekendt Ejland a pronounced striated pattern in the area with negativ anomalies can be seen (Enclosures 4, 5). This pattern continues towards the north and covers most of Svartenhuk Halvø as well (Rasmussen, in press). The fault pattern onshore Svartenhuk Halvø (Larsen & Pulvertaft, 2000) seems to coincide perfectly with the striated pattern of the magnetic anomalies (Enclosures 4, 5).

6.6 Area 3: Basalt area west of Vaigat and Uummannaq Fjord

Older seismic surveys in the offshore area W and NW of Disko and Nuussuaq (GGU/1995 and Brandal/1971; Chalmers *et al.* 1999) have shown that there are reflections from below the top basalt reflection. The significance of these reflections is, however, not well understood; the different interpretations of the area so far published (Whittaker 1995, 1996; Geoffroy *et al.* 1998; Chalmers *et al.* 1999) have substantially different implications with respect to its prospectivity. The presence of a type IV AVO (amplitude versus offset) anomaly associated with a bright spot on some of the GGU/1995 lines (Skaarup & Chalmers 1998; Skaarup *et al.* 2000) has significance with respect to hydrocarbon prospectivity.

The GEUS2000G survey lines show excellent reflections down to and below 500 msec below the top of the basalts in many areas (Fig. 25). Some of these sub-top basalt reflections are undoubtedly from lithological variations within the basalt sequences and preliminary correlation of the magnetic data with the seismic data suggests that it may be possible to develop a detailed seismic and magneto-stratigraphy. Other reflections seem to come from half-grabens (Fig. 25). Areas with halfgrabens at top volcanic level are marked on

Enclosure 1. While it is possible that the half-grabens are syn-magmatic, as discussed by Geoffroy *et al.* (1998), it is also possible that they derive from westward-dipping Cretaceous or lower Paleocene sediments beneath thin basalts west of Nuussuaq. Quantitative interpretation of the magnetic data may resolve this question.

The volcanic rocks terminate in general at an escarpment, 350–130 ms high (Figs 6, 26), that can be followed on all the intersecting lines. The escarpment cuts across the fault trends, which is difficult to explain if outcrop pattern is due to basalts, but easier to understand if it is due to a sill.

Penetration of the high resolution GEUS2000G seismic data off Marraat, where the most prolific onshore seeps are located, is inadequate to image the pre-basalt sediments in detail. Seismic line GGU/95-6 (Fig. 27) shows reasonable evidence for the presence of easterly-dipping fault blocks with Cretaceous sediment below the basalts, but the GEUS00 lines (e.g. Fig. 28) show poor penetration and these sediments are poorly imaged on these lines. The possible presence of Cretaceous sediments and a fault pattern is marked on the geological map (Enclosure 1).

7. Conclusion

Data acquisition of project NuussuaqSeis2000 (GEUS2000G survey) was very successful. Due to very favourable weather and ice conditions, 2743 km of good quality data were acquired, nearly 20% more than originally planned. High concentrations of icebergs prevented acquisition of data in the eastern part of Uummannaq Fjord and east of Svartenhuk Halvø.

Data from project NuussuaqSeis 2000 have therefore considerably increased the seismic coverage in the region. Interpretation of the new data has given information on the size and geometry of the individual fault blocks in areas with Cretaceous sediments. Furthermore the new data confirm that the seeps in the Vaigat region are structurally controlled and mainly occur in the block-faulted area north of the Disko gneiss ridge.

Data from the GEUS2000G survey confirm the overall structural interpretation published in Chalmers *et al.* (1999). The interpretation of the structural style in western Vaigat is confirmed as being substantially correct, although the fault patterns have been shown to be much more complex than realised previously, from either the onshore data or from the single line GGU/95-06. The main area of revision has been in eastern Vaigat, but even there the essentials of the Chalmers *et al.* (1999) interpretation remain.

In the area north of Nuussuaq in Uummannaq Fjord and Illorssuit Sund the fault trend is more N–S than in Vaigat, but also here the complexity in the fault pattern prohibites a correlation for too long distances. The general fault pattern from the structural interpretation of Chalmers *et al.* (1999) remains valid in this area as well.

Some of the data acquired under project NuussuaqSeis2000 are highly relevant for an assessment of the petroleum prospectivity of the Disko-Nuussuaq region, and the data and their interpretation will be included in the next revised GEUS Note to the Bureau of Minerals and Petroleum on this matter. The new data and the interpretations are particularly important for discussions of geometry and sizes of structures, position of kitchen and migration pathways, and for discussions of the significance of the well-described seepage in the region.

Suggestions for future work

- Area off Marraat:
  The acquired high-resolution data in this area show that the seismic equipment used during the GEUS2000G survey is not adequate to penetrate the basalts and to image the structure beneath. Acquisition of seismic data with a longer streamer and with a low-frequency source is therefore suggested. The seismic coverage obtained under project NuussuaqSeis2000 provides an excellent basis for planning of these lines.

- Western Vaigat and neighbouring onshore areas:
  In order to see how the complex fault pattern – as interpreted offshore on the GEUS2000G lines – continues onshore, it will be necessary to acquire seismic data

along the northcoast of Disko, in the Kuugannguaq valley and along and across the Aaffarsuaq valley onshore Nuussuaq.

To understand the nature of the bright reflections – sills or porosity with hydrocarbons – more extensive work is needed, initially by compiling a more detailed map of one or more horizons that appear bright and then to acquire additional seismic data onshore followed by the drilling of a shallow well.

- Uummannaq Fjord and Illorsuit Sund
  The area is known for its numerous oil stains in the basalts and along dykes on Ubekendt Ejland, Schades Øer and on Svartenhuk Halvø (Fig. 1; Enclosure 1). Acquisition of seismic data which can penetrate the basalts along the east coast of Ubekendt Ejland, and closer to the southeastern corner of Svartenhuk Halvø is needed to image the structures of the underlying Cretaceous sediments and the structural relations between the volcanic rocks and the sediments.

- Basalt-area west of Nuussuaq and Ubekendt Ejland
  Further interpretational work is needed in this area. The halfgrabens at top volcanic level filled with post-basaltic sediments, might indicate the presence of a rather thin volcanic layer, underlain by dipping Cretaceous or Lower Paleocene sediments. The striated pattern on the map of the magnetic anomalies might reveal a more detailed picture of the structural pattern in the area when compared in detail with the seismic data.

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9. List of enclosures

Enclosure 1: Geological map

Enclosure 2: Index map

Enclosure 3: Bathymetry map

Enclosure 4: Magnetic total field anomaly

Enclosure 5: Vertical gradient of magnetic total field

Enclosure 6: Analytic signal of magnetic total field

10. Figure captions

Please note:
The location of seismic examples of Figures 3–28 is shown in Enclosure 2: Index map.

Fig: 1: Summary map of the geology onshore showing the faults described in this report together with the bathymetry offshore. Aaf: Aaffarsuaq; Ap: Appat; As: Asuk: AtK: Ataata Kuua; G#3: GRO#3 well; Ho: Hollænderbugten; Ik: Ikorfat; It: Itilli; K: Kuugannguaq; Ku: Kuuk fault; K#1: GANK#1 borehole; M: Marraat and the Maaraat-1 borehole; N#1: GANE#1 borehole; P: fault P; Q: Qunniliq; Sa: Saqqaqdalen; Sc: Schades Øer; To: Torsukattak; W#1: GANW#1 borehole (From Chalmers *et al*. 1999).

Fig. 2: Simplified map of the Nuussuaq Basin showing the geology onshore (dark colour tone) and offshore (light colour tones). Seismic lines acquired during the NuussuaqSeis 2000 survey are shown in red. The prefix GEUS00- is omitted from all line numbers for these lines. Line numbers placed at start of line (From Marcussen *et al.* 2000a).

Fig. 3: Part of seismic line GEUS00-03 showing complex mounded structures at the seafloor that Chalmers et al. (1999) interpreted as moraines. However their distribution along Nuussuaq's southwest coast and especially the event of November 2000 Pedersen et al. 2001) strongly suggests that these mounds are the remains of landslides from Nuussuaq's mountains. The presence of the mounds destroys the image of the material below them. In many places it is possible to see that Cretaceous sediments are present, but it is not possible to interpret faults or to see how continuous reflections are. Sills are interpreted within Cretaceous sediments between SPs 4120–5150. Note that this reflection stays at the same stratigraphic level for an interval, then cuts across the Cretaceous stratigraphy. Compare with the bright spots shown in Figure 7.

Fig. 4: Seismic line GEUS00-54 across Vaigat showing that the sediments on the southwest coast of Nuussuaq (to the right of the end of the section) must be 2.5-3 km stratigraphically higher than those exposed on the north coast of Disko (to the left of the end of the section).

Fig. 5: Part of seismic line GEUS00-01 showing large ridges at the seabed that are interpreted as being due to the presence of sills that protected the underlying softer sediments from erosion by glacial ice. The sills in the western (left) part of the image dip westwards into the sediments and have a different appearance from those in the eastern (right) part of the image that are more flat-lying or dip eastwards. It is suggested that the difference between the two appearances is more to do with how the sills are lying at different attitudes to the west-flowing ice responded to erosion than any inherent difference in the sills themselves.

Fig. 6: Part of seismic line GEUS00-06 across the eastern limit of basalt outcrop in Vaigat and across the Kuugannguaq-Qunniliq fault complex. The escarpment at the eastern end of the basalt outcrop is interpreted as being due to the presence of a sill at seabed. The escarpment cuts diagonally across the trend of faults in this region (see Enclosure 1). The Kuugannguaq-Qunniliq fault is much more complex than the single fault shown on the onshore maps, and consists of many splays (Enclosure 1), three of the splays are visible here. Some intra-Cretaceous reflections become much brighter updip as they approach the easternmost splay and terminate at it. These were initially interpreted on line GGU/95-06 (Fig. 7) and their presence is confirmed on the new data. They could indicate the presence of hydrocarbons in thin reservoirs within the Atane Formation, or they could indicate the presence of thin sills intruded in Atane formation bedding planes. If they are due to the latter reason, it is remarkable that they appear to keep rigidly to bedding planes and never cross from one bedding-plane to another. Compare with the sill shown in Figure 3 that cuts across the Cretaceous stratigraphy.

Fig. 7: Part of seismic line GGU/95-06 showing bright spots on the hanging-wall of the Kuugannguaq-Qunniliq fault. See text and caption for Figure 6.

Fig. 8: Part of seismic line GEUS00-06 across the fault identified as fault P in Chalmers et al. (1999). This is a much more complex fault zone than had been previously realised from either onshore exposures or the 1995 seismic data. The structures on the hanging-wall of the main fault at approx. SP 6950 are complex and suggest either that there has been some transtensional movement on this fault, or that an originally extensional fault has later been partially inverted during a period of relative compression.

Fig. 9: Part of seismic line GEUS00-61 across the offshore extension of the Saqqaqdal fault. The ‘fault’ seems to consist of many components bordering a basement ridge somewhere between SPs 3250 and 3620, but the accurate location of basement is unclear due to the complex sills that have invaded the faults and the shallow multiples under the seabed ridge.

Fig. 10: Part of seismic line GEUS00-61 across two of the sub-basins east of the Saqqaqdal fault, that is shown in the western (left) part of this image. This figure is an eastward continuation of the image shown in Figure 9 across the Saqqaqdal fault.

Fig. 11: Part of seismic line GEUS00-02 across a deep trough at the mouth of Torsukattak fjord (Fig. 1) that is partially filled by Quaternary sediments lying directly on basement. This area was interpreted by Chalmers et al. (1999) as a small Mesozoic outlier.

Fig. 12: The landslide at Paatuut where the slide of dark rocks is easily visible against the white snow. The snow along the coast is swept away by the tsunami on its way through Vaigat. Photo: Christoffer Schander, Arktisk Station, Qeqertarsuaq (from Pedersen et al. 2001).

Fig. 13: Part of seismic line GEUS00-13 in Uummannaq Fjord showing easterly dipping Cretaceous sediments in fault-blocks with Precambrian basement outcrop at the eastern end (From Marcussen *et al*. 2000b).

Fig. 14: Part of seismic line GEUS00-17 showing the Ikorfat fault zone at its northern extension into Uummannaq Fjord. The two sides of the fault zone display quite different reflection patterns. Onshore the western side of the Ikorfat fault zone is dominated by shale with thin sandstone layers, whereas the eastern side is sandstone with thin interbeds of mudstone (Birkelund, 1965).

Fig. 15: Part of seismic line GEUS00-35 off the east coast of Ubekendt Ejland. Volcanic rocks, also exposed onshore Ubekendt Ejland, can be seen to the west and Cretaceous sediments to the east. Neither the boundary between the volcanic rocks and the sedimentary units can be clearly defined from these data nor the thickness of the volcanic rocks.

Fig. 16: Part of seismic line GEUS00-32 in the northern part of Illorsuit Sund showing subbasins with Quaternary sediments above the Cretaceous sediments. To the southwest volcanic rocks can be seen. At SP 650 a high can be seen, possible a sill on top of sediments which would have prevented erosion of the underlying softer sediments.

Fig. 17: Part of seismic line GEUS00-14 in the eastern part of Uummannaq Fjord showing a marked eastward dipping unconformity within the Cretaceous sediments.

Fig. 18: Part of seismic line GEUS00-20 in the eastern part of Illorsuit Sund, south of Upernivik Ø, showing several generations of highly reflective, domed units within the Cretaceous sediments. This could be interpreted as delta lobes or channels building out from north (or south).

Fig. 19: Part of seismic line GEUS00-17 north of Hollænderbugten (Fig. 1) showing the possible remains of a Quaternary landslide. To the west a thin layer of volcanic rocks above the Cretaceous sediments can be seen.

Fig. 20: Part of seismic line GEUS00-29 in the northern part of Karrat Fjord showing a 200 ms deep sub-basin filled with Quaternary sediments on top of an eroded Cretaceous surface.

Fig. 21: Part of seismic line GEUS00-30 in the northern part of Karrat Fjord showing the boundary between Cretaceous sediments and the crystalline basement to the east. The boundary might be fault bounded as seen in Uummannaq Fjord (Fig. 13), but in this area the boundary is not as easy interpretable. The reflection pattern shifts from the area with Cretaceous sediment (SP 500–300), where well defined reflections display several dipping events, whereas from SP 150, and maybe 300, the reflection pattern is much more irregular and diffuse.

Fig. 22: Part of seismic line GEUS00-16 in the southern part of Uummannaq Fjord showing bright reflections following the layering within the Cretaceous sediments. The bright reflections stop at the top Cretaceous reflections on this line, whereas on Figure 23 the reflections continue to the surface. The area in Uummannaq Fjord where bright reflections can be seen on the seismic is shown in Enclosure 1.

Fig. 23: Part of seismic line GGU/95-08 showing bright reflections within the Cretaceous sediments. In contrast to Figure 22 the bright reflections continue to the surface, and become a part of the top layer.

Fig. 24: Part of seismic line GEUS00-14 showing a depression in the seabed topography (SP 0–650) which coincides with an area of highly negative magnetic anomalies as seen on the total magnetic field map (Enclosure 4). In the eastern part of Vaigat similar magnetic lows coincides with complex sill structures.

Fig. 25: Part of seismic line GEUS00-48 in area 3 where basalts crop out at seabed (at SP 1450–1550), and display a strongly faulted surface with Quaternary sediments above. The dipping reflections may come from syn-magmatic half-grabens or westward-dipping Cretaceous or Lower Palaeocene sediments below a thin cover of volcanic rocks (From Marcussen *et al.* 2000b).

Fig. 26: Part of seismic line GEUS00-14 in Uummannaq Fjord where the volcanic rocks terminate at an escarpment, 130–350 ms high, which can be followed on all the intersecting lines. The escarpment cuts across the fault trends, which is difficult to explain if outcrop pattern is due to basalts, but easier to understand if it is due to a sill on top of the sediments which would have prevented erosion of the underlying rocks.

Fig. 27: Part of seismic line GGU/95-06 offshore Marraat showing the interpretation of faulted Cretaceous sediments below Paleocene basalts. The interpretation shown here is consistent with the results of drilling onshore in the Marraat area of Nuussuaq in the 1990s.

Fig. 28: Part of seismic line GEUS00-08 offshore Marraat and close to the line shown in Figure 27. There are indications of the presence of Cretaceous sediments below the basalts, but they are much more poorly imaged than on line GGU/95-06 (Fig. 27). The higher frequency system used for the GEUS2000G data is clearly inadequate to image this area, and a lower frequency system, as used in 1995, is clearly needed.

11. Figures

Please note:
The location of seismic examples of Figures 3–28 is shown in Enclosure 2: Index map.

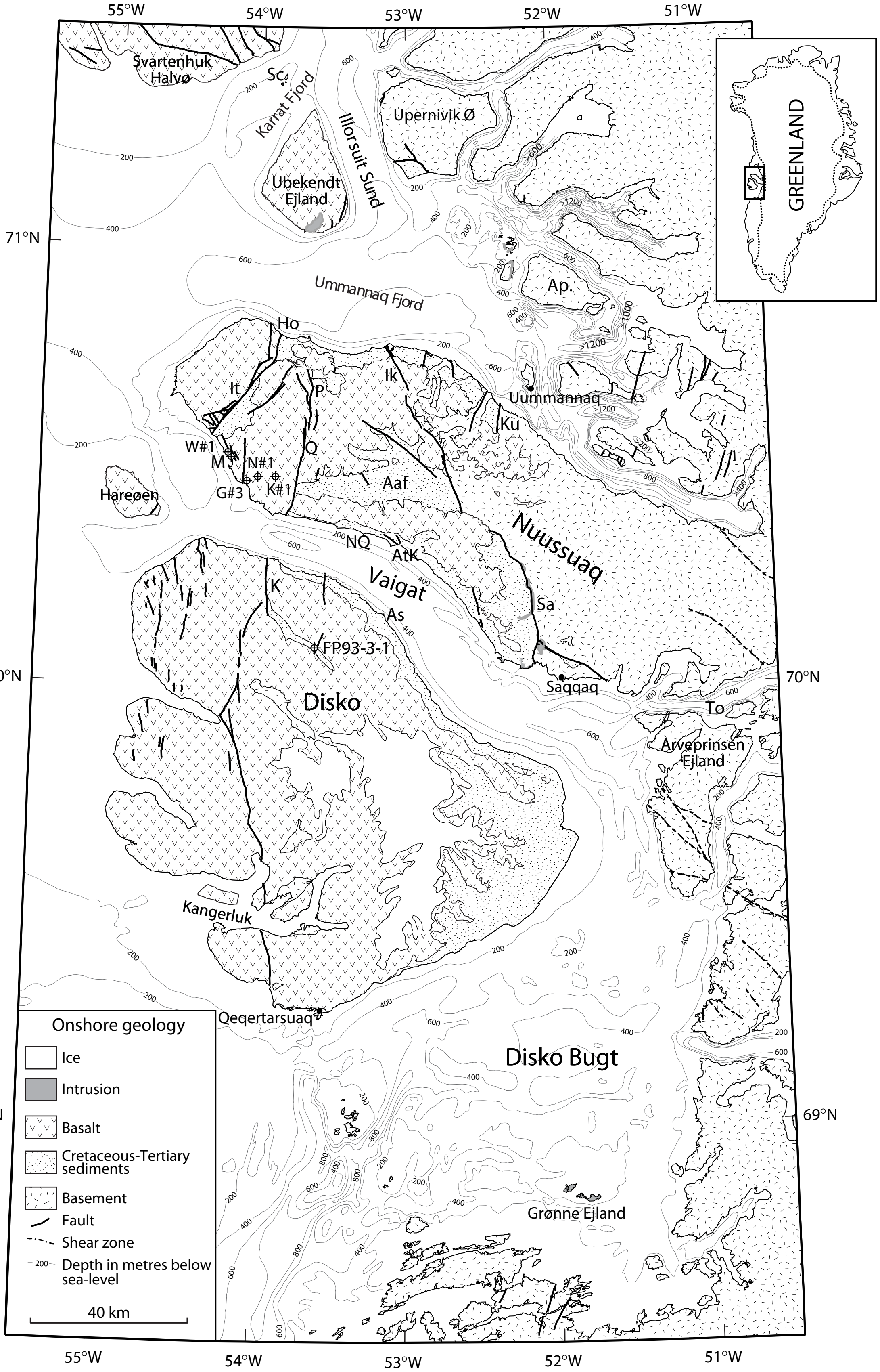
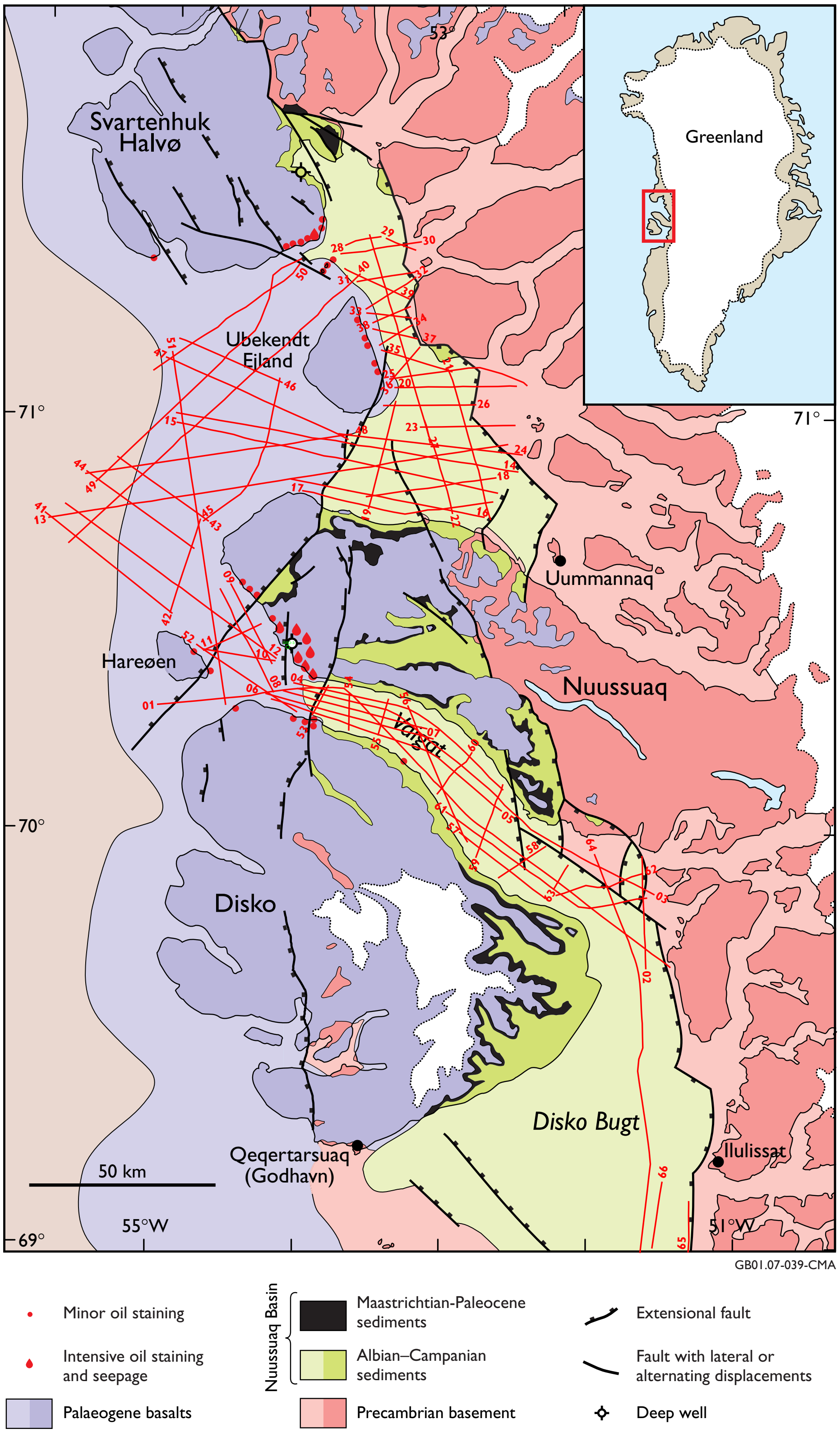

55°W
54°W
53°W
52°W
51°W
71°N
70°N
69°N
Svartenhuk Halvø
Sc
Karrat Fjord
Illorsuit Sund
Ubekendt Ejland
Upernivik Ø
Ummannaq Fjord
Ap.
Uummannaq
GREENLAND
Ho
It
P
Ik
Ku
Q
W#1
M
N#1
G#3
K#1
Aaf
Hareøen
Nuussuaq
NQ
AtK
Vaigat
K
As
Sa
FP93-3-1
Saqqaq
Disko
To
Arveprinsen Ejland
Kangerluk
Qeqertarsuaq
Disko Bugt
Grønne Ejland
Onshore geology
Ice
Intrusion
Basalt
Cretaceous-Tertiary sediments
Basement
Fault
Shear zone
Depth in metres below sea-level
40 km

Fig. 1



Svartenhuk
Halvø
Ubekendt
Ejland
Hareøen
Disko
Nuussuaq
Vaigat
Uummannaq
Disko Bugt
Qeqertarsuaq
(Godhavn)
Ilulissat
Greenland
50 km
71°
70°
69°
55°W
53°
51°W
GB01.07-039-CMA
Minor oil staining
Intensive oil staining and seepage
Palaeogene basalts
Nuussuaq Basin
Maastrichtian–Paleocene sediments
Albian–Campanian sediments
Precambrian basement
Extensional fault
Fault with lateral or alternating displacements
Deep well

Fig. 2

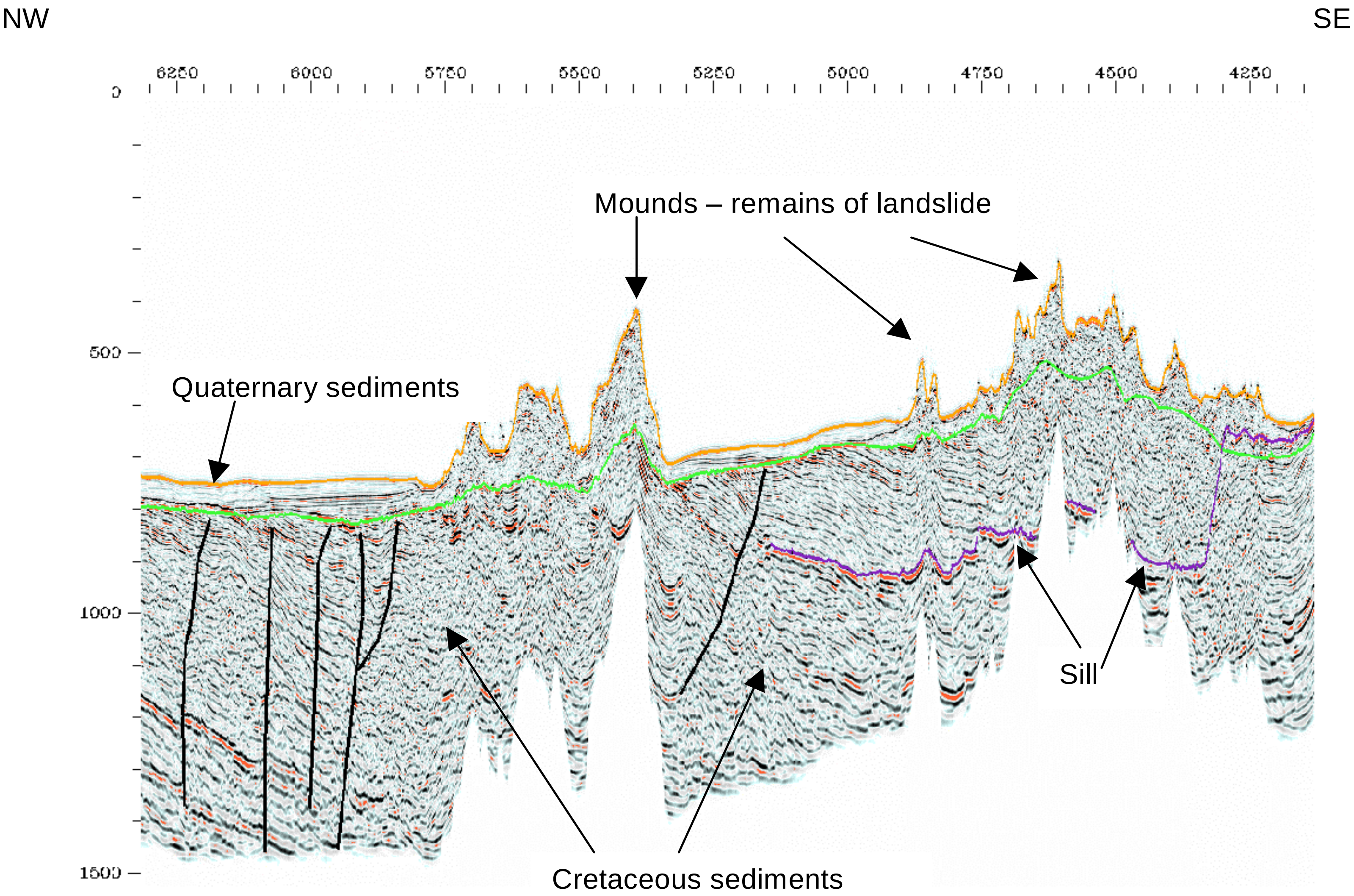


Fig. 3

GEUS00-03

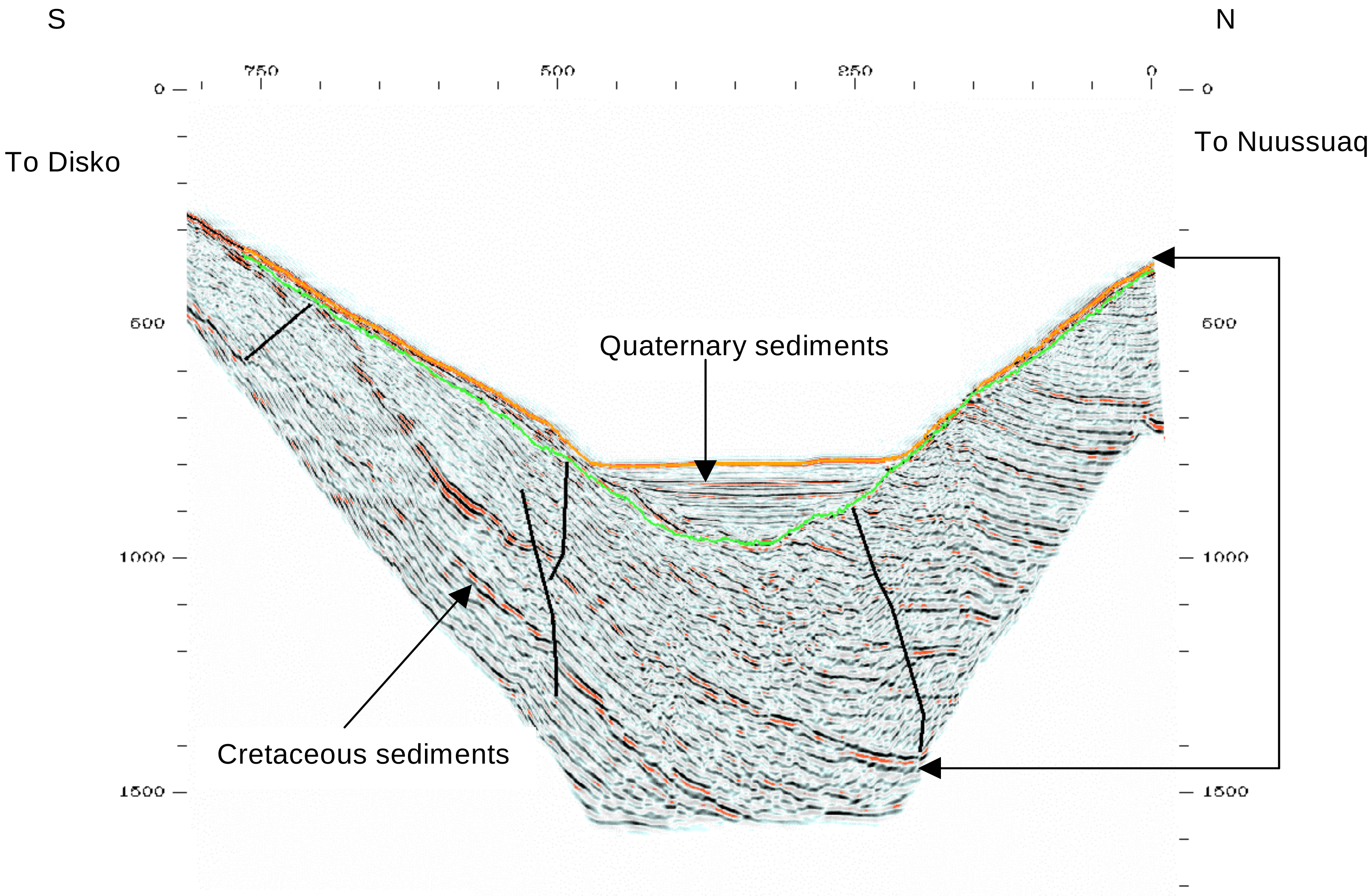


Fig. 4

GEUS00-54

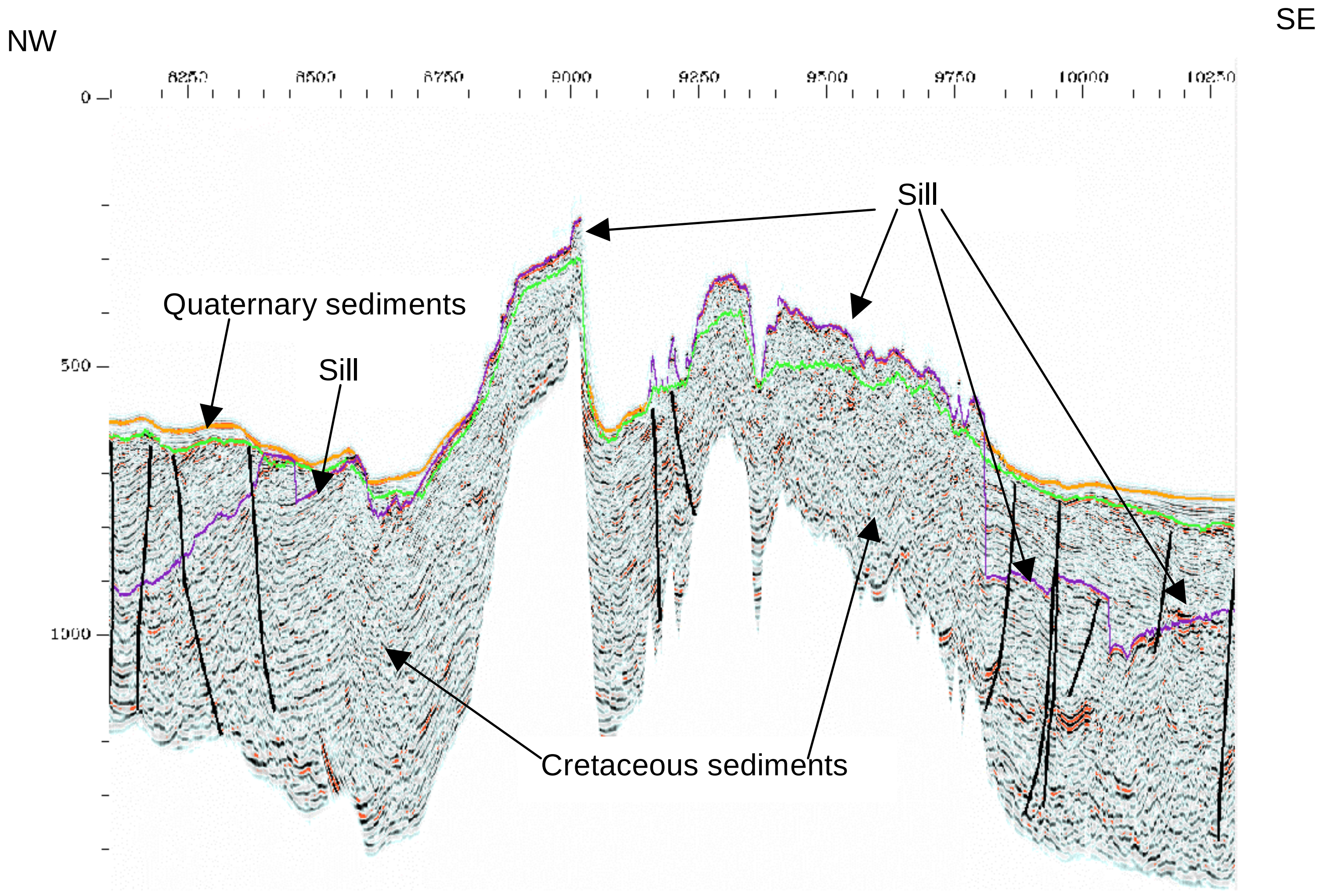


Fig. 5

GEUS00-01

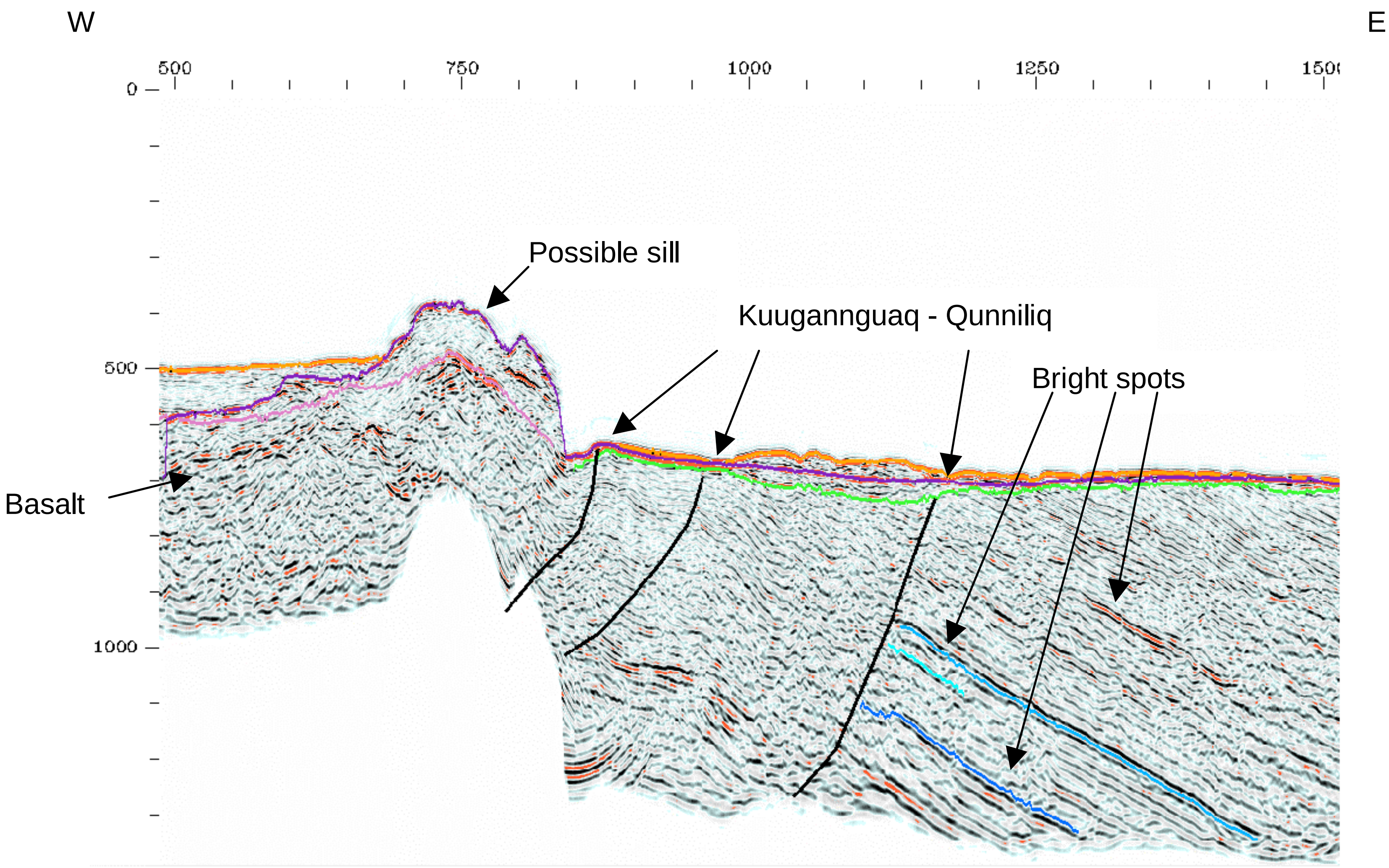


Fig. 6

GEUS00-06

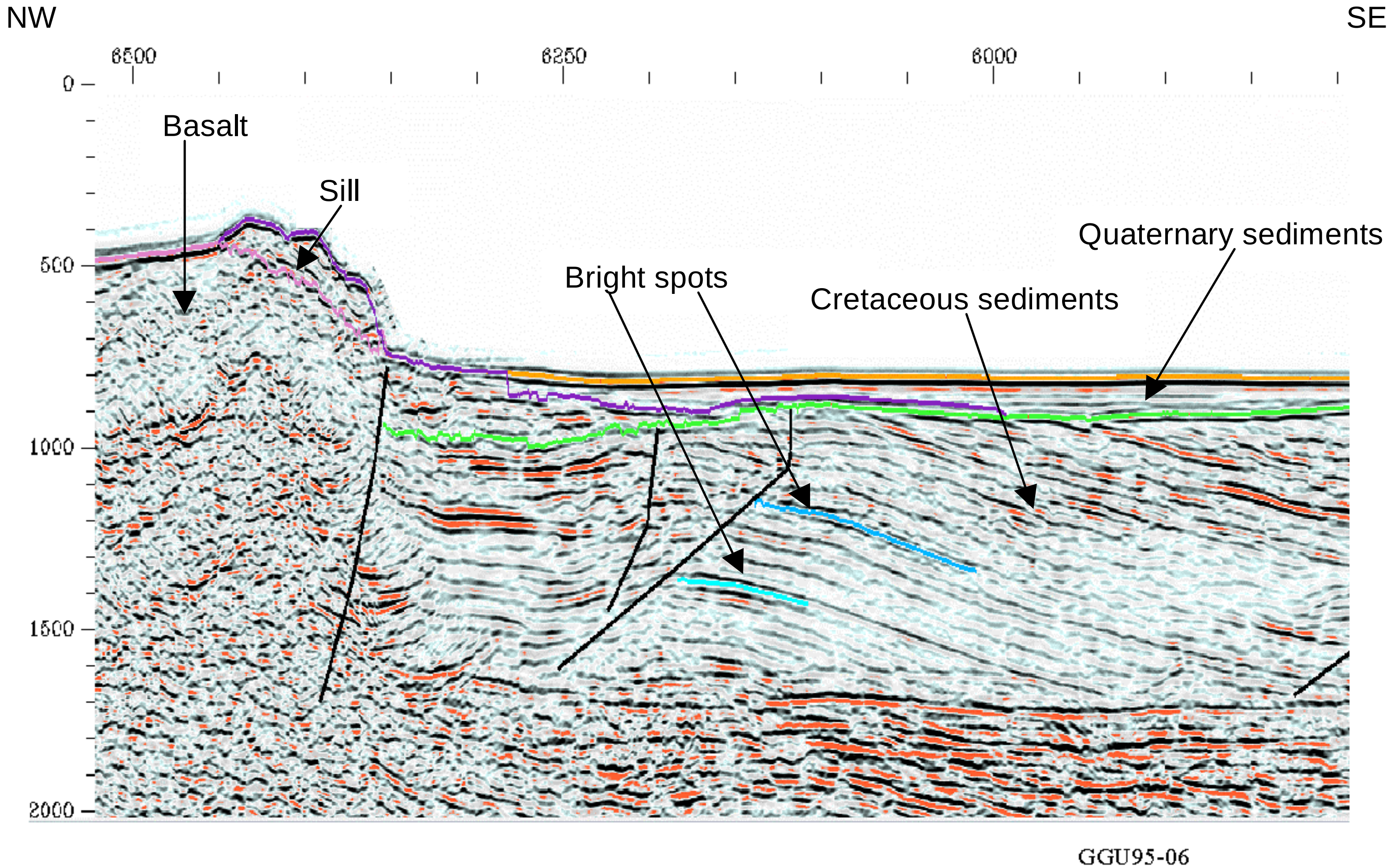

NW
SE
6500
6250
6000
0
500
1000
1500
2000
Basalt
Sill
Bright spots
Cretaceous sediments
Quaternary sediments
GGU95-06

Fig. 7

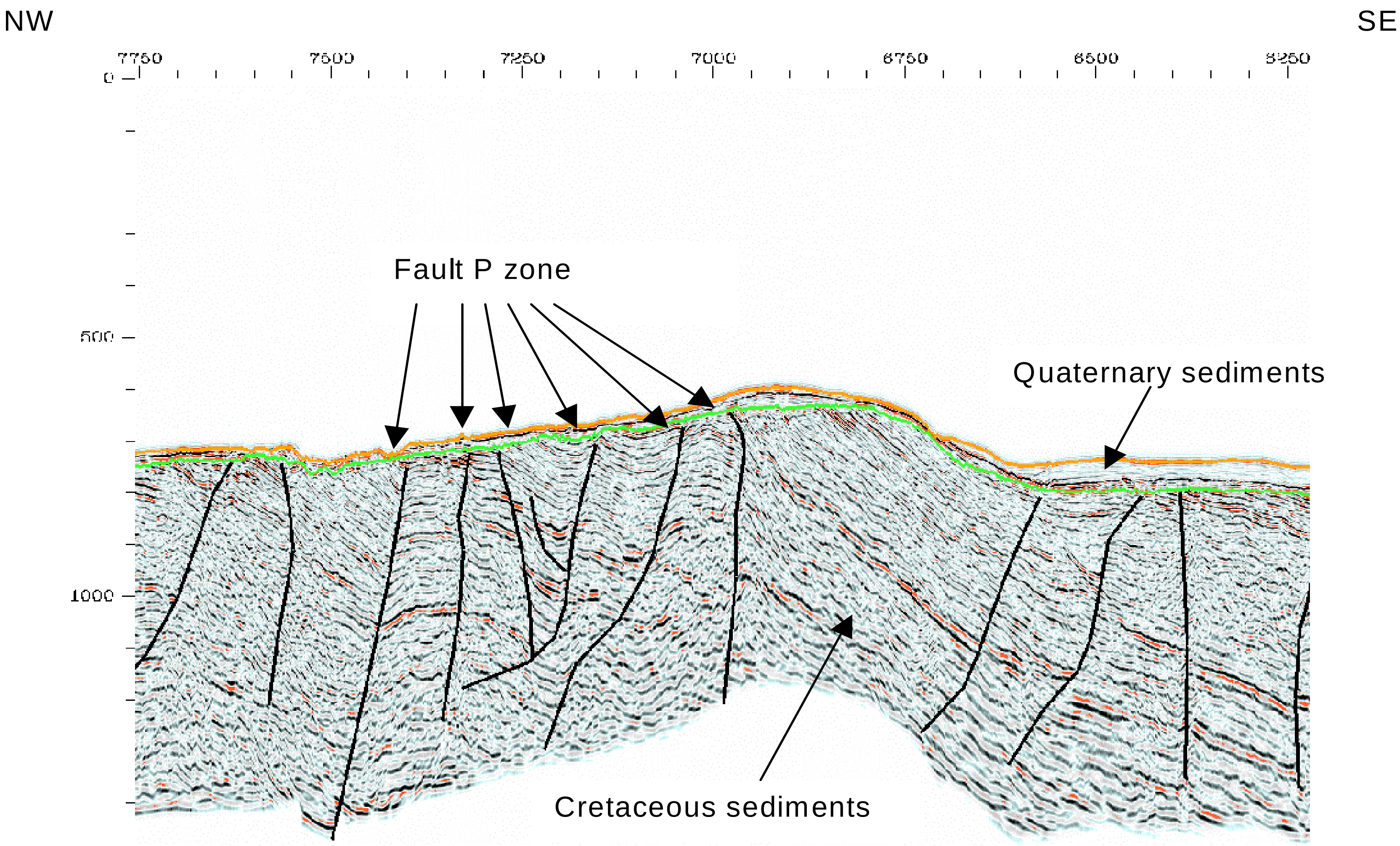


Fig. 8

GEUS00-03

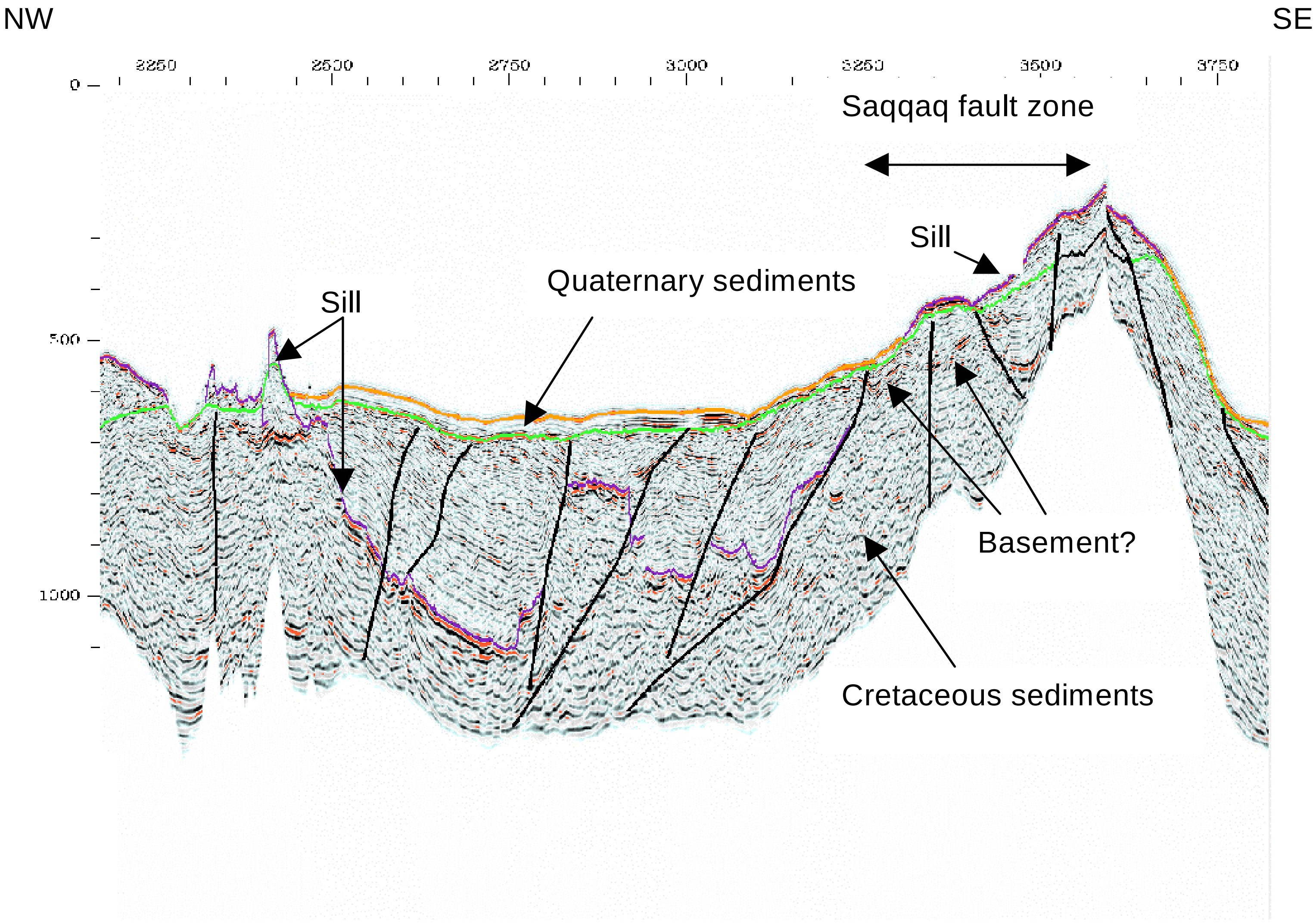


Fig. 9

GEUS00-61

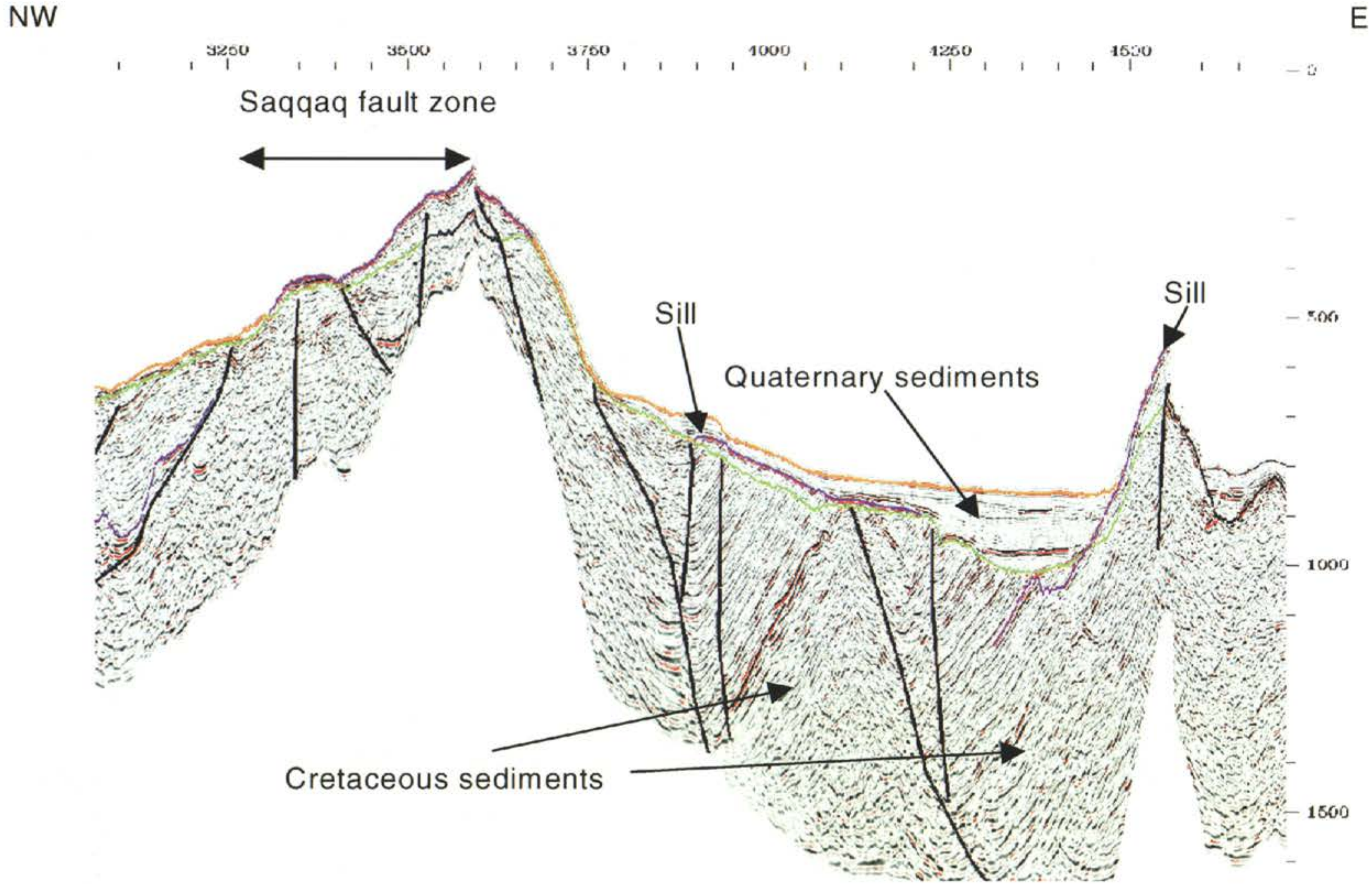


Fig. 10

GEUS00-61

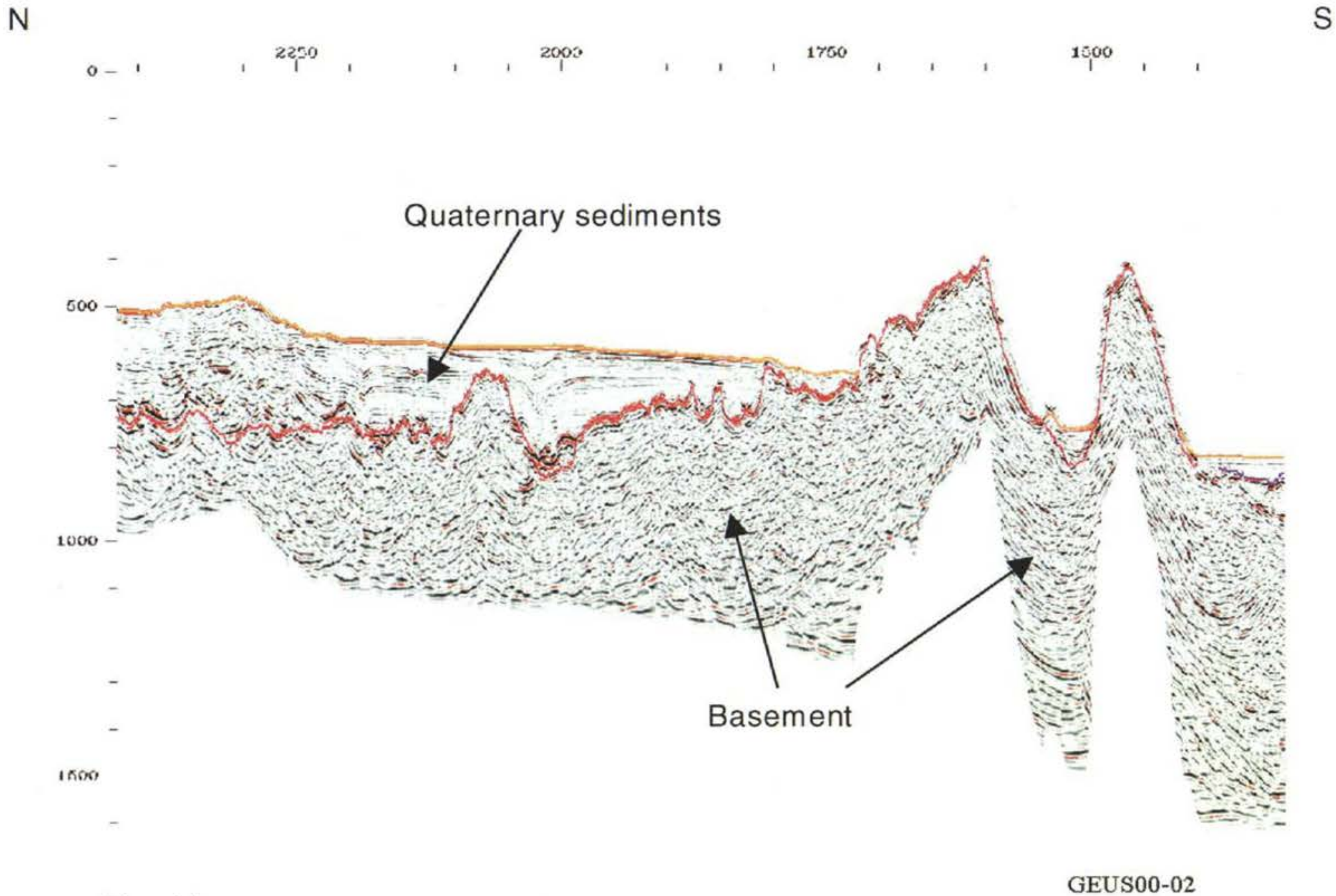
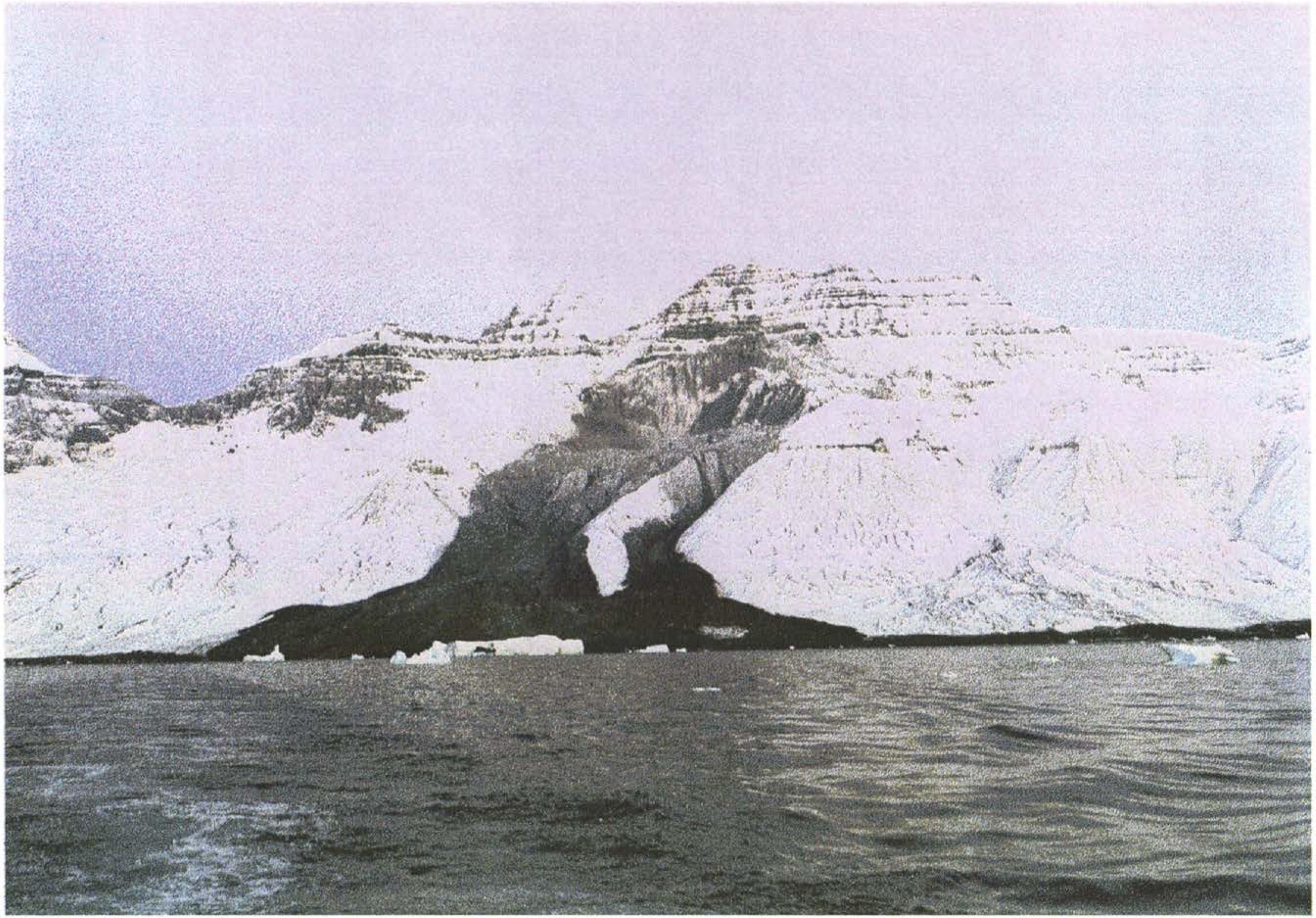

N
S
2250
2000
1750
1500
0
500
1000
1500
Quaternary sediments
Basement
GEUS00-02

Fig. 11



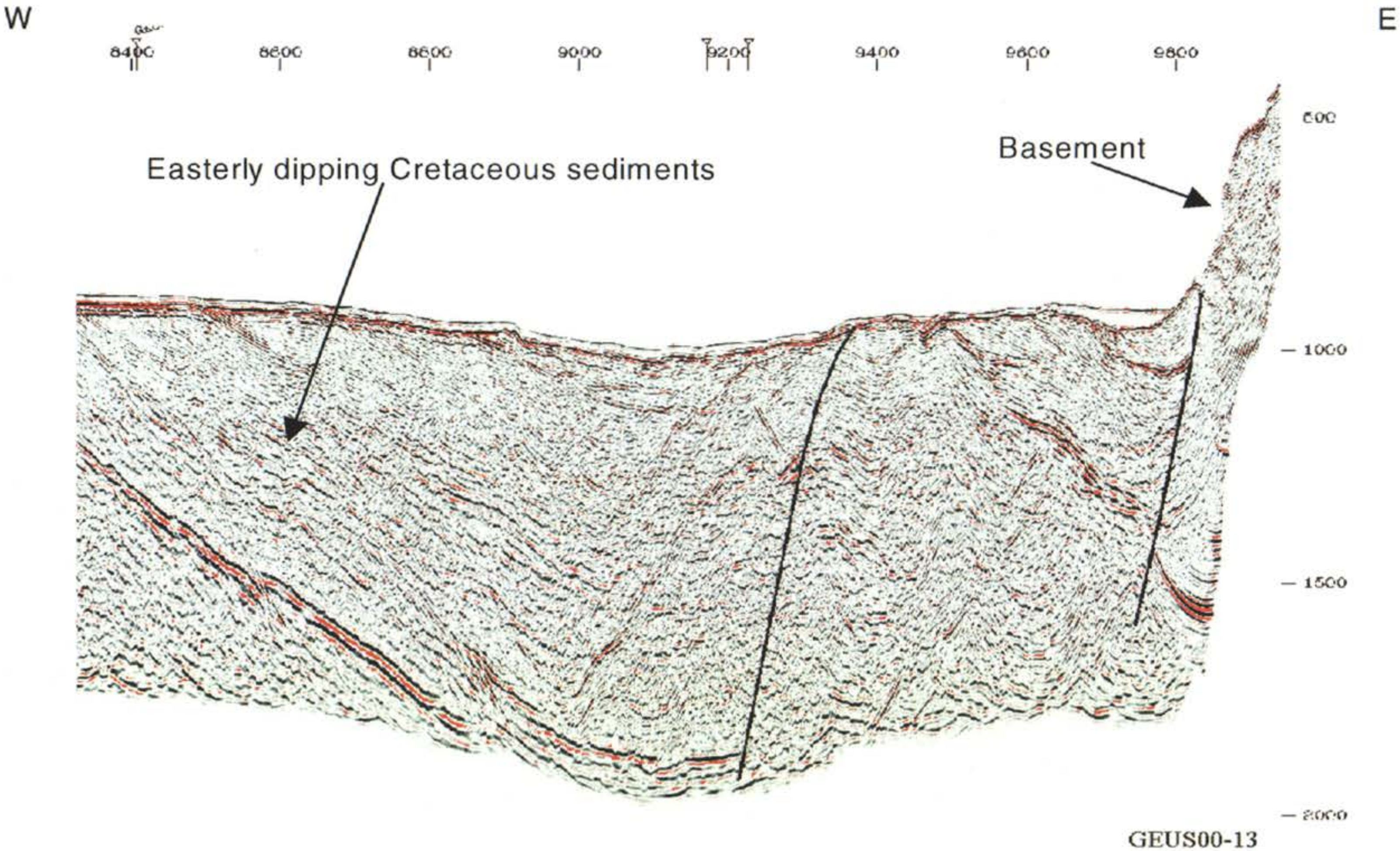

W
E
8400
8600
8800
9000
9200
9400
9600
9800
Easterly dipping Cretaceous sediments
Basement
500
1000
1500
2000
GEUS00-13

Fig. 13

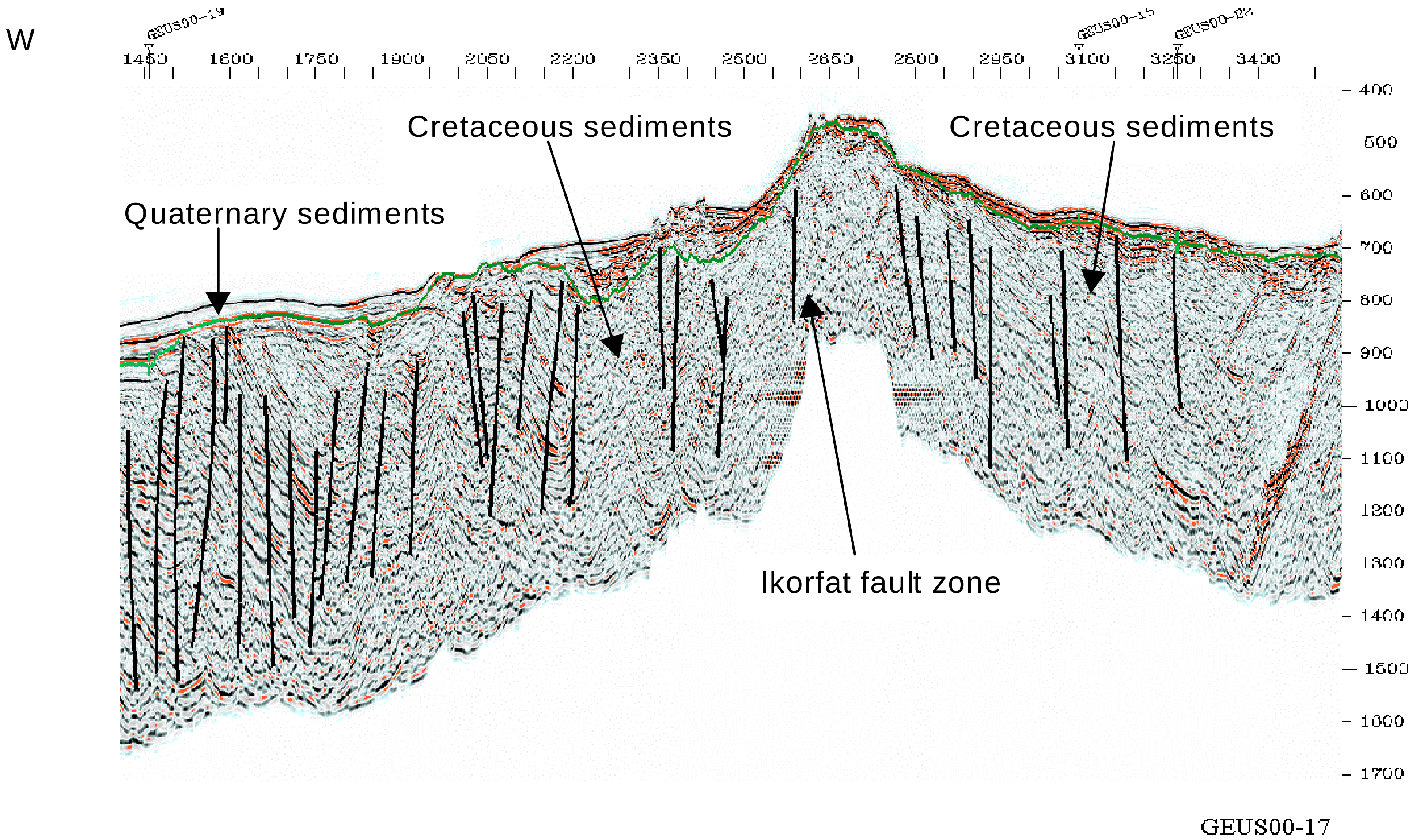

W
E
GEUS00-19
GEUS00-15
1450
1600
1750
1900
2050
2200
2350
2500
2650
2800
2950
3100
3250
3400
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Cretaceous sediments
Cretaceous sediments
Quaternary sediments
Ikorfat fault zone
GEUS00-17

Fig. 14

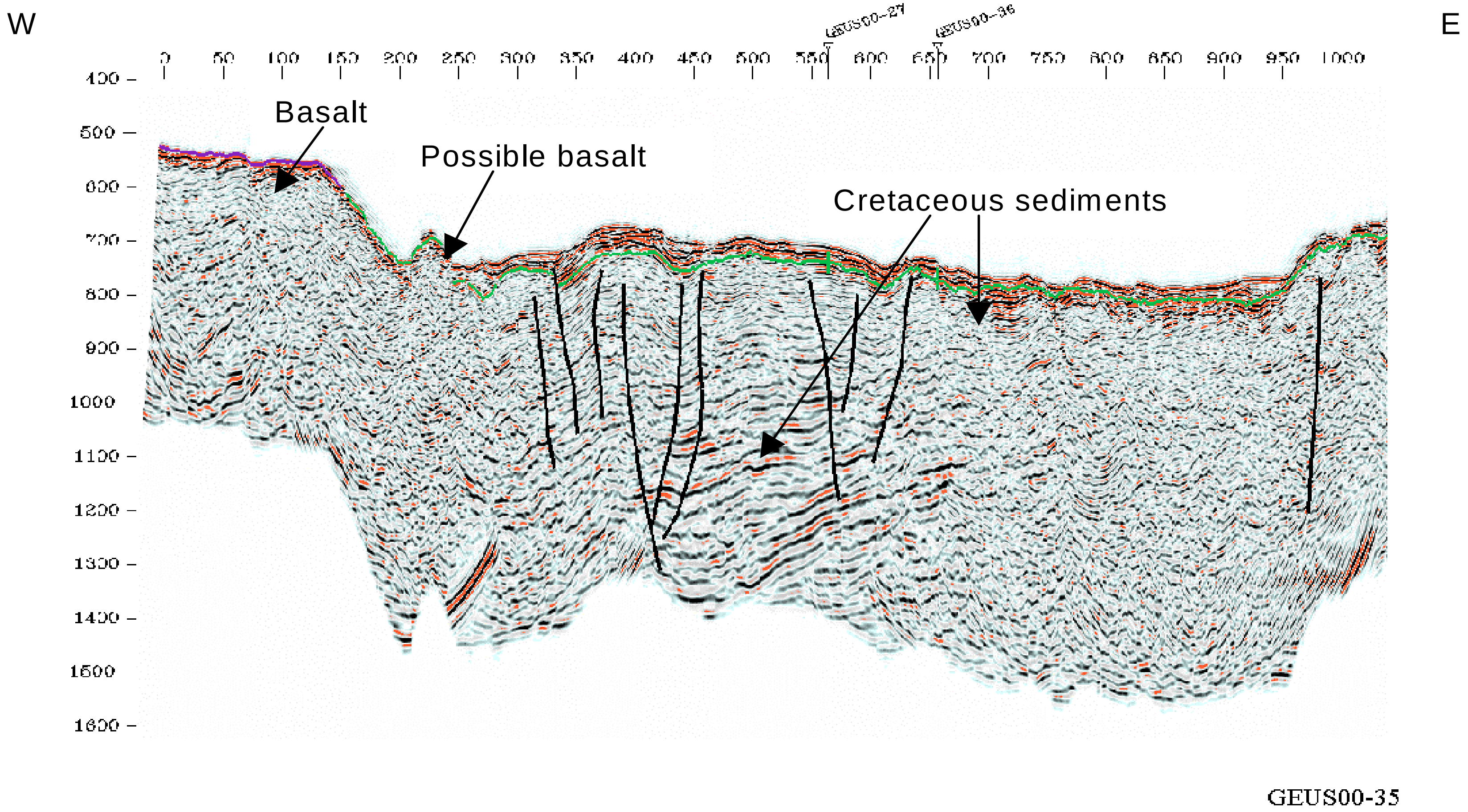

W
E
GEUS00-27
GEUS00-36
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Basalt
Possible basalt
Cretaceous sediments
GEUS00-35

Fig. 15

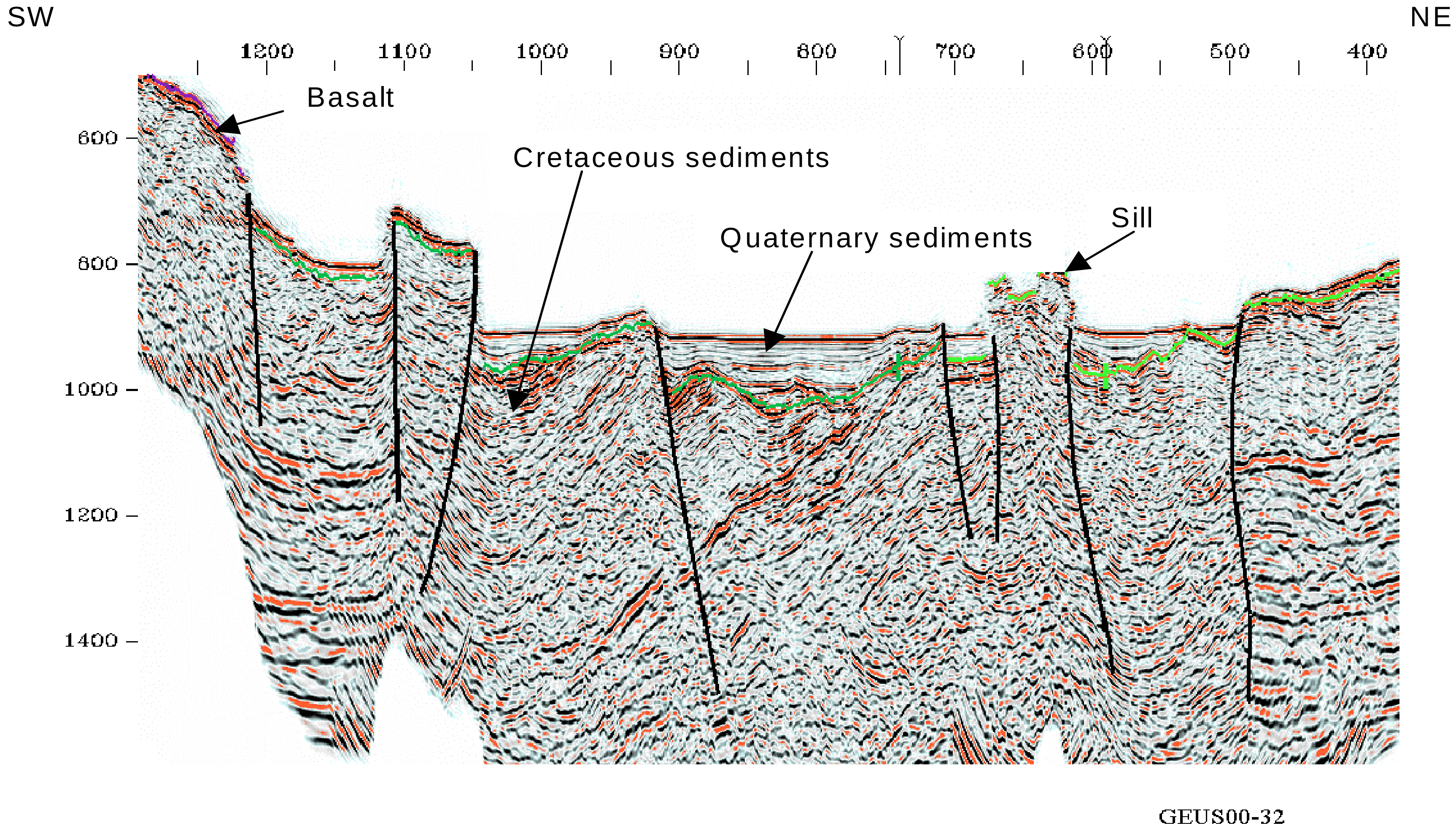
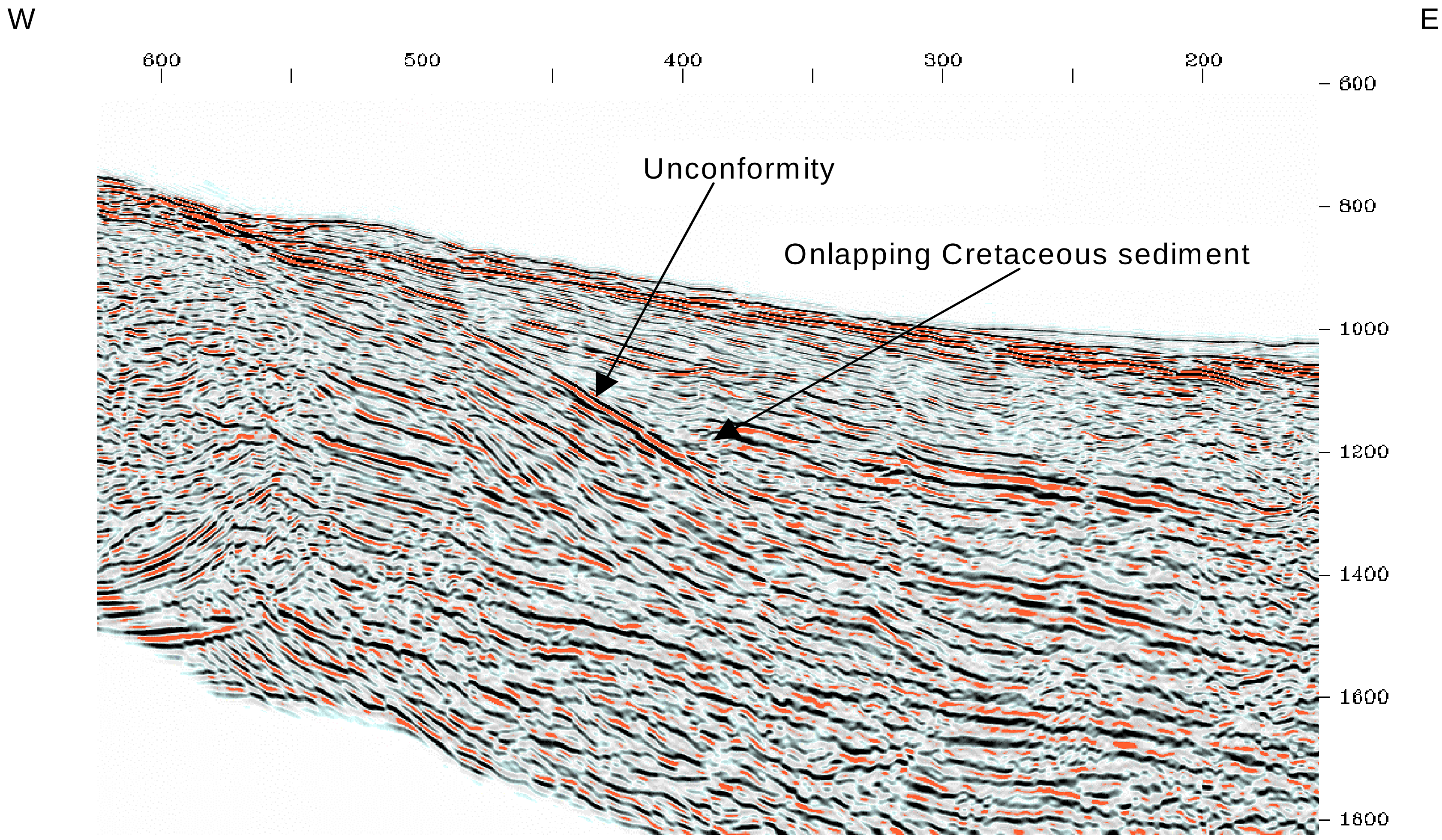

SW
NE
1200
1100
1000
900
800
700
600
500
400
600
800
1000
1200
1400
Basalt
Cretaceous sediments
Quaternary sediments
Sill
GEUS00-32

Fig. 16



GEUS00-14

Fig. 17

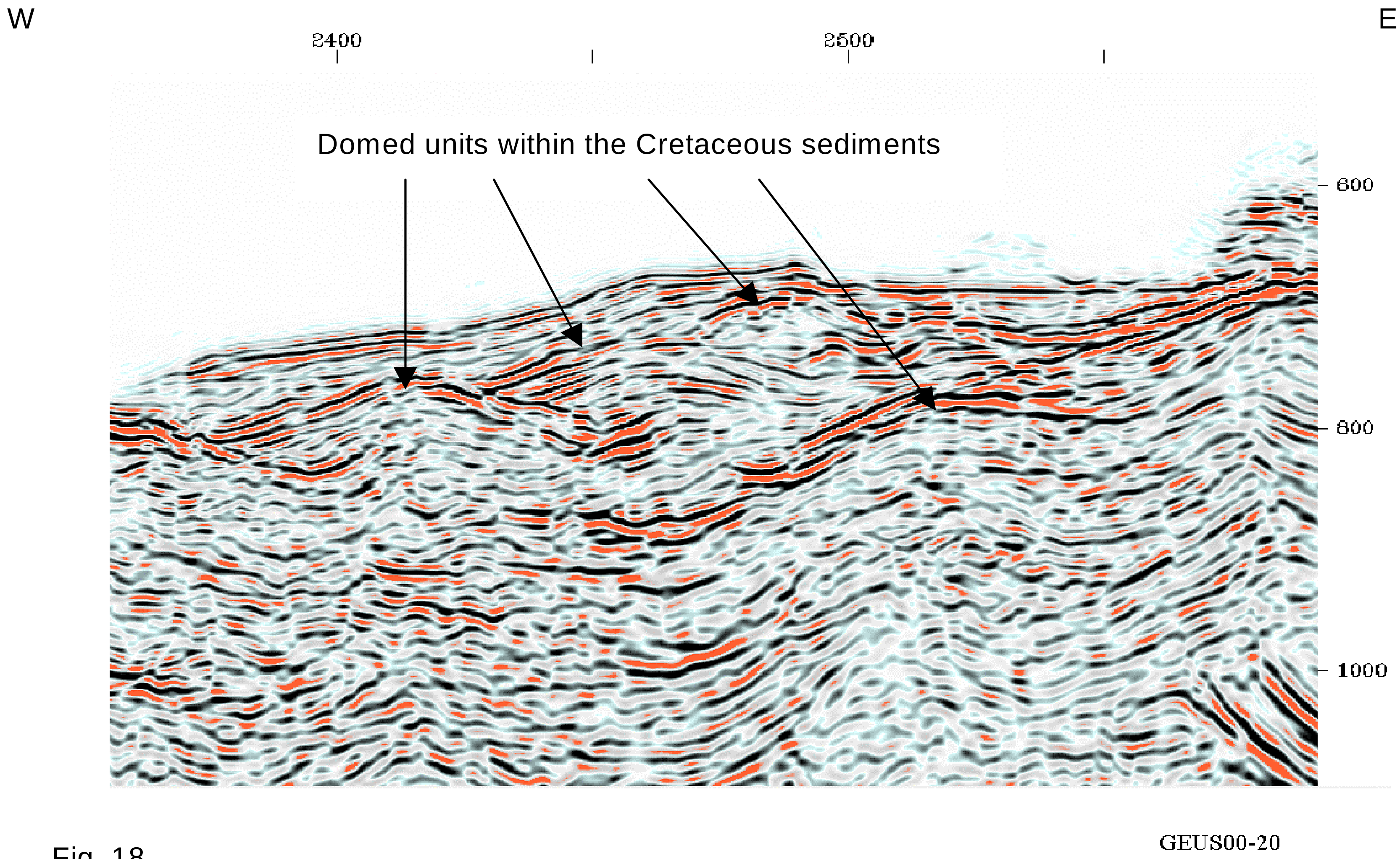

W
E
2400
2500
Domed units within the Cretaceous sediments
600
800
1000
GEUS00-20

Fig. 18

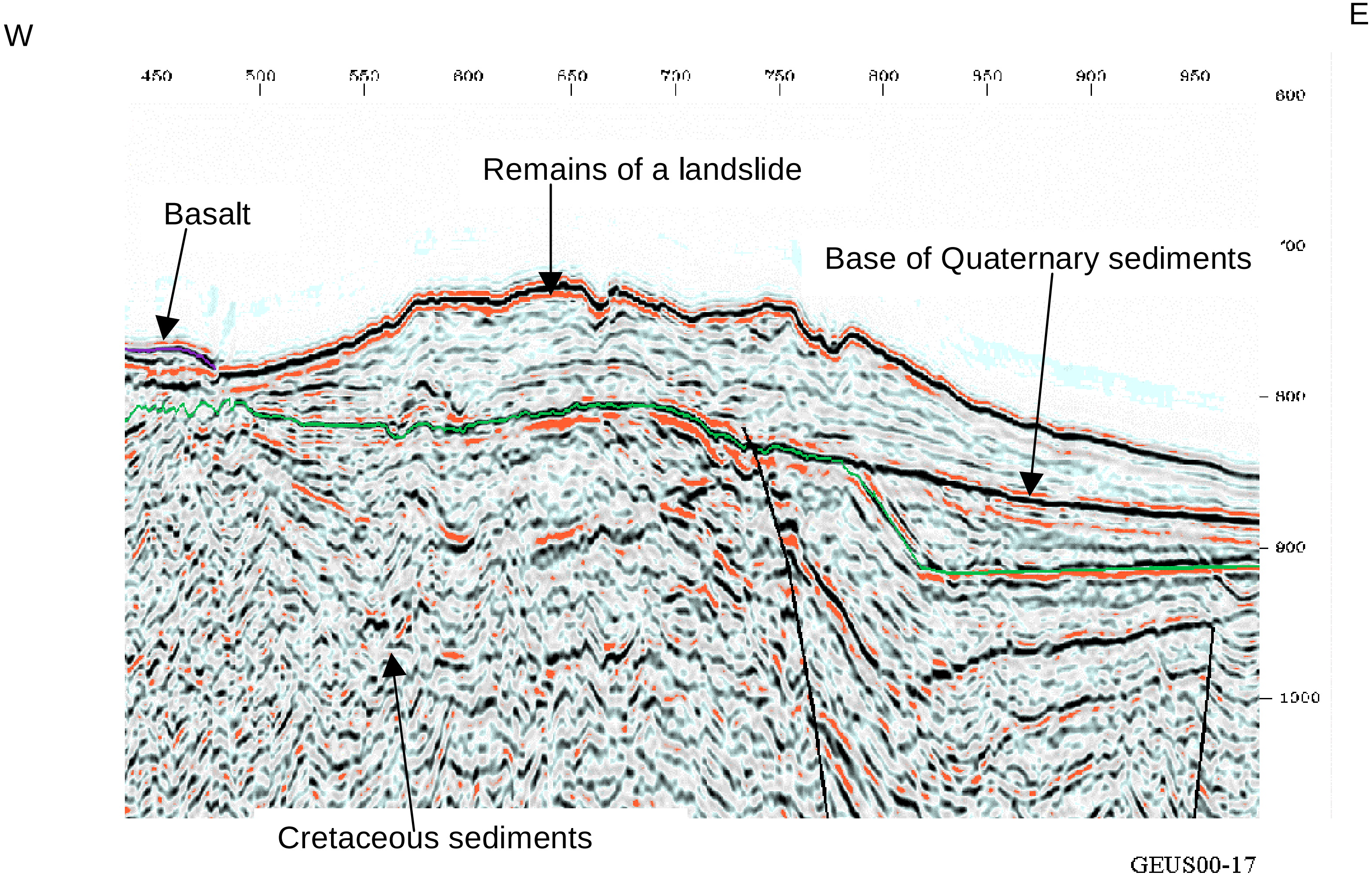

W
E
450
500
550
600
650
700
750
800
850
900
950
600
700
800
900
1000
Remains of a landslide
Basalt
Base of Quaternary sediments
Cretaceous sediments
GEUS00-17

Fig. 19

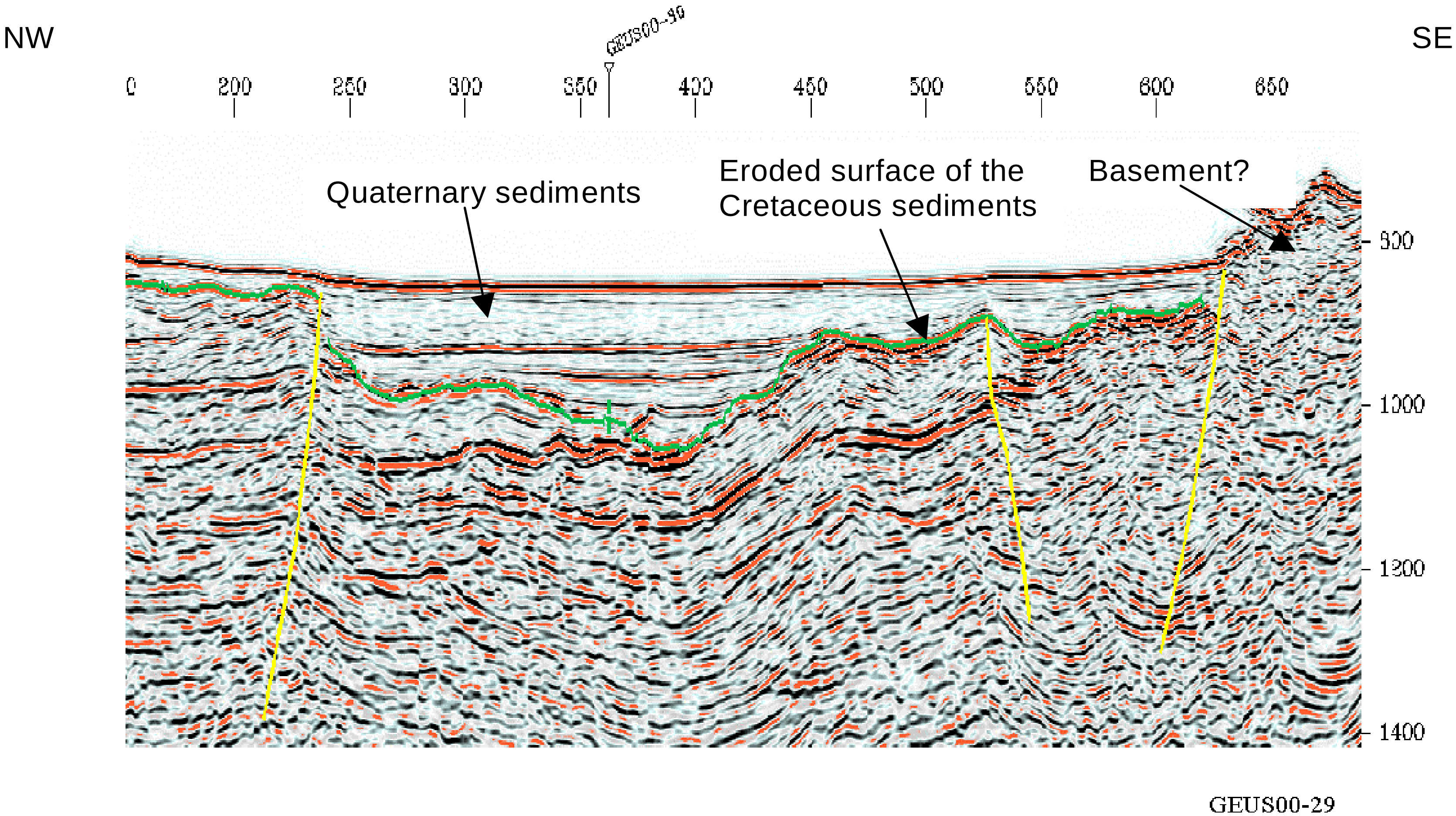

NW
SE
GEUS00-30
200
250
300
350
400
450
500
550
600
650
Quaternary sediments
Eroded surface of the
Cretaceous sediments
Basement?
800
1000
1200
1400
GEUS00-29

Fig. 20

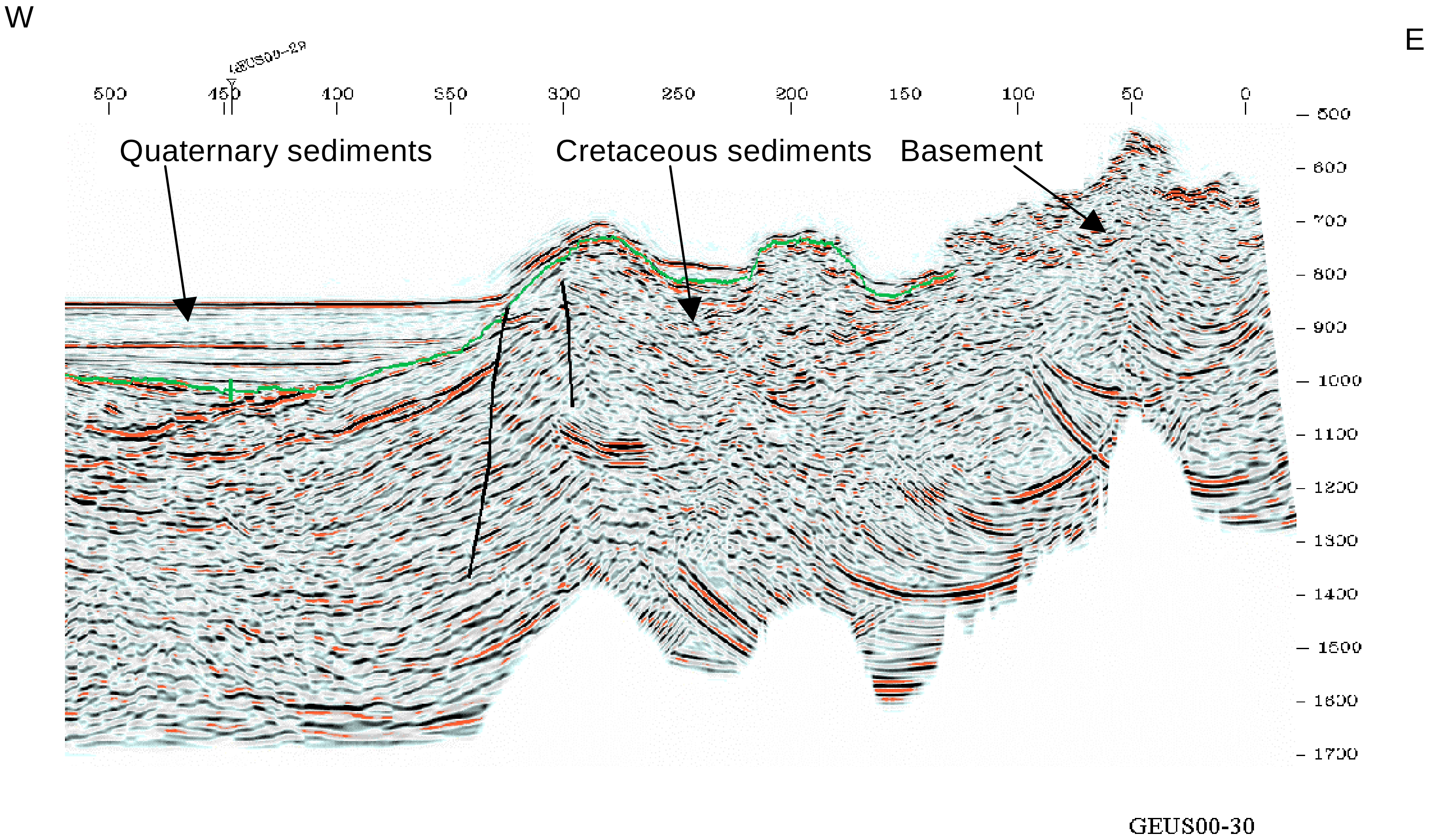

W
E
GEUS00-29
500
450
400
350
300
250
200
150
100
50
0
Quaternary sediments
Cretaceous sediments
Basement
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
GEUS00-30

Fig. 21

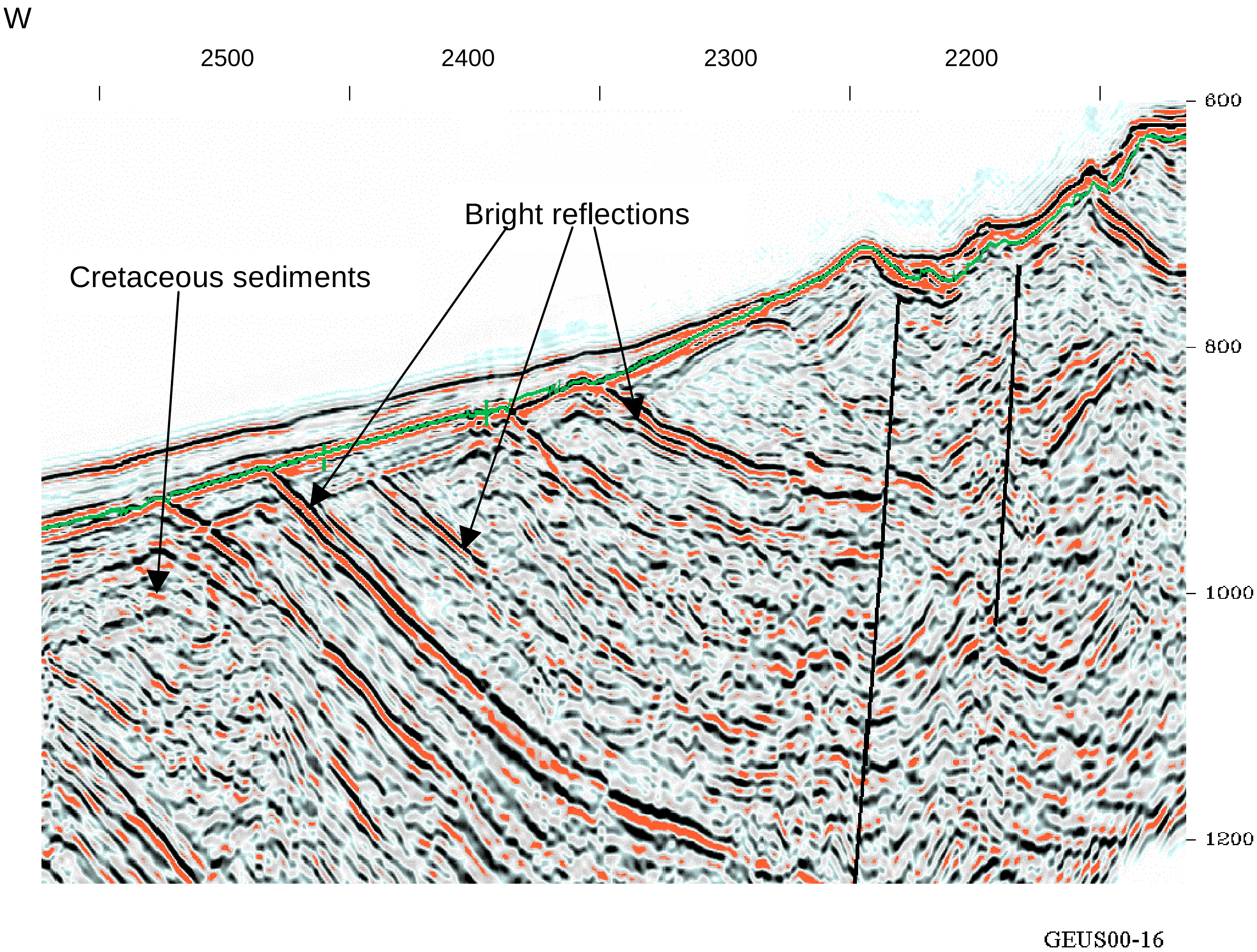

W
E
2500
2400
2300
2200
600
800
1000
1200
Bright reflections
Cretaceous sediments
GEUS00-16

Fig. 22

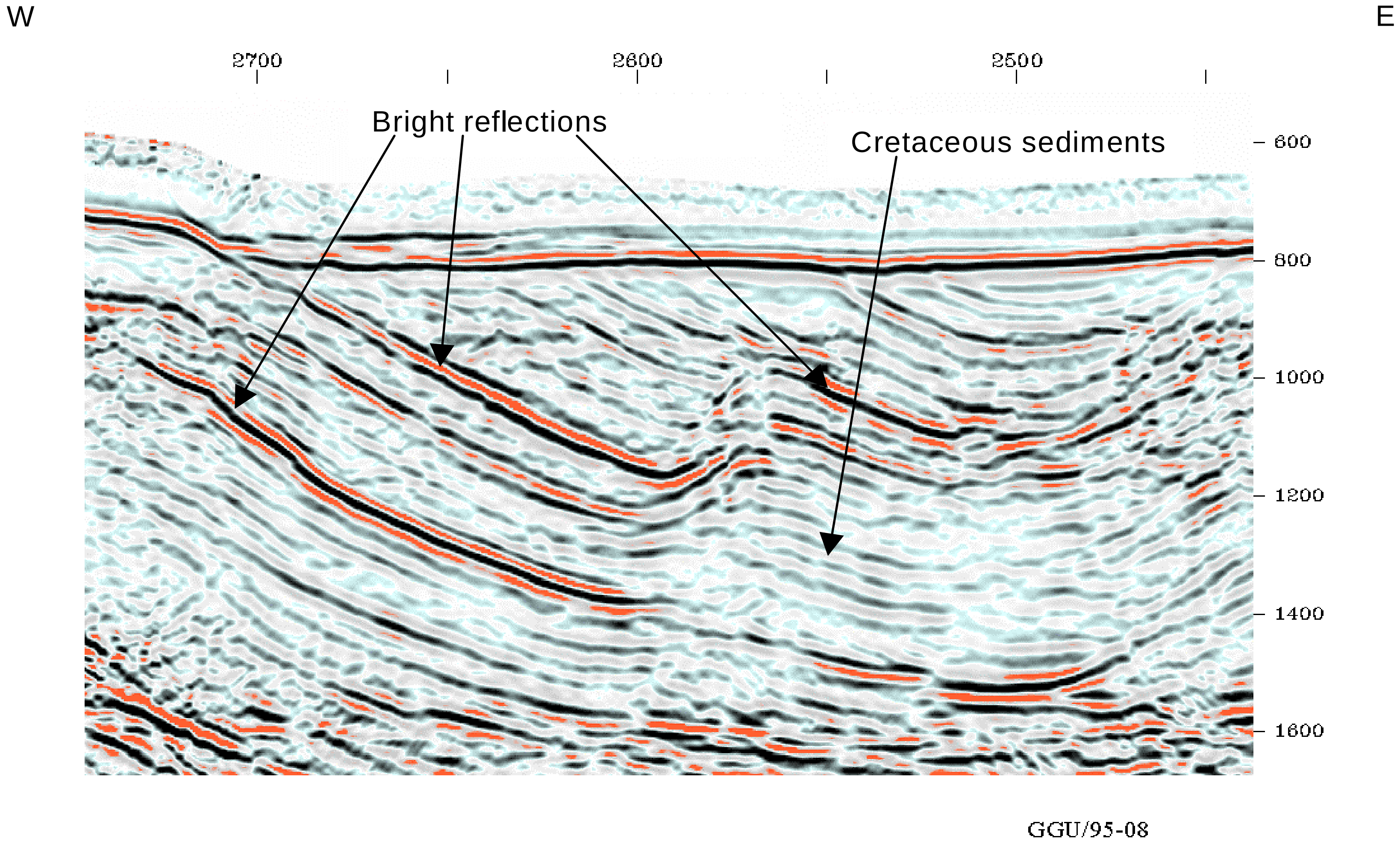

W
E
2700
2600
2500
Bright reflections
Cretaceous sediments
600
800
1000
1200
1400
1600
GGU/95-08

Fig. 23

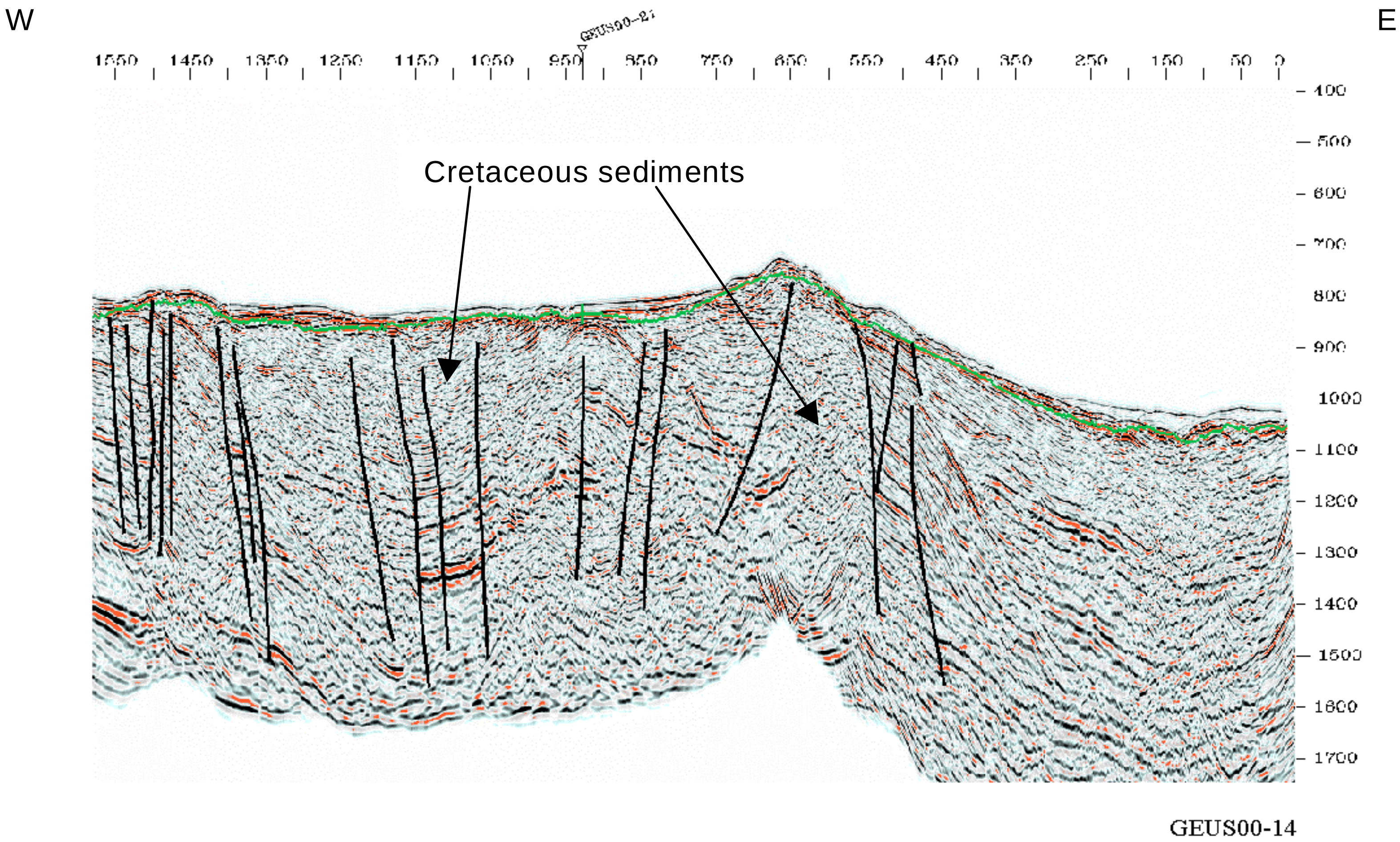
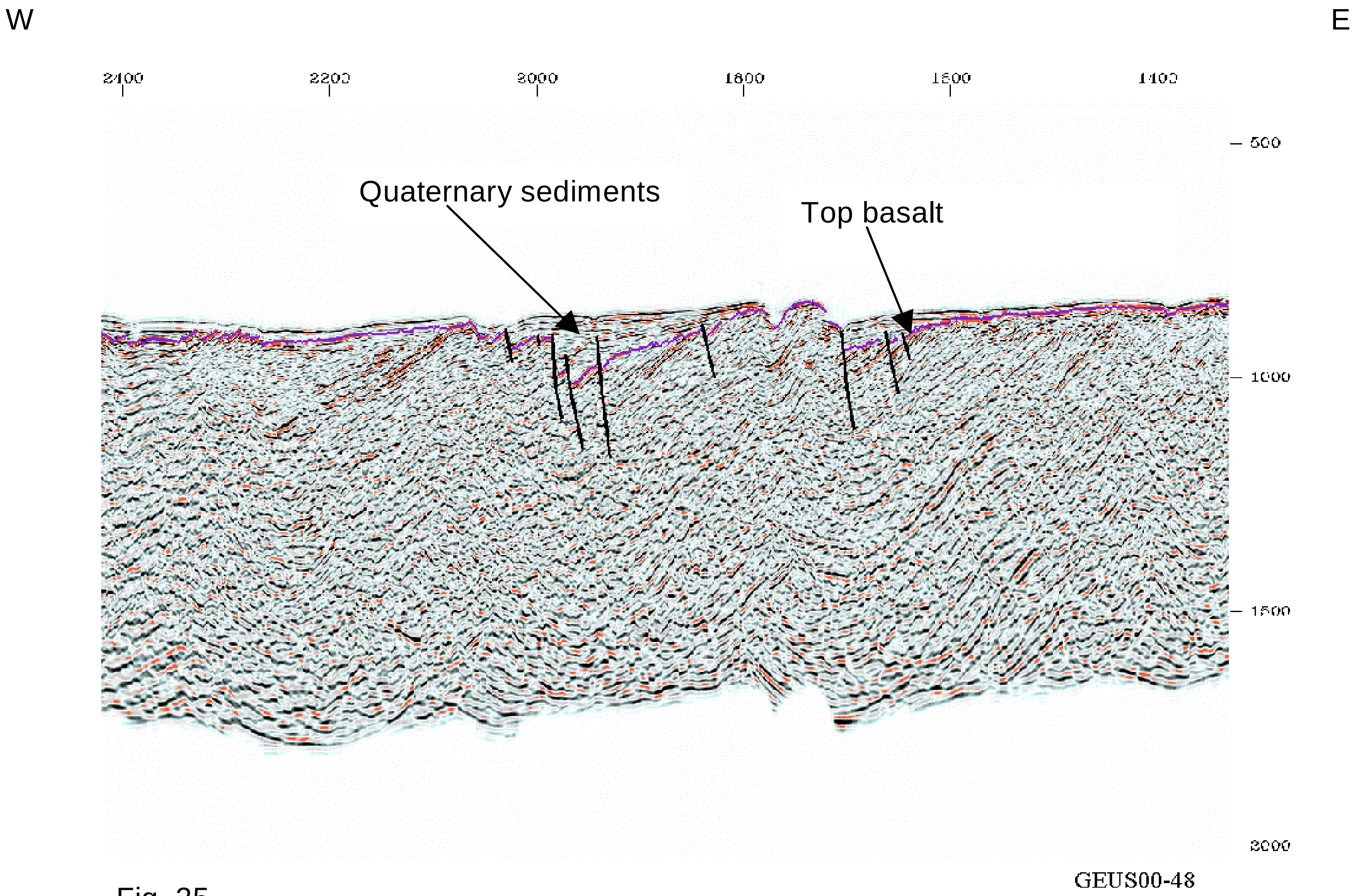

W
E
GEUS00-27
1550
1450
1350
1250
1150
1050
950
850
750
650
550
450
350
250
150
50
0
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Cretaceous sediments
GEUS00-14

Fig. 24



W
E
2400
2200
2000
1800
1600
1400
500
1000
1500
2000
Quaternary sediments
Top basalt
GEUS00-48

Fig. 25

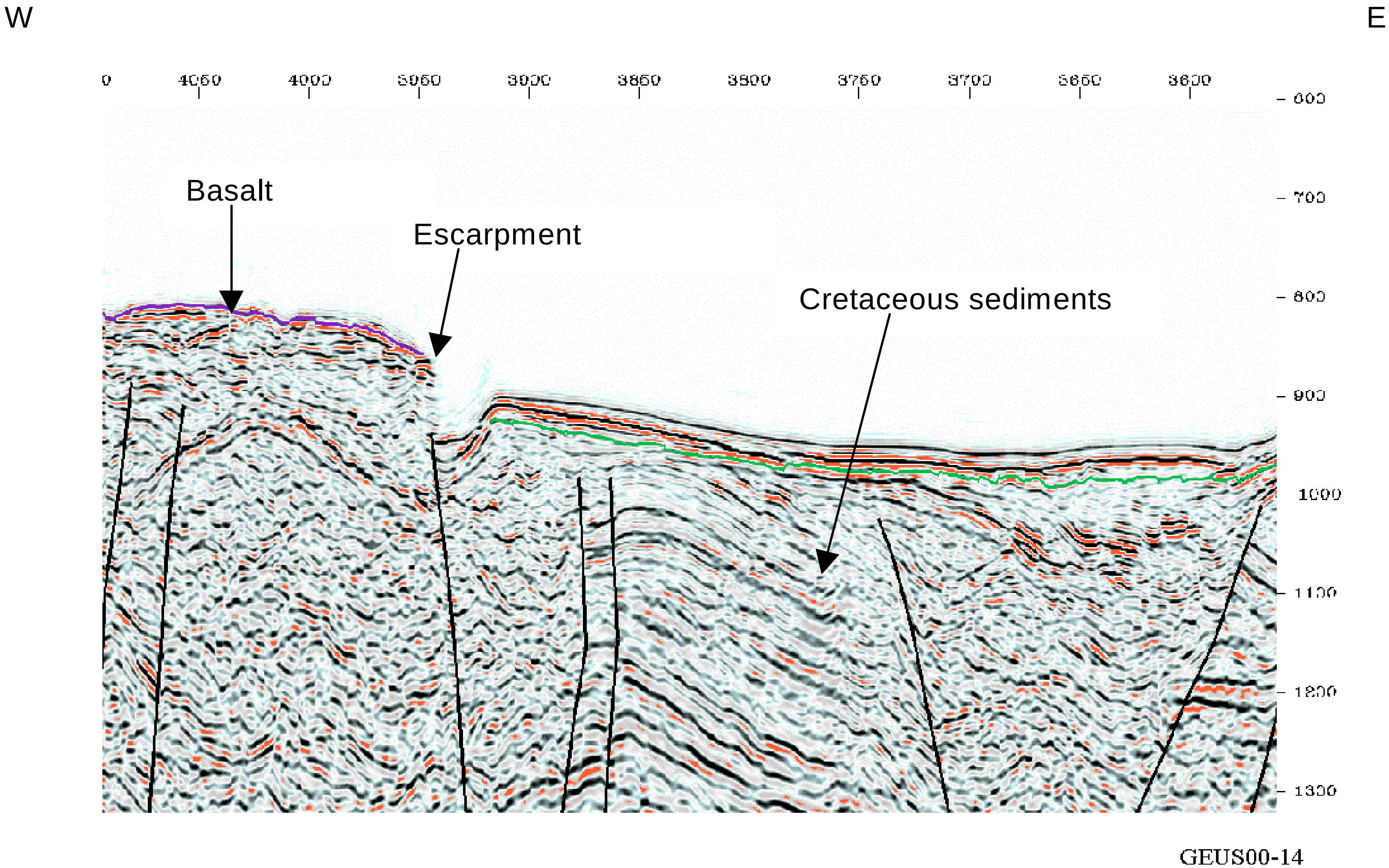
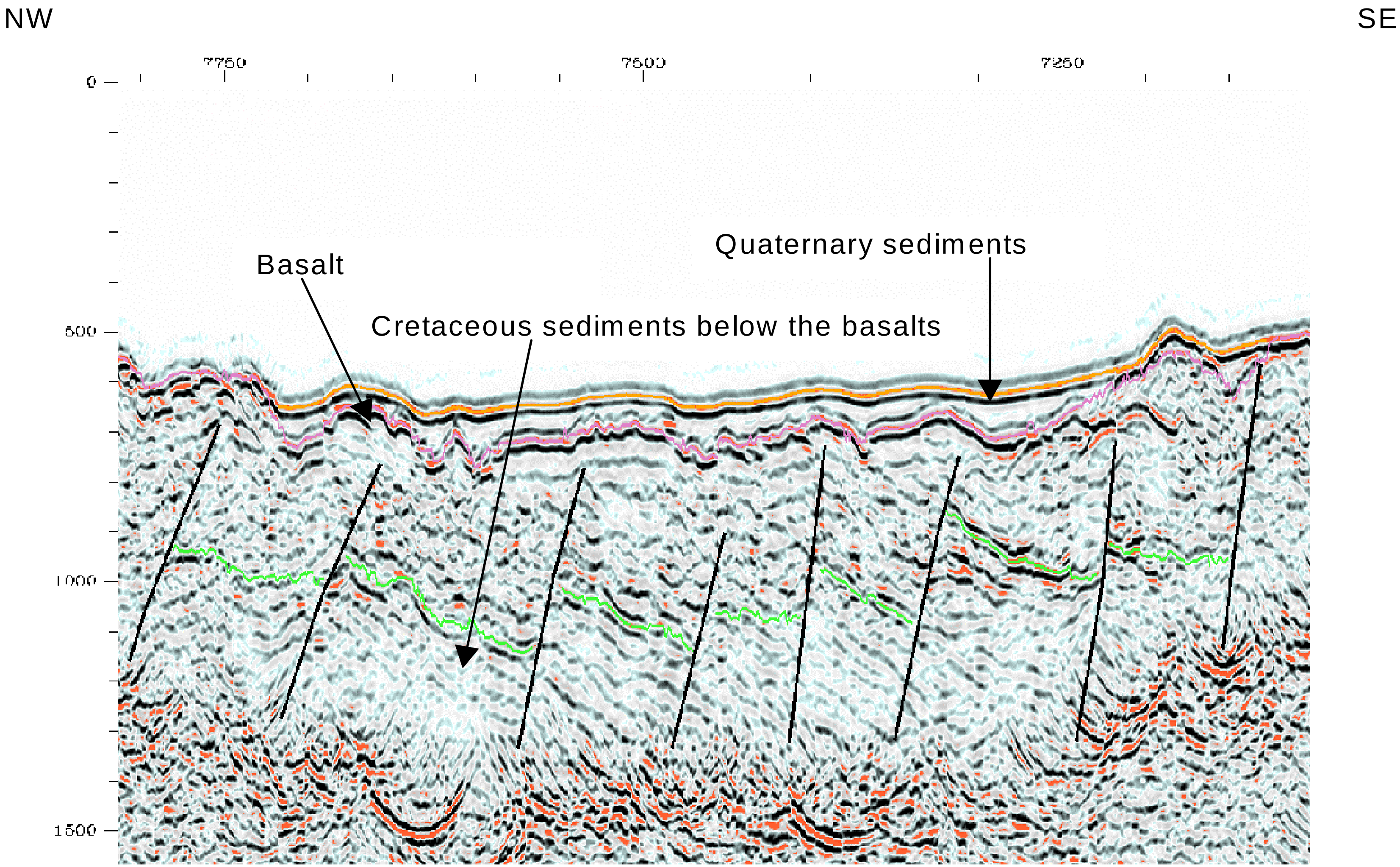

W
E
0
4050
4000
3950
3900
3850
3800
3750
3700
3650
3600
600
700
800
900
1000
1100
1200
1300
Basalt
Escarpment
Cretaceous sediments
GEUS00-14

Fig. 26



GGU95-06

Fig. 27

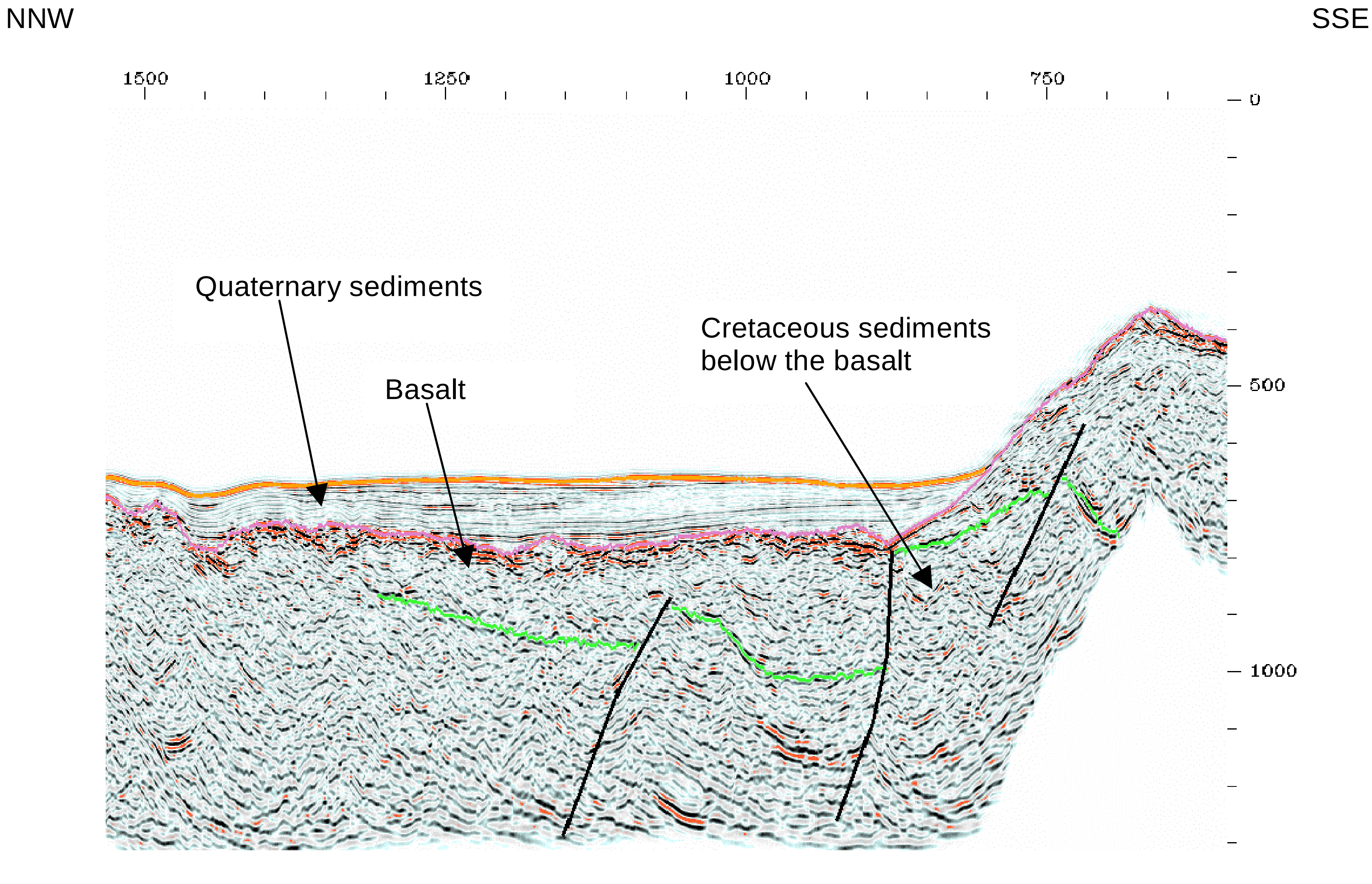
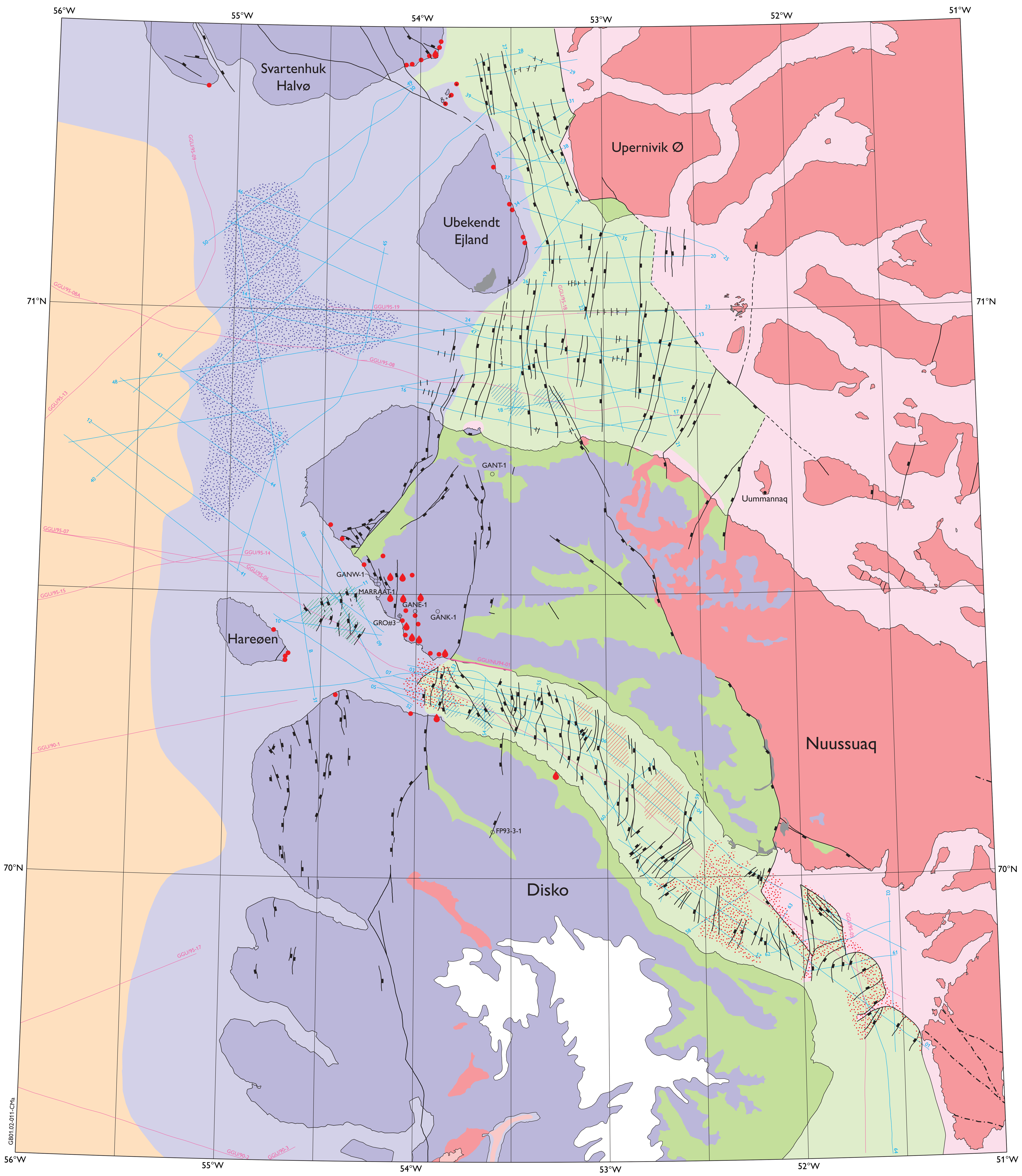

NNW
SSE
1500
1250
1000
750
0
500
1000
Quaternary sediments
Basalt
Cretaceous sediments below the basalt
GEUS00-08

Fig. 28

Project NuussuaqSeis 2000 – Geological map



Legend

- Mounds at seabed indicating major slumps/landslides
- Intrusion
- Eocene and younger sediments
- Basalt onshore
- Basalt offshore at or near seabed/base Quaternary
- Areas with halfgrabens at top volcanic level
- Areas where traces of Cretaceous sediments can be seen below basalts
- Cretaceous–Paleocene sediments onshore
- Cretaceous–Paleocene sediments offshore at or near seabed/base Quaternary
- Area with sills at or near seabed/base Quaternary
- Area of intra-Cretaceous bright spots that might indicate hydrocarbons or sills
- Precambrian basement onshore
- Precambrian basement offshore at seabed/base Quaternary
- Fault at seabed/base Quaternary - downthrown side indicated (where known)
- Shear zone
- Intensive oil staining and seepage
- Minor oil staining
- GEUS2000G seismic line - the prefix GEUS00- is omitted from all line names, number at start of line
- GGU/1990, 1994 or 1995 seismic line - number at start of line
- Exploration well
- Borehole

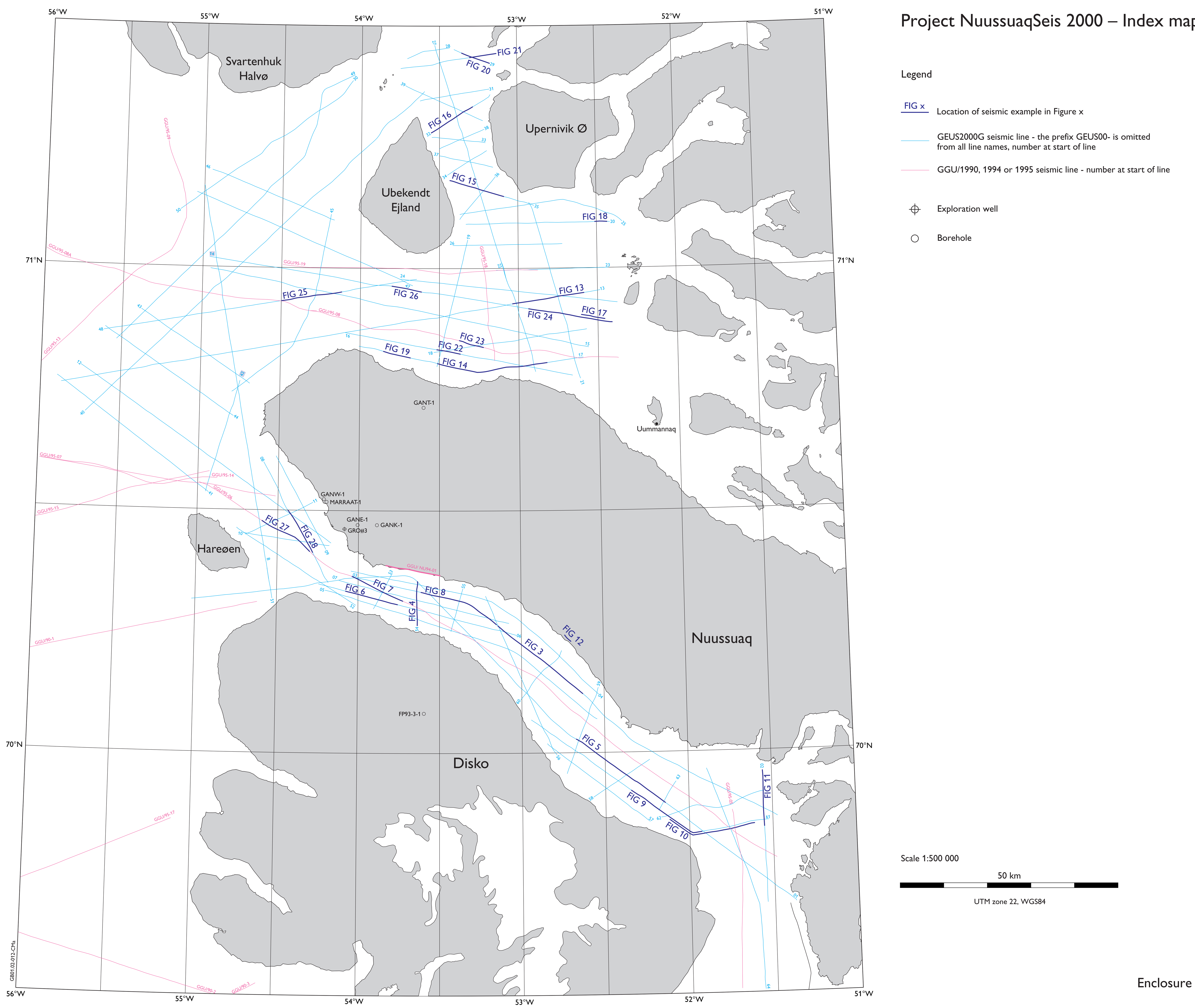
Scale 1:500 000

50 km

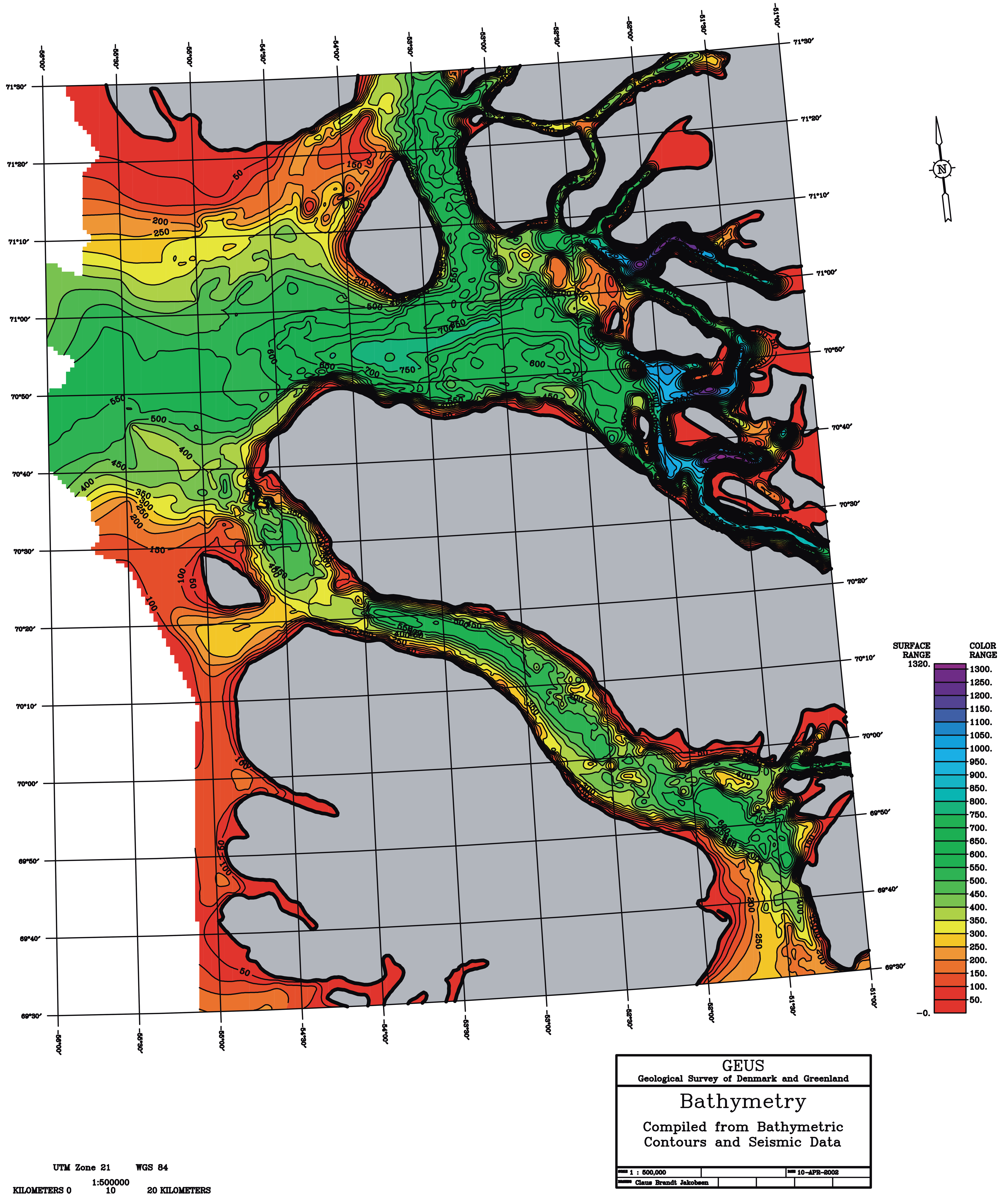
UTM zone 22, WGS84

Enclosure 1

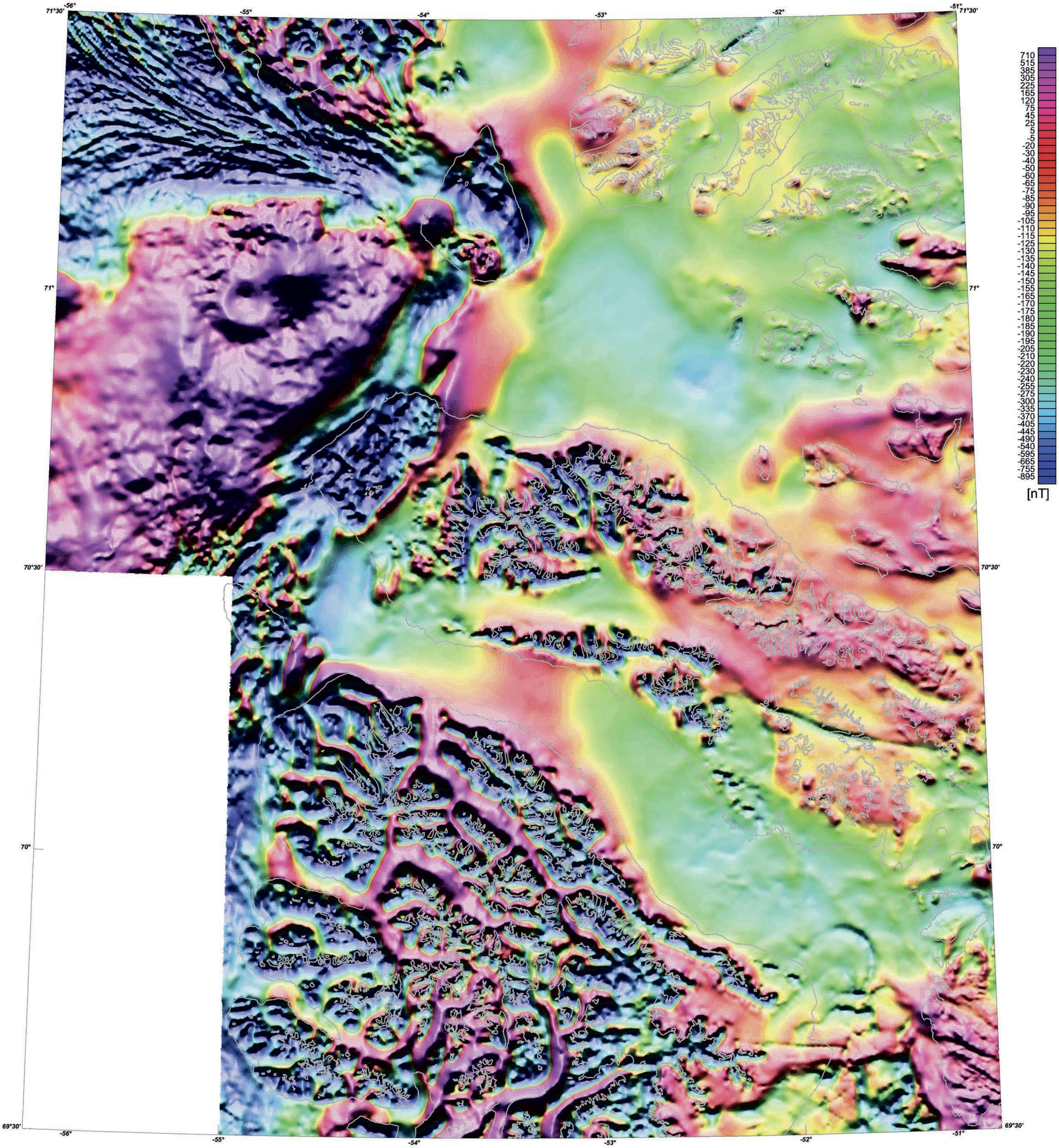
Project NuussuaqSeis 2000 – Index map



Enclosure 2


GEUS
Geological Survey of Denmark and Greenland
Bathymetry
Compiled from Bathymetric Contours and Seismic Data
1 : 500,000
10-APR-2002
Claus Brandt Jakobsen
SURFACE RANGE
1320.
-0.
COLOR RANGE
1300.
1250.
1200.
1150.
1100.
1050.
1000.
950.
900.
850.
800.
750.
700.
650.
600.
550.
500.
450.
400.
350.
300.
250.
200.
150.
100.
50.
UTM Zone 21 WGS 84
1:500000
KILOMETERS 0 10 20 KILOMETERS
71°30′
71°20′
71°10′
71°00′
70°50′
70°40′
70°30′
70°20′
70°10′
70°00′
69°50′
69°40′
69°30′

Enclosure 3



Magnetic total field anomaly

Data from projects Aeromag 1997 and Aeromag 2001

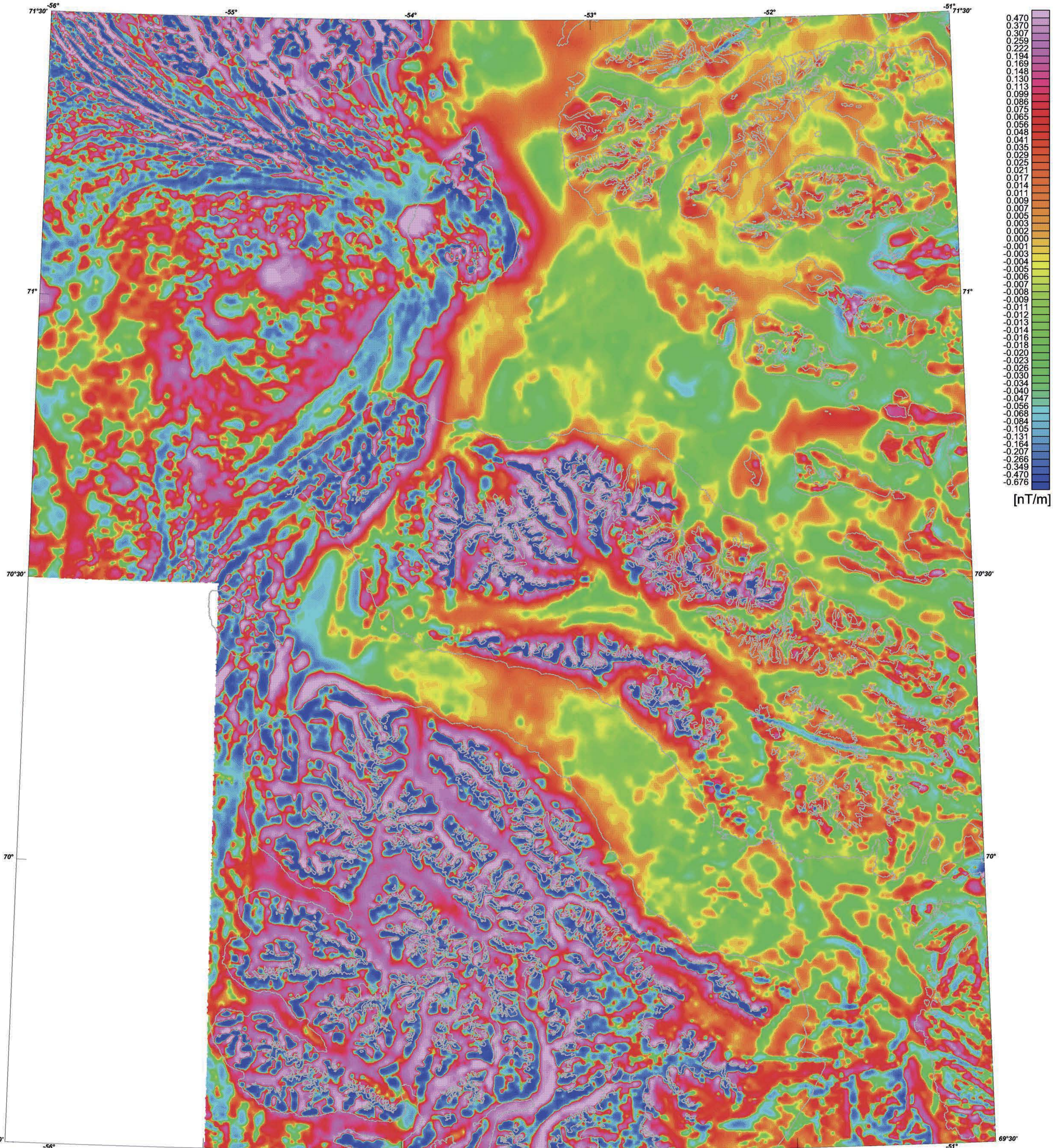
Enclosure 4

Scale 1 : 500 000

5000 0 5000 10000 15000

metres

WGS 84 / UTM zone 22N



Vertical gradient of magnetic total field

Data from projects Aeromag 1997 and Aeromag 2001

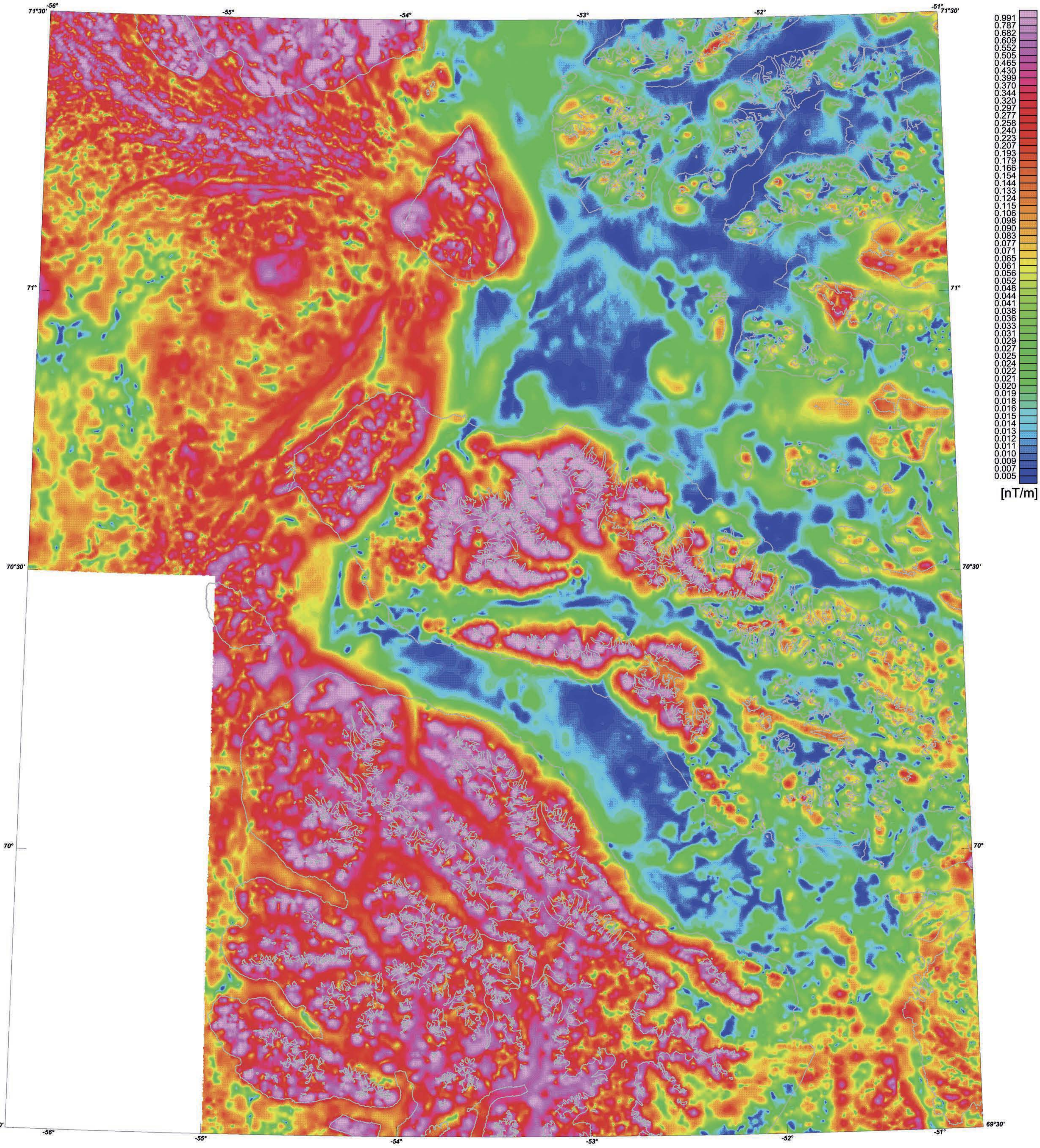
Enclosure 5

Scale 1 : 500 000

5000 0 5000 10000 15000

metres

WGS 84 / UTM zone 22N



Scale 1 : 500 000

5000 0 5000 10000 15000

metres

WGS 84 / UTM zone 22N

Analytic signal of magnetic total field

Data from projects Aeromag 1997 and Aeromag 2001

Enclosure 6