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Report 97.112

Magnetic characterisation of the Norwegian continental shelf

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REPORT

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Summary:

The purpose of the present compilation of the magnetic characteristics of the Norwegian continental shelf is to provide background data for developing a system to reduce the well-bore positional uncertainty in offshore areas. IKU Petroleum Research wants to consider the potential influence from magnetic rocks adjacent to offshore exploration and production wells. An aeromagnetic map at the scale of 1:3 million, depth to magnetic basement maps and compilation of available petrophysical data are presented. The magnetic anomaly pattern on the Norwegian continental shelf is interpreted to reflect three different types of magnetic sources; a) Magnetic basement continuing from mainland Norway below the continental shelf b) Tertiary and Permian volcanic rocks c) Subcropping and buried sedimentary units of late Palaeozoic, Mesozoic, Tertiary or Quaternary age causing low amplitude, high frequency anomalies. The latter is only seen in modern, high-sensitivity data. The depth to magnetic basement estimates indicate a general depth of 7-10 km under the basins of the Norwegian continental shelf. The magnetisation of the basement decreases to zero at a depth of approximately 20 km where the rocks reach the Curie temperature for magnetite (580°C). We conclude from available petrophysical data that the volcanic rocks in the sedimentary basins are the most important contributor to inaccuracy in the positioning of offshore wells. The magnetic basement is in most cases several kilometres deeper than the reservoirs of interest to the petroleum industry and their influence will therefore be relatively small. The magnetisation of the sediments within the basins are one to two orders of magnitude lower than the magnetisation of basement rocks and volcanics.

Keywords: Geofysikk	Kontinentalsokkel	
Petrofysikk	Boring	
Magnetometri		Fagrapport

CONTENTS

1. INTRODUCTION

The purpose of the present compilation of the magnetic characteristics of the Norwegian continental shelf is to provide background data for developing a system to reduce the well-bore positional uncertainty in offshore areas. Russell *et al.* (1995) have developed a system to include variations in the geomagnetic field (measured close to the well site) in the corrections of calculations of the well positions. IKU Petroleum Research wants in addition to consider a potential influence from magnetic rocks in the vicinity of the wells.

The Geological Survey of Norway (NGU) possesses digital aeromagnetic and petrophysical data from the mainland and continental shelf of Norway. These data-sets are traditionally used for interpretation of basement topography and intra-sedimentary volcanics. These data may, however, also be utilised to reduce the well-bore positional uncertainty in offshore wells.

The aeromagnetic maps show that the basement on the mainland are continuous to the offshore sedimentary basins. Petrophysical data on hand specimens from the Norwegian mainland can therefore be utilised to estimate the magnetic properties of the offshore basement rocks.

The high quality of the aeromagnetic data acquired by NGU in recent years also provides the possibility to map high frequency anomalies caused by magnetic sources within the sedimentary sequences. This improved quality is due to the use of (1) state of the art towed bird magnetometers, (2) real time differential GPS navigation equipment, (3) denser line spacing and (4) advanced micro-levelling software.

2. DATA-SETS

2.1 Aeromagnetic data

The whole of Norway (including the largest continental shelf in western Europe) was covered with aeromagnetic surveys from 1959 to 1976. NGU launched a program for remapping the continental shelf in 1989, applying a line spacing of 2 km, with plans to make a complete coverage within 15 years. The resolution of the modern aeromagnetic data is 0.1-0.2 nT. The incorporation of petrophysical data generally leads to more precise quantitative analysis, and reduces the inherent ambiguity in the interpretation of potential field data.

Aeromagnetic data collected prior to 1976 are provided in the form of a matrix digitised from manually drawn contour maps. Flight altitudes, flying directions, and line-spacings of the the aeromagnetic surveys varied widely. The line spacings were smallest over mainland Norway (0.5-2.5 km), intermediate over the continental shelf (3-8 km) and largest over deep oceanic area in the Norwegian and Greenland Seas (10-15 km). Inaccuracy in navigation affects the continuity of some sea floor spreading anomalies. The areas of low flight altitude of mainland Norway (150m-300m) were covered between 1959 and 1968 using a fluxgate magnetometer. From 1968 to 1976, a stinger-mounted proton magnetometer was used, covering western Norway and most of North Norway with measurements made at flight altitudes ranging from 800m to 1500m a.s.l. The cell size of the grid is 500m x 500m. The magnetic total field is reduced to anomaly values using the Definite Geomagnetic Reference Field 1965.0 (DGRF 1965.0).

Aeromagnetic data from the continental shelf collected prior to 1976 are also available as digital profile data (digitised from the original NGU analogue recordings by Geco). Enhancement techniques akin to those commonly used in image processing were applied to the aeromagnetic data. Histogram-equalisation and shaded-relief presentation have been used as standard techniques in the map production of Plate 1.

2.2 Depth to magnetic basement

Previously published maps of depth to magnetic basement from all of the Norwegian continental shelf are shown in Figs. 2.1. - 2.7 from the Norwegian Basin in the south to Spitbergen in the north (Hospers *et al.* 1986, Hospers & Ediriveera 1991, Åm 1970, 1975, Skilbrei 1991, 1992, 1995). Different methods, both automatic inversion methods and manual graphical methods were utilised in the different studies and are described in the respective papers. The depth estimates of the sedimentary basins varies between 5 and 16 kilometres.

2.3 Petrophysical data

Some of the magnetic anomalies within the Norwegian continental shelf are continuous from land onto the continental shelf. It is therefore important to know the magnetic properties of the rocks on land when assessing the potential magnetic influence from basement rocks on well-bore positional uncertainty. NGU has earlier carried out petrophysical sampling programmes (including susceptibility and remanence measurements) in northern Norway (Olesen *et al.,* 1990, 1991, 1997) and southern Norway (Sindre, 1977, Åm & Oftedal 1977, Skilbrei 1988, Skilbrei *et al.* 1991, McEnroe *et al.* 1996). Q-values (Königsberger ratios), the ratios of remanent to induced magnetisation (the product of susceptibility and the earth's magnetic field strength), are reported in Tables 2.1-2.3 rather than the intensity of the natural remanent magnetisation (NRM). The susceptibility can locally be high and the directions of the NRM are mostly dominated by a viscous component (close to the present earth field direction), especially in acidic and intermediate igneous rocks such as granites and ortho-gneisses. Mafic and ultramafic rocks often show a more stable remanence such as the norites from the Sveconorwegian Rogaland Igneous Complex which show negative inclination (McEnroe et al. 1996 and Table 2.1).

Susceptibility measurements on the Eocene volcanics from the Vøring Basin were reported by Eldholm *et al.* (1987) and Kent & Opdyke (1978) and listed in Table 2.2. These rocks are the most magnetic within the sedimentary basins on the Norwegian continental shelf and continental margin. They reveal a high remanence intensity with alternating positive and negative directions (field reversals). Field reversals recorded in remanent magnetisations also cause the characteristic stripes over the oceanic crust in the Norwegian Sea to the west (Plate 1). The NRM-directions carried by Permian volcanics as measured in the Oslo Rift by Thorning & Abrahamsen (1980) and Torsvik (in prep.), are characterised by a viscous component (close to the present earth field direction) and by a flatlying, slightly upward Permian direction (Table 2.2). The thickness of the volcanic flows and sills varies from a few metres (Permian volcanics in the Norwegian-Danish Basin) to more than 1000 metres (Eocene volcanics in the western part of the Vøring Basin). Fig. 2.8 shows a map (Latin *et al.* 1990) of wells penetrating Mesozoic and Lower Permian igneous rocks in the North Sea rift system.

Relatively few susceptibility data for sedimentary rocks of the Norwegian continental shelf are published. Hauger & van Veen (1995) and Løvli & van Veen (1995) have reported magnetic studies of the Brent Formation sandstones. This formation is, however, dominated by a pure quartz-bearing high-quality reservoir sandstone with low susceptibility. We do, however, anticipate finding parts of the sediments to be as magnetic as in other basin areas of similar age. We have therefore included data on Fe-Ti oxide- and siderite-bearing Cretaceous sediments from the North Slope Basin in Alaska (Table 2.3) published by Reynolds *et al.* (1994). The thickness of these layers varies generally from a decimetres to a few tens of metres. We think that these rocks are representative of magnetic units within the stratigraphical column of the Norwegian continental shelf.

Table 2.1 Magnetic properties of basement rocks from the coastal part of mainland Norway. Declination (Dec.) and inclination (Inc.) of the natural remanent magnetisation (NRM) are reported from some of the locations. No - number of samples.

Rock type	Location	No.	Suscept.	Q-value	NRM Dec./Inc.	Reference
Greenstone	Alta-Kautokeino	698	0.003	0.21		Olesen et al. 1990
Gabbro	Seiland	78	0.019	0.71		Olesen et al. 1990
Gneiss	Senja, Kvaløya	500	0.005	0.59		Olesen et al. 1997
Gneiss	Vesterålen	153	0.021	0.27	2/81 (n=11)	Olesen et al. 1991
Gneiss	Roan, Fosen Peninsula	66	0.023	0.25	348/74 (n=10)	Skilbrei et al. 1991
Gabbro	Smøla	11	0.020			Sindre 1977
Norite	Tellnes, Rogaland	191	0.037	7.3	293/-64 (n=32)	McEnroe *et al.* 1996

Table 2.2 Magnetic properties of Tertiary volcanics from the Norwegian continental margin and Permian volcanics on the mainland of southern Norway. Declination (Dec.) and inclination (Inc.) of the natural remanent magnetisation (NRM) are reported from some of the locations.

Rock type	Location	No.	Mean Suscept.	Q-value	NRM Dec./Inc.	Reference
Basalt	Bærum	20	0.072	0.3		Åm & Oftedahl 1977
Basalt	Vestfold	42	0.067	0.8		Åm & Oftedahl 1977
Basalt	Skien	60	0.109	1.3		Åm & Oftedahl 1977
Diabase	Bohuslän	6	0.068	0.66	181/-6 (n=5) 264/81 (n=1)	Thorning & Abrahamsen 1980
Diabase	Tvedestrand	15	0.015	2.7	216/-27(n=15)	Torsvik in prep.
Basalt	Vøring Basin (site 338)	7	0.016	4.8	?/70.4	Kent & Opdyke 1978
Basalt	Vøring Basin (site 342)	3	0.015	2.3	? /-81.0	Kent & Opdyke 1978
Basalt	Vøring Basin (site 642)	221	0.030	4.1	? /-63.0	Eldholm et al. 1987

Table 2.3 Magnetic properties of sedimentary rocks from the continental shelf offshore Norway and Alaska.

Rock type	Location	No.	Suscept.	Q-value/ NRM-intensity	Reference
Sandstone	Brent Formation, Viking Graben	162	0.00013	0.20 0.001 A/m	Løvlie & van Veen 1995, Hauger & van Veen 1995
Fe-Ti oxide-bearing sandstone	Simpson Peninsula, Alaska, Cretaceous units	4	0.00140	0.07 0.004 A/m	Reynolds *et al.* 1994
Siderite-bearing mudstone	Simpson Peninsula, Alaska, Cretaceous units	4	0.00240	0.02 0.002 A/m	Reynolds *et al.* 1994

3. DISCUSSION AND CONCLUSIONS

The magnetic anomaly pattern on the Norwegian continental shelf is interpreted to reflect three different types of magnetic sources; a) Magnetic basement continuing from mainland Norway below the continental shelf b) Tertiary and Permian volcanic rocks and c) Subcropping and buried sedimentary units of late Palaeozoic, Mesozoic, Tertiary or Quaternary age causing low amplitude, high frequency anomalies. The latter is only seen in modern, high-sensitivity data.

Depth to magnetic basement estimates indicate a general depth of 7-10 km in the basins of the Norwegian continental shelf. The magnetic anomaly pattern indicates a complex system of fault blocks along some of the basin margins. The depth estimates in the shallower parts of the shelf are to a great extent consistent with what is known from exploration drilling. We expect that the magnetisation of the basement decreases to zero where the rocks reach the Curie temperature (580°C) at a depth of approximately 20 km for magnetite. This estimate is based on measured geothermal gradients in continental crust elsewhere (Kanestrøm 1980).

We anticipate that the volcanic rocks within the sedimentary column will be the most important contributor to inaccuracy in the positioning of offshore wells, especially where these units are penetrated by the well. The magnetic basement will in most cases be several kilometres deeper than the reservoirs of interest to the petroleum industry and their influence will therefore be relatively small. The magnetisation of the sediments within the basins are one to two orders of magnitude lower the magnetisation of basement rocks and volcanics.

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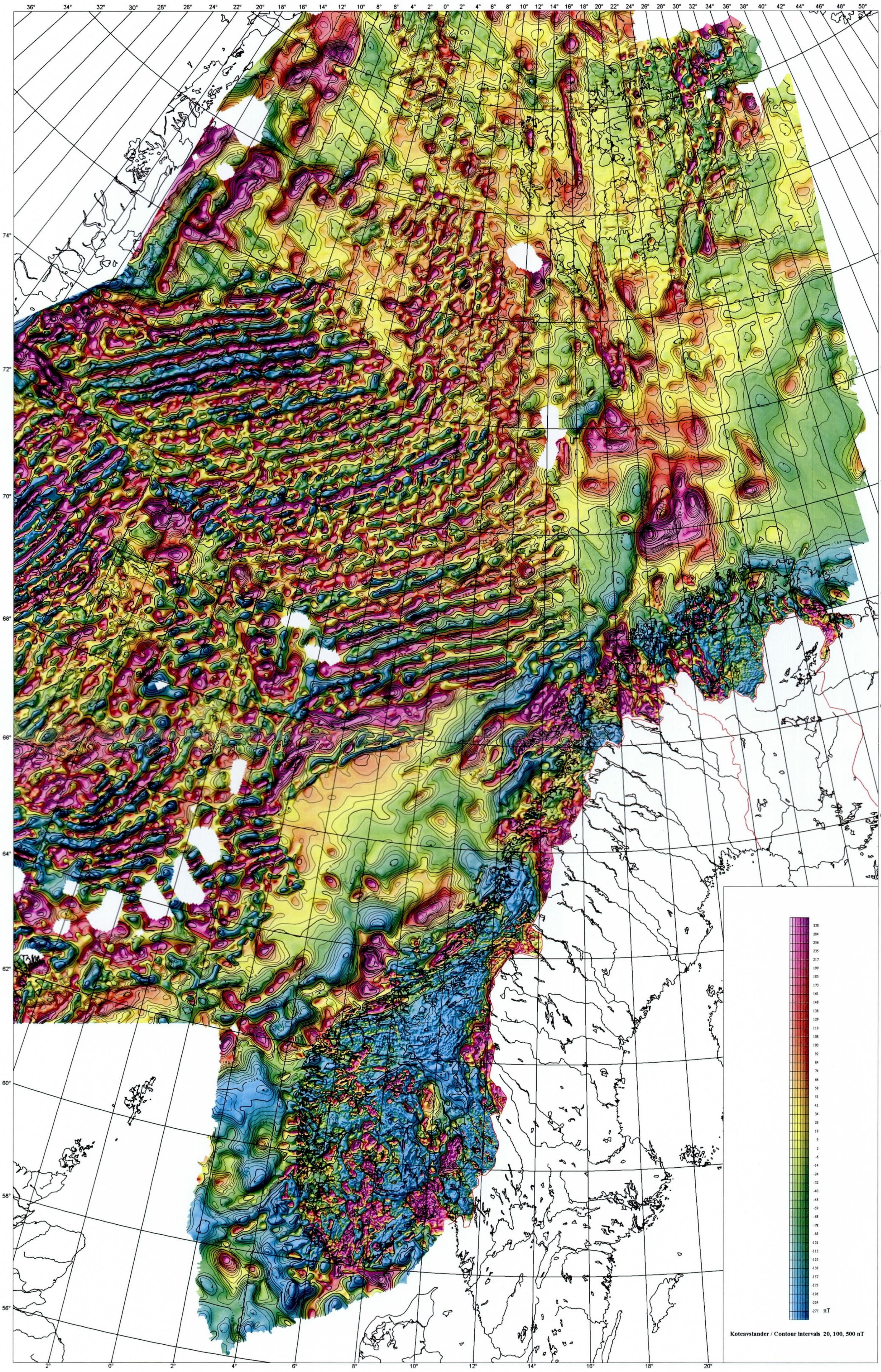
List of figures and tables

Appendix,

Aeromagnetic data from the Geological Survey of Norway

Digital geophysical data sets		Price
1. Aeromagnetic data, Norway 500mx500m grid,	NOK	120.000
2. Aeromagnetic data, Norway and adjacent sea areas (North Sea, Norwegian Sea and southern Barents Sea) 1kmx1km grid,	"	400.000
Reduced price for companies which have already acquired the offshore profile data	"	200.000
3. Aeromagnetic profile data, southern Barents Sea , 55,000 km	"	240,000
4. Aeromagnetic profile data, Mid Norwegian shelf, 68,000 km	"	370,000
5. Aeromagnetic profile data, Norwegian North Sea, 43,000 km	"	280,000
6: Aeromagnetic profile data, Nordland VI - VII areas, (LAS-89), 30,000 km	"	500,000
7: Aeromagnetic profile data, Nordland I - V areas, (NAS-94), 36,000 km	"	1.080,000
8: Aeromagnetic profile data, northern Viking Graben, (Viking-93), 28,000 km	"	700,000
9: Aeromagnetic profile data, southeastern North Sea, (SAS-96), 43,000 km	"	600,000

Aeromagnetic maps at a scale of 1:250,000, 1:500,000 and 1:1 mill. are also available. NGUs map catalogue provides information on the maps.



MAGNETISK ANOMALIKART

NORGE MED HAVOMRÅDER

MAGNETIC ANOMALY MAP NORWAY AND ADJACENT OCEAN AREAS

FORELØPIG UTGAVE / PRELIMINARY VERSION

Målestokk / Scale 1 : 3 million

50 0 50 100 150 200 (kilometers)

Kartbeskrivelse

Kartområdet dekker fastlands-Norge, Svalbard, deler av Nordsjøen, Norskehavet Grønlandshavet, og vestlige deler av Barentshavet. Kartet er sammensatt hovedsaklig av flymagnetiske data i tillegg til noen marine magnetiske data i vestlige deler av Norskehavet. Flyhøyde, profilretning og profilavstand til de flymagnetiske målingene varierer mye (se indekskart). Profilavstanden er minst over fastlands-Norge (0.5-2.5 km), middels over kontinentalsokkelen (3-8 km) og størst over de store havdyp i Norskehavet og Grønlandshavet (10-15 km). Unøyaktigheter i navigasjonen har derfor medført at forløpet av enkelte spredningsanomalier i sistnevnte område er noe usikker. Fjellområdene med ujevn topografi på Vestlandet, i Nord-Norge og på Svalbard er målt på konstant barometrisk høyde (800, 1000 og1500 m) mens det i de øvrige områdene på fastlands-Norge er fløyet med konstant terrengklaring (150 og 300 m). Magnetfeltet er ikke omregnet til en felles flyhøyde.

De flymagnetiske data fra fastlands-Norge og kontinentalsokkelen er basert på et 500x500 m rutenett interpolert fra digitaliserte håndkonturerte kart. Digitale magnetiske profildata fra det nordlige Barentshavet og Svalbard er interpolert til et regulært 1x1 km rutenett med 'minimalisering av flatekurvatur'-metoden. Et 5x5 km grid sammenstilt av Geological Survey of Canada er interpolert til 1x1km celler for å fylle inn de gjenværende områder i Norskehavet og Grønlandshavet. Cellestørrelsen på det sammenslåtte datasettet er 1x1km. Anomalikartet er beregnet ved å trekke det globale referansefeltet DGRF 1965.0 (Definite Geomagnetic Reference Field 1965.0) fra det magnetiske totalfeltet. På det endelige kartet dekker hver farge i fargeskalaen tilnærmet samme areal på kartet. En pseudo-relieff teknikk med 'belysning' fra sørøst er også benyttet. Denne type kart framhever lineasjoner og kontraster som ikke er så lett synlige på konvensjonelle konturkart.

Dette kartet er utgitt i samme målestokk og utsnitt som det berggrunnsgeologiske kartet over Norge med havområder (Sigmond 1992). Det er planlagt å publisere gravimetrisk og neotektonisk kart over samme område.

Map Description

The mapped area includes mainland Norway, Svalbard, part of the North Sea, the Norwegian Sea, the Greenland Sea and the western Barents Sea. Sources of magnetic data include mostly total-intensity airborne measurements and some additional shipborne measurements in the western part of the Norwegian Sea (see index map). Flight altitudes, flying directions, and line-spacings of the aeromagnetic surveys varied widely. The line spacings were smallest over mainland Norway (0.5-2.5 km), intermediate over the continental shelf (3-8 km) and largest over deep oceanic area in the Norwegian and Greenland Seas (10-15 km). Inaccuracy in navigation affects the continuity of some sea floor spreading anomalies. The mountainous areas with rough topography in western and northern Norway and on Svalbard were flown at a constant barometric height (800, 1000 and 1500 m) while the remaining areas of mainland Norway were drape-flown (150 and 300 m altitude). No attempt was made to transform magnetic-anomaly data to a common altitude.

The aeromagnetic data from mainland Norway and the Norwegian continental shelf are based on a 500x500 m grid interpolated from digitised hand-drawn contour maps. Digitally recorded aeromagnetic data covering Svalbard and the northwestern Barents Sea were merged and interpolated to a 1x1 km grid using the minimum curvature method. A 5x5 km grid compiled by the Geological Survey of Canada from various sources was re-gridded to fill in the remaining parts of the Norwegian and Greenland Seas. After some level adjustments the grids were combined into a single grid with 1x1km cells. The magnetic total field was reduced to anomaly values by using the Definite Geomagnetic Reference Field 1965.0 (DGRF 1965.0). The final map was produced using the equal-area colour scale and the pseudo-relief technique with 'illumination' from the southeast. This type of map enhances lineations and contrasts not easily discernible in the conventional contour maps.

The present map covers the same area as the Bedrock Map of Norway and Adjacent Areas (Sigmond 1992). There are plans to produce gravity and neotectonic maps from the same area.

Dette kartet kan bestilles fra:
Norges geologiske undersøkelse, P.Boks 3006, N-7002 TRONDHEIM

This map can be obtained from:
Geological Survey of Norway, P.O.Box 3006, N-7002 TRONDHEIM

Referanse til kartet : Olesen, O., Brækstad, G., Gellein, J., Håbrekke, H., Kihle, O., Skilbrei, J.R. and Smethurst, M.A. 1997: Magnetisk anomalikart, Norge med havområder. Målestokk 1:3 million, Norges geologiske undersøkelse.

Reference to the map: Olesen, O., Brækstad, G., Gellein, J., Håbrekke, H., Kihle, O., Skilbrei, J.R. and Smethurst, M.A. 1997: Magnetic anomaly map, Norway and adjacent ocean areas. Scale 1:3 million, Geological Survey of Norway.

Kartgrunnlag
Reprografi
Trykk

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Andre bidragsytere (Other contributors):
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Fairey Survey: datainnsamling Viking Graben (data acquisition Viking Graben)
Geco: prosessering nordlige Barentshavet og sørvestlige Svalbard (processing northern Barents Sea and southwestern Svalbard)
Geological Survey of Canada: prosessering dyphavområdene i Norskehavet og Grønlandshavet (processing deep oceanic areas of the Norwegian and Greenland Seas)
Sevmorgeo: datannsamling nordlige og østlige Svalbard og nordøstlige Barentshavet (data acquisition northern and eastern Svalbard and northeastern Barents Sea)
Naval Research Laboratory: datainnsamling dyphavsområdene i Norskehavet og Grønlandshavet (data acquisition deep oceanic areas of the Norwegian and Greenland Seas)

Plate 1

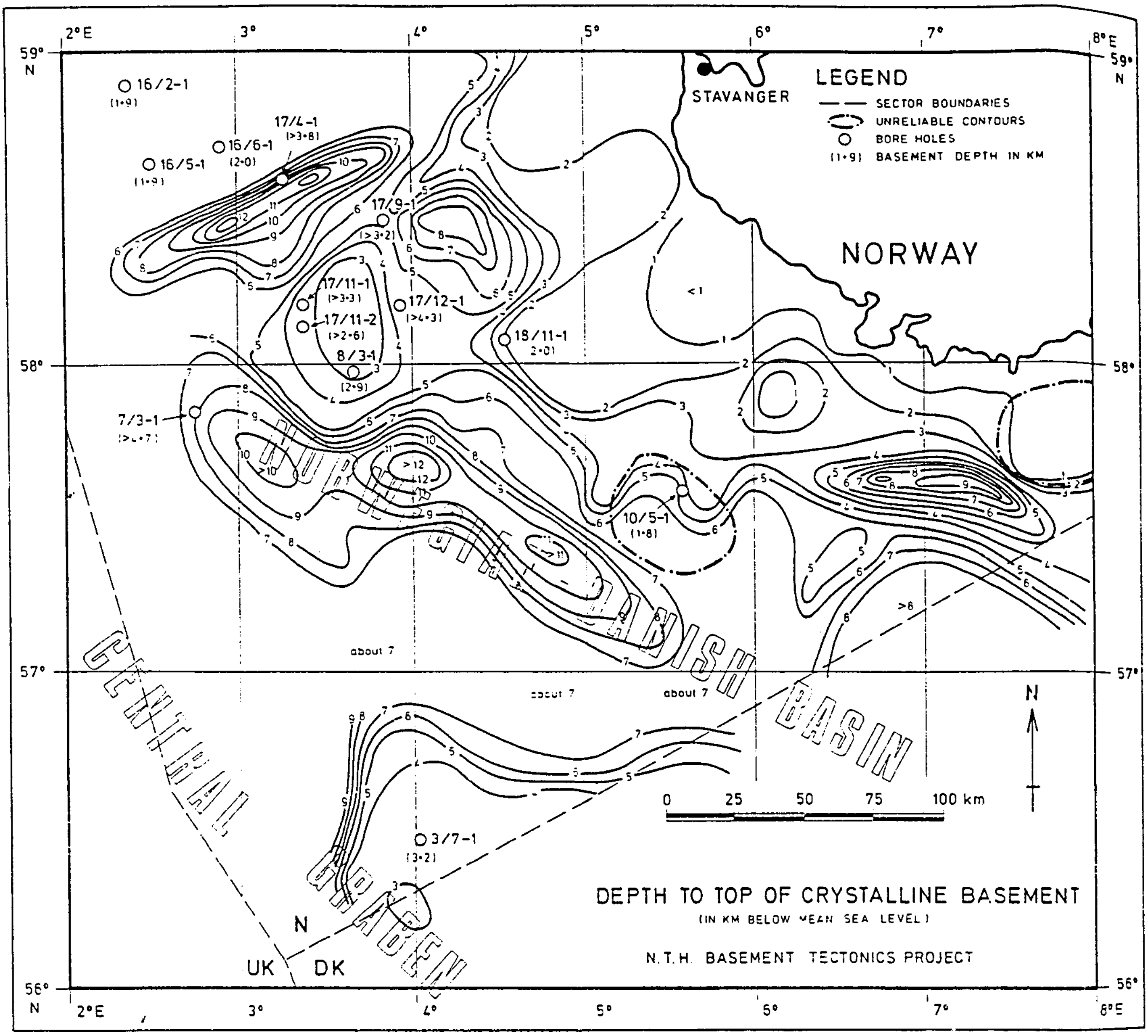

Fig. 2.1 Depth to magnetic basement interpretation map, Norwegian-Danish Basin (Hospers & Rathore 1984, Hospers *et al.* 1986).

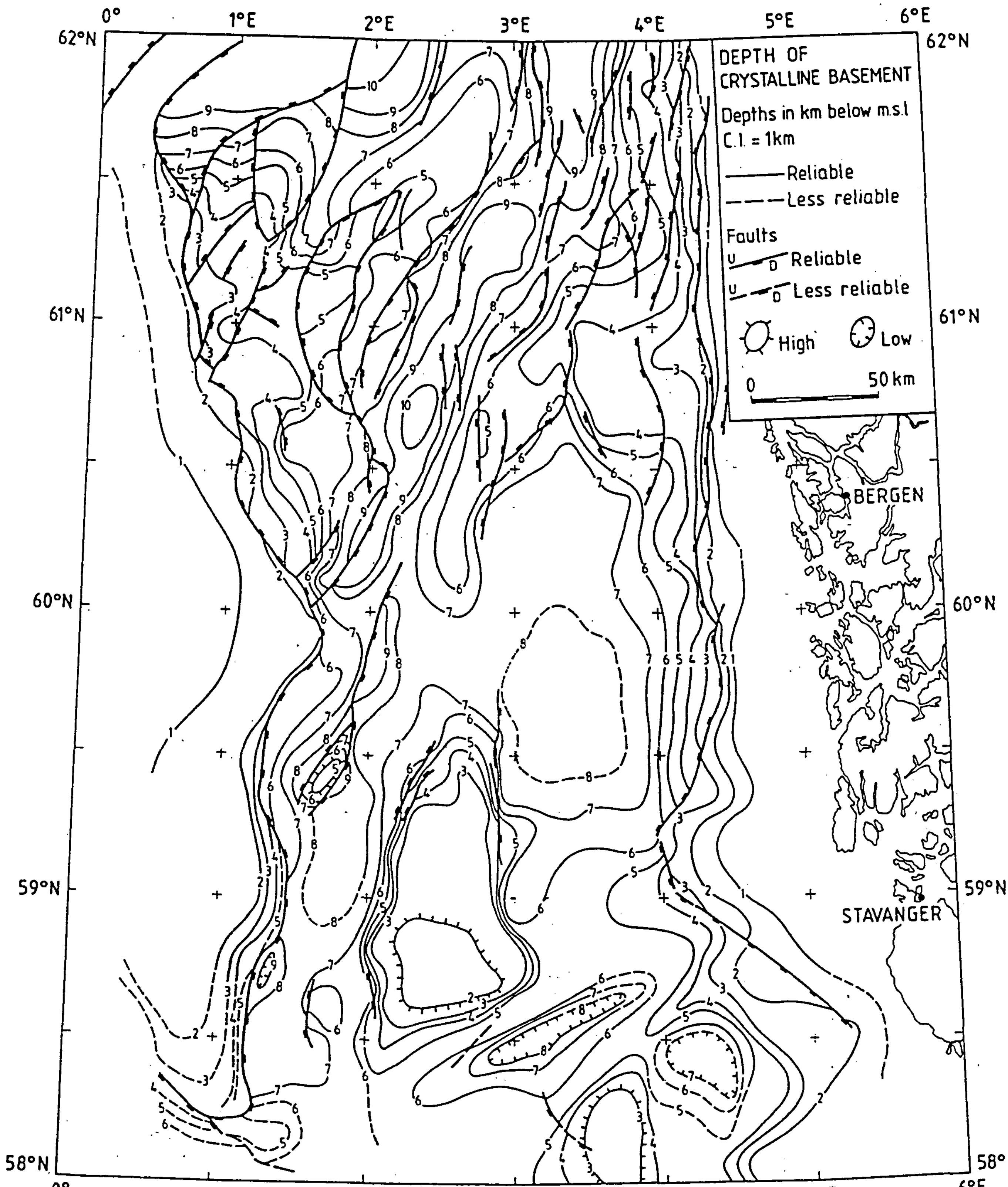

Fig. 2.2 Depth to magnetic basement interpretation map, northern North Sea (Hospers & Ediriweera 1991).

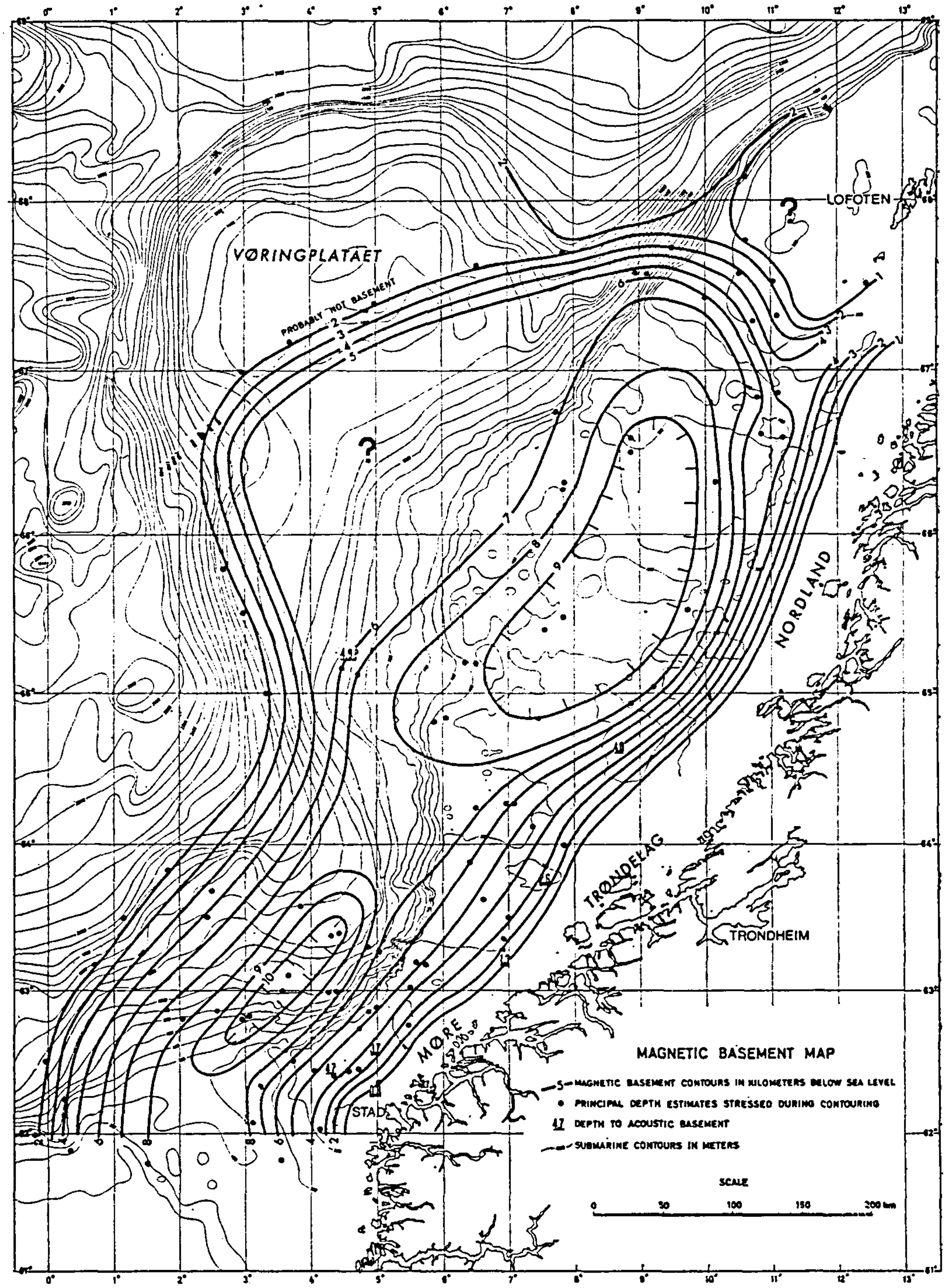

Fig. 2.3 Depth to magnetic basement interpretation map, Norwegian Sea (Åm 1970).

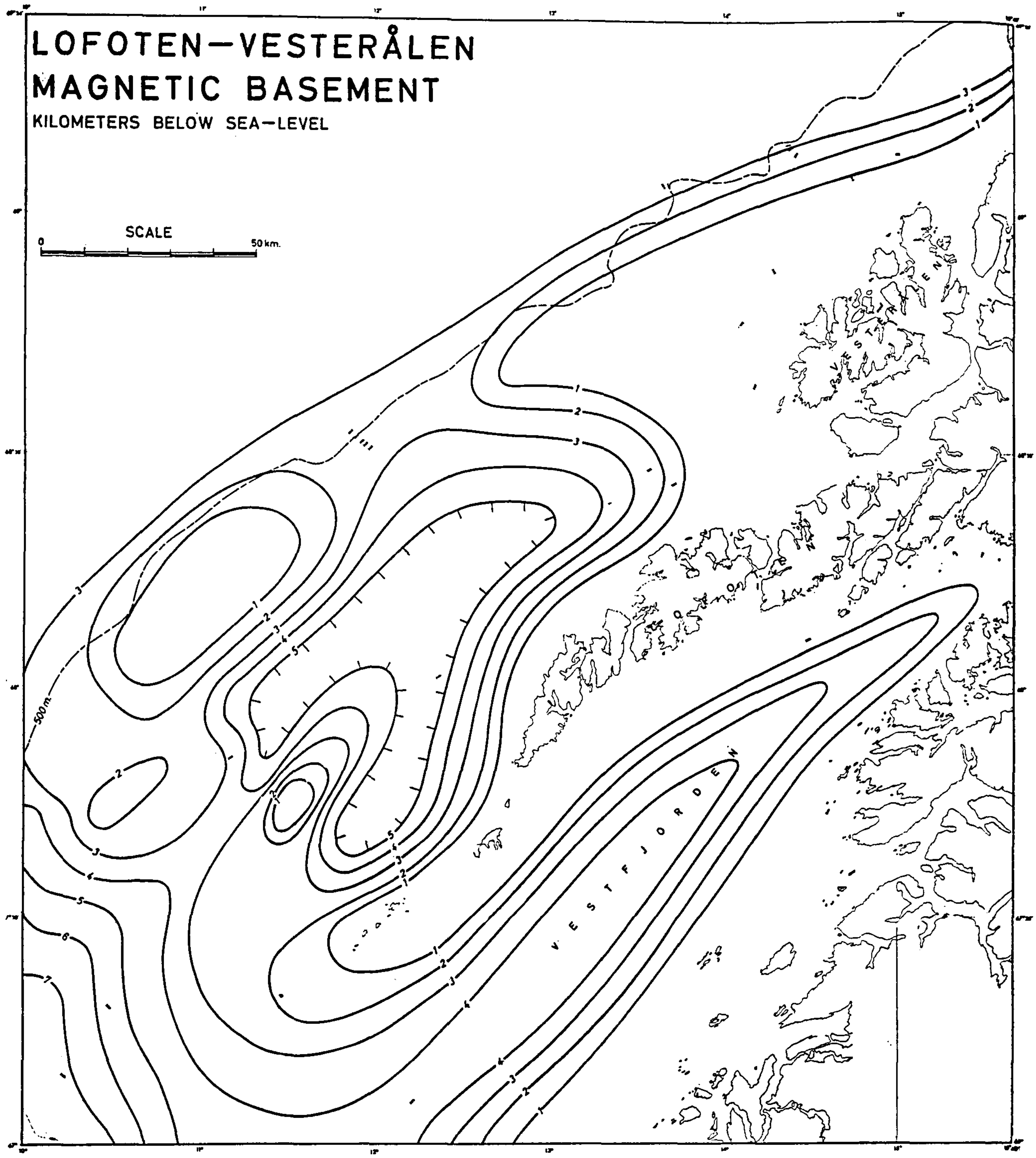

Fig. 2.4 Depth to magnetic basement interpretation map, Lofoten area (Åm 1975).

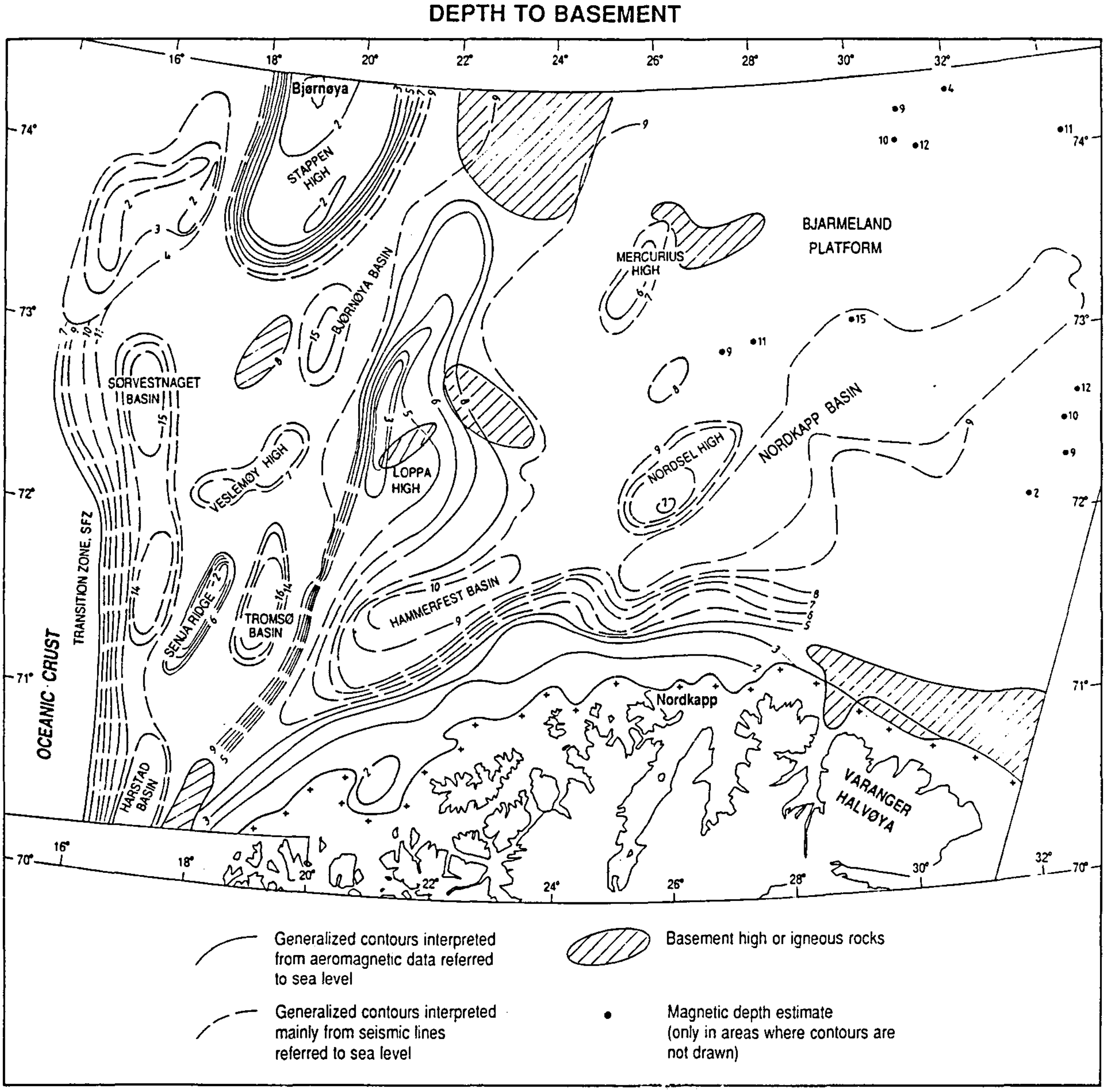

Fig. 2.5 Depth to magnetic basement interpretation map, southern Barents Sea. (Skilbrei 1995).

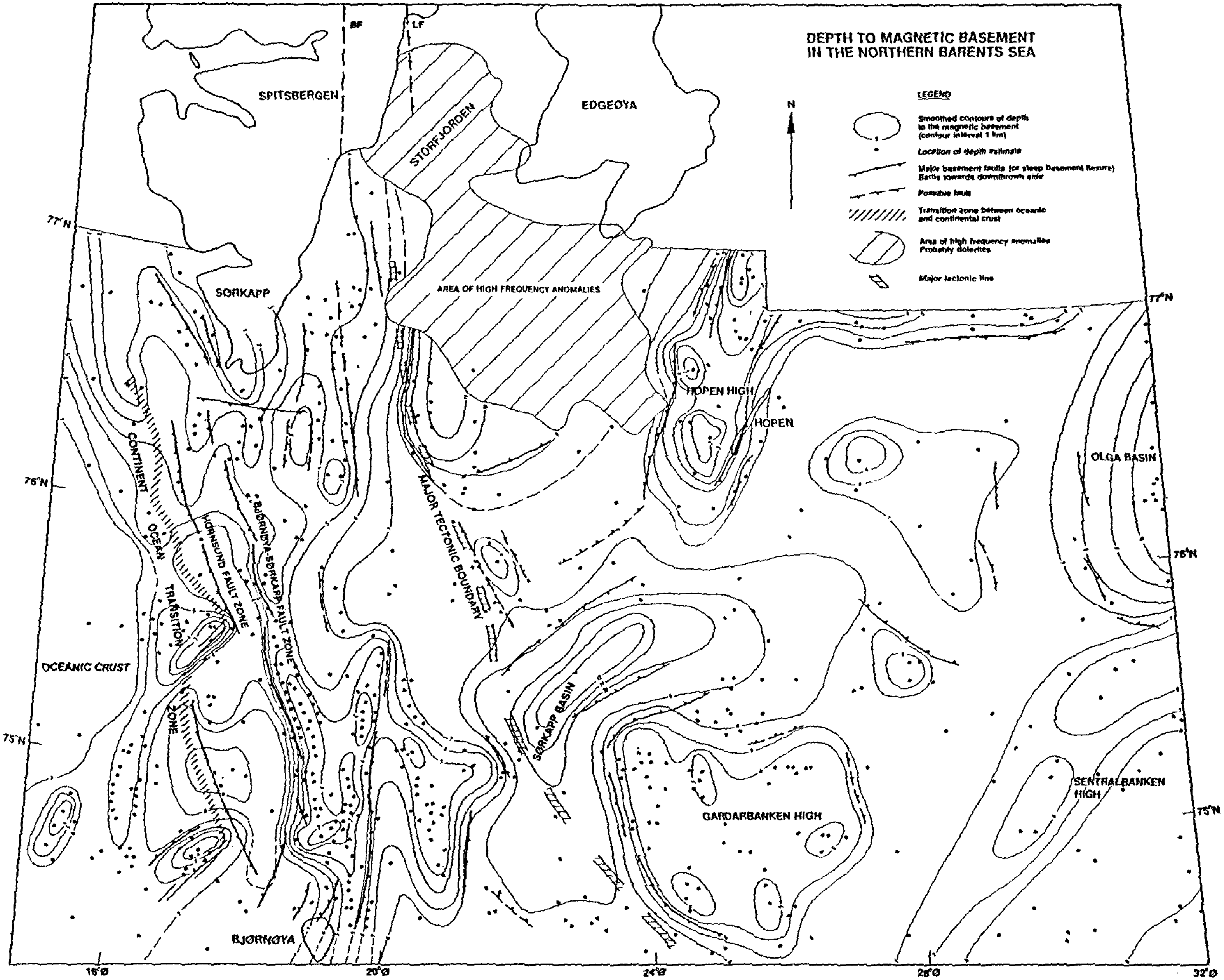

Fig. 2.6 Depth to magnetic basement interpretation map, northern Barents Sea (Skilbrei 1991).

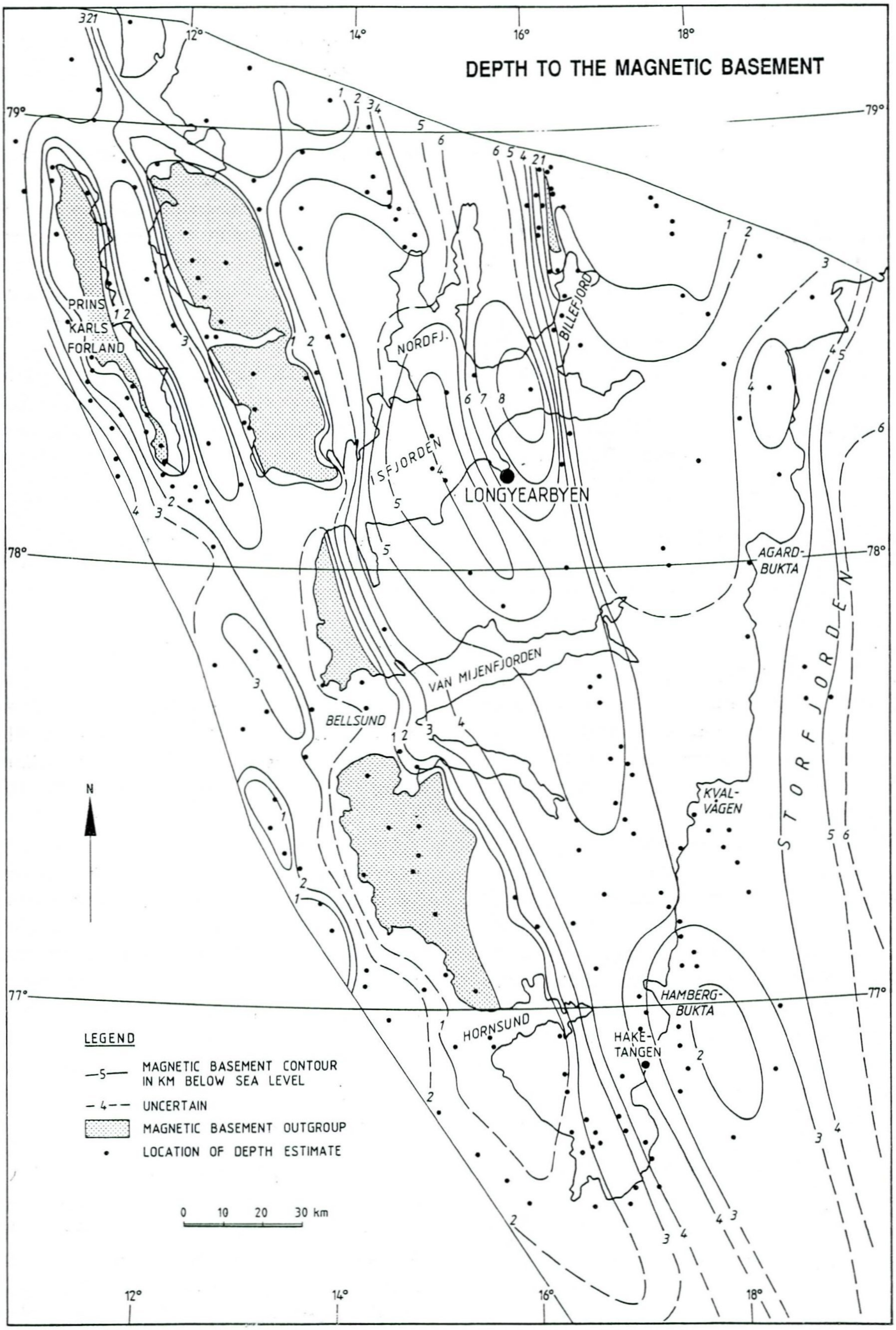

Fig. 2.7 Depth to magnetic basement interpretation map, Spitbergen (Skilbrei 1992).

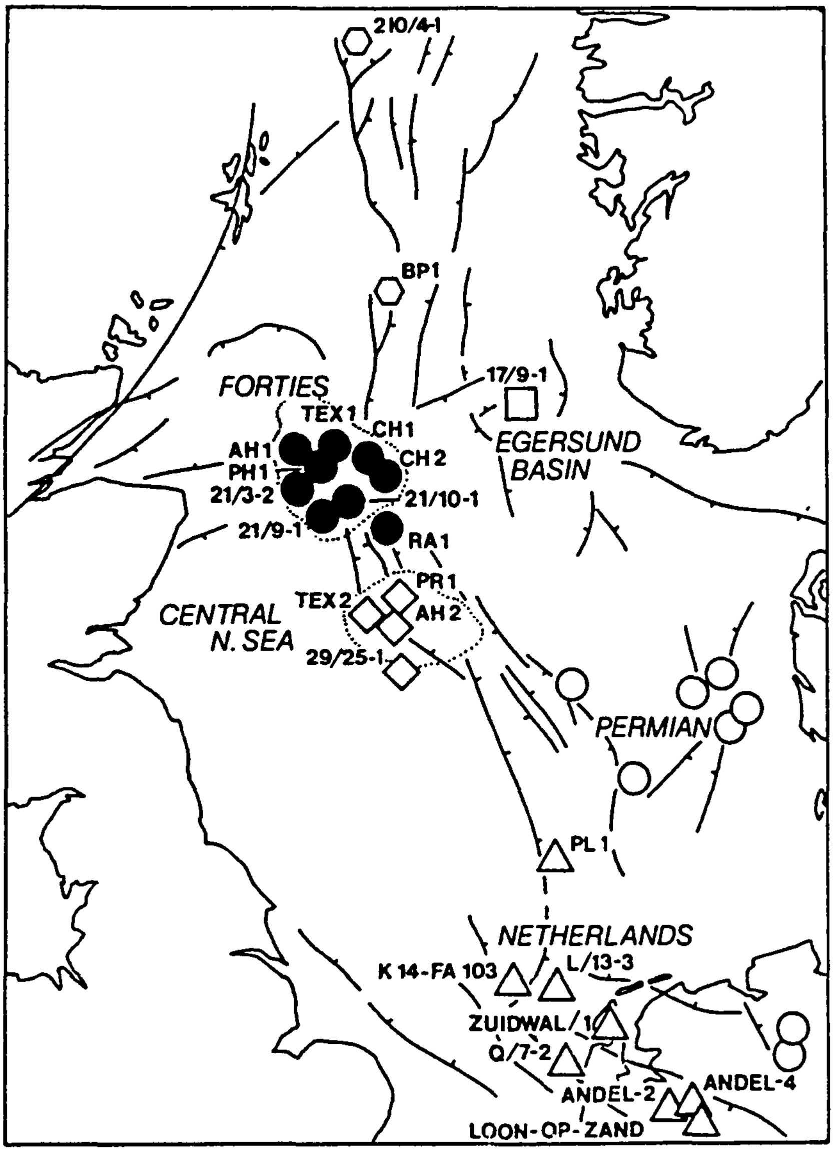

Fig. 2.8 Location of Mesozoic and Lower Permian igneous rocks in the North Sea rift system. Labels correspond to well locations, but some wells are unreleased and so are given code names.
● Forties Province rocks; ◇ Central North Sea Mesozoic rocks; ⬡ Viking Graben occurrences; △ Netherlands on-shore and off-shore Mesozoic rocks; ○ Permian occurrences. (Latin *et al.* 1990).