Report 93.129

The Lofoten - Lopphavet Project - an integrated approach to the study of a passive continental margin, Summary report

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REPORT

Report no. 93.129	ISSN 0800-3416	Grading: Confidential to 2000

Title:
The Lofoten-Lopphavet Project - an integrated approach to the study of a passive continental margin, Summary report

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County: Nordland and Troms	Commune:
Map-sheet name (M=1:250.000) Bodø, Svolvær, Narvik, Andøya, Tromsø, Nordreisa, Helgøy and Hammerfest	Map-sheet no. and name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 54 Price: Map enclosures: 1

Fieldwork carried out:	Date of report:	Project no.:	Person responsible:
1991 - 1993	22.12.93	61.2574.00	[signature]

Summary:

An integrated study of geophysical and geological data from the offshore and onshore areas of northern Norway between 67°N and 71°N was carried out as a collaboration project between Elf Petroleum, Norsk Hydro, the Norwegian Petroleum Directorate, Statoil and the Geological Survey of Norway. The interpretation of aeromagnetic, gravimetric and petrophysical data was integrated with mapping and palaeomagnetic dating of post-Caledonian faults on land.

Most of the magnetic and gravity anomalies within the shelf area have been interpreted in terms of a complex series of uplifted and rotated basement blocks. Some of the basement highs were not previously identified from seismic data since they lie below flow basalts. Gravity modelling indicates that the Lofoten - Vesterålen islands constitute two basement highs within the rifted and thinned crust of the continental shelf. An axis of late elevation runs NW-SE across Vesterålen to the Jenegga High, resembling an accommodation zone between the Ribban-Vestfjorden Basins to the southwest and the Harstad Basin to the northeast. Opposing slip directions of faults in the Vesterålen area may be related to this 'accommodation tectonics'. The Vestfjorden Basin consists of two sub-basins or half grabens; one to the north with a boundary fault to the east and one to the south with a boundary fault to the west. To the west of the Bodø High, and northwards along the shelf edge, there is a continuous zone of high frequency anomalies interpreted as the eastward termination of intrasedimentary volcanic rocks.

On-shore geological mapping in the coastal region from Lofoten to Loppa shows that rocks in the lineament-zones have suffered both ductile and brittle deformation. The senses of relative movements are indicated in some places; mainly dip-slip. Several basement faults on the continental shelf can be traced onto the mainland. Reactivation of old shear zones is commonly observed. The Senja Fracture Zone represents a reactivation of the Proterozoic Bothnian-Senja Shear Zone.

A palaeomagnetic study was carried out in Vesterålen, Senja and Kvaløya in order to furnish temporal constraints on near-shore fault-activity in the Lofoten area. At Senja and Kvaløya, two phases of faulting and brecciation were identified. A young phase, associated with the formation of fault-gouges, is recent/Tertiary in origin, whereas an older phase, associated with brecciation, is of Permian age. There may have been a narrowing zone of rifting and a consequent westward shift of the regional fault activity on the Nordland shelf and coastal area from the Carboniferous-Permian to the late Jurassic-early Cretaceous and Tertiary.

Keywords: Geofysikk	Gravimetri	Kontinentalsokkel
Berggrunnsgeologi	Magnetometri	Forkastning
Petrofysikk	Tolkning	Fagrapport

CONTENTS

1 INTRODUCTION

The Lofoten - Lopphavet Project is a collaborative project between Elf Petroleum, Norsk Hydro, the Norwegian Petroleum Directorate, Statoil and the Geological Survey of Norway. The survey area extends from 67° to 71°N and from the oceanic crust to the west (spreading anomaly 22) eastward to the Swedish border. This shelf area consequently lies between the traditional active petroleum exploration areas in the Norwegian Sea to the south and the Barents Sea to the north and is not yet opened for petroleum exploration. The geological knowledge of this area is therefore relatively limited compared with the above-mentioned regions to the north and the south.

The project is organized within four subprojects:

1) Interpretation of aeromagnetic and gravimetric data

2) Geological mapping of faults on land

3) Palaeomagnetic dating of faults

4) Analysis of remote sensing data from the Vesterålen area

The four projects were reported separately; 1) Olesen & Torsvik 1993 and Gundersen & Olesen 1992, 2) Tveten & Zwaan 1993, 3) Torsvik & Olesen 1993 and 4) Bax 1993. The present report summarises the main results from the project. New palaeomagnetic data based on last summers field work is included in the present report.

Studies of potential field data provide an aid to the geological mapping of both onshore and offshore areas. On-shore bedrock-mapping has the purpose of giving supplementary information about the faults in the actual segment of the coast. A further objective of the fieldwork carried out during this project was collect samples for palaeomagnetic study, and to supply the petrophysical laboratory with representative sample material and *in situ* susceptibility measurements. The palaeomagnetic method is applied to date fault rocks and study the regional tectonics.

2 GEOLOGICAL SETTING

The basement rocks of the Lofoten-Lopphavet area are dominated by Precambrian polymetamorphic high-grade migmatitic gneisses and intrusives; of intermediate composition to the south and granitoid composition to the north (Griffin et al. 1978, Tveten 1978, Zwaan in prep.). The age of the oldest gneisses are 2.7 GA (Griffin et al. 1978), while the large plutons of almost undeformed intrusive rocks are 1.8 Ga old. The Lofoten-Vesterålen area is a province of deep-seated origin with associated regional magnetic and gravimetric anomalies. These anomalies are believed to reflect a shallow Mohorovičić discontinuity (Svela 1971, Sellevoll 1983) and as a consequence, rocks formed in the deep crust are exposed. Gaal & Gorbatschev (1987) have interpreted these rocks to be an integral part of the Transscandinavian Granite-Porphyry Belt (TGPB) which continues to the south beneath the Caledonides all the way to southern Sweden and is characterized by regional magnetic anomalies (Henkel & Eriksson 1987). To the west of the TGPB lies the Protogine Zone (PZ) which is a continental-scale zone of deformation, and which has been reactivated several times during the Proterozoic (Larson et al. 1990). The Lofoten Lineament and the Lofoten Fracture Zone may constitute the continuation of the PZ onto the continental shelf and the oceanic crust, and may therefore represent rejuvenation of a much older zone of crustal weakness (Mokhtari & Pegrum 1992).

Two other regional shear zones within the Precambrian basement are the Bothnian-Kvænangen (Berthelsen & Marker 1986, Olesen et al. 1990, Henkel 1991 and Olesen & Sandstad 1993) and Bothnian-Senja fault complexes (Henkel 1991). The Senja Shear Belt constitutes a part of the latter and is the dominating structural element in northern Senja.

The bulk of the interpreted offshore area is occupied by extended continental crust containing numerous sedimentary basins which may contain reserves of petroleum. The main structural elements of the offshore survey area (Blystad et al. in prep and Gabrielsen et al. 1990) were digitized and plotted on Map sheet 1 and Figs. 3, 5, 6 & 21. Several authors have also reported thinning and extension of the continental crust in the coastal areas of northern Norway (e.g. Sellevoll 1983, Forslund 1988, Andresen in prep).

The Vøring Basin to the south is a large sedimentary basin province with grabens, sub-basins and structural highs (Skogseid et al. 1992, Blystad et al. in prep.). The Træna Basin belongs to the eastern basin province of the Vøring Basin, flanked by the Dønna Terrace and the Nordland Ridge which has been interpreted as the structural culmination of the Trøndelag Platform.

The area offshore the Lofoten and Vesterålen Islands is also characterized by several faultbounded basins and highs (Åm 1975, Rønnevik & Navrestad 1977, Eldholm et al. 1979, Mokhtari & Pegrum 1992 and Blystad et al. in prep.). The major features include a structural high, the Utrøst Ridge, on the landward side of the shelf edge and a basinal area, the Ribban Basin (including the Skomvær and Havbåen Sub-basins), on the inner shelf. Late Jurassic-Early Cretaceous extension was responsible for collapse grabens within the former half graben basins. The Røst High and the Jennegga High occur to the south and to the north, respectively, on the Utrøst Ridge. The Marmæle Spur is situated to the west of the Skomvær Subbasin. The seaward boundary of the Utrøst Ridge has large faults (Mokhtari & Pegrum 1992) with northwest throws and forms the landward boundary of the Røst Basin which is covered by a sequence of basalt flows. The evidence of a sub-basalt sedimentary basin is based on data derived from ocean bottom seismographs (Mjelde et al. 1992) and inversion of gravity data (Sellevoll et al. 1988).

Sea-floor spreading type anomalies were identified by Talwani and Eldholm (1977) and Hagevang et al. (1983) in the northwesternmost part of the survey region. The Harstad Basin (Gabrielsen et al. 1990) stretches from offshore Andøya northeastwards to the west of the islands of Senja, Kvaløy and Ringvassøy. The basin is bounded to the west by the southernmost part of the Troms-Finnmark Fault Complex and the western limit coincides with the transition to oceanic crust. The southern part of the Ringvassøya-Loppa Fault Complex coincides with the transition zone between the Hammerfest and Tromsø Basins and merges with the Troms-Finnmark Fault Complex to the south. Two well known NNW-SSE trending transform faults continue into the survey area; i.e. the Lofoten and Senja fracture zones.

A prominent set of high-angle semi-ductile to cataclastic faults called the Vestfjord-Vanna Fault Zone (Andresen in prep.) continues from the Vestfjorden area through the sounds to the east of Hinnøya, Senja, Kvaløya, Ringvassøya and Vanna into the Lopphavet area. The fault zone constitutes the contact between the Precambrian terrain to the northwest and the Caledonian nappe sequence to the southeast and has been interpreted to be of Upper Jurassic/Lower Cretaceous age (Andresen in prep.).

3 DATA-SETS

3.1 Geological data

The bedrock geology data-set used in this study was accumulated during 20 years of on-shore mapping. Some detailed investigations of fault zones were, however, carried out as part of the present project. The project area was subdivided into two provinces separated by the Senja Shear Belt. This is partly because the two regions are geologically quite different and have been studied separately of two of the present authors (Tveten & Zwaan 1993). The two onshore structural element maps originally at a scale of 1:250.000 are presented at a reduced scale in Figs. 1 & 2.

3.2 Aeromagnetic and gravimetric data

A total of four offshore aeromagnetic surveys were compiled and interpreted in the present project. Specifications for the surveys are shown in Olesen & Torsvik (1993). The final grid is displayed in shaded relief form in Figs. 3 & 7 using the THEMAP map production system by Kihle (1992) and the ERDAS image processing system, respectively. To enhance the high frequency component of the high resolution LAS-89 survey, a shaded relief map of the vertical derivative was produced (Fig. 4). Short wavelength anomalies presumed to be caused by flow basalts and sills are clearly visible on this map.

The present study is based on measurements from 7520 gravity stations on land and approximately 20.000 km of marine gravity profiles (Fig. 5). The marine data-sets were compiled and levelled by Amarok a.s. A regional gravity field (Olesen & Torsvik 1993) was subtracted from the Bouguer gravity data to obtain the residual field shown in Figs. 5 & 8.

3.3 Petrophysical data

Approximately 3050 rock samples were measured with respect to density, susceptibility and remanence. An additional 2220 *in situ* susceptibility measurements were carried out from c. 210 localities in the Precambrian basement of Vesterålen, Senja, Kvaløy and Ringvassøy. The results from this survey are presented by Olesen & Torsvik (1993). With the exception of the Seiland Igneous Complex, the rocks within Caledonian Nappes of Nordland, Troms and western Finnmark are practically non-magnetic (usually below 0.003 SI). The weakly magnetic component of the nappes is caused by Palaeozoic mafic intrusives and slices of

Archaean-Proterozoic gneisses and amphibolites. The Precambrian rocks have variable but usually high magnetic susceptibilities. The high-amplitude magnetic anomalies in the Lofoten-Vesterålen and northwestern part of Senja are caused by granulite-facies intrusives (mangerites) and gneisses. The Q-values are generally low, in the order of 0.5 or lower. Schlinger (1985), Kaada (1987) and Olesen et al. (1991) have shown that the remanence is viscous and parallel to the present Earth's field. The mafic and ultramafic rocks, however, often have much higher Q-values.

In order to constrain the gravity models we have used information from petroleum exploration wells immediately to the north and the south of the survey area. The densities of sedimentary sequences taken from density logs for wells in the Nordland I and II areas are given in Table 1.

*Table 1. Density of sedimentary sequences from density logs of wells in the Nordland I an II areas. The estimates (in 1000*kg/m^3) are used for gravity modelling along profiles TB-38-87, LO-06-86, LO-16-86 and LO-46-88. Numbers in parenthesis show depth of base of the different sequences.*

	Well 6609/7-1 Phillips Petroleum Nordland Ridge	Well 6607/5-1 Esso Bodø High	Well 6507/2-1 Norsk Hydro Dønna Terrace	Density estimates from sonobuoys Univ. of Bergen T. Henningsen, Statoil pers. comm.	**Density adapted for modelling**
Water depth	250m	368m	381m		1.03
Start of log	1025m	900m	1050m		
Pleistocene	-	2.21 (1220m)			
Tertiary	2.10 (1635m)	2.21 (2510m)	2.18 (2005m)	2.25	2.20
Cretaceous	2.25 (1845m)	2.32 (3785m+)	2.37 (3610m)	2.30	2.35
Jurassic	-	-	2.54 (4400m+)	2.35	2.45
Triassic	-	-	-		2.45
Permian	2.31 (1920m)	-	-		-
Basement	2.64 (1960m+)	-	-	2.70-2.85	2.75
Magmatic underplating					3.00
Mantle					3.30

3.4 Bathymetric and topographic data

The bathymetric and topographic data were provided by the Norwegian Mapping Authority and were described by Olesen & Torsvik (1993). The colour shaded-relief map (Fig. 6) was produced from the combined grid of 1km x 1km cells. A processed image of another high resolution topographic grid (100m x 100m), also provided by the Norwegian Mapping Authority, is shown in Fig. 9. This data-set was combined with remote sensing data to interpret the dip of lineaments in the Vesterålen area within the frame of the Lofoten-Lopphavet Project (Bax 1993).

4 INTERPRETATION METHODS

The potential field interpretation is obtained using the IMP software (Torsvik 1992, Torsvik & Olesen 1992 and Torsvik & Fichler 1993) which was developed at the Geological Survey of Norway. Depths to basement were estimated from inversion of aeromagnetic and gravity data, applying the autocorrelation algorithm by Phillips (1979) and a least-squares optimizing algorithm by Murthy & Rao (1989), respectively. A combined interpretation was arrived at by applying forward modelling of both the aeromagnetic and gravity data. Constraints offered by seismic interpretation on the structure of the uppermost parts of the sedimentary sequences were incorporated to improve the interpretation of the deeper level of the basins. Seismic interpretations along the profiles TB-38-87, LO-06-86, LO-16-86 and LO-46-88 in the Lofoten area and T-01-85, T-06-85 and T-01-84 in the Troms area were provided by Statoil (T. Henningsen, pers. comm. 1993) and Norsk Hydro (E. Rasmussen pers. comm. 1992), respectively. To reduce the inherent ambiguity in the modelling of the potential field data further, petrophysical data from both basement rocks and sediments were used in the forward modelling (Olesen & Torsvik 1993).

The c. 800 depth estimates and locations of the ten gravity inversion profiles and seven model calculation profiles are plotted at a scale of 1:1 million on Map sheet 1 and at a reduced scale in Fig. 21. The gravity inversion data and forward modelling along profiles TB-38-87, LO-06-86, LO-16-86 and LO-46-88 are shown in Figs. 22 & 23-26, respectively.

The image processing of the grid data-sets (Figs. 7-9) is reported in detail by Olesen & Torsvik (1993). Image processing of gravity and aeromagnetic data from the northern part of the survey area has earlier been presented by Sæther et al. (1991). Fault zones within the basement and partly within the sediments are interpreted from the processed images and maps and displayed on the interpretation map at a scale of 1:1 million (Map sheet 1) and 1:500.000 (Olesen & Torsvik 1993). The regional magnetic trends and high frequency anomalies (possible volcanic rocks) are also included in the interpretation map.

The combined interpretation of depth estimates from both gravity and aeromagnetic data was carried out by interpolation and contouring of depth to basement. In areas where the two data-sets give diverging depth estimates the gravity interpretation is given the highest priority, especially in areas were we expect to find low-magnetic basement continuing from onshore or down-faulted Caledonian nappes within the deep basins. High frequency anomalies interpreted to represent magnetic volcanics are excluded in the contouring.

Palaeomagnetic studies of fault rocks furnish a direct technique for dating phases of fault movements and rejuvenation. The success of the method, however, requires that several conditions are satisfied (Torsvik et al. 1992a; Trench et al. 1992): (1) Remanence must be unaffected (undeflected) by the structural grain. (2) Well-defined reference data or an established apparent polar wander path (APWP) is required. (3) Unaccounted-for post-acquisitional structural rotations are precluded. (4) An appropriate sampling strategy is required. (5) The magnetic mineral(s) carrying remanences must relate to mineral growth during significant fault displacements rather than later fluid movements along the fault zone or regional magnetic resetting.

5 RESULTS

5.1 General aeromagnetic and gravity features

The character of the gravity and aeromagnetic maps in the Lofoten - Vesterålen and the Senja - Lopphavet areas are different (Figs. 3 & 5), and it is therefore natural to divide the study area into two provinces. The transition zone is located in the Narvik - Andøya area. This zone coincides on Andøya with a thrust which is most likely of Caledonian age. South of this line anomalies generally trend NE-SW while the northern area is characterized by NNW-SSE trending anomalies. The latter trend reflects the structural grain of the autochthonous or parautochthonous Precambrian basement whilst the former pattern is most likely due to a Palaeozoic and Mesozoic reworking of the Precambrian basement. Along extensions of the Lofoten and Senja fracture zones we observed lineaments on the continental shelf and on land indicating that the Cenozoic structures follow Proterozoic NW-SE trending zones of weakness.

The onshore area of the Senja-Lopphavet area is dominated by a NNW-SSE trend which is characteristic of the Precambrian bedrock of northern Sweden and Finland which can be seen from the aeromagnetic map of northern Fennoscandia (Geol. Surveys of Finland, Norway and Sweden 1986). The aeromagnetic map (Fig. 3) shows that magnetic Precambrian rocks on Andøya are continuous across Andfjorden to Senja and further to the southeast below the magnetically 'transparent' skin of Caledonian nappes into the Precambrian basement in Sweden. This indicates that the Precambrian rocks in the Lofoten-Lopphavet area belong to the Baltic Shield.

The aeromagnetic and gravity anomalies of the Lofoten-Vesterålen area and the adjacent offshore area generally trend NE-SW and NNE-SSW. The anomalies within this area are probably caused by suprabasement susceptibility contrast and may result from fault-related basement relief. The most prominent positive anomalies on Figs. 3 & 5 correspond to the Bodø High, Nyk High, Nordland Ridge, Utrøst Ridge, Lofoten High, Vesterålen High and Marmæle Spur. Negative anomalies represent the Træna Subbasin and Røst, Ribban Vestfjorden and Harstad Basins. The structural grain is parallel to the Caledonian trend as well as to the main direction of the offshore Mesozoic basins. This indicates Caledonian reworking of the Proterozoic rocks in the Lofoten-Vesterålen area. Recent geological mapping of the Precambrian in Vesterålen has revealed evidence of Caledonian thrusting (Tveten & Zwaan 1993).

The Bouguer and free air anomaly maps are dominated by a high gradient trending parallel to the coast. The negative component of the gravity field is located on land and the positive component offshore and at the Lofoten - Vesterålen islands. Calculation of the long wave-length component of the gravity field is shown by Olesen & Torsvik (1993). This part of the field is interpreted in terms of a Mohorovičić topography and indicates that the Lofoten and Vesterålen islands constitute two basement highs within a rifted and thinned crust of the continental shelf similar to the basement highs within the Vøring Basin to the south (e.g. Planke et al. 1991). The gravity modelling in Fig. 24 also shows that there exists a Mohorovičić bulge below the islands as observed by Svela (1971), Sellevoll (1983) and Mjelde & Sellevoll (1993).

High frequency anomalies occur in a continuous zone from the western margin of the Bodø High northwards along the shelf edge to the west of the Utrøst Ridge and Andøya (Map sheet 1, Figs. 4 & 21). The high frequency anomalies are often negative which suggests that they represent flow basalts and/or sills.

5.2 Ribban and Vøring Basins

This area is characterized by large depths to the magnetic basement. The largest depths, up to 10 km, correspond to the Skomvær and Havbåen Subbasins within the Ribban Basin and are consistent with the depth estimates of Olesen & Myklebust (1989). Modelling of gravity data give much shallower depths (5 km and less, Fig. 22 B-C). We interpret this discrepancy to be caused by downfaulted low-magnetic Caledonian nappes or low-magnetic amphibolite-facies gneisses. Åm (1975) observed a similar divergence in depth estimates from aeromagnetic data and refraction seismics. The Skomvær Basin is modelled along line LO-06-86 (Fig. 24) as a half-graben, bordered by a steep fault towards the Lofoten Islands, which represents a horst between the Ribban and Vestfjorden Basins (as already pointed out by Åm 1975 and Rønnevik & Navrestad 1977). There are, however, depths to basement obtained from both gravity and magnetic data to the north of the Marmæle Spur, which are significantly deeper than base-Cretaceous depths reported by Brekke et al. (1992), indicating that there may be significant amounts of sediments below base-Cretaceous in this area. The shallow basement ridge at 1-3 km depth between the Røst High and the Skomvær Subbasin is the Marmæle Spur (Blystad et al. in press). This structure represents a rotated block within the crystalline basement, which is clearly indicated by the gravity inversion along profile D (Fig. 22).

The seaward boundary of the dome-shaped Utrøst Ridge consists of large faults with northwest throws, forming the landward boundary of the Røst Basin which is covered by a sequence of basalt flows (Sellevoll et al. 1988). The main fault within this fault complex is, however, located 6-7 km further to the west compared with what is apparent on seismic sections. The depth of the Røst Basin is c. 9 km. The magnetic spreading anomalies are subdued seaward of the Røst Basin indicating subsidence of the crust and a possible above-lying Tertiary wedge of sediments in this area. The ocean/continent boundary is displayed on the interpretation map (Map sheet 1 and Fig. 21) but is not well defined on the gravity and aeromagnetic maps indicating a gentle ocean/continental crust transition. Interpreted fracture zones in the oceanic crust are indicated on the interpretation map (Map sheet 1, Fig. 21). They seem to be more frequent in the older part of the oceanic crust than the younger as also shown by Hagevang et al. (1983). Frequently occurring transform faults are also observed in the initial phase of drifting in the Red Sea (Martinez & Cochran 1988) .

The depth to basement rocks under the Bodø High is c. 6 km while the Træna Basin is more than 10 km deep. The Bodø High is interpreted as a large rotated block with a high density core (Olesen & Myklebust 1989). A coinciding gravity and aeromagnetic anomaly (denoted by H/V on Map sheet 1 and Fig. 21) is located to the north of the Bodø High and southwest of the Røst High. The magnetic anomaly is, however, restricted to a smaller area than the gravimetric one. These anomalies may be related to a basement high or a thick sequences of volcanic rocks. We favour the former interpretation since both the aeromagnetic and gravity anomalies are continuous southwestward to the Nyk High. The gradient of the gravity field is highest on the eastern flank of the anomaly (Fig. 5) indicating a zone of boundary fault zone to the east (Figs. 21 & 23). Some of the high frequency magnetic anomalies in the area may, however, represent mafic sills or lava flows which were brought to an elevated position during Tertiary uplift of the underlying basement high.

The highly magnetic rocks on the Jennegga High represent a continuation of the granulite facies rocks in Vesterålen. The outermost part of the Jennegga High is characterized by NE-SW trending linear magnetic lows. The depths to these anomalies are less than 300 m which is almost consistent with the outcropping basement in this area (Lien 1976). The negative magnetic anomalies lie within a continuous zone of high frequency anomalies extending from the west of the Bodø High northwards to Andøya and therefore most likely represent volcanic rocks with reverse polarity remanence. This fault-zone can be traced to the southwest of the Jennegga High due to three very pronounced steps in the magnetic anomalies, most likely representing three steeply dipping fault-zones within a fault complex. A large number of the NNE-SSE trending faults in the area merge into the regional ENE-WSW trending fault along the shelf edge (Figs. 7, 8 & 21). Fig. 25 shows a gravity model along line LO-16-86. The negative anomaly which we find to the west of the Utrøst Ridge is not developed in this area. The lack of this anomaly is possibly related to either thinner sedimentary sequences below the basalts or very thick layers of volcanics. The latter possibility finds support in the presence of large amplitude negative magnetic anomalies.

5.3 Vestfjorden Basin

The interpretation of Brekke & Riis (1987) indicates that the Vestfjorden Basin is essentially a Lower Cretaceous basin and not a possible Palaeozoic basin as suggested by Bøen et al. (1984). The southern part of the Vestfjorden Basin is a c. 7 km deep half graben defined by a boundary fault zone along the western margin as shown by Brekke & Riis (1987). The northern part of the Vestfjorden Basin, however, is a shallower (approximately 2 km deep) half graben with the boundary fault along the eastern margin of the basin. This basin may be older than the outer Cretaceous Vestfjorden Basin. As shown by the palaeomagnetic dating (Chapter 5.7), the Vestfjorden-Vanna Fault Zone was mainly active during the Permian. This date is consistent with the interpretation of the Sørvær Basin that is located along the northern segment of the Vestfjorden-Vanna Fault Zone being of Permian-Carboniferous age (Olesen et al. 1990, Sigmond 1992).

Gravity interpretation along profiles LO-06-86 and LO-16-86 (Figs. 24 & 25) and Profiles G, H and I (Fig. 22) illustrates this shift of polarity of subsidence. A similar shift of polarity is also seen offshore Lofoten and Vesterålen where the faults shift from throwing down to the northwest to downthrow to the southeast, respectively. The shift seems to occur along the landward continuation of the Jennegga Fracture Zone (Mokhtari & Pegrum 1992 and Map sheet 1/Fig. 21).

The western margin of the Vestfjorden Basin in the Lødingen area is interpreted to consist of several rotated fault blocks (Olesen & Torsvik 1993). Raftsundet, Øksfjorden and Øyhellsundet are very conspicuous topographic/bathymetric lineaments, being represented mainly by narrow sounds and fjords. These lineaments are visible as negative magnetic anomalies between the rotated, magnetic fault blocks and seem to contain the faults separating these blocks (Map sheet 1, Figs. 1, 3 & 21). The fault blocks continue to the southwest beneath the Vestfjorden Basin. The lineament along Øksfjorden seems not to be linked directly to the exposed fault labelled "I" (Fig. 1) in Gullesfjorden. As for the faults along Eidsfjorden and Sortlandssundet, we see that faults are not continuous across a line from Eidsfjord to Lødingen, which apparently acts as a NW-SE barrier for single-fault propagation.

5.4 Lofoten and Vesterålen Highs

As discussed in Chapter 5.1 the islands of Lofoten and Vesterålen constitute two basement highs on the continental shelf. The boundary faults to the neighbouring basins are described in Chapters 5.2, 5.3 and 5.5. The Lofoten High (Lofoten Horst) and Vesterålen High are partly separated by the Havbåen Subbasin (Fig. 21). Modelling of seismic and gravimetric data by Sellevoll (1983) shows Moho depths of 22 and 24 km beneath the Lofoten and Vesterålen Highs, respectively, while the depth in between is 26 km. The two basement highs are strongly faulted and fractured. This observation may explain why the seismic velocities of the rocks estimated from refraction experiments are significantly lower than the velocities acquired from laboratory measurements on rock samples which was pointed out by Chroston & Brooks (1989). The faults within this province is of interest for the understanding of the tectonic development of the offshore sedimentary basins.

Several regional faults occur within the two highs: Eastern Andøy Fault, Gullesfjord Fault, Vikeid Fault Zone, Sortlandsundet, Gimsøysundet and Eidsfjord Lineaments and Heier's Zone (Figs. 1, 9 & 21). The northernmost regional fault is the Eastern Andøya Fault bordering the Jura-Cretaceous sediments (Dalland 1975) on Andøya ("P" in Fig. 1). Cemented fault-breccias were in 1993 located along this fault on southern Andøy (Fig. 1). The fault-belt is thought to be of Tertiary age. (Sturt et al. 1979 p. 529). A further extension of the structure towards the south is indicated by a sub-sea gully in the fjord south of Risøyhamn. The mean direction of the lineament is N30E.

Another regional fault is the Vikeid Fault Zone on Langøy. Most of the land strip between Vikeid and Eidsfjord is intersected by several sets of faults, and together they form a 1 km wide fault belt. Small scale faults are observed, that strike E280°W-E290°W (dip to the right). The faults in this zone may be classified on basis of petrography into three groups: a) Cemented breccia formation (Fig. 10), b) Crush breccia formation, c) Black chlorite breccia formation. Details and examples of these groups are given by Tveten & Zwaan (1993).

A very conspicuous bathymetric lineament runs along Eidsfjord for more than 30 km, as also shown on the aeromagnetic map, and "Q" in Fig. 1. The direction is about E50°W, which is parallel to the main Vestfjord lineament. The lineament is not traceable to the NE, but at the SW end it may join the main listric fault on the southern side of the Havbåen Subbasin. Close to the northern shore of inner Eidsfjord, a subsurface gully indicates the probable trace of the fault. Heier (1960) pointed out a structure south of Eidsfjorden, which he interpreted as a thrust (see "B" in Fig. 1). Anorthosite and other Proterozoic and Archaean rocks rest upon mylonites later called the "Heier's Zone", which grades downwards into augen gneiss and mangerites. Simple shear indicators beneath the mylonite show a component of normal movement. Cognate mylonites are observed on Hinnøy (see section A-A' in Fig. 1), where the same situation with anorthosite above augen gneiss, above mangerite, is exposed for a few km south of the profile line. The absolute age of the structure is unknown, but pseudo-tachylites and zeolite-filled small-scale faults, cut the mylonitic foliation. Thin-sections from the mylonite show a fairly low-grade rock, with obvious post-tectonic amphibole and syn-tectonic sphene.

A sub-surface groove in the middle of the Sortlandsundet between Langøy and Hinnøy indicates the presence of a fault. In section A-A' (Fig. 1), this fault is assumed to take up a major part of the down-throw of the SE part of the sound. It terminates outside Sortland. This structure, together with the faults along Eidsfjorden and Øksfjorden, seem to delimit fault-blocks lying in between. The terminations of these blocks towards the NE and SW, are apparently either the E-W or the NW-SE lineaments. At locality "C" in Fig. 1, a ductile shear zone, at least 60 m thick, has an almost horizontal attitude. It is cut by 20-50 cm thick breccia-zones striking parallel with the Sortlandssundet lineament. The shear-zone has chlorite, recrystallised red K-feldspar and epidote, and is believed to be a SE continuation of the "Heier's Zone". Downfaulted fragments of the same structure is found 25 km SE of the locality on Langøy, see section A-A' in Fig. 1.

The regional Gullesfjorden Fault (Fig. 11) is exposed at locality "I", Fig. 1. Fault rocks are polygenic, mostly cemented breccias. They are light in colour and partly cemented with calcite. Marble fragments are also found. It has not been possible to follow the structure across to Øksfjorden. East and south of Harstad, Gustavson (1974) indicates a system of faults; two of them displace the Caledonian rocks in the area apparently for more than a kilometre. The dip of the Caledonian front in this area is not accurately known, but conforms with downward movement of the SE block if the true movement is vertical (On locality "M" south of Harstad, Fig. 1).

Through Gimsøysundet in Lofoten, a lineament is thought to represent an important fault system on the eastern side of the huge gravity anomaly beneath the outer Lofoten islands. Some authors have proposed that granulites have a brittle behaviour even at larger crustal depths (Weber 1986). This opens up the possibility that late extensional faulting might have been strongly influenced by very old crustal structures.

East Langøy, Skogsøya and Hinnøya east of Sortlandssundet are the main localities for the conspicuous pseudotachylites. Pseudotachylites represent friction melt produced by upper crustal brittle faulting. In case of a fault origin, it is generally accepted that they represents fossil remnants of palaeoseismic events (Allen 1979, Sibson 1975). Pseudotachylites (PT), are found in numerous localities in the areas mentioned above. They are usually only a few mm thick, black and aphanitic. Often the observed PT are clean-cut dykes without any signs of abrasive activity or fragmentation. In these cases the PT may follow the margin of a pegmatite dyke, make a sharp, angular shift in direction, or otherwise show the characteristics of a true intrusive dyke. However, most of the cases are braided, complex zones of angular fragmentation of the host rock (Figs. 12 & 13). Sometimes the sense of shear along the faults may be deduced from the observed shear deformation structures related to the PT-formation. PT is observed to offset older structures in the gneiss. The amount of apparent offset is between 30 and 250 cm the largest offset is on the largest found fault plane, which is represented by a surface trace of about 600 m. Most PT's dip between moderate angles and horizontal, the graphic presentation of their orientations are therefore best achieved by a spherical projection of the data. (See Fig. 14 a; equal-area net, lower hemisphere is chosen). One may see from the figure that there is an element of girdle distribution within the selected sub-domains. For two of the sub-domains the girdle-axis are horizontal, for the Northwest Hinnøy the axis is tilted about 30°. If the PT's are related to rotation of extensional allochthonous blocks, these blocks must have approximate prismatic shape bounded by coaxial surfaces, within one sub-domain. The 30° tilt for one sub-domain, may be a late rotation for this particular subdomain, or that two of the principal axis of stress are not laying in the horizontal plane. Non of the samples used for palaeomagnetic dating are taken from this sub-domain, which contains the tallest mountains on Hinnøy. Further details on petrography, chemical composition and dating of pseudotachylites are given by (Tveten & Zwaan 1993).

Few indications for regional and local strike-slip movement are found. One exception may be the island of Anda, where "pinnate joints" indicate local sinistral movement on NE - SW lineaments which pass the island. In the area south of Harstad, clear indications exist for a several hundred meter downfaulting to the SE. The same sense of displacement is demonstrated across the Sortlandsundet.

The oldest fault-phase is clearly younger than the high grade texture, and is located along low-angle ductile shear-zones accompanied by subsequent retrogression. The age of this episode is unknown on Langøy, but possible equivalents have a Caledonian age on Vestvågøy (W. Hames pers. comm. 1992). Following the formation of ductile and semiductile shear-zones, the rocks must have been through a period of seismic activity. Pseudotachylites were formed at a crustal depth where microlites could grow, probably more than 6 km depths (Swanson 1992). Analysis of mesostructures indicates that pseudotachylites are segments of faults, mostly of low-angle NW or N striking orientations. Observations of pseudotachylites on small listric faults of a few hundred meters in length, indicate that they are related to the formation of the extensional allochthon in the province and that their mainly horizontal attitude reflect an origin near the soles of an early set of listric faults. Later elevation may have occurred with minimal rotation since both horizontal positions and the horizontal NE-striking axis of faultblocks are preserved. An exception is the sub-domain on SW Hinnøy where the axis of extensional allochthon blocks may have been tilted from an original horizontal position to a slightly northerly dipping position by a late, local rotation, about an E-W axis (Fig. 15)

A zone across Hinnøy, from Lødingen, to Langøy and the head of Eidsfjord, acts as a barrier for propagation of single regional faults. The significance of the zone is uncertain. Irregular fault directions offshore Northern Langøy may indicate that the mechanism is resembling the "accommodation zone" of Bosworth (1985) and Rosendahl et al. (1986).

5.5 Harstad Basin

In the area offshore Vesterålen-Andøya the basement surface is smoother than in the Lofoten area. The basement-faults are also less distinct, and the vertical offsets along them are smaller. A gravity model (Fig. 26) along the seismic profile LO-46-88, illustrates the situation offshore to the Vesterålen-Andøya area. The uplift of the Vesterålen area is of a more domelike character compared with the typical horst structure of the Lofoten Islands. There is, however, a more than 7 km deep basin to the west of Andøya which most likely represents a continuation of the Harstad Basin. Note that this depth is interpreted from gravity data. All the depth estimates from the aeromagnetic interpretation are shallower, but these depths do, however, most likely represent depth to magnetic volcanics. The Harstad Basin may represent a half-graben with the main fault to the west as shown in Fig. 26. The magnetic anomalies at the eastern margin of the basin are continuous from the Vesterålen islands and must therefore reflect the basement. These elongated anomalies may represent rotated blocks within the basement. The abundant high frequency anomalies in this area may, however, represent volcanic rocks. The easternmost anomalies occur along a zone coinciding with the shelf edge and most likely represent the easternmost limit of the flow-basalts. The interpreted depths to these anomalies are in the order of 0.5 - 2.0 km below sea level. Because flat-lying or gently dipping magnetic bodies do not fulfil the vertical dyke approximation the uncertainty of these estimates are in the order of ±20%.

To the northwest of the Harstad Basin, ocean spreading anomalies 22, 23, 24A and 24B have been identified by Talwani & Eldholm (1977) and Hagevang et al. (1983). The depth to these anomalies are in the order of 2 - 3 km. Accounting for a water depth of 2 - 2.5 km implies that the thickness of the Tertiary sediments in this area is less than 1 km. On the continental slope anomalies with intermediate wavelength and partly negative amplitude occur immediately to the east and south of anomaly 24B. They are subparallel to anomaly 24B and most probably represent volcanic rocks (lava flows). The northernmost part of the Harstad basin is described by Gundersen & Olesen (1992). A coinciding gravity and aeromagnetic anomaly is especially intriguing (denoted by H/V on Map sheet 1 and Figs. 3, 5, 6 & 21) and is located to the northwest of the Senja Fracture Zone and south of the Sørvestnaget Basin. These anomalies may be related to a basement high at a depth of approximately 7 km or a mafic intrusion. There are some similarities to the anomalies to the north of the Bodø High which were discussed in Chapter 5.2. We favour the former interpretation in this case as well, since both the aeromagnetic and gravity anomalies are continuous to the Senja Ridge (Gabrielsen et al. 1990) to the north.

The northern part of the Harstad Basin is flanked towards the east by the Troms-Finnmark Fault Complex represented by magnetic fault blocks at a depth of 5-9 km (Gundersen & Olesen 1992) which may have been rotated. The NNW-SSE trending Proterozoic Bothnian-Senja Fault Complex (BSFC) is manifested on land as several steeply dipping mylonite zones (Tveten & Zwaan 1993) and the continuation offshore represents the southern termination of the Finnmark Platform. The BSFC seems to govern the location of the Troms-Finnmark Fault Complex since the latter makes a N-S deflection were it encounters the BSFC. The Senja Fracture Zone may also initially have developed along this preexisting zone of weakness in the crust. An up to 6 km deep halfgraben of Palaeozoic sediments is located on the Finnmark Platform (see Gundersen & Olesen 1992 for further discussion of the area). The main post-Caledonian faults on land, the Vestfjorden-Vanna Fault Zone (VVF), the Kvænangen-Langfjord Fault (KLF) and the Lyngen-Rotsund Fault (LRF) may have been active during this early phase of rifting (see next chapter for discussion of palaeomagnetic dating)

5.6 Senja Shear Belt - Vestfjorden-Vanna Fault Zone

The Precambrian shear-zones on Senja and the southwestern part of Kvaløya define a ca. 30km-wide, NW-SE trending linear zone, which we here refer to informally as the Senja Shear Belt (Figs. 16-18). The zone constitutes a section of the Bothnian-Kvænangen Fault Complex (Fig. 21). The southwestern border of the Senja Shear Belt is defined by the several kilometre wide Svanfjellet Shear Zone (SS) and the northeastern border by the 1.5 km wide Torsnes Shear Zone (TS). Within the belt, the gneissic foliation and faults/shear zones form a coherent pattern suggesting a mutual relationship (Fig. 2). The rocks are mylonitised in narrow shear zones, the most prominent of which is the 800 m-wide Astridal Shear Zone (AS) in the Hekkingen area. Petrographic details of the shear zones are reported by Zwaan (1992) and Tveten & Zwaan (1993).

In the Tromsø and Helgøy map areas there are a prominent set of high-angle semi-ductile to cataclastic faults called the Vestfjord-Vanna Fault Zone (Andresen & Forslund 1987, Forslund 1988, Andresen in prep.). In the southwestern part of the Tromsø map area the high-angle, normal Solbergfjord Fault (SBF) shows a vertical displacement of 1000 m or more down to the south. Along the Stonglandeid Fault, a westward branch running along the shore of Senja, a cataclastically deformed fault rock is exposed at one locality (Fig. 19). Strike-slip movement along this fault is indicated by the dome like structure of the Stonglandet Peninsula.

The Stonglandeid/Solbergfjord Fault, and the Heggdal Fault (HF) in the middle of Senja, are ENE-WSW striking, first-order high-angle faults with an intervening widespread set of secondary high-angle faults trending NE-SW. The Heggdal Fault is characterised by an up to 200 m-wide semi-ductile breccia with a strike-slip movement of 500m or more. To the east, in Lenvik, the faults are bounded by a 20-30 km wide subsidence zone (the Lenvik Zone; see Fig. 16), which is a northeastward continuation of the Solbergfjord Fault, although the movement polarity seems to shift. Curvilinear listric geometry indicates an extensional regime for the above-described system of first- and second-order faults. The NE-SW trend of the secondary faults (possible Riedel faults) further indicates a sinistral movement of the system.

The Lenvik Zone displays a system of curvilinear faults with a convex bending to the west for the eastern faults and concave for the western faults. The Caledonian thrust sheet is preserved within these faults. The crustal block to the west of the Lenvik zone is possibly elevated, while an extensional graben is developed within it. The Lenvik Zone is underlain by the Bothnian-Senja Shear Zone (Henkel 1991), which is assumed to be an old shear zone which was reactivated during the formation of the Senja Fracture Zone in the early Tertiary. There is a shift of polarity of the individual faults within the Lenvik Zone across the Senja Shear Belt indicating that this older shear zone was also reactivated during the formation of the VVF. Petrographic evidences indicate a complex deformation history of the area, where several fault sets were active at different times. It is also interesting to note that the Mauken tectonic window (Map sheet 1, Fig. 21) within the Caledonian orogen is located within the Bothnian-Senja Shear Zone. The depth to the Precambrian basement below the Lenvik Zone is shallow, i.e. less than 1 km, according to depth to magnetic basement interpretation by Olesen et al. (1990). The Lenvik Zone of subsidence contrasts with the Vestfjorden-Vanna Fault Zone to the east of the islands of Kvaløya, Ringvassøya and Vanna. The Caledonian rocks in the latter area are separated from the basement by a continuous set of high-angle normal faults, called the Straumsbukta-Vanna Fault (SKF), with a down-to-the-east displacement of 2 to 3 km (Forslund 1988 and Andresen in prep.). On the island of Vanna the presence of an antiform suggests a possible component of strike-slip movement.

5.7 Palaeomagnetic studies

A total of 85 drill-cores and hand-samples were collected from Vesterålen, Senja and Kvaløya in order to furnish temporal constraints on near shore fault-activity (Fig. 27).

Kvaløya:

Samples from Kvaløya were taken across a zone of several generations of crush-breccias. The younger breccias show clear evidence for a late phase of fluid circulation and precipitation of haematite giving the fault-rocks a distinct dark red colour. The natural remanent magnetization (NRM) of these breccias resides in the high-stability haematite. The stability of NRM was tested by means of thermal demagnetization which revealed a stable high-unblocking temperature magnetization (650-660°C) with southwest declination and upward pointing inclination (Fig. 28). The haematite component is often partially overprinted by a low unblocking component with downward dipping inclination towards north (Fig. 29; remanence group marked with LB). This component compares with recent/Tertiary reference data.

Vesterålen:

Two localities were sampled from Vesterålen. Location 1 embraces pseudotachylites (thin veins; mm scale) and host-rocks (banded gneisses), whereas location 2 comprised pseudotachylites and a mafic dyke. Palaeomagnetic studies demonstrate that pseudotachylites, banded gneisses and mafic dyke carry same remanence direction (Figs. 28 & 29). We presume, therefore, that they may record a regional overprint magnetization direction and offer no constraints on the age of faulting in the area.

Senja:

The sampled locality from Senja covers a wide brecciated zone which has evidence for at least two phases of brecciation. The youngest fault-movements produced fault-gouges and fault-rocks which carry steep northerly directed magnetizations with steep inclination of recent/Tertiary age (see group marked LB in Fig. 29). A mafic dyke, located within the zone of brecciation, however, carries two remanence directions; one steep remanence similar to the LB directions found in fault-rocks and a second dec./inc. direction (group HB in Fig. 29) similar to fault-rock directions on Kvaløya.

Interpretation:

In Fig. 30, pre-Tertiary palaeomagnetic results from Vesterålen, Senja (Group HB in Fig. 29) and Kvaløya (Group HB in Fig. 29) are compared with the reference APWP for Baltica (Torsvik et al. 1992b). At least two phases of faulting and brecciation can be identified at Kvaløya and Senja. The youngest phase (fault-gouges) is recent/Tertiary in origin (Fig. 29 - group LB), almost obliterating an older Permian phase (see discussion below). It is evident that the results from the two latter areas plots close to the early Permian part of the APWP path, and it is therefore evident that important phases of on-shore faulting and/or phases of fluid circulation (breccia cementation) took place at that time (c. 270-280 Ma). These ages represent **minimum** ages for faulting, i.e. the ages of cementation/lithification of the breccias. Fault-activity is probably linked to the near-shore tectonic evolution, and probably witnesses an early rift-phase on the continental margin. Similar dual polarity Permian (and also younger) magnetizations have been observed on elements of the Møre-Trøndelag Fault Zone (Grønlie & Torsvik 1989) and on faults in western Norway (Torsvik et al. 1992a). The palaeomagnetic results from Vesterålen indicate an early Palaeozoic magnetic overprint. The palaeomagnetic data, however, are removed from the reference APWP (Fig. 30), which may suggest that the area has suffered younger rotations or tilting. A seaward block-tilting of the order of 15-20 degrees on a NE tilt-axis would bring the Vesterålen results in correspondence with the Ordovician section of the APWP for Baltica. This agrees with the observations and measurements of pseudotachylites related to listric faults, showing a similar rotation (see Chapter 5.7).

A Permian age of the Vestfjorden-Vanna Fault Zone is consistent with the regional pattern of rifting in the Barents Sea where the oldest faulting extended to the east while younger rifting successively shifted westwards. The collapse of halfgrabens formed in the Late Palaeocene occurred in late Jurassic - early Cretaceous time in the Lofoten area. The Tertiary uplift has also strongly affected the area.

6 CONCLUSIONS

1. The Bouguer and free air gravity fields within the Lofoten area are dominated by coast-parallel gradients. This pattern indicates that the Lofoten - Vesterålen area constitutes a basement high within the rifted and thinned crust of the continental shelf, similar to the basement highs within the Vøring Basin to the south.

2. The majority of the interpreted magnetic and residual gravity anomalies within the offshore area appear to be caused by suprabasement susceptibility and density contrasts associated with a fault-related basement relief. In the Ribban Basin the geophysical interpretation map shows a complex structural pattern with several uplifted and possibly rotated basement blocks.

3. The combined interpretation of depths to basement based on the gravity and aeromagnetic data reveals a maximum depth of 5 km in the Ribban Basin offshore Lofoten, and depths of more than 10 km in the Træna, Sørvestnaget and Tromsø Basins. Locally within the Ribban Basin greater magnetic depth estimates than 5 km occur. We interpret these to represent downfaulted Palaeozoic Nappes, Devonian sediments or low-magnetic Precambrian rocks.

4. There are two distinct fault trends within the survey area: NNE-SSW and ENE-WSW. The western margins of the Bodø High, Nordland Ridge, Lofoten Islands, Marmæle Spur and Utrøst Ridge are characterized by complex and large scale faults. A large number of the NNE-SSE trending faults merge into a large scale ENE-WSW trending fault along the shelf edge. Another less pronounced, but still important, set of faults trends NW-SE and coincides with extensions of the fracture zones in the oceanic crust. The orientation of the fault pattern on land is similar to the offshore fault pattern.

5. An axis of late elevation seems to run NW-SE across Vesterålen to the Jenegga High resembling a possible accommodation zone between the Ribban-Vestfjorden Basins to the southwest and the Harstad Basin to the northeast. Geological mapping on land shows that the NE-SW trending faults are discontinuous across this line. Opposing slip directions of faults in the Vesterålen area may also be related to this 'accommodation tectonics'.

6. Coinciding gravity and aeromagnetic anomalies situated along the Lofoten Lineament at the extension of the Nyk High most likely represent a basement high.

7. Offshore Andøya and to the south on the seaward side of the Utrøst Ridge - Bodø High area, there are numerous high frequency magnetic anomalies indicating intrasedimentary volcanic or intrusive rocks.

8. The shelf edge coincides with the large-scale faults on the seaward side of the Bodø High, Røst High, Utrøst Ridge and Jenegga High. The eastward termination of the flow-basalts also coincides with this line, and may represent a rift escarpment during the extrusion of lavas in early Eocene times.

9. The magnetic anomalies in the Andøya-Ringvassøy area show that the Precambrian basement continues below the Caledonian nappe sequences and re-appear at the surface in northern Sweden and Finland. This indicates that the Precambrian rocks in the Lofoten-Vesterålen area, in spite of Mesozoic reactivation along possible Caledonian thrusts and faults, belong to the Baltic Shield.

10. The northern part of the Harstad Basin, flanked towards the east by the Troms-Finnmark Fault Complex, is represented by rotated magnetic fault blocks at depths of 5-9 km.

11. It is evident from the mapping of faults on Langøya and Hinnøya that two distinct types of faults exist: One group hosting pseudotachylites formed by the strain-hardening process of friction melting. They are related to widespread intermediate-scale extensional faulting. The other group of faults is more diverse, characterised by breccias, fault gouges and phyllonites. They represent a strain-softening process along steep regional structures.

12. At Senja and Kvaløya, two phases of faulting and brecciation were identified. Palaeomagnetic studies reveal that a young phase, attendant on the formation of fault-gouges, is Recent/Tertiary in origin, whereas an older phase has a Permian age. An early Permian age (c. 270-280 Ma) is also indicated from haematite cemented fault-breccias from Kvaløya, and the Permian fault-activity probably witnesses an early rift-phase on the continental margin. We have found no evidence for Mesozoic fault-activity in the tested areas onshore.

13. There may have been a narrowing zone of rifting and a consequent westward shift of the regional fault activity on the Nordland shelf and coastal area from the Carboniferous-Permian to the late Jurassic-early Cretaceous and Tertiary.

14. The Lofoten-Lopphavet study has revealed several new structures which to our knowledge have not been previously reported.

7 ACKNOWLEDGEMENTS

This study was financed by Elf Petroleum, the Norwegian Petroleum Directorate, Norsk Hydro, Statoil and the Geological Survey of Norway. The gravity survey was performed by Jomar Gellein and Atle Sindre. Gerhard Bax, Rognvald Boyd, Ingvar Lindahl and Rolf Lynum participated in the petrophysical sampling. Charles Schlinger provided rock samples from his Ph.D. study in the Lofoten-Vesterålen area. Ivar Svensson and Ole Morten Øian carried out the petrophysical laboratory measurements. Jon Sandvik, Amarok compiled the marine gravity data and Tormod Henningsen, Statoil, Roy Gabrielsen and Eigil Rasmussen, Norsk Hydro, Robert Johannessen, Elf Petroleum and Harald Brekke, NPD gave advice and consultancy during the interpretation phase. To all these persons and institutions we express our sincere thanks. We are also indebted to Drs. Mark Smethurst and Jan Reidar Skilbrei for critically reading the manuscript and for suggestions towards its improvement. We are further grateful to Gunnar Grønli for drafting the figures.

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List of figures, table and map sheet

4265, UTM-coord. (ED50) 582920E/7787120N. Northern shore of Sifjorden.

Fig. 21. Geophysical interpretation map, modified from Map sheet 14 (Olesen & Torsvik 1993).

Fig. 22. Gravity inversion using GDEPTH (Torsvik & Fichler 1993) along ten sections across the Ribban Basin (incl. Marmæle Spur and Skomvær and Havbåen Subbasins) and Vestfjorden Basin. Location of the profiles A-J is shown on Map sheet 1 and Figs. 3, 5, 6 and 21. Yellow colour illustrates sediments and depths are shown in km. Density contrast between basement and sediments: 400 kg/m^3.

Fig. 23. Gravity interpretation along the seismic profile TB-38-87. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

Fig. 24. Gravity interpretation along the seismic profile LO-06-86. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

Fig. 25. Gravity interpretation along the seismic profile LO-16-86. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

Fig. 26. Gravity interpretation along the seismic profile LO-46-88. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

Fig. 27. Location of palaeomagnetic sampling areas. K=Kvaløya, V=Vesterålen & S=Senja. A more detailed location of the sampling points is shown on Map sheet 1.

Fig. 28. Examples of stepwise thermal demagnetization of a breccia sample from Kvaløya (Top diagram) and a banded gneiss sample from Vesterålen (Lower diagram). In stereoplots, open (closed) symbols denote negative (positive) inclinations. Diagrams to the right show intensity as function of temperature.

Fig. 29. Distribution of characteristic remanence components, i.e. components identified via thermal demagnetization from Kvaløya, Senja and Vesterålen. HB=High unblocking components; LB=Low unblocking temperature components. LB components have a characteristic Tertiary/recent direction.

Fig. 30. Palaeomagnetic poles from Kvaløya, Vesterålen and Senja displayed together with the reference apparent polar wander path for Baltica (Torsvik et al. 1992). Note that poles from Kvaløya and Senja correspond with the Permo-Carboniferous part of the reference path (c. 270 Ma), whereas the Vesterålen pole (probably a regional uplift magnetization) does not correspond with any part of the polarwander path. However, adjustment for a possible tilting of Vesterålen of the order of 15-20 degrees on a northeast axis brings the Vesterålen pole in correspondence with the Upper Ordovician (c. 445 Ma) part of the polarwander path (see stippled line). It is also interesting to note that the Kvaløya and Senja poles lie to the left of the reference path which may suggest minor tilting in post-Permian times.

Table

Table 1. Density of sedimentary sequences from density logs of wells in the Nordland area.

Map sheet

Map sheet 1. Geophysical interpretation map, Scale 1:1 mill.

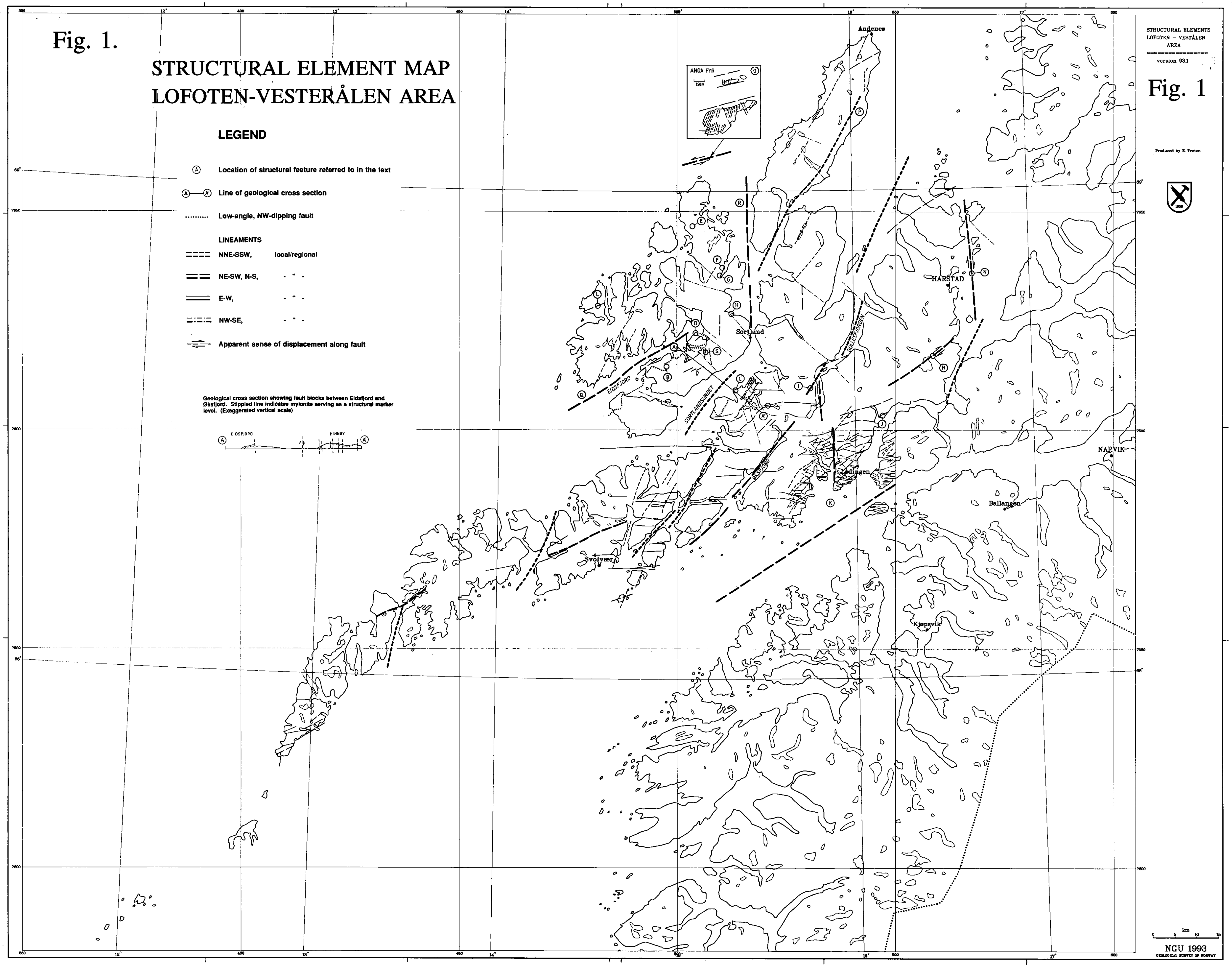


Fig. 1.
STRUCTURAL ELEMENT MAP
LOFOTEN-VESTERÅLEN AREA
LEGEND
Location of structural feature referred to in the text
Line of geological cross section
Low-angle, NW-dipping fault
LINEAMENTS
NNE-SSW, local/regional
NE-SW, N-S, " "
E-W, " "
NW-SE, " "
Apparent sense of displacement along fault
Geological cross section showing fault blocks between Eidsfjord and Øksfjord. Stippled line indicates mylonite serving as a structural marker level. (Exaggerated vertical scale)
EIDSFJORD
HINNØY
ANDA FYR
Andenes
Sortland
HARSTAD
Svolvær
Lødingen
NARVIK
Ballangen
Kjøpsvik
EIDSFJORD
SORTLANDSUNDET
ØKSFJORD
GULLESFJORDEN
STRUCTURAL ELEMENTS
LOFOTEN – VESTÅLEN
AREA
version 93.1
Fig. 1
Produced by E. Tveten
NGU 1993
GEOLOGICAL SURVEY OF NORWAY

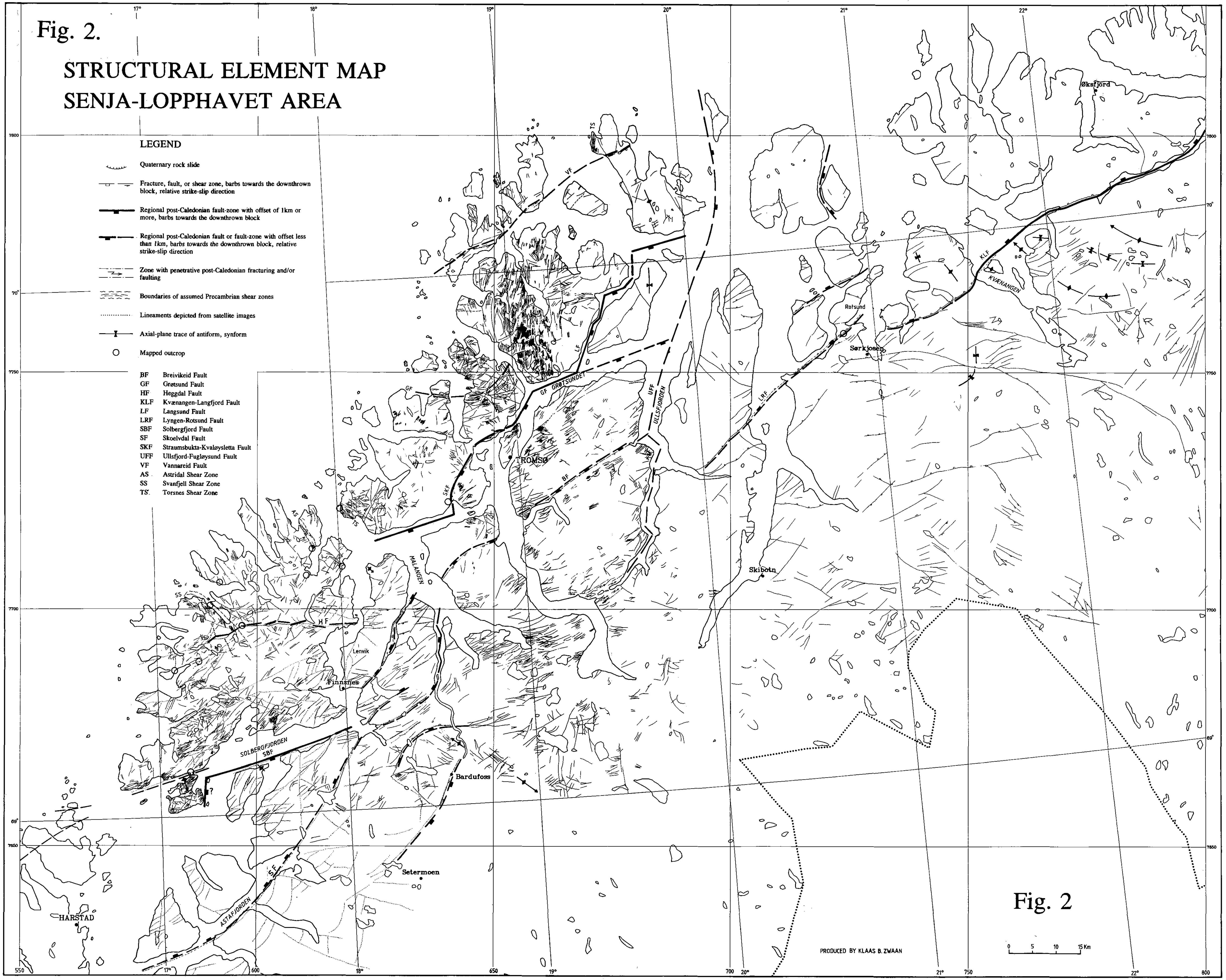
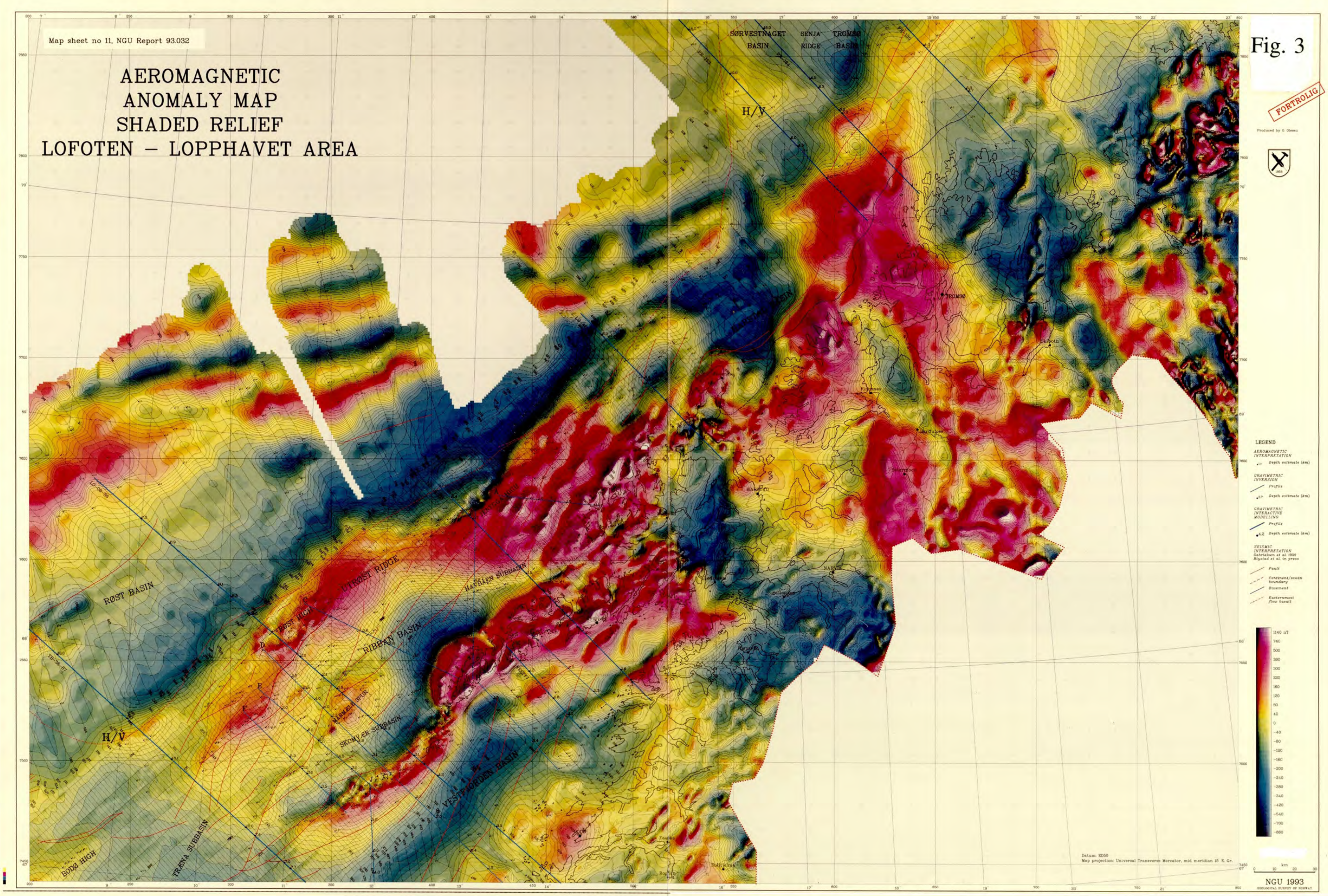
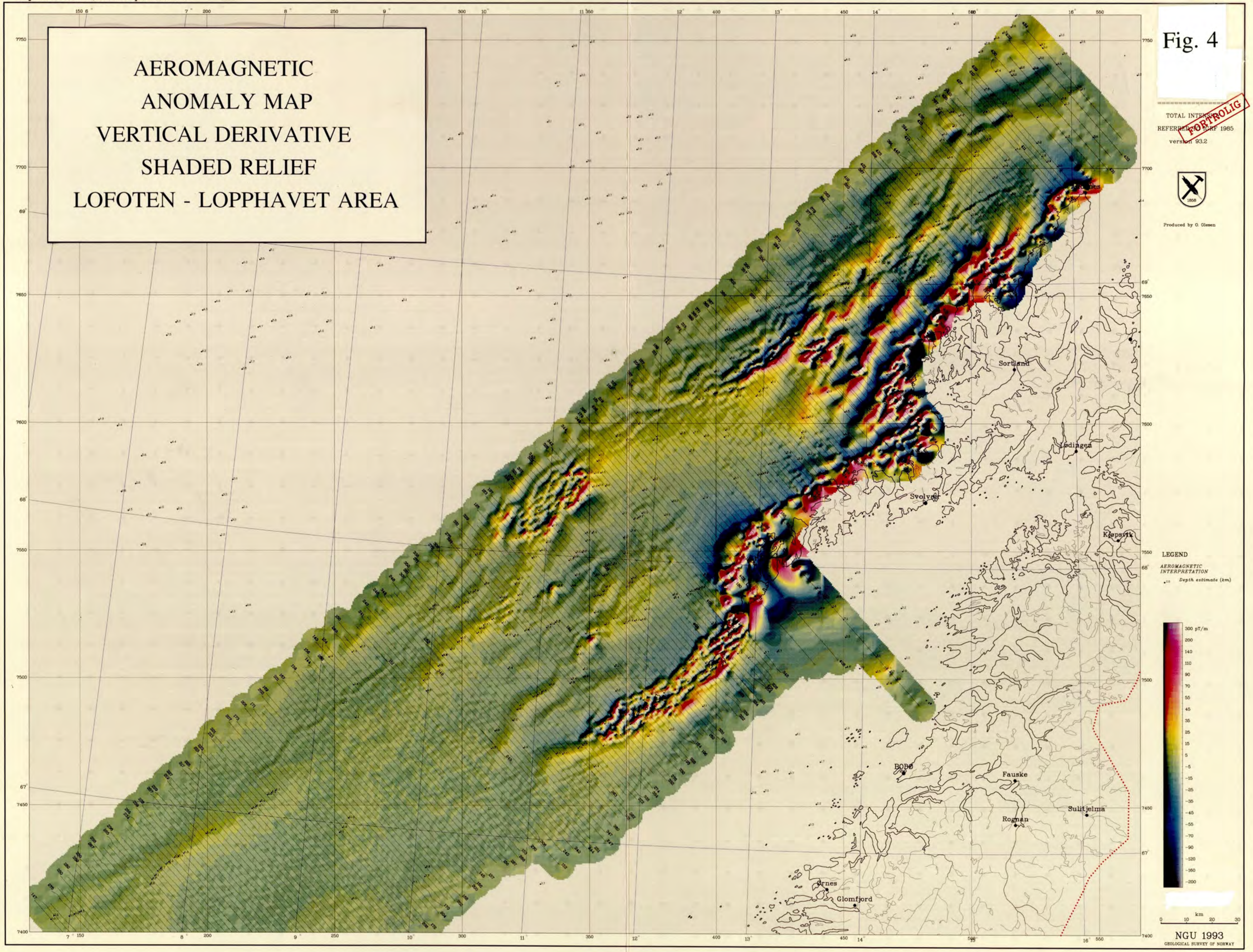


Fig. 2.
STRUCTURAL ELEMENT MAP
SENJA-LOPPHAVET AREA
LEGEND
Quaternary rock slide
Fracture, fault, or shear zone, barbs towards the downthrown block, relative strike-slip direction
Regional post-Caledonian fault-zone with offset of 1km or more, barbs towards the downthrown block
Regional post-Caledonian fault or fault-zone with offset less than 1km, barbs towards the downthrown block, relative strike-slip direction
Zone with penetrative post-Caledonian fracturing and/or faulting
Boundaries of assumed Precambrian shear zones
Lineaments depicted from satellite images
Axial-plane trace of antiform, synform
Mapped outcrop
BF Breivikeid Fault
GF Grøtsund Fault
HF Heggdal Fault
KLF Kvænangen-Langfjord Fault
LF Langsund Fault
LRF Lyngen-Rotsund Fault
SBF Solbergfjord Fault
SF Skoelvdal Fault
SKF Straumsbukta-Kvaløysletta Fault
UFF Ullsfjord-Fugløysund Fault
VF Vannareid Fault
AS Astridal Shear Zone
SS Svanfjell Shear Zone
TS Torsnes Shear Zone
TROMSØ
GRØTSUNDET
ULLSFJORDEN
MALANGEN
SOLBERGFJORDEN
ASTAFJORDEN
KVÆNANGEN
Øksfjord
Rotsund
Sørkjosen
Skibotn
Lenvik
Finnsnes
Bardufoss
Setermoen
HARSTAD
PRODUCED BY KLAAS B. ZWAAN
0 5 10 15 Km
Fig. 2


Map sheet no 11, NGU Report 93.032
AEROMAGNETIC
ANOMALY MAP
SHADED RELIEF
LOFOTEN – LOPPHAVET AREA
Fig. 3
FORTROLIG
SØRVESTNAGET BASIN
SENJA RIDGE
TROMSØ BASIN
H/V
RØST BASIN
UTRØST RIDGE
RØST HIGH
RIBBAN BASIN
HADSEN SUBBASIN
SKOMVÆR SUBBASIN
VESTFJORDEN BASIN
TRÆNA SUBBASIN
BODØ HIGH
TROMSØ
LEGEND
NGU 1993

Map sheet no 12, NGU Report 93.032



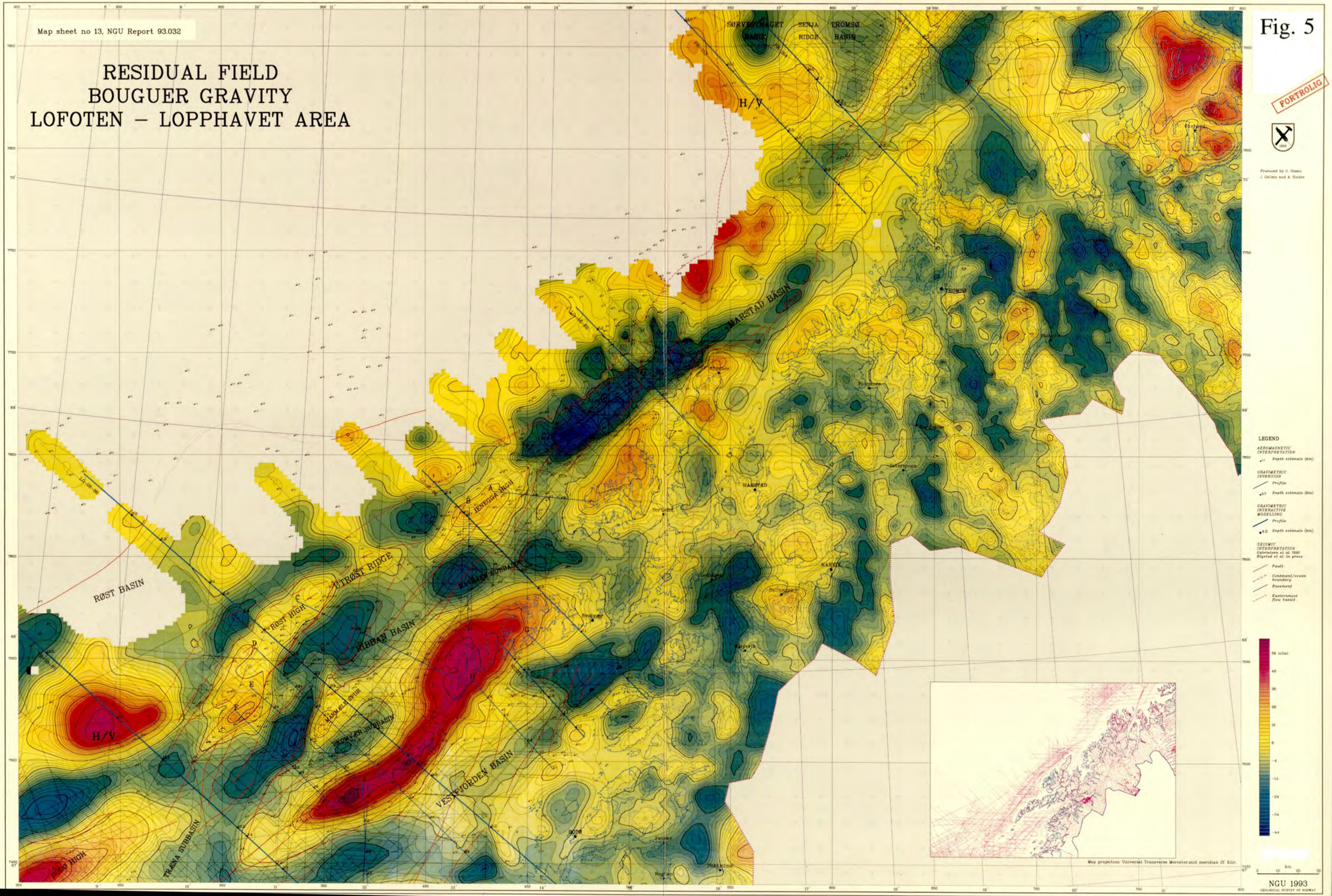


Fig. 5
Map sheet no 13, NGU Report 93.032
RESIDUAL FIELD
BOUGUER GRAVITY
LOFOTEN – LOPPHAVET AREA
FORTROLIG
SØRVESTNAGET BASIN
SENJA RIDGE
TROMSØ BASIN
H/V
HARSTAD BASIN
TROMSØ
HARSTAD
NARVIK
JENEGGA HIGH
RØST BASIN
UTRØST RIDGE
RØST HIGH
RIBBAN BASIN
SKOMVÆR SUBBASIN
VESTFJORDEN BASIN
TRÆNA SUBBASIN
BODØ
LEGEND
AEROMAGNETIC INTERPRETATION
Depth estimate (km)
GRAVIMETRIC INVERSION
Profile
Depth estimate (km)
GRAVIMETRIC INTERACTIVE MODELLING
Profile
Depth estimate (km)
SEISMIC INTERPRETATION
Gabrielsen et al. 1990
Blystad et al. in press
Fault
Continent/ocean boundary
Basement
Easternmost flow basalt
56 mGal
46
Map projection: Universal Transverse Mercator,mid meridian 15° E.Gr.
NGU 1993
GEOLOGICAL SURVEY OF NORWAY

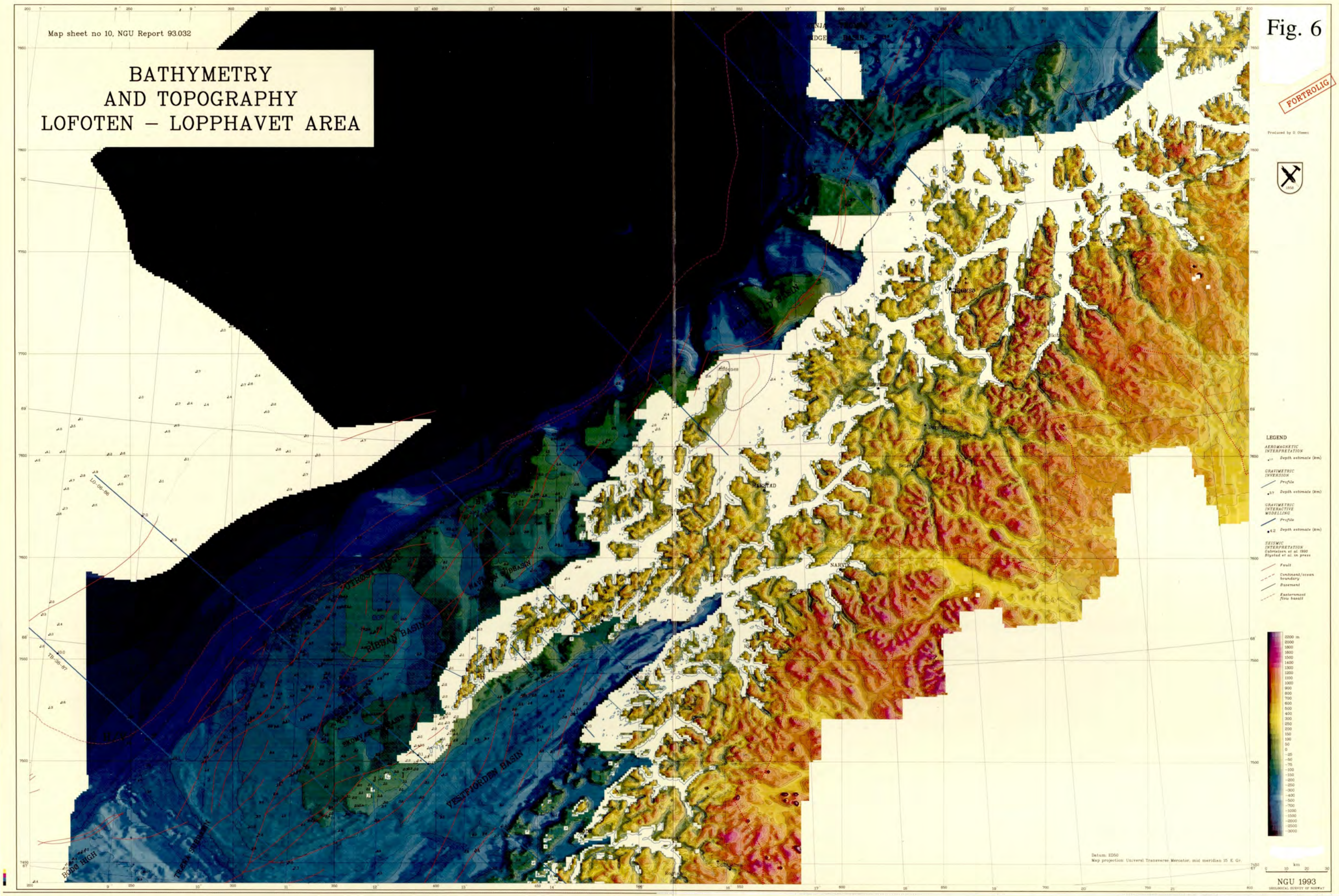


Fig. 6
Map sheet no 10, NGU Report 93.032
BATHYMETRY
AND TOPOGRAPHY
LOFOTEN – LOPPHAVET AREA
FORTROLIG
VESTFJORDEN BASIN
RIBBAN BASIN
HARSTAD
NARVIK
BODØ HIGH
LEGEND
AEROMAGNETIC INTERPRETATION
Depth estimate (km)
GRAVIMETRIC INVERSION
Profile
Depth estimate (km)
GRAVIMETRIC INTERACTIVE MODELLING
Profile
Depth estimate (km)
SEISMIC INTERPRETATION
Gabrielsen et al. 1990
Blystad et al. in press
Fault
Continent/ocean boundary
Basement
Easternmost flow basalt
2200 m
Datum: ED50
Map projection: Universl Transverse Mercator, mid meridian 15 E. Gr.
km
0 10 20 30
NGU 1993
GEOLOGICAL SURVEY OF NORWAY

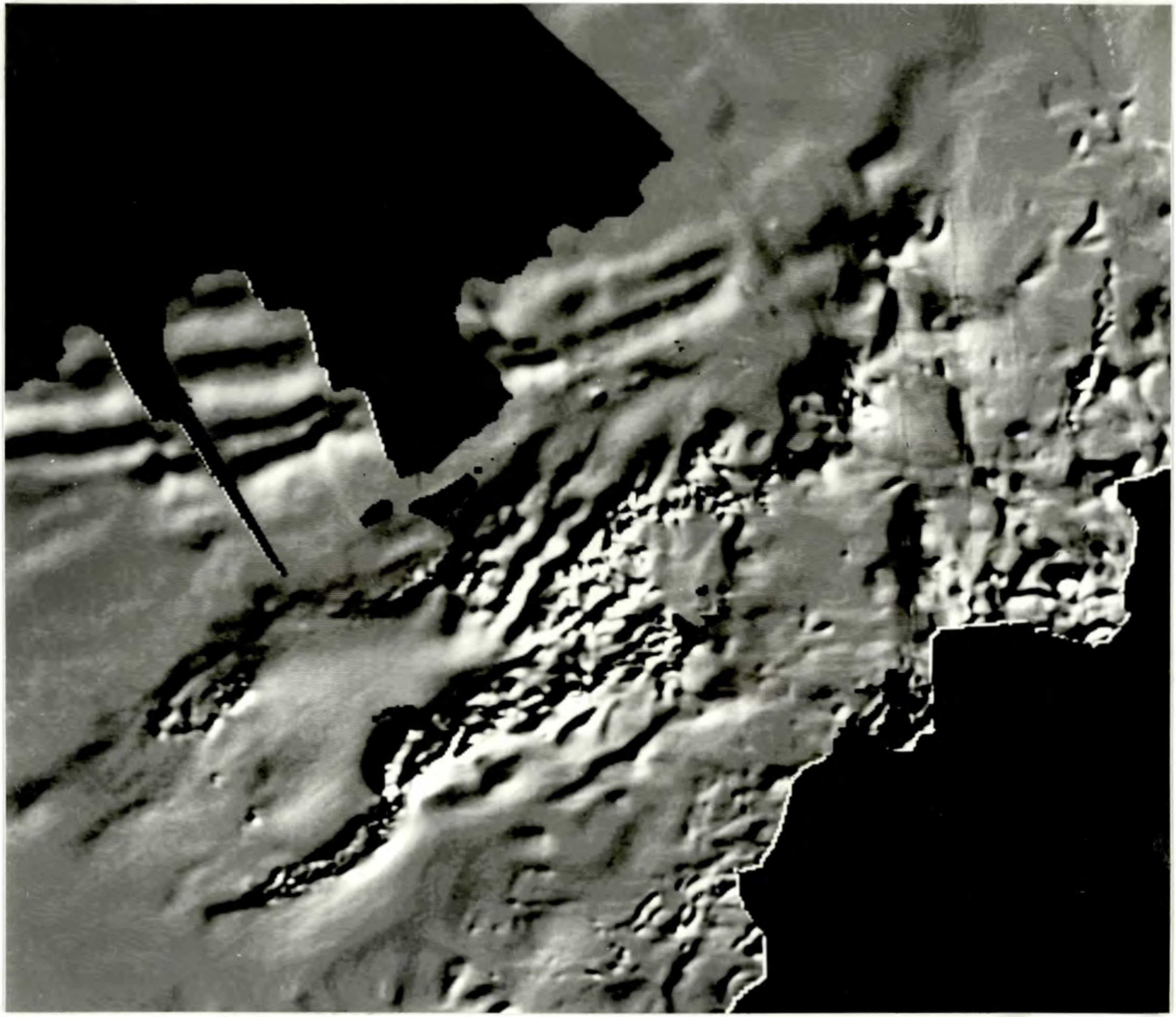


Fig. 7. Shaded relief image of the residual magnetic field from the Lofoten-Lopphavet area ('illumination from the southeast'). For scale and location of the image; see Fig. 3.

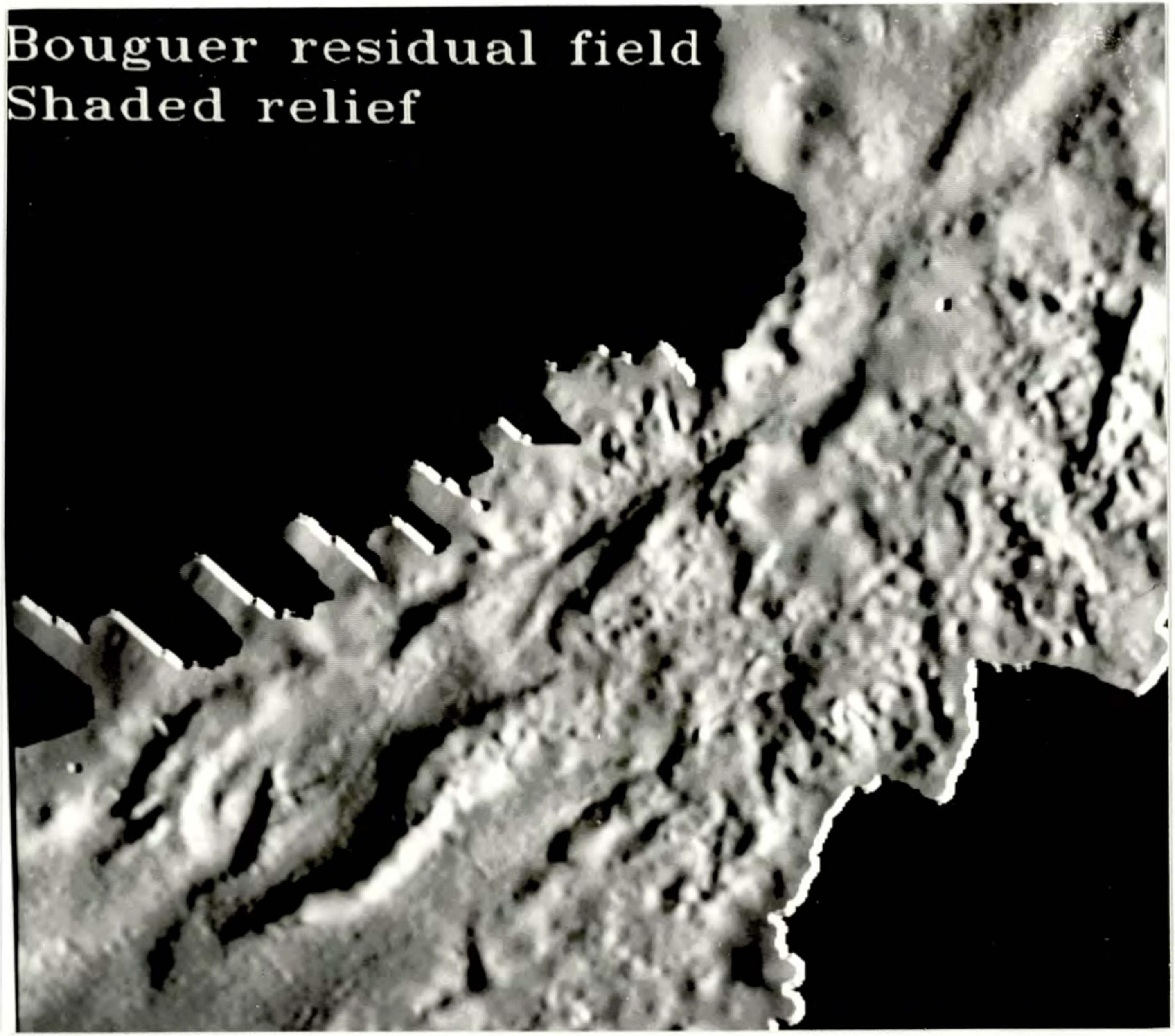


Fig. 8. *Shaded relief image of the residual Bouguer gravity field from the Lofoten-Lopphavet area ('illumination from the southeast'). For scale and location of the image; see Fig. 5.*

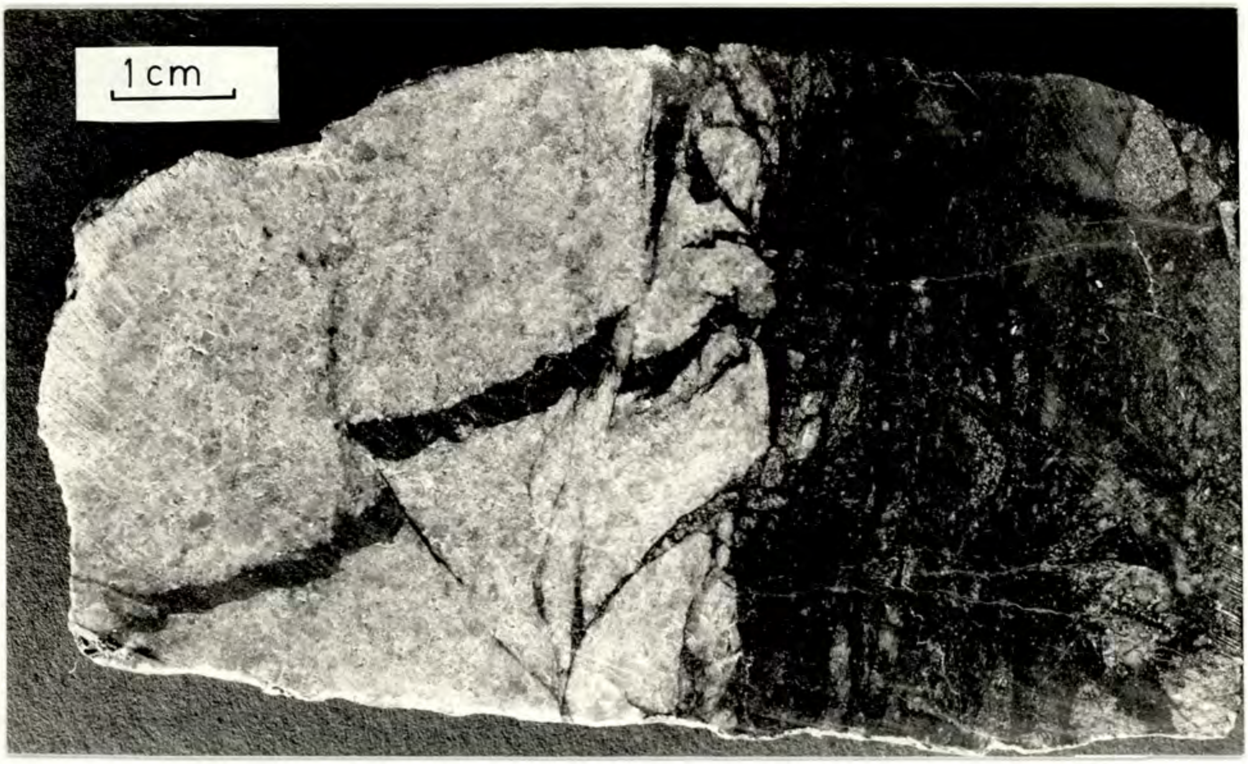
Fig. 9. Shaded relief image of the digital topography from the Lofoten-Vesterålen area ('illumination from the east'). For scale and location of the image; see Fig. 6.

Fig. 10. Breccia from the stream-bed at Bruland, Vikeid. Map sheet no. 1232 IV, UTM-coord. (ED50) 510210E/7626450N. Red fragments are strongly altered feldspar and quartz. White cement is mainly prehnite. Note dark coloured fragment (pseudotachylite), containing smaller fragments indicating that the brecciation is younger than the formation of the pseudotachylite. Tics at the edge are mm.

Fig. 11. Fault-canyon at Gullesfjorden, locality "I" in Fig. 1, looking to the northeast. Map sheet no. 1232 II, UTM-coord. (ED50) 531000E/7609500N.

Fig. 12. Westward dipping pseudotachylite cutting banded granulite-facies gneiss at Nyksund, northern Langøy. Map sheet no. 1132 I, UTM-coord. (ED50) 500500E-7654600N

Fig. 13. More than 5 cm thick pseudotachylite from locality "D" in Fig. 1, Eidsfjorden, central Langøy. Map sheet no. 1232 III, UTM-coord. 503200E-7620900N. The vein to the left is an "injection-vein", while the right (dark) half is a "fault-vein". The movement on the "fault-vein" has caused formation of "rip-outs" from the wall-rock, and these were moved after formation of the "injection-vein".



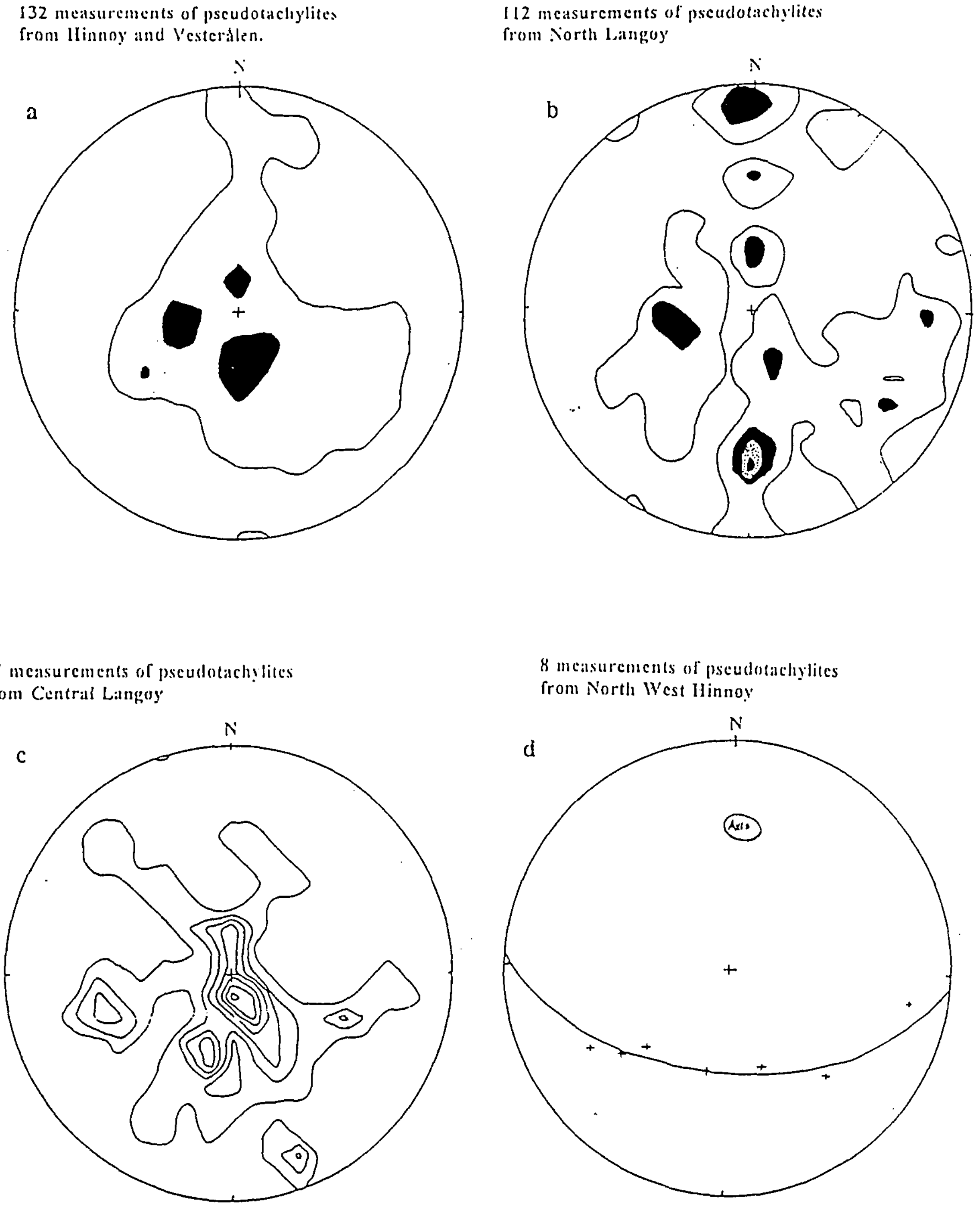


Fig. 14a-d. Stereographic projections of poles, lower hemisphere, of selected structural elements.

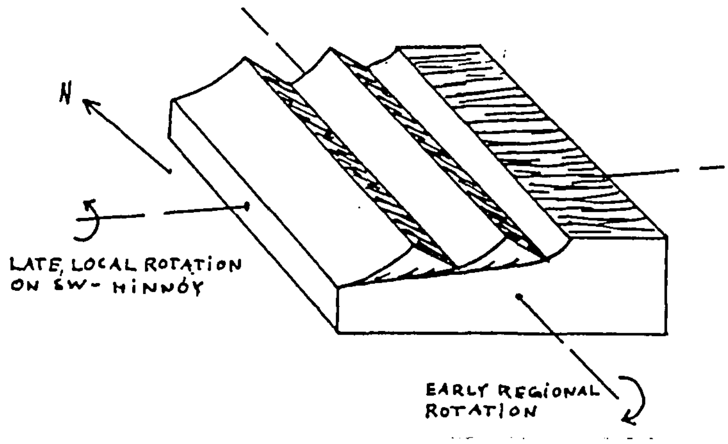
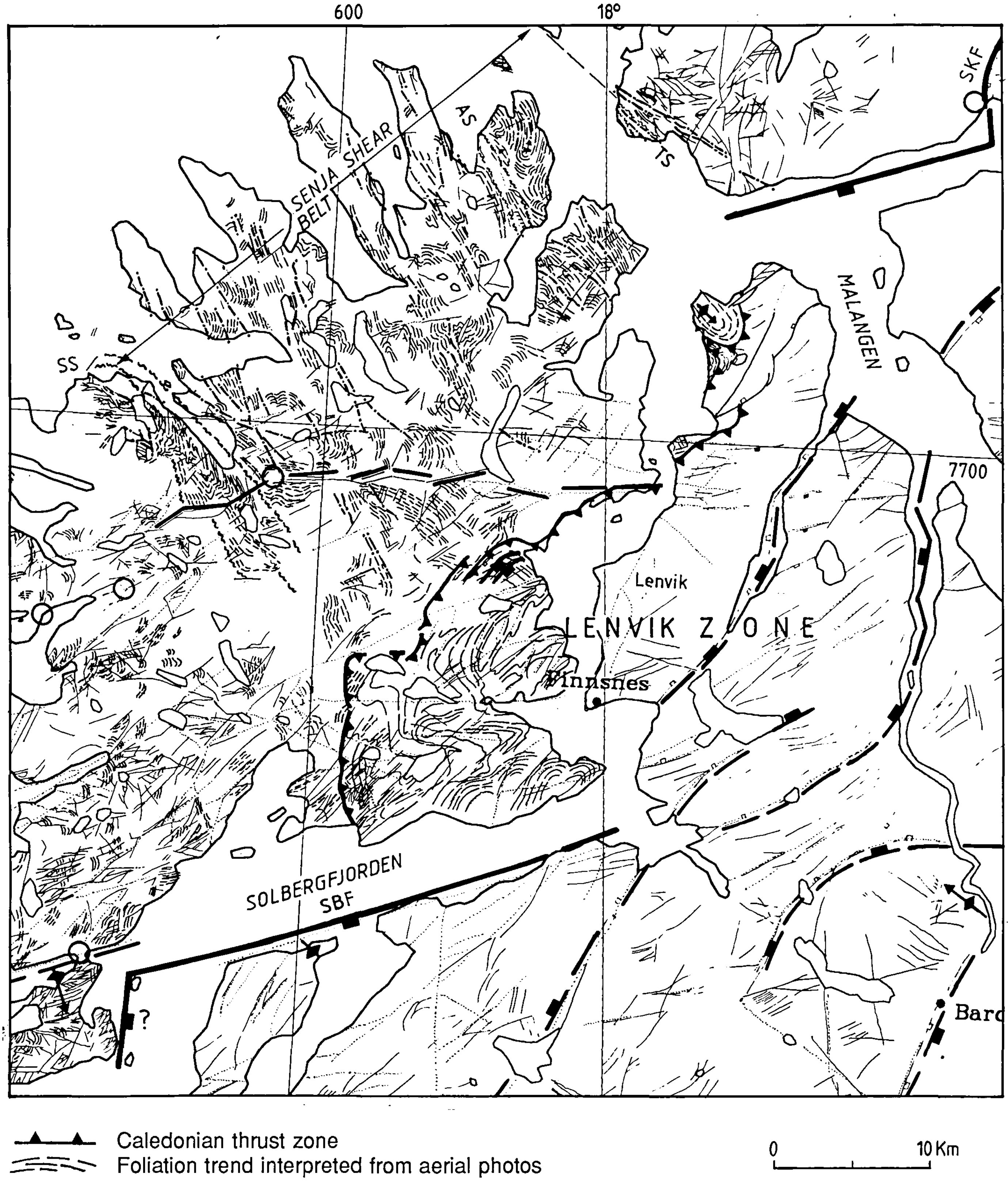


Fig. 15. Schematic block diagram of rotated fault blocks in the Vesterålen region.



Caledonian thrust zone
Foliation trend interpreted from aerial photos
Precambrian fault or shear zone
Other fracture, fault, or shear zone
For other symbols, see legend to the structural map, Senja-Lopphavet area in scale 1:250,000.

0 10 Km

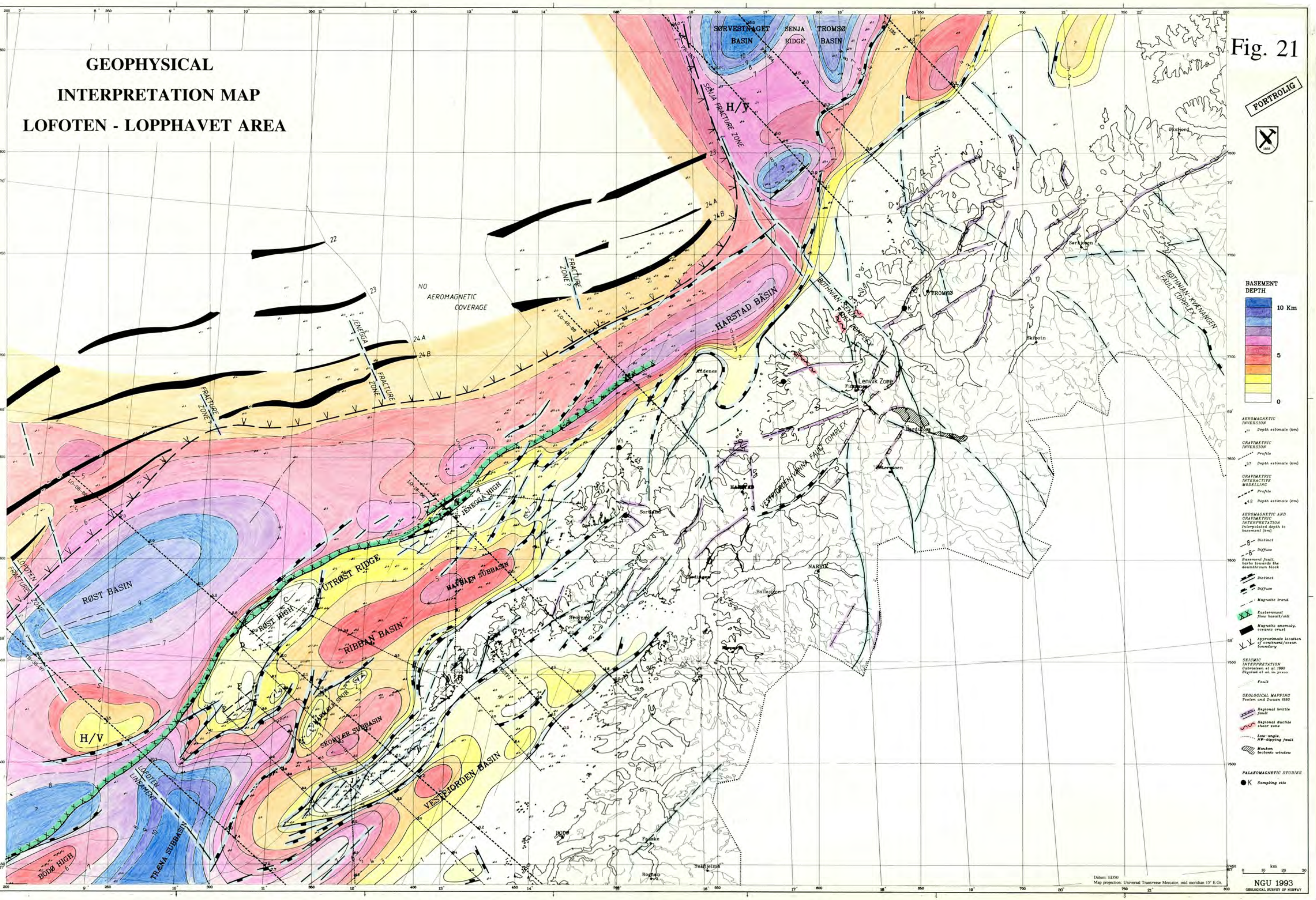
Fig. 16. Structural element map, Senja area. SKF - Straumsbukta-Kvaløysletta Fault, SS - Svanfjellet Shear Zone, AS - Astridal Shear Zone, TS - Torsnes Shear Zone, SBF - Solbergfjord Fault.

Fig. 17. Precambrian shear-zone within the Senja Belt represented by a fault-canyon. Map sheet no. 1433 IV, loc. 92.4014, UTM-coord. (ED50) 595310E/7700850N. Looking to the north with Luttind in the background.

Fig. 18. Precambrian ductile shear-zone. Tonalitic country rock is mylonitized into a relatively finegrained homogeneous porfyroclastic gneissfoliation. Same locality as Fig. 17.

Fig. 19. Postcaledonian fault at Stonglandeidet, normal fault with sinistral strike-slip component - (Tveten & Zwaan 1993). The granodioritic country rock is cataclastically deformed and fragments are cemented by calcite and silica. Map sheet 1333 II, loc. no. 92.3590, UTM-coord. (ED50) 586700E/7665400N.

Fig. 20. Postcaledonian fault on Senja sampled for palaeomagnetic dating. Two phases of deformation are developed. The oldest (the greenish coloured rock with the bore holes) has chlorite, recrystallized red K-feldspar, epidote and haematite. This semicataclastic mylonite is enveloped by a later cataclastic gouge zone. Map sheet no. 1333 I, Loc. no. 4265, UTM-coord. (ED50) 582920E/7787120N. Northern shore of Sifjorden.


GEOPHYSICAL
INTERPRETATION MAP
LOFOTEN - LOPPHAVET AREA
Fig. 21
FORTROLIG
SØRVESTNAGET BASIN
SENJA RIDGE
TROMSØ BASIN
SENJA FRACTURE ZONE
H/V
NO AEROMAGNETIC COVERAGE
FRACTURE ZONE
JENEGGA FRACTURE ZONE
HARSTAD BASIN
BOTHNIAN-SENJA FAULT COMPLEX
BOTHNIAN-KVÆNANGEN FAULT COMPLEX
Lenvik Zone
TROMSØ
Skibotn
Andenes
NARVIK
VESTFJORDEN-VANNA FAULT COMPLEX
JENEGGA HIGH
UTRØST RIDGE
HADSELØEN SUBBASIN
RØST BASIN
RØST HIGH
RIBBAN BASIN
LOFOTEN FRACTURE ZONE
SKOMVÆR SUBBASIN
VESTFJORDEN BASIN
LOFOTEN LINEAMENT
TRÆNA SUBBASIN
BODØ HIGH
BASEMENT DEPTH
10 Km
5
0
AEROMAGNETIC INVERSION
GRAVIMETRIC INVERSION
GRAVIMETRIC INTERACTIVE MODELLING
AEROMAGNETIC AND GRAVIMETRIC INTERPRETATION
SEISMIC INTERPRETATION
GEOLOGICAL MAPPING
PALAEOMAGNETIC STUDIES
Datum: ED50
Map projection: Universal Transverse Mercator, mid meridian 15° E.Gr.
NGU 1993
GEOLOGICAL SURVEY OF NORWAY

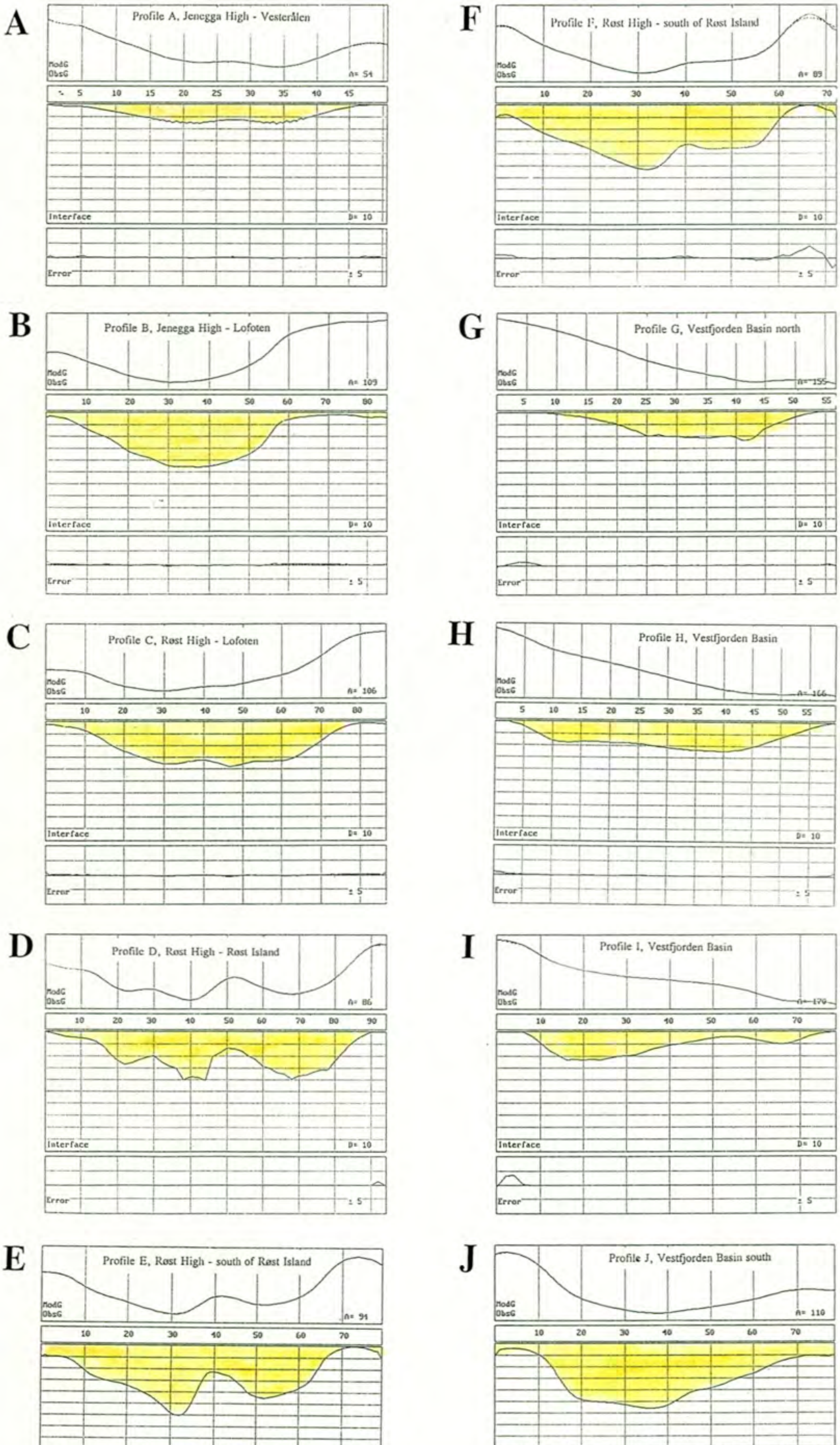


Fig. 22. Gravity inversion using GDEPTH (Torsvik & Fichler 1993) along ten sections across the Ribban Basin (incl. Marmæle Spur and Skomvær and Havbåen Subbasins) and Vestfjorden Basin. Location of the profiles A-J is shown on Map sheet 1 and Figs. 3, 5, 6 and 21. Yellow colour illustrates sediments and depths are shown in km. Density contrast between basement and sediments: 400 kg/m³.

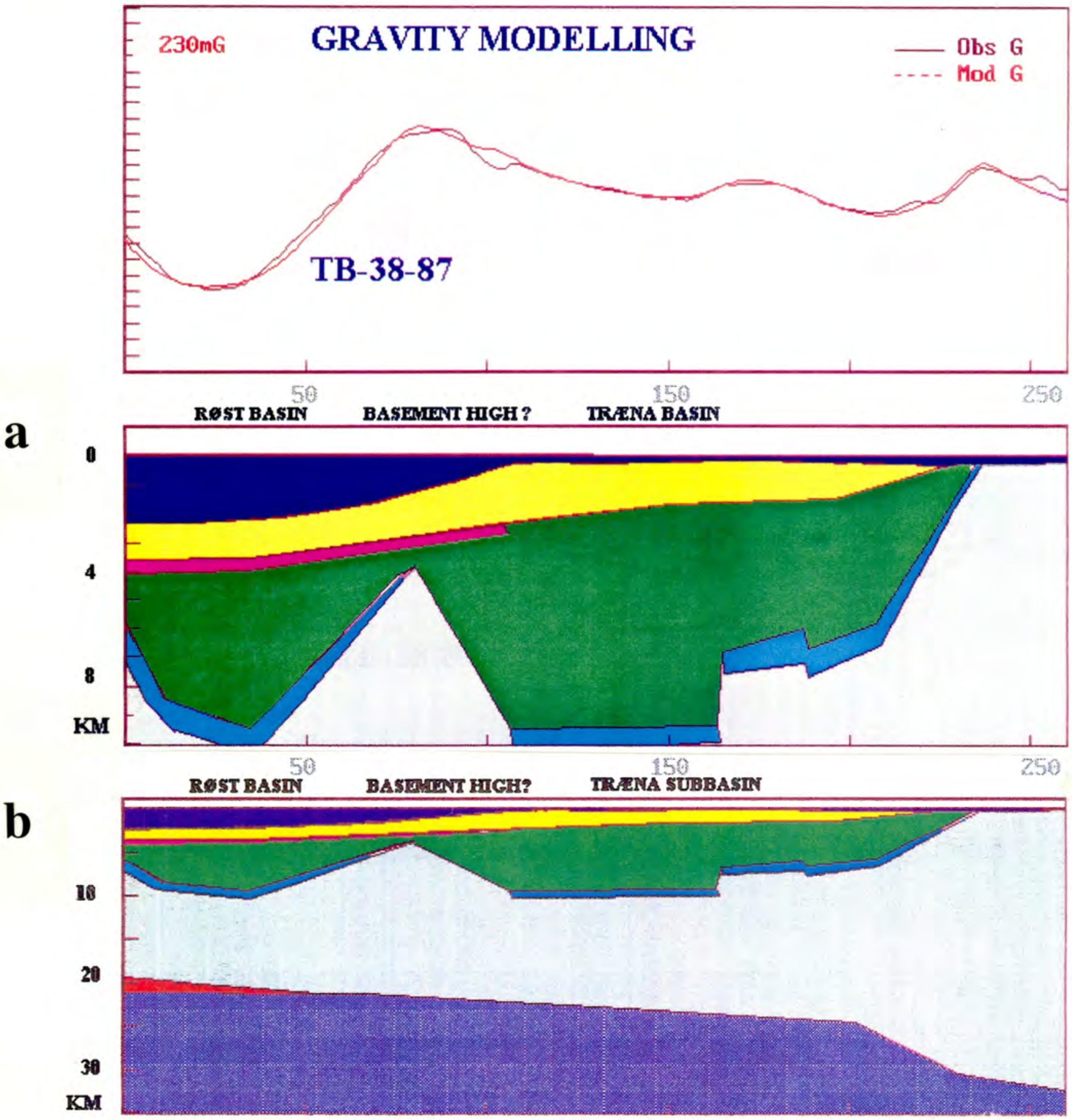


Fig. 23. Gravity interpretation along the seismic profile TB-38-87. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

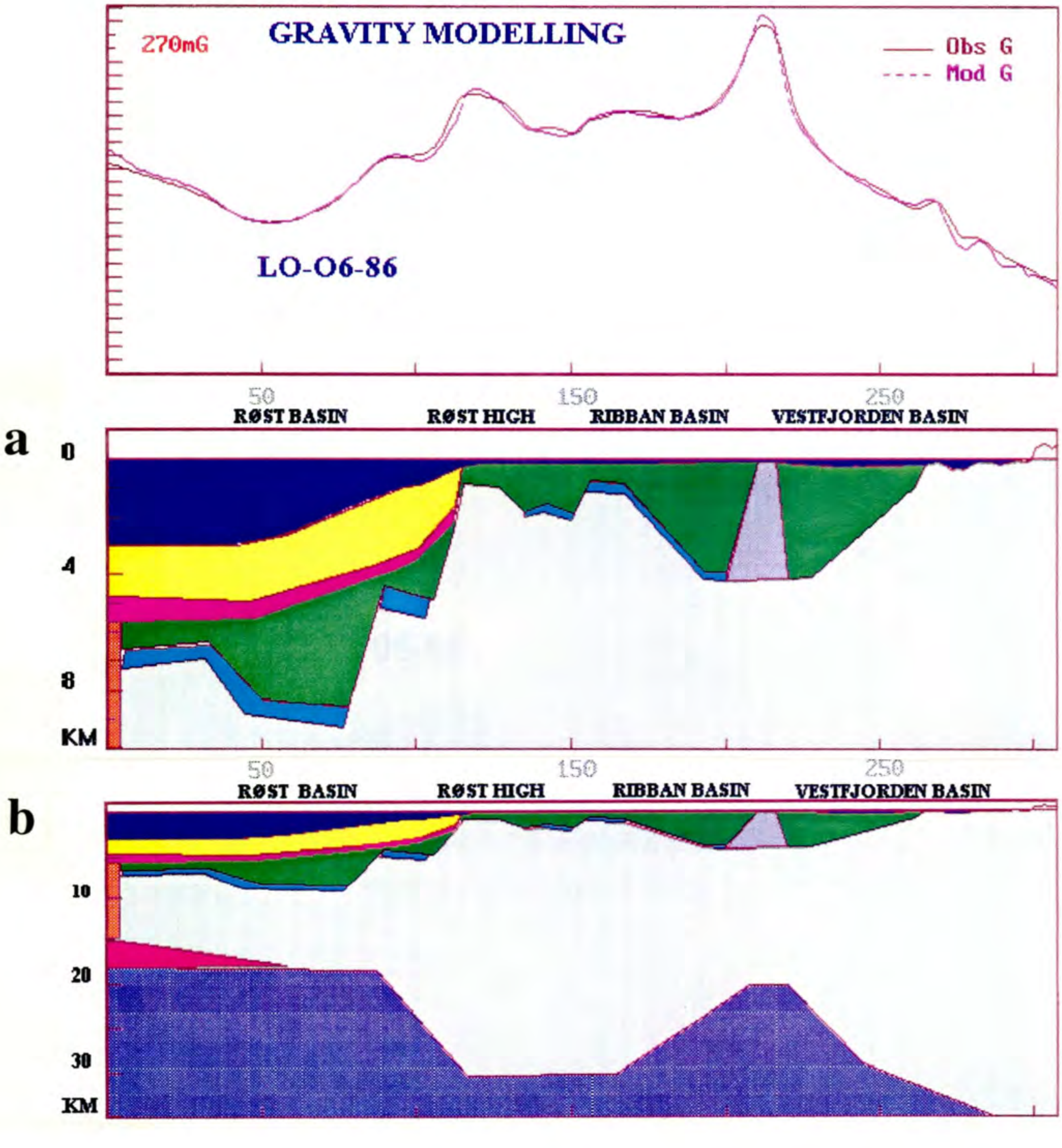


Fig. 24. Gravity interpretation along the seismic profile LO-06-86. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

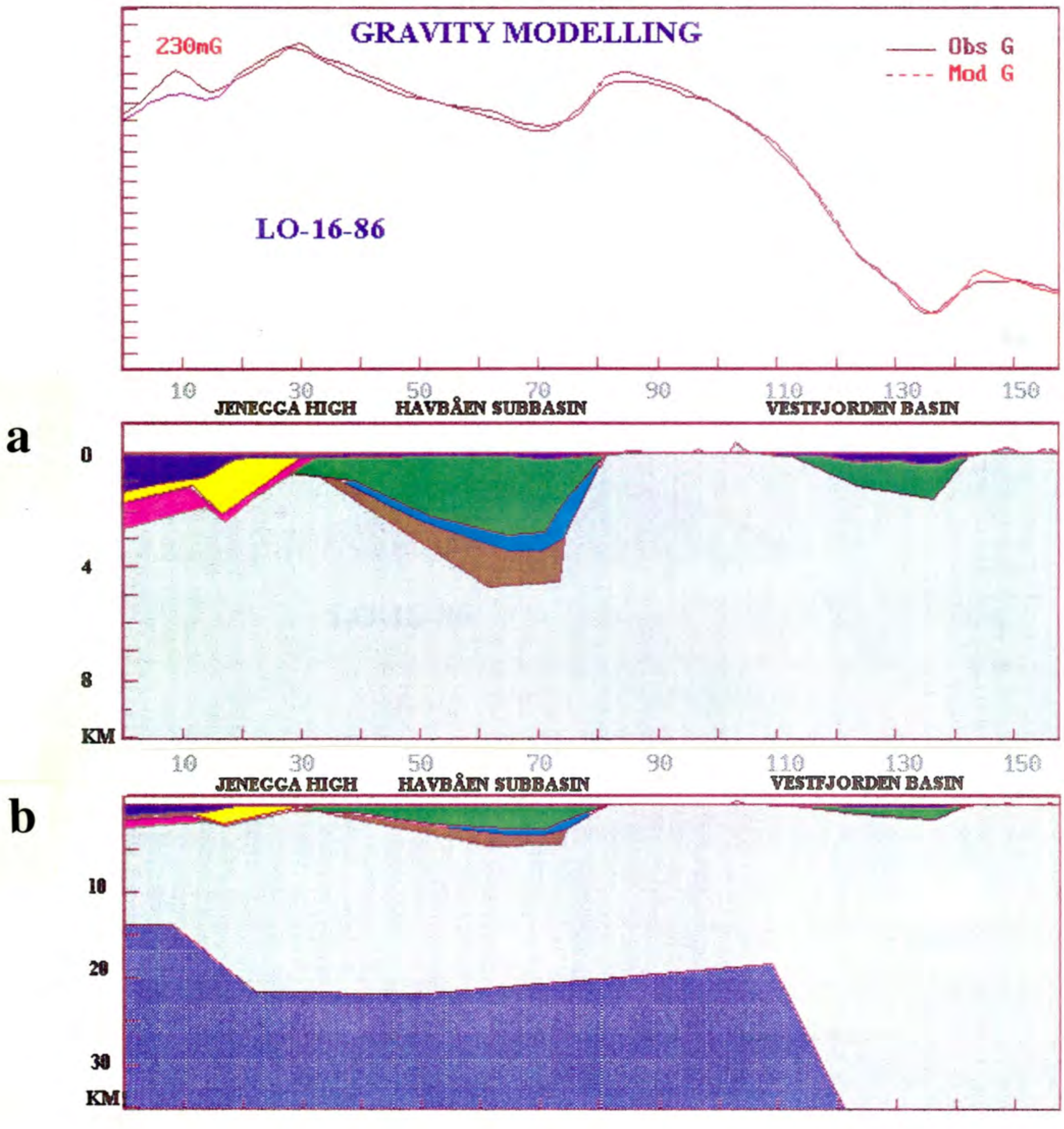


Fig. 25. Gravity interpretation along the seismic profile LO-16-86. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

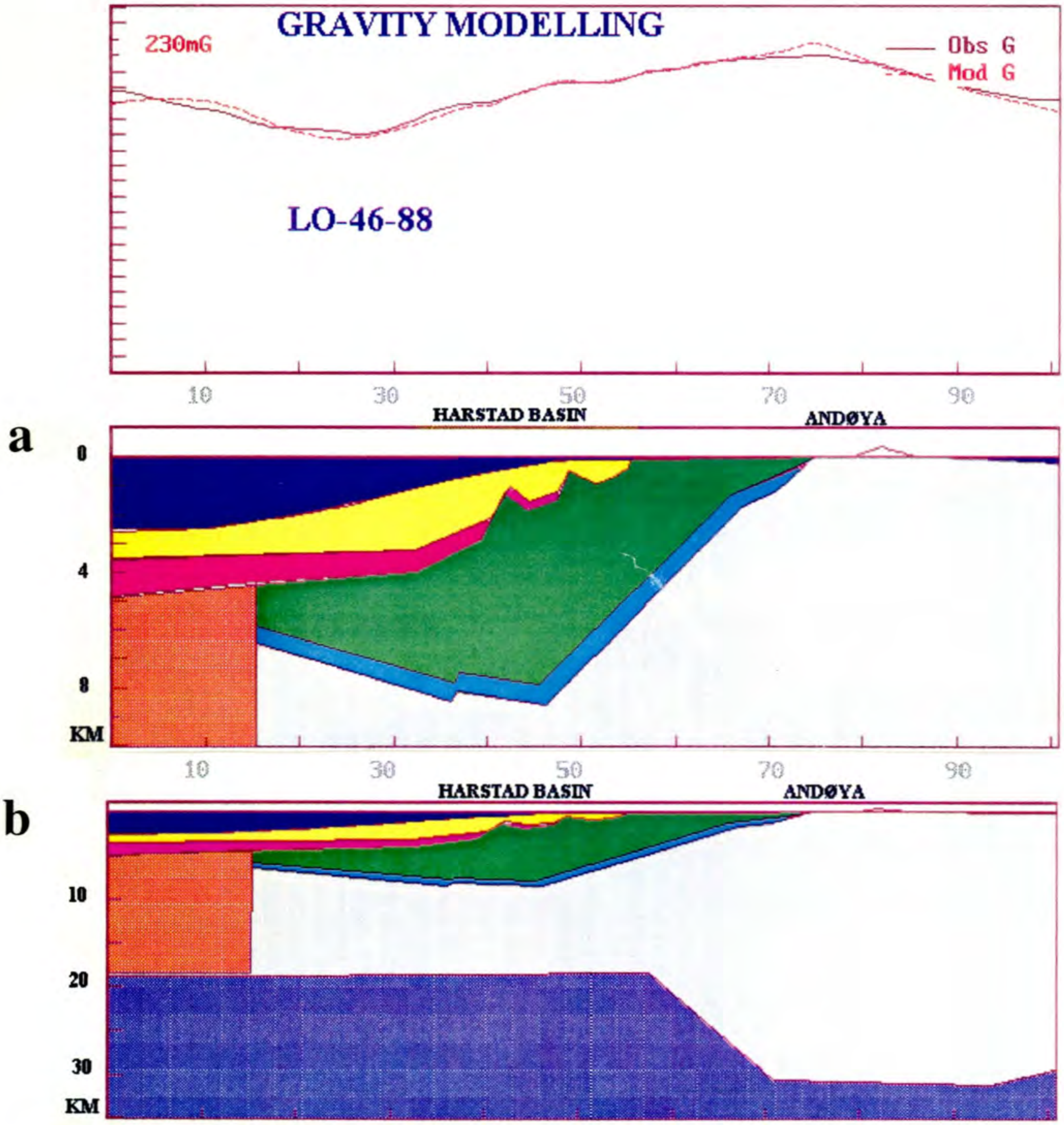


Fig. 26. Gravity interpretation along the seismic profile LO-46-88. Depth extent: a) 10 km and b) 35 km. The applied densities are shown in Table 1. The location of the profile is shown on Map sheet 1 and Figs. 3, 5, 6 and 21.

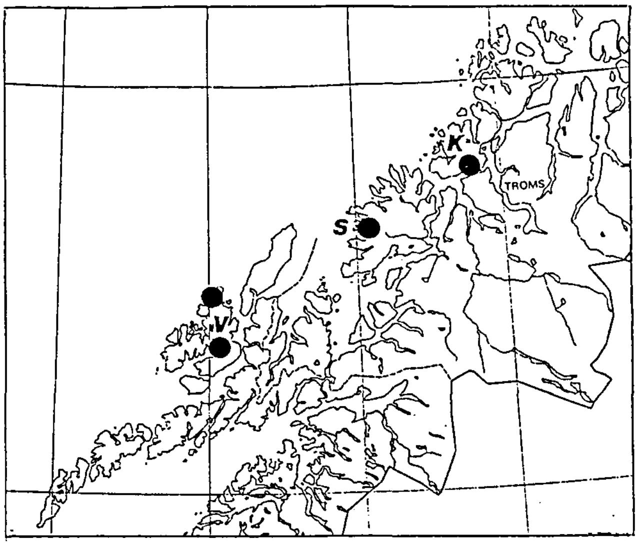
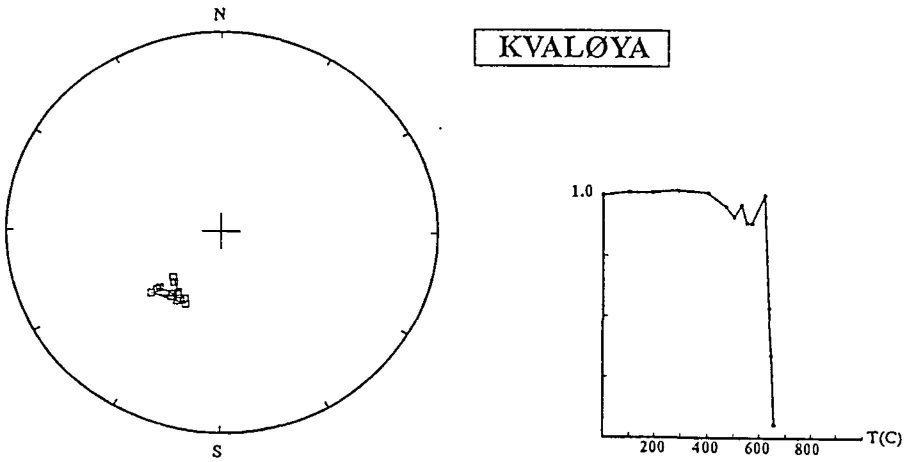


Fig. 27. Location of palaeomagnetic sampling areas. K=Kvaløya, V=Vesterålen & S=Senja. A more detailed location of the sampling points is shown on Map sheet 1.



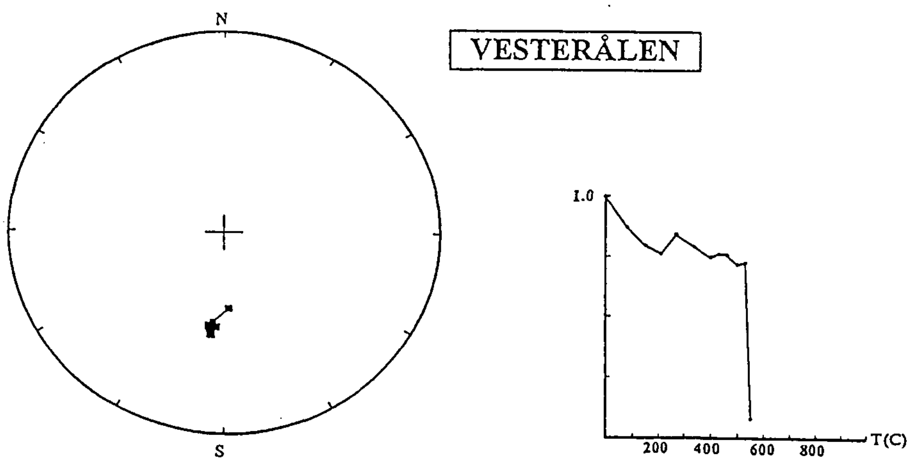


Fig. 28. Examples of stepwise thermal demagnetization of a breccia sample from Kvaløya (Top diagram) and a banded gneiss sample from Vesterålen (Lower diagram). In stereoplots, open (closed) symbols denote negative (positive) inclinations. Diagrams to the right show intensity as function of temperature.

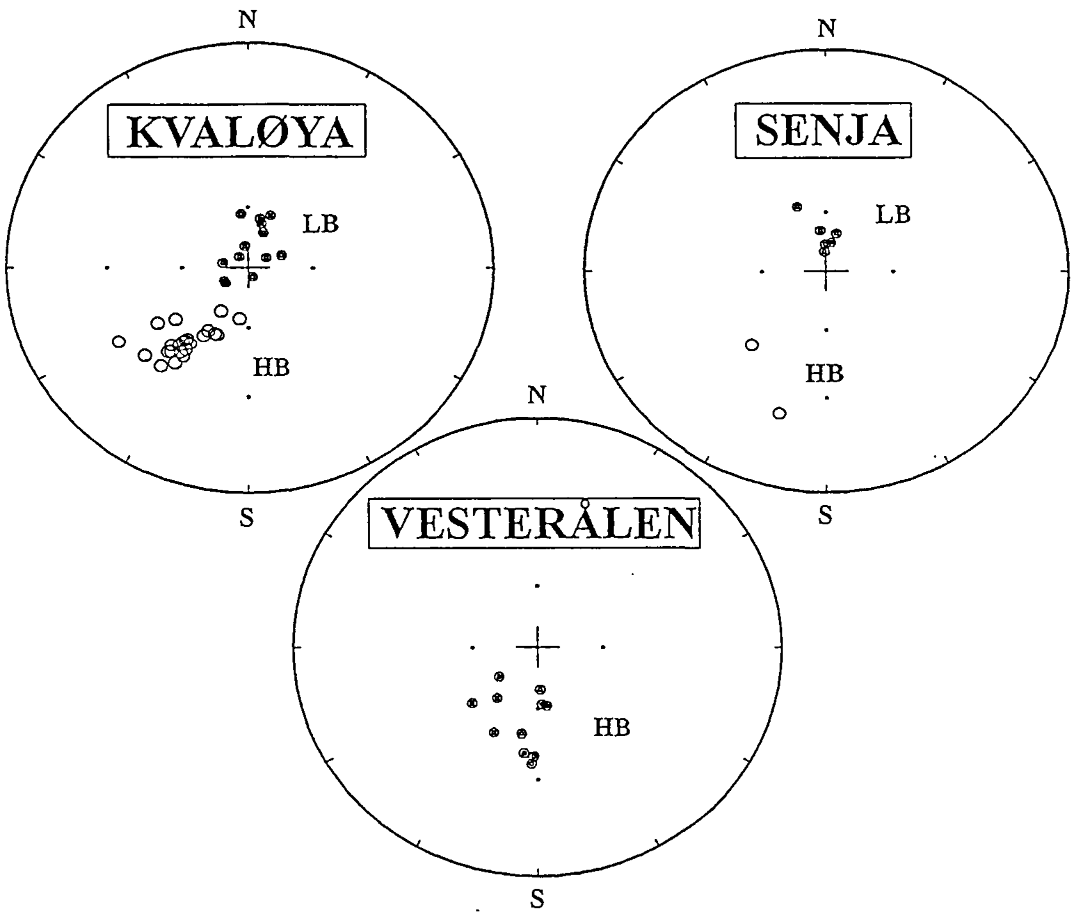


Fig. 29. Distribution of characteristic remanence components, i.e. components identified via thermal demagnetization from Kvaløya, Senja and Vesterålen. HB=High unblocking components; LB=Low unblocking temperature components. LB components have a characteristic Tertiary/recent direction.

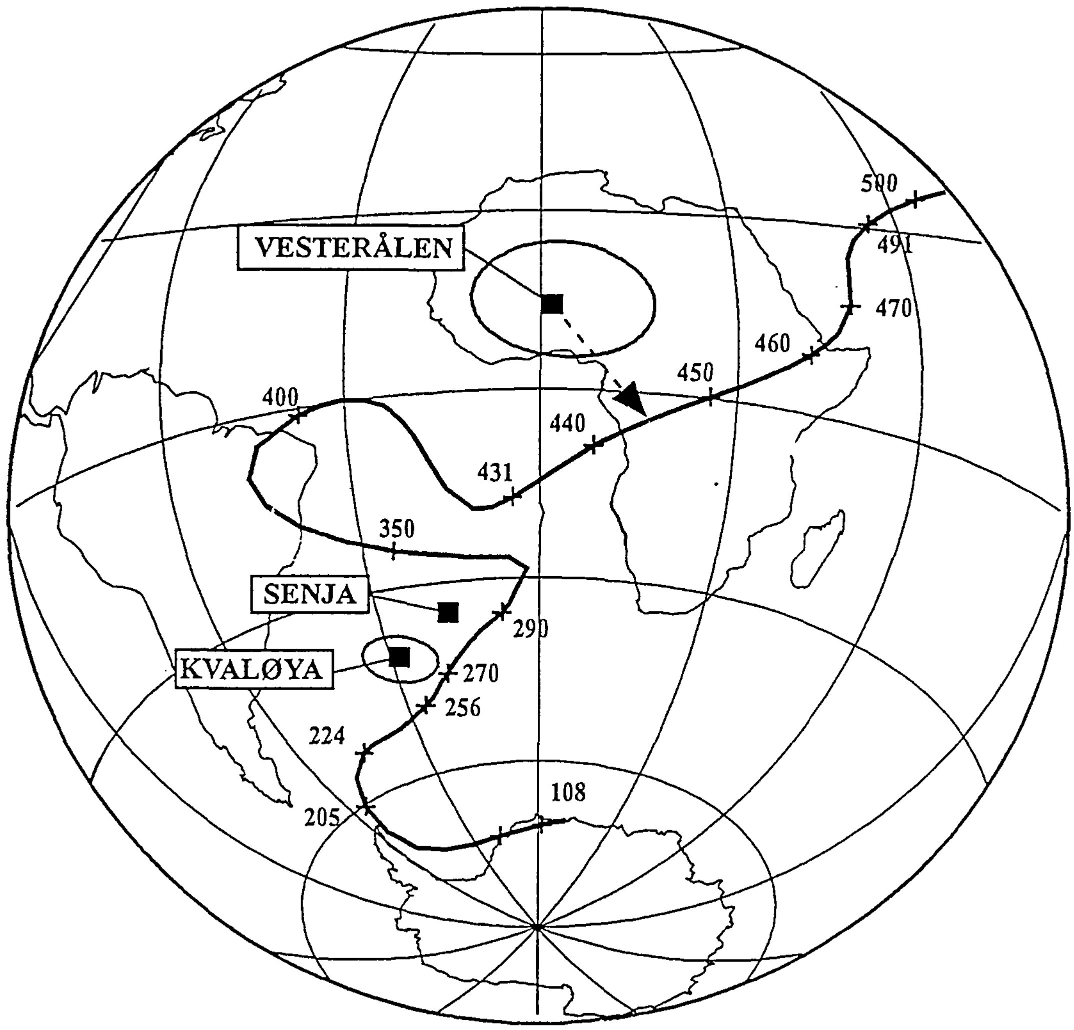
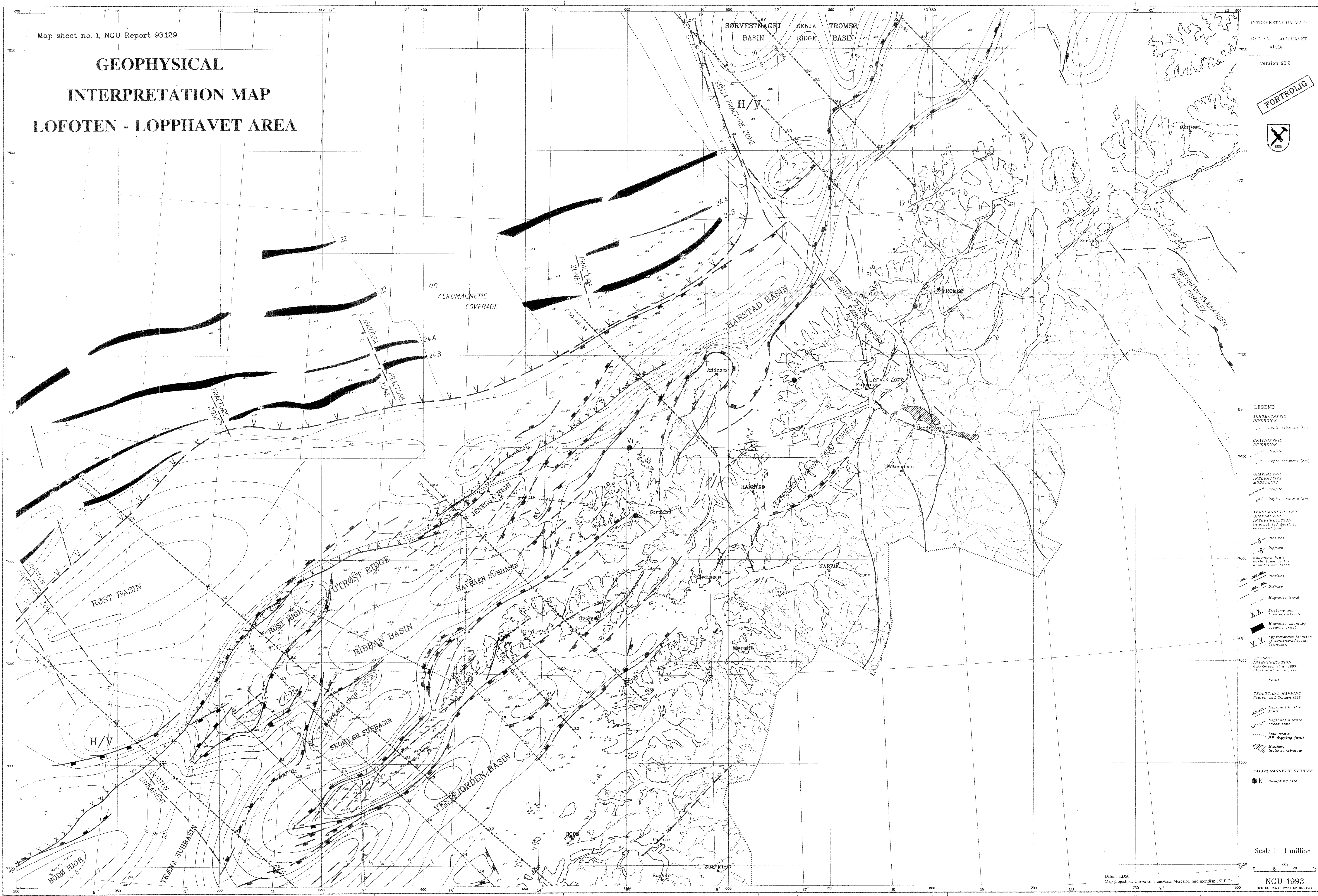


Fig. 30. Palaeomagnetic poles from Kvaløya, Vesterålen and Senja displayed together with the reference apparent polar wander path for Baltica (Torsvik et al. 1992). Note that poles from Kvaløya and Senja correspond with the Permo-Carboniferous part of the reference path (c. 270 Ma), whereas the Vesterålen pole (probably a regional uplift magnetization) does not correspond with any part of the polarwander path. However, adjustment for a possible tilting of Vesterålen of the order of 15-20 degrees on a northeast axis brings the Vesterålen pole in correspondence with the Upper Ordovician (c. 445 Ma) part of the polarwander path (see stippled line). It is also interesting to note that the Kvaløya and Senja poles lie to the left of the reference path which may suggest minor tilting in post-Permian times.



Map sheet no. 1, NGU Report 93.129
GEOPHYSICAL
INTERPRETATION MAP
LOFOTEN - LOPPHAVET AREA
INTERPRETATION MAP
LOFOTEN LOPPHAVET AREA
version 93.2
FORTROLIG
SØRVESTNAGET BASIN
SENJA RIDGE
TROMSØ BASIN
SENJA FRACTURE ZONE
H/V
NO AEROMAGNETIC COVERAGE
FRACTURE ZONE?
JENEGGA FRACTURE ZONE
HARSTAD BASIN
BOTHNIAN-SENJA FAULT COMPLEX
BOTHNIAN-KVÆNANGEN FAULT COMPLEX
VESTFJORDEN-VANNA FAULT COMPLEX
Lenvik Zone
LOFOTEN FRACTURE ZONE
RØST BASIN
UTRØST RIDGE
JENEGGA HIGH
HAVBÅEN SUBBASIN
RØST HIGH
RIBBAN BASIN
SKOMVÆR SUBBASIN
VESTFJORDEN BASIN
LOFOTEN LINEAMENT
TRÆNA SUBBASIN
BODØ HIGH
Tromsø
Skibotn
Andenes
Harstad
Sortland
Narvik
Svolvær
Bodø
Fauske
LEGEND
AEROMAGNETIC INVERSION
Depth estimate (km)
GRAVIMETRIC INVERSION
Profile
Depth estimate (km)
GRAVIMETRIC INTERACTIVE MODELLING
Profile
Depth estimate (km)
AEROMAGNETIC AND GRAVIMETRIC INTERPRETATION
Interpolated depth to basement (km)
Distinct
Diffuse
Basement fault, barbs towards the downthrown block
Distinct
Diffuse
Magnetic trend
Easternmost flow basalt/sill
Magnetic anomaly, oceanic crust
Approximate location of continent/ocean boundary
SEISMIC INTERPRETATION
Gabrielsen et al. 1990
Blystad et al. in press
Fault
GEOLOGICAL MAPPING
Tveten and Zwaan 1993
Regional brittle fault
Regional ductile shear zone
Low-angle, NW-dipping fault
Mauken tectonic window
PALAEOMAGNETIC STUDIES
Sampling site
Scale 1 : 1 million
km
Datum: ED50
Map projection: Universal Transverse Mercator, mid meridian 15° E.Gr.
NGU 1993
GEOLOGICAL SURVEY OF NORWAY