Bridging the gap between the onshore and offshore geology in Nordland, northern Norway

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Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T. & Fichler, C: Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. *Norwegian Journal of Geology*, Vol. 82, pp. 243-262. Trondheim 2002. ISSN 029-196x.

We have utilised potential field data in combination with seismic interpretation and bedrock mapping to improve the understanding of basement structures and rifting processes on the continental shelf offshore Nordland, northern Norway. Comparing the Bouguer gravity field to gravity responses from Airy roots at different depths for the northern Scandinavia mountains it is shown that the compensating masses are situated at a relatively shallow depth in the upper crust. The Tysfjord granite within the Transscandinavian Igneous Belt extends to a substantial depth (minimum 22 km) in the crust. These voluminous granites may be related to Proterozoic plate subduction along the western edge of the Baltic shield, analogous to the Sierra Nevada Batholith in California.

The NW-SE trending late Devonian extensional structures (Kollstraumen detachment, and Nesna and Sagfjord shear zones) extend from the mainland north-westwards below the Helgeland, Vestfjorden and Ribban basins. The Bivrost Lineament most likely represents a detachment dipping 5-15° to the southwest and may constitute the offshore extension of the Nesna shear zone. The entire Nordland mainland and offshore area is to a great extent affected by the NE-SW trending late Caledonian gravity collapse. Later (Late-Palaeozoic – Mesozoic) offshore rifting events have resulted in a shallow Moho and rotated fault-blocks separated by transfer zones giving rise to intermediate wavelength gravity and aeromagnetic anomalies. Changes in Moho depths occur across the Surt, Bivrost and Vesterålen transfer zones indicating that these structures are continuous to great depths within the crust. The more local transfer zones separate structural domains characterised by different fault-polarities within the Ribban and Vestfjorden basins. The Myken intrusive complex (Palaeocene age?) to the northeast of the Utgard High gives rise to large gravity and magnetic anomalies comparable to the anomalies originating from the basement structuring.

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Introduction

Potential field data provide continuous coverage of the mainland and offshore areas and act as a bridge between areas traditionally investigated by two different methods; field bedrock mapping and seismic interpretation. There is usually a gap of 10-30 km kilometres between the areas mapped by the two methods. The gravity and aeromagnetic data allow basement structures to be traced across this transition zone between the mainland and offshore areas. The areas offshore Nordland are covered with modern aeromagnetic surveys acquired by the Geological Survey of Norway during the last 15 years. Several groups of high frequency anomalies, not discernible in the old dataset, have been revealed. The improved quality relates to the use of more sensitive magnetometers, closer flight line spacing, more accurate navigation and improved processing and data presentation techniques.

Previous studies have taken the advantage of potential field data to extrapolate basement structures across the onshore-offshore divide in the Nordland area (Olesen et al. 1997b; Fichler et al. 1999). The present paper describes a new offshore map depicting the depth to crystalline basement as well as an onshore map of the depth to Precambrian basement. The basement structure is outlined in a 3D model interpreted from gravity data and constrained by aeromagnetic and petrophysical data, seismic interpretations and bedrock mapping. The modern aeromagnetic datasets also allow us to map the continuation of basement faults from the onshore to the offshore realm. We have concentrated on outlining the offshore extension of late Caledonian collapse structures that have been mapped on the mainland recently (Braathen et al. 2000, 2002; Osmundsen et al. 2003; Nordgulen et al. 2002).

We have addressed the mechanism of isostatic compensation of the Scandinavian mountains in order to define the regional gravity field for the 3D modelling. Assuming that the region is close to isostatic equilibrium, these uplifted mountainous areas along the Norwegian-Swedish national border must be supported

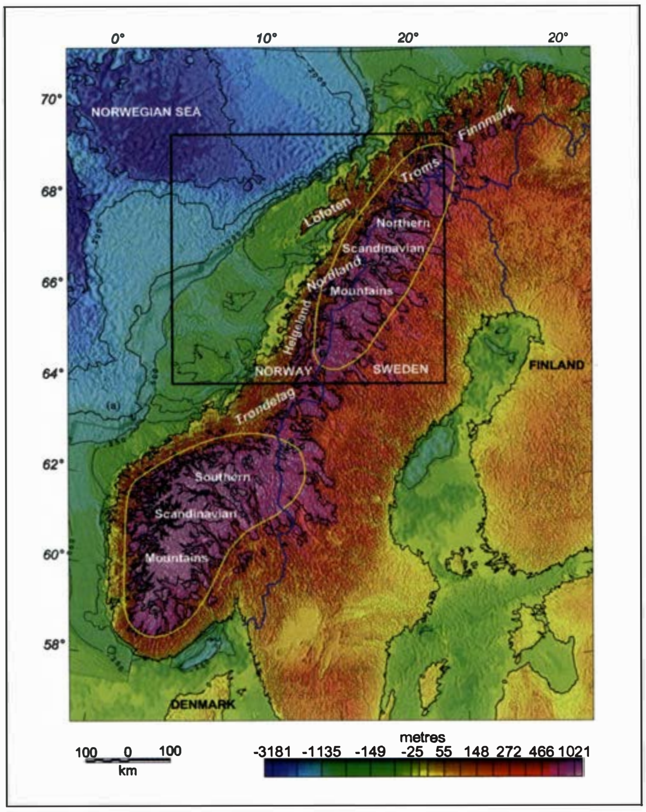


Fig. 1. Compilation of topography/bathymetry from Fennoscandia (Dehls et al. 2000). The yellow lines depict the two mountainous areas in Scandinavia. The 500 m and 1000 m contours are outlined. The Nordland area is outlined by the black box.

at depth by substantial volumes of low-density material within the crust or the mantle, or by relief at the crust/mantle or lithosphere/asthenosphere interfaces. The former models represent a Pratt-type isostasy model, while the latter two are consistent with an Airy-Heiskanen type model.

The western Scandinavian mountains (Fig. 1) are partly of Plio-Pleistocene age (Rohrman et al. 1995; Riis 1996) and constitute part of a circum Atlantic belt of Neogene uplift including the mountains in Scotland, Svalbard and East Greenland (e.g. Japsen & Chalmers 2001). As yet, there is no generally accepted hypothesis that explains the Neogene uplift phase of these mountainous areas. However, several different models have been proposed:

1) Glacial erosion, isostatic uplift (Doré 1992; Riis & Fjeldskaar 1992)
2) Migrating phase boundaries (Riis & Fjeldskaar 1992)
3) Pre-subduction instability (Sales 1992)
4) Plate reorganization – intraplate stress (Jensen & Schmidt 1992)
5) Mantle convection (Bannister et al. 1991; Stuevold et al. 1992; Vågnes & Amundsen 1993)
6) Mantle diapirism (Rohrman & van der Beek 1996)

Assuming neither erosion nor sedimentation, Neogene uplift implies either that the Moho depth has increased during this time period, or that substantial volumes of low-density rocks have been introduced in the crust or mantle. Rohrman & van der Beek (1996) and Riis (1996) proposed a Neogene uplift of more than 1000 metres in southern Norway from apatite fission track data, modelling of geomorphology and extrapolation of the offshore late Tertiary stratigraphy. Riis (1996) and Hendriks & Andriessen (2002b) have also proposed a Neogene bedrock uplift of more than 1000 m in the Lofoten-Vesterålen area, and 600 metres on the mainland to the east.

Geological setting

The bedrock geology (Fig. 2) of the mainland Nordland and Troms is dominated by the Caledonian Upper and Uppermost Allochthons that were thrust onto the Precambrian basement during the Scandian continent-continent collision in Silurian and Devonian time (Roberts & Gee 1985). In the Devonian, the nappes were dismembered by a late gravity collapse phase of the Caledonian orogen (Rykkelid & Andresen 1994; Braathen et al. 2000, 2002; Eide et al. 2002; Nordgulen et al. 2002; Osmundsen et al. 2003). The Lofoten-Ringvassøya area and the Central Norway basement window in Trøndelag make up the bulk of the Precambrian basement terrains to the north and south, respectively. These geological provinces are of deep-seated origin with associated regional magnetic and gravimetric anomalies (Figs. 3 - 5). The positive gravity anomalies reflect a shallow Moho discontinuity and uplifted, high-grade rocks of intermediate density (Sellevoll 1983; Skilbrei 1988). The exhumation of the deep-crustal rocks in the Lofoten area and the Central Norway basement window has lately been interpreted as a core complex formation denudated during large-magnitude extension along detachments (Hames & Andresen 1996; Braathen et al. 2000). Several minor basement windows occur within the Caledonian thrust belt between these two larger basement areas (e.g. the Børgefjell and Nasafjäll tectonic windows). These tectonic windows have been interpreted in terms of antiformal stacks or compressional duplexes, consisting of basement rocks within the Lower Allochthon (e.g. Greiling et al. 1998). Recent investigations indicate that the Børgefjell and Nasafjäll windows are bordered in the west by ductile to brittle extensional shear zones, and that the windows represent erosional sections through footwall culminations (Braathen et al. 2002; Osmundsen et al. 2003). Thus, these structures are also candidates for extensional unroofing as they appear today.

The basement infrastructure of the Lofoten-Ringvassøya area is dominated by Precambrian polymetamor-

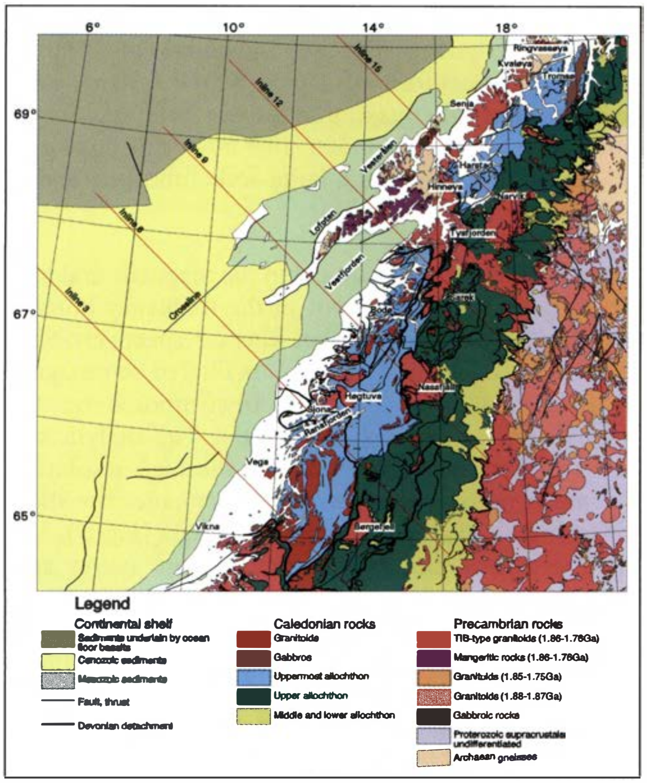


Fig. 2. Bedrock geology of the Nordland area (modified from Koistinen et al. 2001). Inlines/crossline: see Fig. 4.

phic high-grade migmatitic gneisses and intrusives (Griffin et al. 1978). Gaal & Gorbatschev (1987) have interpreted the intrusive rocks in the Lofoten-Ringvassøya basement area and the Høgtuva-Sjona and Nasafjäll tectonic windows to be an integral part of the Transscandinavian Igneous Belt which continues to the south and east beneath the Caledonides into Sweden. The belt of Proterozoic igneous rocks extends to southern Sweden and is characterised by regional magnetic anomalies (Henkel & Eriksson 1987; Fichler et al. 1999).

The Arjeplog-Karesuando and the Bothnian-Senja fault complexes (Henkel 1991; Zwaan 1995; Olesen et al. 1997b) constitute two major shear zones within the Precambrian basement (Fig. 6). A prominent set of high-angle, ductile to brittle faults called the Vestfjorden-Vanna fault complex (Andresen & Forslund 1987) continues from the Vestfjorden area NNE-wards through the sounds to the east of Hinnøya, Senja, Kvaløya, Ringvassøya and Vanna and into the Lopphavet area (Figs. 2 & 7). The fault complex constitutes the contact between the Precambrian terrain to the west and the Caledonian nappe sequence to the east. There is evidence of both Late Palaeozoic and Mesozoic activity along the fault complex (Andresen & Forslund 1987; Olesen et al. 1997b).

The Nordland offshore area covers the northern Trøndelag Platform, the Træna, Vestfjorden, Ribban and Røst basins, and the Nordland, Lofoten and Utrøst ridges (Blystad et al. 1995). At the base Cretaceous level (Fig. 6), the southern Trøndelag Platform corresponds to a seaward dipping, relatively little faulted monocline, which grades northward into the gently synformal Helgeland Basin. The Trøndelag Platform is underlain by Upper Palaeozoic and Triassic strata. Upper Palaeozoic sedimentary rocks reach their greatest thickness in the central part of the Trøndelag Platform, suggesting a westward shift of the depocentre from Permian to Cretaceous time. The Trøndelag Platform terminates along the Nordland Ridge, which changes in orientation from NNE-SSW to almost E-W immediately offshore the Meløy area. The Ylvingen Fault Zone makes up the southern margin of the Mesozoic Helgeland Basin. The western boundary of the Utrøst Ridge is bound by large faults with down to the northwest throws and forms the landward boundary of the Røst Basin that is covered by Early Tertiary flood basalts. The Harstad Basin (Gabrielsen et al. 1990) extends from offshore Andøya northeastwards to the west of the islands of Senja, Kvaløya and Ringvassøya. The basin is bound to the east by the southernmost part of the Troms-Finnmark Fault Complex, and the western limit coincides with the transition to oceanic crust. The evidence of sub-basalt sedimentary strata in the Røst Basin is based on gravity inversion studies (Sellevoll et al. 1988) and wide-angle seismic surveys utilising ocean-bottom seismographs (Mjelde et al. 1992). A high-velocity lower crustal body occurs below the Vøring Basin in the southwesternmost part of the Nordland area (Planke et al. 1991; Mjelde et al.1998). The sea-floor spreading magnetic anomalies 22-24B (Talwani & Eldholm 1977; Eldholm et al. 1979; Hagevang et al. 1983) occur in the northwesternmost part of Fig. 6. Three NNW-SSE oriented oceanic fracture zones extend into the Nordland-Troms area: the Bivrost, Jennegga and Senja fracture zones.

Datasets

A total of seven offshore and two onshore aeromagnetic surveys were compiled (Fig. 4). The surveys were acquired by the Geological Surveys of Norway and Sweden, the US Naval Research Laboratory and Hunting Ltd. Survey details are described by Åm (1970, 1975), Olesen & Smethurst (1995), Olesen et al. (1997a,b), Ruotoistenmäki et al. (1997), Skilbrei & Kihle (1999) and Mauring et al. (1999). The modern aeromagnetic surveys (Fig. 5) (Hunting-1986, LAS-89, NAS-94 and VAS-98) were flown with a line spacing of 2 km and a tie-line separation of 5-8 km. The sensor altitudes for the different surveys vary between 150 and 500 metres. The NGU-73, LAS-89 and US Naval Research Laboratory surveys have been reprocessed applying the new median levelling technique by Mauring et al. (2002). Verhoef et al. (1996) and Olesen et al. (1997a,b) published previous data compilations from the area, but the

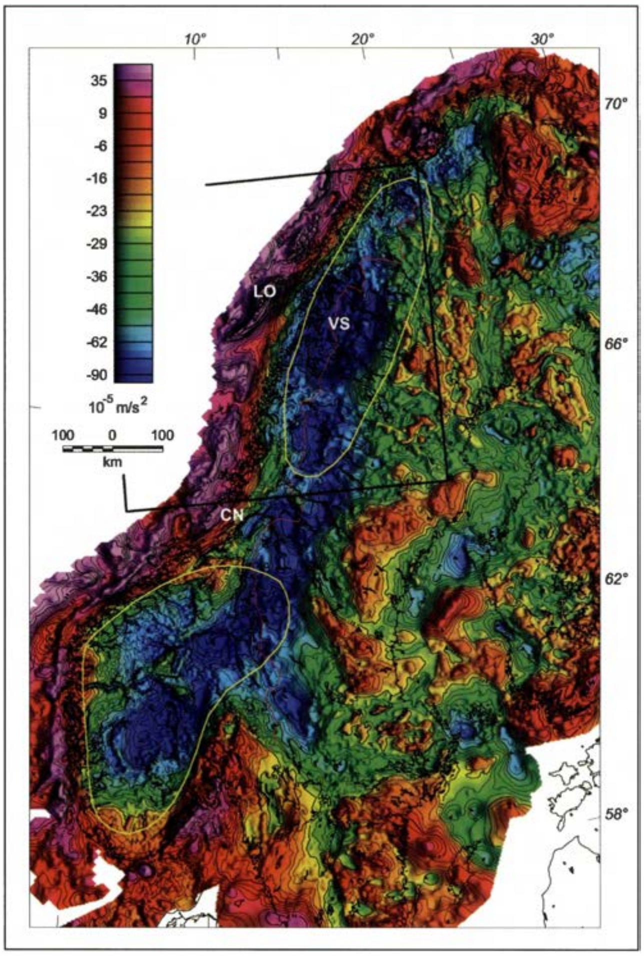


Fig. 3. Compiled Bouguer gravity data from Scandinavia compiled from Korhonen et al. (1999) and Skilbrei et al. (2000). The yellow lines depict the two mountainous areas in southern and northern Scandinavia. CN - Central Norway basement window; LO - Lofoten area; VS - Vestfjorden-Sarek area. The extent of the Nordland area is outlined by the black box.

present dataset is considerably more detailed since it contains both modern high-resolution surveys and reprocessed versions of the vintage datasets.

The mainland gravity dataset consists of terrain-corrected Bouguer data from the University of Bergen, Norway; the University of East Anglia, Great Britain; the Norwegian Mapping Authority and the Geological Surveys of Norway and Sweden (Svela 1971; Chroston 1974; Henkel 1991; Ruotoistenmäki et al. 1997; Skilbrei et al. 2000). In addition, marine data were obtained from the Norwegian Mapping Authority and the Norwegian Petroleum Directorate, and satellite altimetry in the deep-water areas from the National Survey and Cadastre Denmark (Andersen & Knudsen 1998; Skilbrei et al. 2000). The complete Bouguer reduction of the gravity data was computed using a rock density of 2670 kg/m^3 on land. The simple Bouguer correction at sea was carried out using a density of 2200 kg/m^3. The International Standardisation Net 1971 (I.G.S.N. 71) and the Gravity Formula 1980 for normal gravity were used to level the surveys. The amplitudes of the mainland Bouguer gravity field are -140 and $+130 \cdot 10^{-5}$ m/s^2 (mGal). This contrast of $270 \cdot 10^{-5}$ m/s^2 is large even compared with the maximum gravity difference in the Andes and Himalayas of $500 \cdot 10^{-5}$ m/s^2. The large gravity amplitude points to a large-scale lithospheric discontinuity within the area.

Separation of the residual field in the magnetic and gravity datasets was carried out in the frequency domain using 8 and 100 km Gaussian filters, respectively. Shaded relief versions of the high pass filtered aeromagnetic datasets in grey-tone are superimposed on the colour-contoured total field in Fig. 4. The analytic signal (total gradient amplitude) of the high-resolution aeromagnetic data was also used to enhance the short wave-length (shallow) content of the data (Fig. 5). The main structural elements of the offshore survey area (Blystad et al. 1995) and the sedimentary subcrop pattern (Rokoengen et al. 1988) are shown on the analytic signal map (Fig. 5).

Petrophysical data (density, magnetic susceptibility and remanence) of approximately 5100 rock samples from the mainland were used in the interpretation of the potential field data (Table 1). The results from the petrophysical survey are detailed in Mørk & Olesen (1995) and Olesen et al. (1991, 1997b). We have used density data from shallow drilling in the Helgeland-Brønnøysund basins (Bugge et al. 1993) and from petroleum exploration wells on the Nordland Ridge and the Utgard High (Olesen et al. 1997b) to constrain the gravity modelling. The densities of sedimentary sequences calculated from density logs are shown in Table 2. These estimates were used to constrain the 3D modelling.

The base Cretaceous map (Fig. 6) was mainly compiled from Brekke et al. (1992) and Brekke (2000). The map has been modified in the Vestfjorden area from re-interpretation of the NPD seismic reflection data in a SeisVision workstation utilising information from the 6610/3-1 well on the northern flank of the Nordland Ridge and potential field data. A base Tertiary grid adopted from Brekke (2000) has been applied in the regional 3D modelling.

Offshore basement depth estimates have been compiled from Olesen & Smethurst (1995) and Olesen et al. (1997b). These depth estimates were calculated using the autocorrelation algorithm of Phillips (1979), the Euler deconvolution algorithm of Reid et al. (1990) and a least-squares optimising algorithm of Murthy & Rao (1989). To further reduce the inherent ambiguity in the modelling of the potential field data, petrophysical data (Tables 1 & 2) from both the basement rocks and the sedimentary succession were used in the forward modelling. Incorporation of seismic structural inter-

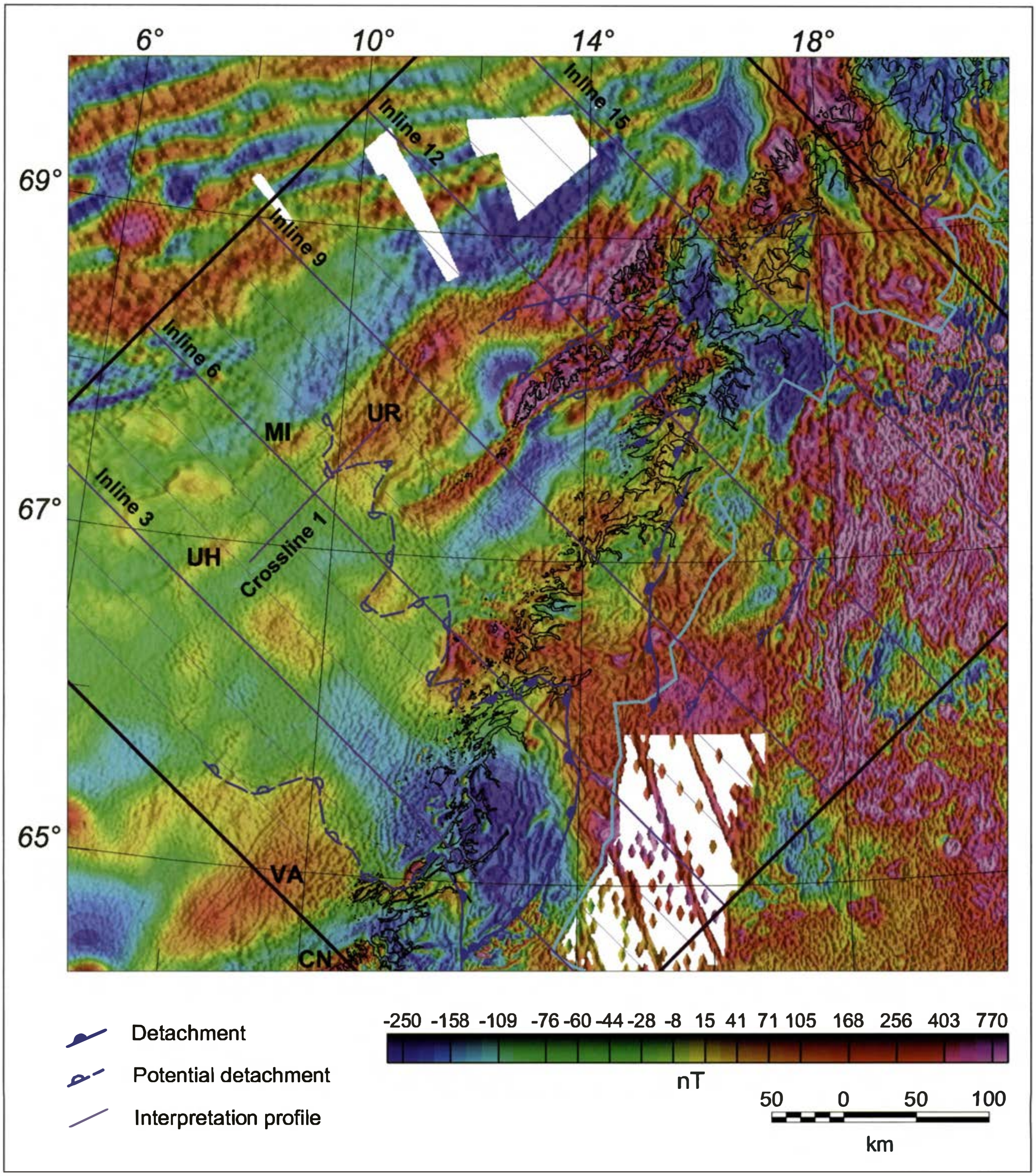


Fig. 4. Shaded relief of high-pass filtered aeromagnetic data superimposed on the colour map of the total aeromagnetic field referred to IGRF. The violet lines show the interpreted inlines/crossline within the 3D model. Interpretations along every third inline (thicker line) are displayed in Fig. 12. CN - Central Norway basement window; MI - Myken intrusive complex; UH - Utgard High; UR - Utrøst Ridge; VA - Vikna magnetic anomaly. Devonian detachment zones on the mainland (Rykkelid & Andresen 1994; Braathen et al. 2000, 2002; Osmundsen et al. 2003; Nordgulen et al. 2002) have been extrapolated into the offshore area.

pretation of the uppermost offshore sedimentary sequences improved the gravity interpretation of the deeper levels of the basins. In areas where the gravity and magnetic datasets gave diverging depth estimates, the gravity interpretation was given highest weight. In particular, this applies to areas where we expect to find shallow, low-magnetic basement continuing from onshore areas, or where down-faulted Caledonian nappes occur beneath the deep basins. Depth estimates originating from high-frequency magnetic anomalies inter-

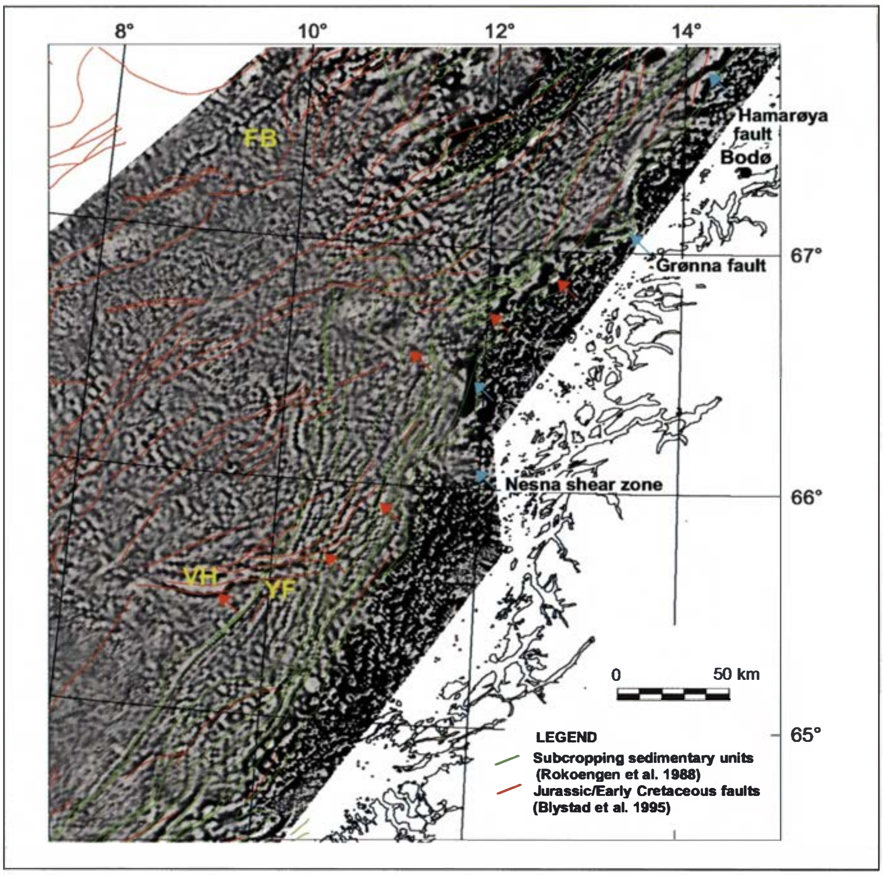


Fig. 5. Shaded relief map of analytic signal (total gradient amplitude) from high resolution aeromagnetic surveys with superimposed subcrop pattern (Rokoengen et al. 1988) and Jurassic/Early Cretaceous faults (Blystad et al. 1995). VH – Vega High, YF – Ylvingen Fault Zone, FB – flow basalts. The map offers a plane view of the subcrop and fault pattern in the Nordland area. Blue arrows show magnetic discordances in the magnetic basement pattern; Nesna shear zone, Grønna and Hamarøya faults. The red arrows show two offshore ENE-WSW-oriented faults cutting through Late Palaeozoic and Mesozoic sedimentary rocks. The southernmost arrows represent the Ylvingen Fault Zone (Blystad et al. 1995).

preted to represent magnetic intra-sedimentary igneous rocks were excluded from the depth to basement contouring. The thickness of the mainland Caledonian nappes is included in the basement structure map and the 3D modelling (Figs. 7 & 12-13) and has been compiled from earlier gravity and aeromagnetic interpretations in Sweden (Lind 1986), Troms (Olesen et al. 1990) and Nordland (Sindre 1997). The depth to the Precambrian basement in Troms and northern Sweden was estimated using the magnetic autocorrelation algorithm, while forward gravity modelling was applied in the Nordland area.

The Moho depth map by Kinck et al. (1993) was updated by more recent refraction lines in the Vøring Basin and the Lofoten margin (Mjelde et al. 1992, 1993, 1998). Existing profiles along the Lofoten-Vesterålen islands (Sellevoll 1983), the Blue Road across the Norwegian-Swedish border (Lund 1979) and Fennolora Profile in Sweden (Guggisberg et al. 1991) were also included in the updated Moho depth map (Fig. 8).

Interpretation methods

Isostasy

An Airy-Heiskanen 'root' (Heiskanen & Moritz 1967) shown in Fig. 9 was calculated from the topographic and bathymetric dataset using the formula:

$$H = h_{coast} + h_{topo} \cdot \rho_{topo} \,/\, \rho_{root} \qquad (1)$$

where
H = depth to Airy root
h_{coast} = depth to the Airy root at the coast
h_{topo} = elevation relative to sea level
ρ_{root} = density contrast across the Airy root
ρ_{topo} = density of topography

We have applied a density of 2670kg/m^3 to the mountains in Norway, a density contrast of 330kg/m^3 at the base of the Airy root, and a crustal thickness of 30 km along the coast.

The gravitational attraction from the 'root' was calculated in the frequency domain using the AIRYROOT algorithm (Simpson et al. 1983). The isostatic residual was achieved by subtracting the gravity response of the Airy-Heiskanen 'root' from the 'observed' Bouguer gravity data (Fig. 3). Fig. 10 shows the gravity residuals for the Nordland area.

The main model is based on a 30 km Moho depth along the coast of Norway. These depths agree in general with Moho depths (Fig. 8) obtained from refraction seismic studies compiled by Kinck et al. (1993). Applying the Airy root equation [equation (1)] results in a maximum Moho depth of 40 km below the mountainous part of Scandinavia. However, the low altitude areas of eastern Scandinavia have an even thicker crust, imply-

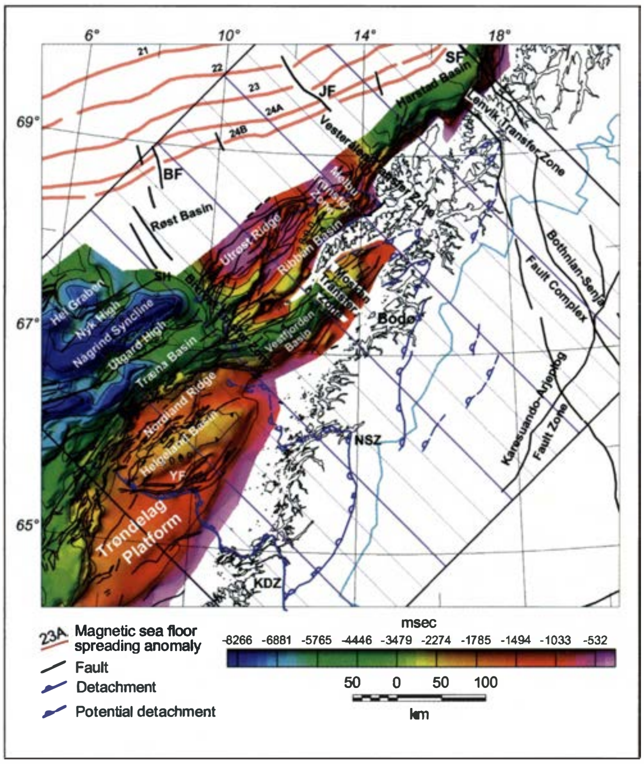


Fig. 6. Base Cretaceous compiled from Brekke et al. (1992) and Brekke (2000). The depths in the Vestfjorden area have been reinterpreted in a seismic workstation environment utilising information from the 6610/3-1 well on the northern flank of the Nordland Ridge, NPD reflection data in the Vestfjorden area and potential field data. BF - Bivrost Fracture Zone; JF - Jennegga Fracture Zone; SF - Senja Fracture Zone; SH - Sandflesa high; YF - Ylvingen Fault Zone; KDZ - Kollstraumen detachment zone; NSZ - Nesna shear zone.

ing that the crust and/or the mantle must be denser in this area. This 'isostatic Moho depth' below the Lofoten-Vesterålen islands and the mountainous areas of northern Scandinavia is significantly different from the Moho depth interpreted from the refraction seismic line, e.g. along the Blue Road profile (Figs. 8 & 9). To investigate the potential contribution from intra-crustal and/or intra-mantle low-density rocks to the isostasy and gravity field in the region, we (a) simulate an intra-mantle low-density rock by increasing the depth to the Airy root [ρcoast in equation (1)] or (b) make the Airy root shallower (i.e. decrease h_{coast}) to test a potential intra-crustal low-density contribution to the isostasy. The former model produces an anomaly with longer wavelength and lower amplitude than the latter. We tested various models by calculating the gravity response from Airy roots with coastal depths (h_{coast}) varying from 10 to 60 km, including the original 30 km model. Root mean squares (RMS) and correlation coefficients (Fig. 11) between the Bouguer gravity grid and the gravity response were calculated for the northern and southern Scandinavian mountains. Fig. 11a-b shows the scatter-diagrams for selected models in the two investigated areas.

3D modelling

The potential field data have been interpreted using the 3D modelling packages ModelVision and Oasis Montaj (Encom 2001; Geosoft 2000 & 2001a,b). The existing interpretation described in the section above (base Tertiary, base Cretaceous, offshore depth to crystalline basement and onshore depth to Precambrian basement rocks, Moho depth) and lithosphere thickness (Calcagnile 1982) have been applied as the initial model for the interpretation. The density of the lithospheric mantle was calculated by assuming a stepwise increase (200 K) in temperature from the Moho (c. 500°C) to the asthenosphere at a temperature of c. 1300°C. The applied thermal expansion factor is $3.2 \times 10^{-5} K^{-1}$, which is adapted from an equivalent study by Breivik et al. (1999) in the southwestern Barents Sea. The 3D model was constructed by slicing 10 horizons by 17 parallel profiles, spaced 35 km apart. The total gravity response is calculated as the sum of the responses from each individual body along all 17 inlines. We have modified the deeper interfaces to fit the regional field, and subsequently shallower interfaces to fit the high-frequency part of the gravity field. Every third line of the 3D model is displayed in Fig. 12. Magnetic data have been included in the modelling along Crossline 1 (Fig. 13) intersecting the Inlines 4-8.

Fault zones (Fig. 14) within the basement and partly within the sedimentary units were interpreted from the geophysical maps. High gravity gradients along the basin boundaries are generally interpreted to be caused by faults, but may in some cases be related to flexuring and steeply dipping sedimentary bedding.

Results

Regional isostasy

Locating the isostatic compensating low-density rocks at shallow depth, yields a gravity field that is the most similar to the observed gravity field in northern Scandinavia (Fig. 11). The calculated RMS is lowest ($25.0 \cdot 10^{-5}$ m/s^2) for the 10 km Airy root model below the northern Scandinavian mountains. This differs significantly from the southern mountains where the RMS is lowest ($17.6 \cdot 10^{-5}$ m/s^2) for the 45 km Airy root model (Fig. 11). A similar comparison between 100 km low-pass filtered Bouguer data and the gravity responses from the various Airy roots yield almost identical results, showing that the correlation is not an artefact caused by the high-frequency component. The results imply that the mountains in northern Scandinavia are partly compensated by low-density rocks within the crust. The results agree with the findings from the Blue Road refraction experiment (Lund 1979) that the upper crust extends to larger depths (27 km) below the

Table 1.

Rock Unit/Type	No.	Density mean	Density std.	Q-value mean	Q-value std.	Susceptibility mean	Susceptibility std.
Uppermost Allochthon							
Rödingsfjell Nappe Complex	821	2787	137	3.26	12.8	0.0060	0.034
Helgeland Nappe Complex	488	2811	126	4.41	15.9	0.0032	0.018
Bindal Batholith	304	2738	136	3.30	11.6	0.0040	0.014
Upper Allochthon							
Narvik Nappe Complex	164	2811	130	1.60	4.6	0.0032	0.017
Precambrian Basement							
Senja, Kvaløy and Ringvassøy, gneiss etc.	384	2716	106	2.11	5.4	0.0078	0.020
Senja, Kvaløy and Ringvassøy, greenstone belts	125	2942	136	0.46	0.6	0.0266	0.059
The Lofoten area	470	2764	130	1.36	5.6	0.0339	0.050
Tysfjord Granite Complex	607	2678	79	1.22	4.0	0.0074	0.024
Sjona-Høgtuva tectonic windows	1140	2643	39			0.0084	0.012
Central Norway basement window (Trøndelag)	419	2729	106	1.04	2.8	0.0091	0.026

Table 1. Arithmetical mean and standard deviation of density, susceptibility and Q-values measured on hand specimens from the Nordland area. The measurements are extracted from the national petrophysical database at the Geological Survey of Norway. Skilbrei (1988), Olesen et al. (1990), Mørk & Olesen (1995) and Olesen et al. (1997b) have reported a more detailed presentations of the statistical data. SI units are used. Density values are reported as kg/m^3

Table 2.

	Well 6609/7-1 Phillips Petroleum Nordland Ridge	Well 6607/5-1 Esso Utgard High	Well 6507/2-1 Norsk Hydro Dønna Terrace	Density estimates from sonobouys Univ. of Bergen	IKU well 6611/09-U-01 Helgeland/ Brønnøysund Basin	IKU well 6611/09-U-02 Helgeland/ Brønnøysund Basin	Density adapted for modelling
Water depth	250m	368m	381m		352 m	355m	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	-	-	-		2.59 (200m)	2.57 (280m+)	2.58
Permian	2.31 (1920m)	-	-		2.58 (560m+)		2.58
Basement	2.64 (1960m+)	-	-	2.70-2.85			2.75
Magmatic underplating							3.00
Mantle							3.25

*Table 2. Density of sedimentary sequences from density logs of wells in the Nordland I, II and IV areas (Bugge et al. 1993; Olesen et al. 1997b). The estimates (in 1000*kg/m3) are used for the 3D gravity modelling. Numbers in parenthesis show depth (relative to sea-bed) of the base of the various sequences.*

mountains of northern Norway than below the Precambrian shield to the east (13 km), [to the east of shotpoints 1 and 4, respectively, in Figs. 7-8]. The mountains in southern Norway are, from our results, partly supported by low-density rocks below the Moho. The Pratt type of isostasy is consequently deduced to be important for the isostatic compensation of the Scandinavian mountains, supporting the conclusions of Skilbrei (1988) for central Norway. The Neogene uplift of southern Norway may originate from low-density

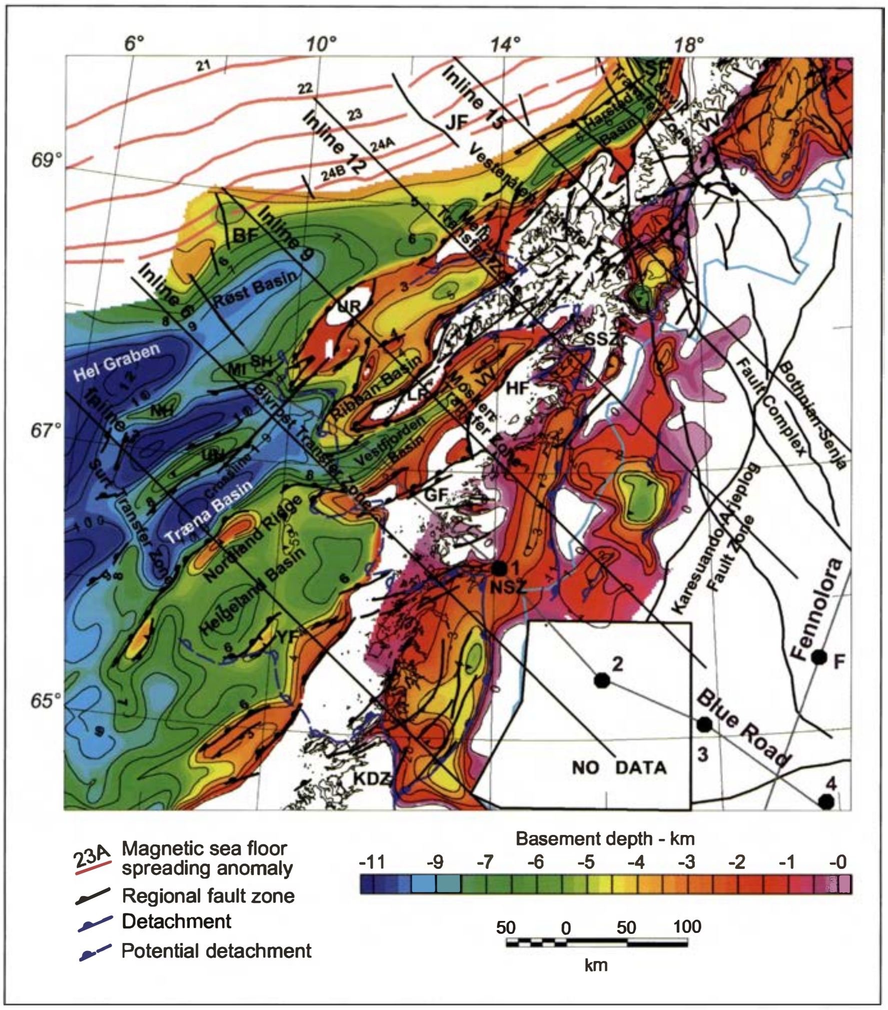


Fig. 7. Regional basement structures within the offshore-onshore Nordland area. The depth to basement surface represents depth to crystalline rocks in the offshore region while it constitutes the depth to Precambrian gneisses and granites in the onshore area. GF - Grønna fault, HF - Hamarøya fault, KDZ - Kollstraumen detachment zone, NSZ - Nesna shear zone, SSZ - Sagfjord shear zone; SH - Sandflesa high; UH - Utgard High; UR - Utrøst Ridge; NH - Nyk High; VV - Vestfjorden-Vanna fault complex; MI - Myken intrusive complex; BF - Bivrost Fracture Zone; JF - Jennegga Fracture Zone; SF - Senja Fracture Zone; YF - Ylvingen Fault Zone. The Caledonian nappes are most likely down-faulted to a maximum depth of c. 5 km along late Devonian detachments. Black dots along the Blue Road and Fennolora profiles show shotpoints.

mantle rocks. The results are in agreement with the conclusions of Riis (1996) and Lidmar-Bergström (1999) that the southern Norwegian plateau was partly uplifted in the Neogene, while the northern Scandinavian mountains originated mainly as rift-shoulders in late Cretaceous to early Tertiary times. Hendriks & Andriessen (2002a) reported that analyses of observed apatite fission track data along a profile from Lofoten into Sweden fit best with those expected from a retreating scarp model (Beaumont et al. 2000).

This modelling shows that the uplift of the northern Scandinavian mountains was not caused by low-density material within the mantle. The main uplift phase is therefore neither caused by mantle convection along the boundary between a warm oceanic asthenosphere and a colder continental asthenosphere (Bannister et al. 1991; Stuevold et al. 1992; Vågnes & Amundsen 1993), nor by mantle diapirism (Rohrman & van der Beek 1996). Part of the uplift of the Lofoten area may alternatively be explained by the isostatic effect following glacial erosion similar to the Barents Sea region uplift (Doré 1992; Riis & Fjeldskaar 1992) and the Svalbard area (Skilbrei 1998). The results from the isostatic studies also show that the compensating mass below the southern Scandinavian mountains is much deeper and may consequently be situated within the lithospheric mantle or at the lithosphere/asthenosphere interfaces, consistent with the mantle diapirism model by Rohrman & van der Beek (1996). This diapir model, based on the Rayleigh-Taylor instability can give explanation to the equidistant spaced doming (~900 km spacing) along the northern North Atlantic rifted margins. However, the model cannot explain that the most of the Neogene uplift occurred in southern Norway compared to northern Norway. Thus it is possible that a modified mantle diapirism model linking the southern Norwegian diapir to the Iceland hotspot can explain the observed uplift. Bijwaard and Spakman (1999) succeeded in imaging the Iceland plume to great depths in the mantle using tomographic analysis of teleseismic data. Lateral branches of the plume were interpreted to extend below Great Britain and southern Scandinavia.

Transcandinavian Igneous Belt

The aeromagnetic data (Fig. 4) show that Precambrian intrusive rocks in the Lofoten-Senja-Ringvassøya basement complex are continuous below the Vestfjorden Basin and the Caledonian nappes to the tectonic win-

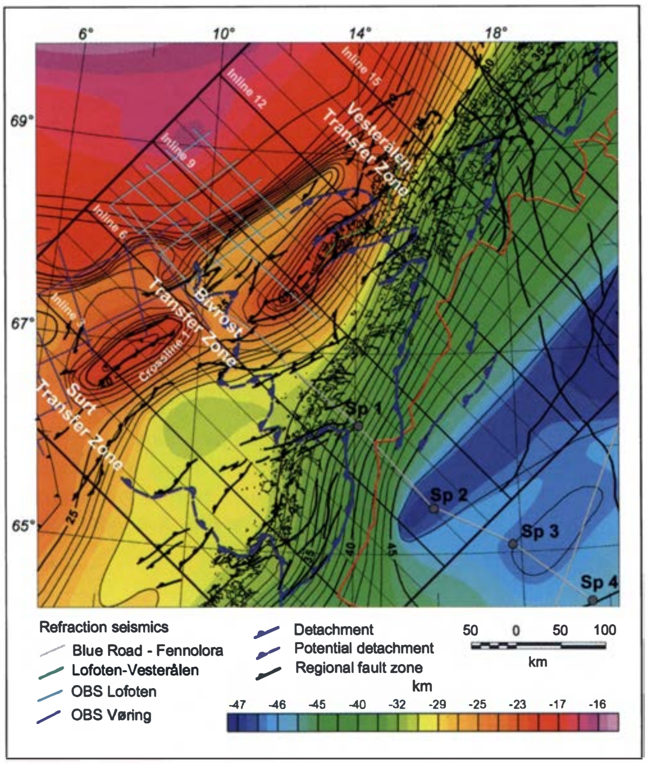


Fig. 8. Depth to Moho compiled from refraction seismic studies (Lund 1979, Kinck et al. 1993, Mjelde et al. 1992, 1993, 1998 and Sellevoll 1983). The black lines show the interpreted inlines/crossline within the 3D model. Interpretations along every third inline (thicker line) are displayed in Fig. 12. The shallow Moho along the main Late Jurassic - Early Cretaceous rift axis is deflected by the Surt, Bivrost and Vesterålen transfer zones.

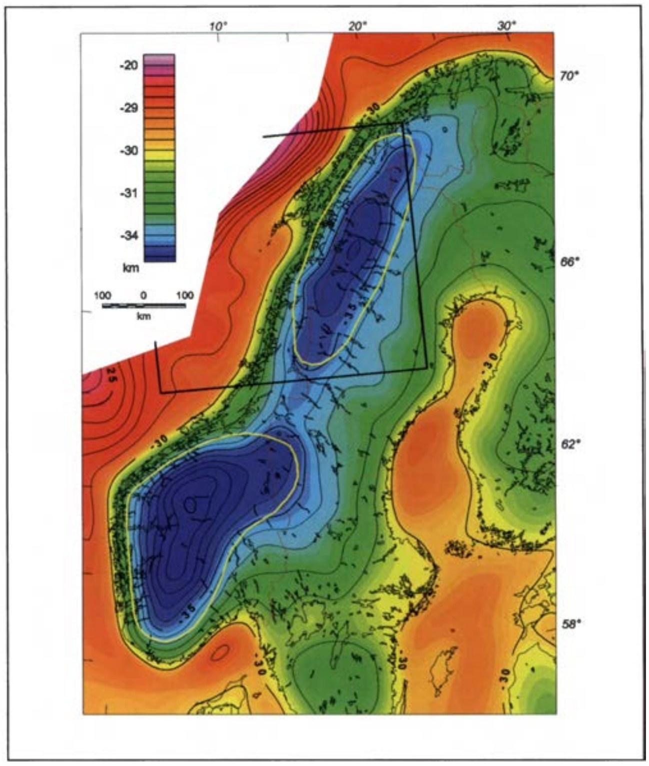


Fig. 9. The Airy root calculated from the topography/bathymetry in Fig. 1. A Gaussian 200 km lowpass-filter has been applied to the Airy-root grid to smooth the high-frequency variation. The yellow lines depict the two mountainous areas in Scandinavia. The Nordland area is outlined by the black box.

dows in Nordland and further into Sweden. They constitute part of the Transscandinavian Igneous Belt (TIB) (Gaal & Gorbatschev 1987). A regional negative gravity anomaly occurs in the Vestfjorden-Sarek area (Figs. 3 & 10), immediately to the east of the Lofoten-Vesterålen positive gravity anomaly, and includes the area with the highest mountains in northern Scandinavia. The oval, wide (200 km) shape of the anomaly may indicate a deep-seated source. Low P- and S-wave velocities in the mantle below the mountainous area of Scandinavia (Bannister et al. 1991) also indicate the presence of low-density rocks in the mantle. An iterative, least-square optimising algorithm (Marquardt 1963) shows that to explain the observed steep gradients, the low-density body occurs at relatively shallow depths (and is most likely outcropping). Applying a density contrast of -100 kg/m^3 (Table 1) between the granitoid rocks and the intermediate rocks of the Transscandinavian Igneous Belt (equivalent to the granites in the Tysfjord area and the high-grade rocks in the Lofoten area, respectively) shows that the granitoids must extend to a depth of c. 22 km, making up a significant part of the c. 40 km thick crust in the area (Figs. 12a-c & 15). These deep granites constitute parts of the TIB. The bedrock map (Fig. 2) shows that the TIB-granites extend to the east of the negative gravity anomaly in Sweden. When including a thin layer of granites in this area, the deep TIB-body will tilt eastwards and increase in overall thickness. The estimated depth of 22 km is therefore most likely a minimum value. Analogue deep granites (c. 30 km) within the Sierra Nevada Batholith in California are related to Mesozoic plate subduction along the western edge of the North American plate (Ducea 2001). This mechanism also involves large-scale continental shortening and the formation of voluminous lower crustal residues such as granulites and eclogites. The Lofoten-Vestfjorden-Sarek region may be in regional isostatic equilibrium due to the opposing effects of voluminous bodies with positive and negative density contrasts. This phenomenon may also contribute to the observed high rock stress in this particular area of Norway (Myrvang 1993).

Late Devonian detachments

On the assumption that the thickness of the Caledonian nappes in Nordland was relatively uniform immediately after Silurian nappe emplacement, the strongly varying depth to Precambrian basement may be the result of later tectonic deformation and late- to post-orogenic extensional and strike-slip deformation.

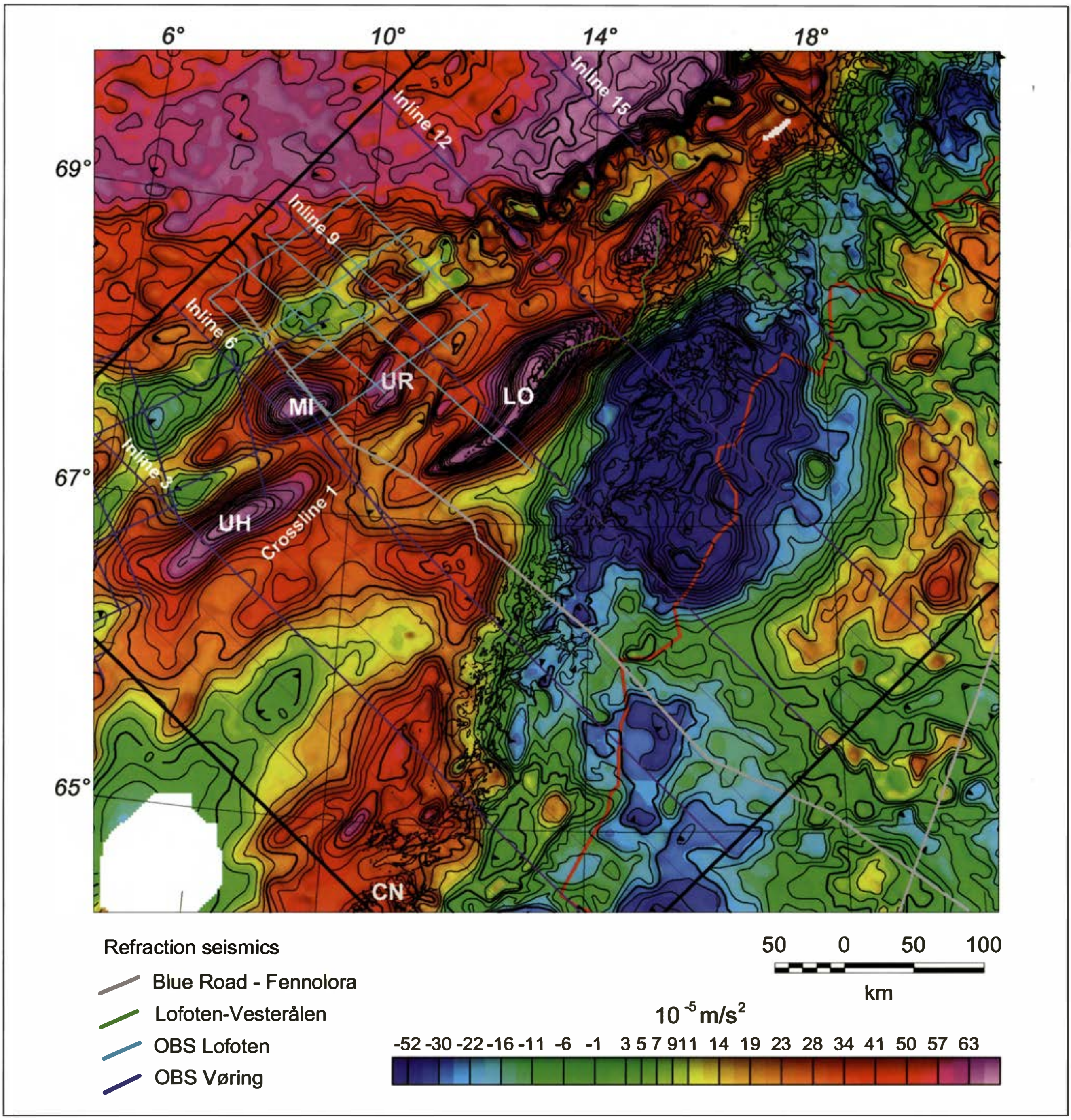


Fig. 10. Residual gravity after isostatic correction of Bouguer gravity data. The isostatic correction has been calculated applying the AIRYROOT algorithm (Simpson et al. 1983) to the topography/bathymetry dataset in Fig. 1 (rock density 2670 kg/m³ on land, 2200 kg/m³ at sea and a crust-mantle density-contrast of 330 kg/m³). The violet lines show the interpreted inlines/crossline within the 3D model. Interpretations along every third inline (thicker line) are displayed in Fig. 12. CN - Central Norway basement window; LO - Lofoten Ridge; MI - Myken intrusive complex; UH - Utgard High; UR - Utrøst Ridge.

Notably the Caledonian successions (Figs. 2 & 7), including the Uppermost Allochthon, occur in the hanging wall block of the observed Devonian detachments and shear zones in the Nordland area (Osmundsen et al. 2003; Braathen et al. 2002). The Caledonian nappes are therefore most likely down-faulted to a maximum depth of c. 5 km (below the present surface) along late Devonian detachments as illustrated in Fig. 7.

A significant portion of the basement in the offshore Helgeland Basin and along the Nordland Ridge is low-magnetic. The depth to magnetic basement on both flanks of the Helgeland Basin is between 8 and 10 km, i.e. 2-5 km deeper than the depths obtained from gravity modelling. The low-magnetic nature of the basement is most likely caused by down-faulting of the Helgeland Nappe along the offshore extensions of the

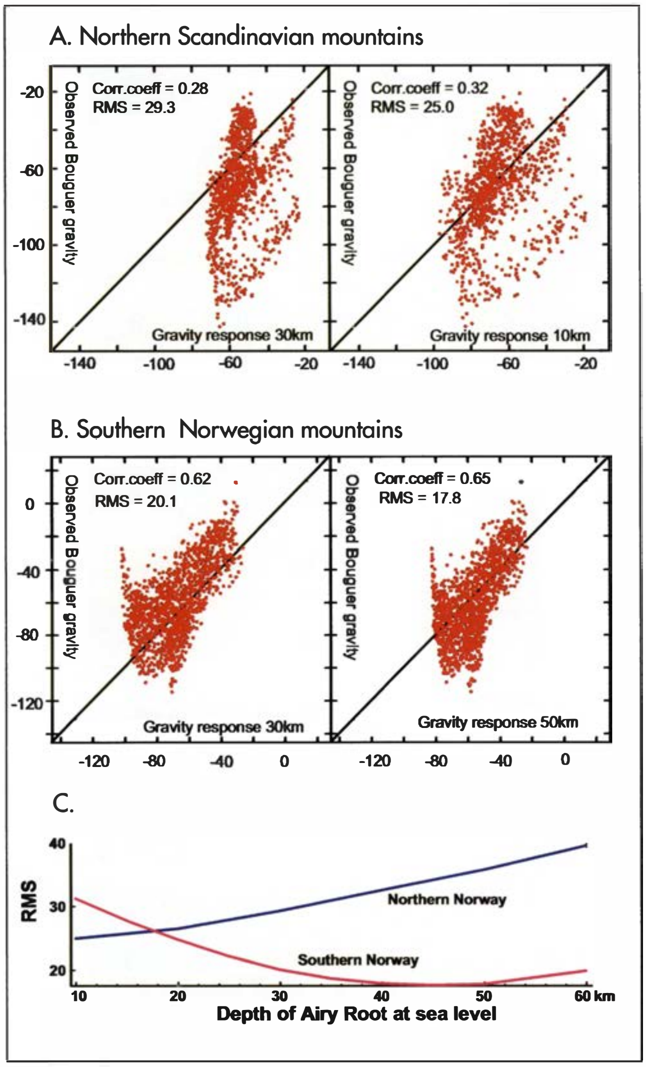
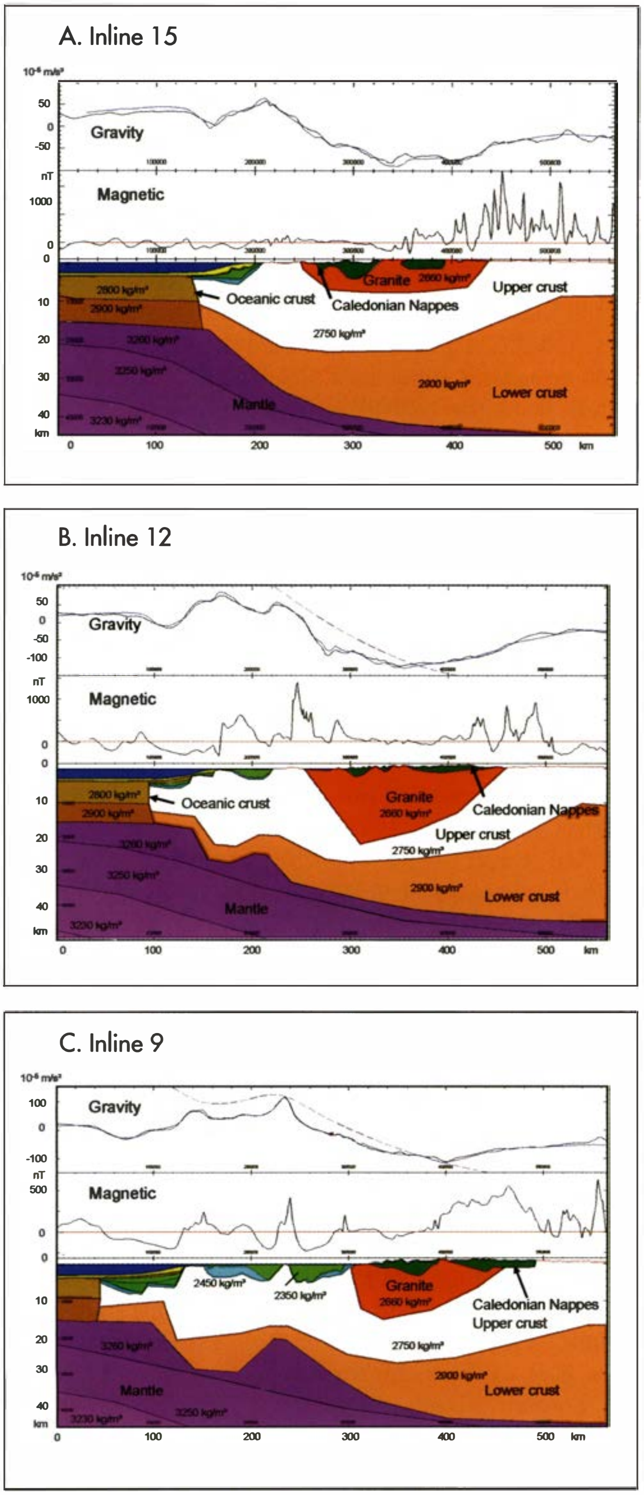


Fig. 11. Comparison of calculated gravity response of 'Airy roots' at different depths with the observed Bouguer gravity for the mountainous part (above c. 500 m asl) of northern and southern Scandinavia. A) Northern Scandinavia; scatter-diagrams of the gravity response of Airy roots at the depths of 30 km and 10 km (at the coast) versus observed Bouguer gravity. The lowermost cluster in the diagrams represents data from the Vestfjorden-Sarek area. B) Southern Scandinavia; scatter-diagrams of the gravity response of Airy roots at the depths of 30 km and 50 km (at the coast) versus observed Bouguer gravity. C) Root mean squares (RMS) quantify the similarity between the observed Bougner gravity and calculated effect of Airy roots at various depths. The best fit occurs for a shallow depth (10 km) in northern Scandinavia while a deep source (Airy root of 40-50 km at the coast) seems to compensate for the southern Scandinavian mountains. The units of the gravity data are 10^{-5} m/s^2 (mGal).

Devonian Nesna shear zone and the Kollstraumen detachment which have been mapped on land by Braathen et al. (2000), Eide et al. (2002), Nordgulen et al. (2002) and Osmundsen et al. (2003). Another alternative is the occurrence of low-magnetic, amphibolite-facies Precambrian gneisses similar to the rocks on eastern Hinnøya. However, the model along a crossline (Fig. 13) through the 3D model suggests that the Bivrost Lineament is a folded, gently dipping structure (5-15° to the SW). The Kollstraumen detachment represents the northward termination of the large magnetic body situated at a depth of 8-10 km in the Trøndelag Platform. The associated Vikna magnetic anomaly (220 nT) (Fig. 4) is comparable in size and parallel to the Roan anomaly on the Fosen Peninsula, 100 km to the south, and could therefore have a similar cause. The magnetic rocks in Roan were formed during Caledonian high-grade metamorphism (Möller 1988, Skilbrei et al. 1991), and were most likely uplifted during the Devonian orogenic collapse (Braathen et al. 2000).

Some of the offshore, low-magnetic basement may also constitute Devonian sandstones deposited above the offshore extensions of the Nesna and Kollstraumen detachments, i.e. similar to the tectonic situation further south along the Nordfjord-Sogn and Høybakken detachments. Bugge et al. (2002) argued that a shallow-marine, reddish, Permian sandstone unit offshore Helgeland represents re-deposited Late Devonian-Early Permian continental sedimentary rocks. This interpretation supports the hypothesis that Devonian sandstones could have been deposited above the Caledonian nappes during gravity collapse of the orogen. An E-W trending section of the potential offshore Kollstraumen detachment coincides with the western part of the Ylvingen Fault Zone (Figs. 6 & 7), indicating that this late Mesozoic feature is governed by a deep-seated structure. Interpretation of the basement topography reveals a central north-trending ridge at c. 5 km depth separating the Helgeland Basin into two 6-7 km deep sub-basins (Fig. 7). The easternmost sub-basin represents the Permian Brønnøysund Basin (Doré et al. 1999; Bugge et al. 2002). The 3D modelling of gravity data along Inline 3 (Fig. 12e) using constraints from densities (Table 2), indicates that the basement of the Trøndelag Platform is 2 km shallower than interpreted from the seismic profile (4.5 versus 6.5 km). The basement reflector is, however, not well defined in these profiles. An alternative model to the shallower basement is a higher density than 2580 kg/m^3 for the Triassic and Permian sedimentary successions. The latter model implies practically no porosity of these sediments, and we therefore prefer the former model.

The Sagfjord shear zone (Braathen et al. 2002) farther north may analogously to the Nesna shear zone be extended beneath the offshore Vestfjorden and Ribban basins. A significant part of the basement below these basins consists of low-magnetic amphibolite-facies gneisses that may have been emplaced along Devonian detachments (Fig. 16). Relatively flat-lying deformation zones in the uppermost mountainous part of Hinnøya are candidates for mainland extensions of these structures. Low-grade rocks are emplaced on top of high-grade rocks along these structures (Tveten 1978; E. Tveten pers. comm. 2001). The Nordfjord-Sogn detachment (Norton 1987) constitutes an equivalent boundary



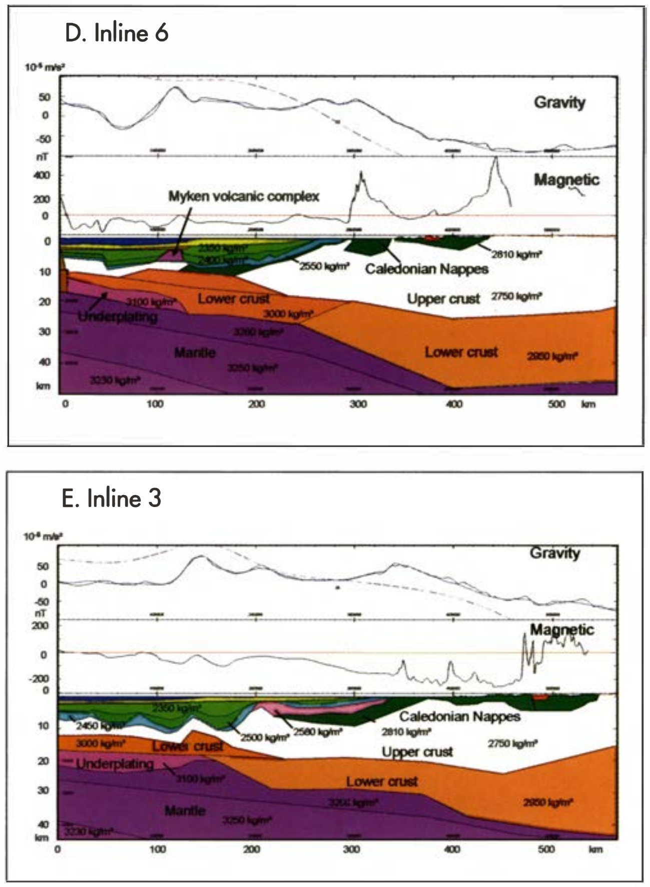


Fig. 12. Five cross sections through the 3D gravity model; Inlines 3, 6, 9, 12 and 15. Applied densities are shown in Table 2. Sedimentary succession: yellow - Tertiary, brown - Tertiary flow basalts and oceanic crust, light green – Upper Cretaceous, green – Lower Cretaceous, blue – Pre-Cretaceous, pale pink – pre-Jurassic; dark green – Caledonian Nappes. The black lines show the observed gravity and magnetic fields while the blue lines illustrate the gravity response of the total 3D model. The dashed purple line represents the regional gravity response from the mantle.

through the gneisses of western Norway. The Hamarøya fault and the Lofoten border faults may have reactivated the flanks of Devonian detachments extending beneath the Vestfjorden and Ribban basins. This model implies that the Melbu transfer zone is located along the northeastern termination of the Devonian shear zone. The Bivrost transfer zone may represent an analogous reactivation of the folded offshore Nesna shear zone. A similar set of NW-SE trending late-Caledonian detachments occurs on the conjugate East Greenland margin (Hartz et al. 2002).

Transfer zones and rift segmentation

The Træna - Vestfjorden - Ribban - Harstad basins constitute the main Late Jurassic-Early Cretaceous rift in the Nordland area. Previous seismic studies have shown that the Moho depth varies between 19 and 26 km

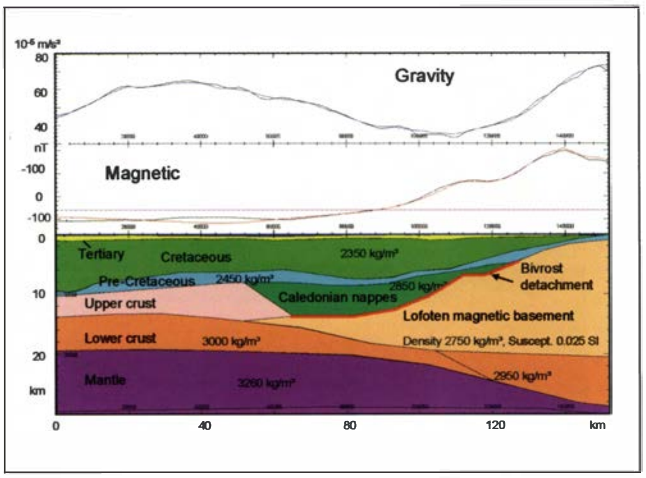


Fig. 13 One crossline (1) through the 3D gravity model. Applied densities are shown in Table 2. The black lines show the observed gravity and magnetic fields while the blue and red lines illustrate the gravity and magnetic responses, respectively, of the total 3D model. The gentle dip (5-15°) of the Bivrost detachment is mainly determined from modelling the gradient of the magnetic anomaly.

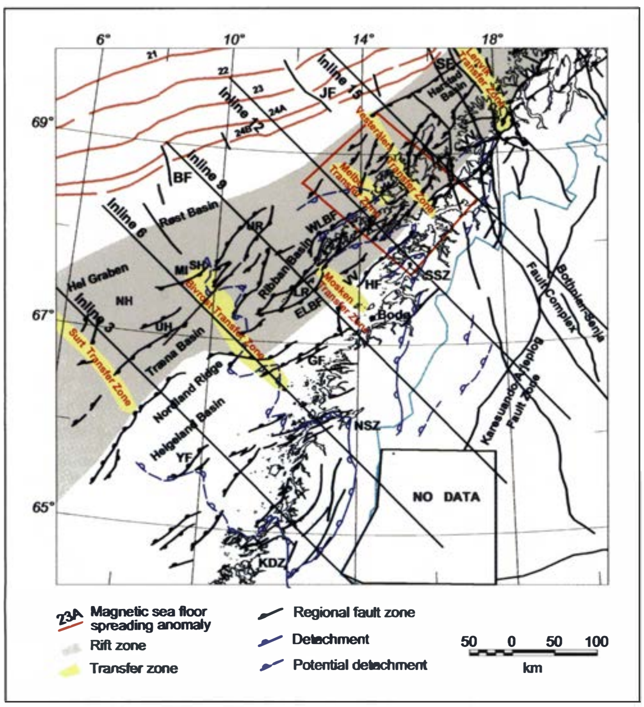


Fig. 14. Interpretations of regional basement faults within the Nordland area. ELBF - Eastern Lofoten border fault; GF - Grønna fault; HF - Hamarøya fault; KDZ - Kollstraumen detachment zone; NSZ - Nesna shear zone; SSZ - Sagfjord shear zone; SH - Sandflesa High; UH - Utgard High; UR - Utrøst Ridge; NH - Nyk High; MI.- Myken intrusive complex; VV - Vestfjorden-Vanna fault complex; WLBF - Western Lofoten border fault, BF - Bivrost Fracture Zone; JF - Jenegga Fracture Zone; SF - Senja Fracture Zone. The nomenclature is adapted from Andresen & Forslund (1987), Blystad et al. (1995), Løseth & Tveten (1996), Olesen et al. (1997b) and Braathen et al. (2002). The red box shows the location of the 3D diagram in Fig. 16. The map illustrates the onshore-offshore links of basement faults in the region exemplified by the Grønna fault, the Vestfjorden-Vanna fault complex, the Bothnian-Senja fault complex and the offshore extensions of Devonian detachment and reactivation of the latter structures as Mesozoic normal faults and transfer zones.

along the rifted margin (Planke et al. 1991; Mjelde et al. 1993). Moho bulges occur in the Lofoten-Vesterålen area and below the Utgard High/Træna Basin. The major Surt, Bivrost and Vesterålen transfer zones coincide with regional changes in Moho depth (Fig. 8) and are consequently deep-seated crustal features, strongly influencing the segmentation of the rift. These cross-margin transfer systems have earlier been delineated by Olesen et al. (1997b) and Tsikalas et al. (2001, submitted). In the present study, we have refined the location of the local transfer zones compared to previous studies. Tsikalas et al. (2001) oriented the Jenegga and Vesterålen transfer zones in a NNW-SSE direction which differs from the NW-SE oriented Bivrost and Lenvik transfer zones. We argue that these transfer zones have the same NW-SE-orientation as the regional Bivrost and Lenvik transfer zones. The Jennegga transfer zone cannot be extended beyond the Ribban Basin; bedrock geology, reflection seismic, aeromagnetic and gravity data do not support that the Jennegga transfer cuts across the middle of the Lofoten Ridge and the innermost Vestfjorden Basin. (Figs. 2, 4 & 10). The main structural break across the Lofoten Ridge and Vestfjorden Basin occurs along the Mosken sound between Moskenesøy and Værøy (Figs. 4, 7, 10 & 14). The Vestfjorden Basin reveals a polarity shift across this transfer zone (Olesen et al. 1997b), which we refer to as the Mosken transfer zone. This zone is most likely a twist-zone (Colletta et al. 1988) similar to the Vesterålen transfer zone. The Vestfjorden Basin north of the Mosken transfer zone is, however, a shallower (approximately 2 km deep) half graben with the boundary fault along the eastern margin of the basin (Olesen et al. 1997b). We suggest applying the name Hamarøya fault for this major structure (Figs. 7 & 14) that constitutes a section within the Vestfjorden-Vanna Fault Complex. Detailed seismic interpretations by Tsikalas et al. (2001) to the west of the Lofoten Ridge show that the Mosken transfer zone does not continue into the Skomvær Sub-basin, and must consequently be of more local character. On the other hand, the northwestern part of the Jenegga Transfer Zone (Tsikalas et al. 2001) seems to terminate towards the Lofoten Ridge, since we have not been able to trace this structural discontinuity across the Lofoten islands. We suggest applying the name Melbu transfer zone to this structure since Jennegga has already been used for the Jennegga High (Blystad et al. 1995) and Jennegga Fracture Zone (Mjelde et al. 1993). The spacing between the transfer zones along the Lofoten margin is 70-140 km. In comparison, corresponding transfer zone spacing along the Gulf of Suez rift is 80-100 km (Colletta et al. 1988).

The NW-trending Vesterålen transfer zone constitutes a continuous zone across the onshore-offshore region and separates two regions with differing fault polarity (Figs. 7, 14 & 16). This transfer zone links up with an apparent (more than 10 km long) offset in the oceanic

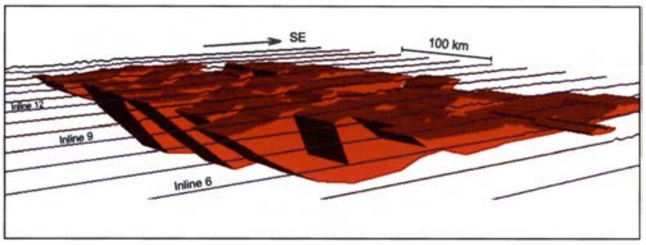


Fig. 15. 3D model of the Tysfjorden-Sarek granite intrusion within the Transscandinavian Igneous Belt. The model consists of a total of 10 bodies with polygonal cross-sections placed next to each other. Each body is 35 km wide. The maximum depth extent is 22 km. The model is displayed with a vertical exaggeration of 2. The perspective view is from the WSW.

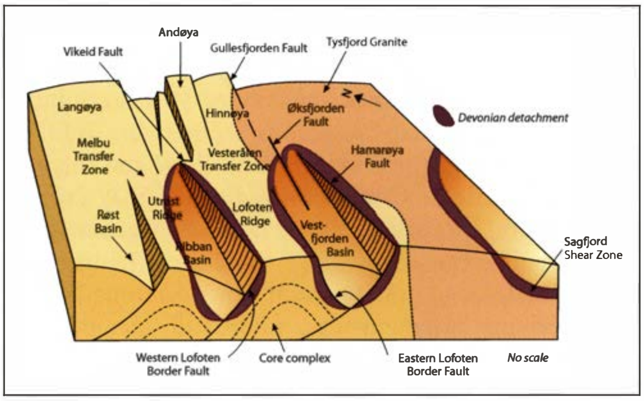


Fig. 16. Schematic block diagrams of the Lofoten area illustrating how the late-Caledonian detachments were exploited in the subsequent rifting. The nomenclature is adapted from Andresen & Forslund (1987), Blystad et al. (1995), Løseth & Tveten (1996), Olesen et al. (1997b) and Braathen et al. (2002). Low-magnetic amphibolite-facies gneisses have been emplaced on top of the magnetic granulite-facies gneisses during the Devonian gravity collapse of the Caledonian orogen. The Hamarøya and Lofoten border faults reactivated the flanks of the Devonian detachment zones. The Vesterålen transfer zone coincides with the northeastern termination of the detachments.

spreading anomalies 22 and 23 (Fig. 7). This dislocation represents the Jennegga fracture zone of Mjelde et al. (1993). The magnetic anomalies 24A and 24B have a poor aeromagnetic coverage offshore Vesterålen since there is a gap in NGUs regional datasets in this particular area (Fig 4). Three profiles from the 1973 survey by US Naval Research Laboratory extend into the gap, but the line spacing is more than 12 km, which is too large to allow identification of small offsets in the oceanic spreading anomalies. There is consequently evidence for only one oceanic fracture zone in this region (the Vesterålen fracture zone), and not two as suggested by Tsikalas et al. (2001); i.e. the Jenegga and Vesterålen fracture zones.

One of the major onshore-offshore linear magnetic discontinuities discernible on the magnetic analytic signal map (Fig. 5) is caused by a basement fault to the southwest of Bodø. The fault is 150 km long and continues from the Nordland Ridge in the southwest and seems to continue into Fleinværfjorden and Landegodefjorden to the west of Bodø. We have applied the name Grønna fault (Figs. 7 & 14) to this structure that is making up the southern boundary to a small, near-shore sub-basin (Figs. 6 & 7; Brekke et al. 1992).

Myken intrusive complex

The western part of interpretation Inline 6 (Fig. 12d) intersects a coinciding positive gravity and aeromagnetic anomaly located between the Utgard High and the Utrøst Ridge (Figs. 4 & 10). The magnetic anomaly is restricted to a smaller area than the gravity anomaly which is one of the largest observed gravity anomalies ($90 \cdot 10^{-5}$ m/s^2) on the Mid-Norwegian continental margin. To explain this anomaly, a substantial excess of mass must be present in the crystalline basement and/or the sedimentary sequence. In addition, there is a shallow Moho (22 km) in this area (Mjelde et al. 1998). The depth to the magnetic sources is approximately 3 km below the sea floor (Fig. 7). We conclude that three models may explain the gravity and magnetic anomalies: (a) mafic igneous intrusions, (b) a basement high or (c) a thick sequence of flow basalt rocks. Interpretation (a) is favoured because Mjelde et al. (1998) have reported intermediate seismic velocities (4-5 km/s) at a depth of 7 km in this area. Sedimentary rocks must therefore occur below the high-density body. A shallow basement high is not a viable model although basement rocks could form a positive structure at larger depth in this area, as indicated in Fig. 7. The large size of the body points to an intrusive complex rather than a thick pile of extrusives. We envisage a complex mixture of volcanic and sedimentary rocks within this volcanic centre. In the 3D model this is simplified to a simple, box-shaped body (Fig. 12d). (Note that the potential field data alone cannot resolve details within the complex). Berndt et al. (2001) have interpreted a gently dipping, strong seismic reflection in terms of a tuff sheet in the Sandflesa area (Fig 7). An alternative interpretation is an erosional surface in sub-aerial volcanics. We suggest applying the name Myken (from one of the outermost islands on the Nordland coast) to the volcanic complex. A possible cauldron complex (Lundin et al. 2002) is located within the Hel Graben immediately to the west of the Myken complex (Fig. 7). The Hel Graben has earlier been interpreted to be a centre of igneous activity on the basis of seismic velocities (Berndt et al. 2000). Our interpretation suggests that a basement high (Sandflesa High) is situated below the Myken intrusive complex and a sedimentary succession. This is also consistent with earlier interpretation by Olesen et al. (1997b) and Mjelde et al. (1998). The age of the intrusions is uncertain, but a latest Cretaceous-Palaeocene age is likely because the area is located adjacent to the Vøring volcanic province. This igneous complex may resemble the seamounts or 'hot points' occurring as intrusive (dolerite/gabbro/peridotite) complexes in the Red Sea (Bonatti & Seyler 1987; Cochran & Martinez 1988). Lundin & Doré (1997) have interpreted similar seamounts in the Rockall Trough and the Faeroe-Shetland Basin. These intrusive complexes are mostly of Palaeocene age (Stoker et al. 1993).

Sedimentary subcrop pattern

The compilation of modern aeromagnetic surveys (Hunting-86, LAS-89, NAS-94 and VAS-98) has revealed several sets of high-frequency anomalies caused by magnetic sources within the sedimentary sequences (Fig. 5). When compared with susceptibility measurements on cores from the shallow drilling programme of Sintef Petroleum Research (previously IKU; Mørk & Olesen 1995), the bulk of the anomaly pattern is caused by buried magnetic sedimentary rocks and sub-cropping sedimentary rock units. The asymmetry of the anomalies, with a steep gradient and a negative anomaly to the east and a more gentle gradient to the west (Olesen & Smethurst 1995), shows that the sources of the anomalies dip gently towards the west, consistent with interpretations of seismic data (Rokoengen et al. 1988). The most distinct of the anomalies represents 'unit IX' on the IKU bedrock geology map of the Mid Norwegian Shelf (Rokoengen et al. 1988), later called the Molo formation by Gustavson & Bugge (1995). The unit was assigned an Oligocene age by Bugge et al. (1984) and Eidvin et al. (1998) and later an Oligocene to early Miocene age by T. Eidvin (pers. comm. 2002).The susceptibility measurements on IKU's cores (Mørk & Olesen 1995) indicate that the positive, coast-parallel anomalies are caused either by 1) alternating beds of sandstone and claystone/siltstone/mudstone, 2) caliche and siderite-cemented sedimentary rocks or 3) sedimentary units containing detrital Fe-Ti-oxides (magnetite, ilmenite or haematite) or pyrrhotite. Negative anomalies are most likely caused by low-magnetic sandstones, gypsum or coal. The pattern of subcrop-related anomalies link up with anomalies further south in the Trøndelag area (Skilbrei & Kihle 1999).

The sub-cropping units in the Lofoten-Vesterålen area do not cause the same distinct set of anomalies as those along the coast of Helgeland and Trøndelag (Fig. 5). A low magnetic susceptibility of the sedimentary rocks in the Lofoten area may be the explanation for this difference in magnetic anomaly pattern, in addition to more tectonic disturbance than further south. There may be a lower content of siderite or Fe-Ti oxides in the sedimentary strata in the Ribban and Vestfjorden basins compared to the equivalent strata on the Trøndelag Platform. Siderite is usually formed as cement or nodules a few tens of metres below the sea floor (K. Bjørlykke pers. comm. 2002). The sedimentary units offshore Helgeland are eroded from the Fe-rich Caledonian Nappes, while the equivalent rocks offshore Lofoten most likely originate from the Fe-poor Precambrian basement to the east. The shaly sedimentary rocks offshore Lofoten and southern Norway may also indicate a longer transport distance. These relationships can explain the contrasting anomaly patterns in the two areas and may also explain the lack of subcrop anomalies along the coast of southern Norway, where the bedrock geology is dominated by Fe-poor Proterozoic granitoids.

Another set of anomalies trends WSW-ENE (Fig. 5) and coincides with the graben segments of the Ylvingen Fault Zone bounding the Vega High. Susceptibility measurements on cores from the IKU shallow drilling programme (Mørk & Olesen 1995) show that Lower Cretaceous claystones and siltstones have higher susceptibilities than Jurassic sandstones. A susceptibility contrast between the Cretaceous sedimentary infill in the grabens along the Ylvingen Fault Zone and the juxtaposed Jurassic sandstones on both sides may explain the magnetic anomalies. A correlation between magnetic anomalies caused by early Cretaceous faulting on the Vega High and gravity and magnetic anomalies due to underlying basement topography indicates that the deep structural setting may have guided the location of later faulting.

A continuous belt of high-frequency anomalies (Fig. 5) reflecting flow basalts and sills extends from the western margin of the Utgard High northwards along the shelf edge to the west of the Utrøst Ridge and up to Andøya.

Conclusions

Comparing the Bouguer gravity field to gravity responses from Airy roots at different depths for the northern Scandinavia mountains shows that the compensating masses are situated at a relatively shallow depth in the upper crust. Consequently, the long-wavelength gravity field in the northern Scandinavian mountains seems to originate from intracrustal, low-density rocks in addition to Moho depth variation. These results are in contrast to southern Norway where the mountains to a large extent are supported by low-density rocks within the mantle.

The aeromagnetic data indicate that the Precambrian intrusive rocks in the Lofoten-Ringvassøya basement complex continue below the Vestfjorden Basin and the Caledonian nappes and further to the tectonic windows in Nordland and into Sweden constituting part of the Transscandinavian Igneous Belt. An oval, 200 km wide negative anomaly in the isostatically-corrected Bouguer gravity dataset occurs in the Sarek-Vestfjorden area immediately to the east of the Lofoten-Vesterålen positive gravity anomaly. An iterative least-square optimising algorithm shows that to explain the observed steep gradients, the low-density body must be located at relatively shallow depths and is most likely exposed at the surface. Applying a density contrast of -100 kg/m^3 between the granitoid rocks of the Transscandinavian Igneous Belt and the high-grade rocks in the Lofoten area shows that the granitoids must extend to a depth of minimum 22 km. The Lofoten-Vestfjorden-Sarek region may be in isostatic equilibrium due to the opposing effects of the mass excess and the mass deficiency.

The Helgeland Nappe Complex has been downfaulted along the offshore extensions of the Devonian Nesna and Kollstraumen detachments. This interpretation is supported by the correspondence between the depth extent of the low-magnetic nappes on land and the thickness of the offshore low-magnetic basement (calculated as the difference between the offshore magnetic depth estimates and the depths obtained from gravity and seismic interpretations). Some of the offshore low-magnetic basement may also constitute Devonian sandstones deposited above the offshore extensions of the Nesna and Kolstraumen detachments, similar to the tectonic situation further south along the Nordfjord-Sogn and Høybakken detachments. Modelling of the aeromagnetic data suggests that the Bivrost Lineament is a detachment dipping 5-15° to the southwest and may represent the offshore extension of the Nesna shear zone. The Sagfjord shear zone further north may analogously be extended below the low-magnetic amphibolite-facies gneisses beneath the Vestfjorden and Ribban basins. Relatively flat-lying deformation zones in the uppermost mountainous part of Hinnøya are candidates for mainland extensions of these structures.

Several shifts in the polarity of faults occur along the continuation of the Mid-Norwegian rift-structures into the Lofoten-Ringvassøya area. A shallow Moho underlies the Late Jurassic to Early Cretaceous rift axis, consisting of the Træna, Ribban, Vestfjorden and Harstad basins. The rifting events have in addition resulted in uplifted core complexes and rotated fault-blocks separated by transfer zones giving rise to a characteristic set of intermediate wavelength gravity and aeromagnetic anomalies. Changes in Moho depths occur across the Surt, Bivrost, Vesterålen and Lenvik transfer zones, indicating that these structures are continuous to large depth within the crust. The more local Mosken and Melbu transfer zones separate structural domains characterised by different fault-polarities within the Ribban and Vestfjorden basins. The Myken intrusive complex (Palaeocene age?) situated along the northwest section of the Bivrost transfer zone gives rise to large gravity and magnetic anomalies comparable in both amplitude and aerial extent to the anomalies originating from the basement structuring.

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 and the Lenvik transfer zone are reactivations of the Proterozoic Bothnian-Senja fault complex, while the Bivrost transfer zone (lineament) could represent a rejuvenation of the Devonian Nesna shear zone.

Acknowledgements. - This study is carried out within the frame of the BAT Project (Basin Analysis and Applied Thermochronology). Norsk Agip, BP, ChevronTexaco, ConocoPhillips, ExxonMobil, Norsk Hydro, Norske Shell, Statoil and the Geological Survey of Norway funded the project managed by Elizabeth Eide. Research affiliations and exchanges with the Norwegian Petroleum Directorate and the University of Oslo have also been of an advantage to the project. We have benefited from discussions with Alvar Braathen, Elizabeth Eide, Roy Gabrielsen, Ebbe Hartz, Jon Mosar, Tim Redfield and Trond Torsvik. The Norwegian Petroleum Directorate provided seismic data from the Vestfjorden area. Asbjørn Breivik, Peter Gunn and Fridtjof Riis reviewed the manuscript and offered important suggestions towards its improvement. To all these persons, companies and institutions we express our sincere thanks.

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