Basement structure of the continental margin in the Lofoten–Lopphavet area, northern Norway: constraints from potential field data, on-land structural mapping and palaeomagnetic data

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Magnetic and gravity anomalies within the northern Norwegian margin, 67° to 71°N are generally interpreted in terms of a complex series of uplifted and rotated basement blocks. Some of the basement highs were previously not identified on seismic reflection data because they lie below basalt flows. Several shifts in polarity occur along the faults in the continental shelf and the adjacent onshore area. This is most pronounced along the Ribban and Vestfjorden Basins and further to the northeast along the Vestfjorden–Vanna fault complex. The individual segments of the fault complexes are connected by transfer zones, which occur as either: (1) transverse faults, e.g. the Lenvik transfer zone, or (2) twist zones, e.g. the Vesteralen transfer zone. The Vestfjorden Basin consists of two subbasins or half-grabens: one to the north with a border fault to the east and one to the south with a border fault to the west. 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 is a reactivation of the Proterozoic Bothnian–Senja fault complex. A palaeomagnetic study of Vesterålen, Senja and Kvaløya has furnished temporal constraints on the near-shore fault activity. On Senja and Kvaløya, two phases of faulting and brecciation have been identified. A young phase, associated with the formation of fault-gouges, is recent–Tertiary in age, whereas an older phase, associated with brecciation, is of Permian age. The lack of Cretaceous/Jurassic faulting along the central Vestfjorden–Vanna fault complex indicates that there may have been a westward shift of the regional fault activity in the Nordland–Troms area from the Carboniferous–Permian to the late Jurassic–early Cretaceous.


Introduction

The study area extends from 67° to 71°N and from the oceanic crust in the west (magnetic anomaly 22) eastwards to the Swedish border and includes the shelf areas of the northern Norwegian Sea and the southern Barents Sea. The purpose of the study was to delineate the basement structural grain of the area and its influence on Late Palaeozoic–Tertiary rift phases from an integrated interpretation of potential field data and on-land structural mapping. The geological knowledge of this offshore transition area is relatively limited because most of the region has not been open for petroleum exploration until recently. The crust in the Lofoten–Vesterålen area has earlier been identified as particularly thin by Sellevoll (1983) and the area, therefore, most likely constitutes a part of the continental margin that has been uplifted above sea level. This province is readily available for studies of the structural geology and can be used as an analogue for studies of offshore basement faults and consequently can improve our understanding of the basin tectonics in the area. Potential field data provide continuous data coverage of both the mainland and offshore areas which are traditionally mapped by two different methods, conventional bedrock mapping and multi-channel seismic data, respectively. Aeromagnetic and gravity data can thus supply the necessary means for tracing the basement structures through the transition zone between the mainland and offshore areas.

Onshore structural mapping data from coastal faults have also been complemented by palaeomagnetic studies to date the fault reactivation episodes. A further onshore sample collection was carried out for petrophysical laboratory measurements in addition to in situ susceptibility measurements. Additional onshore gravity acquisition improved the resolution for tectonic interpretation.

Geological setting

The basement infrastructure of the Lofoten–Lopphavet area is dominated by Precambrian polymetamorphic high-grade migmatitic gneisses and intrusives (Griffin et al. 1978; Tveten 1978; Zwaan 1995; Zwaan et al. in press). The oldest gneisses are 2.7–2.8 Ga old (Griffin et
al. 1978; Jacobsen & Wasserberg 1978; Zwaan & Tucker 1996), while large, almost undeformed plutons date to 1.8 Ga. The Lofoten–Vesterålen area is a province of deep-seated origin with associated regional magnetic and gravimetric anomalies. The positive gravity anomaly is believed to reflect a shallow Moho discontinuity and uplifted high-grade rocks of intermediate density (Svela 1971; Sellevoll 1983; Mjelde et al. 1993). A multi-stage exhumation of the Lofoten Archipelago has been deduced from K-Ar data (Griffin et al. 1978; Sturt et al. 1979) and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology (Andresen & Hames 1995). Gaal & Gorbatschev (1987) have interpreted these rocks to be an integral part of the Transscandinavian Granite-Porphyry Belt which continues to the south beneath the Caledonides all the way to southern Sweden and is characterized by regional magnetic anomalies (Henkel & Eriksson 1987).

Several regionally important shear zones occur within the Precambrian basement in Sweden, some of which may be present in the study area. The Protogine Zone is a continental-scale zone of deformation which constitutes the western margin of the Transscandinavian Granite-Porphyry Belt in southern Scandinavia where the zone was reactivated several times during the Proterozoic (Larson et al. 1990). The Bivrost Lineament (Fig. 1) may constitute the continuation of the Protogine Zone onto the continental shelf, and may therefore represent rejuvenation of a much older zone of crustal weakness (Mokhtari & Pegrum 1992). Two other major shear zones within the basement are the Bothnian–Kvænangen (Berthelsen & Marker 1986; Olesen et al. 1990; Henkel 1991; Olesen & Sandstad 1993) and the Bothnian–Senja fault complexes (Henkel 1991; Zwaan 1995). The Caledonian nappes within the Lofoten–Loppahavet area are dominated by the Middle Allochthon to the north and the Upper Allochthon to the south (Roberts & Gee 1985).

The bulk of the interpreted offshore area is dominated by an extensionally thinned continental crust containing numerous sedimentary basins and basement highs. The Træna Basin (Fig. 1) belongs to the eastern basin province of the Voring Basin (Skogseid et al. 1992; Blystad et al. 1995). The area offshore the Lofoten and Vesterålen archipelagos is also characterized by several fault-bounded basins and basement highs (Åm 1975; Rønnevik & Navrestad 1977; Eldholm et al. 1979; Mokhtari & Pegrum 1992; Mjelde et al. 1992; Løseth & Tveten 1996). The major features include a structural

![Fig. 1. Main structural elements within the Lofoten–Loppahavet area. Modified from Gabrielsen et al. (1990), Henkel (1991), Blystad et al. 1995 and Andresen (in prep.). The locations of palaeomagnetic sampling areas are indicated by circles, K = Kvaløya, V = Vesterålen, S = Senja. A more detailed location of the sampling points is shown in Fig. 4.](image-url)
AEROMAGNETIC ANOMALY MAP

LEGEND
AEROMAGNETIC INTERPRETATION
Flight line
Depth estimate
SEISMIC INTERPRETATION
Gabrielsen et al. 1990
Blystad et al. 1995
Fault
Continental/ocean boundary
Basement
Easternmost flow barrier
Datum: ED50
Kap projection: Universal Transverse Mercator, mid meridian 5°E.

Fig. 2. Residual magnetic field from the Lofoten-Lopphavet area, shaded relief presentation. 'Illumination' from the SE. H/V = basement high or volcanic centre.
high, the Utroest Ridge, on the landward side of the shelf edge and a basinal area, the Ribban Basin on the inner shelf (Fig. 1). Early Cretaceous extension formed the half grabens (Blystad et al. 1995). The western boundary of the Utroest Ridge has large faults (Mokhtari & Pegrum 1992) with northwest throws and forms the landward boundary of the Rost basin which is covered by Early Tertiary flood basalts. The evidence of sub-basalt sediments in the Rost basin is based on gravity inversion studies (Sellevoll et al. 1988) and wide-angle seismic surveys utilizing ocean-bottom seismographs (Mjelde et al. 1992).

Sea-floor spreading-type magnetic anomalies were identified by Taiwani & 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, Kvaløya and Ringvassøya (Fig. 1). The basin is bounded to the east by the southernmost part of the Troms–Finnmark Fault Complex and the western limit coincides with the transition to oceanic crust. Three well-known NNW–SSE trending transform faults extend into the survey area: the Bivrost, Jennegga and Senja Fracture Zones. Several authors have also reported thinning and extension of the continental crust in the onshore coastal areas of northern Norway (e.g. Sellevoll 1983; Forslund 1988). A prominent set of high-angle semi-ductile to cataclastic faults called the Vestfjorden–Vanna fault complex (Andresen & Forslund 1987) continues from the Vestfjorden area through the sounds to the east of Hinnøya, Senja, Kvaløya, Ringvassøya and Vanna into the Lophavet area (Fig. 1). The fault zone which has been interpreted to be of Upper Jurassic–Lower Cretaceous age (Andresen & Forslund 1987; Andresen in prep.) constitutes the contact between the Precambrian terrain to the west and the Caledonian nappe sequence to the east. The island of Senja constitutes a horst situated between the Vestfjorden–Vanna fault complex to the southeast and the Harstad Basin to the northwest.

Data sets

The north and south provinces of the onshore study area have been mapped by Zwaan (1988; Zwaan et al. in press) and by Tveten (1978) and Tveten & Henningsen (in press), respectively. A synthesis of the onshore structural elements is included in Figs. 1 & 4. The main structural elements of the offshore survey area (Blystad et al. 1995; Gabrielsen et al. 1990) were digitized and plotted on the aeromagnetic and gravity maps (Figs. 2 & 3). Seismic interpretations along seven Norwegian Petroleum Directorate profiles have been provided by Norsk Hydro (E. Rasmussen pers. comm. 1992) and Statoil (interpreted by one of us, T.H.).

A total of four offshore aeromagnetic surveys were compiled and interpreted. Survey details are described by Olesen & Torsvik (1993). The final grid is displayed in shaded relief form in Fig. 2 using the THEMAP map production system (Kihle 1992). To enhance the high-frequency component of the Lofoten Aeromagnetic Survey 1989 (LAS-89) data set, a shaded relief map of the vertical derivative has been produced and reported by Olesen & Torsvik (1993).

The on-land gravity data set consists of 7520 gravity stations including data by Svela (1971) in the Lofoten area and by Chroston (1974) from the area to the northeast of Tromso. An additional ~20,000 km of marine gravity profiles provided by the Norwegian Mapping Authority and the Norwegian Petroleum Directorate (Fig. 3) are also included. A regional gravity field obtained from a moving median filter with a radius of 50 km was subtracted from the Bouguer gravity data to obtain the residual field shown in Fig. 3.

Approximately 3050 rock samples were measured for density, susceptibility and remanence. Q-values, the ratios of remanent to induced magnetization, are reported rather than NRM intensity. An additional 2220 in situ susceptibility measurements were carried out from ca. 210 localities in the Precambrian basement of Vesterålen, Senja, Kvaløya and Ringvassøya. The results from the petrophysical survey are summarized in ‘Results’ and in Table 1 and Fig. 5.

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 well-log densities of sedimentary sequences in the Nordland I and II areas immediately to the south of the study area are given in Table 2.

Interpretation methods

The potential-field interpretation was obtained using the IMP software package (Torsvik 1992; Torsvik & Olesen 1992; Torsvik & Fichler 1993). Depths to basement were estimated from inversion of aeromagnetic and gravity data, applying the autocorrelation algorithm of Phillips (1979) and a least-squares optimizing algorithm of Murthy & Rao (1989), respectively. A combined depth-to-basement map was constructed from the magnetic and gravity depth estimates. Constraints offered by seismic interpretation on the structure of the uppermost parts of the sedimentary sequences were incorporated to improve the gravity interpretation of the deeper level of the basins. 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.

The c. 700 magnetic depth estimates are reported by Olesen & Torsvik (1993); locations of these estimates are plotted in Figs. 2 and 4. Ten gravity inversion profiles and seven model calculation profiles are shown in Figs. 3 and 4. The gravity inversion data of five profiles and forward modelling along profiles TB-38-87, LO-06-86,
LO-16-86 and LO-46-88 are shown in Figs. 6–10. Forward modelling along the three lines in the Troms area is reported by Gundersen & Olesen (1992).

The image processing of the grid data sets is reported in detail by Olesen & Torsvik (1993). Fault zones within the basement and partly within the sediments (Fig. 4) were interpreted from the processed images and geophysical maps (Figs. 2 & 3). Regional magnetic trends and high-frequency anomalies (possible volcanics) are also included in the interpretation map. High gravity gradients along the basin boundaries are generally interpreted to be caused by faults but may in some cases be related to steeply dipping sedimentary bedding.

The combined interpretation of depth estimates from 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 highest priority, especially in areas where we expect to find shallow low-magnetic basement continuing from onshore areas or as a result of down-faulted Caledonian nappes within the deep basins. High-frequency anomalies interpreted to represent magnetic volcanics were 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, necessitates that several conditions are satisfied (Torsvik et al. 1992a; Trench et al. 1992): (1) Remanence must be unaffected (undeferred) by the structural grain; (2) Well-defined reference data or an established apparent polar wander path (APWP) are required; (3) Unaccounted-for post-acquisitional structural rotations are precluded; (4) An appropriate sampling strategy must be undertaken; (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.

Results

Petrophysical properties

With the exception of the Seiland Igneous Complex in the northeasternmost part of the study area, the rocks within the Caledonian Nappes of Nordland, Troms and western Finnmark are practically non-magnetic, i.e. susceptibility <0.003 SI (Fig. 5 and Table 1). A magnetic component of the rocks within the Middle and Upper Allochthon is caused by Palaeozoic mafic intrusives and slices of Archaean–Proterozoic gneisses and amphibolites. The Precambrian rocks of the western gneiss region have variable, but usually high, magnetic susceptibilities. The high-amplitude magnetic anomalies are related to granulite-facies gneisses and intrusives (mangerites) (Schlinger 1985; Olesen et al. 1991) in the Lofoten–Vesterålen area and similar anomalies are caused by granulite-facies gneisses on the northwestern part of Senja. The medium-amplitude magnetic anomalies in the Senja–Kvåleøya area are mostly caused by granitic and quartz-dioritic rocks and migmatitic gneisses. The orthopyroxene isograd in the Vesterålen area coincides with the boundary between the high-magnetic and low-magnetic gneisses. West of this line the migmatites are at granulite-facies grade, whereas to the east they have amphibolitic grade. The understanding of this isograd is critical for the interpretation of the magnetic field on the mainland as well as on the continental shelf in the Lofoten–Vesterålen area. In this particular area the magnetic basement surface reflects the depth to the granulite-facies gneisses.

The Q-values in the Lofoten–Vesterålen area are generally low (<0.5). Schlinger (1985), Kaada (1987) and Olesen et al. (1991) have shown that the remanence is viscous and parallels the Earth’s present magnetic field, which makes aeromagnetic interpretations in the area simpler. The mafic and ultramafic rocks, however, often have much higher Q-values, <10.

The susceptibility of the high grade gneisses is highest in SW Lofoten (Flakstadøyøya and Moskenesøya): 0.058 SI (Schlinger 1985) and 0.054 SI (Kaada 1987). The southwesternmost islands within Lofoten represent the deepest part of the crust in the area (Sellevoll 1983). The highest density can also be observed in this area: 2850 kg/m³ (average of 53 samples, this study) and 2870 kg/m³ (average of 8 samples, Svela 1971). The average density for all basement rocks in the Lofoten–Vesterålen area is 2750 kg/m³. The average density for the Upper Allochthon which constitutes the bulk of the Caledonides within the Lofoten–Lopphavet area (Tables 1 and 2) is 2820 kg/m³. Table 2 shows average densities applied in the gravity modelling. The density of sedimentary sequences calculated from the density logs of exploration wells in the Nordland I and II areas is also included in Table 2.

Regional basement configuration

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 over the Lofoten–Vesterålen islands. Calculation of the long wavelength component of the gravity field is shown by Olesen & Torsvik (1993). This part of the field is interpreted in terms of a Moho topography and indicates that the Lofoten and Vesterålen islands constitute a basement high within a rifted and thinned continental shelf crust similar to the basement highs within the Voring Basin to the south (e.g. Planke et al. 1991). The gravity modelling in Fig. 8 also shows that a Moho bulge exists below the southern and central Lofoten islands as observed by Svela (1971), Sellevoll (1983) and Mjelde et al. (1993).

The gravity and aeromagnetic anomaly pattern in the Lofoten–Vesterålen area is different from that in the Senja–Lopphavet area (Figs. 2 & 3). The two areas are
Fig. 3. Residual gravity anomaly map obtained by subtraction of a 50-km-radius median filtered regional field from the Bouguer gravity field. H/V - basement high or volcanic centre.
Fig. 5. Susceptibility spectra of major rock units in the Lofoten–Lopphavet area. The numbers of measurements (n) are shown. The histograms for the Precambrian rocks also include in situ measurements.

Table 1. Statistical data; density, susceptibility and Q-value for main rock units within the Caledonides and Precambrian in the Lofoten–Lopphavet area. The letters a, b and c denote total sample, low-magnetic fraction and high-magnetic fraction, respectively. Units are in SI. The standard deviation of susceptibility and Q-values is expressed in decades. Susceptibility and Q-values have logarithmic mean values.

<table>
<thead>
<tr>
<th>ROCK UNIT/TYPE</th>
<th>DENSITY</th>
<th>Q-VALUE</th>
<th>SUSCEPTIBILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>Precambrian of Lofoten and Vesterålen</td>
<td>639</td>
<td>2579</td>
<td>3553</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Precambrian of Senja, Kvaløya and Ringvassøya, Gneiss, etc.</td>
<td>500</td>
<td>2526</td>
<td>3058</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Precambrian of Senja, Kvaløya and Ringvassøya, Greenstone belts</td>
<td>111</td>
<td>2512</td>
<td>3212</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Seiland Igneous Complex</td>
<td>172</td>
<td>2593</td>
<td>3438</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Uppermost Allochthon of the Caledonian Orogen</td>
<td>55</td>
<td>2593</td>
<td>3137</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Upper Allochthon of the Caledonian Orogen</td>
<td>474</td>
<td>2524</td>
<td>3192</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>Middle Allochthon of the Caledonian Orogen (except the Seiland Igneous Complex)</td>
<td>695</td>
<td>2521</td>
<td>3506</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
</tbody>
</table>
separated by a prominent transition zone running between Narvik and Andøy (Figs. 1 & 2). This zone coincides on Andøy with a thrust fault most likely of Caledonian age. Southwest of this transition zone anomalies generally trend NE–SW while the northeastern 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 the Palaeozoic to Tertiary basin configuration partially controlled by the older Caledonian trends in the Precambrian basement. Along the landward extensions of the Bivrost and Senja fracture zones we observe lineaments on the continental shelf and on land, indicating that the Cenozoic fracture zones originated as reactivations of NW–SE trending zones of weakness of Proterozoic age.

The gravity and aeromagnetic anomalies of the Senja–Loppfjøvet onshore area are dominated by a NW–SE to NNW–SSE trend which is also clearly reflected on the aeromagnetic map of northern Fennoscandia (Geological Surveys of Finland, Norway and Sweden 1986). This anomaly pattern coincides with the structural grain of the Precambrian basement in northern Sweden and Finland (Henkel 1991). The aeromagnetic map (Fig. 2) shows that magnetic Precambrian rocks on Andøy 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. A similar continuous anomaly can be traced from southern Hinnøya across Vestfjorden to mainland Norway and further to the southeast into the Precambrian Transcandinavian Granite-Porphyry Belt in Sweden. The Lofoten–Vesterålen province is thus part of the Baltic Shield and cannot have been accreted to this shield during the Caledonian orogeny as suggested by Tull (1977).

The aeromagnetic and gravity anomalies of Lofoten–Vesterålen and the adjacent offshore area generally trend NE–SW and NNE–SSW. The anomalies within this region are probably caused by supra-basement susceptibility contrasts and are interpreted as a result of fault-related or steeply dipping basement relief. The most prominent positive anomalies in Figs. 2 & 3 correspond to the Utgard High, Utrøst Ridge, Lofoten Ridge and Marmåle Spur. Negative anomalies characterize the Træna, Røst, Ribban, Vestfjorden and Harstad Basins. The anomalies are parallel to the Caledonian trend. This indicates that the Mesozoic rifting has exploited already existing Caledonian zones of weakness in the Proterozoic rocks of the Lofoten–Vesterålen area. The NE–SW trending ‘Heier Zone’ on Langeyøya may represent such a late Caledonian structure (Løseth & Tveten 1996).

Several shifts in the polarity of faults occur along the continental shelf and adjacent onshore area (Fig. 4). This is most pronounced along the Ribban and Vestfjorden Basins and further to the northeast along the Vestfjorden–Vanna fault complex. The individual segments of the faults are connected by transfer zones (Gawthorpe & Hurst 1993) which have also been called ‘accommodation zones’, ‘relay zones’ and ‘segment boundaries’. These zones occur as two different types: (1) transverse faults e.g. the Lenvik transfer zone or (2) twist zones (Colletta et al. 1988) e.g. the Vesterålen transfer zone. The former is bounded by steeply dipping transverse faults inherited from old weakness zones along the Bothnian–Senja fault complex, while no major transverse fault seems to occur within the latter.

High-frequency magnetic anomalies occur in a continuous zone from the western margin of the Utgard High northwards along the shelf edge to the west of the Utrøst Ridge and Andøy (Figs. 2 & 4). The vertical derivative map by Olesen & Torsvik (1993) reveals this zone most clearly. The high frequency anomalies are often negative, which suggests that they represent basalt flows and/or sills.

**Ribban and northern Træna Basins**

The greatest depths to magnetic basement within the Ribban Basin are 10 km and are located in two areas.

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**Table 2.** Density of sedimentary sequences from density logs of wells in the Nordland I and II areas. The estimates (in 1000*kg/m³) are used for gravity modelling along profiles TB-38-87, LO-06-86, LO-16-86 and LO-46-88. Numbers in parentheses show depth to the base of the sequences.

<table>
<thead>
<tr>
<th>Well</th>
<th>Water depth</th>
<th>Start of log</th>
<th>Pleistocene</th>
<th>Tertiary</th>
<th>Cretaceous</th>
<th>Jurassic</th>
<th>Triassic</th>
<th>Permian</th>
<th>Caledonian nappes</th>
<th>Density estimates</th>
<th>Density adapted for modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 6607/7-1 Phillips Petroleum</td>
<td>250 m</td>
<td>1025 m</td>
<td>2.10 (1635 m)</td>
<td>2.25 (1845 m)</td>
<td>2.32 (3785 m*)</td>
<td>—</td>
<td>—</td>
<td>2.31 (1920 m)</td>
<td>2.64 (1960 m*)</td>
<td>2.70–2.85</td>
<td></td>
</tr>
<tr>
<td>Well 6607/5-1 Norsk Hydro</td>
<td>368 m</td>
<td>900 m</td>
<td>2.21 (1220 m)</td>
<td>2.21 (2510 m)</td>
<td>2.32 (3785 m*)</td>
<td>—</td>
<td>—</td>
<td>2.25 (2005 m)</td>
<td>2.70–2.85</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>Well 6507/2-1 Donna Terrace</td>
<td>381 m</td>
<td>1050 m</td>
<td>2.18 (2005 m)</td>
<td>2.37 (3610 m)</td>
<td>2.54 (4400 m*)</td>
<td>—</td>
<td>—</td>
<td>2.25 (2005 m)</td>
<td>2.70–2.85</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>Well 6507/1 Univ. of Bergen</td>
<td>—</td>
<td>—</td>
<td>2.25</td>
<td>2.30</td>
<td>2.35</td>
<td>—</td>
<td>—</td>
<td>2.25</td>
<td>2.70–2.85</td>
<td>3.00</td>
<td></td>
</tr>
</tbody>
</table>

**Density estimates**

1.03

2.82

2.75

2.84
Fig. 4. Basement structural map interpreted from combined geophysical and geological data. AS - Astridal Shear Zone, EAF - Eastern Andoya Fault, EF - Eidefjorden Fault, ELF - Eastern Lofoten Border Fault, GF - Gullefjorden Fault, HZ - Hein's Zone, HAZ - Halsfjorden Fault, KLF - Kvenangen - Langfjorden Fault, LRF - Lyngen - Rotund Fault, LTZ - Lenvik transfer zone, SBF - Sotrebergfjorden Fault, SF - Stonglandet fault, SS - Svanfjellet Shear Zone, STF - Storstasjonet Fault, SVF - Straumsbukta - Vanna Fault, SSF - Straumsfjorden Fault, H/V - basement high or volcanic centre. The locations of palaeomagnetic sampling areas are indicated by filled circles; K = Kvaløya, V1 - V1 = Vesterålen, and S = Senja.
termed the Skomvær and Havbåen Subbasins. Modelling of gravity data gives depths of ≤5 km (Figs. 8 and 9). Åm (1975) observed a similar divergence in depth estimates from aeromagnetic data and refraction seismics. We interpret this discrepancy to be caused by downfaulted low-magnetic Caledonian nappes or low-magnetic amphibolite-facies gneisses. There is no support for the possible occurrence of Devonian sediments in the deeper parts of the basin from interpretation of the reflection seismic data. The Skomvær Subbasin is modelled along line LO-06-86 (Fig. 8) as a half-graben. The basin is bordered by the steep Western Lofoten Border Fault (Løseth & Tveten 1996) towards the Lofoten islands which represent a horst between the Ribban and Vestfjorden Basins (Åm 1975; Rønnevik & Navrestad 1977). Depths to basement obtained from both gravity and magnetic data north of the Marmæle Spur are significantly deeper than base-Cretaceous depths interpreted on multi-channel seismic data (Brekke et al. 1992). This suggests that either: (1) base-Cretaceous is situated at a greater depth than previously estimated, (2) significant volumes of low-density sediment exist below the base-Cretaceous in this area, or (3) the basement locally has a lower density and susceptibility than the bulk of the Precambrian rocks in the area. The last of these possibilities does not seem to be likely since both the gravity and aeromagnetic anomalies are integrated parts of the anomalies caused by the Ribban Basin to the east. Possibility (1) may be correct, as the base-Cretaceous reflector is obscured by multiples from the hard seafloor in this area and is consequently difficult to define. The shallow basement block at 1–3 km depth between the Røst High and the Skomvær Subbasin constitutes the Marmæle Spur (Blystad et al. 1995). This spur is the footwall to a half-graben termed the northern Træna Basin and is clearly indicated by the gravity inversion along profile E (Fig. 6a).

The seaward boundary of the dome-shaped Utrøst Ridge consists of a fault complex with downthrow to the NW and forms the landward boundary of the Røst basin; the latter 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 than indicated on seismic sections. The depth of the top basement of the Røst basin obtained from gravity interpretation is ~9 km. The magnetic spreading anomalies have longer wavelengths seaward of the Røst basin, and imply subsidence of the crust and a possible overlying wedge of Tertiary sediments in this area. The ocean-continent boundary is displayed on the interpretation map (Fig. 4) but is not well defined on the gravity and aeromagnetic maps. This is interpreted to be due to a gradational oceanic/continental crust transition. Inter-

Fig. 6. Depth to basement from gravity inversion applying the GDEPTH software (Torsvik & Fichler 1993) along one section (E) across the Ribban Basin and four sections (G–J) across the Vestfjorden Basin. The location of the profiles is shown in Figs. 3 and 4. Shading illustrates sediments and depths are shown in km. Density contrast between basement and sediments: 400 kg/m³.
Interpreted fracture zones in the oceanic crust are shown on the interpretation map (Fig. 4). They seem to be more frequent in the older part (magnetic anomalies 24A and B) of the oceanic crust than in the younger (see also Hagevang et al. 1983). A high frequency of transform faults of this type has been documented in the initial phase of oceanic crust formation in the Red Sea (Martinez & Cochran 1988).

The depth to the magnetic basement under the Utgard High is ca. 6 km and over 10 km in the Træna Basin. The Utgard High is interpreted as a faulted anticline. A coinciding gravity and aeromagnetic anomaly (denoted by H/V in Fig. 4) is located to the north of the Utgard High and southwest of the Røst High. The magnetic anomaly is, however, restricted to a smaller area than the gravimetric anomaly. These anomalies may be related to a basement high or a thick sequence of volcanic rocks. We favour the former interpretation since both the aeromagnetic and gravity anomalies are continuous southwestward to the Nyk High. This interpretation also gains support from the interpretation of a shallow basement on multi-channel seismic data. We propose to name this structure the Sandflesa high. The gradient of the gravity field is highest on the eastern flank of the anomaly (Fig. 3) indicating a border fault zone to the east (Figs. 4 & 7). Some of the high-frequency magnetic anomalies in the area may, however, represent mafic sills or lava flows that 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 anomalies. The depth to these anomalies is <300 m which is almost consistent with the basement outcrop in this area (Sigmond 1992). Negative magnetic anomalies lie within a continuous zone of high-frequency anomalies extending from west of the Utgard High northwards to Andøya and most likely represent volcanic rocks with reverse polarity remanence. This zone is even more pronounced on the shaded relief map of the vertical derivative (Olesen & Torsvik 1993). Three very pronounced steps in the magnetic anomalies with successively longer wavelengths to the southwest of the Jennegga High most likely represent three steeply dipping fault zones within a fault complex. Many of the NNE-SSW-trending faults in the area merge into the regional ENE-WSW-trending fault along the shelf edge (Figs. 3 & 4). Fig. 9 shows a gravity model along line LO-16-86. The negative anomaly which we find to the west of the U트rost 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 is supported by the presence of large amplitude negative magnetic anomalies.
Vestfjorden Basin

The interpretation of Brekke & Riis (1987) indicates that the Vestfjorden Basin is essentially a Lower Cretaceous basin and not a Palaeozoic basin as suggested by Bøen et al. (1984). The southern part of the Vestfjorden Basin is a ~7-km-deep half-graben defined by a border fault zone along the northwestern margin (Brekke & Riis 1987). The northern part of the Vestfjorden Basin is a shallower (~2 km deep) half-graben with the border fault along the southeastern margin of the basin. Gravity interpretation along profiles LO-06-86 and LO-16-86 (Figs. 8 & 9) and profiles G, H and I (Fig. 6b–d) illustrates this shift in subsidence polarity. The depth to basement is shallower in the transition zone between these two subbasins and this region is defined as a transfer zone. A similar shift of polarity is also seen offshore of Lofoten and Vesterålen where the faults change from having a northwesterly downthrow to a southeasterly downthrow. The shift seems to occur along the landward continuation of the Jennegga fracture zone (Fig. 4).

The age of the sediments within the northeastern subbasin of the Vestfjorden Basin is not known but is assumed to be Jurassic and/or Cretaceous. As shown by the palaeomagnetic dating (see below), the Vestfjorden–Vanna fault complex along the northeast extension of the Vestfjorden Basin was active during the Permian. This date is consistent with the interpretation that the Sorvær basin (Olesen et al. 1990; Johansen et al. 1994), located along the northern segment of the Vestfjorden–Vanna fault complex is of Permian–Carboniferous age (Sigmond 1992).

The western margin of the Vestfjorden Basin in the Lødingen area is interpreted to consist of several rotated fault blocks (Olesen & Torsvik 1993). Raftsundet and Øksfjorden (Fig. 4) are very conspicuous topographic/bathymetric lineaments, mainly represented by narrow sounds and fjords. These lineaments are visible as negative magnetic anomalies between the rotated, magnetic fault blocks (Olesen 1992). The exposed Gullesfjorden Fault (labelled GF in Fig. 4) along Øksfjorden does not seem to be linked directly to the exposed Gullesfjorden Fault (labelled GF in Fig. 4). As for the faults along Eidsfjorden and Hadsselfjorden, we notice that these faults are not continuous across a line from Eidsfjorden to Lødingen, which apparently acts as a NW–SE barrier for single-fault propagation. This region, extending northwestwards from Hinnoya across Langøya and possibly westward to the Jennegga High, constitutes a transfer zone of the twist zone type with no major transverse faults (Colletta et al. 1988). We propose to name this zone the Vesterålen transfer zone.

Loften Ridge – Vesterålen transfer zone

The islands of Lofoten constitute the Lofoten Ridge which is partly separated from the islands of Vesterålen by the Havbåen Subbasin (Fig. 4). Modelling of seismic and gravimetric data by Sellevoll (1983) allows Moho depths of 22 and 24 km beneath the islands of Lofoten and Vesterålen, respectively, while the depth between them is 26 km. Several regional faults occur along the Lofoten Ridge. The basement rocks on the islands are strongly faulted and fractured as also indicated from the dense set of lineaments identified on Landsat TM data (Gabrielsen & Ramberg 1979; Bax 1993). 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 by Chroston & Brooks (1989). The influence of fracturing on the seismic velocities implies that density estimates deduced from seismic velocities should be used cautiously in the Lofoten–Vesterålen area.

Heier (1960) interpreted a major structure south of Eidsfjorden as a thrust. Anorthosite and other Proterozoic and Archaean rocks rest upon mylonites in the area which was later called 'Heier's Zone' (HZ in Fig. 4); these rocks grade downsection into augen gneiss and mangerite. Shear sense indicators beneath the mylonite show a component of normal movement; pseudotachylites and zeolite-filled small-scale faults cut the mylonitic foliation. The absolute age of the mylonite structure is unknown. Similar mylonites and shear zones can be observed on Hinnoya. Løseth & Tveten (1996) interpret these shear zones as remnants of the first post-Caledonian extension in the area.

Eastern Langøya, Skogsøya and Hinnoya east of Sortlandsundet are the main localities for the conspicuous pseudotachylites (Løseth & Tveten 1996). The observed pseudotachylites which we have sampled for palaeomagnetic studies are sharp dykes without any signs of abrasive activity or fragmentation. However, most of the samples are braided, complex zones of angular fragmentation of the host rock (Fig. 11). Pseudotachylites are seen to offset older structures in the gneiss. Most

Fig. 10. Gravity interpretation along the seismic profile LO-46-88 (Figs. 2, 3, and 4). Applied densities are shown in Table 2. Yellow – Tertiary, magenta – Tertiary flow basalts, orange – oceanic crust, green – Cretaceous, blue – Jurassic, grey – basement, violet – mantle.
Pseudotachylites dip between moderate angles and horizontal (Fig. 12a). It can be seen from Fig. 12a that there is an element of girdle distribution. The girdle-axis is generally horizontal; the axis in the Blokken area on western Hinnøya, however, plunges about 30° (Fig. 12b). This locality is situated to the southeast of the Vesterålen transfer zone. This interpretation of the girdle distribution is based on the assumption that the pseudotachylites are related to rotation of extensional allochthonous blocks, these blocks must have an approximately prismatic shape bounded by coaxial surfaces within one subdomain (Fig. 13). The 30° tilt for one subdomain may be a late rotation for this particular subdomain, or may indicate that two of the principal stress axes do not lie in the horizontal plane.

The NNE–SSW trending, subvertical Eastern Andøya and Gullesfjorden faults are situated on the northeastern side of the Vesterålen transfer zone; the former (EAF in Fig. 4) defines the border to the Jurassic–Cretaceous sediments (Dalland 1975) on Andøya and in Andfjorden. Cemented fault breccias occur along this fault on southwestern Andøya (Fig. 4). Fault activity has occurred in the late Cretaceous and early Tertiary (Sturt et al. 1979, p. 529). The regional Gullesfjorden Fault (GF in Fig. 4) comprises polygenic, mostly cemented breccias where exposed. It has not been possible to follow this structure across the Vesterålen transfer zone to Øksfjorden farther to the southwest.

The NE–SW trending Eidsfjorden Fault (EF) and Hadsfjorden Fault (HAF) are identified by Løseth & Tveten (1996) from subsurface grooves close to the northern shore of Eidsfjorden and in the middle of Sørlandsundet between Langøya and Hinnøya, respectively. These interpreted faults are situated to the southeast of the Vesterålen transfer zone. The Eidsfjorden Fault is also clearly identified on the aeromagnetic map. The fault is not traceable to the northeast, but at the southwest end it may join the Western Lofoten Border Fault (WLF) (Løseth & Tveten 1996), which is the main listric fault separating the Lofoten Ridge from the Ribban Basin to the west. The Hadsfjorden Fault is assumed to take up a major part of the downthrow of the southeastern part of the sound; it terminates outside Sørland and, like other faults in the Lofoten–Vesterålen area, cannot be traced along the total length of the region. The Hadsfjorden Fault, together with the faults along Eidsfjorden and Øksfjorden, appear to delimit a series of fault blocks. These blocks terminate towards the northeast into the Vesterålen transfer zone. This zone across Hinnøya, from Lødingen, to Langøya and the head of Eidsfjorden acts as a barrier to propagation of the rotated fault blocks. The Eastern Andøya and Gullesfjorden faults continue from the Harstad Basin area to the north and terminate against the northern side of the zone. This type of structure indicates that the mechanism of formation resembles the ‘transfer zone’ of Morley et al. (1990) or ‘accommodation zone’ of Bosworth (1985) and Rosendahl et al. (1986).

Another regional fault is the Vikeid Fault Zone (VFZ in Fig. 4) on Langøya. Most of the land strip between Vikeid and Eidsfjorden is intersected by several sets of faults which together form a 1-km-wide fault belt. Small-scale faults in the area strike E280°W–E290°W (dip to the north). The faults in this zone may be classified on the basis of petrography into three groups: (a) faults with cemented breccia (Fig. 14), (b) faults with crush breccia, and (c) faults with black chlorite breccia. These faults may constitute a part of the Vesterålen transfer zone.
At Storvatnet, southeast of Harstad, Gustavson (1974) mapped a system of faults, two of which displace the Caledonian rocks in the area. Bartley (1982) and Øvreli (1995) studied the faults in more detail and interpreted them to be of Mesozoic age. The dip of the Caledonian front conforms with downward movement of the south-eastern block if the true movement is vertical. The Storvatnet Fault (STF) is the largest of the faults that constitute parts of the Vestfjorden–Vanna fault complex (Fig. 4).

Løseth & Tveten (1996) interpret the pseudotachylites to be intermediate in age between the subhorizontal mylonites and the subvertical cataclasites. Following the formation of ductile and semi-ductile shear zones, pseudotachylites were formed as friction melts by upper-crustal brittle faulting (Sibson 1975), probably at depths of more than 6 km (Swanson 1992). Analysis of mesostructures indicates that pseudotachylites are segments of faults, mostly of low-angle northeast- or east-striking orientations. The apparent offset along each of the individual faults is minor, between 30 and 250 cm. Observations of pseudotachylites on small listric faults a few hundred metres in length indicate that they are related to the formation of the extensional allochthon in the province and that their predominantly horizontal attitudes reflect origins 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 northeast-striking axis of the fault blocks are preserved.

**Harstad Basin**

In the area offshore of Vesterålen–Andøya the basement surface is smoother than in the Lofoten area. The basement faults are less distinct and have apparently smaller vertical offsets. A gravity model (Fig. 10) along the seismic profile LO-46-88 illustrates the situation offshore of the Vesterålen-Andøya area. The uplift of the Vesterålen area is of dome-like character compared to the typical horst structure of the Lofoten islands. A basin >7 km deep to the west of Andøya is the southward continuation of the Harstad Basin. This depth is interpreted from gravity data. All the depth estimates from the aeromagnetic interpretation are shallower than this basin and most probably represent depth to magnetic volcanics. The elongated magnetic anomalies at the eastern margin of the basin are continuous from the Vesterålen islands and, therefore, represent basement and/or rotated basement blocks. The abundant high-frequency anomalies in this area, in contrast, probably represent volcanic rocks. The easternmost anomalies occur along a zone coinciding with the shelf edge and most likely identify the easternmost limit of the basal flows. The interpreted depths to these anomalies are of the order of 0.5–2.0 km below sea level. Because flat-lying or gently dipping magnetic bodies do not fulfill the vertical dyke approximation, the uncertainty on these depth estimates is approximately ±20%.

*To the northwest of the Harstad Basin, ocean-spread- ing anomalies 22, 23, 24A and 24B have been identified by Talwani & Eldholm (1977) and Hagevang et al. (1983). The depths to these anomalies are about 2–3 km. A water depth of 2–2.5 km would imply 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 east and south of, and subparallel to anomaly 24B; these are interpreted to represent lava flows. An intriguing, coincident gravity and aeromagnetic anomaly (denoted by H/V in Figs. 2, 3 & 4) is located northeast of the Senja Fracture Zone and south of the Sørvestnaget Basin. These overlapping anomalies may be related to a basement high at a depth of ~7 km, or to a mafic intrusion. Finstad (1995) has studied multi-channel seismic data from the area and argues that the potential field anomalies are caused by Early Tertiary intrusives. The northern part of the Harstad Basin is flanked towards the east by the Troms–Finnmark Fault Complex (Gabrielsen et al. 1990). A group of possibly rotated fault blocks lying at 5–9 km depth is interpreted from the combined data sets. The Troms–Finnmark Fault Complex shows a N–S deflection where it encounters the NNW–SSE trending Bothnian–Senja fault complex and may therefore be governed by this Proterozoic structure. The Bothnian–Senja fault complex is manifested on land as several steeply dipping mylonite zones (Zwaan 1995) and the continuation offshore represents the southern termination of the Finnmark Platform. The Senja Fracture Zone may also initially have developed along this pre-existing zone of weakness in the crust. A half-graben of Palaeozoic sediments (~6 km in thickness) is located on the Finnmark Platform offshore of Ringvassøya (Fig. 4). The main post-Caledonian faults on land, the Vestfjorden–Vanna fault complex, the Kvenangen–Langfjorden Fault (KLF in Fig. 4) and the Lyngen–Rotsund Fault (LRF in Fig. 4) may have been active during a Palaeozoic phase of rifting (see next chapter for discussion of palaeo-magnetic dating).
The Proterozoic shear zones on Senja and the southwestern part of Kvaløya define a ca. 30-km-wide, northwest–southwest-trending shear zone, the Bothnian–Senja fault complex (Henkel 1991; Zwaan 1995 and Fig. 4). The southwestern border of the fault complex 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). The former is described by Dallmeyer (1992) who states that the shear zone has profound tectonic significance and may have been reactivated during the Caledonian orogeny. Within the Bothnian–Senja fault complex, the gneissic foliation and faults/shear zones form a coherent pattern suggesting a mutual relationship. The rocks are mylonitized in narrow shear zones, the most prominent of which is the 800-m-wide Astridal shear zone (AS). Structural details of the shear zones are reported by Zwaan (1995). The Senja Fracture Zone is a continuation of the Torsnes and Astridal shear zones and were most likely reactivated during the formation of the fracture zone in the early Tertiary.

The Vestfjorden–Vanna fault complex occurs along the southeastern coast of Hinnøya, Senja, Kvaløya and Ringvassøya as a prominent set of high-angle, semi-ductile to cataclastic faults (Andresen & Forslund 1987; Forslund 1988; Andresen in prep.). The Solbergfjorden (SBF in Fig. 4), Stonglandeideit (SF) and Straumbukta–Vanna faults (SVF) are situated within the Vestfjorden–Vanna fault complex (Fig. 4) and constitute the boundary between the Precambrian basement to the northwest and the Caledonian nappes to the southeast. The high-angle, normal Solbergfjorden fault shows a vertical displacement of ≥1000 m down-to-the-SSE. The Stonglandeideit and Solbergfjorden faults are ENE-striking, first-order, high-angle faults with an intervening widespread set of secondary high-angle faults trending NE–SW. Along the Stonglandeideit fault, a westward branch running along the shore of Senja, a cataclastically deformed fault rock is exposed at one locality.

The individual fault segments of the Vestfjorden–Vanna fault complex show shifts of polarity and significant offsets at the intersection with the Bothnian–Senja fault complex (Fig. 4). The offsets and polarity shifts are located on the sea bottom at Reisafjord and Malangen and are therefore not accessible for field studies. We can, however, from the aeromagnetic data (Fig. 2), trace the southeastward continuations of the Svanfjellet and Torsnes shear zones below the Caledonian Nappes. These shear zones coincide exactly with the location of the shifts and offsets of the Vestfjorden–Vanna fault complex and were therefore most likely reactivated as transverse faults connecting the different segments within the fault complex (Colletta et al. 1988). Zwaan (1995) has proposed the name ‘Lenvik Zone’ for the system of NE–SW trending curvilinear faults cutting the Caledonian nappes within this part of the Vestfjorden–Vanna fault complex. We interpret the Lenvik Zone as a transfer zone because the characteristic shifts of polarity and offsets of the faults can be connected by transverse faults (Fig. 4). 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) and the contact between the basement and the nappes is preserved as a thrust. The Vestfjorden–Vanna fault complex changes abruptly to the NE of the Lenvik transfer zone where the Caledonian rocks on the islands of Kvaløya, Ringvassøya and Vanna are separated from the Precambrian basement by a continuous set of high-angle normal faults, called the Straumsbukta–Vanna Fault (SVF), with a down-to-the-east displacement of 2 to 3 km (Forslund 1988; Andresen in prep.). The elongated Mauken tectonic window (Fig. 4), a part of the Caledonian orogen, is located within the Bothnian–Senja fault complex and indicates that the formation of this window was governed by the Precambrian fault complex.

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. 1).

Kvaløya

Samples from Kvaløya were taken across a zone of several generations of crush-brecias (Forslund 1988). The younger breccias show clear evidence for a late phase of fluid circulation and precipitation of haematite that gives the fault rocks a distinctive 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. 15). The haematite component is often partially overprinted by a low unblocking component with downward-dipping inclination towards the north (Fig. 16; remanence group marked with LB). This component compares with recent/ Tertiary reference data.

Vesterålen

Two localities were sampled on Vesterålen. Location 1 consists of pseudotachylites (thin veins; millimetre scale) and host rocks (banded gneisses), whereas location 2 comprises pseudotachylites and a mafic dyke. Palaeomagnetic studies demonstrate that the pseudotachylites, banded gneisses and the mafic dyke carry the same remanence direction (Figs. 15 & 16). We presume, therefore, that they may record a regional overprint magnetization direction and offer no constraints on the age of faulting in the area.
Fig. 15. 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.

Senja

The sampled locality on Senja covers a wide brecciated zone that yields evidence of at least two phases of brecciation (Fig. 17). The youngest fault movements produced fault gouges and fault rocks which carry steep, northerly directed magnetizations with a steep inclination of recent/Tertiary age (see group marked LB in Fig. 16). 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 declination/inclination direction (group HB in Fig. 16) similar to fault rock directions on Kvaløya.

Interpretation

In Fig. 18, pre-Tertiary palaeomagnetic results from Vesterålen, Senja (Group HB in Fig. 16) and Kvaløya (Group HB in Fig. 16) are compared with the reference apparent polar wander path for Baltica (Torsvik et al. 1992b). At least two phases of faulting and brecciation can be identified on Kvaløya and Senja. The youngest phase (fault gouges) is recent/Tertiary in age (Fig. 16 - group LB), and almost obliterates an older Permian phase. It is evident that the results from the two latter areas plot close to the early Permian part of the apparent polar wander path, and it is, therefore, evident that important phases of onshore faulting and/or phases of fluid circulation (breccia cementation) took place at that time (~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 indicates an early rift phase on the continental margin. Similar Permian (and also younger) magnetization directions have been observed on elements of the Møre–Trøndelag Fault Zone (Grønlie & Torsvik 1989) and on faults in western Norway (Torsvik et al. 1992a). In the latter area, Permian and Late Jurassic/Early Cretaceous fault movements prevail. The palaeomagnetic poles from Vesterålen are removed from the reference apparent polar wander path (Fig. 18) but may indicate an early Palaeozoic magnetic overprint. A seaward block-tilting of the order of 15–20° on a northeast-trending tilt axis would bring the Vesterålen results into correspondence with the Ordovician section of the apparent polar wander path for
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. A complex structural pattern with several uplifted and possibly rotated basement blocks occurs in the Ribban Basin. Coinciding gravity and aeromagnetic anomalies situated along the Bivrost Lineament at the extension of the Nyk High most likely represent a basement high.

4. 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, and depths of >10 km in the Træna, Sørvestnaget and Tromsø Basins. Locally within the Ribban Basin, magnetic depth estimates of >5 km occur. We interpret these greater depth estimates to represent downfaulted Caledonian Nappes or low-magnetic Precambrian rocks.

5. There are two distinct fault trends within the survey area: NNE–SSW and ENE–WSW. The western margins of the Utgard High, Lofoten Ridge, Marmøle Spur and Utrest Ridge are characterized by complex and large-scale faults. Several shifts in the polarity of the faults occur along the continental shelf and the adjacent onshore area. The individual segments of the faults are connected by transfer zones, e.g. the Lenvik and Vesterålen transfer zones.

6. Mapping of faults on Langøya and Hinnøya indicates that three distinct types of fault exist: The oldest type consists of low-angle ductile and semi-ductile shear-zones accompanied by subsequent metamorphic retrogression. The second group hosts pseudotachylites formed by the strain-hardening process of friction melting and related to widespread intermediate-scale extensional faulting. The third group of faults is more diverse, characterized by breccias, fault gouges and phyllonites. The last-mentioned represents a younger strain-softening process along steep regional structures.

7. A barrier for propagation of rotated fault blocks runs NW–SE across Hinnoya, from Ledingen, to Langøya and the head of Eidsfjorden and resembles a transfer zone. Geological mapping on land shows that the NE–SW-trending faults are discontinuous across this zone and opposing slip directions of faults in the Vesterålen are also most likely related to this ‘transfer zone tectonics’. The Vesterålentransfer zone connects separate segments within the Vestfjorden–Vanna fault complex on eastern Hinnoya.

8. Many of the NNE–SSW-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. Some of the faults constitute transfer zones such as the Lenvik transfer zone. The orientation of the fault
pattern on land is similar to that of the offshore fault pattern.

9. Numerous high-frequency magnetic anomalies indicate of intrasedimentary volcanic or intrusive rocks occur offshore of Andøya and southward on the seaward side of the Utsrød Ridge–Utgard High area. The shelf edge coincides with the large-scale faults on the seaward sides of Utgard High, Rost High, Utsrød Ridge and Jennegga High. The eastward termination of the basalt flows also coincides with this line, and may represent a rift escarpment during the extrusion of lavas in early Eocene times.

10. Palaeomagnetic studies on Senja and Kvaløya reveal two phases of faulting and brecciation. 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 (ca. 270–280 Ma) is also indicated from haematite cemented fault breccias from Kvaløya, and the Permian fault activity probably signifies an early rift phase on the continental margin. We have found no evidence of Mesozoic fault activity in the areas onshore tested.

11. There may have been a westward shift of the regional fault activity in the Norwegian Sea and coastal area from the Carboniferous–Permian to the late Jurassic–early Cretaceous.

12. The present integrated study has revealed several new structures which to our knowledge have not been previously reported. These include the Vestvågøya and Lenvik transfer zones, the two subbasins within the Vestfjorden Basin and a possible basement high along the Bivrost Lineament.

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