A study of basement structures and onshore-offshore correlations in Central Norway

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A combined interpretation of gravity, aeromagnetic and petrophysical data is reported. The estimated depths to the top of the crystalline basement in the Møre Basin show that the sedimentary deposits are thicker than 14 km. In the Møre Basin, the basement features reveal a deeply buried, rift-related relief at pre-Cretaceous, or possibly Jurassic, level. On the Trøndelag Platform, a series of structural highs and lows with NE-SW and NNE-SSW strike, modified by N-S relief, occur. From the aeromagnetic map, the oldest (Devonian) extensional structures have been interpreted to extend from the land onto the shelf. The detachments exhibit a NNW-SSE trend in the shelf, which is locally modified by ENE-WSW- to NE-SW-trending synforms and antiforms, and by the post-Devonian faulting. Regional gravity modelling has been performed along the only modern seismic reflection line that crosses the Scandinavian mountains. The combined analysis of the deep seismic data and gravity modelling, constrained by density data, indicates that the negative Bouguer anomalies approximately aligned along the axis of the Scandinavian mountains are the combined effect of: 1) Moho topography and 2) Lateral density variations between the Western Gneiss Region, the Transcandinavian Igneous Belt and rocks of the Svecofennian domain. This suggests a combined Airy- and Pratt type of isostatic compensation/mass balancing of the central Scandinavian mountains. Several high-amplitude magnetic anomalies on land and in the adjacent eastern continental shelf are interpreted to represent high-grade rocks. These occur along some of the major fault zones and known rift flanks, possibly in association with basement antiforms.

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Introduction

Although potential field data do not provide direct identification of lithology, these data can be used to study the nature of the basement underneath sedimentary basins, the depth and extent of sedimentary basins, and the offshore extensions of basement terranes and fault zones. The depth of the deepest sedimentary basins off Central Norway is largely unknown due to poor seismic imaging below the base of the Cretaceous. Hamar and Hjelle (1984) suggested that the Møre Basin is extremely thick (> 10 km). Most later studies (Grunnaleite & Gabrielsen 1995; Brekke 2000) have focused mainly on the post Triassic structuring and subsidence. It has been suggested from basement depth maps that extremely deep, buried intracontinental rift valleys and half grabens exist underneath the Cretaceous fill of the Møre Basin (Skilbrei et al. 1995; Skilbrei & Olesen 2001). Quantitative models of the gravity and magnetic fields support this model (Sæterstad 1996; Fichler et al. 1999).
We use potential field and petrophysical data of rock samples from main lithological units reported earlier from onshore Norway (Skilbrei 1988a; Skilbrei 1989; Olesen et al. 1997a) to aid in extending lithological units and structures across the coastal zone and into the offshore area. The magnetic and non-magnetic basement terrains have been extended into the offshore, complementing the work of Olesen et al. (2002). The density and magnetic susceptibility data are used in forward modelling of the potential fields, resulting in a basement map that covers the area between 62° and 69° N. The main study area extends from 62° to 65° 30' N. North of this, Olesen et al. (2002) report similar integrated geophysical studies.

We have modelled the gravity field along a deep seismic transect that crosses the Scandinavian mountains (Juhojunnti et al. 2001). The combined analysis, constrained by density data is used to study the deep structure of the transect, and to suggest which type of isostatic model can explain the mass balancing of the topography. Earlier work (Skilbrei 1988a,b), prior to the acquisition of the modern deep reflection seismic data, suggested a combined Pratt- and Airy model.

General geology of the study area

The thrust sheets of the Norwegian Caledonides are composed of a variety of Mesoproterozoic to Silurian metasedimentary and igneous rocks (Fig. 1). The Western Gneiss Region (WGR) and the Central Norway basement window (CNBW) are made up of mainly Precambrian gneisses and granitic rocks (Sigmond et al. 1984; Sigmond 1992; Robinson 1995) with narrow synclinal belts in which thinned remnants of the thrust sheets have been deeply in-folded. Thus, the structural fabric of most of the WGR and the CNBW is dominated by tight folding of basement and tectonic cover produced during Devonian phases of extensional deformation. Also, the nappes were dismembered by the late collapse of the Caledonian orogen (e.g. Braathen et al. 2000).

On the shelf, the main study area covers the south-central part of the Trøndelag Platform, the Halten Terrace, the Frøya High, the Møre Basin, and the Klakk Fault Complex. Structures associated with the tectonic transition zone at the northern end of the Møre Basin, where the junction forms between the offshore Møre Trøndelag Fault Complex (MTFC) and the southeastward continuation of the Jan Mayen Lineament (Gabrielsen et al. 1984; Brekke 2000), were also a focus in the study. We further note the onshore, northeastern extent of the MTFC into the Grong District (Fig. 1) (Oftedahl 1975; Sigmond 1992), as well as Lower Tertiary (55 Ma; Bugge et al. 1980) intrusive rocks and volcanic plugs southwest of the island of Smøla, on the southern part of the Frøya High (Fig. 2). These latter features were critical to specific aspects of our interpretations of the potential field data presented here.

Data sets

The regional aeromagnetic data shown in Fig. 2 have been described by Åm (1970, 1975) and Olesen et al. (1997b). In addition, four modern offshore aeromagnetic surveys have been used for the depth to magnetic source analysis. Survey details are described by Olesen & Smethurst (1995), Olesen et al. (1997a,b, 2002) and Skilbrei & Kihle (1999). The modern aeromagnetic surveys were flown with a line spacing of 2 km and a tie-line separation of 5-8 km. The regional aeromagnetic survey in the Vøring and Møre Basins was acquired in 1973 with a line spacing of c. 5 km. The survey flight altitude varies between 200 and 500 metres.

Rock samples from the nearby mainland, collected during geological mapping and geophysical studies,

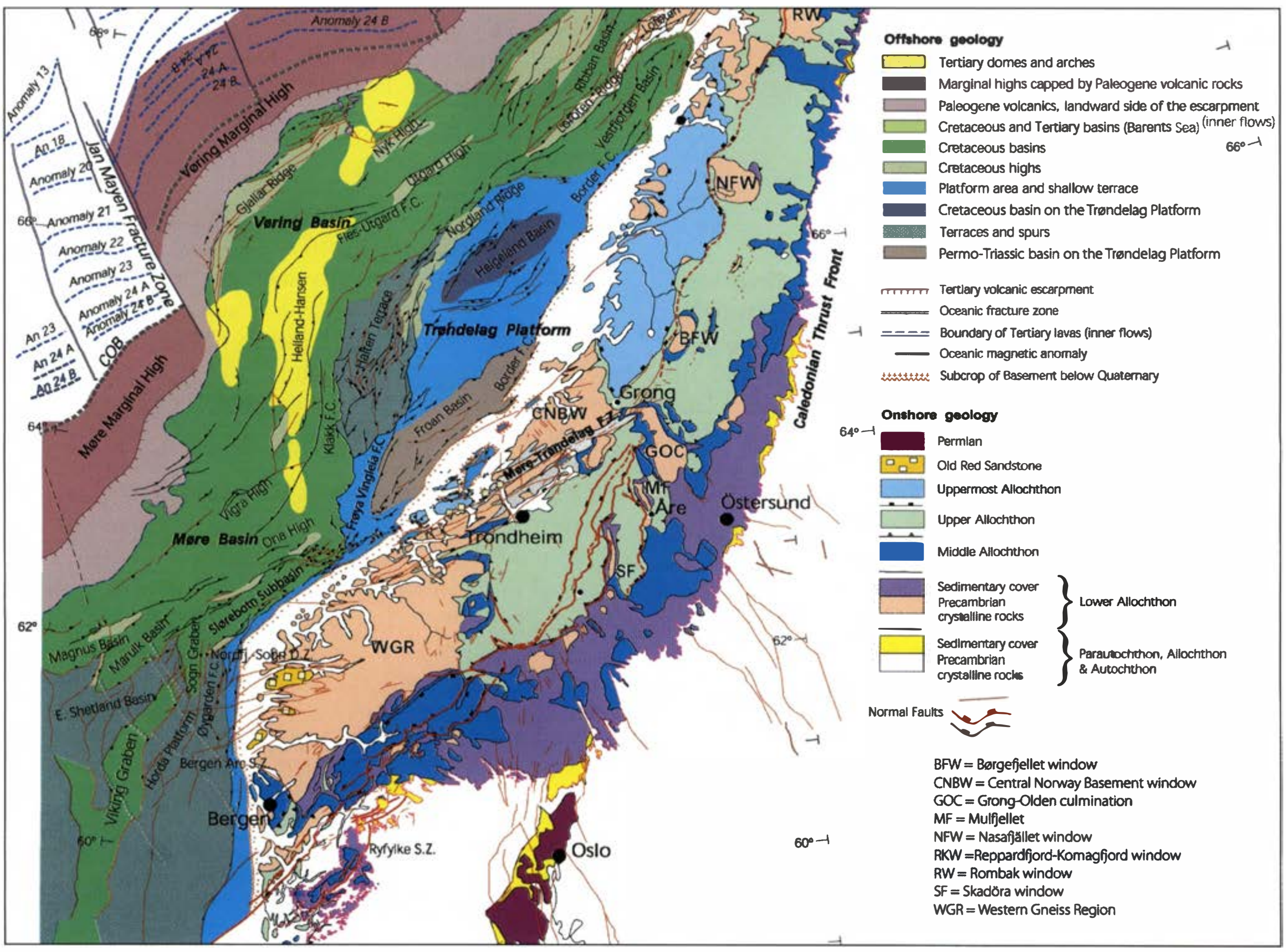

Fig. 1. Tectonic map (modified from Mosar et al. 2002).

have been analysed with respect to density, magnetic susceptibility and magnetic remanence (Skilbrei 1989). Figure 3 shows a map of magnetic susceptibility values in colour based on these data. High magnetic susceptibility values occur in the coastal zone of Fosen (CNBW) and the WGR. We have measured physical properties of three unweathered samples of the volcanic plugs from the Vestbrona area on the south side of the Frøya High (samples courtesy of Tore Prestvik). The magnetic susceptibilities of the samples of olivine-nephelinite are 596 x 10^{-5}, 2060 x 10^{-5} and 3577 x 10^{-5} SI. The Q-values are low (<0.5), indicating that the Natural Remanent Magnetization will not contribute significantly to the magnetic field.

The marine gravity lines were acquired by the Norwegian Mapping Authority, the Norwegian Petroleum Directorate, the Geological Survey of Norway and commercial companies. On land, data have been collected by foreign and national universities and institutions. Recent description of these data is given in Skilbrei et al. (2000) and in Korhonen et al. (1999). On land, the complete Bouguer reduction of the gravity data was computed using a rock density of 2670 kg/m^3. Free-air anomalies are used for all marine areas. 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 gravity maps are shown in Figs. 4 and 5. Fig. 5 is a residual map calculated using a Gaussian high-pass filter with 200 km cut-off wavelength.

Interpretation methods

The depth to basement map shown in Figure 6 is a new compilation partly based on reported work from Olesen & Smethurst (1995), Olesen et al (1997a), Skilbrei et al. (1995) and Mjelde et al. (1992, 1997). Depths to basement have been estimated from inversion of aeromagnetic and gravity data, applying the autocorrelation algorithm of Phillips (1979), the 3-D Euler deconvolution algorithm of Reid et al. (1990) and a least-squares optimising algorithm of Murthy & Rao (1989). The autocorrelation method assumes that the magnetic basement is defined as a 2-D surface constructed from a large number of thin vertical 'dykes' of differing magnetisation. The upper terminations of the 'dykes' define the basement surface. The depth to this surface is estimated by passing a short window along the magnetic profile, with a depth estimated for each position of the window. The method has the advantage that sources at different depths can be separated, i.e. anomalies caused by deep and shallow bodies in the same profile can be differentiated. This is especially useful in the western Lofoten area where abundant lava flows/sills occur within the sedimentary sequence.

The Euler deconvolution method (Reid et al. 1990) is a 3-D inversion approach and was also used to estimate the depth to top of the magnetic basement. Structural indices were tested, and an index (SI) of 0.5 (thick step) gave the most focused depth estimates in the eastern platform areas. A structural index of one (1) (sill/dyke) was used in the western part of the Møre Basin and in the Møre Marginal High. We have incorporated depth to basement depth interpretations from ocean bottom seismographs (OBS) in the Vøring area (Mjelde et al. 1997), and depth estimates from Fichler et al. (1999). The latter depths are shallower in the Hel Graben-Gjallar Ridge area than depths obtained from OBS data.

Seismic-, borehole-, and petrophysical data were used to constrain the estimates. The different methods yield errors that generally vary between 5% and 15%. Systematic errors will add to the spread shown by the different methods. However, where possible, the depth estimates were calibrated with known depths from boreholes and seismic lines, as well as gravity and magnetic forward models. Depths thought to represent intrasedimentary magnetic rocks have been excluded during the contouring of the final surface shown here. As a consequence of this, the basement depths are less reliable in the westernmost areas.

Results

Magnetic data

In this report, the interpretation is focused on the regional features on the continental shelf. Both regional and more detailed interpretations from the Trøndelag area, based on ground-truth work (in situ magnetic susceptibility measurements), can be found in Skilbrei (1988a) and Skilbrei et al. (1991a,b). Offshore Mid-Norway, interpretations have been reported by Åm (1970, 1975), Olesen et al. (1997a), Skilbrei et al. (1995), Fichler et al. (1999) and Berndt et al. (2001).

Earlier reported studies of magnetic depth estimates and model calculation along the eastern shelf have demonstrated that many of the magnetic anomalies are created by steep basement topography. Consequently, low-intermediate amplitudes occur where the magnetisation of the basement is low-to-intermediate, and high amplitudes occur where the basement is highly magnetic. The regional magnetic anomalies are created by a combination of supra- and intra-basement sources (e.g. Skilbrei et al. 1995; Olesen and Torsvik 1997a; Fichler et al. 1999). However, significant intrasedimentary volcanic sources exist only to the west of the central part of the Møre and the Vøring basins (Åm 1970; Olesen et al. 1997a; Berndt et al. 2001).

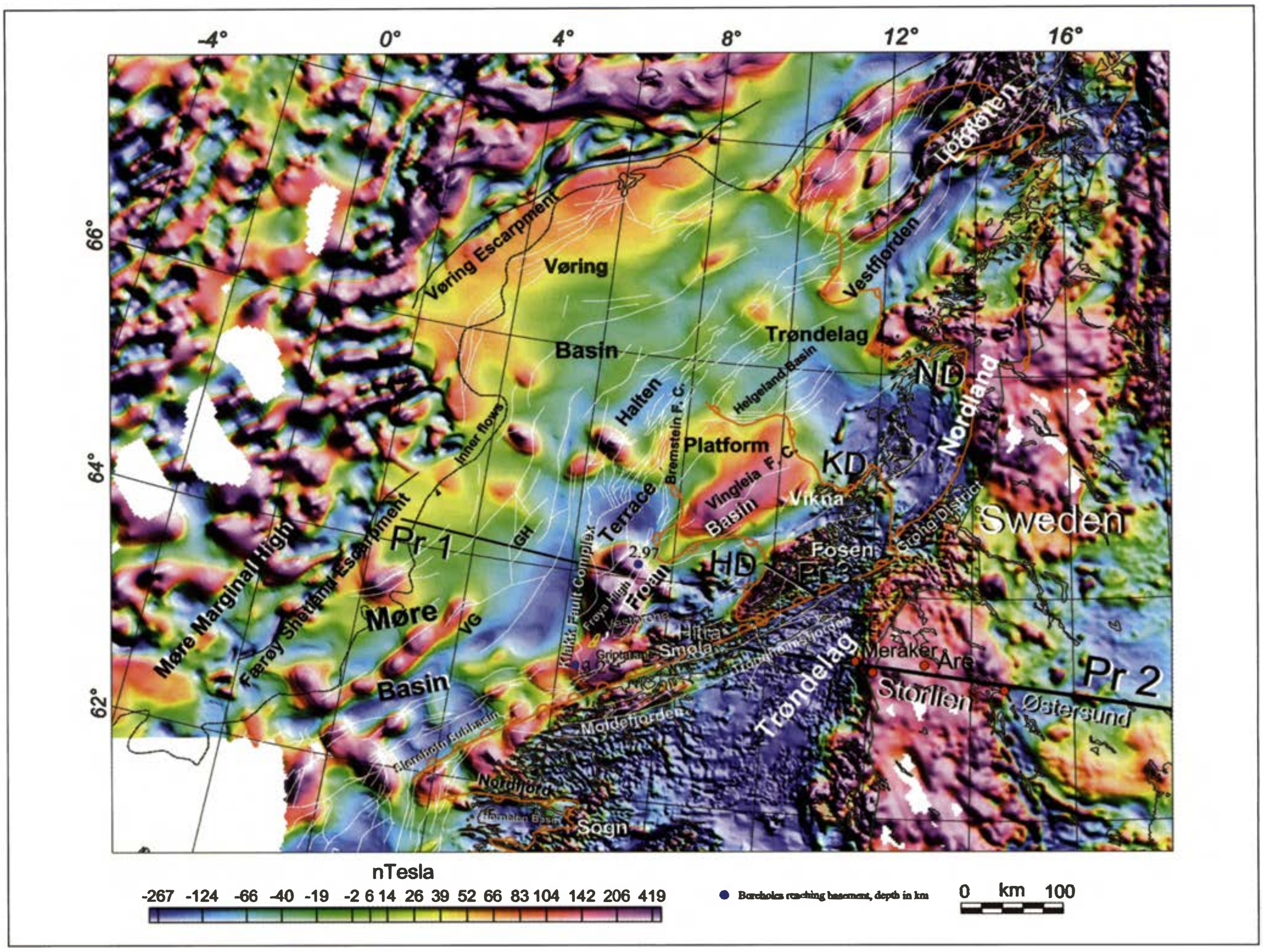

Fig. 2. Regional aeromagnetic map of the study area. Structural elements in white solid lines (from Brekke 2000). VG=Vigra High, GH= Grip High. HD=Høybakken Detachment, KD=Kollstraumen Detachment, ND=Nesna Detachment. Orange solid lines refer to the interpreted offshore projections of the Devonian detachments that have been mapped on land (Braathen et al. 2000). We assume that magnetic and non-magnetic basement terranes on the mainland continue under the basins towards the eastern Møre and Vøring Basins. Note that many of the anomalies on the shelf align along major fault zones, suggesting that rift-related relief and basement flexures in combination with intrabasement features (lithology) have produced the present anomaly pattern. Note that a non-linear colour assignment is used. Anomalies above 419 nT in amplitude appear with the same colour on the figure. Black solid lines show location of model lines (Pr 1, Pr 2 & Pr 3).

Frøya High and the Trøndelag Platform. – The most prominent positive magnetic anomaly occurs above the Frøya High, where the amplitude exceeds 1200 nT. The anomaly is situated directly above the structural high as mapped by seismic reflection lines (Blystad et al. 1995), as can be seen on the magnetic map (Fig. 2) and on individual profiles (not shown). Some relatively short-wavelength anomalies occur along the main faults. These anomalies representing 'top-basement topography' are superimposed on the wider anomaly caused by the deep basement of the Frøya High. Åm (1970) noted that some of the anomalies may indicate the presence of shallow basement and/or intrasedimentary igneous intrusions. A few volcanic plugs within the Vestbrona field are located within an area with a regional magnetic gradient (see Fig. 2) at the southern part of the Frøya High magnetic anomaly. However, from inspection of profile data, it is evident that only local magnetic anomalies, less than 6 nT in amplitude, occur directly above the subcropping volcanic plugs (Skilbrei et al. 1995, p.21). The insignificant magnetic response is due to the fact that the mapped igneous rocks apparently make up small volumes compared with the large basement high, and the intermediate magnetisation values of the rocks. (The diameter of individual plugs are 1-3 km). More plugs may exist, but these are also of small volumes (Sola 1990).

Møre Marginal High and Færøy-Shetland Escarpment. – A series of positive and negative, relatively short-wavelength, magnetic anomalies occur within the Møre Marginal High (Fichler et al. 1999; Berndt et al. 2001). Many of the anomalies are almost linear and trend NE-SW, and may be caused by the Paleogene volcanics underlying the high. The pattern of alternating positive and negative magnetic anomalies also exists on the northeast side of the Jan Mayen Lineament. There are some negative and positive anomalies that trend NW-

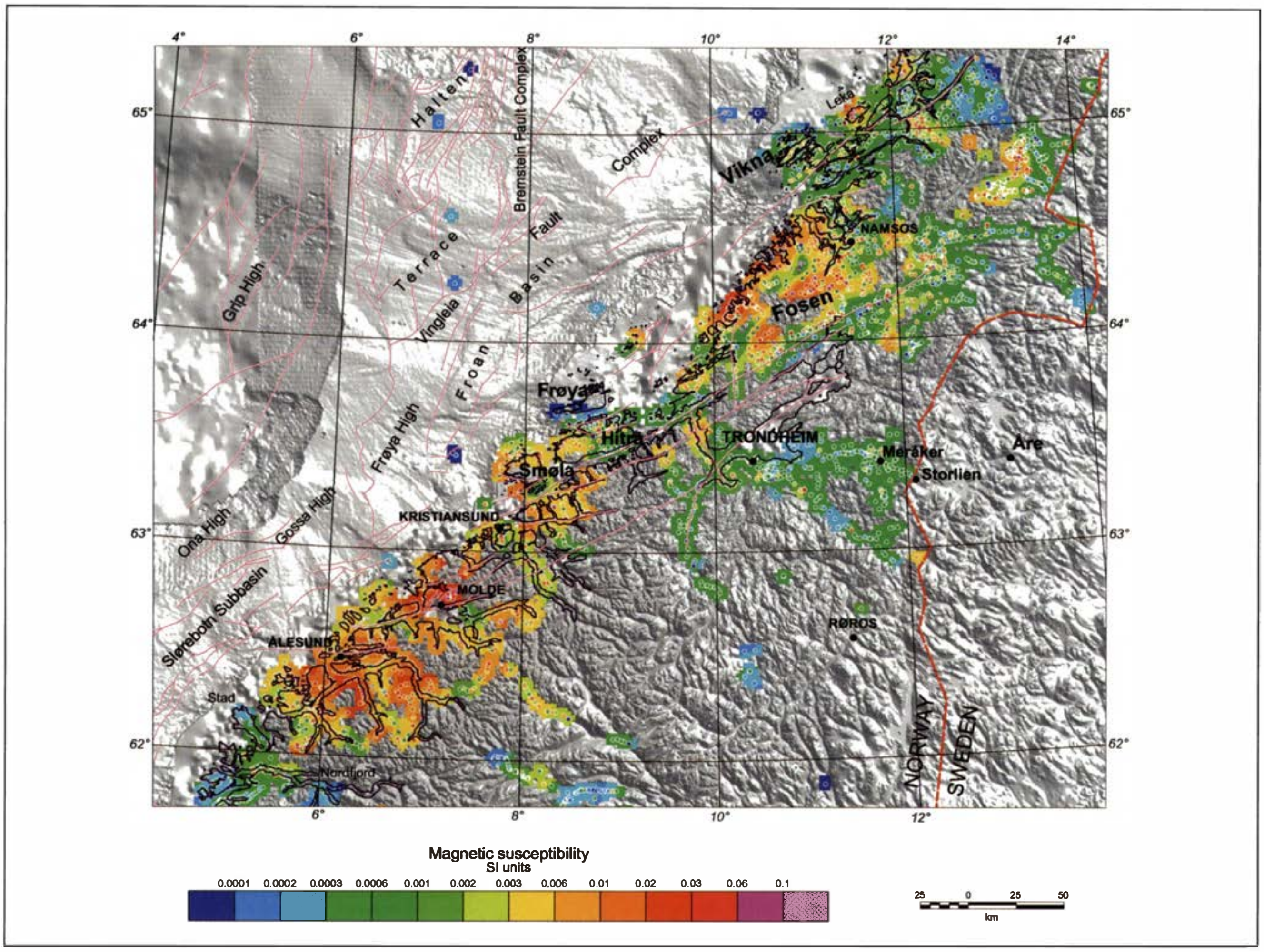

Fig. 3. Magnetic susceptibility data, based on representative samples. Note generally low values from the allochthons of the Caledonides, and high values from Fosen (CNBW), and the coastal part of the WGR (e.g. to the north of Molde).

SE crossing the Færøy Shetland Escarpment (FSE). The anomalies that cross the FSE may be due to large volumes of volcanic rocks, possibly flows, that occur near the FSE. Conversely farther east over the central-western part of the Møre Basin, there are only low-amplitude magnetic anomalies that can be attributed to the 'inner flows' of Hamar & Hjelle (1984), as seen in published high-resolution aeromagnetic data (Skilbrei et al. 1995; Lundin et al. 1997).

Møre Basin. – On the landward side of the FSE the anomalies are more subdued. The area is characterised by the occurrence of both relatively short-wavelength negative and positive magnetic anomalies, and long-wavelength positive magnetic anomalies located at about 63° 40'N, 2° E and at 62° 35'N, 1° 30'E. These long-wavelength features either represent basement blocks (structural highs) within a down-faulted western margin of the Møre Basin, or intrusions at deep levels within the sedimentary section.

Parts of the Møre Basin are characterised by a rather subdued magnetic anomaly field. Two interesting exceptions are the eastern Møre Basin margin, where positive anomalies coincide with some of the structural highs, and a series of NE-SW-trending, elongated positive anomalies that are situated along the central axis of the Møre Basin, to the east of the Early Tertiary lava flows (named 'Inner flows' in Fig. 2). This elongated magnetic anomaly belt exhibits the same trend as the area outlined by lavas at Mid-Cretaceous level described by Hamar & Hjelle (1984) and Gravdal (1985). The northern part of the elongated anomaly belt coincides with the Vigra High. The peak of this magnetic high occurs directly over the western fault-bounded margin of the Vigra High.

Several authors have suggested that the Møre Basin started to open as an ocean in the Cretaceous (Bott 1975; Roberts et al. 1981). However, this interpretation was not supported by Eldholm et al. (1984). The elongated belt of anomalies could represent Cretaceous seamounts (Lundin & Rundhovde 1993). We believe that the absence of a coinciding belt of pronounced gravity anomalies along the axis of the basin makes it unlikely that Cretaceous seamounts exist at the centre of the

Møre Basin. Using several methods, including the method of Vacquier et al. (1951), we have estimated the depth to the top of the magnetic sources from the elongated belt of anomalies along the central Møre Basin. The estimated depths are quite uniform, from 8 to 10 km. This is near to the base of the Cretaceous at the Vigra High, according to the interpreted reflection seismic line of Blystad et al. (1995). Therefore, we suggest two possible interpretations for these anomalies (see also Skilbrei et al. 1995): 1) the anomaly belt represents a series of basement highs at depths of 9-10 km centrally located along the Møre Basin, where the Vigra High is a basement high located at the northern end of the anomaly belt, 2) the elongated anomaly belt represents a series of intrusions along the axis of the basin. Detailed modelling work performed by the NGU isolates the anomalies into separate sources (Sæterstad 1996), incompatible with a continuous belt of basic crust along the axis of the Møre Basin. In order to model the amplitude, it was found necessary to increase the magnetisation of the western central part of magnetic basement blocks by introducing very high magnetisation values, interpreted to represent intrusions along deep fault zones (Vigra fault zone). The southeastern flank has higher magnetic gradients than the northwestern flank, probably indicating tilted fault blocks dipping to the west-northwest or rocks with high magnetic remanence. We favour a combination of basement origin and intrusive origin, where the intrusions form a 'Christmas tree' of dykes and sills. It can be speculated whether high amplitude reflectors observed in the deep reflection seismic data (Osmundsen et al. 2002) may represent intrusions that have ascended along basement shears from the underplated material seen in the seismic data of Olafsson et al. (1992). The igneous intrusives may have been emplaced during the Late Paleocene when the underplating occurred. A regional long-wavelength anomaly trends NE-SW along the Vingleia Fault Complex to the west of Vikna, centered at 9° E and 64° 40' N. The depth to the top of the magnetic source is estimated to be around 8 km. The seismic data show rather shallow depths to the basement over the anomaly. Therefore, and as noted by Åm (1970), the anomaly may originate from far below the top of the crystalline basement. However, Åm also suggested that Devonian sediments occur above the anomaly source, a result also supported by Olesen and Smethurst (1994). This Vingleia-Vikna magnetic anomaly may represent high-grade rocks occurring in a structure (Skilbrei & Olesen 2001), similar to the high-grade rocks that occur on land in Fosen (see Fig. 9) and possibly in the Frøya High where a deep antiform exists (Osmundsen et al. 2002). The offshore anomalies represent magnetic rocks that are suggested to be part of a 'magnetic' basement terrain that can be extended into the offshore from the Fosen peninsula (see also below).

Basement Depths

The smooth basement map is a generalized surface, based on several data-sets. The main errors in the basement map are believed to occur on the western margins of the Møre and the Vøring Basins, where many magnetic anomalies originate from the Cenozoic volcanic rocks. Also, the central part of the Møre Basin is difficult to map at depth. This is because of the presence of deep dolerites/sills at the Cretaceous level (Hamar & Hjelle 1984). The depth estimates (Fig. 6) over the structural highs from the eastern Møre Basin Margin generally vary between 4 and 7 km. The depth estimates along the Frøya High, the Giske High and the Gnausen High are consistent with what is known from reflection seismic data and exploration drilling. The deepest depth estimates of the central axis of the Froan Basin are around 8-9 km, rapidly decreasing towards the Frøya High. The basement depths in the Møre Basin exceed 14 km. Basins on the Trøndelag Platform and the Inner Vestfjorden basin trend NE-SW. These are half-grabens with a left-stepping, en echelon pattern (Doré et al. 1999). Osmundsen et al. (2002) indicate thick Permo-Triassic deposits within the Trøndelag Platform area. The structure (relief) seen in the basement map suggests a complicated series of structural highs and lows in the Trøndelag Platform, with NE-SW grain separated by N-S structures. In addition to the Froan Basin, several sub-basins can be distinguished within the Trøndelag Platform from the depth map. Major pre-Cretaceous basins also underlie the deeply buried Møre and Vøring basins. The principal trend is NE-SW in the Møre Basin and the Vøring Basin, except for the area of the Jan Mayen Lineament between 64° and 65° 30' N, where the grain is N-S and NW-SE, suggesting that this lineament/zone is a fundamental structural grain in the basement. Torske & Prestvik (1989) and Mosar (2002) suggested that the Jan Mayen Fracture Zone marks part of a broad transfer zone. The Halten Terrace trends generally N-S, but the basement map suggests that there is also an internal, NE-SW-trending basement grain.

In the deep parts of the Møre Basin, the basement map suggests deeply buried half-grabens or rift valleys underneath the Cretaceous strata (Skilbrei & Olesen 2001). Based on the fact that the Vigra High is identified as a Jurassic structure (e.g. Brekke 2000), we assume that the rift valley in the Møre Basin, depicted in dark blue colour on the basement map, is of Jurassic or earliest Cretaceous age. The basement topography reveals a central, N-S-trending ridge at a depth of approximately 5 km separating the deeper part of the Helgeland Basin into two 6-7 km deep sub-basins (Olesen et al. 2002). The easternmost basin represents the Permian Brønnøysund basin (Doré et al. 1999).

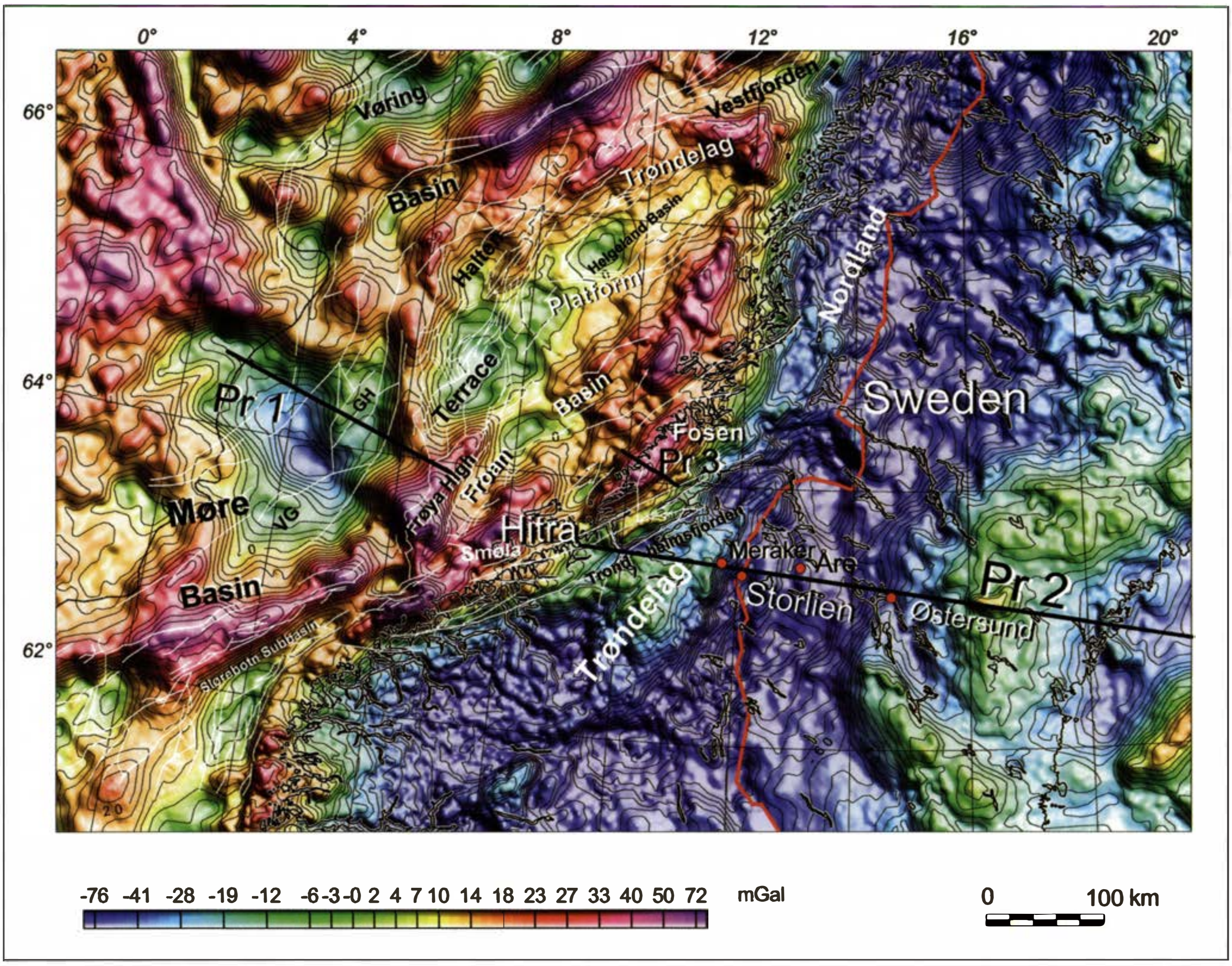

Fig. 4. Gravity map (Bouguer on land, Free-air at sea). Structural elements in white solid lines. Black solid lines show location of model lines (Pr1, Pr2 & Pr3). VG=Vigra High, GH= Grip High.

Offshore continuation of Devonian detachments

The 'magnetic' and 'non-magnetic' basement terrains on land are suggested to continue in a northwestward direction related to the Late Devonian gravitational collapse of the Caledonian mountains (Osmundsen et al. 2002). The Central Norway basement window (CNBW) occurs between the Kollstraumen Detachment (KD) in the north, and the Høybakken Detachment (HD) in the south. Highly magnetic, high-grade rocks (Fig. 3) that are associated with pronounced magnetic anomalies exist within the CNBW to the southwest of Namsos. We suggest that this terrain, consisting of both magnetised rocks and non-magnetic units, can be extended under the offshore basins at least to the Bremstein Fault Complex. The offshore magnetic signature is therefore a combined result of the lithological boundaries and the faults. The main basement relief is associated with horsts in large portions of the study area. In the Frøya High and along the Vingleia- and Bremstein Fault Complexes, these basin margin faults occur close to, and are genetically linked to, Late Devonian basement culminations (Osmundsen et al. 2002). The HD is bounded on the southern side by the Caledonian intrusive rocks, and the Devonian rocks on Ørlandet, as well as the MTFC (Braathen et al. 2000). This is also comparable to the situation from the Nordfjord Sogn Detachment in the WGR (Fig. 1), where the Devonian basins lie upon the detachment that cuts through both the Caledonian nappes and the Precambrian gneisses (Smethurst 1998). On the magnetic map, we have drawn the possible extensions of the Mid Norway detachment and shear zones into the offshore regions. In general, 'synforms' containing Caledonian nappe sequences show low-to-medium magnetisation values, while the basement in the western areas also show very high magnetisation. This is reflected on land as well as offshore. A significant portion of the basement in the Helgeland Basin and along the Nordland Ridge is low-magnetic (Olesen et al. 1997a; Olesen et al. 2002). This is most likely caused by downfaulting of the Helgeland Nappe along the offshore extensions of the NW-SE-trending Devonian Nesna detachment (ND) and KD. The thickness of the low-magnetic Hel-

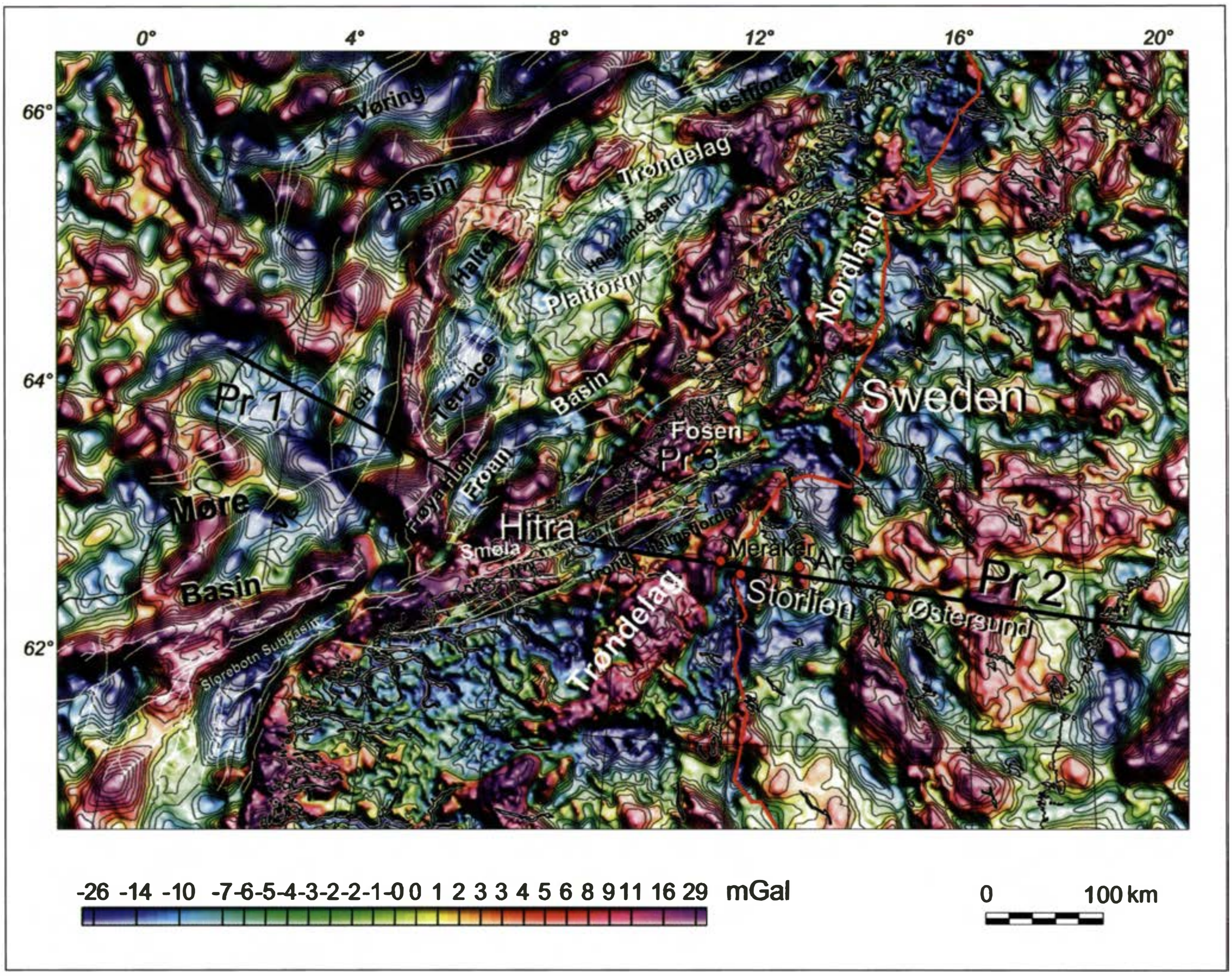

Fig. 5. Residual, high-pass filtered, gravity map. VG=Vigra High, GH= Grip High. Structural elements in white solid lines. Black solid lines show location of model lines (Pr 1, Pr 2 & Pr 3).

geland Nappe reaches 5 km on land, comparable to the discrepancies between the offshore magnetic depth estimates and the depths obtained from gravity and seismic interpretations. Some areas of the offshore low-magnetic basement may also constitute Devonian sandstones deposited above the offshore extensions of the ND and KD (Olesen et al. 2002), similar to the tectonic situation further south along the Nordfjord-Sogn and Høybakken detachments. The possible offshore extension of the KD also coincides with the Linen Fault, indicating that this late Mesozoic structure is governed directly or indirectly by a more deep-seated structure.

Gravity data

The Bouguer anomalies (Fig. 4) show the well-known, prominent low, approximately aligned along the axis of the highest elevation of the Scandinavian mountains. This minimum probably reflects isostatic compensation of the mountain chain (e.g. Balling 1980). Towards the west, the maps are dominated by a pronounced positive coastal gradient, with increasing values towards the shelf. On the residual gravity map (Fig. 5), more local gravity lows occur directly correlating to the (Precambrian) basement windows within the Caledonides (e.g. Wolff 1984; Dyrelius 1985); the residual gravity highs correlate to the basic rock units within the different thrust-sheets belonging to the Central Norwegian Caledonides. Quantitative gravity interpretations constrained by density measurements of representative rock units have given nappe thicknesses of about 1 km to 4 km in Sweden (Elming 1980, 1988) and of about 8 km to 10 km as a maximum in Central Norway (Wolff 1984; Skilbrei & Sindre 1991). Olesen et al. (2002) present a map of the Caledonian nappe thickness in the Nordland area. In eastern Trøndelag (Meråker-Storlien) gravity models demonstrate that the nappes form a half-graben interpreted to indicate post-Caledonian extensional faulting (Skilbrei & Sindre 1991, p. 9-12). A discussion of the gravity field and its relation to the mapped geology in different areas within Central Norway, and to the Moho depth, can be found in Wolff (1984), Dyrelius (1985), Skilbrei (1988a,b, 1989), Faste-

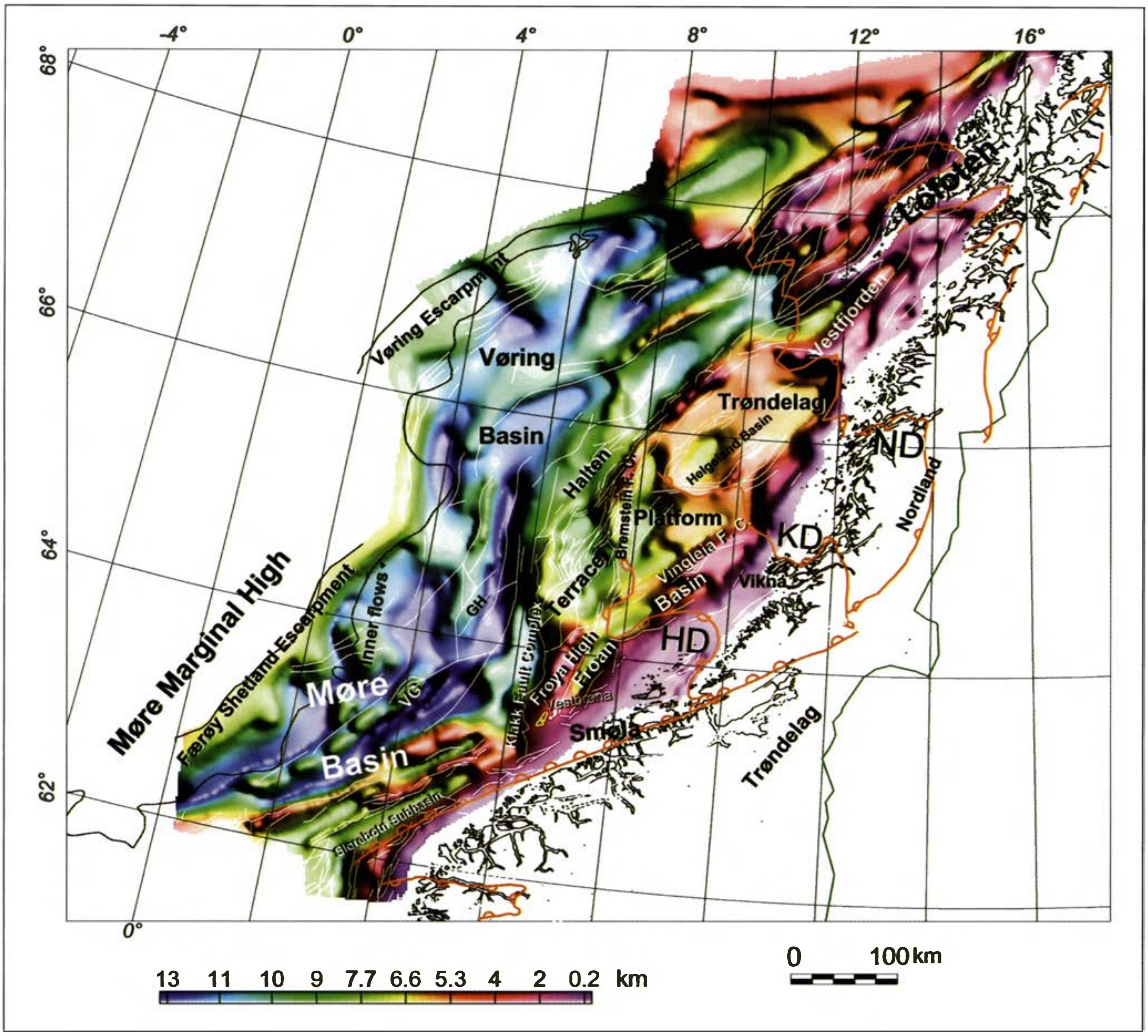

Fig. 6. Estimated depths to the top of the crystalline basement from sea level. Structural elements (white solid lines) from Brekke et al. (2000). The map represents an estimate of the total depth extent of the sedimentary basins of the area. Note deep 'valleys' in the Møre Basin, and detailed topography in the north part of the Frøya High. The latter is constrained by published seismic data (Blystad et al. 1995) and boreholes. Strong gradients in the map coincide with major basement fault zones and/or major basement flexures that define the margins of structural highs and troughs.

land & Skilbrei (1989) and Skilbrei & Sindre (1991). These results were used to constrain the upper part of the model across Central Scandinavia (see below).

The residual gravity highs in the offshore area generally occur along the major faults and geological contacts, and above structural highs. Many of the gravity lows within the Trøndelag Platform correlate to lows seen in the depth-to-basement map. Immediately to the west of the islands Smøla, Hitra, Frøya and the Froan archipelago, a series of positive anomalies occurs with alternating N-S and NE-SW trends, resulting in a 'dog-leg' pattern following the contact between the basement and the subcropping sediments. The southern part of this trend interferes with a pronounced gravity anomaly that occurs to the northwest of Smøla. Sindre (1977) noted that the anomaly extends onto Smøla where basic 'Caledonian' intrusives occur. The density of samples of the Caledonian plutons in the Frøya-Froan area (see Nordgulen et al. 1995 for a brief outline of the geology) is in the range 2.62-2.71 (g/cm^3), with a mean below the average density of the basement within the Western Gneiss Region (Skilbrei 1989). This explains the gravity low situated in the Frøya-Froan area, located to the east of the low above the Froan Basin.

Model Calculations. – The model calculations were performed using $2^1/_2$ D bodies, i.e. bodies of polygonal cross-section with perpendicular end surfaces at variable distance from the profile. The deep interfaces (mantle and lower crust) were extended far away from both ends of the profile in order to avoid edge effects. The location and strike extents of the upper layers were taken from the seismic data and the geological maps (Elming 1988; Juhojunnti et al. 2001; Koistinen et al. 2001; Sigmond et al., 1984; Wolff 1984). The depth to the Moho and upper stratigraphy were from seismic data interpretations. Depth-converted seismic data were scanned and used as 'back-drop' in the forward models.

Northern Møre Basin Model. – A model across the Grip High and the northern Møre Basin (seismic profile VMT95-005, along profile 1) is shown in Fig. 7 (location shown in Fig. 4). Depth-converted seismic horizons have been provided by ExxonMobil. The densities of sedimentary sequences that were calculated from density logs and applied densities are shown in Table 1. The profile crosses the southern part of the Halten Terrace and the northern continuation of the Frøya High.

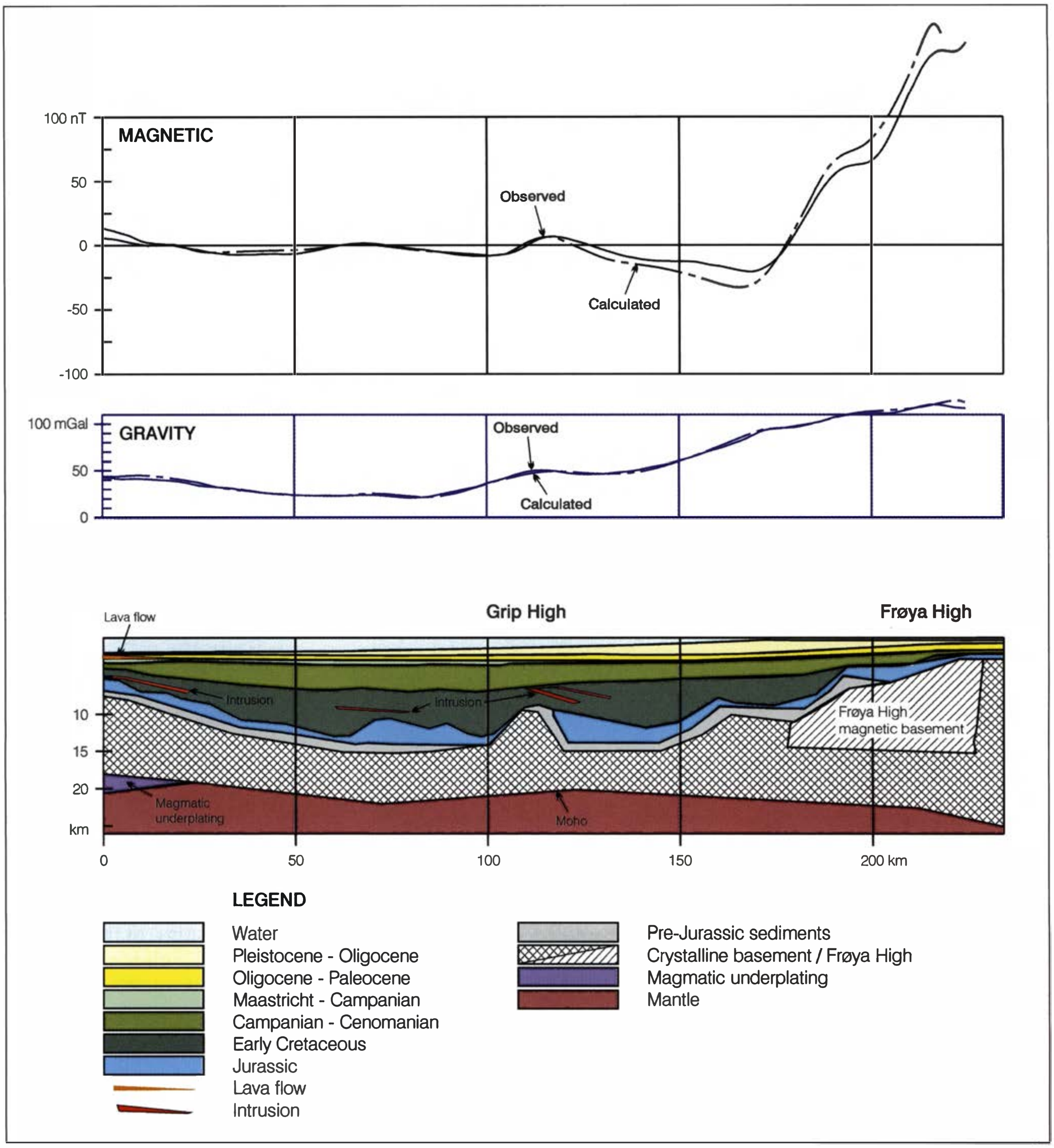

Fig. 7. Gravity and magnetic interpretation along seismic profile VMT95-005 (profile Pr 1) across the northern Møre Basin and the Grip High. See Fig. 3 for location. The applied densities are shown in Table 1.

We observe a long-wavelength gravity low above the Møre Basin. A local positive gravity anomaly occurs above the Grip High (GH), and negative gravity anomalies occur on each side of the GH. The Frøya High is associated with a positive gravity anomaly, and the gravity field values increase towards the western part of the Møre Basin. The main features of the Moho depth and relief used in this model profile are approximately the same as the interpretations of the velocity data published by Olafsson et al. (1992) along a profile located farther south. The thinning of the crust beneath the basins (Moho topography) in the model has a dominant influence on the gravity anomaly. The total depth of the Møre Basin is at least 13 km. The model calculations suggest that the maximum depth extent is 15-17 km. The crust is thicker below the Møre Marginal High than beneath the basin. The regional positive anomaly towards the marginal high may represent a shallowing of the basement surface. The basement core of the Grip High has been given the density of the crystalline crust (2.7 g/cm^3). The Cretaceous section seems to rest directly on the crystalline basement on the Grip High. Elsewhere in our model, approximately 2-4 km of pre-Cretaceous (Jurassic?) sedimentary rocks are present on top of the basement. Mesozoic rift basins are modelled to exist on both sides of the Grip High (Olesen & Skilbrei 1999). Jurassic sediments are modelled between the Grip High and the Møre Marginal High and may be interesting from a hydrocarbon source-rock perspective. At the western end of the profile, the depths to the top of the Jurassic vary between 5 and 6.5 km. To the west of the profile (not shown) depths approach 3 to 4 km.

Gravity model along a seismic transect across Central Scandinavia. – Forward potential field models that are constrained by seismic data provide information on the deep structure of the crust. We have modelled the gravity field (Fig. 8) along the deep seismic profiles between the inner Trondheimsfjorden and Østersund that were published by Hurich and Roberts (1988) and Juhojunnti et al. (2001). Density data (Elming 1988; Sindre & Skilbrei 1991) and geological maps were used to constrain the upper part of the model. The gravimetric expressions of the structure of the nappes have been published earlier (Elming 1988; Skilbrei & Sindre 1991). One of the goals of the modelling was to check whether or not the topography of the Moho surface seen in the depth-converted seismic line of Juhojunnti et al. (2001) could be in agreement with the gravity data. In order to improve the model and avoid edge effects along the seismic lines, the profile extends to the coast of Norway (near Hitra) in the west and to Vasa near the coast of Finland in the east (see Fig. 4 for location). To the east of Østersund, and to the west of Trondheim, the model was kept as simple as possible, using Moho depths close to that of the Moho depth map of Kinck et al. (1993). In the final model that we present, the shape of the Moho surface mirrors that of the depth-converted published seismic line of Juhojunnti et al. (2001). However, the depths are 2-3 km shallower, because we think that the velocity used in the depth conversion (6.2 km/s) lies on the low side for middle-lower continental crust values. Refraction seismic data along the same transect (Vogel & Lund 1971), and farther north (Lund 1979) support this conclusion and Vogel & Lund (1971) applied seismic velocities of 6.2, 6.6 and 7.1 (km/s) for the upper-, middle- and lower crust, respectively. The seismic line from Trondheimsfjorden to Storlien (Hurich et al. 1989) did not image the Moho properly.

The short-wavelength variations of the gravity field correlate with the allochthonous units as explained by Elming (1988), Dyrelius (1985), Wolff (1984) and Skilbrei & Sindre (1991). The main part of the negative gravity and the positive magnetic high is modelled as granitoid units within the Transcandinavian Igneous Belt (TIB). The magnetic modelling indicates that these magnetic batholiths extend to at least 20 km depth, similar to the results of Juhojunnti et al. (2001) and to Dyrelius (1980).

The gravity modelling along deep reflection seismic lines (Fig. 8) demonstrates that the paired, high positive to negative Bouguer gravity anomalies that run parallel to the coast and the mountains are mainly a complex bulk effect of the following: 1) Moho topography due to extensional events, 2) The extension which has brought lower crustal rocks (relatively high grade and high density) up to, or closer to, the present surface along the coastal zone, 3) The local lows (Bouguer minima) associated with basement culminations and caused by granites/batholiths of the Transscandinavian Igneous Belt and increased Moho depth. The latter is demonstrated by the regional, negative gravity anomaly. The variation of the Bouguer pattern is then related to undulations in the 'Moho-surface' both along and across Scandinavia (this may represent the main components of the local Airy isostatic compensation, as discussed also by Olesen et al. (2002) based on isostatic corrections. The effect of the present topography (surface uplift minus erosion) and the local geology, is pronounced. The 'Caledonian'-, Svecofennian- and Sveconorwegian 'domains' represent regional bulk differences in density and thickness of the crust (Pratt compensation +/- regional compensation). Thus, the density model suggests that isostatic balancing of the topographic masses is of combined Airy- and Pratt types.

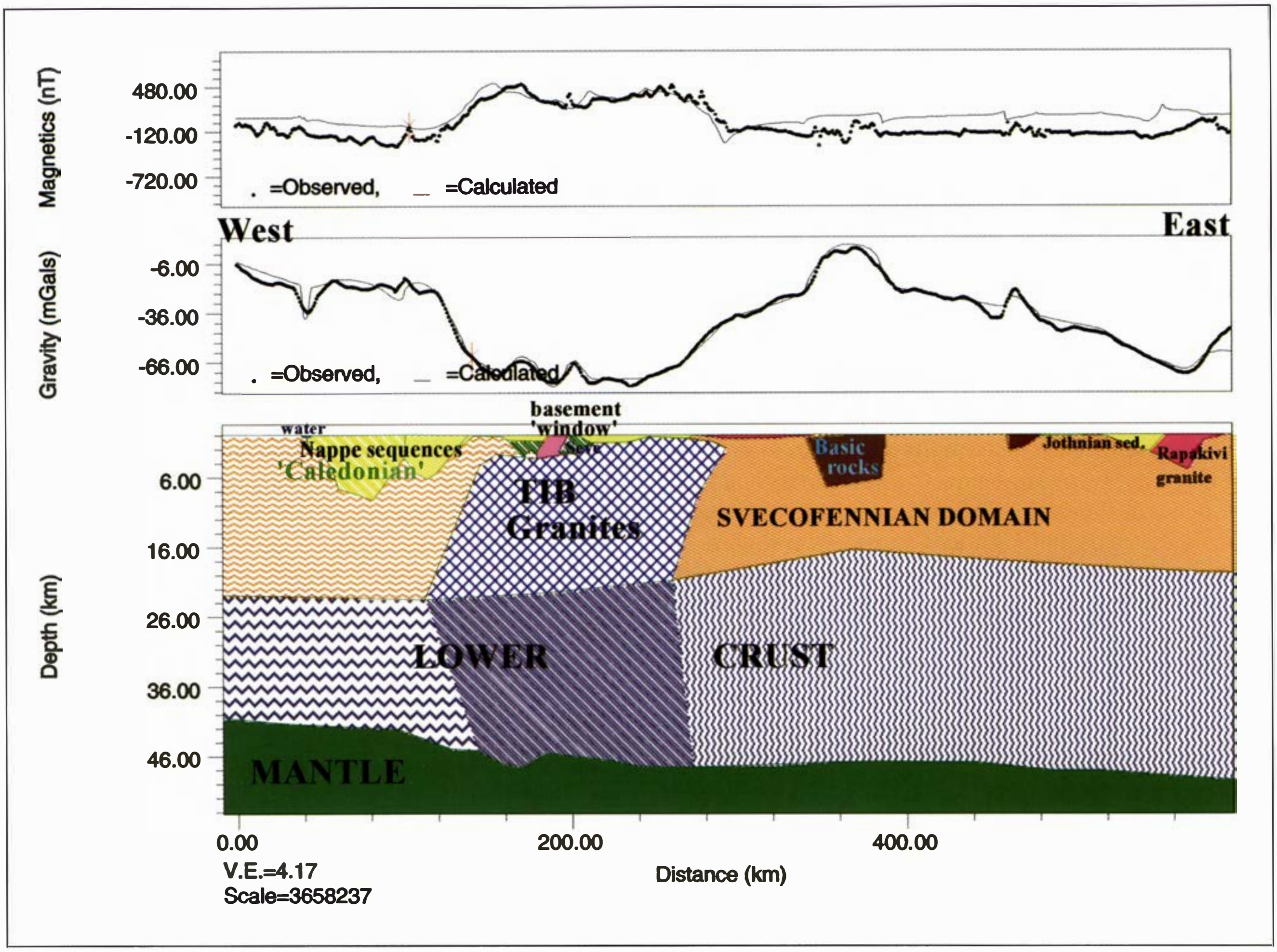

Fig. 8. Forward model of regional gravity and magnetic anomalies from the coastal areas (left in profile Pr 2) across the Central Scandinavian Caledonides and into the coastal zone of Finland (the east end of profile is to the west of Vaasa in the Baltic Sea; see Fig. 3 for location). The regional gravity field (middle panel) is modelled to be caused by the combined effect of the Moho topography, the lower crustal rocks that have been uplifted to shallower depths within the Earth's crust because of extensional events, the 'light' granites of the Transcandinavian Igneous Belt from km 169 to 240, (the granites are highly magnetic, see upper panel), and bulk density differences between Caledonide domain, Sveconorwegian domain, and Svecofennian domain. The profile is constrained by extensive density data in Norway and Sweden (Table 2) and seismic lines that cross the Scandinavian mountains (Juhojuntti 2001). In the model calculation, the asthenosphere-mantle boundary is included at a depth of 80 to 120 km (not shown). Detailed Moho topography from seismic lines. The lower crust has the constant density of 2.9 g/cm^3.

Discussion

1. In order to constrain the gravity modelling, we have presented gravity models along deep seismic lines using measured densities of the main lithological units. In the model, the Moho topography explains the main part of the regional gravity low. This model corresponds to local Airy compensation of the topographic masses as discussed by Olesen et al. (2002). In addition, there are lateral density variations along the profile on a regional scale. In the west, relatively high-grade rocks occur along the coastal regions. These rocks are more dense that those of the eastern mountains in Trøndelag (Skilbrei 1988b). Farther east, the mean density of the rocks of the Svecofennian domain is higher than the granitoid rocks of the TIB. The isostatic compensation of the mountains in central and north Scandinavia is the combined effect of Moho topography (local Airy compensation) and regional lateral density variations (Pratt type of compensation). This suggests some degree of Pratt-type of isostatic compensation of the present topography. A combination of Pratt- and Airy- isostatic compensation can be suggested both for the central and northern Scandinavian mountains since the results we obtained here are similar to those in northern Scandinavia (Olesen et al. 2002). These changes in bulk densities occur along the suture zones between the Svecofennian-, Sveconorwegian- and Caledonian domains.

2. We note that Sola (1990) compared the high-grade rocks in Fosen with the basement in the Frøya High, based on a magnetic model of an antiform (Skyseth 1987, see Fig. 9). The magnetic susceptibility map shows that magnetic rocks occur along the coastal

gneiss region north of Molde and in Fosen. The onshore Fosen magnetic anomaly, and the offshore Frøya High- and the Vingleia-Vikna magnetic anomalies are interpreted to represent high-grade rocks occurring in basement antiforms and rift flanks. Such basement culminations have been mapped, and have been explained to result from the Devonian post-orogenic gravity collapse onshore (Braathen et al. 2000), and offshore by Osmundsen et al. (2002). As pointed out by Osmundsen et al. (2002), the magnetic rocks may occur in basement antiforms/culminations deep within the Frøya High. It is significant that the top of the basement is magnetic in the Frøya High, and that the magnetic basement extends downwards to at least 10 km. This basement topography is depicted in the basement map. Tjore (1977) interpreted the anomaly above the Frøya High to be caused by intrusive rocks. Intrusive rocks would cause much closer spatial correlation between the gravity and magnetic fields; this correlation is not observed in our data. We do not exclude the presence of more Tertiary intrusive rocks within the area than those mapped within the Vestbrona volcanic field and by Sola (1990). However, the absence of strong gravity and magnetic anomalies directly above the mapped intrusive rocks suggests that the main part of the anomalies above the Frøya High, to the north of the mapped Tertiary intrusive rocks, is related to the basement. Based on the above discussion, high-grade basement rocks may constitute the basement beneath the Frøya High. A gabbroic complex (a 'Jotumheimen' equivalent') is excluded because such rocks are dense and would have caused closer spatial correlation between the magnetic and gravity fields. Therefore, the basement is probably of granitic or intermediate composition (Skilbrei et al. 1995, p 34). The magnetic anomaly has a distinct NW-SE trend (transfer zone?). This is particularly well seen in the residual maps (Skilbrei & Kihle 1999). Because the basement in the Frøya High is highly magnetic, the basement complex records major faulting episodes associated with the creation of suprabasement relief that has survived erosion. Therefore, NE-SW, N-S and NW-SE magnetic anomaly trends suggest faults with such trends. The NE-SW and the N-S trends simply reflect known faults (Klakk F.C., Bremstein F.C., and the west margin of the Froan Basin), while the NW-SE trend can represent a basement fault zone within the Frøya High that is parallel to the Jan Mayen Lineament.

3. The most prominent magnetic anomalies occasionally coincide with basement topography. This coincidence probably applies most where there is a combination of strong basement topography and intra-basement structure; the latter structure causes intra-basement density and magnetisation contrasts. An example is the Frøya High (see also Osmundsen et al. 2002), along the Vingleia-Vikna magnetic anomaly, the Bremstein Fault Complex and the Nordland Ridge to the north. In Fig. 10 of Fichler et al. (1999) a magnetic and gravity model across the margin, depicts highly magnetic basement forming a structure (antiform). Towards land in the figure, a syncline and another antiform were modelled. This figure provides independent corroboration of our interpreted seaward continuation of low- and high-magnetic basement that occurs in the structures.

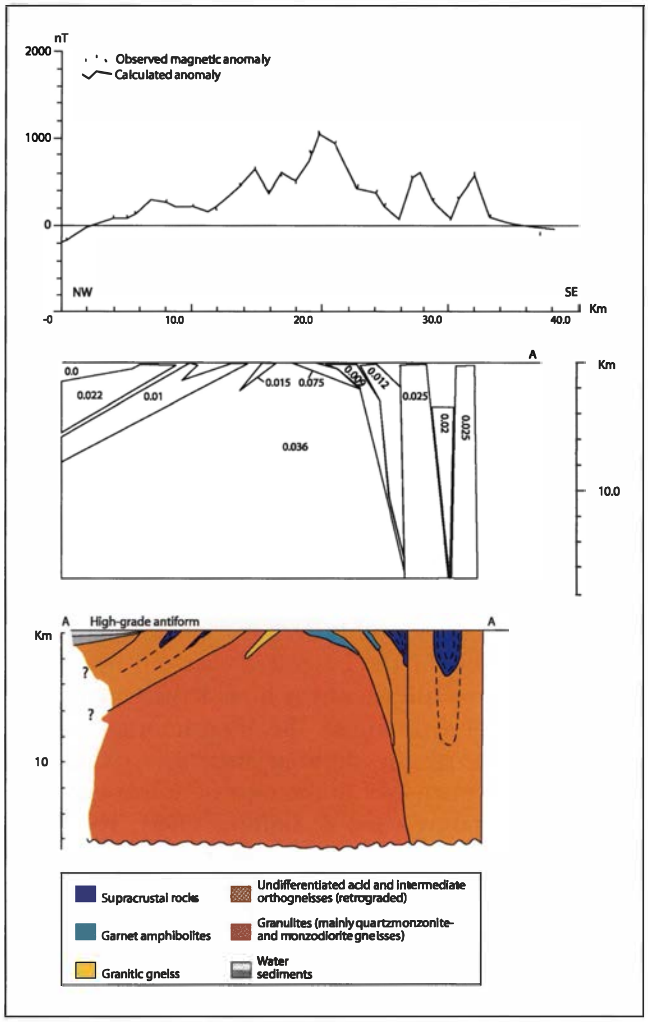

Fig. 9. Magnetic model across the 'Fosen/Roan antiform' (profile Pr 3). Applied magnetic susceptibility values are measured values (from Skyseth 1987), lower section is geology model from Möller (1986). The magnetic anomaly is caused primarily by high grade and retrograded felsic gneisses, although small magnetic mafic rock units occur locally. This is also the 'lithological model' we adapted for the Frøya High magnetic anomaly (Sola 1990, p.124, Osmundsen et al. 2002). In addition, we think that Caledonian intrusive rocks occur on top of the Precambrian basement over the southern part of the Frøya High and towards the island of Smøla. (See text for explanation).

4. Within the southern side of the high-grade basement antiform in Fosen (CNBW), the HD separates Devonian sedimentary rocks and their substrate from the footwall gneisses. The HD and the Devonian detach-

ment along the Møre Trøndelag Fault Complex (MTFC) meet at a triple point to the north of Trondheimsfjorden. A similar triple point may exist at the southern end of the Frøya High, in the vicinity of Grip to the west of Smøla, where Caledonian plutonic rocks overlie a Precambrian high-grade basement. Here, Devonian sedimentary basins occur both along the MTFC (ENE-WSW), and along NNW-SSE-trending faults (e.g. Sigmond et al. 2002). This is where the Klakk F. C., or the deeper parts of the Bremstein F. Z., meet or occur close to the MTFC. This fragment of a fault-controlled, possibly NW-SE- to N-S-trending Devonian basin occurs within the southern part of the Frøya High. This is also where the N-S-trending Frøya High terminates or flexes west of Smøla (Griptarane). We think that this is a triple point where a generally N-S-striking detachment surface (Devonian or younger) meets the detachments along the MTFC. Also noteworthy, in an area along the southeastern margin of Griptarane, are reflections in the basement that dip up to 34° towards the southeast. At the Jurassic/basement margin south of Griptarane, the (Precambrian?) basement shows steeply dipping structures, while the Caledonian intrusives to the west of Smøla exhibit a chaotic signature (Bøe & Skilbrei 1999). The southern flank of the Frøya High thus represents an area joining together the older Devonian detachments, and younger faulting related to the more planar post-Devonian detachment surfaces.

Conclusions

The estimated depths to the top of the crystalline basement indicate that the thickness of sedimentary deposits in the Møre Basin is greater than 14 km, and the basement features reveal narrow, deeply buried, rift-related relief at the pre-Cretaceous, or possibly Jurassic, level. On the Trøndelag Platform, a series of structural highs and lows that show NE-SW and NNE-SSW strike, modified with N-S relief, occur. From the aeromagnetic map, the oldest (Devonian) extensional structures have been interpreted to extend from the land and onto the shelf. The general trend/strike of the detachments is NNW-SSE on the shelf, which is locally modified by ENE-WSW- to NE-SW-trending synforms and antiforms. In the central part of the Møre Basin, an elongated magnetic anomaly belt trends NE-SW. These magnetic sources probably represent crystalline basement blocks (structural highs), possibly in combination with igneous intrusives in the basement and the lower Cretaceous section. Such intrusions may have been emplaced along fault zones at the flanks of the structural highs. This episode is tentatively linked to the magmatic underplating that occurred in the Early Tertiary. Well-constrained magnetic and gravity models depict the structure of the upper-middle crust and important Moho topography across Central Norway and Sweden. The Moho topography in western Scandinavia is the result of multiphase extensional events. The isostatic compensation of the Scandinavian mountains is the combined effect of Moho topography including local Airy-type of compensation and regional lateral density variations due to the presence of the light granites of the Transcandinavian Igneous Belt, and more dense crust in the western gneiss region and in the Svecofennian domain (Pratt-type of compensation). In addition, the lithosphere is stronger in the east and may support loads.

The magnetic susceptibility map shows that magnetic rocks occur along the coastal gneiss region. The onshore Roan magnetic anomaly, and the offshore Frøya High- and the Vingleia-Vikna magnetic anomalies are interpreted to represent high-grade rocks occurring at depth along major fault zones/rift flanks. However, in the Frøya High, top-basement topography (due to several phases of uplift and erosion) explains the anomaly variations, with highly magnetic rocks extending to 10-14 km depth. There is no pronounced signature from the small Tertiary sub-volcanic intrusions. NE-SW and N-S anomaly trends (known trend of faults) and a NW-SE (transfer fault trend) anomaly trend predominate on the Frøya High.

Table 1. Density of sedimentary sequences from density logs of wells in the Møre Basin. The estimates (in g/cm^3) are used for gravity modelling along profile 1. Numbers in parentheses show depth (relative to sea-bed) of the bases of the various sequences. Applied densities shown (profile 1)

	Well 6406/11-1S Frøya High		Profile 1 (VMT95-005)
Water			1.03
Start of log		(1475)	
Pleistocene-Oligocene	2.05	(2328)	2.05
Oligocene-Paleocene	2.1	(2328)	2.20
Maastricht-Campanian			2.30
Campanian-Cenomanian	2.35	(3250)	2.35
Early Cretaceous	2.50	(3418)	2.50
Jurassic	2.43	(4097)	2.45
Pre-Jurassic			2.60
Crystalline Crust			2.70
Magmatic underplating			3.00
Mantle			3.25

Table 2. Densities applied to profile 2 (Central Norway-Sweden)

Caledonian Nappe Sequence (primarily metasedimentary rocks, weighted mean)	2.76
Caledonian Nappe Sequence (primarily metavolcanic, weighted mean)	2.84
Seve-Køli	2.85
Basement windows (Tømmerås-Grong-Olden)	2.65
TIB, granite (Rætan)	2.69
Gabbros, dolerite, some granite (Basic rocks in profile)	2.85
Jotnian sediments	2.61
Rapakivi granite	2.64
Lower Crust	2.90
Mantle	3.25

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