Available online at www.sciencedirect.com

SCIENCE DIRECT®

Tectonophysics 387 (2004) 105–130

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Sveconorwegian igneous complexes beneath the Norwegian–Danish Basin

Odleiv Olesen[a,*], Mark A. Smethurst[a], Trond H. Torsvik[a], Torben Bidstrup[b]

[a] *Geological Survey of Norway, Leif Eirikssons vei 39, N-7491 Trondheim, Norway*
[b] *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 København NV, Denmark*

Received 12 November 2002; accepted 8 June 2004

Abstract

Gravity and magnetic anomalies have previously been interpreted to indicate strongly magnetic Permian or even Tertiary intrusive bodies beneath the Skagerrak waterway (such as the 'Skagerrak volcano') and beneath Silkeborg in Denmark. Our combined modelling of the magnetic and gravity anomalies over these rock bodies indicates that a steep upward magnetisation is required to explain the magnetic anomalies at the surface, reminiscent of the magnetic direction in the Sveconorwegian rocks of the Rogaland Igneous Province in southern Norway. The younger rocks of the Permian Oslo Rift region have intermediate and flat magnetisation that is inadequate to explain the observed magnetic field. The positive part of the Skagerrak aeromagnetic anomaly is continuous with the induced anomalies associated with the eastward extension of the Rogaland Igneous Province. This relation also suggests that rocks of the Rogaland Igneous Province and its offshore extension are responsible for the Skagerrak anomalies. Both the negative, remanence-dominated aeromagnetic anomaly and the positive gravity anomaly can be modelled using constraints from seismic reflection lines and available density data and rock-magnetic properties. A 7 km thick complex of ultramafic/mafic intrusions is located below a southward dipping 1–4 km thick section of Mesozoic sediments and 1–2 km of Palaeozoic sediments. The enormous body of dense, ultramafic/mafic rocks implied by the modelling could be the residue of the parental magma that produced the voluminous Rogaland anorthosites. The application of similar petrophysical properties in the forward modelling of the Silkeborg source body provides an improved explanation of the observed gravity and magnetic anomalies compared with earlier studies. The new model is constrained by magnetic depth estimates (from the Located Euler method) ranging between 6 and 8 km. Forward modelling shows that a model with a reverse magnetic body (anorthosite?) situated above a dense, mafic/ultramafic body may account for the Silkeborg anomalies. The anorthosites may have formed by differentiation of the underlying mafic intrusion, similar to the intrusive relations in the Rogaland Igneous Province. We conclude that there is strong evidence for a Sveconorwegian age for both the Skagerrak and the Silkeborg anomalous rock bodies.
© 2004 Elsevier B.V. All rights reserved.

Keywords: Gravity; Magnetic; Potential field modelling; Sveconorwegian; Crustal structure; Magmatic intrusions

---

* Corresponding author. Fax: +47 7390 4494.
E-mail addresses: Odleiv.Olesen@ngu.no (O. Olesen), Mark.Smethurst@ngu.no (M.A. Smethurst), Trond.Torsvik@ngu.no (T.H. Torsvik), tb@geus.dk (T. Bidstrup).

0040-1951/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2004.06.009

1. Introduction

The Precambrian rocks of the Baltic shield extend southward below the Mesozoic Norwegian–Danish Basin and Ringkøbing–Fyn High to the Caledonian Deformation Front in southern Denmark and northern Germany (Figs. 1 and 2). Potential field data provide information on both outcropping and concealed basement rocks and offer a seamless view of the basement rocks in the land and offshore domains. On land, interpretation of the potential field data is constrained by direct geological observations and petrophysical data. Offshore potential field and seismic data are interpreted together to model the concealed geology. Regional basement structures can be traced below deep sedimentary basins and numerous rock bodies within the basement with contrasting densities and magnetic properties are also in evidence. The Skagerrak and Silkeborg rock bodies and their associated gravity and magnetic anomalies are situated along the margins of the Norwegian–Danish Basin—in the Farsund Basin, just offshore the southern tip of Norway—and in central Jutland, Denmark, respectively (Figs. 3 and 4). Gravity highs partly overlap with magnetic lows over both rock bodies. The origin of these anomalies has been a matter of debate for more than three decades. There is now general agreement that the

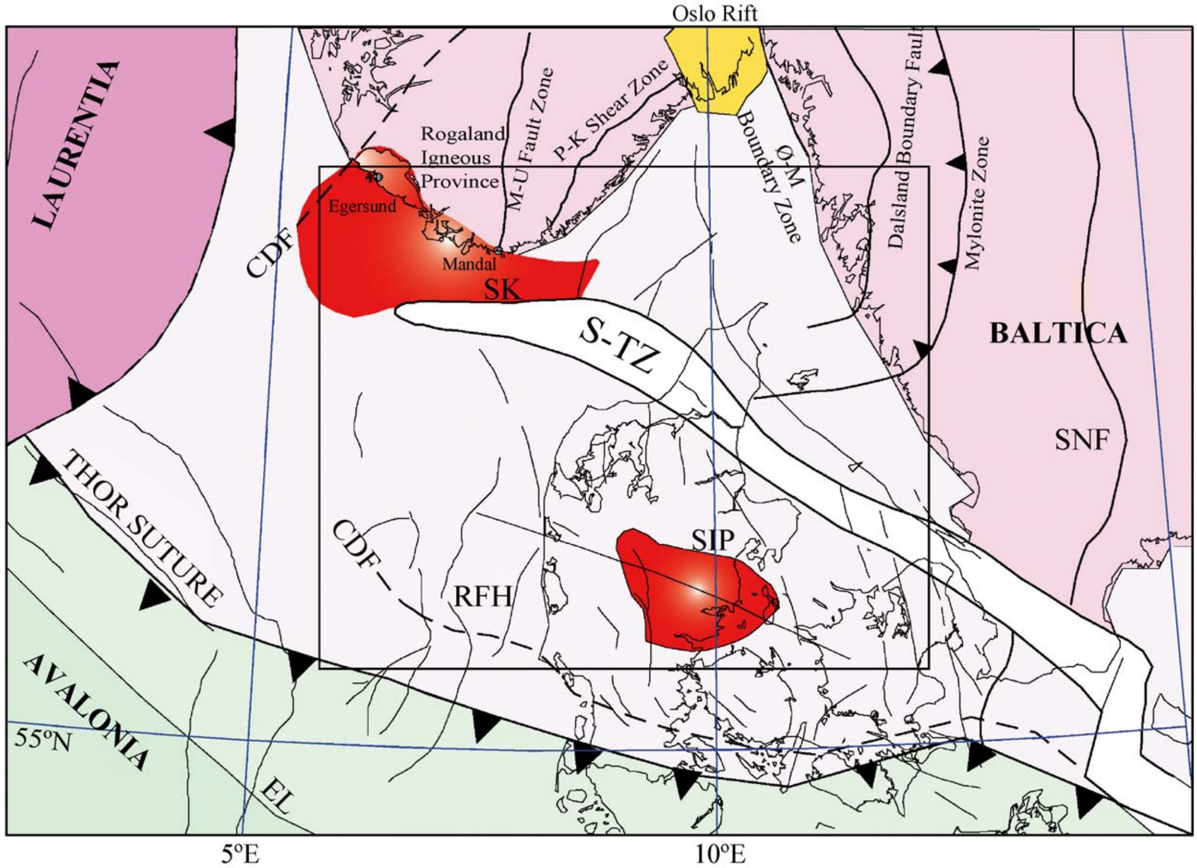

Fig. 1. Geological map of the Norwegian–Danish Basin and adjacent basement area (modified from Pharaoh, 1999 and Bingen et al., 2001). EL, Elbe Line; CDF, Caledonian Front; RFH, Ringkøbing–Fyn High; SNF, Sveconorwegian Front; S–TZ, Sorgenfrei–Tornquist Zone; M–U, Mandal–Ustaoset Fault Zone; P–K, Porsgrunn–Kristiansand Shear Zone; SIP, Silkeborg Igneous Province; SK, Skagerrak igneous body. The rectangular frame shows the location of Figs. 2–4 and Figs. 7–10.

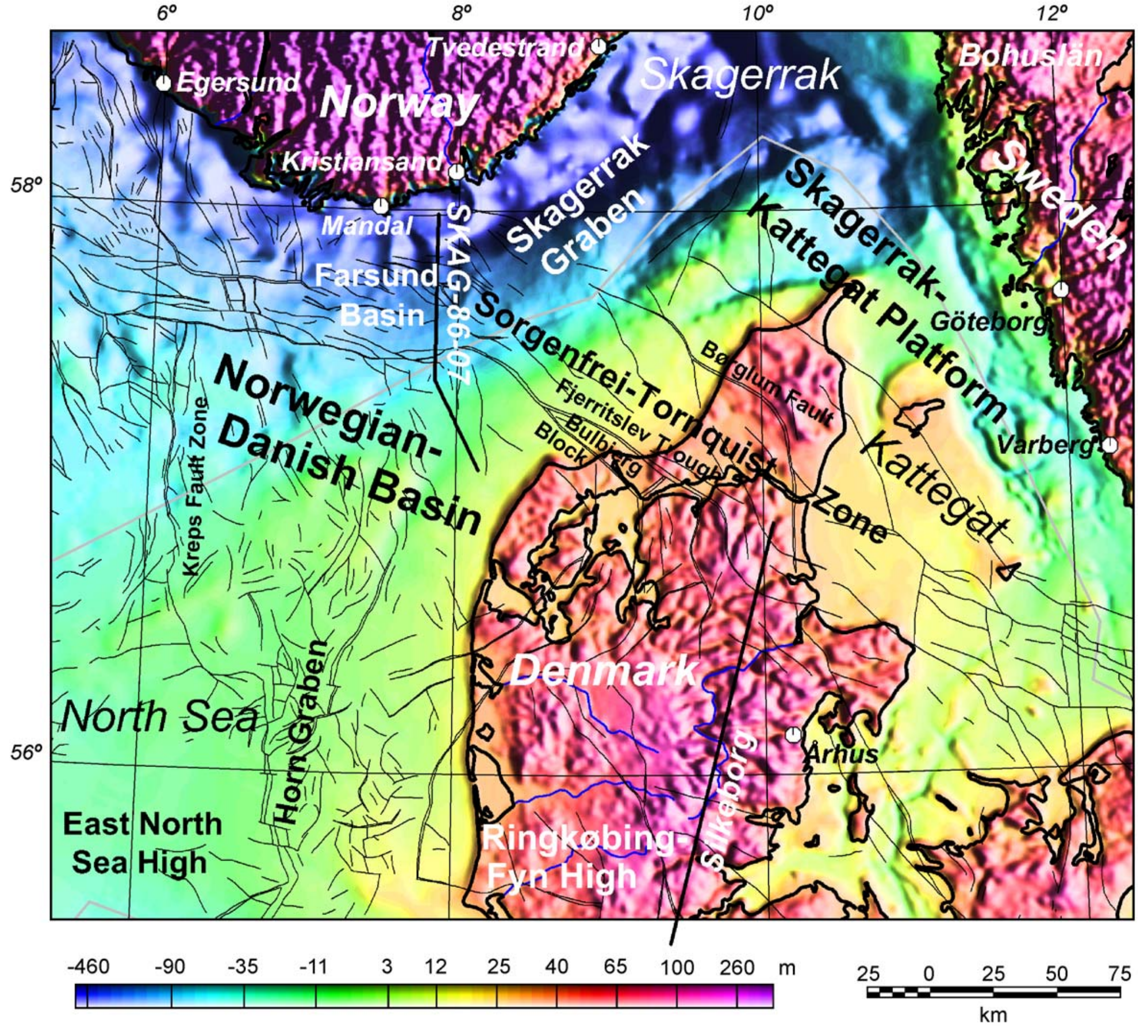

Fig. 2. Compilation of topography/bathymetry southwestern Scandinavia. Structural elements at top pre-Zechstein level (Vejbæk and Britze, 1994) are included as well as the SKAG-86-07 and Silkeborg interpretation profiles. The grey line shows the border between the offshore national sectors.

sources of the anomalies are igneous bodies. Some authors advocate a Permian age for the bodies (Sharma, 1970; Åm, 1973; Abrahamsen and Madirazza, 1986; Thybo and Schönharting, 1991; Berthelsen, 1992; Thybo, 1997, 2000; Strykowski, 2000), while others propose a Tertiary age for the so-called ‘Skagerrak volcano’ (Sharma, 1970; Åm, 1973; Hovland, 1987). A Tertiary age is supported by the presence of Eocene ashes in northern Jutland (Sharma, 1970) and the steep inclination of the inferred remanent magnetisation of the source rock body. Jensen and Langnes (1992) questioned the Tertiary age of the intrusion. Nevertheless, the proximity of the rock bodies to the Permian Oslo Rift and the Late Carboniferous Scania dyke swarm has lead most researchers to accept a Permo-Carboniferous intrusive origin for these subsurface features. Similar negative magnetic anomalies occurring on the mainland of Norway are, however, caused by Sveconorwegian intrusions. This enigma calls for a renewed interpretation of the potential field data sets in the region to try to distinguish magnetic anomalies

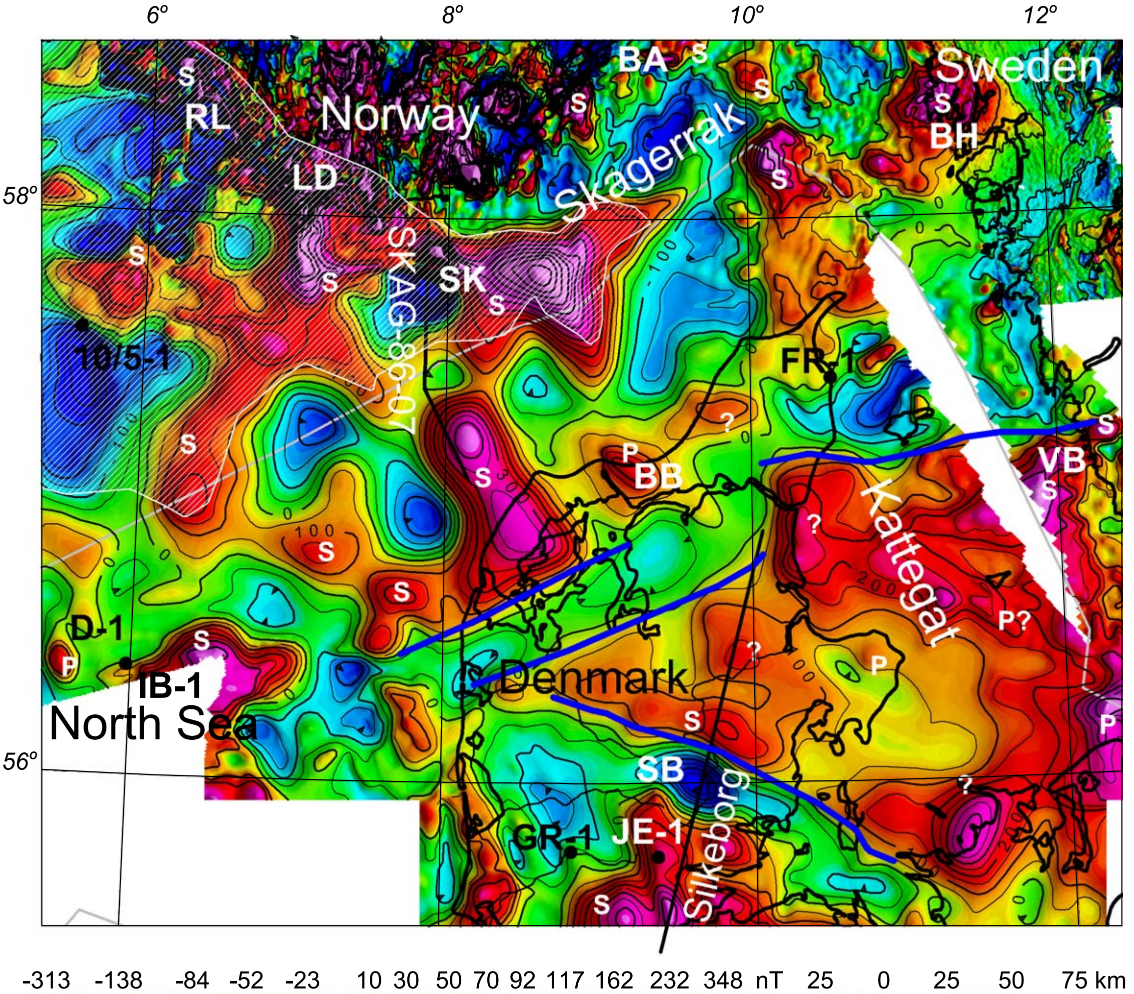

Fig. 3. Total magnetic field anomaly map of southwestern Scandinavia. The contour interval is 50 nT. List of compiled datasets is shown in Table 1. Magnetic anomalies: BA, Bamble; BB, Bulbjerg Block; BH, Bohus; D-1, D-1 well; IB-1, Ibenholt-1 well; LD, Lyngdal; RL, Rogaland; SB, Silkeborg; SK, Skagerrak anomaly; VB, Varberg. The diagonal, white hatching indicates the areal extent of the Rogaland Igneous Province. Blue lines indicate regional basement structures. Interpreted age of anomaly sources: P, Permian; S, Sveconorwegian; ?, unidentified. The five wells, 10/5-1, FR-1, IB-1, GR-1 and JE-1 are penetrating Precambrian basement and are shown with filled circles. The grey line shows the border between the offshore national sectors.

related to the Proterozoic basement from those caused by younger Permian igneous bodies.

2. Main structural elements

Fig. 2 shows the Skagerrak–Kattegat Platform, the Norwegian–Danish Basin and the Ringkøbing–Fyn High. The main structural elements in the adjacent basement north and east of the Norwegian–Danish Basin are the N–S trending Mandal–Ustaoset Fault Zone (MUFZ in Fig. 1; Sigmond, 1985) and the NE–SW trending Porsgrunn–Kristiansand Shear Zone (PKSZ in Fig. 1; Starmer, 1991) in mainland Norway and the N–S trending Dalsland Boundary Fault (Fig. 1; Berthelsen, 1977) in Sweden. Igneous provinces within the area are the Upper Carboniferous–Permian (c. 300–245 Ma) Oslo Rift in the

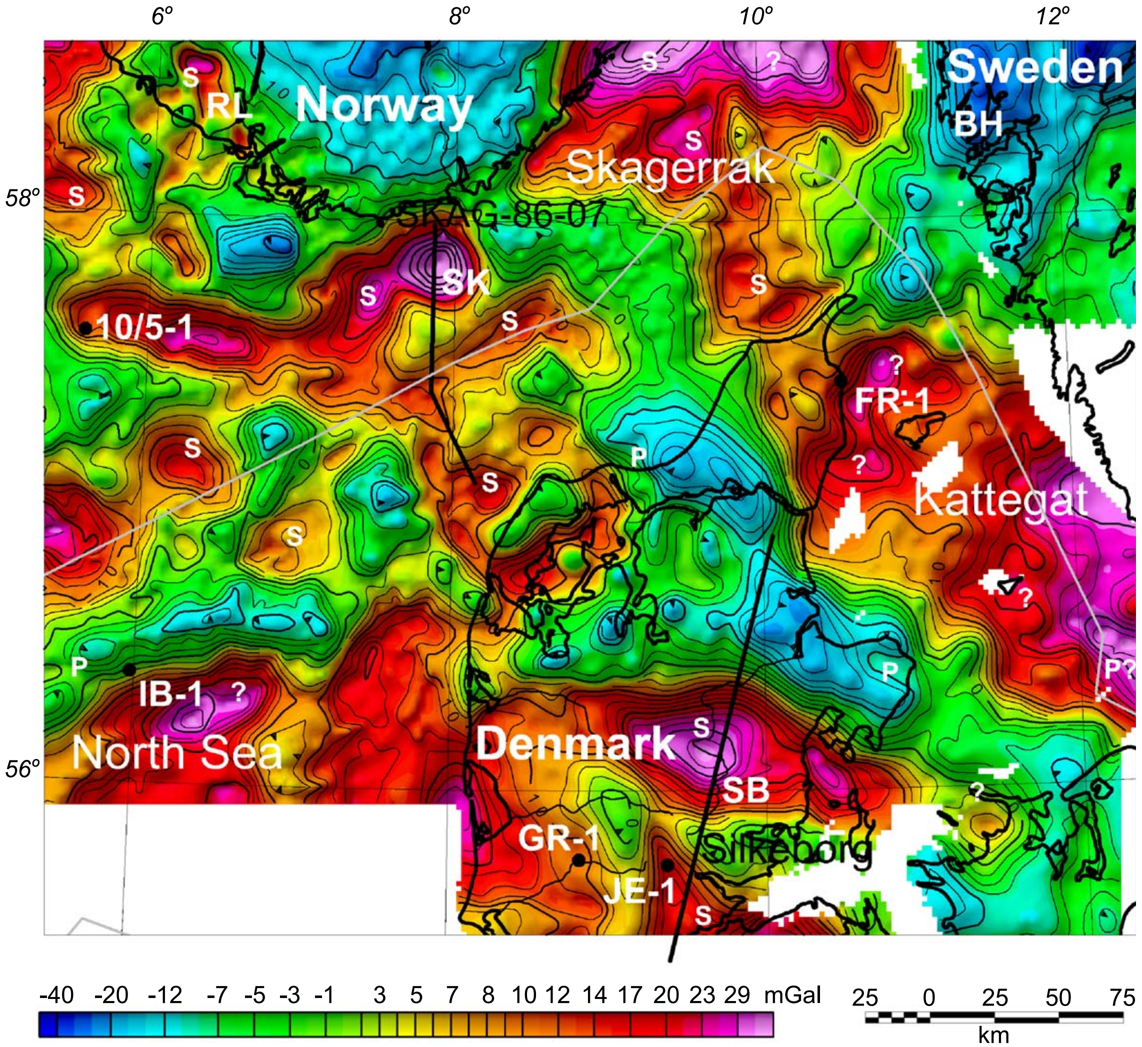

Fig. 4. Bouguer gravity map of southwestern Scandinavia based on a compilation of data sets from the mainland (Table 2) and 40,000 km of marine gravity profiles collected by the Norwegian Petroleum Directorate, Mobil Exploration, Statoil and the Norwegian Mapping Authority. The contour interval is 2.5×10^{-5} m/s^2 (mgal). Gravity anomalies: BH, Bohus; RL, Rogaland; SB, Silkeborg; SK, Skagerrak. Interpreted age of anomaly sources: P, Permian; S, Sveconorwegian; ?, unidentified. The five wells, 10/5-1, FR-1, IB-1, GR-1 and JE-1 are penetrating Precambrian basement and are shown with filled circles. The grey line shows the border between the offshore national sectors.

northeast (Fig. 1; Ramberg, 1976; Neumann et al., 1992; Olaussen et al., 1994; Sundvoll and Larsen, 1994) and the Sveconorwegian (c. 930 Ma) Rogaland Igneous Province (Fig. 1; Duchesne et al., 1987) in the northwest. The Oslo Rift is dominated by intermediate and acidic intrusive rocks and the Rogaland Igneous Province comprises a wide range of norites, anorthosites, granodiorites and granites. The latter complex is often referred to as an anorthosites–mangerite–charnockite–granite (AMCG) suite.

The Trans-European Suture Zone (TESZ) has a long history (see review in Pharaoh, 1999), and its early development includes the amalgamation of Avalonia and Baltica along the Thor Suture (Fig. 1). Late Ordovician suturing between these two plates eliminated the Tornquist Sea that had separated these palaeocontinents during most of the Ordovician (see reviews in Cocks and Torsvik, 2002; Torsvik and Rehnström, 2003). The Caledonian Deformation Front to the south of the Ringkøbing–Fyn High (CDF in Fig. 1) constitutes the nappe front between Baltica and Avalonia (Berthelsen, 1992; Abramovitz et al., 1998; Thybo, 2001). The Sorgenfrei–Tornquist Zone (S–TZ in Fig. 1) forms part of the TESZ and is a complex tectonic zone forming the northwestern part of the Tornquist–Teisseyre Lineament, one of the major European tectonic sutures (Liboriussen et al., 1987). The Sorgenfrei–Tornquist Zone (S–TZ) lies north of the older Thor Suture and separates the Skagerrak–Kattegat Platform from the Norwegian–Danish Basin. The S–TZ was mostly active during late Palaeozoic and Mesozoic times (Liboriussen et al., 1987; Mogensen, 1994; Pegrum, 1984; Mogensen and Jensen, 1994) and curvilinear faults and rift basins were formed during this tectonic phase. The main structures bordering the northwestern segment of the Sorgenfrei–Tornquist Zone are the Børglum Fault to the northeast and the Fjerritslev Trough and the Bulberg Block to the southwest. The formation of the Permo-Carboniferous Oslo Rift system (including the Skagerrak Graben and the Oslo Graben) to the northeast represents a reactivation of a Sveconorwegian structure and is closely linked to dextral strike–slip movements along the Sorgenfrei–Tornquist Zone (Ro et al., 1990; Sundvoll and Larsen, 1994; Lie, 1995). Extensive volcanic activity was associated with this tectonism around the Oslo Rift and around the Sorgenfrei–Tornquist Zone in Scania (Neumann et al., 1992; Klingspor, 1976). The subsequent thermal relaxation may have initiated the late Palaeozoic and Mesozoic subsidence of the Norwegian–Danish Basin (Sørensen, 1986). The Norwegian–Danish Basin is, to a large extent, dominated by salt-related tectonics (Sørensen et al., 1992; Vejbæk and Britze, 1994).

3. Geophysical data sets

We have produced new compilations of aeromagnetic and gravity data for the Norwegian–Danish Basin and adjacent areas in Denmark, Norway and Sweden. High-sensitivity aeromagnetic data acquired during the summer of 1996 in Danish, Norwegian and Swedish waters of the Skagerrak (Olesen et al., 1996, 1997) and four vintage aeromagnetic surveys (Table 1) have been compiled. The combined dataset is displayed in Fig. 3 using shaded relief and histogram–equalisation techniques. The Swedish data from the Bohuslän area were upward continued from 30 to 150 m and resampled from 200×200 to 500×500 m cells. The aeromagnetic data from northern and central Jutland in the form of hand-contoured maps were digitised by the Geological Survey of Denmark and Greenland (GEUS) and were gridded to a 500×500 m grid. The Kattegat data had previously been digitised to a 4×4-km grid by the European Geotraverse Project (Wonik et al., 1992). Manually drawn aeromagnetic contour maps at a scale of 1:50,000 of mainland Norway have earlier been digitised into a 500×500-m matrix and the Definite Geomagnetic Reference Field 1965 has been subtracted (Nor. geol. unders., 1992). Grids from the different data sets were merged with the SAS-96 data using a minimum curvature algorithm, GRIDSTITCH, developed by Desmond Fitzgerald and Associates (1996). The new 500×500 m grid represents a significant improvement compared to the previous 5×5 km grid of the European Geotraverse Project (Wonik et al., 1992). Studies of the depth to magnetic basement from the latter coarse grid will (upward, continued to 3000 m) not give reliable depth estimates in the range of 0–3 km.

The gravity grid in Fig. 4 is based on a compilation of 3614 gravity stations (Table 2) on the mainland of

Table 1
Aeromagnetic surveys compiled for the present study (Fig. 3)

Year	Contractor	Area	Flight altitude	Line spacing	Tie-line spacing	Recording
1996	NGU	Skagerrak-North Sea (SAS-96)	140 m a.m.s.l.	2 km	5 km	digital
1959–71	NGU	Southern Norway	150–300 m a.g.	500–1000 m		analogue
1969–93	SGU	Bohuslän, Sweden	30 m a.g.	200 m		analogue–digital
1965	Hunting Surveys	Jutland, Denmark	750 m a.m.s.l.	3–6 km	12 km	analogue
1970–71	Fairey Surveys	Kattegat, Sweden	600 m a.m.s.l.	4 km	20–30 km	analogue

a.g., above ground; a.m.s.l., above mean sea level; NGU, Geological Survey of Norway; SGU, Geological Survey of Sweden.

Sweden and Norway collected by NGU, SGU, SK (Norwegian Mapping Authority) and Balling and Falkum (1975), and approximately 40,000 km of marine gravity profiles collected by the Norwegian Petroleum Directorate, ExxonMobil, Statoil and the Norwegian Mapping Authority (Skilbrei et al., 2000). The marine data sets were compiled by TGS–Nopec. Gravity data on mainland Denmark were digitised from hand-contoured maps by GEUS. The complete Bouguer reduction of the gravity data was computed using a rock density of 2670 kg/m^3 on mainland Norway and Sweden and 2000 kg/m^3 on mainland Denmark. The spacing between the gravity stations varies in most of the on land areas between 1 and 3 km. A simple Bouguer correction was carried out on the marine gravity measurements using a density of 2200 kg/m^3. The International Gravity Standardisation Net 1971 (IGSN 71) and the Gravity Formula 1980 for normal gravity were used to level the surveys. The combined data set was interpolated to a square grid of 2×2 km using the minimum curvature method (Swain, 1976).

Some of the magnetic and gravimetric anomalies are continuous from land on to the continental shelf. It is therefore important to know the density and magnetic properties of the rocks on land when interpreting potential field data covering offshore areas. NGU has earlier carried out petrophysical sampling programmes (for density, susceptibility and remanence measurements) in the Arendal and Egersund areas (Sindre, 1992; McEnroe et al., 1996; 2001a). Rock density studies (Table 3) from the nearby mainland, collected during geological mapping and geophysical studies, have earlier been published by other geophysicists interpreting gravity data (Smithson, 1963; Lind, 1967; Smithson and Barth, 1967; Lind and Saxov, 1970; Ramberg and Smithson, 1971; Balling and Falkum, 1975; Ramberg, 1976; Smithson and Ramberg, 1979). Representative rocks units (mainly gneisses) are selected from the area. Density data from the Rogaland Igneous Province and the Herefoss, Grimstad and Iddefjord granite complexes (Bingen et al., 2001) are excluded in the estimate of the general basement density. The 'normal' density of the Precambrian basement below the Norwegian–Danish Basin is estimated to be 2730 kg/m^3.

As further constraints for the gravity modelling, we have used information from 10 petroleum exploration

Table 2
On land gravity data from NGU, GEUS, LMV, SGU, SK and the Universities of Oslo and Århus compiled in the present project (Fig. 4)

Area	No.	Institution	Reference
Bohuslän	232	Geological Survey of Sweden (SGU)	
Bohuslän	541	Swedish Mapping Authority (LMV)	
Southern Norway	261	Norwegian Mapping Authority (SK)	Skilbrei et al., 2000
Agder-Rogaland	773	Geological Survey of Norway (NGU)	Sindre, 1993
Grimstad and Herefoss	173	University of Oslo	Smithson, 1963
Agder	1637	University of Århus	Balling and Falkum, 1975
Denmark	*	Geological Survey of Denmark and Greenland (GEUS)	

(*), digitised hand-contoured maps.

Table 3
Density of basement rocks from the coastal area of southern Norway and western Sweden, Bohuslän

Location	Rock type	No.	Density (kg/m^3)	Reference
Egersund area	Gneiss	N/A	2700	Smithson and Ramberg, 1979
Flekkefjord area	Gneiss	287	2690	Balling and Falkum, 1975
Mandal area	Gneiss	37	2730	Smithson and Barth, 1967
Telemark area	Gneiss, etc.	36	2760	Smithson, 1963
Bamble	Gneiss, etc.	54	2810	Smithson, 1963
Bamble	Gneiss	166	2734	Sindre, 1992
Skien-Gvarv	Gneiss, etc.	29	2680	Ramberg, 1976
Østfold	Gneiss	42	2660	Lind and Saxov, 1970
Østfold	Gneiss	61	2750	Ramberg and Smithson, 1971
Bohuslän	Gneiss	20	2730	Lind, 1967
Egersund area	Norite	N/A	3000	Smithson and Ramberg, 1979
Egersund area	Norite	86	3090	McEnroe et al., 1996

Representative rock units are selected from the area. Density data from the Egersund Igneous Province and the Herefoss, Grimstad and Iddefjord granite complexes (Bingen et al., 2001) are excluded in the compilation of the 'normal' density of the Precambrian basement.

Table 4
Density of sedimentary sequences from density logs of wells in the Norwegian–Danish Basin

Well No. Operator Year Structure Name	L-1 Chevron 1970 Else	D-1 Gulf 1968 Jane	Ibenholt-1 Phillips 1987 Ibenholt	R-1 Chevron 1973 Kaye	Inez-1 Chevron 1977 Inez	F-1 Gulf 1968 Nina	K-1 Chevron 1970 Lena	C-1 Gulf 1968 Dora	Felicia-1 Statoil 1987 Felicia	J-1 Gulf 1970 Lisa	Density adapted for modelling
Water depth	55 m	49 m	40 m	37 m	35 m	41 m	56 m	27 m	69 m	44 m	1.03
Start of log	1179 m	695 m	1134 m	1041 m	1023 m	755	957 m	1130 m	120 m	1026 m	
Pleistocene											
Post Chalk Goup	2.16 (2015)	2.06 (1205)	2.10 (1447)								2.15
Chalk Group	2.54 (2316)	2.47 (1462)	2.47 (1641)	2.24 (−1180)	2.43 (−1250)	2.28 (1283)	–	–	2.25 (712)		2.45
Lower Cretaceous	2.47 (2377)	2.29 (1511)	2.37 (1701)	2.30 (1262)	2.25 (1394)	2.23 (1511)	2.29 (1240)	2.27 (1286)	2.14 (905)		2.35
Jurassic	2.39 (2416)	2.23 (1543)	2.27 (1749)	2.35 (1303)	2.30 (1633)	2.33 (2041)	2.33 (1947)	2.18 (1373)	1.79 (1505)	2.41 (−1697)	2.35
Triassic	2.45 (2455)	2.41 (1687)	2.39 (1954)	2.29 (1998)	2.30 (1949+)	2.39 (2384+)	2.28 (2256+)	2.36 (2529)	2.42 (4695)	2.35 (1952+)	2.40
Zechstein Group, salt	2.86 (2553)	2.12 (3321)	2.06 (2141)	–				2.08 (3034)	2.01 (5057)		2.05
Zechstein Gr., dolomite			2.80 (2491)					2.75 (3161)	2.67 (5134)		2.75
Rotliegende Group	2.67 (2671+)	2.46 (3528+)	2.38 (2533)	2.49 (2676+)				2.59 (3171+)	2.64 (5290)		2.60
Cambro-Silurian											2.78[a]
Precambrian basement			2.63 (2558+)								2.73[b]
Granitoid intrusive, Silkeborg											2.70
Intermediate intrusive, Silkeborg											2.80
Mafic intrusions, Skagerrak and Silkdeborg											3.00[c]
Mantle											3.30

The estimates (*1000 kg/m^3) are used for gravity modelling along the SKAG07 and Silkeborg profiles. Numbers in parentheses show depth in metres to the base of the different sequences.

[a] Density data from the Cambro-Silurian of the Oslo Region (31 samples, Ramberg, 1976).

[b] Density data from the mainland Norway and Sweden (see Table 3) are included in the calculation of the mean basement density.

[c] Density data from the Egersund area (see Table 3; Smithson and Ramberg, 1979).

wells in the Danish sector of the Norwegian–Danish Basin. The densities of sedimentary sequences calculated from density logs are shown in Table 4. The average values were used to constrain 2 1/2D modelling along the SKAG-86-07 and Silkeborg profiles.

Previous petrophysical studies have also documented that the Permian volcanics within the Oslo Region are highly magnetic (Thorning and Abrahamsen, 1980; Åm and Oftedahl, 1977). Permian dykes/basalts within the Oslo Rift and Permian dykes within the Precambrian of southern Norway and southwestern Sweden carry a viscous component (close to the present earth field direction) and a characteristically flat-lying remanent magnetisation direction of probable Permian age (van Everdingen, 1960; Thorning and Abrahamsen, 1980; Torsvik et al., 1998; in prep. and Table 5). The NRM directions either point downwards (positive inclination) with declination/inclination of 210°/30°–80° or are relatively flat lying with declination/inclination of 200°/−5–−30° (Fig. 5 and Table 5) depending on the influence of the viscous component. The coercivity force of the Permian flat-lying component is weak and the median destructive field (MDF) in most rocks is lower than 5 mT. Remanence directions carried by Sveconorwegian rocks in southern Norway (McEnroe et al., 1996, 2001a) have steep, upward-pointing NRM, i.e., negative inclination (Fig. 5). In the Rogaland Igneous Province, 50 km to the NW of the negative Skagerrak anomaly, there are numerous Sveconorwegian (c. 930 Ma) intrusive bodies (Duchesne et al., 1987) that also carry an upward-directed magnetisation, predominately anorthosites and norites (Table 5). The *Q*-values (ratio of remanent to induced magnetisation) range from 0.1 to 150 (McEnroe et al., 1996, 2001a) and MDF ranging from 20 to 50 mT; the anorthosites having both the highest *Q*-value and coercivity. The *Q*-value of the anorthosites is consequently 30–100 higher than for the Permian diabases and basalts, while the coercivity is 10 times higher. Hemo-ilmenite and titano-magnetite carry the remanence in the Rogaland Igneous Province and Permian volcanics, respectively (McEnroe et al., 2001a; Thorning and Abrahamsen, 1980). Hemo-ilmenite has been shown to be a more stable carrier of remanence than titano-magnetite (McEnroe et al., 2001b).

The remanence directions of the late Proterozoic and Tertiary are both steep (negative or positive) because Baltica was located at high southerly and northerly latitudes, respectively, during these time

Table 5
Magnetic properties of Permian and Proterozoic rocks from western Sweden and southern Norway (Torsvik, in prep; Thorning and Abrahamsen, 1980; McEnroe et al., 1996)

Rock type	Age	Location	No.	Sus. SI	Rem. int. mA/m	Mdf mT	*Q*-value	NRM declination, inclination	Reference
Basalt	Permian	Vestfold	42	0.067			0.8		Åm and Oftedahl, 1977
Basalt	Permian	Skien	60	0.109			1.3		Åm and Oftedahl, 1977
Diabase	Permian	Bohuslän, Sweden	6	0.068	2200	≤5	0.7	183, 84 (*n*=7); 94, 87 (*n*=10); 181, −6 (*n*=9)	Thorning and Abrahamsen, 1980
Diabase	Permian	Tvedestrand	15	0.015	6500		2.7	216, −27(*n*=15)	Torsvik, in prep.
Anorthosite	Sveconorwegian	Åna-Sira, Rogaland		0.003	5400	≈50	77.1	–	McEnroe et al., 2001a
Norite	Sveconorwegian	Tellnes, Rogaland	190	0.108	5000	20–50	7.3	293, −64 (*n*=32)	McEnroe et al., 1996
Gneiss	Sveconorwegian	Bamble, Telemark–Agder	76	0.030					Sindre, 1992
Granite	Sveconorwegian	Bamble, Telemark–Agder	13	0.040					Sindre, 1992

Sus., susceptibility; mdf, median destructive field. A declination and inclination of 295° and −60°, respectively, have been applied in the modelling of the magnetic Skagerrak and Silkeborg anomalies. The remanence intensity and susceptibility in the modelling are 5000 mA/m and 0.05 SI, respectively. These parameters produce a ratio of remanent to induced magnetisation (*Q*-value) of 2.55.

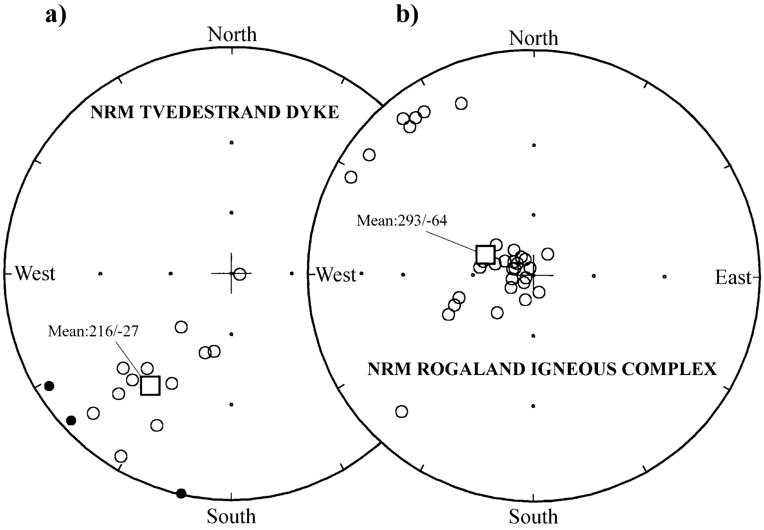

Fig. 5. Natural remanent magnetisation (NRM) of Permian diabases from the Oslo Region (Torsvik, in prep.) and Sveconorwegian norites and anorthosites from the Rogaland Igneous Province (McEnroe et al., 1996).

periods (Fig. 6) and are therefore difficult to distinguish from each other. Late Proterozoic is therefore a plausible alternative for the previously suggested Tertiary age of the magnetisation in the Skagerrak area.

4. Depth to magnetic basement

The Euler 3-D deconvolution method (Thompson, 1982; Reid et al., 1990) was used to estimate the depth to magnetic rocks within both the crystalline

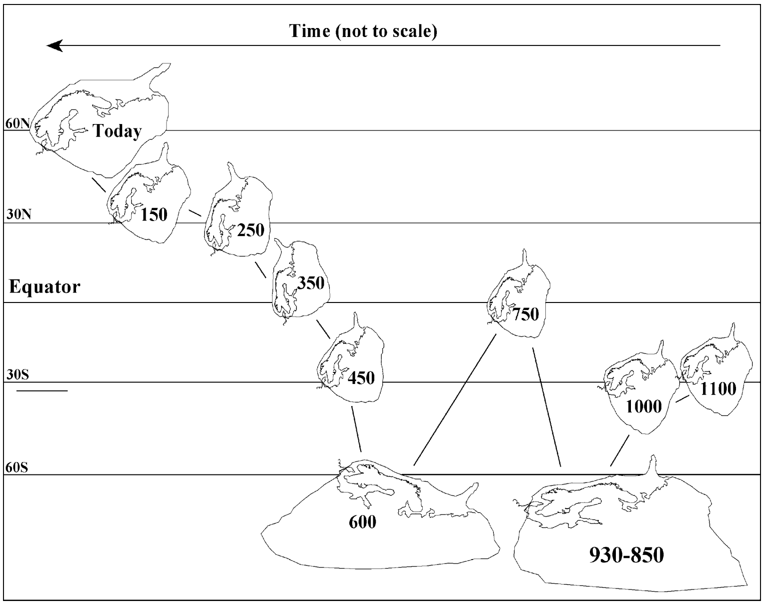

Fig. 6. Palaeomagnetic plate reconstruction of Baltica through time. Southern Scandinavia was located at a high southern latitude during the formation of the Rogaland Igneous Province and at a low northern latitude during Permian time (modified from Torsvik et al., 1996; Walderhaug et al., 1999).

basement and the Palaeozoic intrasedimentary volcanics. The method has the advantage of being applicable to anomalies caused by a wide variety of geological structures and of being independent of remanent magnetisation and ambient field direction. The depths to the magnetic sources constrain the interpretation of the Silkeborg and Skagerrak anomalies and aid in the separation of anomalies related to basement structures from anomalies related to younger intrusions. Permian volcanics in the Rotliegendes Group are somewhat deeper than the top pre-Zechstein level but may be difficult to separate from the deeper basement sources. Depth estimates from potential field data have been tested against both well and seismic reflection data.

We applied the improved 'Located Euler 3D method' (Geosoft, 2003), making use of the analytic signal to locate edges of the magnetic field sources. The Blakely and Simpson (1986) grid peak-picking

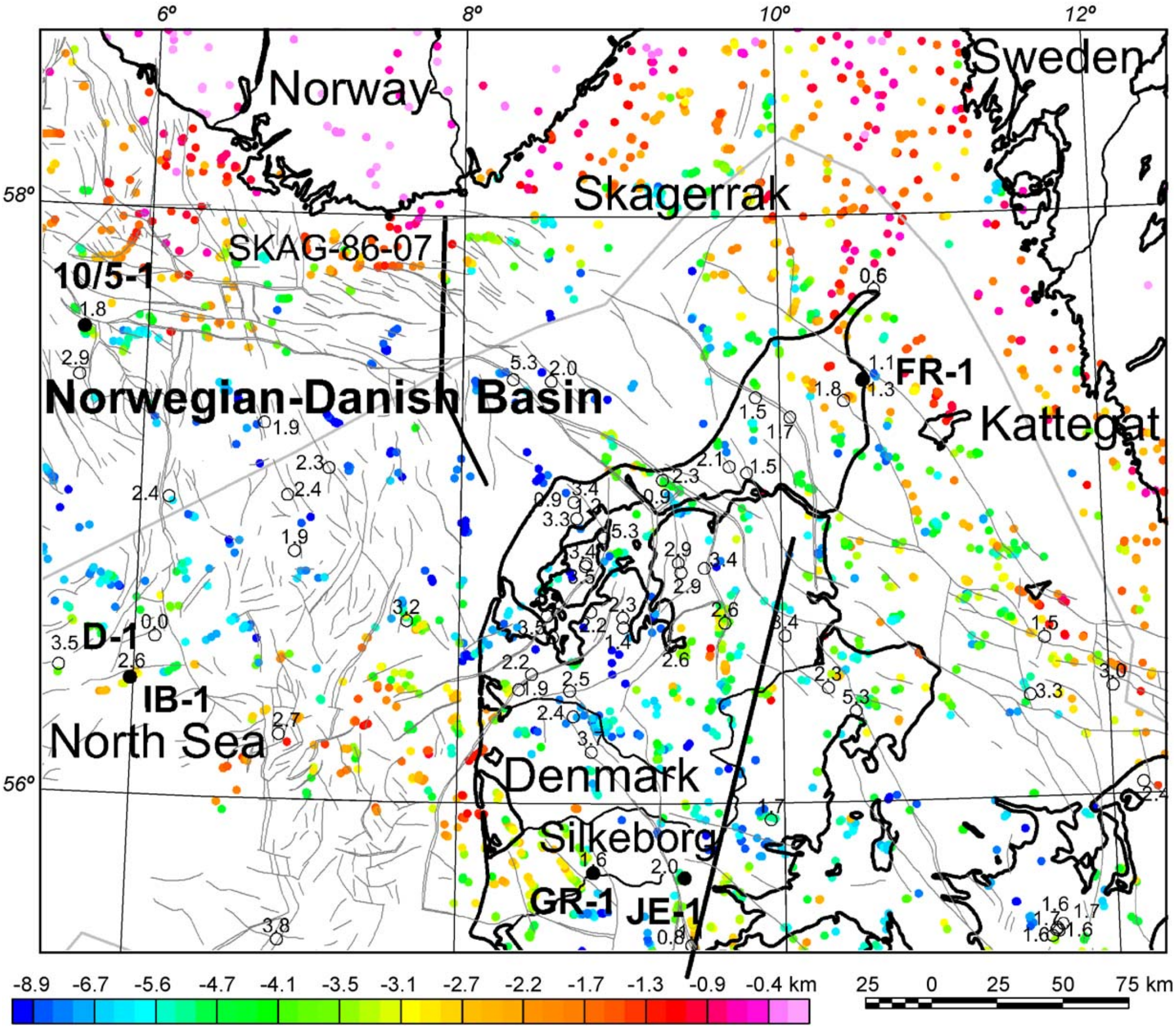

Fig. 7. Depth to magnetic sources (Euler method) illustrated with coloured dots. Structural index=0.5. Structural elements (Vejbæk and Britze, 1994) at top pre-Zechstein are included. Location and depth extent of exploration wells are added to the map. Five wells, 10/5-1, FR-1, IB-1, GR-1 and JE-1, penetrating Precambrian basement are shown with filled circles and wells not reaching basement are shown with open circles. Bold black lines denote interpretation profiles.

algorithm locates the crest of the analytic signal anomalies improving the location of the depth estimates. The window size for this analysis is determined from the location of the adjacent anomaly inflection points. The Located Euler method produces fewer solutions than the Standard Euler method and the spray pattern of source positions commonly observed in Euler depth solutions is avoided.

We chose to compute Euler depth solutions for a ‘thick-step’-type source geometry where the interface between magnetic and nonmagnetic rocks is step-shaped. This geometry is applicable to, for example, a faulted magnetic basement. We also computed depths using ‘contact’- and ‘thin-plate’-type models where magnetic and nonmagnetic materials are juxtaposed on a continuous planar surface. The source positions derived from the ‘thick step’ model were better focused in position and were consistent with directly observed basement depth from drilling of the Ibenholt 1 well. Reid et al. (1990), Smethurst (1994), Olesen and Smethurst (1995), Olesen et al. (1996, 1997) and Skilbrei et al. (2002) conclude that structural indices between zero and unity are appropriate for basement anomalies similar in form to those of the present

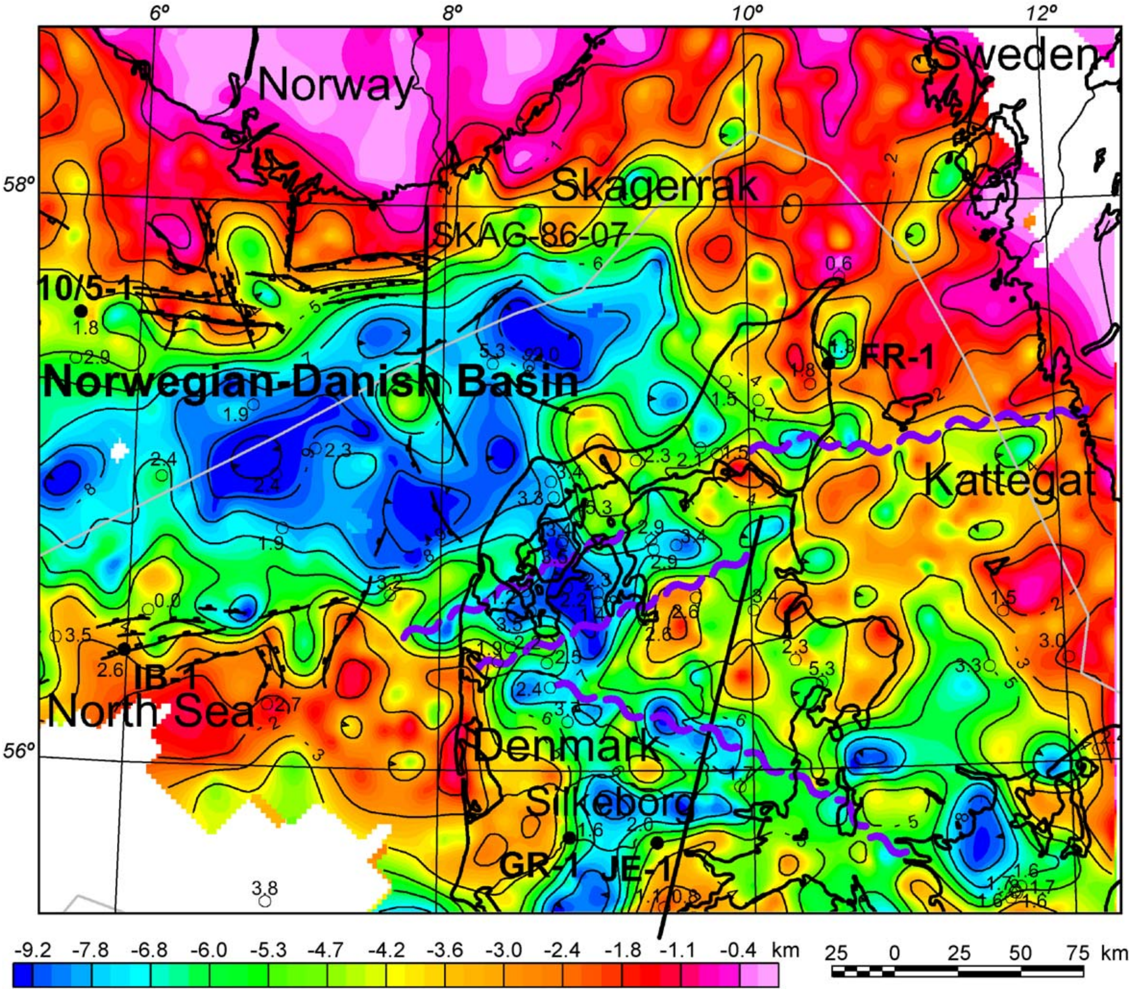

Fig. 8. Interpolated depth to magnetic sources, Euler method. Structural index=0.5. Depth extent (in km) of exploration wells is added to the map (five wells, 10/5-1, FR-1, IB-1, GR-1 and JE-1, penetrating Precambrian basement are shown with filled circles and wells not reaching basement are shown with open circles). Violet lines indicate regional basement structures interpreted from the aeromagnetic data. Black lines represent more local basement faults.

study. Experience from the Norwegian continental shelf shows that flat-lying sills and basalt flows produce anomalies in the order of 2–3 nT which is far below the amplitudes of the anomalies in the Norwegian–Danish Basin (>100 nT).

The interpretation map with depth to magnetic basement estimates is presented in Fig. 7. The depth estimates were interpolated to a regular grid using the minimum curvature method and displayed in Fig. 8 using a histogram–equalisation technique. The grid constitutes a smoothed surface implying draping of steep faults and deep basins. The top pre-Zeichstein fault interpretation of Vejbæk and Britze (1994) is included in Fig. 7, as are the locations and depths of exploration wells (Nielsen and Japsen, 1991). Five of the wells penetrate the Precambrian basement; 10/5-1, Fredrikshavn 1, Ibenholt 1, Grindsted 1 and Jelling-1 (labelled 10/5-1, FR-1, IB-1, GR-1 and JE-1 in (Figs. 3, 4 and 7–10). The other well data represent minimum depths to crystalline basement. Regional fault zones interpreted from aeromagnetic and gravity data are included in Fig. 8. Isopach map (Fig. 10) of pre-Zechstein low-magnetic rocks in the Norwegian–Danish Basin has been calculated by subtracting the

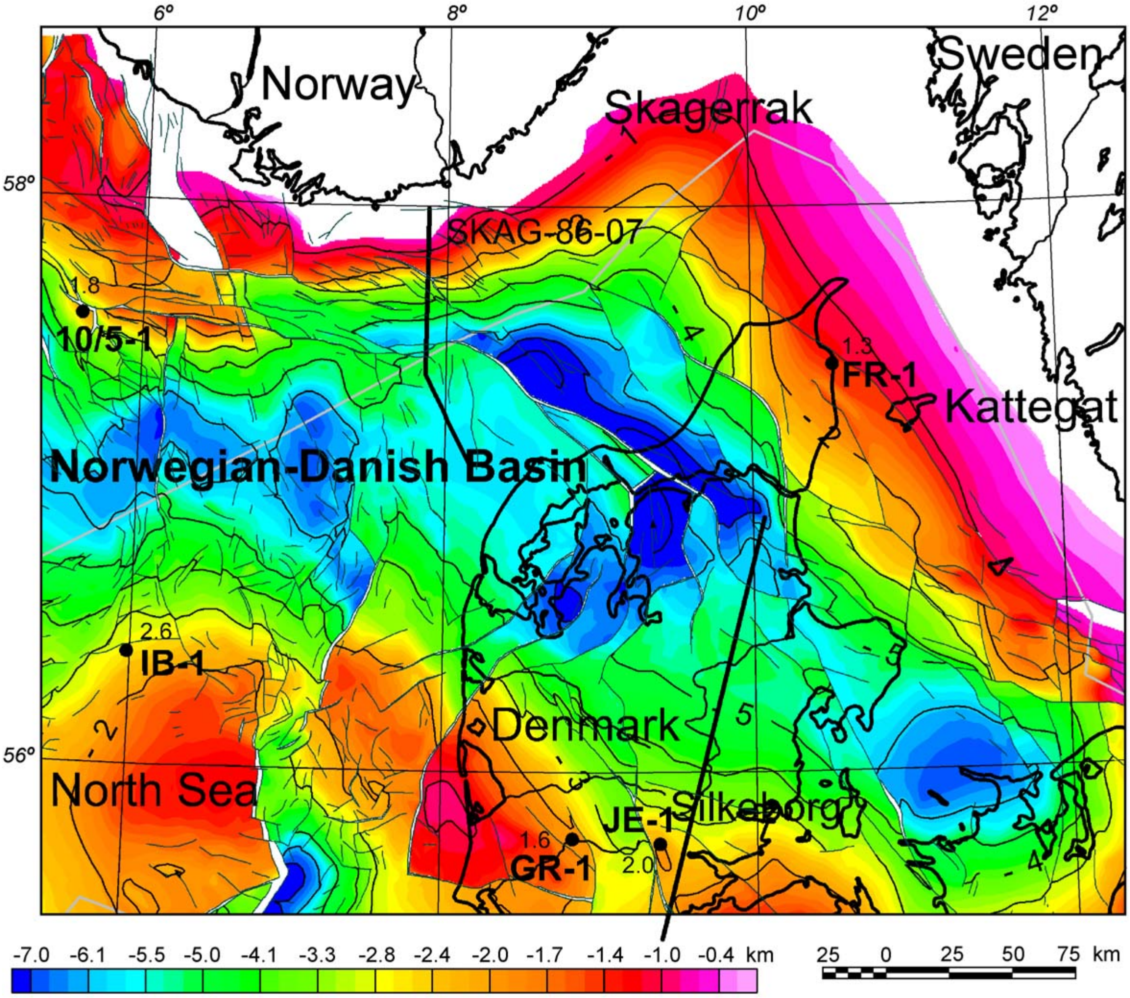

Fig. 9. Part of the Geological map of Denmark 1:750,000, Top pre-Zechstein, Structural depth map (Vejbæk and Britze, 1994). The location of two interpretation profiles is shown on the map: SKAG-86-07 (including the RTD-81-06 extension) and Silkeborg. Five wells, 10/5-1, FR-1, IB-1, GR-1 and JE-1, penetrating Precambrian basement are shown with filled circles and encountered basement depths.

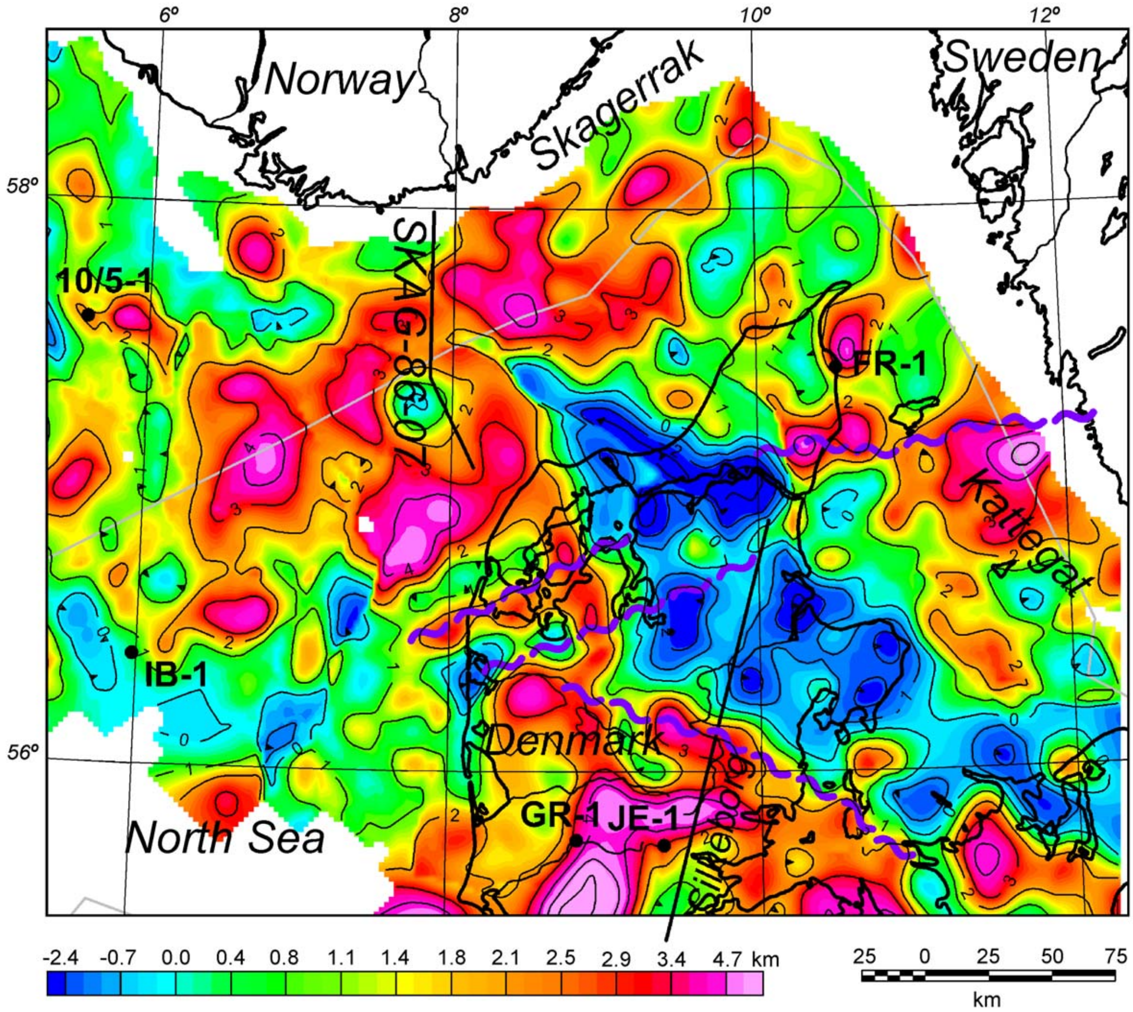

Fig. 10. Isopach map of pre-Zechstein low-magnetic rocks in the Norwegian–Danish Basin, calculated by subtracting the top pre-Zechstein depths (Fig. 8) from the interpolated depth to magnetic sources map (Fig. 9). Five wells, 10/5-1, FR-1, IB-1, GR-1 and JE-1, penetrating Precambrian basement are shown with filled circles. Violet lines indicate regional basement structures interpreted from the aeromagnetic data.

top pre-Zechstein depths (Fig. 9) from the grid of interpolated depth to magnetic sources (Fig. 8).

5. Forward modelling

We have carried out forward modelling of the gravity and magnetic field along two profiles across the Norwegian–Danish Basin. Constraints provided by seismic information have been used. One of the profiles consists of two seismic lines, SKAG-86-07 and RTD-81-06 (Figs. 11, 12). Seismic interpretations were digitised and depth-converted using the interval stacking velocities (Table 6) from the seismic sections. The Silkeborg interpretation profile is located across the Silkeborg gravity and magnetic anomalies at the boundary between the southern Norwegian–Danish Basin and Ringkøbing–Fyn High. The depth to the stratigraphic horizons along this line was extracted from depth-converted grids (Japsen and Langtofte, 1991a,b; Britze and Japsen, 1991; Vejbæk and Britze, 1994). When computing the response from the models we have used the Windows version of the IMP computer program of Torsvik (1992). The applied

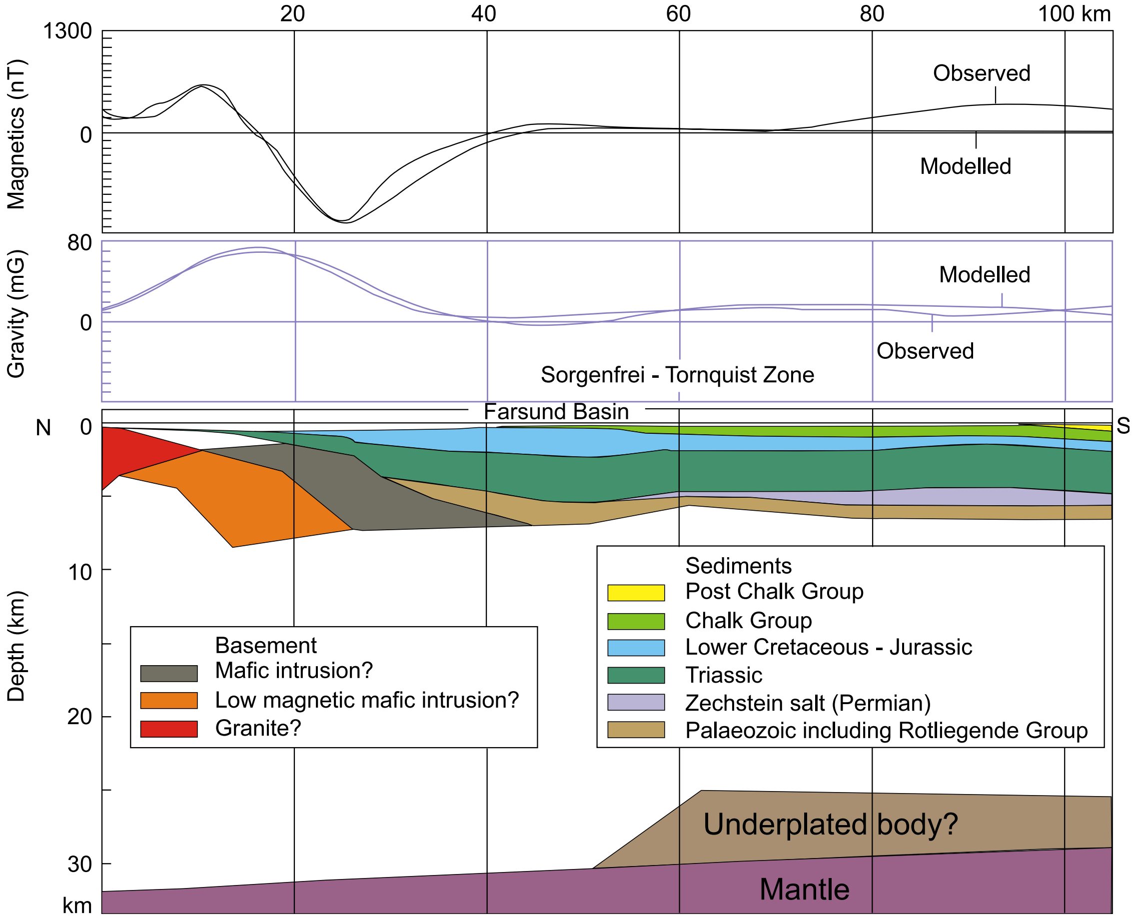

Fig. 11. Gravity and magnetic interpretation along the seismic profile SKAG-86-07 and RTD-81-06. Applied densities and magnetic properties are shown in Tables 3, 4 and 5, respectively. A Sveconorwegian NRM direction is applied in the magnetic modelling.

densities and magnetic properties are shown in Tables 4 and 5, respectively. The basic model in this program comprises 2½ dimensional bodies, i.e., bodies of polygonal cross-section of finite length in the strike direction. The depth-converted seismic horizons were imported directly into the IMP programme package. The depth estimates obtained from the Euler method were also used to constrain the models.

6. Discussion

6.1. Regional aeromagnetic and gravity anomalies

The magnetic anomalies in the Skagerrak and northern Kattegat area are continuous from the mainland of southern Norway and southwestern Sweden, respectively. The igneous rocks within the Rogaland Igneous Province, Bohus Granite and Varberg Charnockite cause the bulk of these anomalies (Fig. 3). Anorthositic and noritic rocks similar in type and age to the rocks in the Rogaland Igneous Province are also associated with the Bohus granite (Scherstén et al., 2000), indicating that these rocks occur throughout the Sveconorwegian domain. An extension of the high-grade gneisses within the Bamble Complex also produces magnetic anomalies in the northern Skagerrak. The WSW continuation of the Mylonite Zone from western Sweden and the extension of the N–S trending Mandal–Ustaoset Fault Zone from southern Norway are continental-scale fault zones dominating the magnetic and gravity pattern in the northern part

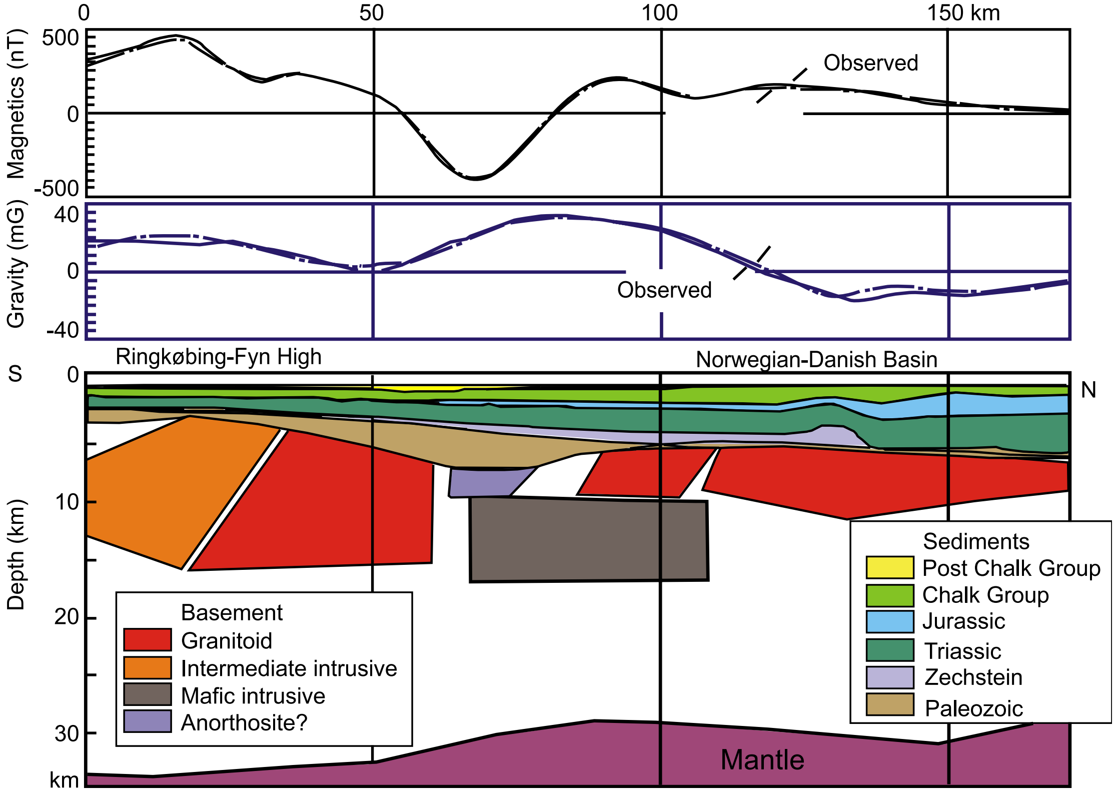

Fig. 12. Gravity and magnetic interpretation along the Silkeborg profile. Applied densities and magnetic properties are shown in Tables 3, 4 and 5, respectively. A Sveconorwegian NRM direction is applied in the magnetic modelling.

of the Norwegian–Danish Basin. The magnetic anomalies in the southern part of the Kattegat can be traced to the mainland of Scania where numerous Carboniferous–Permian diabase dykes produce positive magnetic anomalies (Klingspor, 1976; Erlström and Sivhed, 2001).

Figs. 7 and 8 show that the interpolated depths to magnetic sources below the Norwegian–Danish Basin constitute a saucer-shaped surface with a maximum depth of more than 10 km. The isopach estimates of top pre-Zechstein low-magnetic rocks vary between 5 km in the North Sea–Skagerrak area and −2 km in the northern Jutland–southern Kattegat area. Negative isopach values imply magnetic sources at a shallower depth than top pre-Zechstein, systematic inaccuracies in our magnetic depth estimates or incorrect seismic depth conversion by Vejbæk and Britze (1994). The estimated thickness of the top pre-Zechstein low-magnetic rocks (possibly sediments) in the Skagerrak and Silkeborg areas is 2–3 km. Permian diabases and rhomb porphyry dykes in Bohus, southwestern Sweden and in Agder, southern Norway, produce no distinguishable anomalies on the aeromagnetic map (Fig. 3). The Permian volcanics in the Rønde and Nøvling boreholes adjacent to the Silkeborg anomalies do not produce distinguishable anomalies either. Some of the local magnetic anomalies in the Norwegian–Danish Basin are, however, most likely

Table 6
Interval stacking velocities (*1000 m/s) from the SKAG-86-07 and RTD-81-06 seismic sections applied in depth conversion of the seismic profiles

Profile unit	SKAG-86-07	RTD-81-06
Sea water	1.48	
Pleistocene	1.8	
Post chalk group	1.9	
Chalk group	3.3	
Lower Cretaceous–Jurassic	2.8	
Triassic	4.5	
Zechstein group	4.6	

related to Permian igneous rocks (marked with the letter P in Fig. 3), especially in those areas where the depth to magnetic sources is close to the depth to the top pre-Zechstein (isopach depths around zero in Fig. 10). The oval-shaped positive anomaly in the Danish Sector at 5°30′ E, 56°25′ N (labelled D-1 in Fig. 3) yields Euler, e.g., depth estimates of 3.1 to 3.7 km, and an exploration well (D-1) located 3 km from the centre of the anomaly has encountered Lower Permian basalts at a depth of 3.508 km (Rasmussen, 1974; Nielsen and Japsen, 1991). The eruptive rocks make up 18 m of the deepest part of the well (total depth, 3.526 km) and the total thickness is unknown. This local anomaly is therefore most likely caused by Permian volcanics. The thickness of the top pre-Zechstein sediments outside the areas with magnetic Permian volcanics is in general accordance with the thickness estimates calculated from gravity and seismic data by Zhou and Thybo (1996, 1997) (i.e., on the Ringkøbing–Fyn High, Skagerrak Graben and on the southeastern Norwegian–Danish Basin).

The long wavelength component of the Bouguer gravity field (Fig. 4) can be partly interpreted in terms of the Moho topography. A density contrast of 570 kg/m^3 between the lower crust and mantle is assumed (densities of 2730 and 3300 kg/m^3, respectively). The Moho depth is adapted from Kinck et al. (1991) and Thybo (2001) and applied in the forward modelling of the interpretation profiles. The Moho depth is shallowest below the central part of the Norwegian–Danish Basin (29 km) and the Skagerrak Graben–Fjerritslev Trough (26–28 km) in the eastern part of the study area. The Moho gets successively deeper towards the Farsund Basin and the mainland of Norway to the north (31–32 km) and towards the Ringkøbing–Fyn High in the south (32 km).

The positive gravity effect from the shallow Moho below the Norwegian–Danish Basin is, however, not sufficient to compensate for the highly reduced gravity effect from the low-density sediments within the basin. There is a need to introduce more dense material at depth in the crust below the basin. We have chosen to add a body of mafic rocks immediately above the Moho. The thickness varies between 3 and 9 km, and the width between 80 and 100 km. It is thickest below the deepest part of the Norwegian–Danish Basin and thins successively towards the east where it is about 3 km on the SKAG-86-07 profile. A similar deep-seated, dense, mafic rock unit and shallow Moho are included in the gravity model of the Skagerrak Graben by Ramberg and Smithson (1975). An alternative model is to modify the Moho depth interpreted by Kinck et al. (1991) to make it shallower below the Norwegian–Danish Basin and deeper below the Sorgenfrei–Tornquist Zone is suggested by Lie and Andersson (1995). By introducing a mafic body above the Moho, there is no need to modify the Moho depth. Reinterpretations of the Oslo Graben by Afework et al. (2004) and Ebbing et al. (in preparation) show that the gravity anomaly in this area to a large degree is produced by dense Sveconorwegian complexes (Bamble and Kongsberg) extending eastwards below the graben. The inherent ambiguity of the gravity method makes it difficult to decide which of the two Moho models below the Skagerrak Graben is the correct one. A similar coincident shallow Moho and a dense mafic body in the upper part of the deep crust are also applied to model the Silkeborg gravity high by Thybo and Schönharting (1991).

By increasing the density of the consolidated deep sediments of the Norwegian–Danish Basin, the size of the mafic body at depth will be reduced but cannot be excluded. Some of the wells in the Danish sector are quite deep and provide information about the consolidated part of the stratigraphy. The average density of the Triassic sediments between 1505 and 4695 m in the Felicia-1 well is, for instance, 2420 kg/m^3, while the applied density of the Triassic in our modelling is 2400 kg/m^3.

Five wells (labelled 10/5-1, IB-1, FR-1, GR-1 and JE-1 in Figs. 3 and 7–10) penetrate the Precambrian basement within the study area. The Ibenholt-1 well (5°58′ E, 56°23′ N; labelled IB-1 in Figs. 3 and 7) intersected Precambrian basement at a depth of 2558 m (Nielsen and Japsen, 1991), while the nearest Euler depth estimates show a depth estimates ranging from 2700 to 3000 m. These tests show that the chosen Euler structural index of 0.5 (thick step) is appropriate for this type of anomaly in concordance with the conclusion that most of the aeromagnetic anomalies are caused by voluminous intrusive and metamorphic complexes within the Fennoscandian Shield. We anticipate the accuracy of the depth estimates to be within 10–15%. The estimated depths to magnetic sources are, however, 1.5–2 km deeper than the basement depths obtained from drilling of the 10/5-1, FR-1, GR-1 and JE-1 wells. These discrepancies of more than 50% are too large to be related to an inappropriate choice of structural index. Therefore, we partly attribute this result to the effect of a weakly magnetised basement (10/5-1, FR-1, GR-1) and partly to the effect of local structures that are not discernable in the draped depth surface (JE-1). Hospers et al. (1986) arrived at the same result for the 10/5-1 well on the northern margin of the Norwegian–Danish Basin (Figs. 7 and 8). Williamson et al. (2002) reported low-susceptibility gneisses in the GR-1 and IB-1 wells. The depth to magnetic basement (Figs. 7 and 8) is generally deeper than the estimates of Sellevoll and Aalstad (1971), but locally somewhat shallower than the estimates by Hospers and Rathore (1984), especially in the western Norwegian–Danish Basin (including the Egersund Basin) where depths in excess of 11 km are reported by the latter authors. Our estimates show depths of 7–8 km in this area. The depth estimates of the Norwegian–Danish Basin indicate a general depth of 7–8 km in large parts of the basin, which is similar to the estimates by Hospers and Rathore (1984) but deeper than estimates of 6 km by Sellevoll and Aalstad (1971). Our calculations of the depth of the Farsund Basin are approximately 8 km while Hospers and Rathore (1984) estimate depths in excess of 9 km. An estimate of the pre-Zechstein-salt Palaeozoic sediments by Hospers et al. (1986) reveals a thickness in excess of 4 km in the central parts of the Norwegian–Danish Basin and the Farsund Basin and less than 2 km on the neighbouring basement highs.

6.2. Skagerrak and Silkeborg anomalies

The Skagerrak gravity and magnetic anomalies reach +85 mgal and −1300 nT, respectively, while the Silkeborg anomalies reach +40 mgal and −600 nT. The Silkeborg gravity high is the dominant anomaly in the gravity field of Denmark. The Skagerrak and Silkeborg anomalies are situated along the regional Sorgenfrei–Tornquist Zone and Silkeborg–Samsø Fault at the northern and southern margin of the Norwegian–Danish Basin, respectively. The centres of the negative magnetic anomalies in Skagerrak and Silkeborg are situated 12 and 15 km, respectively, to the south of the respective gravity maxima. Both the negative aeromagnetic and the positive gravity Skagerrak anomalies can be modelled using the petrophysical constraints from the Rogaland Igneous Province. A 7-km-thick complex of mafic intrusions is located below a southward-dipping 1- to 4-km-thick section of Mesozoic sediments and 1- to 2-km-thick section of Palaeozoic sediments (including the Permian Rotliegende Group). Using a steeply dipping, upward (Proterozoic)-pointing remanence (declination and inclination of 295° and −60°, respectively; Table 5) requires that the source body be inclined towards the south, below the Farsund Basin. Use of this remanence direction also requires the introduction of a low-magnetic region to the north. A neighbouring profile (SKAG-85-05) across the westward extension of the Skagerrak gravity anomaly reveals a similar model (Olesen et al., 1997) to the Precambrian, southward dipping dense body of SKAG-86-07. The magnetisation of this western part of the body is, however, downward pointing.

The gravity anomaly of the ‘Skagerrak volcano’ was interpreted by Åm (1973) in terms of a dense body extending from the upper crust, 1–4 km in depth, down to a depth of approximately 15 km. In this case, the source body had to be split into two parts, with opposite remanence magnetisation directions to conform to the observed magnetic anomaly. A southward inclination of the magnetic body with steeper negative magnetisation was pointed out by Åm (1973). Note that Åm (1973) utilised the stable Permian component of the magnetisation after removal of the viscous-positive component. Applying the observed positive NRM magnetisation directions will produce a mainly positive magnetic anomaly.

Our forward modelling shows that a similar body to that required to account for the Skagerrak anomalies may also be inferred to account for the Silkeborg anomalies [i.e., a magnetic body with steep upward-pointing remanent magnetisation (<−50°) situated above a dense, mafic body]. Measured magnetic properties and densities from the Rogaland Igneous Province were used in the modelling of the Silkeborg anomalies. Fig. 12 shows that the basement along the Silkeborg profile contains voluminous bodies (more than 10-km thick) of magnetic, low-density rocks (most likely granitoids). These rock bodies must occur both below the Ringkøbing–Fyn

High, as shown by Thybo and Schönharting (1991), and below the Norwegian–Danish Basin.

The aeromagnetic anomalies associated with the basement of the Norwegian–Danish Basin are continuous with aeromagnetic anomalies on mainland Norway and Sweden, supporting the conclusion that they are caused by Sveconorwegian intrabasement sources rather than Permian (or younger) intrusive/extrusive rocks. High-grade metamorphic rocks along the coast of southern Norway and southwestern Sweden are magnetite bearing (Sindre, 1992; Möller et al. 1997) and cause magnetic anomalies that can be traced below the offshore Palaeozoic and Mesozoic sediments. The continental-scale Sorgenfrei–Tornquist Zone continues below the Norwegian–Danish Basin and partly determines the extent of the aeromagnetic and gravity anomalies.

Two of the most prominent anomalies on Fig. 3 correspond to the continuation of the Rogaland Igneous Province (negative magnetisation) and the postorogenic Sveconorwegian belt of granites along the Late Proterozoic Mandal–Ustaoset Fault Zone (MUFZ). The aeromagnetic data indicate that the belt of magnetic Precambrian granites along the MUFZ continues below the Farsund Basin where it seems to be dextrally offset by approximately 10 km along the Sorgenfrei–Tornquist Zone. This constitutes the accumulated offset during several deformation periods from the Palaeozoic to the present. This observation suggests that the more recent interpretation of 15- to 20-km dextral displacement along the Sorgenfrei–Tornquist Zone since the Early Palaeozoic (Mogensen, 1994) is more likely than the earlier interpretation of approximately 350-km dextral displacement (Pegrum, 1984). A relatively minor lateral offset along the Sorgenfrei–Tornquist Zone is also supported by the aeromagnetic data in the Kattegat–northern Jutland area (Fig. 3) where the NE–SW trending aeromagnetic anomalies from mainland Sweden are continuous across the zone.

The offshore Late Palaeozoic and Mesozoic structures seem partly to have been governed by the older structures. The Kreps Fault Zone (Brekke et al., 1989; Vejbæk and Britze, 1994), for instance, coincides with the eastern border of the N–S trending belt of postorogenic granites (1000–800 Ma) along the MUFZ (Sigmond, 1985). The Kreps Fault Zone throws down rocks on the western side (approximately 0.5–1.0 km offset at top pre-Zechstein level) in the western part of the Norwegian–Danish Basin (Fig. 2). The contours of the depth to basement map (Fig. 8) show an offset of approximately 1 km along this fault, supporting the calculated depth estimates. The central section of the N–S trending Krabbe Fault Zone (Vejbæk and Britze, 1994) immediately to the west of the map area in Fig. 2 coincides with the boundary of a large gravity anomaly suggesting that this structure represents a reactivation of a deep-seated basement structure.

Widespread volcanic activity occurred during Late Palaeozoic time in the Oslo Region (300–245 Ma) and the southern North Sea–Skagerrak–Kattegat area (Ziegler, 1990; Neumann et al. 1992). The partial negative Skagerrak and Silkeborg magnetic anomalies have previously been compared with the magnetic anomalies over the Oslo Graben. The anomalies over the Oslo Graben are, however, largely positive due to the dominance of large intrusive granite and monzonite bodies and sheets of basalt and diabases (also positively magnetised) over reversely magnetised volcanic plugs producing small-scale negative anomalies (Kristoffersen, 1973; Åm and Oftedahl, 1977). The dykes rarely show up on the regional aeromagnetic map of the area (Nor. geol. unders., 1992). This is also partly due to the low Q-values of the Permian volcanics (Table 5). Reflection seismic data from the Farsund Basin and shallow drilling have shown that no volcanics penetrate the Palaeozoic and Mesozoic sediments offshore Kristiansand (Fanavoll and Lippard, 1994; Smelror et al., 1997) and that the magnetic rocks are therefore most likely older than these. It is not viable that the original flat-lying remanence of Permian volcanics would be preserved at great depths below the Norwegian–Danish Basin due to the low coercivity force of the Permian volcanics. Both the Skagerrak and Silkeborg anomaly sources are located further away from the Caledonian front (>100 km) than the Rogaland Igneous Province where original Sveconorwegian remanence directions are observed (McEnroe et al., 2001a). It is therefore likely that an original Sveconorwegian magnetisation of the Silkeborg and Skagerrak rock bodies would survive a Caledonian thermal event. The Silkeborg remanent rock body was situated at a depth of 3–5 km during the Permian. A thermal gradient of more than 100 °C/km is needed to bring the temperature to the Curie temperature of 580 °C. Paleomagnetic studies by Meert et al. (1998) have also shown that the Neoproterozoic remanence of the Fen Province is preserved at a horizontal distance of 12 km from the Permian batholiths of the Oslo Rift. A Neoproterozoic remanence direction of the Silkeborg rock body could therefore survive the Permian sill intrusions in the area. Remanence resetting usually occurs in a zone that is half the width of the sill- or dyke-intrusion. The fact that the observed magnetic anomaly cannot be explained by a Permian magnetisation direction supports this conclusion.

The northern area of the Skagerrak Graben has the same low magnetic field (Fig. 3) as the Precambrian basement on the mainland of Norway indicating that

(1) this part of the Oslo Rift lacks igneous activity or
(2) that the igneous rocks in the area have low magnetisation.

Petrophysical measurements (Åm and Oftedahl, 1977; Thorning and Abrahamsen, 1980; see Table 5) of Permian basalts/diabases from adjacent mainland areas show that these volcanics are generally highly magnetic, indicating that possibility (1) is the most likely situation, in concordance with the conclusions by Lie et al. (1993) who did not find evidence for plutonic rocks below the Skagerrak Basin from refraction seismic data. On the other hand, Heeremans and Faleide (in press) propose a rather thick sequence of Permian volcanics in the Skagerrak Graben. Local positive anomalies in the Norwegian–Danish Basin may be attributed to Permian volcanics, e.g., the magnetic anomalies above the Bulberg Block next to the Fjerritslev Trough (Figs. 2 and 3) in the Skagerrak–northern Jutland area, as also suggested by Madirazza et al. (1990). Our estimates of the depth to magnetic sources of the Fjerritslev anomaly vary between 4 and 5 km, being somewhat shallower than the top pre-Zechstein at a depth of 5–6 km (Vejbæk and Britze, 1994).

The evidence for a Tertiary volcanic centre in the Skagerrak as presented by Sharma (1970) and Åm (1973) is not compelling either. An argument for a Tertiary volcano in the northwestern part of the Skagerrak area is the distribution of Eocene ashes in northern Jutland (Sharma, 1970). Reflection seismic data from the area have shown that the potential volcanics offshore Kristiansand do not penetrate the Mesozoic sediments (Fanavoll and Lippard, 1994). Aeromagnetic anomalies offshore Kragerø to the northeast of Tvedestrand in Fig. 2 were modelled by Åm (1973), applying a steep, negative Tertiary NRM direction. Paleomagnetic dating of ultramafic dykes (damtjernites) outside Kragerø by Storetvedt (1968), giving Tertiary ages, was used to support this interpretation. However, new Rb–Sr and ^{40}Ar/^{39}Ar ages (Dahlgren, 1994; Meert et al., 1998) yield Late Proterozoic ages (576–589 Ma). The Kragerø anomaly can consequently be modelled using a Late Precambrian remanence direction.

In the Rogaland Igneous Province, 50 km to the NW of the negative ‘Skagerrak Volcano’ anomaly there are numerous intrusive bodies, predominately anorthosites and norites, revealing reversed magnetisation and Q-values in the range of 0.1–150 (McEnroe et al., 1996, 2001a). The presence of Permian intrusions below the Farsund Basin may also be questioned since the positive aeromagnetic anomalies of the area blend with aeromagnetic anomalies on nearby mainland Norway. The E–W trending (c. 940 Ma) Lyngdal granite (Bingen and van Breemen, 1996) on the coast 20 km to the north of the Skagerrak anomalies is an eastward extension of the Rogaland Igneous Province (Fig. 1) and coincides with an E–W trending aeromagnetic grain (Fig. 3). This anomaly is continuous with the positive part of the Skagerrak aeromagnetic anomaly and we suggest that the anomalies are caused by rocks of the Rogaland Igneous Province and its offshore extension.

The enormous body of mafic (or possibly ultramafic) rock implied by the modelling could be the residue of the parental magma that produced the voluminous Rogaland anorthosites. These intrusions and other similar anorthosites around the world are interpreted to result from the differentiation of a mafic magma (Ashwal, 1993). Schiellerup et al. (2001) showed that the source of the parental magmas of the Rogaland intrusion suite is most likely a melting of lower crustal mafic rocks. The norite within the Rogaland Igneous Province is, however, of minor volume [up to 4 km deep from gravity modelling by Smithson and Ramberg (1979)] compared with the volume of anorthosite. The mafic body below the Farsund Basin is approximately 60-km long, 30-km wide and up to 6-km thick and could be the mafic residue from the anorthosite differentiation.

An inversion of the Silkeborg gravity and magnetic anomalies using the Euler deconvolution method (Reid et al., 1990) revealed source depths ranging between 6 and 8 km. Autocorrelation depth estimates (Phillips, 1979) using magnetic data are approximately 7 km. Thybo and Schönharting (1991) attributed the gravity and magnetic anomalies to two separate bodies; a 2-km-thick layer of magnetic volcanics within the Palaeozoic sedimentary sequence at a depth of c. 7 km and a dense mafic complex at a depth of 11 km. The flat-lying, volcanic body with a reversed flat-lying magnetisation (10° and $-30°$) of assumed Permian age had a thickness of 2 km in the central part, tapering off in both directions. Thybo and Schönharting (1991) had to modify this model significantly to concur with the filtered gravity data that consisted of two anomalies. The high-density body was thinnest (<200 m) where the remanence-dominated magnetic body was thickest (c. 2 km), implying that the central part of the volcanics must be low-density, intermediate or acidic volcanics. Carmichael (1989) and Clark (1997) showed that these rock types have most frequently a low remanence. The combined modelling by Thybo and Schönharting (1991) is therefore not a likely candidate to account for both the observed negative and positive aeromagnetic anomaly pair and the two positive gravity anomalies. Åm (1973) utilised an inclination of $-20°$ for the Skagerrak anomaly and had similar problems with his interpretations. Thybo and Schönharting (1991) discuss the possibility of an older age for the magnetisation of the Silkeborg rock body. A Silurian age was considered but rated as a secondary candidate because the encountered Late Silurian ’lavas’ in the Nøvling and Rønde wells did not produce magnetic anomalies and because there was no long reverse magnetic epoch during this period. Later studies (Vejbæk and Britze, 1994; Heeremans et al., in press) have, however, revealed that the ’lavas’ are Permian sill intrusions.

A similar Proterozoic igneous body to the Skagerrak rock body can consequently be envisaged to account for the Silkeborg anomaly in central Jutland. The magnetic anomaly can more easily be modelled with a steeply upward-pointing ($<-50°$) remanent magnetisation. The arguments are therefore similar to the ones applied to the Skagerrak anomaly. The magnetic anomalies within this area are, however, not continuous to the outcropping basement on the mainland as in the Skagrerrak, but a Sveconorwegian age is most likely for the source of the magnetic Silkeborg anomaly. The calculated P-wave velocity of 6.25 km/s (Thybo and Schönharting, 1991) indicates an anorthosite source because this rock commonly has a velocity of 6.2–6.9 km/s (Carmichael, 1989), while norites and other gabbros usually have P-velocities of 6.4–7.2 km/s. The accompanying Silkeborg gravity anomaly is caused by a body at greater depth and could, strictly speaking, be caused by an intrusion of another age (e.g., Permian), but since it is parallel to the magnetic anomaly, both source bodies are most likely to be genetically related to each other. We cannot rule out the possibility that the magnetic grain defines a Sveconorwegian basement, the structure of which was exploited during a later Permian igneous phase. There are observed Permian 3- to 40-m-thick sills within the pre-Zechstein sediments in the Nøvling-1 and Rønde-1 wells, 30–40 km to the northeast and northwest of the Silkeborg anomaly. There are, however, 5- to 50-m-wide Permian dykes on the mainland of southern Norway and southwestern Sweden but no evidence of large-scale Permian plutonism below these areas.

The voluminous rock bodies (more than 10 km in thickness) of granitoid and intermediate compositions below the Ringkøbing–Fyn High (Fig. 12) constitute most likely an integrated part of the Sveconorwegian basement. There are no signs of acid Permian volcanism in wells or reflection seismic data in this region. A complex of large-scale magnetic bodies ranging from granitoid to mafic composition below the Ringkøbing–Fyn–Silkeborg area bears resemblance to the so-called AMCG (anorthosite–mangerite–charnockite–granite) suite in the Rogaland Igneous Province. Especially norites and anorthosites with magnetic high coercivity seem to be diagnostic for these complexes. Because the formation of lamellar ilmeno-hematite or hemo-ilmenite is favoured by slow-cooling, deep-seated igneous rocks, and metamorphic terrains can have this oxide assemblage with the appropriate oxygen fugacity (McEnroe et al., 2001a,b; Robinson et al., 2002).

7. Conclusions

Most of the regional aeromagnetic anomalies in the Norwegian–Danish Basin are continuous with the aeromagnetic anomalies on mainland Norway and Sweden, suggesting that the offshore anomalies to a large extent are caused by the Sveconorwegian intrusions in basement rocks observed at the surface on land, rather than Permian (or younger) intrusions/extrusions. The depth estimates to magnetic sources below the central part of the basin are 7–8 km. Depths between 3 and 9 km were obtained along the Farsund Basin, and the magnetic anomaly pattern indicates a complex system of fault blocks along the Sorgenfrei–Tornquist Zone. Approximately 3 km of pre-Zechstein sediments exist at depth in the Farsund Basin. We propose that the negative magnetic anomaly in the Skagerrak, previously attributed to the Permian or Tertiary 'Skagerrak Volcano', may instead be a mafic rock body of Proterozoic age. We suggest that this rock body is part of the Sveconorwegian Rogaland Igneous Province that outcrops 50 km to the north on the Norwegian mainland because:

(1) The magnetic anomalies in the Farsund Basin are continuous with the Rogaland Igneous Province;
(2) An upward pointing Sveconorwegian magnetisation can explain the large negative magnetic anomalies—a flat-lying Permian magnetisation of the large bedrock volumes fails to mimic the observed field;
(3) The Q-values and coercivity of Permian volcanics are small compared with the anorthosites and norites within the Rogaland Igneous Province;
(4) The Permian igneous rocks in the Oslo Rift and the late Carboniferous Scania dyke swarm do not produce large-scale negative aeromagnetic anomalies;
(5) Neither Permian nor Tertiary volcanics have been observed on seismic sections or in shallow drilling of the Mesozoic and Paleozoic strata in the area.

A similar Sveconorwegian igneous body most likely accounts for the Silkeborg anomaly in central Jutland. The magnetic anomaly is easily modelled with a steeply upward-pointing remanent magnetisation. A possible complex of large-scale magnetic intrusions ranging from granitoid to mafic in composition may constitute a so-called AMCG (anorthosite–mangerite–charnockite–granite) suite similar to the Rogaland Igneous Province. The new model with Sveconorwegian mafic intrusive complexes situated along the regional Sorgenfrei–Tornquist Zone and the Silkeborg–Samsø Fault implies that Proterozoic basement structuring has determined the location of the Mesozoic Norwegian–Danish Basin. The newly proposed models are more likely explanations for the Skagerrak and Silkeborg anomalies because the previously published models fail to explain both the observed negative magnetic anomalies and the positive gravity anomalies. The absence of Permian and Tertiary igneous activity in the Farsund Basin may have implications for evaluating the maturation of potential petroleum source rocks in the basin.

Acknowledgements

ConocoPhillips, ExxonMobil, the Geological Survey of Denmark and Greenland (GEUS), the Geological Survey of Norway (NGU), Norsk Hydro, the Norwegian Petroleum Directorate (NPD) and Statoil financed the acquisition of the Skagerrak Aeromagnetic Survey 1996 (SAS-96). Oddvar Blokkum, Janusz Koziel, John Olav Mogaard and Stig Rønning (NGU) carried out the airborne data acquisition. Atle Sindre and Einar Dalsegg, NGU carried out gravity measurements on land in the Rogaland and Agder areas. Other Norwegian mainland gravity data were provided by the Norwegian Mapping Authority (SK), Ivar Ramberg, Norsk Hydro and Niels Balling and Svend Saxov, University of Århus. Sergej Usov, TGS-Nopec provided the offshore gravity data-set. Kajsa Hult and Sven Aaro, SGU supplied aeromagnetic and gravity data, respectively, from the Kattegat and Bohuslän areas. René Forsberg, Danish Geodetic Institute supplied modern gravity data from northern Jutland enabling us to calculate the reference field of the digitised 1949 gravity data. Bernt Egeland, Norwegian Petroleum Directorate provided seismic interpretation along the SKAG07 seismic line. The Norwegian Mapping Authority, The Royal Danish

Administration of Navigation and Hydrography and the Geological Survey of Denmark supplied the topographic and bathymetric data. Jean-Claude Mareschal and an anonymous referee reviewed the manuscript and made suggestions towards its improvement. Peter Padget corrected the English text. To all these persons, companies and institutions we express our sincere thanks.

References

Abrahamsen, N., Madirazza, J., 1986. Gravity and magnetic anomalies: the enigma of the Silkeborg gravity and magnetic anomalies, Central Jutland, Denmark. In: Møller, J.T. (Ed.), Twenty-five Years of Geology in Aarhus, Geoskrifter, vol. 24, pp. 45–59.

Abramovitz, T., Thybo, H., MONA LISA Working Group, 1998. Seismic structure along the Caledonian Deformation Front along MONA LISA profile 1 in the southeastern North Sea. Tectonophysics 288, 153–176.

Afework, Y., Olesen, O., Ebbing, J., Skilbrei, J.R., Nordgulen, Ø., Bingen, B., 2004. Reinterpretation of regional gravity data in the Permian Oslo Rift. Abstract, 26th Nordic Geological Winter Meeting, Uppsala 6–9 January, 2004, Geol. Föreningens i Stockholm Förhandlingar, vol. 126, pp. 88–89.

Åm, K., 1973. Geophysical indications of Permian and Tertiary igneous activity in the Skagerrak. Norges geologiske undersøkelse 287, 1–25.

Åm, K., Oftedahl, C., 1977. Brief comments on some aeromagnetic anomalies in the Oslo Region. In: Heier, K.S. (Ed.), The Norwegian Geotraverse Project. A Norwegian contribution to The International Upper Mantle Project and The International Geodynamics Project. pp. 209–222.

Ashwal, L.D., 1993. Anorthosites. Springer-Verlag, New York. 422 pp.

Balling, N.P., Falkum, T., 1975. A combined geophysical and structural–geological investigation of the Precambrian intrusive Homme granite in south-western Norway. Geol. Föreningens i Stockholm Förhandlingar 97, 338–356.

Berthelsen, A., 1977. Tentative tectonic division of the Sveco-Norwegian belt. Field Guide COMTEC 77 on Tectonics of Precambrian Orogens of Southern Scandinavia, Copenhagen. 93 pp.

Berthelsen, A., 1992. From Precambrian to Variscan Europe. In: Blundell, D., Freeman, R., Mueller, S. (Eds.), A Continent Revealed, The European Geotraverse. Cambridge University Press, Cambridge, pp. 153–164.

Bingen, B., van Breemen, O., 1996. U–Pb titanite geochronology in Rogaland–Vest Agder (SW Norway): regional temperature at the time of intrusion of the Rogaland anorthosites. In: Demaiffe, D. (Ed.), Petrology and Geochemistry of Magmatic Suites of Rocks in the Continental and Oceanic Crusts. Université Libre de Bruxelles. Royal Museum for Central Africa (Tervuren), pp. 145–160.

Bingen, B., Birkeland, A., Nordgulen, Ø., Sigmond, E.M.O., 2001. Correlation of supracrustal sequences and origin of terranes in the Sveconorwegian orogen of SW Scandinavia: SIMS data on zircon in clastic metasediments. Precambrian Research 108, 293–318.

Blakely, R.J., Simpson, R.W., 1986. Approximating edges of source bodies from magnetic or gravity anomalies. Geophysics 51, 1494–1498.

Brekke, H., Færseth, R., Gabrielsen, R., Gowers, M.B., Pegrum, M., 1989. Nomenclature of tectonic units in the Norwegian North Sea, south of 62°N. Structural and Tectonic Modelling and Its Application to Petroleum Geology. Norwegian Petroleum Society, p. 61. Abstract.

Britze, P., Japsen, P., 1991. Geological maps of Denmark 1:400,000. Top Zechstein and the Trissic Geological Survey of Denmark. Map Series 31.

Carmichael, R.S., 1989. Practical Handbook of Physical Properties of Rocks and Minerals. CRC Press, Boca Raton, Florida. 741 pp.

Clark, D.A., 1997. Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. AGSO Journal of Australian Geology and Geophysics 17, 83–103.

Cocks, L.R.M., Torsvik, T.H., 2002. Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. Journal of Geological Society London 159, 631–644.

Dahlgren, S., 1994. Late Proterozoic and Carboniferous ultramafic magmatism of carbonatitic affinity in southern Norway. Lithos 31, 141–154.

Desmond Fitzgerald and Associates Pty Ltd., 1996. INTREPID Geophysical Processing and Visualisation Tools Reference Manual, vol. 2. 241 pp.

Duchesne, J.C., Michot, J., Maquil, R., Maijer, C., Tobi, A.C., 1987. The Rogaland intrusive massifs. In: Maijer, C., Padget, P. (Eds.), The Geology of Southernmost Norway, An Excursion Guide, Norges geologiske undersøkelse Spec. Publ. vol. 1, pp. 48–87.

Ebbing, J., Olesen, O., Afework, J., Nordgulen, Ø. in prep. Is there evidence for magmatic underplating beneath the Oslo Rift? Submitted to Terra Nova.

Erlström, M., Sivhed, U., 2001. Intra-cratonic dextral transtension and inversion of the southern Kattegat on the southwest margin of Baltica—seismostratigraphy and structural development. Sveriges Geologiska Undersökning Research Paper C, vol. 832. 33 pp.

Fanavoll, S., Lippard, S.J., 1994. Possible oblique-slip faulting in the Skagerrak Graben, as interpreted from high resolution seismic data. Norsk Geologisk Tidsskrift 74, 146–151.

Geosoft, 2003. 3-D Euler 3D deconvolution (v5.1.5). Processing, Analysis and Visualization System for 3D Inversion of Potential Field Data, Tutorial and Users Guide. Geosoft Incorporated. 64 pp.

Heeremans, M., Faleide, J.I., in press. Permo-Carboniferous rifting in the Skagerrak, Kattegat and the North Sea: evidence from seismic and borehole data. In: Wilson, M., Neumann, E.-R., Davies, G., Timmerman, M.J., Heeremans, M. and Larsen, B.T. (Eds.), Permo-Carboniferous Rifting in Europe. Geol. Soc., London, Spec. Publ.

Heeremans, M., Timmerman, M.J., Kirstein, L.A., Faleide, J.I., in press. New constraints on the timing of late Carboniferous-early Permian volcanism in the central North Sea. In: Wilson, M., Neumann, E.R., Davies, G., Timmerman, M.J., Heeremans, M. and Larsen, B.T. (Eds.), Permo-Carboniferous Rifting in NW Europe. Geol. Soc., London, Spec. Publ.

Hospers, J., Rathore, J.S., 1984. Interpretation of aeromagnetic data from the Norwegian sector of the North Sea. Geophys. Prospecting 32, 929–942.

Hospers, J., Rathore, J.S., Jianhua, F., Finnstrøm, E.G., 1986. Thickness of pre-Zechstein-salt Palaeozoic sediments in the southern part of the Norwegian sector of the North Sea. Norsk Geologisk Tidsskrift 66, 295–304.

Hovland, M., 1987. Tertiary intrusives in western Skagerrak? Marine Geology 78, 175–182.

Japsen, P., Langtofte, C., 1991. Geological maps of Denmark 1:400,000. Base Chalk and the Chalk Group. Geological Survey of Denmark. Map Series 29.

Japsen, P., Langtofte, C., Geological maps of Denmark 1:400,000. Top Triassic and the Jurassic–Lower Cretaceous. Geological Survey of Denmark. Map Series 30.

Jensen, L.N., Langnes, O., 1992. Obituary: the Tertiary Skagerrak volcano. 20th Nordic Geological Winter Meeting. The Icelandic Geoscience Society, Reykjavik, p. 83. Abstract.

Kinck, J.J., Husebye, E.S., Lund, C.-E., 1991. The south Scandinavian crust: structural complexities from seismic reflection and refraction profiling. Tectonophysics 189, 117–133.

Klingspor, I., 1976. Radiometric age-determination of basalts, dolerites and related syenite in Skaane, southern Sweden. Geol. Föreningens i Stockholm Förhandlingar 98, 195–216.

Kristoffersen, Y., 1973. A magnetic investigation of the larvikite complex of the lake Gjerdingen, Nordmarka. Norsk Geologisk Tidsskrift 53, 267–281.

Liboriussen, J., Ashton, P., Tygesen, T., 1987. The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21–29.

Lie, J.E., 1995. Deep seismic reflection mapping of crustal and upper mantle structures beneath the Skagerrak Sea, SW Scandinavia. PhD thesis, University of Oslo. 138 pp.

Lie, J.E., Andersson, M., 1995. The deep seismic image of the crustal structure of the Tornquist Zone beneath the Skagerrak Sea, northwestern Europe. In: Deep seismic reflection mapping of crustal and upper mantle structures beneath the Skagerrak Sea, SW Scandinavia. J.E. Lie. PhD thesis, University of Oslo.

Lie, J.E., Husebye, E.S., Kinck, J.J., Larsson, F.R., 1993. Geophysical evidence of Cambrian–Silurian sedimentary rocks in the northern Skagerrak. Geol. Föreningens i Stockholm Förhandlingar 115, 181–188.

Lind, G., 1967. Gravity measurements over the Bohus Granite in Sweden. Geol. Föreningens i Stockholm Förhandlingar 88, 542–548.

Lind, G., Saxov, S., 1970. Some geophysical profiles in Østfold. Norges geologiske undersøkelse 266, 37–48.

Madirazza, I., Jacobsen, B.H., Abrahamsen, N., 1990. Late Triassic tectonic evolution in northwest Jutland, Denmark. Bulletin of the Geological Society of Denmark 38, 77–84.

McEnroe, S., Robinson, P., Panish, P., 1996. Rock-magnetic properties, oxide mineralogy and mineral chemistry in relation to aeromagnetic interpretation and search for ilmenite reserves. NGU Report 96.060 (153 pp).

McEnroe, S., Robinson, P., Panish, P., 2001a. Aeromagnetic anomalies, magnetic petrology, and rock magnetism of hemo-ilmenite- and magnetite-rich cumulate rocks from the Sokndal Region, South Rogaland, Norway. American Mineralogist 86, 1447–1468.

McEnroe, S., Harrison, R., Robinson, P., Golla, U., Jercinovic, M.J., 2001b. The effect of fine-scale microstructures on the acquisition and stability of NRM in granulite–facies metamorphic rocks in Southwest Sweden. Journal of Geophysical Research 106, 30.523–30.546.

Meert, J.G., Torsvik, T.H., Eide, E.A., Dahlgren, S., 1998. Tectonic significance of the Fen Province, S. Norway: constraints from geochronology and paleomagnetism. Journal of Geology 106, 553–564.

Mogensen, T.E., 1994. Palaeozoic structural development along the Tornquist Zone, Kattegat area, Denmark. Tectonophysics 240, 191–214.

Mogensen, T.E., Jensen, L.N., 1994. Cretaceous subsidence and inversion along the Tornquist Zone from Kattegat to the Egersund Basin. First Break 12, 211–222.

Möller, C., Andersson, J., Söderlund, U., Johansson, L., 1997. A Sveconorwegian deformation zone (system?) within the Eastern Segment, Sveconorwegian orogen of SW Sweden—a first report. Geol. Föreningens i Stockholm Förhandlingar 119, 73–78.

Neumann, E.R., Olsen, K.H., Baldridge, W.S., Sundvoll, B., 1992. The Oslo Rift: a review. Tectonophysics 208, 1–18.

Nielsen, L.H., Japsen, P., 1991. Deep wells in Denmark 1935–1990. Geological Survey of Denmark. Series A 31 (177 pp.).

Norges geologiske undersøkelse, 1992. Aeromagnetisk anomalikart, Norge M 1:1 mill, Norges geologiske undersøkelse, Trondheim.

Olaussen, S., Larsen, B.T., Steel, R., 1994. The Upper Carboniferous–Permian Oslo Rift: basin fill in relation to tectonic development. Pangea: Global Environments and Resources, Canadian Society Petroleum Geologists, Memoir 17, pp. 175–197.

Olesen, O., Smethurst, M.A., 1995. NAS-94 Interpretation Report: Part III. Combined interpretation of aeromagnetic and gravity data. NGU Report 95.040. 50 pp.

Olesen, O., Beard, L., Smethurst, M.A., 1996. SAS-96: Part I. Skagerrak Aeromagnetic Survey 1996 Processing and Preliminary Interpretation Report NGU Report 96.149. 32 pp.

Olesen, O., Smethurst, M.A., Beard, L., Torsvik, T., Bidstrup, T., Egeland, B., 1997. SAS-96 Part II, Skagerrak Aeromagnetic Survey 1996, Interpretation Report NGU Report 97.022. 56 pp.

Pegrum, R.M., 1984. The extension of the Tornquist Zone in the Norwegian North Sea. Norsk Geologisk Tidsskrift 64, 39–68.

Pharaoh, T.C., 1999. Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review. Tectonophysics 314, 17–41.

Phillips, J.D., 1979. ADEPT: A program to estimate depth to magnetic basement from sample magnetic profiles. U.S. geol Surv. open-file report 79–367. 35 pp.

Ramberg, I.B., 1976. Gravity interpretation of the Oslo Graben and associated igneous rocks. Norges geologiske undersøkelse Bull. 325 (194 pp.).

Ramberg, I.B., Smithson, S.B., 1971. Gravity interpretation of the southern Oslo Graben and adjacent Precambrian rocks, Norway. Tectonophysics 11, 419–431.

Ramberg, I.B., Smithson, S.B., 1975. Geophysical interpretation of crustal structure along the southeastern coast of Norway and Skagerrak. Geological Society of America Bulletin 86, 769–774.

Rasmussen, L.B., 1974. Some geological results from the first five Danish exploration wells in the North Sea. Geological Survey of Denmark III (series 42) (46 pp.).

Reid, A.B., Allsop, J.M., Granser, H., Millett, A.J., Sommerton, I.W., 1990. Magnetic interpretation in three dimensions using Euler deconvolution. Geophysics 55, 80–91.

Ro, H.E., Stuevold, L., Faleide, J.I., Myhre, A.M., 1990. Skagerrak Graben—the offshore continuation of the Oslo Graben. Tectonophysics 178, 1–10.

Robinson, P., Harrison, R.J., McEnroe, S.A., Hargraves, R., 2002. Lamellar magnetism in the hematite–ilmenite series as an explanation for strong remanent magnetization. Nature 418, 517–520.

Scherstén, A., Årebäck, H., Cornell, D., Hoskin, P., Åberg, A., Armstrong, R., 2000. Dating mafic–ultramafic intrusions by ion-microprobing contact-melt zircon: examples from SW Sweden. Contributions to Mineralogy and Petrology 139, 115–125.

Schiellerup, H., Lambert, D.D., Prestvik, T., Robins, B., McBride, J.S., Larsen, R.B., 2001. Re–Os isotopic evidence for a lower crustal origin of massif-type anorthosites. Nature 405, 781–784.

Sellevoll, M.A., Aalstad, I., 1971. Magnetic measurements and seismic profiling in the Skagerrak. Marine Geophysical Researches 1, 284–302.

Sharma, P.V., 1970. Geophysical evidence for a buried volcanic mount in the Skagerrak. Bulletin of Geological Society of Denmark 19, 368–377.

Sigmond, E.M.O., 1985. The Mandal–Ustaoset line, a newly discovered major fault zone in South Norway. In: Tobi, A.C., Touret, J.L.R. (Eds.), The Deep Proterozoic Crust in the North Atlantic Provinces. D. Reidel Publishing, pp. 323–331.

Sindre, A., 1992. Regional tolkning av geofysiske data, kartblad Arendal, M 1:250,000. NGU Report 92.213. 30 pp.

Sindre, A., 1993. Tolkning av magnetometri og gravimetri i Skagerrak, kartblad Arendal, M 1:250,000. NGU Report 93.114. 11 pp.

Skilbrei, J.R., Kihle, O., Olesen, O., Gellein, J., Sindre, A., Solheim, D., Nyland, B., 2000. Gravity anomaly map Norway and adjacent ocean areas, scale 1:3 million. Norges geologiske undersøkelse, Trondheim.

Skilbrei, J.R., Olesen, O., Osmundsen, P.T., Kihle, O., Aaro, S., Fjellanger, E., 2002. A study of basement structures and some onshore–offshore correlations in Central Norway. Norsk Geologisk Tidsskrift 82, 263–279.

Smelror, M., Cocks, L.R.M., Mørk, A., Neuman, B.E.E., Nakrem, H.A., 1997. Upper Ordovicium–Lower Silurian strata and biota from offshore Norway. Norsk Geologisk Tidsskrift 77, 251–268.

Smethurst, M.A., 1994. Viking-93 Aeromagnetic Survey: Interpretation Report, NGU Report, vol. 94.011. 32 pp.

Smithson, S.B., 1963. Granite studies: I. A gravity investigation of two Precambrian granites in South Norway. Norges geologiske undersøkelse 214B, 53–140.

Smithson, S.B., Barth, T.F.W., 1967. The Precambrian Holum granite, South Norway. Norsk Geologisk Tidsskrift 47, 21–56.

Smithson, S.B., Ramberg, I.B., 1979. Gravity interpretation of the Egersund anorthosite complex, Norway: its petrological and geothermal significance. Geological Society of America Bulletin 90, 199–204.

Sørensen, K., 1986. Danish Basin subsidence by Triassic rifting on a lithosphere cooling background. Nature 319, 660–663.

Sørensen, S., Morizot, H., Skottheim, S., 1992. A tectonostratigraphic analysis of the southeast Norwegian North Sea Basin. In: Larsen, R.M., Brekke, H., Larsen, B.T., Talleraas, E. (Eds.), Structural and Tectonic Modelling and its Application to Petroleum Geology. Norwegian Petroleum Society (NPF), Elsevier, Amsterdam, pp. 19–42.

Starmer, I.C., 1991. The Proterozoic evolution of the Bamble Sector shear belt, southern Norway: correlations across southern Scandinavia and the Grenvillian controversy. Precambrian Research 49, 107–139.

Storetvedt, K.M., 1968. The permanent magnetism of some basic intrusions in the Kragerø archipelago, S. Norway, and its geological implications. Norsk Geologisk Tidsskrift 48, 153–163.

Strykowski, G., 2000. Silkeborg gravity high revisited: horizontal extension of the source and its uniqueness. Physical Chemistry Earth 25, 375–380.

Sundvoll, B., Larsen, B.T., 1994. Architecture and early evolution of the Oslo Rift. Tectonophysics 240, 173–189.

Swain, C.J., 1976. A Fortran IV program for interpolating irregularly spaced data using the difference equations for minimum curvature. Computers and Geosciences 1, 231–240.

Thompson, D.T., 1982. EULDPH: a new technique for making computer-assisted depth estimates from magnetic data. Geophysics 47, 31–37.

Thorning, L., Abrahamsen, N., 1980. Palaeomagnetism of Permian multiple intrusion dykes in Bohuslän, SW Sweden. Geophysical Journal of the Royal Astronomical Society 60, 163–185.

Thybo, H., 1997. Geophysical characteristics of the Tornquist Fan area, northwest Trans-European Suture Zone: indication of late Carboniferous to early Permian dextral transtension. Geological Magazine 134, 597–606.

Thybo, H., 2000. Crustal structure and tectonic evolution of the Tornquist Fan region as revealed by geophysical methods. Bulletin of the Geological Society of Denmark 46, 145–160.

Thybo, H., 2001. Crustal structure along the EGT profile across the Tornquist Fan interpreted from seismic, gravity and magnetic data. Tectonophysics 334, 155–190.

Thybo, H., Schönharting, G., 1991. Geophysical evidence for Early Permian igneous activity in a transtensional environment, Denmark. Tectonophysics 189, 193–208.

Torsvik, T.H., 1992. IMP5—Interactive Modelling of Potential Field Data (Release 5), NGU Report, vol. 92.305. 75 pp.

Torsvik, T.H., Rehnström, E.F., 2003. The Tornquist Sea and Baltica–Avalonia docking. Tectonophysics 362, 67–82.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A., Walderhaug, H.J., 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic: a tale of Baltica and Laurentia. Earth Science Reviews 40, 229–258.

Torsvik, T.H., Eide, E.A., Meert, J.G., Smethurst, M.A., Walderhaug, H.J., 1998. The Oslo Rift: new palaeomagnetic and ^{40}Ar/^{39}Ar age constraints. Geophysical Journal International 135, 1045–1059.

Van Everdingen, R.O., 1960. Studies on the igneous rock complex of the Oslo Region: XVII. Palaeomagnetic analysis of the Permian extrusives in the Oslo Region, Norway. Skrifter Norske Videnskaps Akademi Oslo 1 (80 pp.).

Vejbæk O.V., Britze, P., 1994. Geological map of Denmark 1:750,000. Danmarks Geologiske Undersøgelse 45. 8 pp.

Walderhaug, H.J., Torsvik, T.H., Eide, E.A., Sundvoll, B., Bingen, B., 1999. Geochronology and palaeomagnetism of the Hunnedalen dykes, SW Norway: implications for the Sveconorwegian–Grenvillian apparent polar wander loop. Earth Planetary Science Letters 169, 71–83.

Williamson, J.P., Pharaoh, T.C., Banka, D., Thybo, H., Laigle, M., Lee, M.K., 2002. Potential field modelling of the Baltica–Avalonia (Thor–Tornquist) suture beneath the southern North Sea. Tectonophysics 360, 47–60.

Wonik, T., Galdéano, A., Hahn, A., Mouge, P., 1992. Magnetic anomalies. In: Blundell, D., Freeman, R., Mueller, S. (Eds.), A Continent Revealed, The European Geotraverse, Atlas of Compiled Data. Cambridge Univ. Press, Cambridge, pp. 31–34.

Zhou, S., Thybo, H., 1996. Calculation of residual gravity anomalies in Northern Jutland, Denmark. First Break 14, 129–134.

Zhou, S., Thybo, H., 1997. Pre-Zechstein geology of the south-east North Sea, offshore Denmark—a geophysical perspective. First Break 15, 387–395.

Ziegler, P.A., 1990. Tectonic and palaeogeographic development of the North Sea Rift System. In: Blundell, D.J., Gibbs, A.D. (Eds.), Tectonic Evolution of the North Sea Rifts. Oxford Univ. Press, pp. 1–36.