Aspects of the geology of the southwestern Barents Sea from aeromagnetic data.

JAN REIDAR SKILBREI

Jan Reidar Skilbrei, Geological Survey of Norway, P.O. Box 3006-Lade, N-7002 Trondheim, Norway.

Introduction

NGU has covered large parts of the Barents Sea and Svalbard with aeromagnetic measurements. The Barents Sea holds oil and gas potential and forms one of the largest continental shelf areas in the world. The magnetic studies carried out in this region include the mapping of volcanic rocks on Svalbard and in the northern Barents Sea, and the mapping of major basement faults and estimation of the depth to the magnetic basement. Such studies are of substantial value in petroleum exploration work. NGU has delivered confidential reports to the oil companies that financed the interpretation work. Portions of that work have already been published (Skilbrei, 1991, 1992). This abstract focuses on two, previously unpublished examples that serve to illustrate *some* of the applications of the magnetic method.

Example 1: Mapping the top of the crystalline crust in the southwestern Barents Sea.

Several structural highs and sedimentary basins within the southwestern Barents Sea (70°-74°N) are bordered by major fault complexes (e.g. Rønnevik & Jacobsen 1984, Faleide et al. 1993). The basinal areas are underlain by large thicknesses of Upper Palaeozoic to Cenozoic rocks.

The aim of this study has been to map the top of the crystalline basement, using all available data. Neither magnetic data alone nor released gravity or reflection seismic profiles can be used to map the deeply buried crystalline basement. Fortunately, exploration for oil has provided a dense network of seismic reflection data, as well as 47 exploration wells from the area (NPD, 1986-1992). A combination of methods allows one to construct a tentative regional depth map. Depth estimates were made on the original aeromagnetic profiles (the straight slope and Peters methods were used). The wells are unevenly distributed and only three have reached the basement. They therefore provide only minimum depths to the basement surface from a part of the area. Seismic data and gravity data have been used to obtain tentative depths from the deep basins. The data sets have been described in a dr.ing. thesis (Skilbrei 1993, chapter 8). The depth map is an aid in elucidating the general structure of the area and provides insights into the deep structure of a rifted region.

Fig. 1 shows the map of depths to the crystalline basement which is derived from all available sources. The figure legend shows which data sets have been the basis for the contours in the different parts of the map. It is important to note that only in some of the areas are the contours drawn solely from the magnetic depth estimates, and that the map is a smoothed, generalised map. Locally (along the deep-seated fault zones that form some of the margins of the structural highs), the basement surface may be much steeper. Before contouring, the magnetic depth estimates were compared, where possible, with seismic data and well data. In this manner, an attempt was made to differentiate between intrasedimentary volcanic sources and basement sources. In the eastern part of the study area, only the magnetic depth estimates are shown, because neither the point distributions of these nor the seismic data would allow contouring.

A large portion of the study area is occupied by basins, some of which are extremely deep rift basins. As can be seen in Fig. 1, the continental crust is fragmented and divided into blocks by several highs and basins that are the result of different rifting events (e.g. Faleide et al. 1984, 1991, 1993). An appropriate name for this tectonic region would therefore be the 'Southwestern Barents Sea Rift Zone'. The structural elements that can be recognised on the map in Fig. 1 are: the Nordkapp, Hammerfest, Tromsø, Bjørnøya, Sørvestnaget and Harstad Basins, the Loppa, Stappen, Nordsel, Veslemøy and Senja Highs, as well as the shallow magnetic basement close to the Norwegian coast. In structural highs, the depths shown in Fig. 1 are similar to the depths that appear in a magnetic basement map that was published by Åm (1975). However, from the deep basins, there is a marked difference. This difference arises because of the lack of magnetic anomalies from the deep basins (and thereby no *magnetic* depth estimates), and because seismic and gravity data are now available. From the deep basins, gravity and reflection seismic data were used to obtain tentative depths to the *crys-*

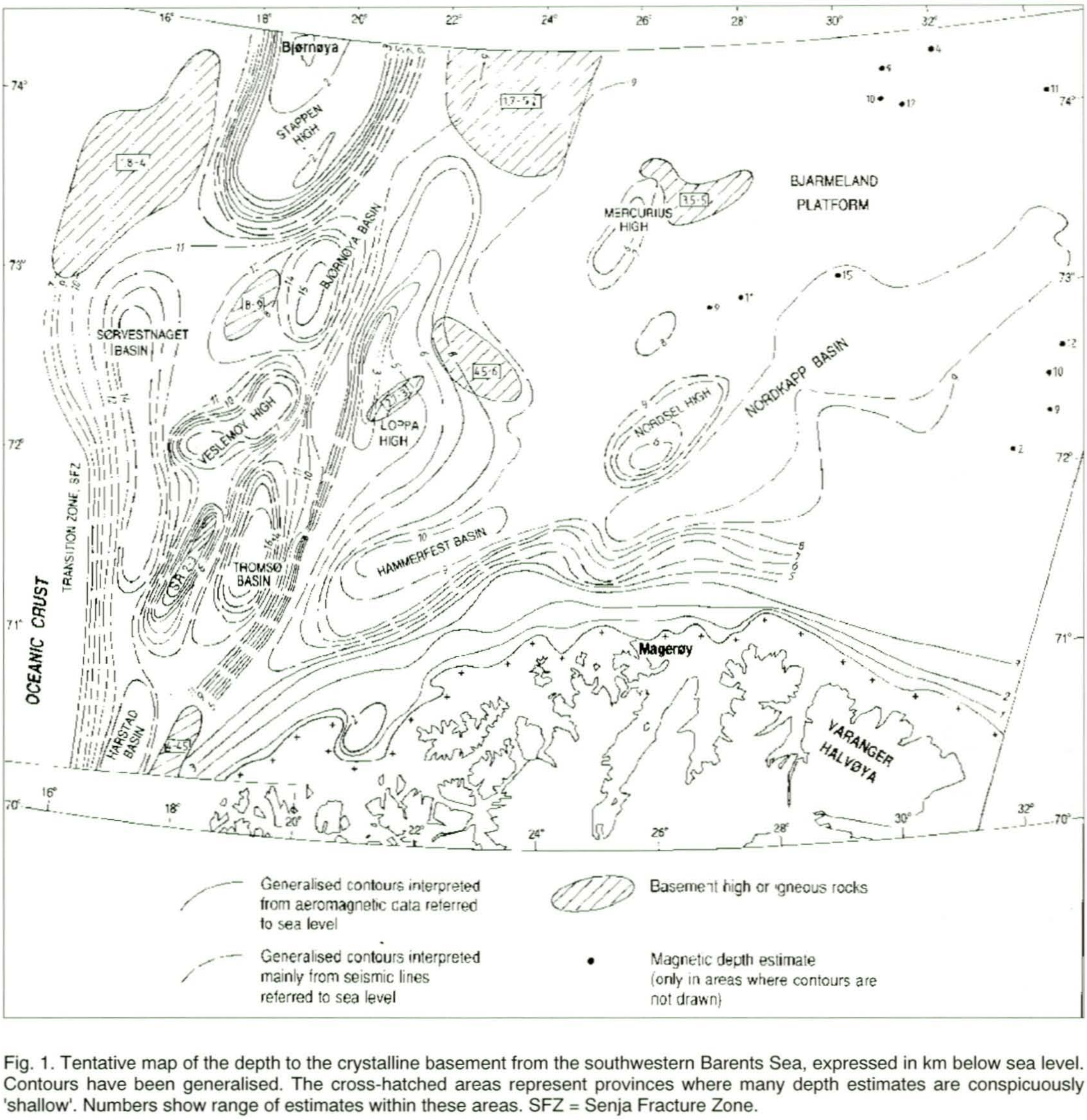

Fig. 1. Tentative map of the depth to the crystalline basement from the southwestern Barents Sea, expressed in km below sea level. Contours have been generalised. The cross-hatched areas represent provinces where many depth estimates are conspicuously 'shallow'. Numbers show range of estimates within these areas. SFZ = Senja Fracture Zone.

talline basement. From the southern parts of the map, the depths are very similar to the depths that appear in a magnetic basement map published by Olesen et al. (1990) that covers Finnmark and the adjacent sea areas.

Also of interest are relatively small areas where the shallow estimates may indicate either basement blocks at relatively shallow depths, or the presence of igneous rocks within the sedimentary rocks overlying the crystalline basement (Fig. 1). The high area on the map southwest of Bjørnøya represents Tertiary volcanic rocks within the Vestbakken Volcanic Province (Faleide et al. 1988). Low-amplitude aeromagnetic anomalies occur over the Senja Ridge (SR). The magnetic depth estimates beneath the SR range from 1.8 km (in the north) to 2.8 km (in the south). The magnetic sources may represent crystalline basement or volcanic intrusions. On the Loppa High, on the landward side of the Harstad Basin, on the SR, and north of Varangerhalvøya, it is likely that the basement is relatively shallow. In the other cases shown, intrasedimentary volcanic rocks may be present (see discussion below). In the case of the area marked to the west of the deepest part of the Bjørnøya Basin, these sources occur relatively deep within the sedimentary basin (c. 8 km). On the east side of the Harstad Basin, magnetic sources occur at 4-4.5 km depth. This is within the Cretaceous sedimentary sequence. The magnetic sources probably represent volcanic rocks (basalts?).

Magnetic depth determinations performed on the analog profiles showed some conspicuously shallow values in the northern part of the study area. The estimated depths were compared with published reflection seismic profiles (Gabrielsen et al. 1990). Apparently, magnetic sources exist within both the Carboniferous-Permian and the Mesozoic sequences. No volcanic rocks are known from the boreholes. However, the shallow estimates are located to the north of the wells. On Spitsbergen (Svalbard) and in Storfjorden, there are high-frequency magnetic anomalies that are probably due to the presence of dolerites occurring high up in the sedimentary section, far removed from the basement. The Carboniferous period is associated with rifting throughout the entire region (Ziegler 1988), and this may well have involved some volcanic activity. On Magerøy (North Finnmark), a dolerite dyke of a Late Carboniferous age has been reported (Roberts et al. 1991). On the Russian Barents Sea shelf, the Triassic strata are associated with lava units that give rise to magnetic anomalies northeast of Hopen (unpublished map, Amarok Inc., Oslo). Also, Permian strata in the Timan-Pechora and South Barents Basins, northwestern Russia, are known to contain volcanic rocks. On the basis of the above discussion, magnetic sources within the sediments may be due to volcanic activity associated with the Late Palaeozoic rifting that affected the whole region. The shallowest sources probably represent dolerites of Late Jurassic/Early Cretaceous age and/or Triassic rocks. (In addition, Tertiary volcanic rocks occur along the western margin).

Example 2: Mapping the continent-ocean boundary

A particular fruitful area of investigation is the continental margin. After image enhancement of the aeromagnetic data, the transition zone between the continental crust and the oceanic crust displays a distinct magnetic anomaly signature. The following example is from the southwestern Barents Sea where the Senja Fracture Zone (SFZ) approximates to the continent-ocean boundary (COB). A thick, Upper Cenozoic, sedimentary wedge covers the COB. Because of this, and because few seismic lines actually cross the COB, the location and nature of the COB is not well known. In order to compare with earlier interpretations, all the information appearing in NPD Bulletin No. 6 (Gabrielsen et al. 1990) was digitised (at a scale of 1:1 million) and

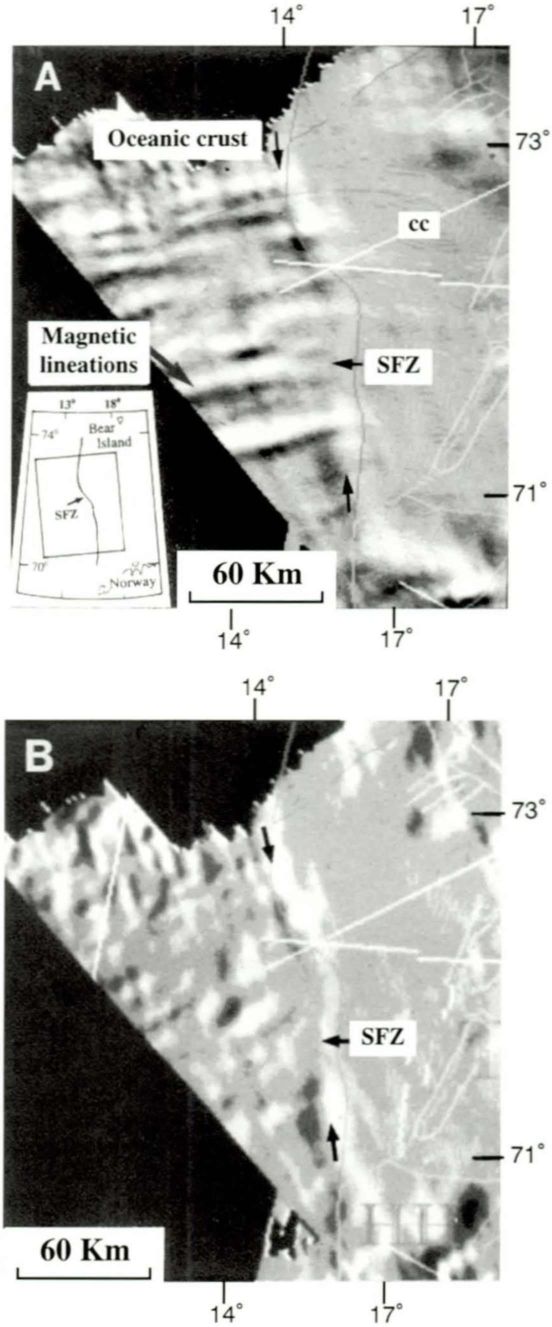

Fig. 2. Grey scale, shaded relief versions of aeromagnetic data covering the Senja Fracture Zone (SFZ) in the southwestern Barents Sea. In Fig. 2a, the relief is obtained using an artificial sun direction from the north; in Fig. 2b, the image is 'illuminated' from the east. On the left side of the image in Fig. 2a, there are well defined, sea floor spreading, magnetic lineations. See text for explanation.

studied, in combination with gravity and magnetic images, on an image analysis system.

Grey scale, shaded relief versions of aeromagnetic data covering the southwestern Barents Sea are shown in Fig. 2. In Fig. 2a, the relief is obtained using an artificial sun direction from the north; in Fig. 2b, the image is 'illuminated' from the east. On the left side of the image (Fig. 2a), well defined magnetic bands occur, caused by sea floor spreading. This pattern terminates abruptly in the middle part of the figure. The line of termination strikes roughly NNW-SSE and is curvilinear. There is a regional magnetic low on the eastern side of this feature. A magnetic gradient occurs along the above-mentioned curvilinear feature. The magnetic gradient stands out more clearly in Fig. 2b, where the image is illuminated from the east. The gradient is marked with arrows. It arises from the contrast in magnetisation between the oceanic crust (west) and the continental crust (east). The continent-ocean transition zone is thus interpreted to occur along a relatively narrow zone as defined by: (i) termination of magnetic lineations (Fig. 2a), and (ii) a curvilinear magnetic gradient (Fig. 2b). Additional support for this interpretation comes from the fact that the maximum gradient in gravity data also runs along this gradient (Skilbrei et al. 1990, 1991). In Figs. 2a & 2b, the lines represent digitised geology (from Gabrielsen et al. 1990). The continuous line along the SFZ represents the COB as interpreted by Gabrielsen et al. (1990). The magnetic data show that the COB actually is situated up to 20 km from the continuous line. In the southern part of the SFZ, a magnetic anomaly occurs along the zone indicating that volcanic rocks may occur along segments of the SFZ.

Conclusions

By combining aeromagnetics, gravity, well data and seismic data, it was possible to obtain a tentative map of the depths to the crystalline basement in the southwestern Barents Sea. The magnetic basement depths vary from 2-3 km to 5-6 km on the structural highs in the southwestern Barents Sea, after removal of the shallowest estimates thought to be due to volcanic rocks. (The results were checked with well data and seismic data). The basins are very deep over wide areas (>10 km). The depth map indicates that there is only very thin crystalline crust left beneath the Bjørnøya, Sørvestnaget and Tromsø Basins.

Comparison of aeromagnetic depth estimates and seismic lines showed that volcanic rocks probably occur within the sediments overlying the crystalline crust in the southwestern Barents Sea. This is the first report of possible intrasedimentary volcanic rocks from this area (except for Tertiary volcanics that are known to be present southwest of Bear Island). Sources probably occur within the Late Palaeozoic successions. The shallowest sources probably represent dolerites of Late Jurassic/Early Cretaceous age and/or Triassic rocks.

The distinct aeromagnetic signature along the Senja Fracture Zone (SFZ) allows a more precise mapping of the continent-ocean transition zone than has been achieved by reflection seismic data. It is possible that subvolcanic intrusions occur along segments of the SFZ.

References

Faleide, J.I., Gudlaugsson, S.T. & Jacquart, G. 1984: Evolution of the western Barents Sea. *Marine Petrol. Geol. 1*, 123-150.

Faleide, J.I., Myhre, A.M., & Eldholm O. 1988: Early Tertiary volcanism at the western Barents Sea margin. *In* Morton A.C. & Parson L.M. (eds.), Early Tertiary Volcanism and the Opening of the NE Atlantic. *Geol. Soc. Special Publ. 39*, 135-146.

Faleide, J.I., Gudlaugsson, S.T., Eldholm, O., Myhre, A.M. & Jackson, H.R. 1991: Deep seismic transects across the western Barents Sea. *Tectonophysics 189*, 73-89.

Faleide, J.I., Vågnes, E. & Gudlaugsson, S.T. 1993: Late Mesozoic-Cenozoic evolution of the southwestern Barents Sea in a regional rift-shear tectonic setting. *Marine Petrol. Geol. 10*, 186-214.

Gabrielsen, R.H., Færseth, R.B., Jensen, L.N., Kalheim, J.E. & Riis, F. 1990: Structural elements of the Norwegian continental shelf. Part I: The Barents Sea Region. *Norw. Petrol. Dir. Bull. 6*, 33 pp.

Norwegian Petroleum Directorate, 1986-1992: Well data summary sheets, vol. 12-23. *Norw. Petrol. Dir., Stavanger.*

Olesen, O., Roberts, D., Henkel, H., Lile, O.B. & Torsvik, T.H. 1990: Aeromagnetic and gravimetric interpretation of regional structural features in the Caledonides of West Finnmark and North Troms, Northern Norway. *Nor. geol. unders. Bull. 419*, 1-24.

Roberts, D., Mitchell, J. G. & Andersen, T. B. 1991: A post-Caledonian dolerite dyke from Magerøy, North Norway: age and geochemistry. *Nor. Geol. Tidsskr. 71*, 289-294.

Rønnevik, H.C. & Jacobsen, H.P. 1984: Structures and basins in the western Barents Sea, *In* Spencer A.M. (ed.), *Petroleum Geology of the North European Margin*. Graham and Trotman, London, 19-32.

Skilbrei, J.R., Faleide, J.I. & Myklebust, R. 1990: Magnetic anomalies and regional geology of the Barents Sea. Paper presented in Tromsø, Norway, 15-17 August 1990: *International conference on Arctic Geology and Petroleum Potential. Abstracts Volume*, p. 18.

Skilbrei, J.R. 1991: Interpretation of depth to the magnetic basement in the northern Barents Sea (south of Svalbard). *Tectonophysics 200*, 127-141.

Skilbrei, J.R., Håbrekke, H., Olesen, O., Kihle, O. & Macnab, R. 1991: Shaded relief aeromagnetic colour map of Norway and the Norwegian-Greenland and Barents Seas: Data compilation and examples of interpretation. *Nor. geol. unders. report 91.269*, 15 pp.

Skilbrei, J.R. 1992: Preliminary interpretation of aeromagnetic data from Spitsbergen, Svalbard Archipelago (76°-79° N): Implications for structure of the basement. *Marine Geol. 106*, 53-68.

Skilbrei, J.R. 1993: *An evaluation of magnetic basement depth determinations from the southwestern Barents Sea. (Chapter eight)*. Doktor ingeniøravhandling 1993:68. Norges tekniske høgskole, Trondheim.

Ziegler, P.A. 1988: Evolution of the Arctic-North Atlantic and the western Tethys. *Amer. Assoc. Petrol. Geol. Mem. 43*, 198 pp. and 30 plates.

Åm, K. 1975: Aeromagnetic basement complex mapping north of latitude 62°N, Norway. *Nor. geol. unders. 316*, 351-374.