

Depth and configuration of the crystalline basement in the Viking Graben area, Northern North Sea

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Abstract: The depth of the crystalline basement in the Viking Graben area has been mapped. The dominant structural feature in the study area is a N–S trending zone approximately 150 km wide, containing a variety of structures (graben, basins and structural highs) and named the ‘Northern North Sea Rift Zone’. The Viking Graben is only one structural element, though a major one, in this zone. The following depth ranges appear to apply: (a) on platforms, basement shelves and major structural highs (1–3 km), (b) in basins (7–9 km maximum depth), (c) in graben (8–10 km maximum depth).

The Viking Graben is situated in the northern North Sea, approximately half-way between the Norwegian mainland and the Shetland Islands. Depth-to-basement data are here presented for a larger ‘Viking Graben area’, situated between 58° and 62°N, and 0° and 6°E (Fig. 1). The study area (Fig. 2) comprises the following main structural elements: the East Shetland Platform (in part), the East Shetland Basin, the Viking Graben (continuing towards the north into the Sogn Graben), the Horda Platform, the Ling Graben, the Sele High, the Egersund Sub-basin, and two major fault zones: the Øygarden and Horda Fault Zones. In addition, a number of smaller tectonic elements occur.

Two major episodes of rifting appear to have occurred in the Viking Graben area, the first in Permo-Triassic times, the second in Middle Jurassic to Early Cretaceous times (Ziegler 1982; Glennie 1984; Giltner 1987; Badley *et al.* 1988). Between these active rift phases a compressional pulse may have occurred (Frost 1987). The graben developed between rift phases and in the tectonically quiet final phase by more gradual (thermal) subsidence and the deposition of substantial thicknesses of sediment.

The study area is underlain by Caledonian crystalline basement rocks (Frost *et al.* 1981; Ziegler 1982). Mapping this crystalline basement is not simple. Neither well data alone nor released data from one single geophysical method (magnetic, gravity or reflection seismic profiles) can achieve this. However, a combination of methods allows one to arrive at a reliable regional depth map. Such a map is of invaluable assistance in the gravity modelling of the Moho (Fichler & Hospers 1990a), as well as in the interpretation of deep seismic reflection data (Fichler & Hospers 1990b). In addition, the results provide insights into the regional deep structure of a rifted basin.

Data used

The following data sets have been evaluated. (1) *The tectonic map of the North Sea* prepared by Hamar (1979) using released and confidential petroleum industry data. (2) Selected released well data from the UK sector (Department of Energy 1984) and the Norwegian sector (Norwegian Petroleum Directorate 1976–1985, 1986a). The locations of these 175 wells are shown in Fig. 3. The majority of these wells are situated in the UK sector. They are evenly

distributed and are, as such, satisfactory for use in the present regional study. However, the wells situated in the Norwegian sector are unevenly distributed. Accordingly, newer wells there (Norwegian Petroleum Directorate 1986b, 1987, 1988) have been reviewed. These numerous new wells show no discrepancies with the interpretation presented in Fig. 4, except that the northern part of the Utsira High (cf. Fig. 2) may be somewhat shallower than shown. (3) Aeromagnetic and marine magnetic data as compiled and interpreted by Hospers & Ediriweera (1988). (4) Gravity data as compiled and interpreted by Hospers & Finnstrøm (1984) for the Norwegian sector of the North Sea and by Hospers *et al.* (1985) for a major part of the northern North Sea. (This is the only data set which has not actually been used, for reasons given below.) (5) Ten conventional seismic reflection sections (maximum displayed two-way travel time 6 or 7 s) made available by Statoil, Stavanger and four deep seismic reflection sections (maximum displayed two-way travel time 15 s). The latter sections are the NSDP-84 data

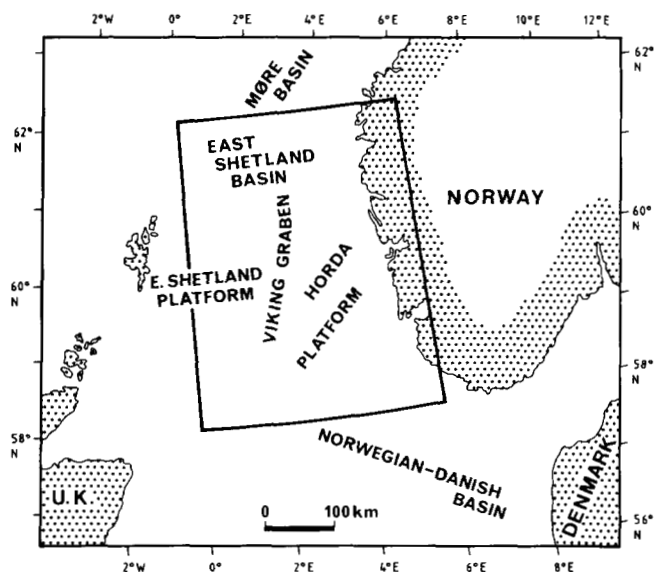


Fig. 1. Map showing the position of the study area (58°–62°N, 0°–6°E)

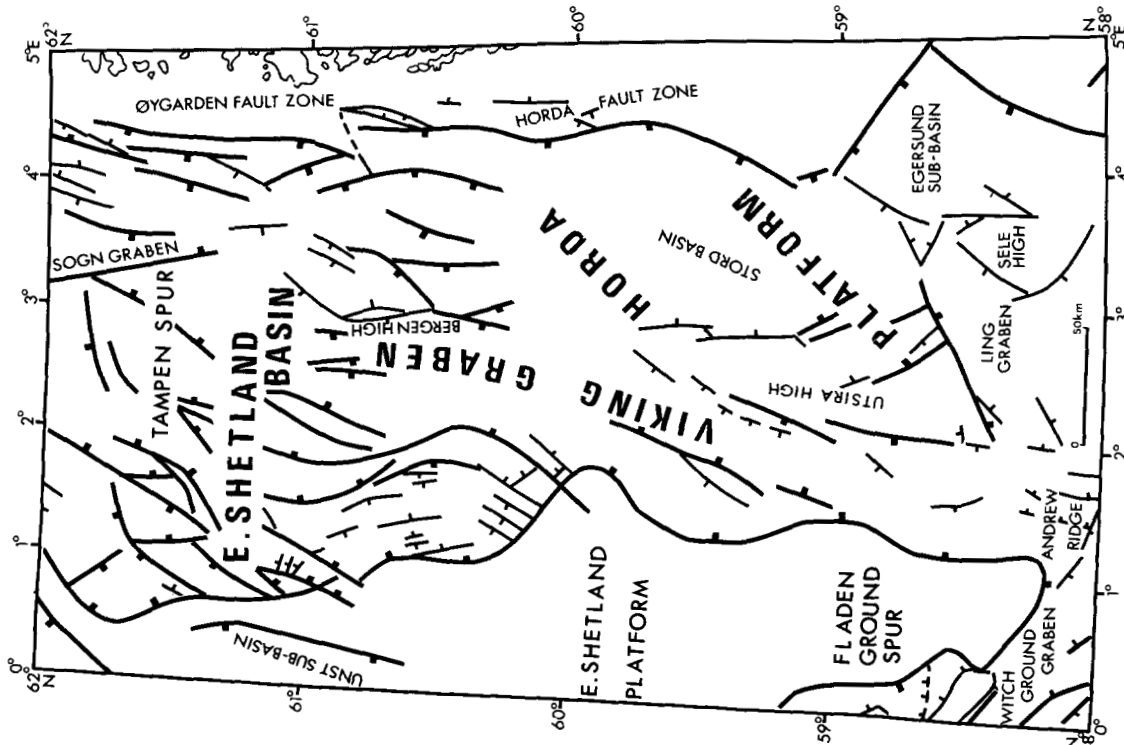


Fig. 2. Tectonic map of the Viking Graben area (here only shown to 5°E), redrawn from Hamar (1979).

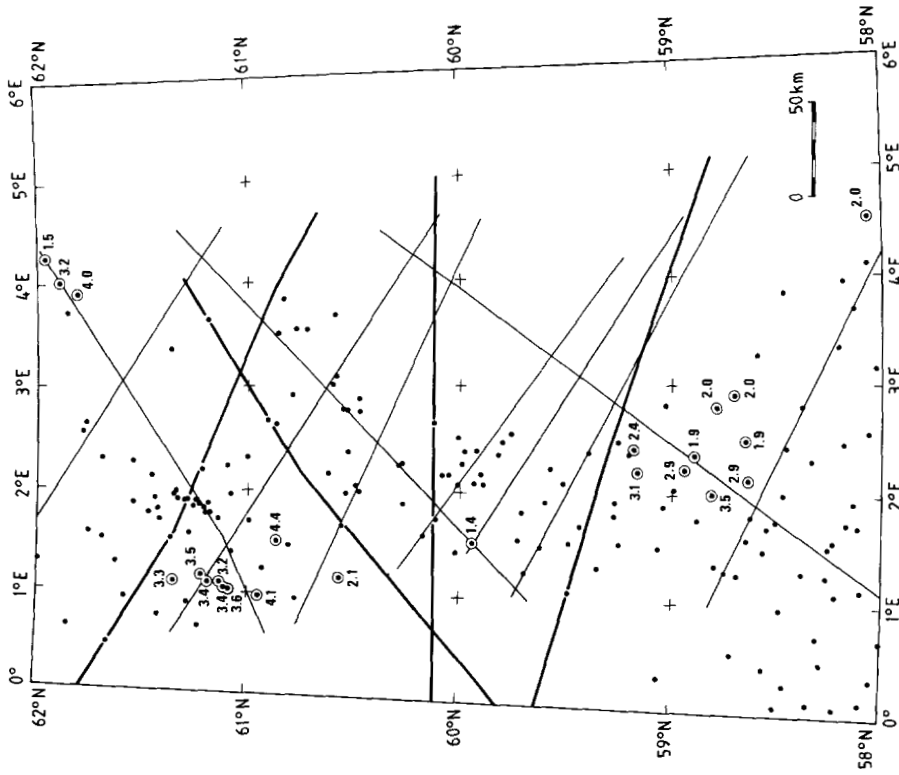


Fig. 3. Locations of wells and seismic reflection profiles used in this study. Wells which reached the crystalline basement have been circled; depths to basement are quoted in kilometres below mean sea level. (For a more detailed description of these well data, see Hospers & Ediriweera (1988)). Thin lines represent the ten conventional seismic reflection profiles (Statoil, lines SL 805201-805203 (incl.) and SL 805401-805407 (incl.)), thick lines the four deep profiles (NSDP-84), described in the text. (Norwegian coast line omitted).

set which is now in the public domain (for details, see Klemperer, 1988). The location of these lines is shown in Fig. 3. (6) Information gleaned from the literature presenting detailed studies of areas of limited extent.

Interpretation of the data

The tectonic map (Fig. 2) is based mainly on proprietary conventional seismic reflection data, and has been used as a general guide to the regional structure of the study area. The well data by themselves do not allow an independent map of the crystalline basement to be made, but are extremely useful when used in conjunction with magnetic and seismic reflection data.

The magnetic data and their interpretation have been discussed earlier by Hospers & Ediriweera (1988). These authors made a compilation of four different data sets which nearly cover the whole study area. The line spacing for these data is *c.* 2 km in the UK sector of the North Sea and *c.* 4 km in the Norwegian sector. Their result (Hospers & Ediriweera 1988, fig. 6) gives a fair regional picture of the depth and configuration of the crystalline basement in the study area. This result has been used as a general guide to the deeper structure of the study area, particularly in its

extreme southern and southeastern parts where seismic data are scarce.

The gravity data did not contribute independent, non-redundant information on the depth and configuration of the crystalline basement in the study area. This applies to all forms in which the gravity data are presented: as Bouguer or residual anomalies (Hospers *et al.* 1985) or as free-air anomalies (Ediriweera 1988; Fichler & Hospers 1990a). The principal reason for this is that the main structural elements in the study area are approximately in isostatic equilibrium. This means that the gravity effect of the light sedimentary fill of basins and grabens is very nearly cancelled by the gravity effect of the corresponding isostatic compensation at depth. Only features which are too small to be locally compensated can be detected by gravity data alone (Donato & Tully 1981; Hospers & Finnstrøm 1984; Hospers *et al.* 1985). In the present context this information is redundant as it can be obtained more accurately from the tectonic map (Fig. 2).

The seismic reflection data provide information on a regional grid (Fig. 3). On the flanks of the basins, where the basement lies at relatively shallow depths, the basement reflection is usually strong and can be identified by the use of well data, by seismic correlations along or between

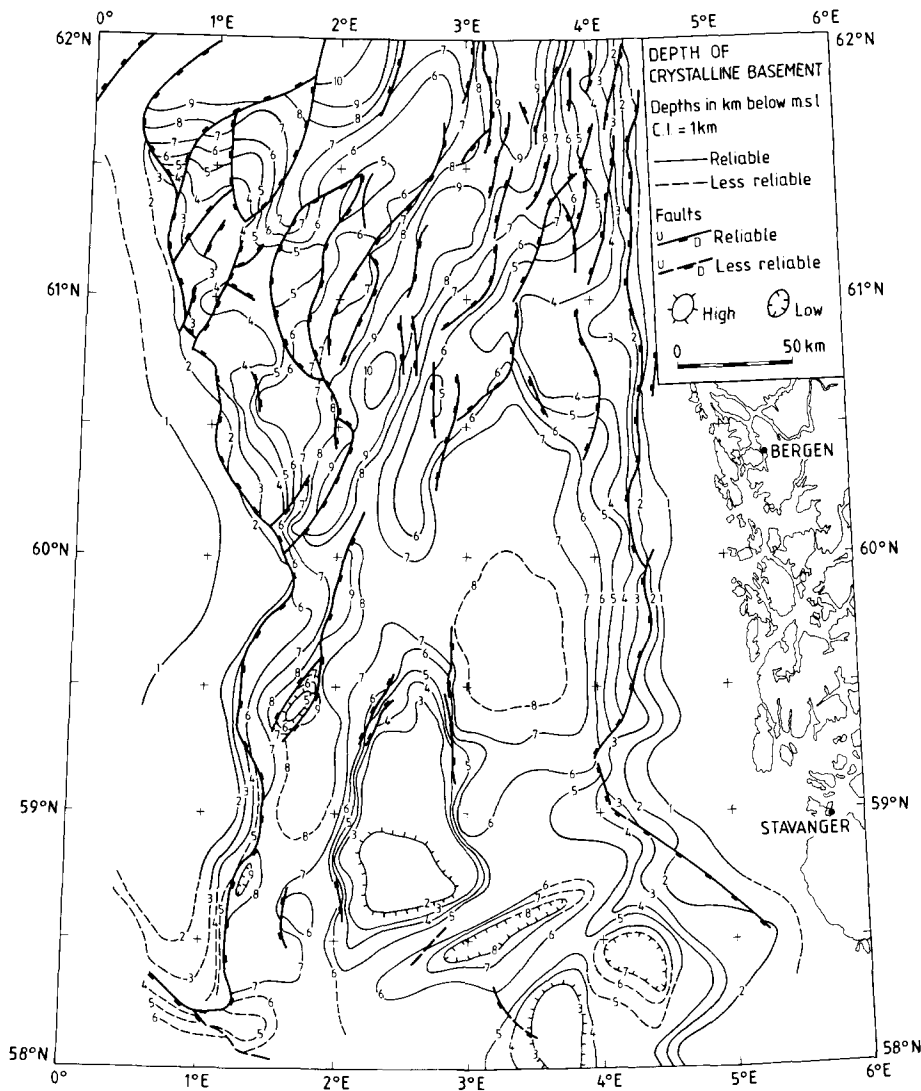


Fig. 4. Map of depths of the top of the crystalline basement in the study area, expressed in km below mean sea level.

seismic sections, or by means of the earlier map based on magnetic and well data (Hospers & Ediriweera 1988). Available velocity analyses on the seismic sections and/or well data then enable one to convert reflection times to depths of the crystalline basement.

In the deeper parts of the basins, the reflection from the top of the crystalline basement is often difficult to recognize. This is a result of a decrease in the contrast in acoustic impedance between sediments and basement at greater depths, as well as a decrease in the signal-to-noise ratio. In such instances, basement depths have to be found by extrapolation from or interpolation between basin flanks, using whatever seismic reflection evidence is available and by using the earlier map by Hospers & Ediriweera (1988) as a guide. Seismic migration does not appear to be necessary, given the regional scale of the mapping effort and other uncertainties in picking reflections and depth conversion. The fault pattern shown on the depth-to-basement map is based on evidence from the seismic data used here, as well as the fault pattern shown by Hamar (1979).

The published literature has only contributed in a minor way to the map (Fig. 4). Some information on the depth of the basement was obtained from Birtles (1986), Wheatley *et*

al. (1987), Speksnijder (1987) and Biddle & Rudolph (1988).

Discussion of results

Major structural elements that can be recognized on the map (Fig. 4) are (cf. Fig. 2): the East Shetland, Stord and Møre Basins, the Viking, Sogn and Ling Grabens, the Utsira, Sele and Bergen Highs, the East Shetland Platform, the Egersund Sub-basin, a shallow basement shelf off the Norwegian mainland, and the Øygarden and Horda Fault Zones. The following depth ranges appear to apply: (a) on platforms, basement shelves and major structural highs (1–3 km), (b) in basins (7–9 km maximum depth); (c) in graben (8–10 km maximum depth).

The configuration of the relatively high and low crustal tracts in Fig. 4 can be accentuated by emphasizing depths of less than 3 km and more than 7 km. This is shown in Fig. 5. It is obvious from this figure that, in the study area, one does not find only the Viking and Sogn Graben in an otherwise unaffected crust. On the contrary, the dominant structural feature is a N–S trending zone, approximately 150 km wide, containing a variety of structures (graben, basins and structural highs), some of which are oblique to the zone boundaries. To the west this zone is limited by the eastern boundary faults of the East Shetland Platform, situated at about 1°E. To the east the zone is limited by the Øygarden and Horda Fault Zones, situated at about 4°E. The Horda Platform (cf. Fig. 2) is not a major shallow basement platform analogous to the East Shetland Platform, as originally defined by Rønnevik *et al.* (1975). The basement configuration (Figs 4 and 5) reflects the presence of a high (the Utsira High) and a basin (the Stord Basin) within this so-called platform area.

This major tectonic zone in the study area is inadequately described by the name 'Viking Graben', as this name only refers to one of many structural features present. Therefore the tectonic zone, discussed here and illustrated in Figs 4 and 5, is named 'Northern North Sea Rift Zone'.

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References

- BADLEY, M. E., PRICE, J. D., RAMBECH DAHL, C. & AGDESTAIN, T. 1988. The structural evolution of the northern Viking Graben and its bearing upon extensional modes of basin formation. *Journal of the Geological Society, London*, **145**, 455–472.
- BIDDLE, K. T. & RUDOLPH, K. W. 1988. Early Tertiary structural inversion in the Stord Basin, Norwegian North Sea. *Journal of the Geological Society, London*, **145**, 603–611.
- BIRTLES, R. 1986. The seismic flatspot and the discovery and delineation of the Troll field. In: SPENCER, A. M. *et al.* (eds) *Habitat of hydrocarbons on the Norwegian continental shelf*. Graham & Trotman, London, 207–215.
- DEPARTMENT OF ENERGY 1984. *U.K. continental shelf well records, releases 1–18*. Her Majesty's Stationery Office, London (distributed through Erico Data Services, London).
- DONATO, J. A. & TULLY, M. C. 1981. A regional interpretation of North Sea gravity data. In: ILLING, L. V. & HOBSON, G. D. (eds) *Petroleum geology of the continental shelf of north-west Europe*. Heyden, London, 65–75.
- EDIRIWEERA, K. K. 1988. *A geological and geophysical investigation of the Viking Graben area, North Sea*. Dr.ing. thesis. Norwegian Institute of Technology, Trondheim.

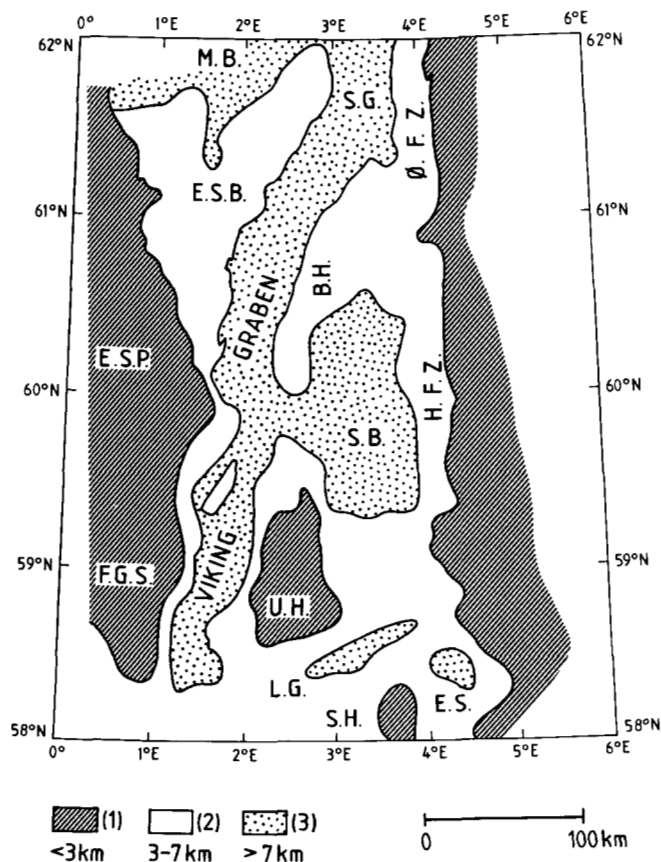


Fig. 5. The Northern North Sea Rift Zone. This map has been derived from Fig. 4. The depth of the top of the crystalline basement is: (1) less than 3 km; (2) 3–7 km; (3) more than 7 km. Key: E.S., Egersund Sub-basin; E.S.B., East Shetland Basin; E.S.P., East Shetland Platform; F.G.S., Fladen Ground Spur; H.F.Z., Horda Fault Zone; L.G., Ling Graben; M.B., Møre Basin; Ø.F.Z., Øygarden Fault Zone; S.B., Stord Basin; S.G., Sogn Graben; S.H., Sele High; U.H., Utsira High.

- FICHLER, C. & HOSPERS, J. 1990a. Gravity modelling in the Viking Graben area. In: BLUNDELL, D. J. & GIBBS, A. (eds) *Tectonic evolution of the North Sea Rifts*. Oxford University Press, Oxford, 67–77 (in press).
- & — 1990b. Deep crustal structure of the northern North Sea Viking Graben: results from deep reflection seismic and gravity data, *Tectonophysics*, **178**, 241–254.
- FROST, R. E. 1987. The evolution of the Viking Graben tilted fault block structures: a compressional origin. In: BROOKS, J. & GLENNIE, K. W. (eds) *Petroleum geology of North West Europe*. Graham & Trotman, London, 1009–1024.
- FROST, R. T. C., FITCH, F. J. & MILLER, J. A. 1981. The age and nature of the crystalline basement of the North Sea Basin. In: ILLING, L. V. & HOBSON, G. D. (eds) *Petroleum geology of the continental shelf of North-West Europe*. Heyden, London, 43–57.
- GILTNER, J. P. 1987. Application of extensional models to the Northern Viking Graben. *Norsk Geologisk Tidsskrift*, **67**, 339–352.
- GLENNIE, K. W. (ed.) 1984. *Introduction to the petroleum geology of the North Sea*. Blackwell Scientific Publications, Oxford.
- HAMAR, G. P. 1979. *Tectonic Map North Sea. Scale 1:2,000,000*. Statoil, Stavanger.
- HOSPERS, J. & EDIRIWEERA, K. K. 1988. Mapping the top of the crystalline continental crust in the Viking Graben area, North Sea. *Norwegian Geological Survey, Special Publication*, **3**, 21–28.
- & FINNSTRØM, E. G. 1984. The gravity field of the Norwegian sector of the North Sea. *Norwegian Geological Survey, Bulletin*, **396**, 25–34.
- , — & RATHORE, J. S. 1985. A regional gravity study of the northern North Sea (56–62°N). *Geophysical Prospecting*, **33**, 543–566.
- KLEMPERER, S. L. 1988. Crustal thinning and the nature of extension in the northern North Sea from deep seismic reflection profiling, *Tectonics*, **7**, 803–821.
- NORWEGIAN PETROLEUM DIRECTORATE 1976–1985. *Well data summary sheets, vol. 1–10*. Norwegian Petroleum Directorate, Stavanger.
- 1986a. *Borehole list*. Norwegian Petroleum Directorate, Stavanger.
- 1986b. *Annual report for the year 1986*.
- 1987. *Annual report for the year 1987*.
- 1988. *Annual report for the year 1988*.
- RØNNEVIK, H. C., VAN DEN BOSCH, W. & BANDLIEN, E. H. 1975. A proposed nomenclature for the main structural features in the Norwegian North Sea. In: FINSTAD, K. G. & SELLEY, R. C. (eds) *Jurassic northern North Sea symposium 1975 (JNNSS-75)*, Norwegian Petroleum Society, Oslo, pp. JNSS/18–0 to 18–16.
- SPEKSNIJDER, A. 1987. The structural configuration of Cormorant Block IV in the context of the northern Viking Graben structural framework. *Geologie en Mijnbouw*, **65**, 357–379.
- WHEATLEY, T. J., BIGGINS, D., BUCKINGHAM, J. & HOLLOWAY, N. H. 1987. The geology and exploration of the Transitional Shelf, an area to the west of the Viking Graben. In: BROOKS, J. & GLENNIE, K. W. (eds) *Petroleum geology of North West Europe*, Graham & Trotman, London, 979–989.
- ZIEGLER, P. A. 1982. *Geological atlas of Western and Central Europe*. Elsevier Scientific Publishing Company, Amsterdam.

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