Thickness of pre-Zechstein-salt Palaeozoic sediments in the southern part of the Norwegian sector of the North Sea

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A procedure for preparing an isopach map of Palaeozoic sediments situated beneath the Zechstein (Upper Permian) salt in an area within the Norwegian sector of the North Sea is described. The procedure makes use of aeromagnetic and borehole data to prepare a map of the depth to the crystalline basement. In combination with published depths to the base of the Zechstein salt, based on seismic reflection data, the thickness of the sediments between the Base Zechstein and the top of the crystalline basement can be determined. The resulting isopach map of the pre-Zechstein-salt Palaeozoic sediments in our study area appears to be meaningful and defines local thicknesses in excess of 4 km. For a smaller part of the investigated area an isopach map of the pre-Zechstein-salt Palaeozoic sediments was produced from available seismic reflection data alone. The appropriate section of the larger isopach map compares well with this seismic isopach map, thus giving credibility to the method used.

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This paper deals with a geophysical investigation of an area which is here designated as the southern part of the Norwegian sector of the North Sea. Geographically, it lies between 2° and 8°E, and 56° and 59°N (Fig. 1). Geologically, the area covers a large part of the Norwegian-Danish Basin as well as the Mandal High situated to the southwest.

The Norwegian – Danish Basin (Rønnevik et al. 1975, Hamar et al. 1983, Skjerven et al. 1983) is named after the two bordering countries. It is a WNW-ESE trending basin of mainly Permian to Early Jurassic age and contains sediments which locally reach up to 8 km in thickness. The basin is limited by the Ringkøbing – Fyn High to the south, the Central Graben and adjacent highs (Mandal High, Jæren High) to the southwest and west, the Horda Platform to the northwest, and the Fennoscandian Shield to the north and northeast. The Norwegian-Danish Basin comprises a number of distinct tectonic sub-units of which we here mention the Ling Graben, the Sele High, the Egersund Sub-basin, the Fiskebank Sub-basin, the Flekkefjord High, the Lista Nose (or: Lista Ridge) and the Farsund Sub-basin (Fig. 1). Zechstein (Upper Permian) salt occurs widely in the Norwegian-Danish Basin and has given rise to intense salt tectonics.

The crystalline basement is exposed on land in Norway and is known from seismic reflection data to be at shallow depth in the near-offshore area. It has also been encountered in a limited number of the boreholes drilled during the course of petroleum exploration, as will be discussed later. The general configuration and depth of the crystalline basement in the deeper parts of the Norwegian-Danish Basin are otherwise only known in broad outline from studies of aeromagnetic data (Hospers & Rathore 1984). The exposed crystalline basement on the adjacent land area in Norway is largely of Precambrian age. In the offshore area under discussion it is mainly of Caledonian age west of the 5°E meridian (Frost et al. 1981) and presumably largely of Precambrian age to the east.

The base of the Zechstein salt ('Base Zechstein') has been mapped by seismic reflection work (Day et al. 1981, Skjerven et al. 1983). It is generally assumed that there are sediments of Rotliegendes (Early Permian) age present below the Zechstein salt (Day et al. 1981, Ziegler 1982, Glennie 1984a, 1984b). It has also been proposed that Devonian or Carboniferous sediments may locally be present within the area under discussion (Skjerven et al. 1983, Glennie 1984a).

There are no published data on the total thick-

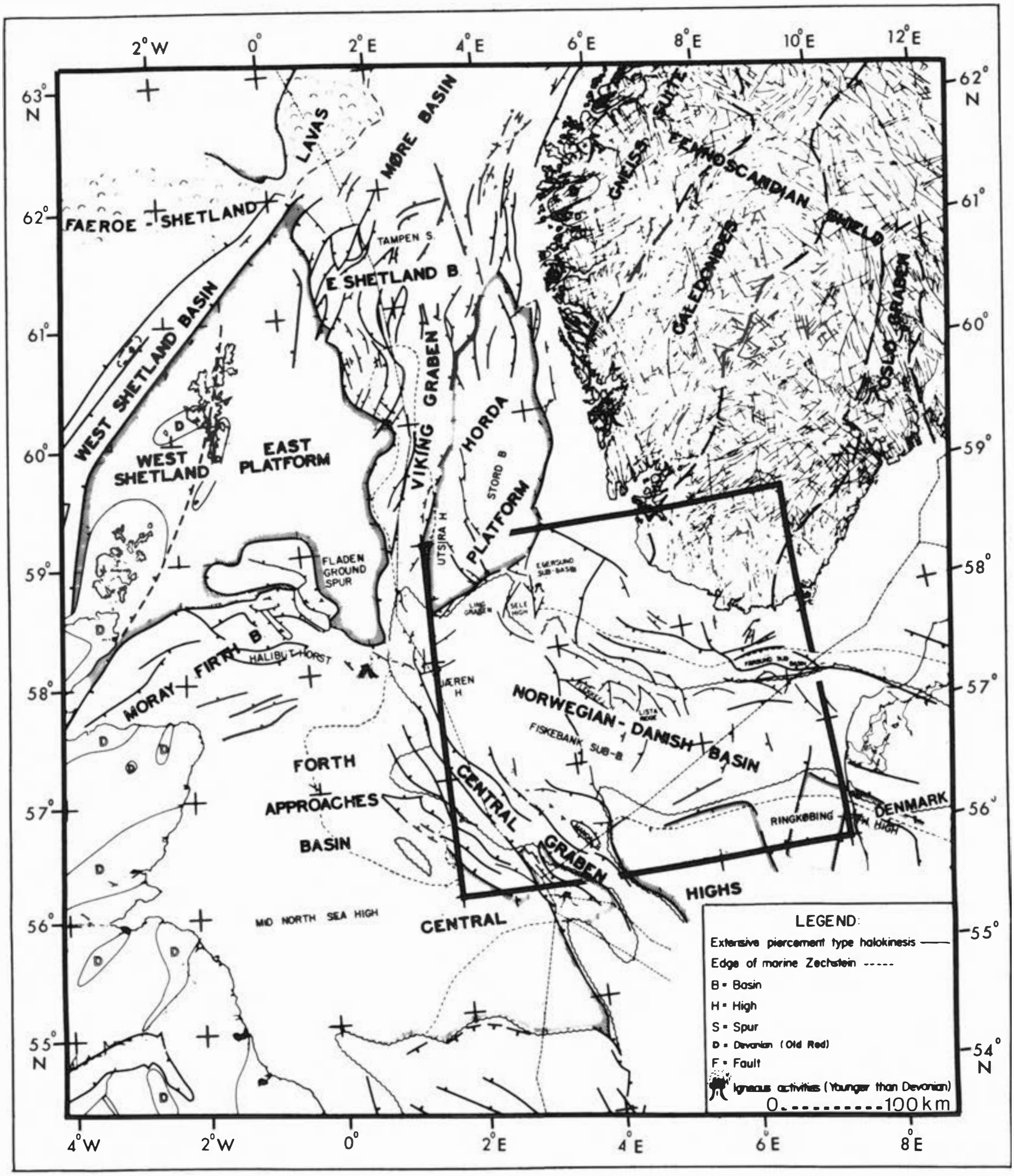


Fig. 1. Tectonic map of the North Sea between approximately 54° and 63°N. This figure is part of a larger map by Hamar (1980) and is reproduced here by permission. The study area is indicated by a frame.

ness of the Palaeozoic sediments between Base Zechstein and the top of the crystalline basement; hence, the possible occurrences and thicknesses of such sediments in the study area are unknown. Some data for the Rotliegendes are given by Ziegler (1982, encl. 28), who shows thicknesses in the range of 200 to 600 m in the area under discussion, and Glennie (1984b, fig. 3.2) who shows thicknesses in the range of 150–480 m. It is also known that about 300 m of sediments of Rotliegendes age were penetrated in well 7/3–1 (Norwegian Petroleum Directorate 1979, Glennie 1984b, fig. 3.5). The position of this well is shown in Figs. 2 and 3.

From the available reflection seismic data very little information can be obtained about the thickness of the pre-Zechstein-salt Palaeozoic sediments in this part of the North Sea. We surmise that there may be no significant contrast in acoustic impedance between the pre-Zechstein-salt Palaeozoic sediments and the crystalline basement. Furthermore, the top of the crystalline basement may lie at such a great depth that corresponding seismic reflection times exceed those normally displayed on seismic reflection sections (5 or 6 seconds). Also, the presence of widespread and intense salt tectonics at depth produces pronounced lateral changes in seismic velocity and this makes it difficult to obtain good continuous reflections from below the salt.

In the present study we have endeavoured to map the approximate thickness of the pre-Zechstein-salt Palaeozoic sediments in the area by upgrading an earlier map of depths to the magnetic basement (Hospers & Rathore 1984) into a map of depths to the crystalline basement and then subtracting the known depths to Base Zechstein.

Depths to the magnetic basement and the crystalline basement

Two of the present authors have earlier carried out an interpretation of aeromagnetic data from a large part of the Norwegian sector of the North Sea (situated between 2° and 10°E, 56° and 60°N), following procedures described by Vacquier et al. (1951). The resulting estimates of depths to magnetic basement, in conjunction with data from just three wells which reached basement (as a control), were used to prepare a contour map of the magnetic basement for the area (Hospers & Rathore 1984, fig. 4).

In general, the top of the magnetic basement, as derived from aeromagnetic data, coincides with the top of the crystalline basement. However, there may be discrepancies when (a) the source of a magnetic anomaly does not satisfy the geometrical or other model requirements on which the interpretation is based (Vacquier et al. 1951), or (b) there are highly magnetic igneous rocks present within the sedimentary column. Examples of the above two situations are actually encountered in the area under discussion and will be described later.

The actual conversion of the earlier map of depths to the top of the magnetic basement into a map of depths to the top of the crystalline basement (Fig. 2) has followed the following steps: (1) All available well data (Norwegian Petroleum Directorate 1976–1981, Frost et al. 1981) have been used to establish depths to the crystalline basement where it was reached, or minimum depths where it was not (Fig. 2). (2) In the light of these borehole data the depth contours were appropriately adjusted in the neighbourhood of a point at 4°E, 58°10′N (Fig. 2). (This is the general neighbourhood of the Sele High, cf. Fig. 1). (3) In the area around borehole 10/5–1 (Fig. 2) where the crystalline basement was encountered at a depth of 1.8 km, the original depth to magnetic basement is about 4 km. This difference has not been adjusted, but the area around here has been designated as having unreliable contours (Fig. 2). Clearly, the magnetic basement depth here is far in excess of the depth to the crystalline basement and it is thought that this illustrates a discrepancy of the type (a) discussed earlier. (4) Another limited area designated as having unreliable depth contours is situated at the extreme east of the map (Fig. 2). The contours here are thought to indicate unreliably shallow depths because of the presence of the so-called "Kristiansand volcano" (Sharma 1970, Åm 1973). It is thought that the situation here illustrates a discrepancy of the type (b) outlined above.

Inspection of the map of depths to the top of the crystalline basement (Fig. 2) and comparison with the tectonic map (Fig. 1) shows the following features: (1) There is a gently sloping shallow basement shelf off the coast of Norway. Its limit would appear to lie approximately where the 3 km depth contour is shown. (2) Beyond this shallow basement shelf, relatively deep tracts are found where the tectonic map shows the Ling Graben, the Egersund Sub-basin and the Farsund Sub-basin to be situated. A relatively shallow tract occurs in the area of the Sele High and a deep trough occupies the position of the Norwegian-Danish Basin. Maximum depths in this trough exceed 12 km. (3) To the southwest of the Norwegian-Danish Basin shallower depths are encountered, while in the extreme south a more local tract of relatively shallow basement coincides with the Mandal High.

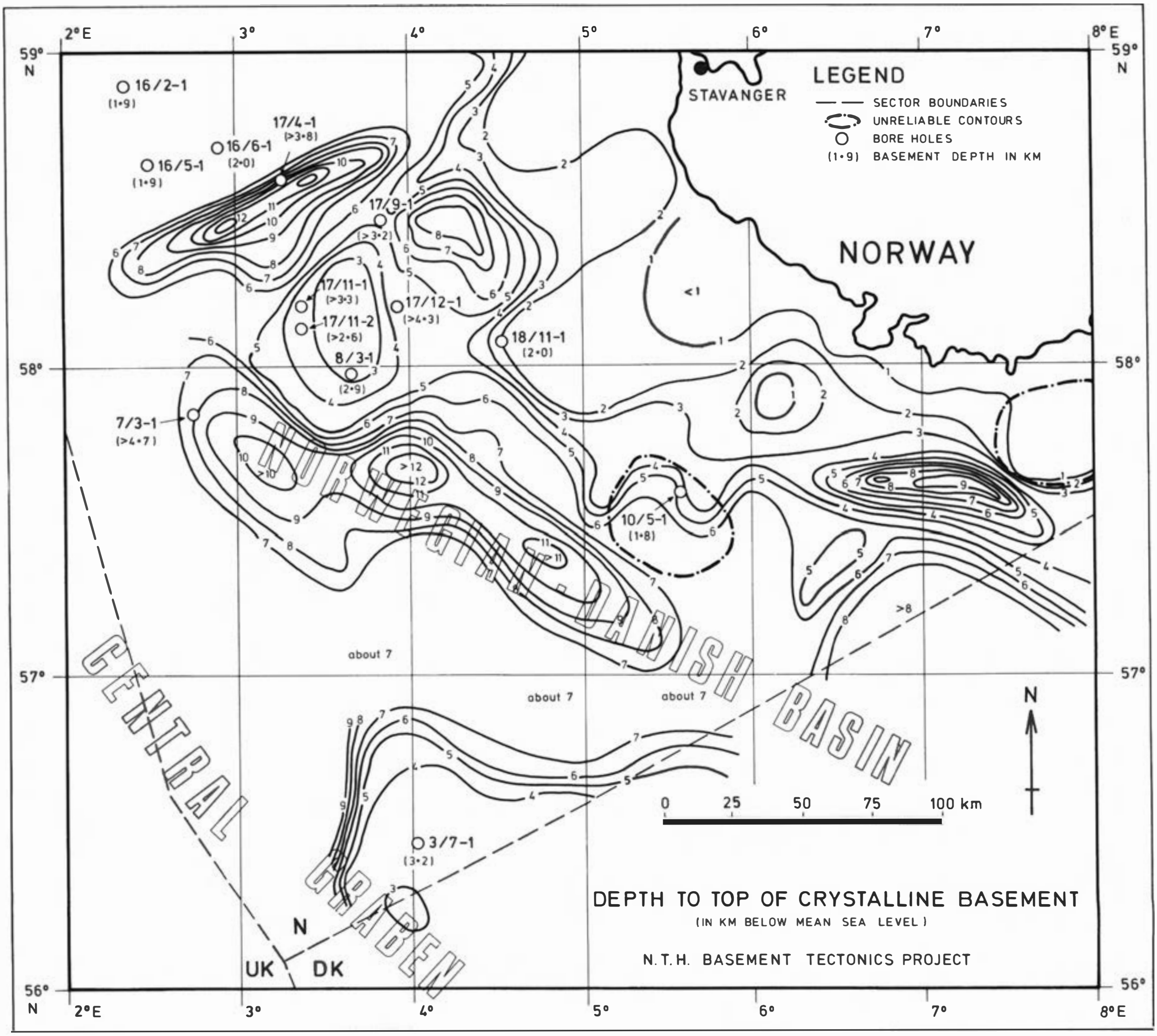


Fig. 2. Map of depths to the top of the crystalline basement in the southern part of the Norwegian sector of the North Sea. Depths are in km below mean sea level.

Thickness of pre-Zechstein-salt Palaeozoic sediments

Hospers & Rathore (1984) noted that when the regional Base Zechstein map of Day et al. (1981) is compared with the magnetic basement map, the latter on the whole shows the greater depths. They interpreted this as being an indication of the presence of sedimentary deposits beneath the Base Zechstein. In the present paper this point is elaborated, using the same Base Zechstein map but replacing the map of depths to the magnetic basement by the map of depths to the crystalline basement (Fig. 2).

The thickness of the pre-Zechstein-salt Palaeozoic sediments is obtained by subtracting the depth to Base Zechstein from the depth to the top of the crystalline basement. The results are presented as an isopach map (Fig. 3). The limits of the area over which both types of depth data are available are shown in Fig. 3 as the 'limit of area with combined data'.

It should be noted that the Base Zechstein map

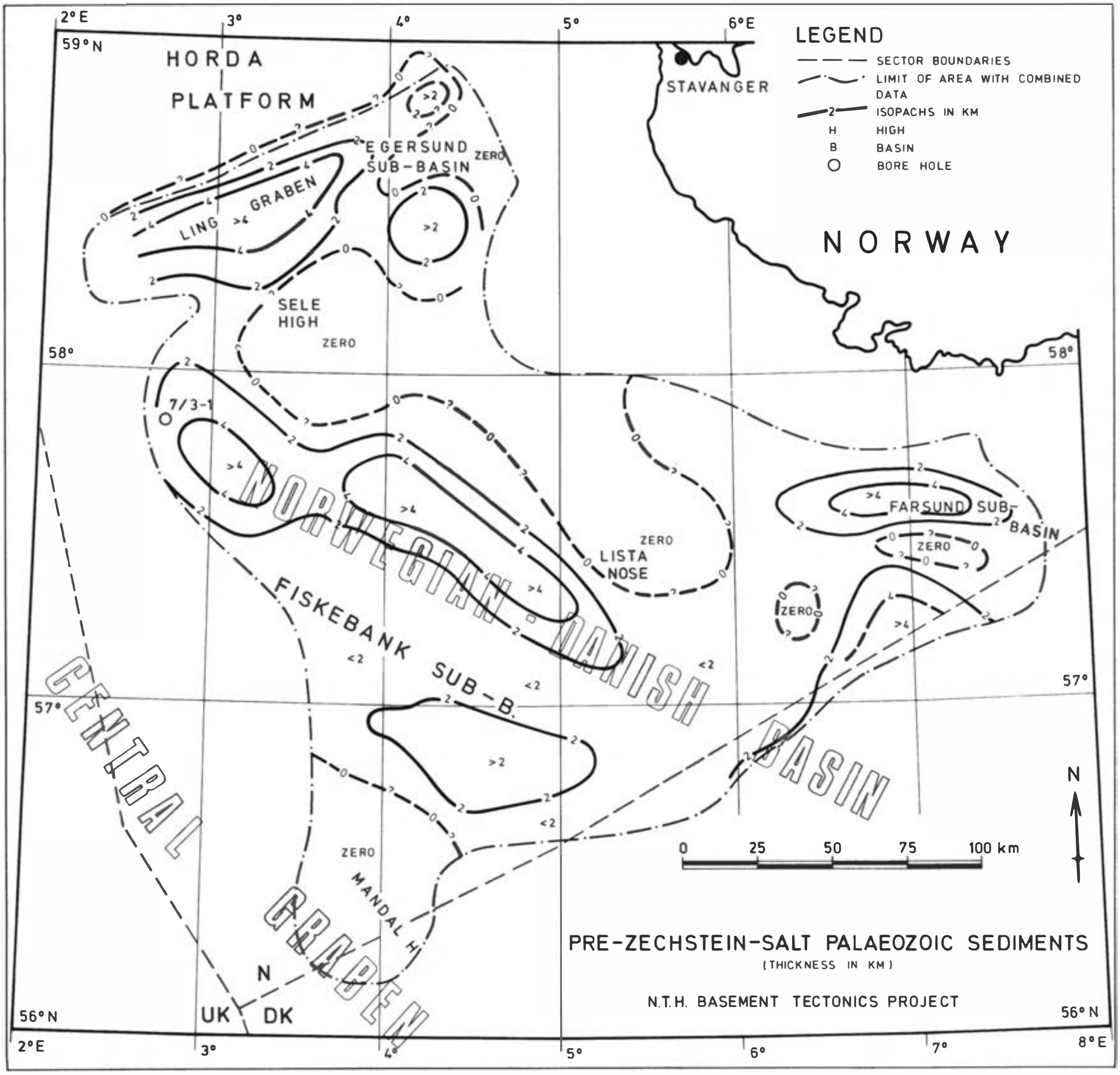


Fig. 3. Isopach map of the pre-Zechstein-salt Palaeozoic sediments in the southern part of the Norwegian sector of the North Sea derived from aeromagnetic and seismic reflection data. The 'limit of area with combined data' shown on the map and in its legend defines the area over which both the depths to the top of the crystalline basement and the depths to the base of the Zechstein salt are known. Thicknesses are expressed in km.

(Day et al. 1981) shows a number of major faults across which the depth changes drastically. The map of the crystalline basement (Fig. 2) should, in principle, show similar changes. It does not do this since it is based on spatially discrete depth determinations, derived from aeromagnetic and well data, which have subsequently been smoothly contoured. The crystalline basement map is therefore a map of smoothed depth data and consequently the isopach map (Fig. 3) is also a map of smoothed thickness data. We have therefore exercised some restraint in drawing the isopachs, as the map can only give a general idea of the thicknesses. We have used a contour interval of 2 km and left thicknesses in excess of 4 km undefined by contours.

The isopach map of Fig. 3 which is the result of our analysis shows a number of interesting features. (1) The pre-Zechstein-salt Palaeozoic sediments are absent in an area on and southeast of the Sele High and north of (possibly also on) the Lista Nose, as well as around the Mandal High. They may also be absent in part of the Egersund Sub-basin and in two small tracts south of the Farsund Sub-basin. (2) They reach moderate thicknesses of up to about 2 km in the area of the Fiskebank Sub-basin and in parts of the Egersund Sub-basin. (3) They reach considerable thicknesses (in excess of 4 km) in what are now the Norwegian-Danish Basin, the Ling Graben and the Farsund Sub-basin. They also reach similar thicknesses south of the Farsund Sub-basin along the sector boundary between Norway and Denmark.

Accuracy of the isopach map

The individual depth determinations from aeromagnetic data are generally considered as having an accuracy of 10 to 15% (Vacquier et al. 1951, Steenland 1963). This almost certainly also applies to our depth determinations. However, once the large number of individual depth determinations are contoured, the resulting magnetic basement map should show the general, smoothed configuration of the magnetic basement with an error which is not in excess of about half the minimum contour spacing which can be confidently used in the contouring.

The contour interval used in the preparation of the magnetic basement map (Hospers & Rathore 1984) is 1 km; it is therefore thought that, as a rule, the contours of the magnetic basement map are not in error by more than 0.5 km in their representation of the *general, smoothed configuration* of the magnetic basement. By converting the magnetic basement depth map into a map of depths to the top of the crystalline basement (Fig. 2), this accuracy is maintained or even improved. Where relevant well data are available, possible errors are reduced to zero, or, alternatively, areas with obvious discrepancies can be eliminated from further analysis. The map of the crystalline basement (Fig. 2), therefore, shows depth contours which are not in error by more than 0.5 km in their representation of the general, smoothed configuration of the crystalline basement.

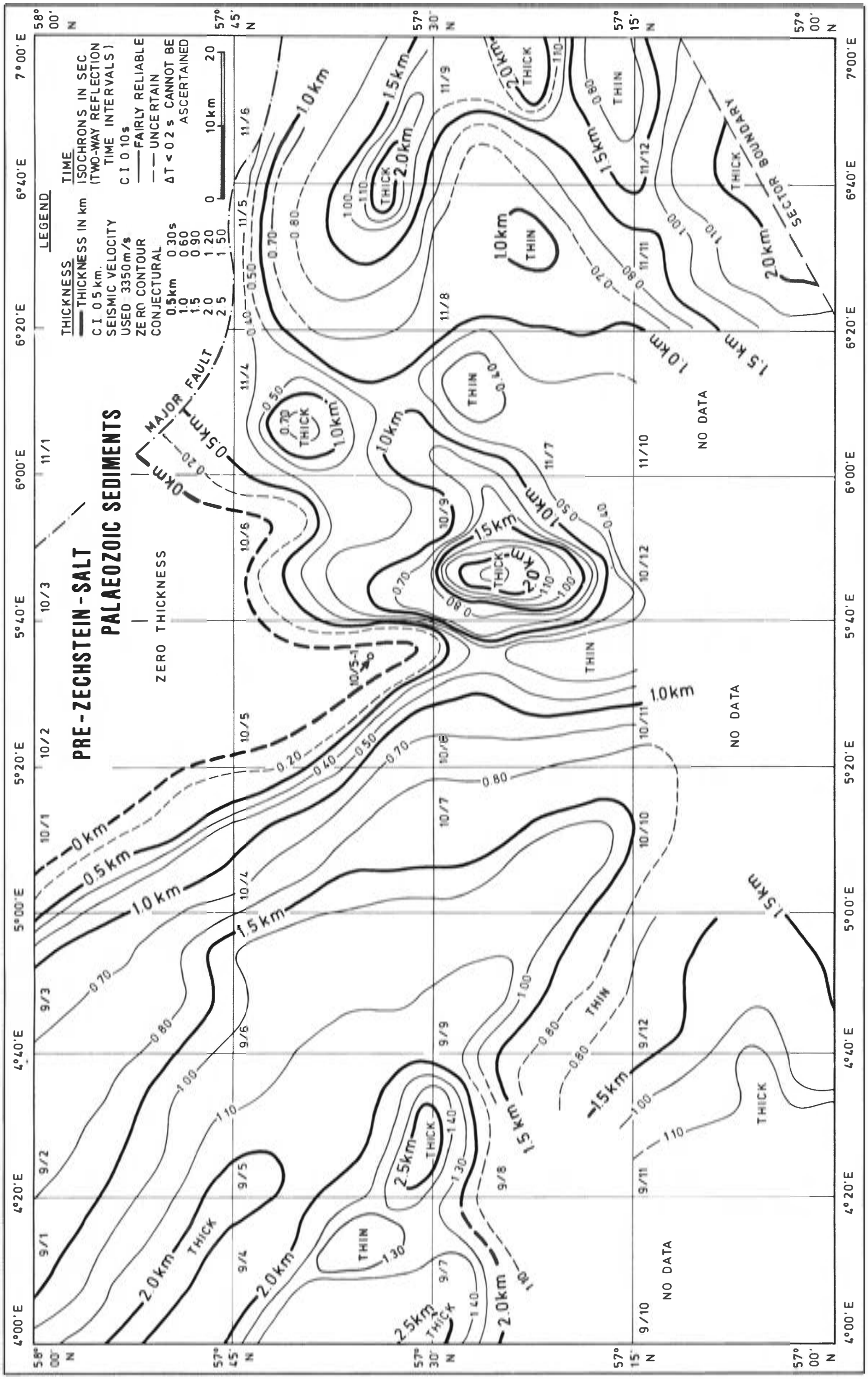
The Base Zechstein map (Day et al. 1981) is more detailed than the map of the crystalline basement. The main uncertainty here is the accuracy of the velocity information used to convert reflection times into depths. From our own seismic interpretation work in the area (now being prepared for publication) and from statements by Day et al. (1981) we estimate that depth errors are unlikely to exceed 0.5 km. By adding the estimated possible errors for the individual maps it is found that the error in the isopach map should not be more than 1.0 km. The contour interval of 2 km used on the isopach map is therefore justified.

In the absence of close well control it might appear difficult to avoid incorporating into the map undetected local areas where the magnetic basement lies deeper than the crystalline basement. However, such areas are necessarily of limited areal extent and they would have been detected during contouring. No evidence of this type has come to light. In fact, the depth differences between Base Zechstein and top crystalline basement are so systematic and consistent that there are no problems in contouring these differences over a large area. This reinforces our belief that the isopach map (Fig. 3) gives a reliable, albeit general, picture of the distribution and thickness of the pre-Zechstein-salt Palaeozoic sediments.

Isopach map of pre-Zechstein-salt Palaeozoic sediments from seismic data alone

The seismic sections, which we have access to, cover the area shown in Fig. 4. They show evidence of sedimentary (layered) strata underlying the Zechstein salt. However, there is very little evidence for reflections from the top of the crystalline basement; only in the northern part of Fig. 4 can such reflections be identified. An additional complication is that, in the deeper part of the basin, any possible reflection from the top of the crystalline basement, if present, would arrive at reflection times in excess of 5 or 6 s and therefore not appear on the seismic sections. The reflection time intervals seen on seismic sections which can,

Fig. 4. Isopach map of pre-Zechstein-salt Palaeozoic sediments for quadrants 9, 10 and 11 from seismic reflection data alone. Thicknesses are shown both in seconds (isochrons) and in km. The seismic velocity used to convert two-way reflection time intervals (ΔT in the legend) to thicknesses is 3350 m/s. All thicknesses are minimum values. The zero contour is conjectural. (N. B. A quadrant is an area of 1° × 1°. The figure shows, from left to right, quadrants 9, 10 and 11. Each quadrant is subdivided into 12 blocks. The area shown in this figure is situated between 57° and 58°N, and 4° and 7°E in Fig. 3).


PRE-ZECHSTEIN-SALT
PALAEOZOIC SEDIMENTS
LEGEND
THICKNESS
THICKNESS IN km
C I 0.5 km.
SEISMIC VELOCITY USED 3350 m/s
ZERO CONTOUR
CONJECTURAL
TIME
ISOCHRONS IN SEC (TWO-WAY REFLECTION TIME INTERVALS)
C I 0.10 s
FAIRLY RELIABLE
UNCERTAIN
ΔT < 0.2 s CANNOT BE ASCERTAINED
ZERO THICKNESS
MAJOR FAULT
NO DATA
SECTOR BOUNDARY
THICK
THIN

with some confidence, be considered as representing Palaeozoic sediments older than Zechstein salt, are therefore minimum values.

There is very little evidence as to the seismic velocities of these pre-Zechstein-salt Palaeozoic sediments. The only available evidence is from well 7/3–1 (Norwegian Petroleum Directorate 1979) where the sonic log shows a velocity of 3350 m/s in sediments of Rotliegendes age. It is thought that this value is somewhat too low to be representative for all possible pre-Zechstein-salt Palaeozoic sediments in the area and it is therefore considered as a minimum value.

The observed reflection time intervals can be converted into thicknesses by means of the seismic velocity of 3350 m/s. As both the reflection time intervals and the seismic velocity are minimum values, the thicknesses are also minimum values. The resulting map, depicting both reflection time intervals and thicknesses, is shown in Fig. 4.

From the available seismic data it appears that the base of the Zechstein salt is conformable with the bedding in the sub-salt sediments. Only in block 11/9 and in the central parts of quadrant 9 (Fig. 4) is there some evidence for a slight angular unconformity at the base of the Zechstein salt.

Given the uncertainties in both maps (Figs. 3 & 4), the general agreement is satisfactory in the area which they have in common. On the basis of this general agreement, it is thought that the isopach map based on seismic and aeromagnetic data (Fig. 3) gives reliable suggestions as to the thicknesses in the entire mapped area.

Features of the pre-Zechstein geology of the area

In this section we comment on a number of features which relate to the areal distribution and thickness of the pre-Zechstein-salt Palaeozoic sediments in the study area, and to the indications of structural trends which are visible on the isopach map (Fig. 3).

(1) There is a striking resemblance between the isopach map and the corresponding part of the generalized palaeogeographic and isopach maps for the Rotliegendes published by Ziegler (1982, encl. 13 and 28) and Glennie (1984b, figs. 3.1, 3.2 and 3.6). This resemblance appears to support the general correctness of our analysis.

(2) Another striking aspect of the isopach map is the presence of considerable thicknesses (in excess of 4 km) of pre-Zechstein-salt Palaeozoic sediments beneath what are now the Ling Graben, the Norwegian-Danish Basin and the Farsund Sub-basin.

In the absence of detailed information on the age, thickness, lithology and environment of deposition of the pre-Zechstein-salt Palaeozoic sediments in the study area, it is not possible to say definitely whether these sediments are downfaulted remnants of a much more extensive cover or actually represent older sedimentary basin fills below the floor of the Norwegian-Danish Basin (which overlies a part of the Northern Permian Basin, cf. Ziegler 1982, encl. 13 and 14). There is a distinct possibility, however, that the isopach map actually shows the presence of such older (Permo-Carboniferous or even Devonian) basins and sub-basins, more or less by analogy with the situation encountered in the Southern Permian Basin (Glennie 1984a). This, in turn, would suggest that the formation of the Norwegian-Danish Basin, the Ling Graben and the Farsund Sub-basin to a considerable extent may have been controlled by relics of the earlier structural history of the area (cf. Johnson & Dingwall 1981, Threlfall 1981, Glennie 1984a, Pegrum 1984a, 1984b).

(3) The isopach map also shows some definite trends. The greatest thicknesses of sediments beneath the Norwegian-Danish Basin show a NW-SE trend (dislocated or interrupted at about 3°30′E), those under the Ling Graben an approximately NE-SW trend, and those beneath the Farsund Sub-basin an E-W trend.

Rathore & Hospers (1986) have studied lineaments on land in southern Norway, based on Landsat, geological and aeromagnetic data, and in the adjacent offshore area (including the area studied in the present paper), based on aeromagnetic data. They recognize four trends (NE-SW, NW-SE, N-S and E-W) which are present both on land and in the offshore area, and which are thought to represent fracture patterns originally of Precambrian age. These authors also find that in the offshore area it is likely that a re-activation of the NE-SW trend in Phanerozoic times played a role in the formation of the Ling Graben. Similar Phanerozoic re-activation along the other trends has influenced the formation of the Sele and Flekkefjord Highs (NW-SE), the Lista Nose (N-S) and the Farsund Sub-basin (E-W). (This confirms and amplifies earlier findings on structural trends, based on geological data, published by Skjerven et al. (1983) and Pegrum (1984a)).

In the light of the foregoing, the NW-SE, NE-SW and E-W trends seen on the isopach map are therefore thought to be associated with a re-activation in pre-Zechstein Palaeozoic times of the corresponding Precambrian fracture trends in the crystalline basement. The direction of these trends suggests that they are more likely to be connected with the Caledonian than the Hercynian orogeny. If this is true, the re-activation is likely to be of Devonian age.

(4) The trend of the isopachs in the area of the Norwegian-Danish Basin is NW-SE (Fig. 3), which is somewhat different from the trend of the Norwegian-Danish Basin itself, which is WNW-ESE (Fig. 1). This may indicate (provided that the pre-Zechstein-salt Palaeozoic sediments indeed represent an old basin fill) that the Norwegian-Danish Basin occupies the same general area as the older basin but differs somewhat in general structural trend. The reason for this difference is not known, but it is conceivably related in some way to a changing tensional stress regime with time.

(5) The possible presence of an older sedimentary basin beneath the floor of the Norwegian-Danish Basin may also be of importance to the petroleum industry. Major gas fields (including the Groningen gas field onshore in the Netherlands) which produce from the Rotliegendes have been found in the Southern Permian Basin in the southern North Sea. The Rotliegendes there is overlain by Zechstein salt, which serves as an impermeable cap rock, and underlain by Carboniferous (Westphalian) coal seams which are the source rocks for the gas (cf. Glennie 1984a, 1984b).

In the area of the Norwegian-Danish Basin, discussed in the present paper, Zechstein salt is present. There is also some evidence that the Rotliegendes may have favourable reservoir properties (cf. Glennie 1984b, Sørensen & Martinsen 1984). Finally, it has been proposed by Ziegler (1982, encl. 11) that Westphalian sedimentary rocks may be present in at least the southern and eastern parts of the area. In this connection we note that the thicknesses of the pre-Zechstein-salt Palaeozoic sediments derived from our analysis (Fig. 3) are locally large (in excess of 4 km) when compared with thicknesses mapped for the Rotliegendes alone in the Southern Permian Basin (Ziegler 1982, encl. 28), which are 1.5 km or less. This would appear to reinforce the probability that, in addition to Rotliegendes sediments, sediments of Carboniferous and/or Devonian age are present in the study areas.

(6) Our analysis suggests that there may be an older basin of Permo-Carboniferous or even Devonian age present beneath the floor of the Norwegian-Danish Basin but a definite proof of its presence or absence can be obtained only by drilling. Here it has to be kept in mind that the Base Zechstein in the Norwegian-Danish Basin reaches great depths. In the study area, Day et al. (1981, plate 1) and Ziegler (1982, encl. 34) show maximum depths in excess of 7000 m, and our own unpublished data show depths in excess of 8000 m. In large parts of the area drilling may therefore not be economically attractive (cf. North 1985, pp. 470–473).

Conclusions

(1) Within the area discussed in this paper it is possible to upgrade a magnetic basement map, based on aeromagnetic data, into a map of depths to the top of the crystalline basement (Fig. 2).

(2) Using the crystalline basement map in combination with a depth map of Base Zechstein, it is possible to map the thickness of the pre-Zechstein-salt Palaeozoic sediments.

(3) The resulting isopach map (Fig. 3) defines a number of areas where these sediments reach moderate (about 2 km) to considerable (more than 4 km) thicknesses. There is a broad belt of relatively thick pre-Zechstein-salt Palaeozoic sediments traversing the mapped area, and there are more localised areas of considerable thickness in the northern and eastern parts of the area.

(4) The geological age of these sediments cannot be ascertained; presumably they are largely of Early Permian (Rotliegendes) age, but sediments of Carboniferous and/or Devonian age may very well be present.

(5) The isopach map (Fig. 3) appears to be very reliable in an area where it was possible to check the thicknesses by using seismic data alone (Fig. 4).

(6) It is thought that the procedure described here for the southern part of the Norwegian sector of the North Sea may also be useful in other areas where similar situations prevail.

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