The influence of tectonics on the land forms in west Jutland, Denmark

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The structural development and its influence on the present land forms is discussed on the basis of the reflection seismic and gravity data. The study area covers the western part of Jutland which was not glaciated during the Weichselian and is delimited by two Weichsel main stationary lines: the line extending from west to east and the line extending from north to south (these two lines join at Dollerup). The southern border of the study area corresponds approximately to the northern limit of the buried Ringkøbing-Fyn High. In this part of west Jutland the base Zechstein faults can be traced to the surface where they control the drainage system. The faults are mainly NW-SE trending strike slip faults which are active also at the present time. Zechstein evaporates are present in the entire area discussed here.

Key words: gravity, seismics, strike slip faulting, neotectonics.

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A location map of the study area is shown in Figure 1, and Figure 2 shows the map of the Quaternary land forms (Ussing 1903) which covers a large part of the area discussed in the present study.

In this part of west Jutland several higher areas, the so-called hill islands (bakkeøer in Danish) are present. At the end of the Weichselian glaciation, these hill islands were partly covered by the meltwater sediments from the east (Figs 1, 2). These higher areas are considered to be the remnants from the penultimate Saale glaciation (Madsen 1926, Milthers 1939, Hansen 1965).

The largest and highest hill island (up to 100 m+), named Skovbjerg, has a circular shape, while several smaller hill islands between Skovbjerg and the N-S trending main stationary line have clearly northwesterly trends. It should be pointed out that several large Zechstein salt diapirs occur along the W-E main stationary line. These diapirs have grown above the W-E striking major base Zechstein faults downthrown to the north. In Figure 3 the topography of the pre-Quaternary surface in a part of the study area is shown (Binzer & Stockmarr 1994, Friborg 2000). Three deeply buried valleys, which have no expression at the present surface, occur in this area. The westernmost valley A attains depths of some 300 m+, the blue-coloured parts being the deepest. It is interesting to note that the modern streams cross this deeply buried valley at right angles and at the places where this valley is deepest. The buried valley B, along the eastern border of the Skovbjerg hill island, is shallower (about 200 m+). From the morphology of these two deeply buried valleys, it is assumed that they were eroded by streams flowing from the south, which suggests that they were formed before the onset of the last Weichsel glaciation. The buried valley C is different, and although it is as deep as the valley B, it extends from the Dollerup area in the southwestern direction. Furthermore, this valley is severely deformed, and several of its segments form angles of nearly 90°. Modern streams flowing in northwesterly directions (such as Storå) cross this buried valley at the places where these segments meet. Such a picture implies that this valley C was deformed by faulting. The valley D is the youngest one, and its approximate borders, marked with red lines, correspond to those of the periglacial stream valley which is presently occupied by the strongly undersized Karup river (Fig. 2). The original periglacial valley was very wide (4–5 km) in its lower course, but apparently quite shallow. It was passing north between the salt structures Mønsted and Sevel, and it entered Limfjorden at Skive (the present Skive fjord is a remnant of its lower course). This valley D has „absorbed“ several segments of the faulted C valley.

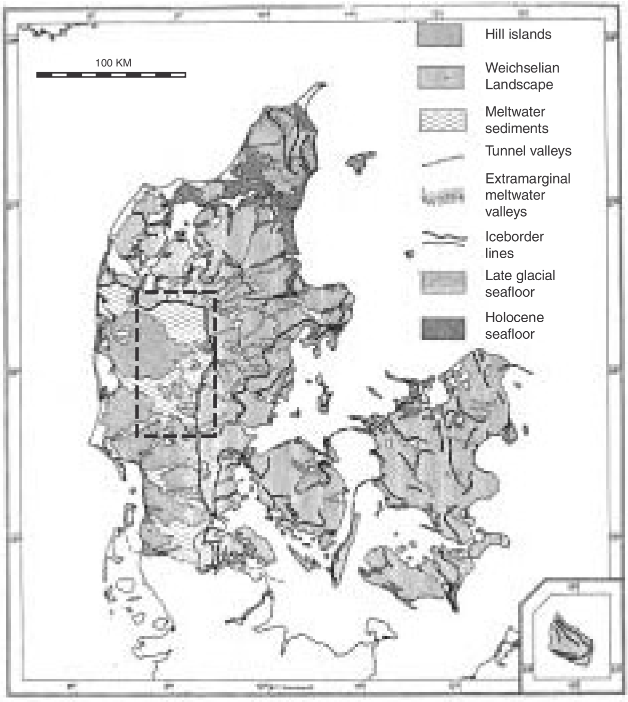


Fig. 1. Study area in west Jutland (Denmark).

Gravity data

In Figure 4 the Bouguer gravity map covering the western part of Denmark is shown, and the residual gravity anomaly map of the same part of Denmark in Figure 5 (both maps by Petersen 1983). In the central part of the residual gravity anomaly map a N-S trending narrow residual positive gravity anomaly, its limits marked in red, is present. At its northern end this anomaly apparently passes between the salt structures Sevel and Mønsted, while in its middle part it bends sharply southeast, but then again turns south where it joins the elongate, residual positive gravity anomaly caused by the eastern flank of the Brande graben. This gravity anomaly, particularly within its northern part, corresponds rather closely to the valley D (Fig. 3). In Figure 4 this residual positive gravity anomaly is superimposed on the Bouguer gravity anomaly map.

Reflection seismic data

The reflection seismic lines in this part of Jutland are shown in Figure 6 against the residual gravity anomalies. Some geomorphological features, such as the two main stationary lines, are also shown. As in the previous figures, the limits of the N-S trending residual positive gravity anomaly are marked with red lines.

Several reflection seismic sections in the northwestern part of the map (Western Geophysical Co. of America 1982, 1983, Amoco Exploration Co. 1985, Phillips Co. 1985, 1986) were interpreted earlier in connection with the study of the Nøvling salt structure (Madirazza & Jacobsen 1998). Two reflection seismic sections (Prakla Seismos 1979) were interpreted in the process of investigating the suitability of the Paarup salt structure for the storage of the radioactive material. Furthermore, a number of the reflection seismic sections

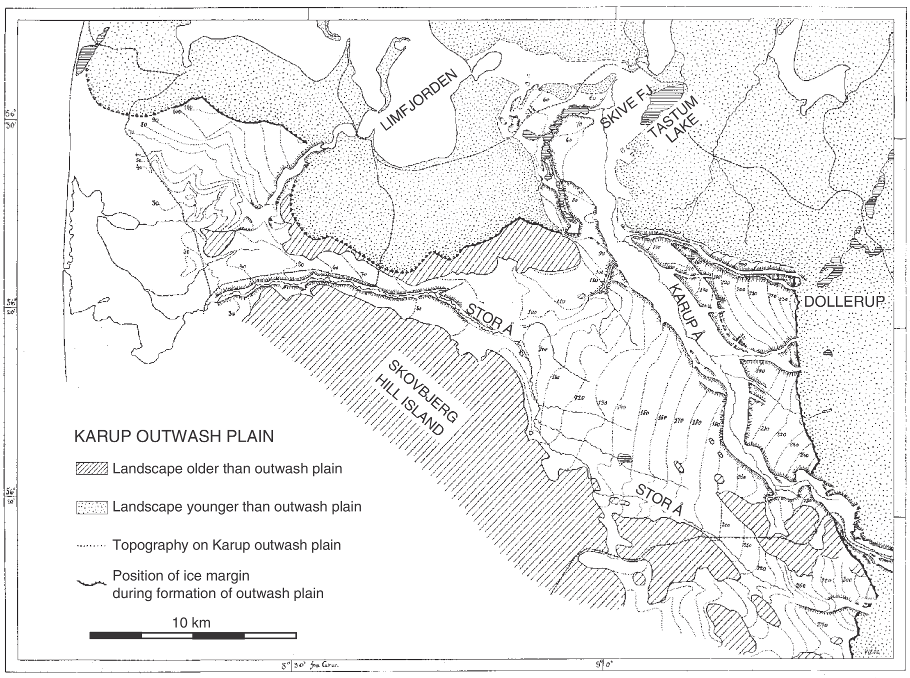


Fig. 2. Map of the Quaternary land forms in the study area (after Ussing 1903).

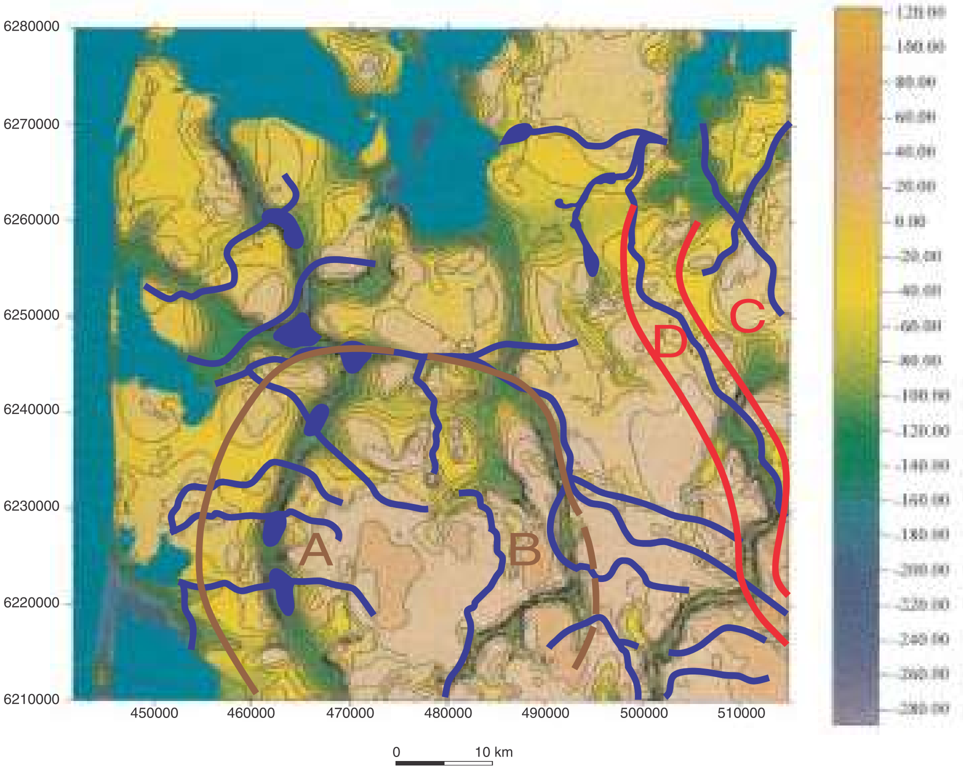


Fig. 3. The topography of the pre-Quaternary surface in a large part of the study area (after Binzer & Stockmar 1994, Friborg 2000).

(Western Geophysical Co. of America 1982, 1983) particularly in the southern part of the map were interpreted earlier (Lykke-Andersen, Madirazza & Sandersen 1996).

Seismic observations

The faults shown on the map (Fig. 7) are considered to be the most important faults, which can explain, in a coherent way, the structural development in the area studied. A majority of these faults are NW-SE trending, parallel, essentially strike slip faults that can be traced from the base Zechstein to the surface. In places, however, they may become very steep normal, or reverse, faults. They may also appear to be normal, or reverse, depending on the topography of the area.

A very important fault for the understanding of the structural development in the study area is the long NW-SE dextral strike slip fault which can be traced from the southeastern part of the Skovbjerg hill island, across the low ground of the late to postglacial outwash plain, to the eastern flank of the Brande graben. In the present discussion this fault will be referred to as the main fault (marked M in the figures).

An exception to the NW-SE trending strike slip faults is a long normal fault (marked W in Fig. 7) which, in its N-S striking part, dips steeply west. On the upthrown side this fault is closely followed by the residual positive gravity anomaly (marked with red lines). This part, as well as the positive gravity anomaly, turn southeast upon joining a long NW-SE dextral strike slip fault, which is subparallel to the main fault. Within this southeastern segment the normal fault dips steeply southwest. Then both the normal fault and the positive gravity anomaly turn sharply southwest. Thereafter the fault, as well as the gravity anomaly, assume their original N-S trends and join the east flank of the Brande graben.

Several reflection seismic sections in the northern part of the study area cross the normal fault (W) and the accompanying residual positive gravity anomaly. All these sections show a similar structural development where the faulting of the base Zechstein has taken place along the steep normal fault downthrown west. The western limit of the positive gravity anomaly coincides with the normal fault along which the base Zechstein has been strongly uplifted. On the upthrown side of this fault, the salt thickens gradually forming pillow type structures which trend parallel to the fault scarp. A typical section is shown in Figure 8. The flow of salt from the basin west of the normal fault began most likely during the post-Early Triassic. The pillow was growing gradually during the remaining Triassic. However, in the Jurassic the salt pillow(s) collapsed on the east side along several east dipping listric faults, and thick Jurassic was deposited on that side. Both in the Cretaceous and the tertiary the collapse has continued, but on a much smaller scale. The tertiary beds

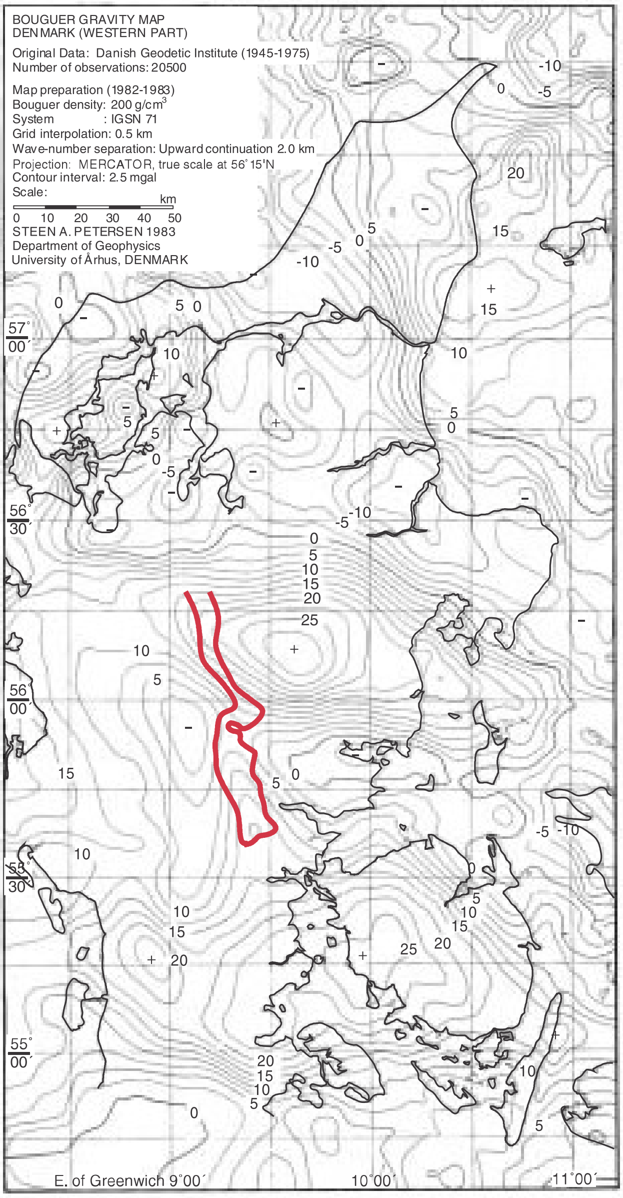


Fig. 4. Bouguer gravity map, western Denmark (Petersen 1983).

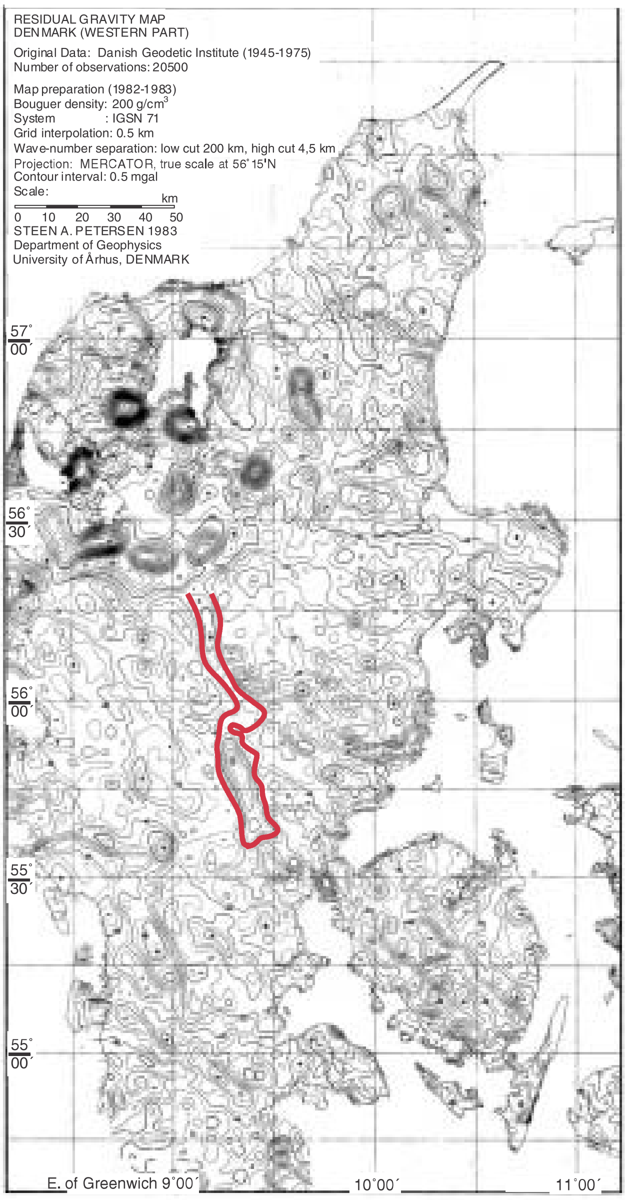


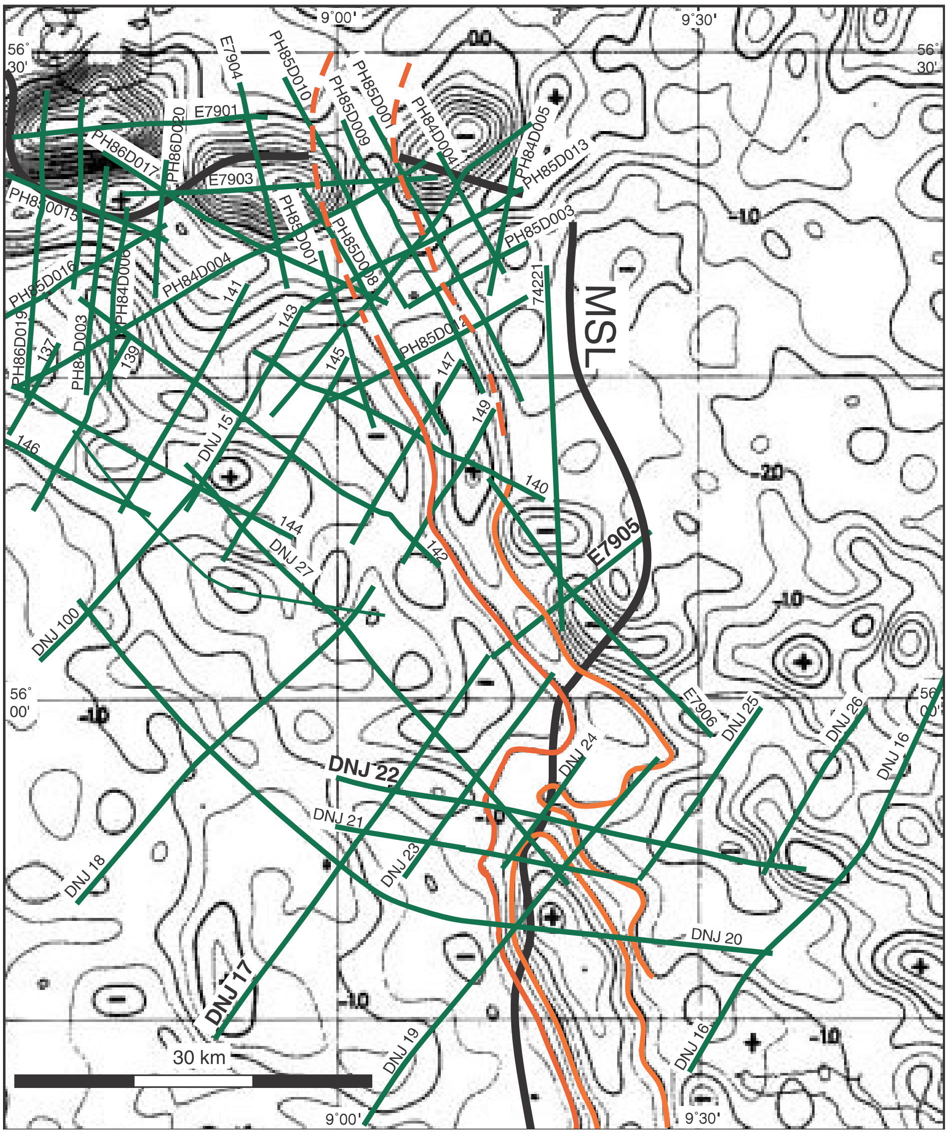
Fig. 5. Residual gravity anomaly map of the western part of Denmark (Petersen 1983). The insert, marked with red lines, shows a narrow residual positive gravity anomaly (which is also transferred to the Bouguer map).

west of the faulted area were uplifted and exposed to strong erosion. This area overlaps quite closely that of the observed positive gravity anomaly. Generally, this uplift did not coincide with the earlier highest lying areas, but it shifted somewhat westwards. In places grabens have developed in these areas above which depressions (up to 20 m deep) occur on the present surfaces (the late glacial Karup river valley has formed as a result of this surface deformation). The residual positive gravity anomaly, which starts at the normal fault downthrown west, ends in the areas where the salt pillows attain a certain thickness, as shown in Figure 8.

On some seismic sections crossing the normal fault the top Zechstein rests on the very top of the fault scarp, although west of the fault thick Zechstein salt is still present (e.g. Fig. 8). It is therefore assumed that the faulting of the base Zechstein took place before the deposition of the Zechstein evaporates. This subject will be treated again below.

The upthrown base Zechstein on the east side of the fault, where also the salt is much thinner, can provide an explanation for the western limit of the N-S trending positive residual gravity anomaly. However, as the salt gradually thickens on the upthrown side of the fault,

Fig. 6. Reflection seismic lines in the study area against the residual gravity anomalies. The limits of the N-S trending residual positive gravity anomaly are marked with red lines.



where pillow-type salt structures were forming, the positive gravity anomaly resulting from density differences, became less pronounced, or negative.

An alternative explanation of the causes of this N-S trending residual positive gravity anomaly could be that this anomaly indirectly reflects the topography of the Moho discontinuity which in this part of Jutland extends in a narrow N-S trending belt achieving the shallowest depths of 24-26 km (Thybo & Schöharting 1991, Zhou & Thybo 1996, Thybo 2000). The discussed N-S striking fault W, downthrown to the west, is parallel to the shallow Moho belt along its western boundary. Approximately in the same area, both the Moho discontinuity and the N-S trending normal fault, as well as the positive residual gravity anomaly which accompanies the fault, also change their directions and make a turn southeast. (For the form and depth of the Moho discontinuity, see Thybo 2000, especially Fig. 7A shown here in Fig. 9).

The change in direction of the normal fault occurs in the area where this fault and the above-mentioned NW-SE dextral strike slip fault join (see Fig. 7). Within this southeastern segment of the fault a depth converted reflection seismic section, E 7905, crosses perpendicularly the basement Zechstein normal fault W which here is nearly vertical and has a throw of about 800 m (Fig. 10). The residual positive gravity anomaly, here about 3 km wide, begins at the fault scarp, but in the vicinity of the Paarup salt diapir it changes to negative. Here the top of salt extends undisturbed across the W fault scarp, and on the upthrown side of the fault the thickness of salt is negligible. Below the salt diapir the dip of the basement increases from about 3° to 8° without any apparent displacement at the base-

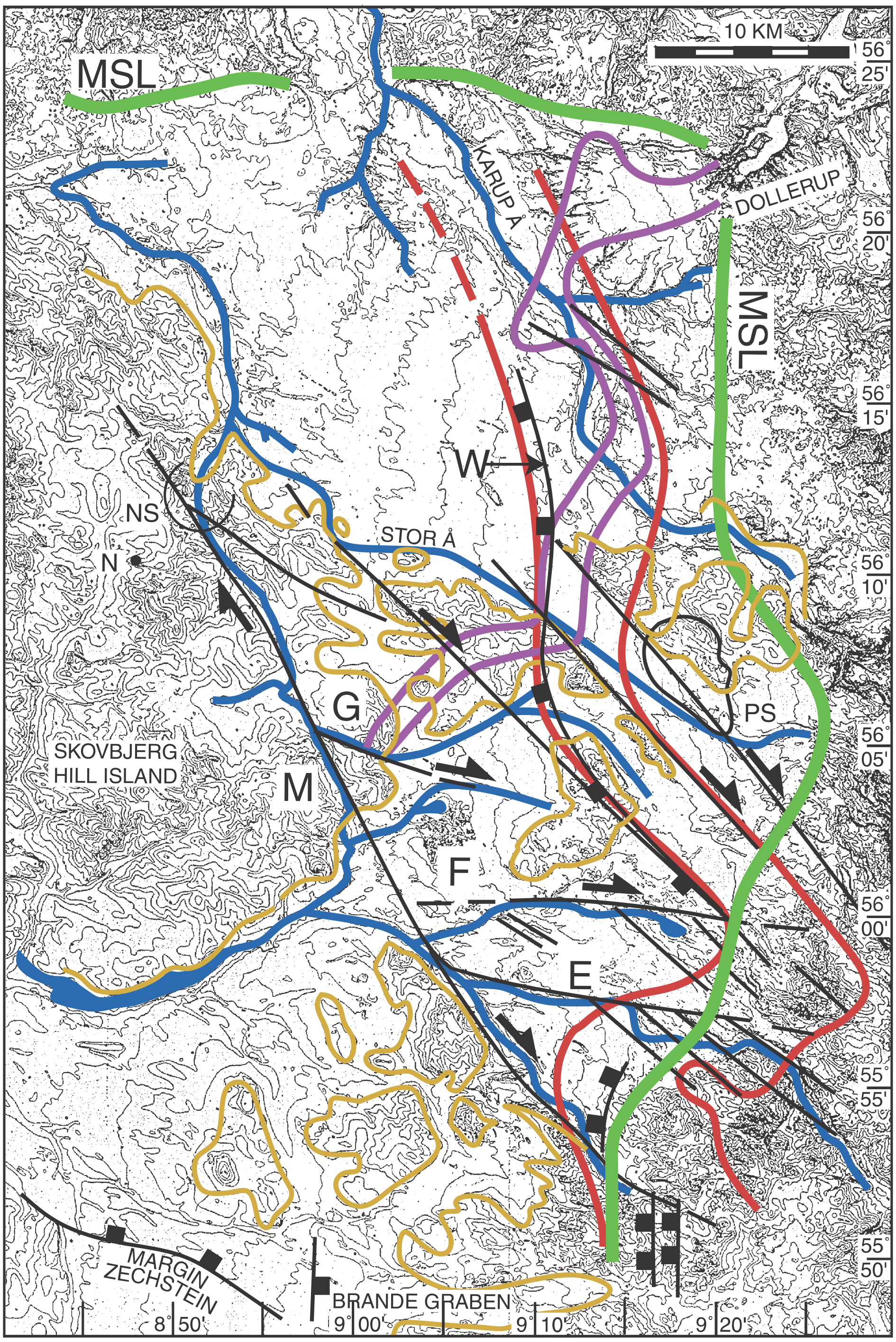
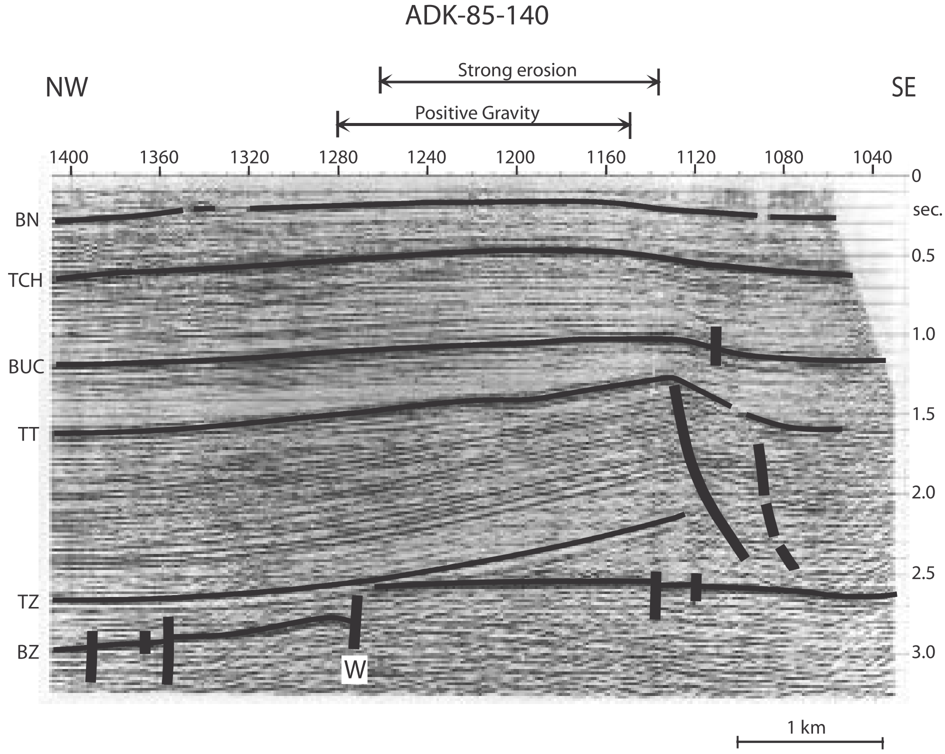


Fig. 7. Study area: Weichsel main stationary lines = green (MSL), two red parallel lines = limits of the residual positive gravity anomaly, PS = Paarup salt diapir, NS = Nøvling salt diapir, W = normal fault, blue = present drainage system.

ment level (an indication of strike slip faulting). This seismic section confirms the above interpretation, i.e.that the faulting of the base Zechstein has occurred before the deposition of the Zechstein evaporates, presumably towards the close of the Carboniferous or, at the latest, at the beginning of the Zechstein time. According to Jenyon (1985), in the British part of the North Sea this type of faulting is also known. It is thought that this was caused by a batholithic intrusion in the Upper Carboniferous-Lower Permian, and that the Zechstein salt was deposited against a high in the basement which resulted from normal faulting.

In the southeastern part of the map (Fig. 7) the normal fault (W), as well as the residual positive gravity anomaly, are strongly folded before they assume their original N-S orientation and join the eastern flank of

Fig. 8. Reflection seismic section ADK-85-140 from the northern part of the study area (for a detailed explanation, see text).



the Brande graben (compare with Figs 4 and 5). In this area the main fault (M) is joined by three E-W striking faults, marked E, F and G, which terminate at the main fault (Fig. 11). It is interesting to note that the N-S trending main stationary line in this area corresponds roughly to the compressed high ground. In front of these higher areas, the topographically low ground consists predominantly of outwash sediments. Here the extensional conditions dominate, but they also extend into the areas which were exposed to compression.

Within the triangular areas between the main fault M and the fault E, and between the fault E and the fault F, several minor NW-SE strike slip parallel faults have developed (see Figs 7 and 11). Narrow linear streams and shallow lakes are displaced in "en echelon" pattern across these secondary NW-SE striking faults. This type of faults is expecially well developed in the triangular area between the main fault and the fault E, but they also ocur between the faults E and F.

Such a complex structural situation can be explained by assuming that the main fault, as well as the faults E, F and G, are dextral strike slip faults, as shown in Figs 7 and 11. Within the inner parts of the folds, where compression is dominant, minor anticlines (max. about 1.5 km long), radiating from a common point, have formed. This is somewhat schematically shown in Figure 11 where there is no topographic background or possibly other disturbing details. The two areas between the main fault and the fault E, and between the faults E and F, share the common strike slip fault E. Here, dextral strike slip faults have formed

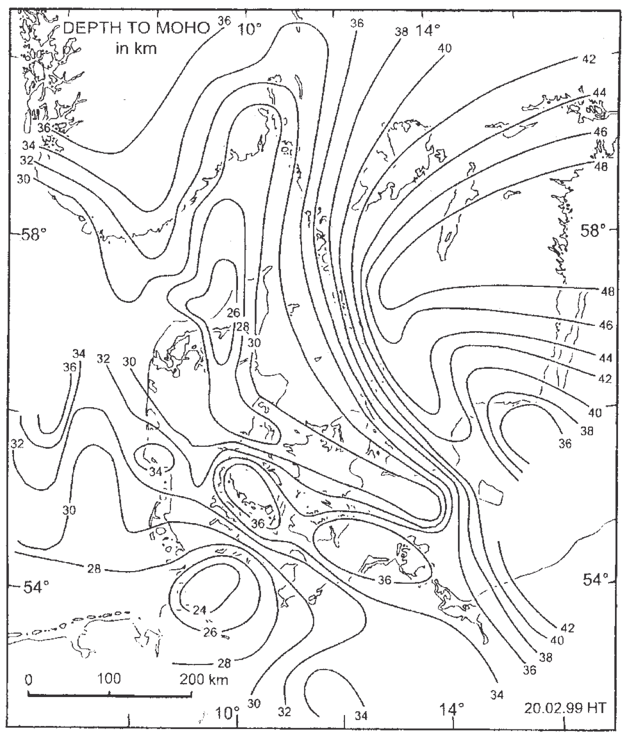


Fig. 9. Form and depth of the Moho discontinuity in Jutland and the surrounding areas (from Thybo 2000).

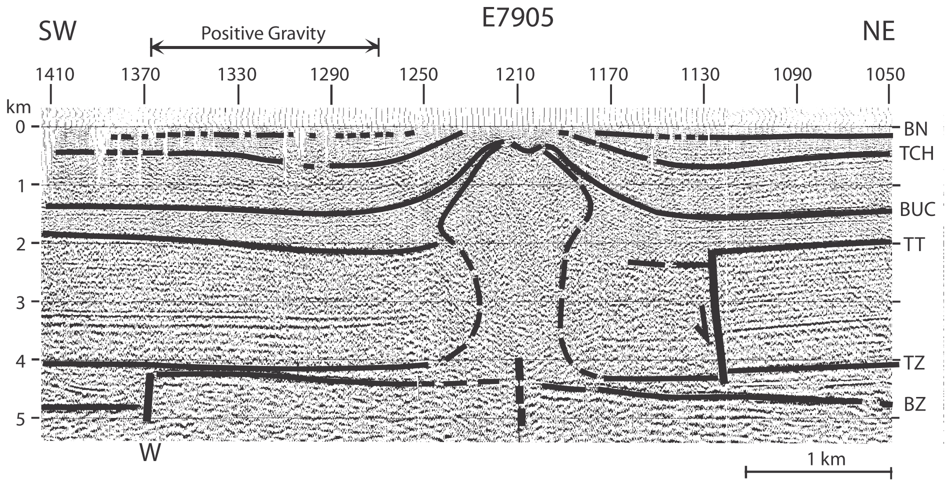


Fig. 10. Depth converted reflection seismic section E7905 crossing the Paarup salt diapir. BZ = Base Zechstein, TZ = Top Zechstein, TT = Top Triassic, BUC = Base Upper Cretaceous (base "chalk sequence"), TCH = Top Danian (top "chalk sequence"), BN = Base Neogene.

in response to a transtensional environment created between the main fault and the fault E, and between the faults E and F. However, these faults usually do not extend to the base Zechstein, but they affect only the tertiary and the upper part of the Cretaceous. Since these secondary extensional joints and faults were not disturbed in the compressed areas, it follows that they are younger than the folding of the N-S striking normal fault and the residual positive gravity anomaly.

The fault G is not so "clean" as the faults E and F, but also here transtension has developed between this fault G and the main fault. This is evidenced by the triangular downfaulted part of the Skovbjerg hill island where these two faults meet and where, conse-

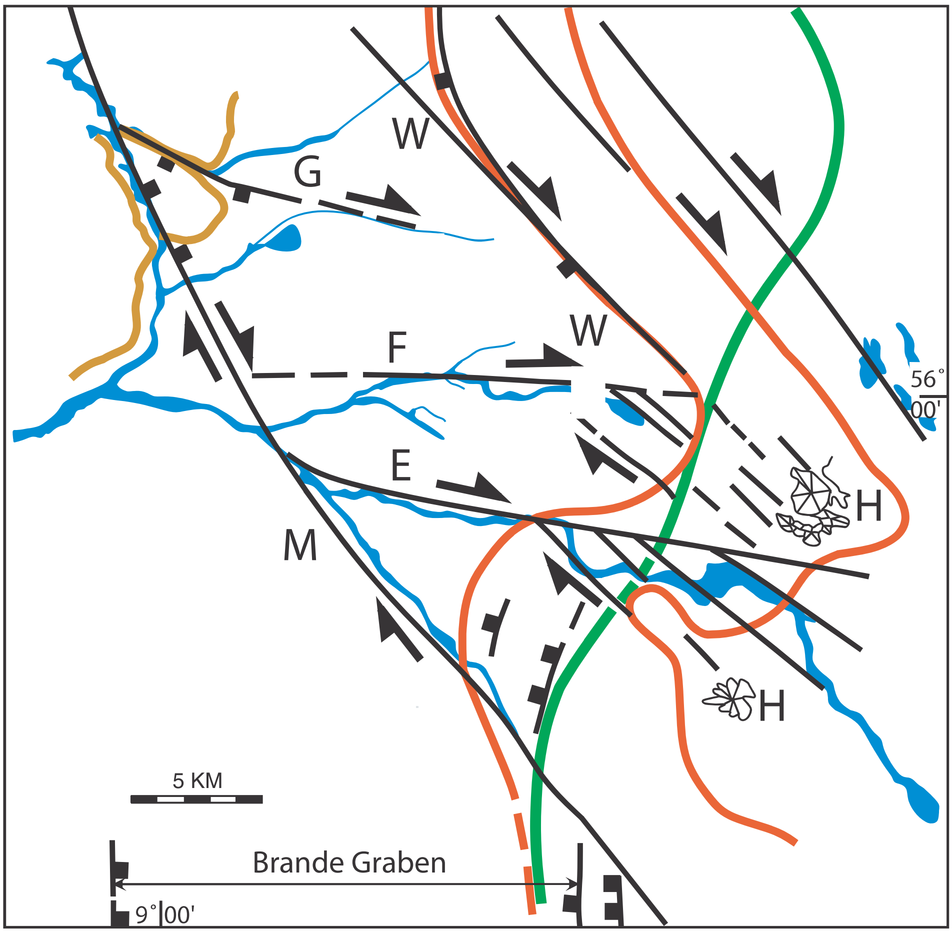


Fig. 11. A representation of the strike slip faulting system in the SE part of the study area.

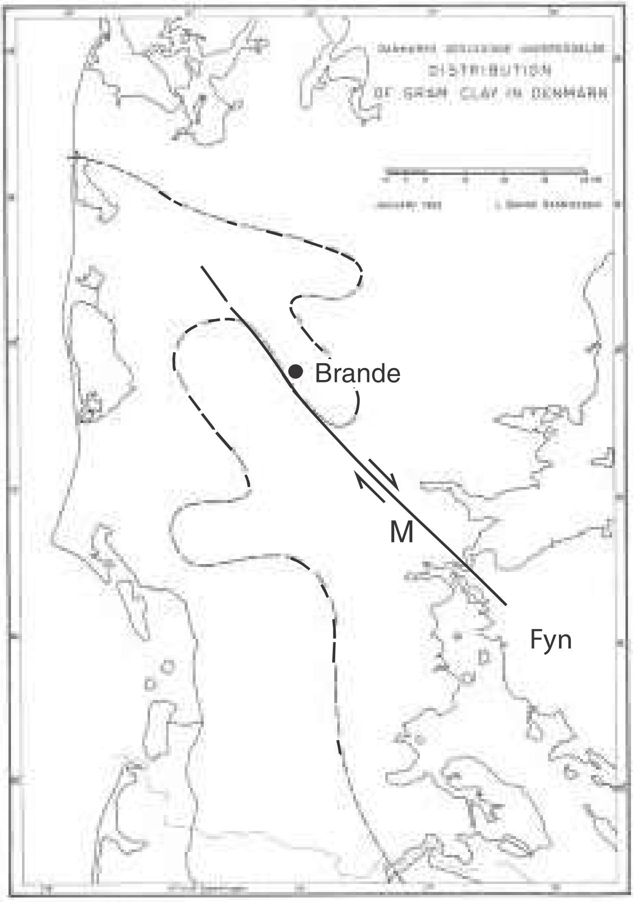


Fig. 12. N-W striking main fault (M) delimits the south side of the marine Neogene Gram Formation (Rasmussen 1966).

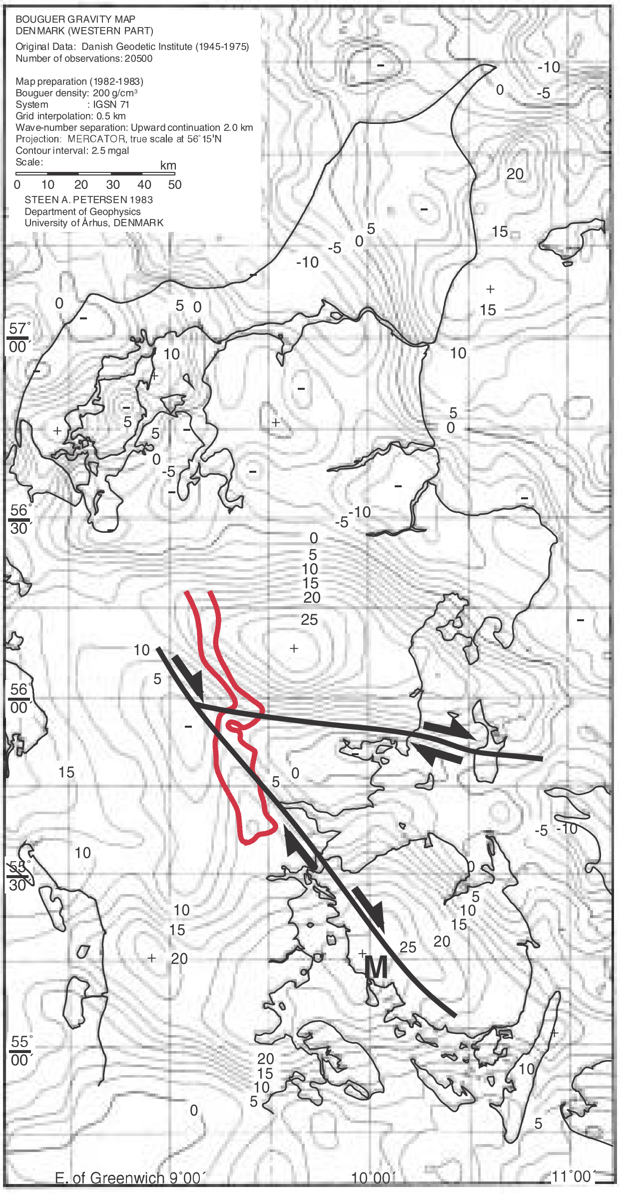


Fig. 13. Two dextral strike slip faults creating transtension between them. These two faults join in the study area. Furthermore, the normal fault and the positive residual gravity anomaly (marked with two red lines) are folded and deformed between the two faults within the study area. The main NW-SE fault (M), if extended in the same direction, would be parallel to the southwest coast of the island Fyn, while the E-W striking fault would touch the south side of Samsoe island.

quently, this part of the hill island is downfaulted (as shown in Figs 7 and 11). This discussion shows that the above described faults have been active also during the late to postglacial time. Within the transtensionally depressed part of the outwash plain between the main fault M and the faults F and G, extensive Middle Miocene brown coal deposits occur (e.g. Koch 1989). This suggests that in this part of Jutland an analogous tectonic regime has persisted since (at least) the close of the Miocene time.

Furthermore, the NW-SE main fault, extended in NW direction, marks the southwestern border of a narrow Upper Miocene marine embayment (Fig. 12) for some 30 km (the limits of the Upper Miocene deposits in this part of Jutland were determined by Rasmussen 1966).

If the main NW-SE fault and the E-W dextral strike slip fault E were projected eastwards, a large transtensional area in east Jutland would be created between them (Fig. 13). Pronounced gravity and topographic lows are present in this part of Jutland, where also large fjords (e.g. Horsens, Vejle) occur. If the E-W strike slip fault were projected even further east, it would touch the southern part of the island of Samsø (a possible existence off-shore of an E-W striking fault in that area was suggested earlier by Andersen & Tychsen 1977). The main fault projected further SE would cross the island of Fyn parallel to its southwestern coast. These considerations show that the main NW-SE fault is an important lineament in this part of the Danish basin which has been active up to the most recent times.

Conclusions

Based primarily on the gravity and reflection seismic data, an area in west Jutland, delimited by the Weichsel main stationary lines, is discussed. A narrow strip of a positive residual gravity anomaly extends from the area of the salt structures in the north to the eastern flank of the Brande graben in the south. On the west side this anomaly is delimited by a large, very steep Zechstein basement fault. Thick basement salt from the basin west of the fault has flowed across this basement fault forming salt pillow(s) on the upthrown side. It may be concluded from the seismic and gravity data that the basement fault is older than the salt movement, and that it is most likely of Carboniferous-Zechstein age. A number of NW-SE, essentially parallel, dextral strike slip faults arranged "en echelon" have dissected the Quaternary land forms. In the area of the Paarup salt diapir the throw of the normal fault amounts to some 800 m. In the southern part of the study area, the normal fault, as well as the positive residual gravity anomaly, are strongly folded before assuming their original N-S trends and joining the eastern flank of the Brande graben. In this southeastern part several E-W trending parallel strike slip faults terminate against the long NW-SE trending fault (here called the main fault). The dextral NW-SE strike slip "en echelon" faults between the E-W faults and the main fault formed in response to the transtensional environment created between the main fault and the E-W striking faults. It is suggested that the folding of the positive residual gravity anomaly resulted from the transtensional stresses created by the E-W fault and the main NW-SE fault. These two faults meet in the area discussed in the present paper.

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References

Andersen, H.L. & Tychsen, J. 1977: Danien kalkens overfladetopografi i egnen og farvandet omkring Århus. Dansk Geologisk Forening, Årsskrift for 1976, 69–73.

Binzer, K. & Stockmarr, J. 1994: Geological map of Denmark (Pre-Quaternary surface of Denmark). Geological Survey of Denmark, map series, No. 44, 10 pp.

Friborg, R. 2000: Kort over prekvartær – overfladens nuværende højdeforhold omkring Skovbjerg bakkeø. In Mellem hav og hede (efter Danmarks Geologiske Undersøgelse, kort serie 44. Aarhus Universitetsforlag, 2000).

Hansen, S. 1965: The Quaternary of Denmark. In Rankama, K. (ed.) The Quaternary 1, Interscience Publishers, New York. 1–90.

Hansen, S. & Milthers, K. 1954: Geological map of Denmark. Danmarks Geologiske Undersøgelse. In Rankama, K. (ed.) The Quaternary 1, Interscience Publishers. New York. 1–90.

Jenyon, M.K. 1985: Fault associated salt flow and mass movement. Journal of the Geological Society 142, 547–553.

Koch, S.E. 1989: Geology of the Søby-Fasterholt area. A paleontological and geological investigation of the Miocene brown coal bearing sequence of the Sæby, Fasterholt area, Central Jutland, Denmark. Danmarks Geologiske Undersøgelse, A22, 170 pp., atlas, 121 pp.

Lykke-Andersen, H., Madirazza, I. & Sandersen, P.B.E. 1996: Tektonik og landskabsdannelse i Midtjylland. Geologisk Tidsskrift 3, 1-32.

Madirazza, I. 1968: An interpretation of the Quaternary morphology in the Paarup salt dome area. Bulletin of the Geological Society of Denmark 18, 241–243.

Madirazza, I & Jacobsen, B.H. 1998: Nøvling: An unusual salt structure on the southern margin of the Danish Zechstein Basin. Bulletin of the Geological Society of Denmark 44, 139–149.

Madsen, V. 1926: Terrainformerne på Skovbjerg Bakkeø. Danmarks Geologiske Undersøgelse B4, 12, 1–24.

Milthers, V. 1939: Beskrivelse til geologisk kort over Danmark. Kortbladet Brande. Danmarks Geologiske Undersøgelse, 1, 18, 162 pp.

Petersen, S.A. 1983: Salthorst kortlægning på grundlag af gravimetri kombineret med seismisk interpretation. Unpublished Ph.D. thesis, Department of Earth Sciences, University of Aarhus, 114 pp.

Rasmussen, L.B. 1966: Moluscan faunas and biostratigraphy of the marine younger Miocene formations in Denmark. Part I: geology and biostratigraphy. Danmarks Geologiske Undersøgelse, II række 88, 358 pp.

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

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.

Ussing, N.V. 1903: Om Jyllands Hedesletter og Teorierne for deres Dannelse. Oversigt over det Kongelige Danske Videnskabernes Selskabs Virksomhed 2, 99–154.

Zhou, Z. & Thybo, H. 1996: Calculation of residual gravity anomalies in Northern Jutland, Denmark. First Break 14, 4, 129–134.