The formation of the Voldum salt pillow in the Danish Zechstein basin, Jutland (Denmark)

IVAN MADIRAZZA

Madirazza, I: The formation of the Voldum salt pillow in the Danish Zechstein basin, Jutland. 1999–12–20. *Bulletin of the Geological Society of Denmark*, Vol. 46, pp. 31–46, Copenhagen. https://doi.org/10.37570/bgsd-1999-46-04

On the basis of seismic and well data, supported by Bouguer gravity data, the sequence of events leading to the formation of a Zechstein salt pillow – called Voldum – in east central Jutland is discussed (the study area is delimited in Fig. 1). The initial salt movements, activated by faulting in the Triassic, resulted in the formation of a minor salt pillow on the edge of a graben within the Zechstein (Upper Permian) basin. During a renewed faulting (Voldum fault) of the base Zechstein in Late Jurassic and consequent deepening of the graben, a syncline developed above the salt where thick sediments of Late Jurassic age accumulated. In the process large quantities of salt, due to differential loading, withdrew from the graben and moved laterally up-dip across the older fault scarps. Thus a new and larger salt accumulation (Voldum pillow) formed above the southern flank of the graben. A relict Triassic thin, formed during the growth of the first pillow, remains, but no salt accumulation which could account for this thin is present. The Voldum pillow continued to grow during the Cretaceous and the Tertiary, but the speed of growth decreased considerably during post-Late Cretaceous times, although there are still large quantities of, virtually undisturbed, salt present south of the pillow in the part of the basin corresponding to the Silkeborg Gravity High. The graben area apparently underwent a mild inversion at the close of the Cretaceous. The reasons why the Voldum pillow did not develop into a diapir are considered to be a strong and thick overburden which existed at the beginning of the Voldum pillow formation, the deeply buried salt which probably acted as a deterrent to the rupture of the overburden, and the nature of the Voldum fault which, apparently, had an appreciable strike-slip component in dextral sense.

Key words: Danish Zechstein basin, Voldum fault, Voldum salt pillow, reflection seismic and gravity data, Silkeborg Gravity High.

Ivan Madirazza, Department of Earth Sciences, University of Aarhus, Finlandsgade 8, DK-8200 Aarhus N, Denmark, 7 June 1999.

A number of authors have theorized on the subject of initiation of salt movement and the beginning stages of the formation of salt structures, e.g.: Arrhenius & Lachmann (1912), Stille (1925), Harrison (1927), Barton (1933), Nettleton (1943), Parker & McDowell (1955), Lotze (1957), Trusheim (1957, 1960), Sannemann (1968), Christian (1969), Seni & Jackson (1983a, 1983b), Jenyon (1985, 1986), Jackson & Vendeville (1994), Sørensen (1998). The role which the faulting of the basin floor played in this process has been assigned differing importance, but there seems to be a general agreement that, once the salt movement is initiated, the density differences inherent in the system are sufficient for the movement to continue. However, certain salt structures, such as Voldum, did not develop beyond the pillow stages, although all the conditions necessary for the rise of salt to shallow depths seem to have been present.

In the onshore part of the Danish basin a majority of salt structures are diapirs grouped in a minor, strongly faulted, part of northwest Jutland, while only a few are of pillow type (Fig. 1). The Bouguer and residual gravity maps (Petersen 1983) are shown in Figures 2 and 3, respectively. From the seismic information it

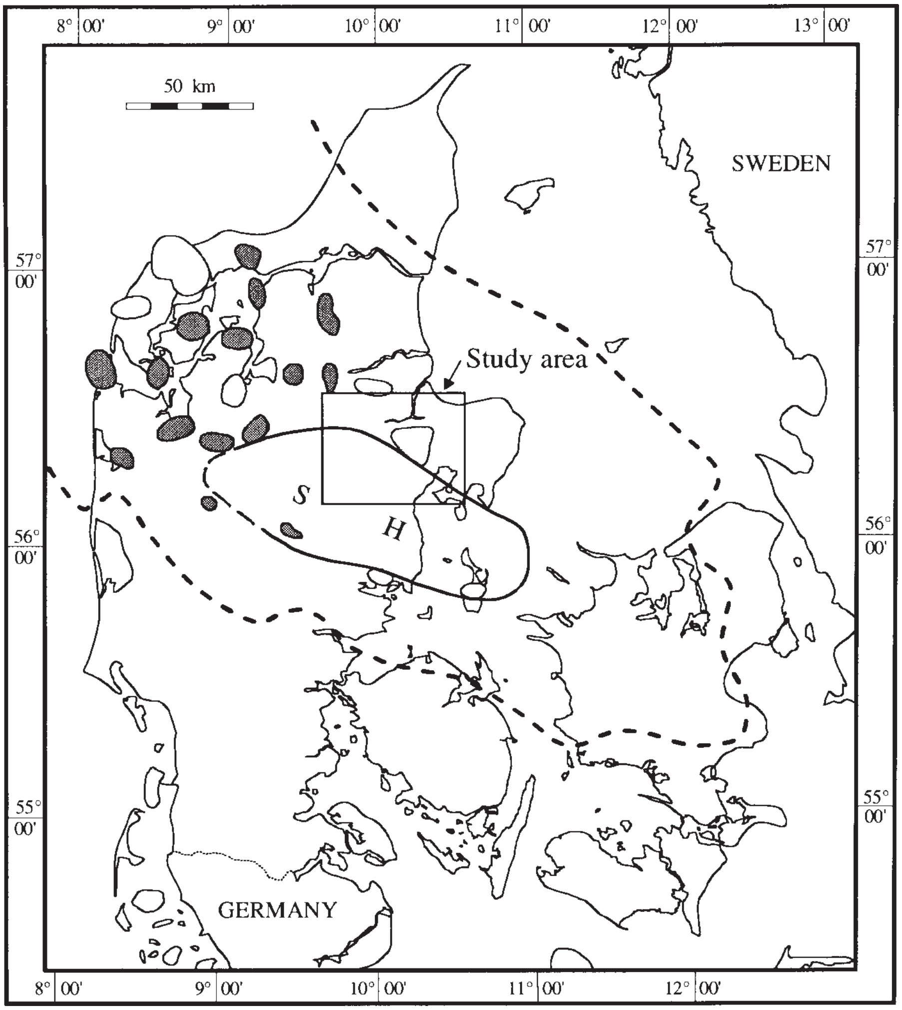


Fig. 1. Study area, east central Jutland, Denmark, with the outline of Voldum salt pillow. Dashed line marks the approximate extent of marine Zechstein (Upper Permian) in the Danish basin (slightly modified after Prisholm & Christensen 1985). Outlines of salt structures: pillows = light grey, diapirs = dark grey. SH = part of the basin corresponding to the Silkeborg Gravity High.

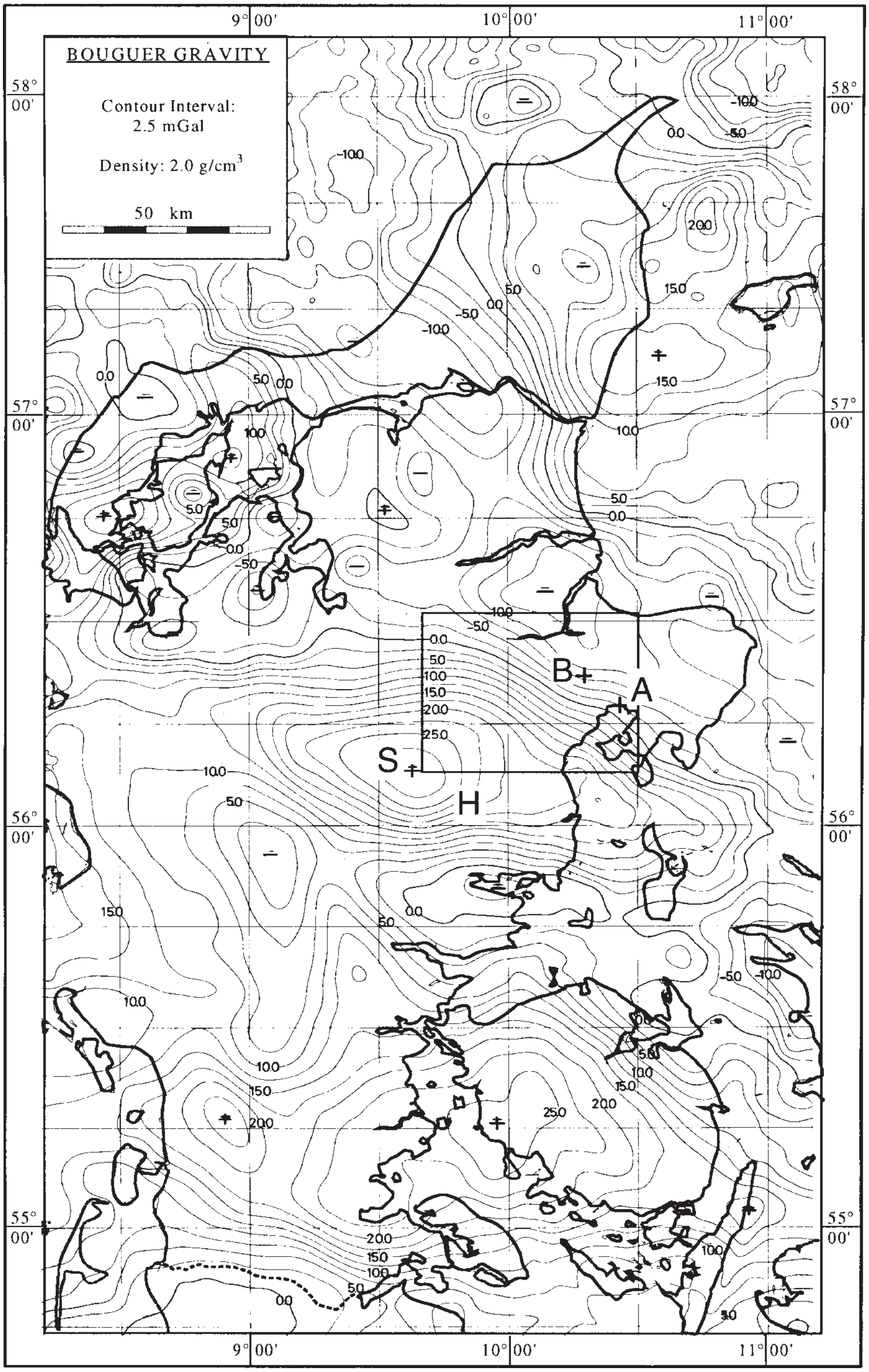
appears that the first salt movements on a larger scale resulting in the formation of pillow-like structures took place mainly during the Middle Keuper and/or Rheatic, contemporaneously with the faulting of the Zechstein basin floor (Madirazza 1986). Apparently all these structures have later developed into diapirs. The younger pillows that began to form in the Jurassic, or at the Jurassic/Lower Cretaceous boundary, e.g. Gassum (Sorgenfrei 1964), Thisted (Madirazza 1981), Voldum (Madirazza 1986) did not develop into diapirs. However, the growth of these pillows continued in the Late Cretaceous and, at a slower rate, in the Tertiary and the Pleistocene. Such a picture implies that for the piercement of the post-Zechstein strata, apart from the density differences inherent in the system, extensional faulting of the basin floor resulting in differential loading, is necessary for the piercement to take place (on this subject see e.g. Jackson, Vendeville, Cramez & Duval 1993, Jackson & Vendeville 1994).

Within a large southern part of the Danish basin „overlapping“ the Silkeborg Gravity High (Figs 1-3) no major salt movements have taken place although the thickness of the Zechstein salt is about 1 km, and that of the Triassic overburden alone some 2 km (Abrahamsen & Madirazza 1986). Only along the margins of this strong positive anomaly, where the Zechstein basin floor is downfaulted away from the center of the anomaly, several salt structures have developed. Along the northeastern side of this anomaly a large pillow, Voldum, has grown (Figs 1, 3). The Silkeborg Gravity High anomaly is attributed to a Lower Permian igneous intrusion in the crust where Moho has risen some 4 km to 28 km depth (Thybo & Schönharting 1991, Zhou & Thybo 1996).

Voldum salt pillow

The inserts in Figures 1-3 delimit the area of the present study. In Figures 2 and 4, the sites of two exploratory wells, Rønde-1 and Voldum-1, drilled in the

Fig. 2. Bouguer gravity, western Denmark (from Petersen 1983, courtesy of the author). The insert shows the study area and the sites of two exploratory wells: A = Rønde-1, B = Voldum-1, SH = Silkeborg Gravity High.



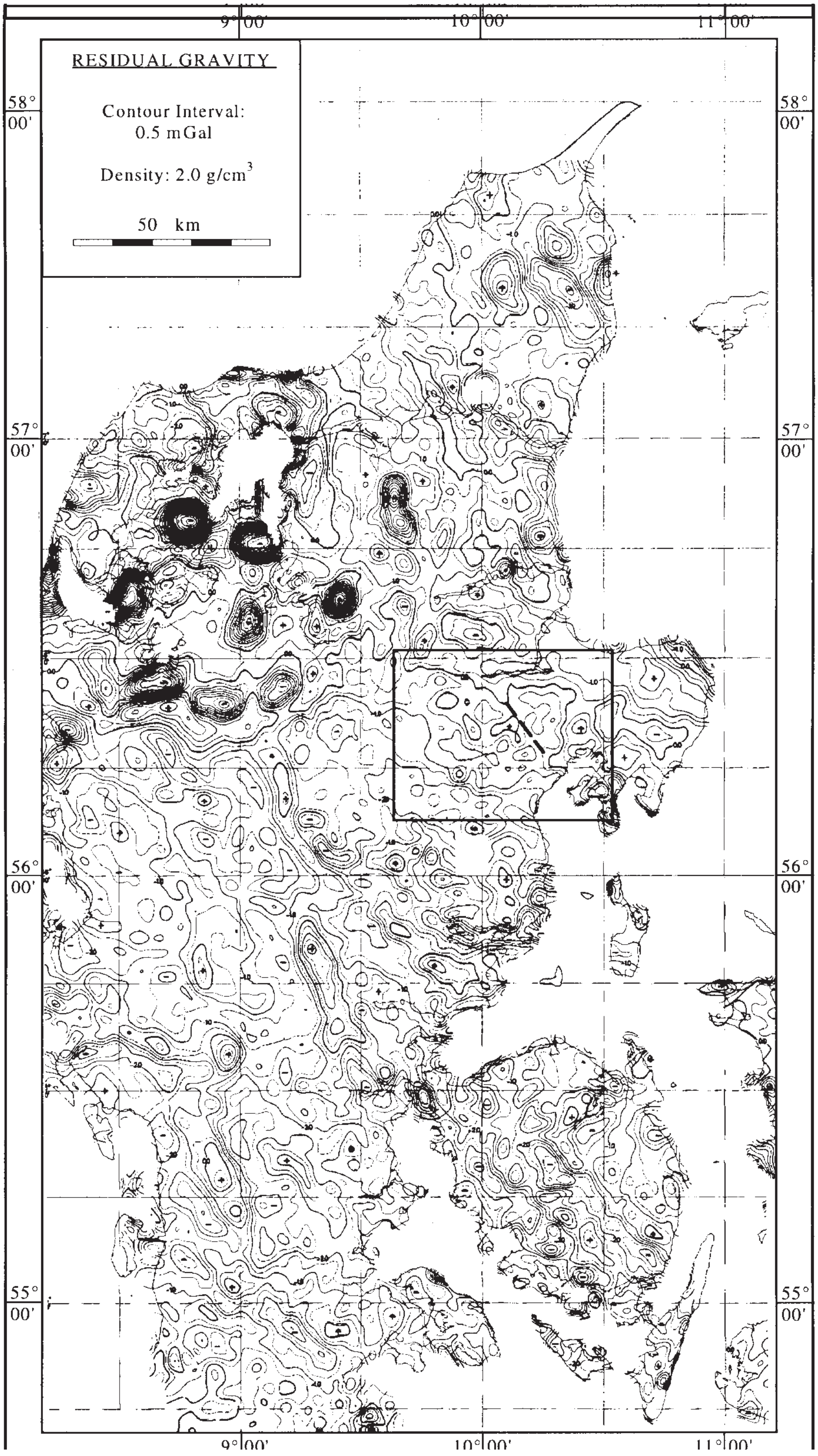


Fig. 3. Residual gravity, western Denmark (from Petersen 1983, courtesy of the author). The insert shows the study area. Dashed line marks the southwest side of the triangular negative anomaly caused by the Voldum salt pillow.

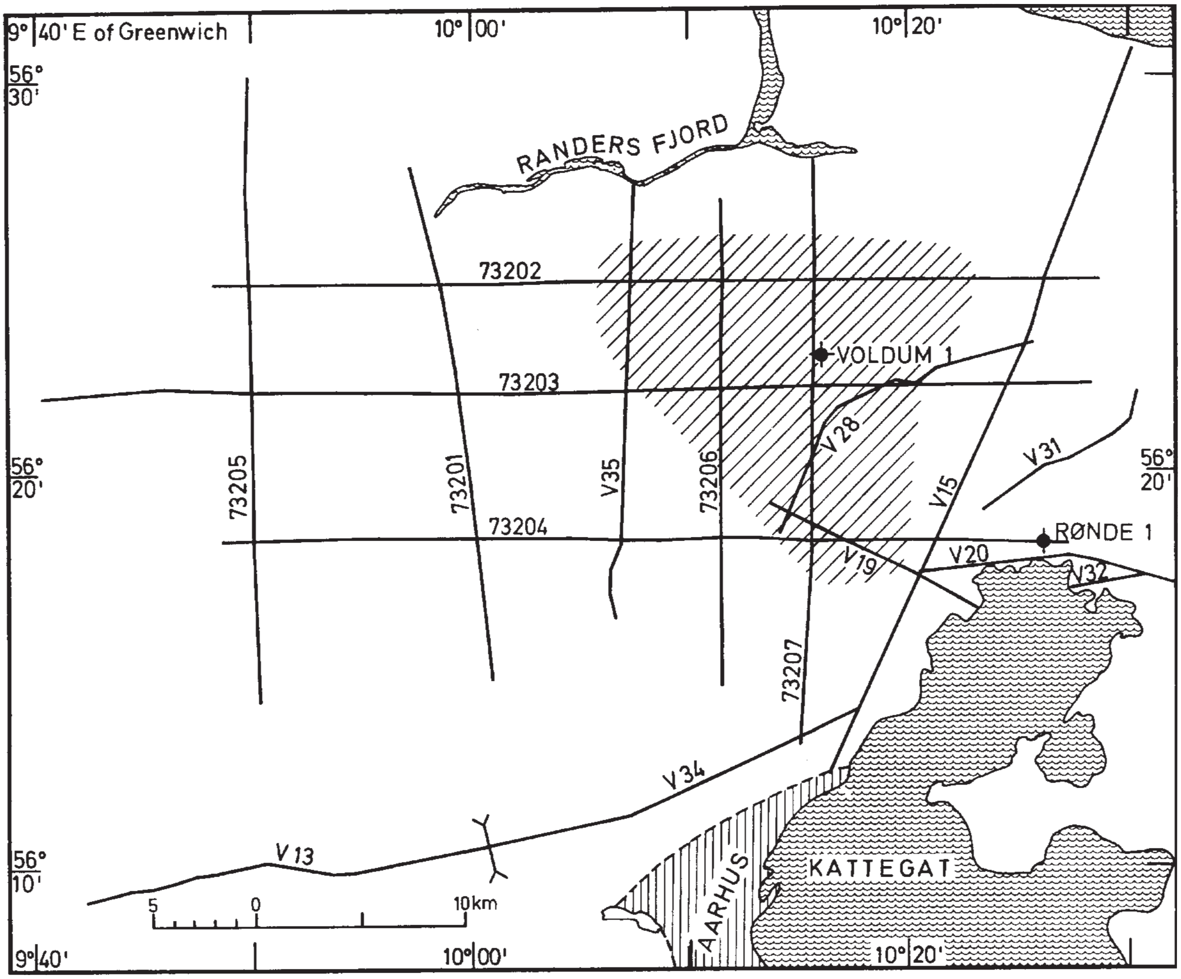


Fig. 4. Location map of the reflection seismic lines and the sites of two exploratory wells Rønde-1 and Voldum-1 in the study area. The reflection seismic sections beginning with "73" were acquired by Prakla-Seismos and those marked with "V" by Seismograph Service Ltd (England). The hatched part indicates the extent of the Voldum salt pillow based on the present seismic study (compare with the residual gravity anomaly caused by this pillow, Fig. 3).

area, are marked. The locations of the reflection seismic time sections used in the present discussion are shown in Figure 4. The triangular area (shaded) occupied by the Voldum salt pillow, as inferred from the present seismic study, compares well with the gravity picture where this pillow causes a minor negative residual anomaly (compare Figs 3 and 4).

Wells Rønde-1 and Voldum-1

Simplified geological logs of these two exploratory wells are shown in Figure 5. A detailed description of Rønde-1 is given in Rasmussen (1971), and that of Voldum-1 in Michelsen (1978a). In Rønde-1 (TD 5294 m) the Zechstein sequence is 230 m thick. Halite makes less than a half of the sequence, the rest consisting of carbonates, anhydrites, and some clastics. Below the Zechstein a thin sandstone of, presumably, Early Permian age occurs (Jacobsen 1971). Voldum-1 (TD 2307 m) was terminated in the rocks of Late Triassic Keuper age. In Figure 5 the thickness of the Triassic at Voldum-1 was constructed assuming that the seismic velocity of this interval is the same as in Rønde-1, while, in the construction of the Zechstein interval, the seismic velocity of 4600 m/s was used.

The thicknesses of the Jurassic/Lower Cretaceous sequence in these wells do not differ significantly (510 m in Voldum-1, 630 m in Rønde-1). The bulk of this sequence in both wells consists of the Lower Jurassic Fjerritslev Formation (334 m in Voldum-1 and 475 m in Rønde-1). The Middle Jurassic is represented by a very thin (30 m) Haldager Formation in Voldum-1, while this formation is absent in Rønde-1. Nondifferentiated Upper Jurassic/Lower Cretaceous is 110 m thick in Voldum-1, and only 37 m in Rønde-1. The

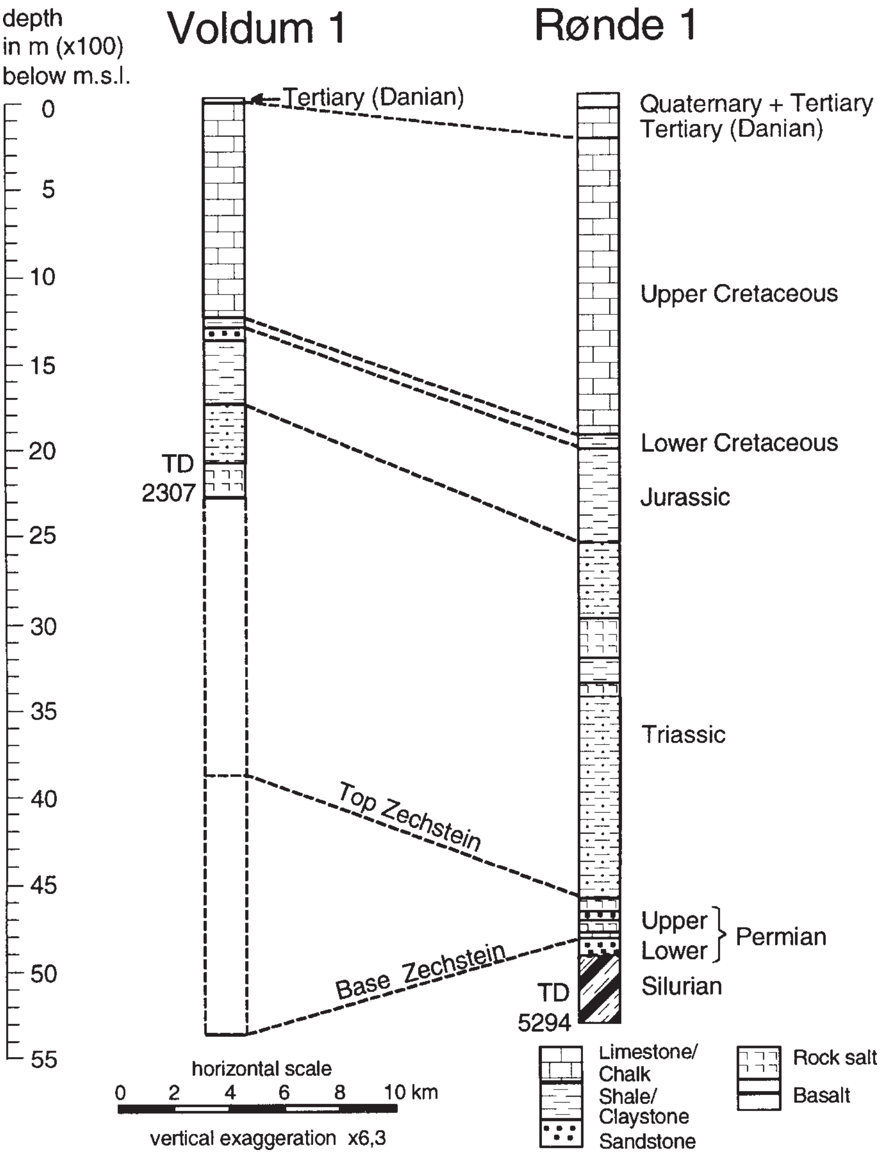


Fig. 5. Simplified geological logs of the wells Voldum-1 and Rønde-1 (after Michelsen 1978a and Rasmussen 1971, respectively). The lower dashed section below Voldum-1 was constructed on the basis of seismic and well data (see text).

thickness of the Upper Cretaceous limestone is 1221 m in Voldum-1 and 1676 m in Rønde-1. The Lower Paleocene Danian limestone is 122 m thick in Rønde-1 and only 26 m in Voldum-1. The post-Danian Tertiary is not present in the area of the Voldum pillow. However, from the regional geological picture (Sorgenfrei & Bertelsen 1954, Fig. 28), it may be concluded that the post-Danian Tertiary sediments, as well as a major part of the Danian limestone, especially in Voldum-1, were eroded. Both wells are located less than 200 m from the seismic lines: Voldum-1 at 73207 and Rønde-1 at 73204. The distance between the two wells is 13.7 km.

Base Zechstein horizon

Figure 6 shows the isochron map of the base Zechstein horizon. In the northeastern part of the map this horizon is dissected by several sub-parallel faults trending northwest, i.e. parallel to the ”border” of the Silkeborg Gravity High (compare with Fig. 2). The faults are downthrown to the northeast, apart from a couple of faults in the corner of the map which are downthrown in the opposite sense. Typically, the offsets across the individual faults vary within short distances, and several faults apparently die out within the area. In this faulted part, limited by the prominent Voldum fault in the southwest, the base Zechstein is strongly deformed, while in the large remaining part, corresponding to the Silkeborg Gravity High, this horizon seems to be

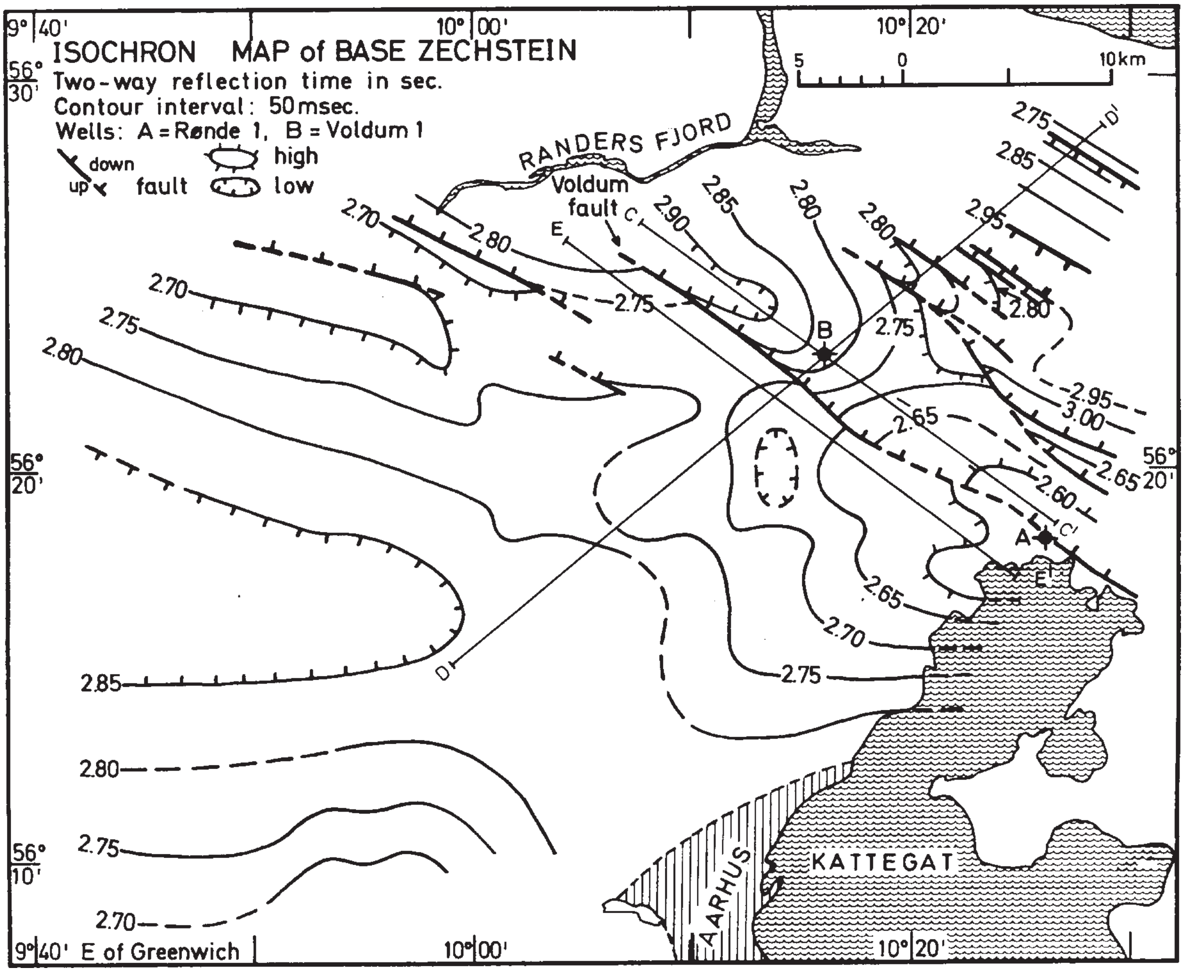


Fig. 6. Isochron map of the base Zechstein horizon. Along the lines C-C', D-D', E-E' profiles were constructed (shown in Figs 8, 9, 10).

essentially undisturbed. West of the Voldum fault, three northwest trending parallel faults with minor offsets are present. North of Aarhus there is a high having a relief of some 500 m. On top of this high the well Rønde-1 is located (for location of this well see also P.A. Ziegler, as published in Liboriussen, Ashton & Tygesen 1986). From the general configuration of the entire area, and the fact that the Zechstein sequence is quite thin in this borehole although it is located well within the limits of the Zechstein basin, it seems that this basinal high is an original topographic feature. We shall return to this question in the discussion on salt movements.

Isopach map of the Zechstein interval

In Figure 7 the isopach map of the Zechstein interval is shown together with the faults displacing the base Zechstein (transferred from Fig. 6). In none of the seismic sections, however, do these faults cut the top Zechstein interval, i.e. displace the base Triassic, regardless of the severity of deformation at the base Zechstein level (see Figs 8, 13). In the northeastern faulted part of the area the Zechstein thickness varies greatly, whereas in the rest of the area, corresponding to the Silkeborg Gravity High, the thickness of this interval remains quite uniform (900 – 1000 m). The Zechstein interval is thickest (up to about 1500 m) on the downthrown side of the Voldum fault. It should be pointed out, however, that the vertical displacement along the southeast segment of this fault is rather negligible, and it might appear that the fault dies out in that direction. In Figure 6 this segment is therefore indicated by a dashed line connecting this part of the fault with a very pronounced normal fault just north of the Rønde well.

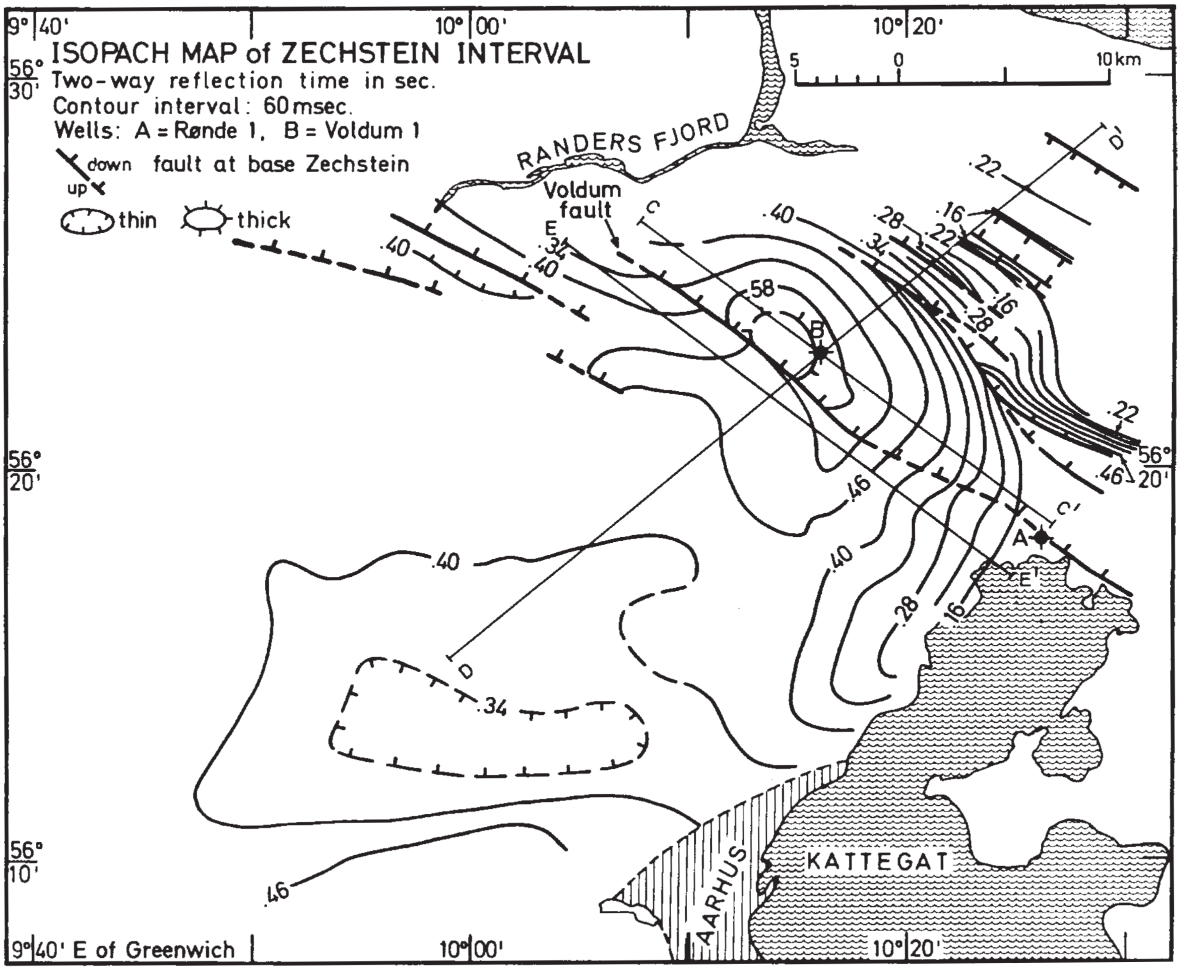


Fig. 7. Zechstein TWT isopach map with the locations of constructed profiles C-C', D-D', E-E'.

Profiles C-C', D-D', E-E'

A profile perpendicular to the faulting trend in the northeast was constructed along the line D-D'. Furthermore, two more profiles, parallel to the Voldum fault, were constructed: one on its downthrown side (line C-C'), and one on its upthrown side (line E-E'). For locations of these profiles, see Figures 6, 7.

In the southwestern end of the profile D-D' (Fig. 8), which is perpendicular to the faulting trend, along the first approximately 5 km, the Zechstein interval retains the thickness considered as normal (~ 1000 m) for the large nonfaulted part of the area . Gradually the salt reaches its greatest thickness above the downthrown side of the Voldum fault, and then it thins rapidly above the other faults and towards the axial parts of the syncline in the northeastern part of the profile. Beyond that the thickness of the Zechstein interval increases again.

In the profile C-C' (Fig. 9), parallel to the Voldum fault on its downthrown side, the salt thickens gradually from the northwest, attaining its maximum thickness in the area of Voldum-1, and thins abruptly up the slope of the base Zechstein high. At the end of this profile the projected thickness of the Zechstein interval would be nearly the same as in Rønde-1, located about 1 km to the south. A similar picture is encountered along the profile E-E' on the upthrown south side of the Voldum fault (Fig. 10). Here, however, the base Zechstein gradient is less steep and the salt accumulation thinner than on the downthrown side of this fault.

Isopach map of the Triassic interval

The isopach map of the Triassic interval with the faults displacing the base Zechstein (transferred from Fig. 6) is shown in Figure 11.

A well defined elongate Triassic „thin“ is present above the faults in the base Zechstein northeast of the

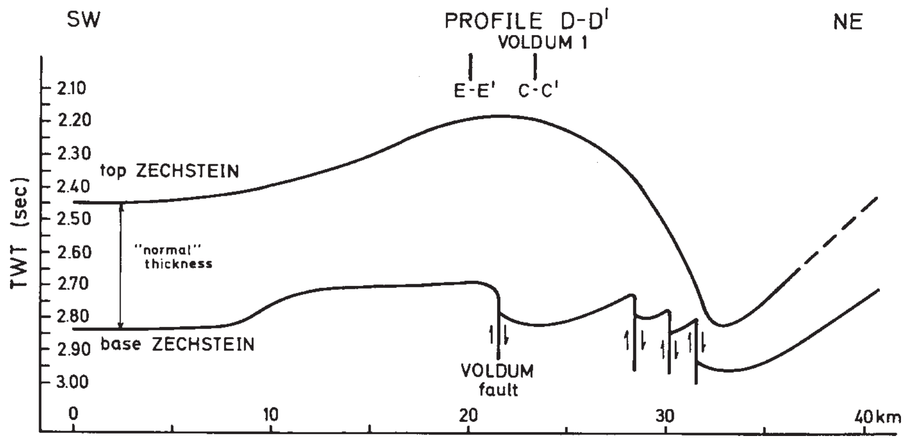


Fig. 8. Seismic profile, constructed along the line D-D', perpendicular to the faulting trend (for location, see Fig. 7).

Voldum fault (similarly, the Triassic thins somewhat above the minor faults west of this fault). The trend of this Triassic thinning parallels the faulting trend. A comparison with the Zechstein isopach map (Fig. 7), or the profile D-D' (Fig. 8), does not show salt thickening which could account for this Triassic „thin". However, in the area of the prominent Voldum fault, where the *largest* salt accumulation occurs, no comparable thinning of the Triassic is present, and the thickness pattern of this interval shows no parallelism to the underlying Voldum fault. The distance between the Voldum fault and the Triassic "thin" is some 7-8 km.

Reflection seismic section V 15

Although the section V 15 is only of fair quality, the main reflections can be safely traced through most of its length (for location see Fig. 4). The seismic line drawing of this section is shown in Figure 12. This section is quite marginal to the Voldum salt pillow, however, it crosses the entire graben structure on the east side of the pillow. The presence of such a structure may also be recognized in the constructed profile D-D' (Fig. 8). Although the seismic evidence in this part of the area is insufficient, from the northwest trending faulting pattern and the isopach maps of both Zechstein and Triassic intervals (Figs 7, 11), it may be safely assumed that the graben has the same trend. This is furthermore supported by the Bouguer gravity (Fig. 2) where this area corresponds to a clear nega-

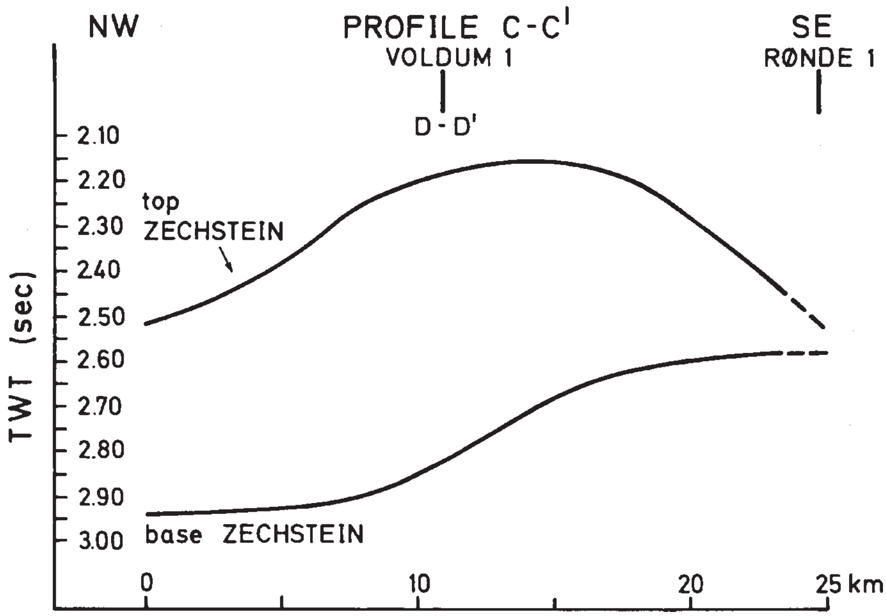


Fig. 9. Seismic profile, constructed along the line C-C', parallel to the Voldum fault on the downthrown side (for location, see Fig. 7).

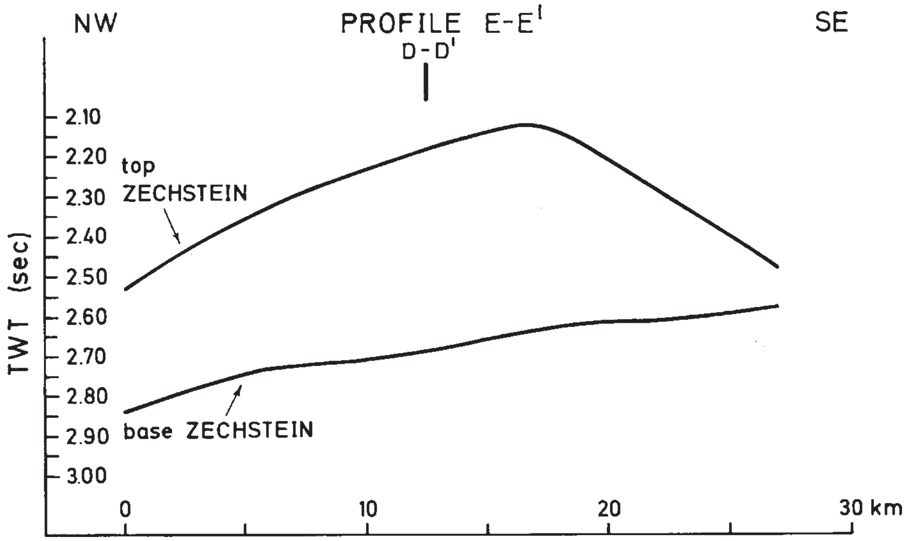


Fig. 10. Seismic profile, constructed along the line E-E', parallel to the Voldum fault on the upthrown side (for location, see Fig. 7).

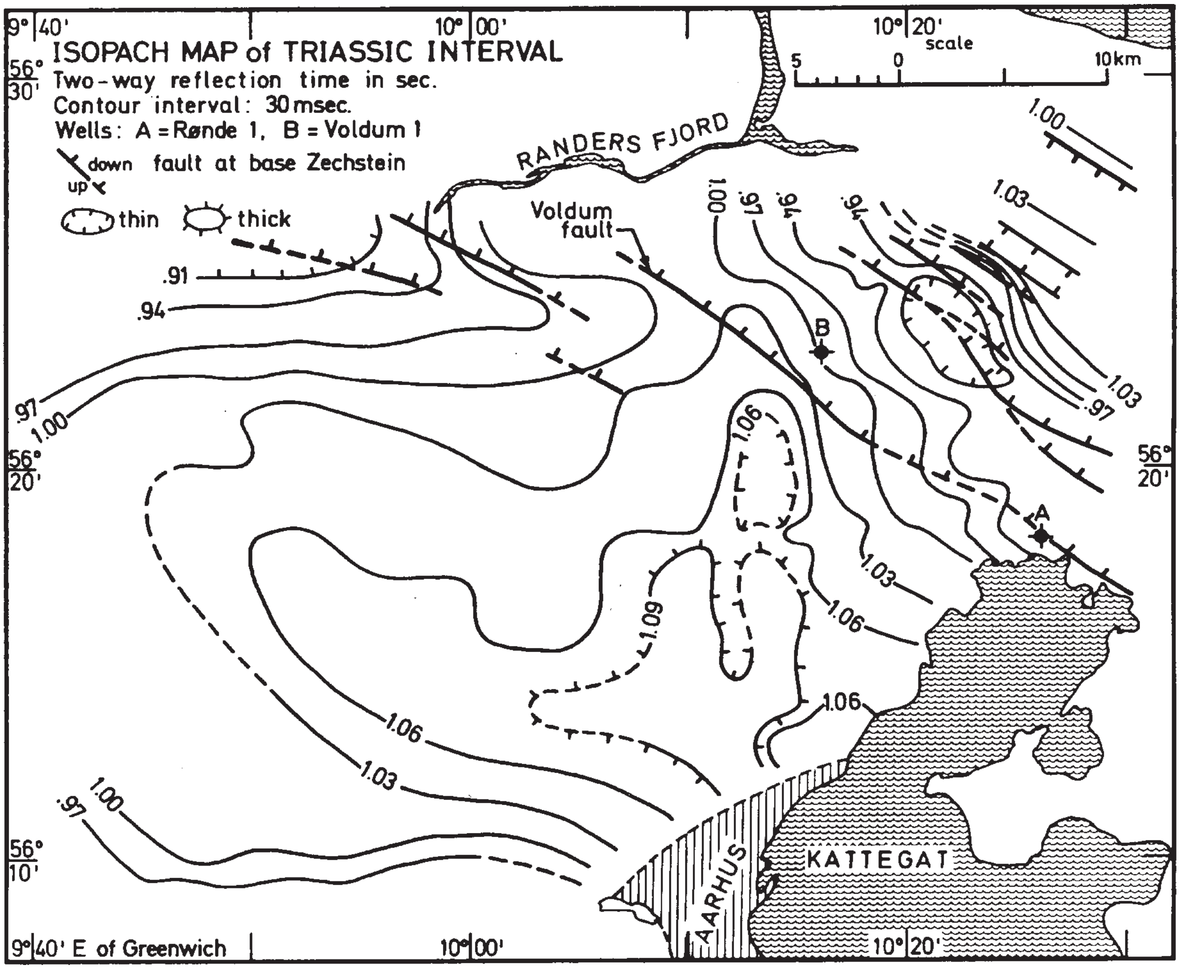


Fig. 11. Triassic TWT isopach map with the faults in the base Zechstein (transferred from Fig. 6).

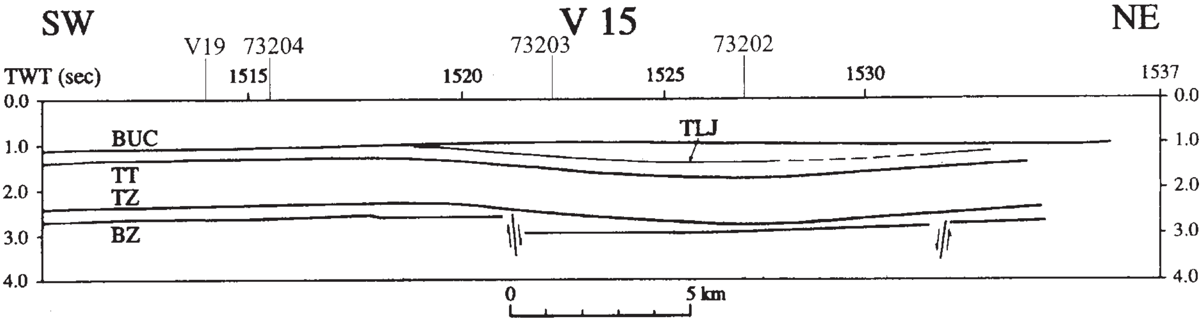


Fig. 12. Seismic line drawing of the reflection seismic section V15 (courtesy of the Geological Survey of Denmark), which is marginal to the Voldum salt pillow on the east side (for location, see Fig. 4). BZ = Base Zechstein, TZ = Top Zechstein, TT = Top Triassic, TLJ = Top Lower Jurassic, BUC = Base Upper Cretaceous.

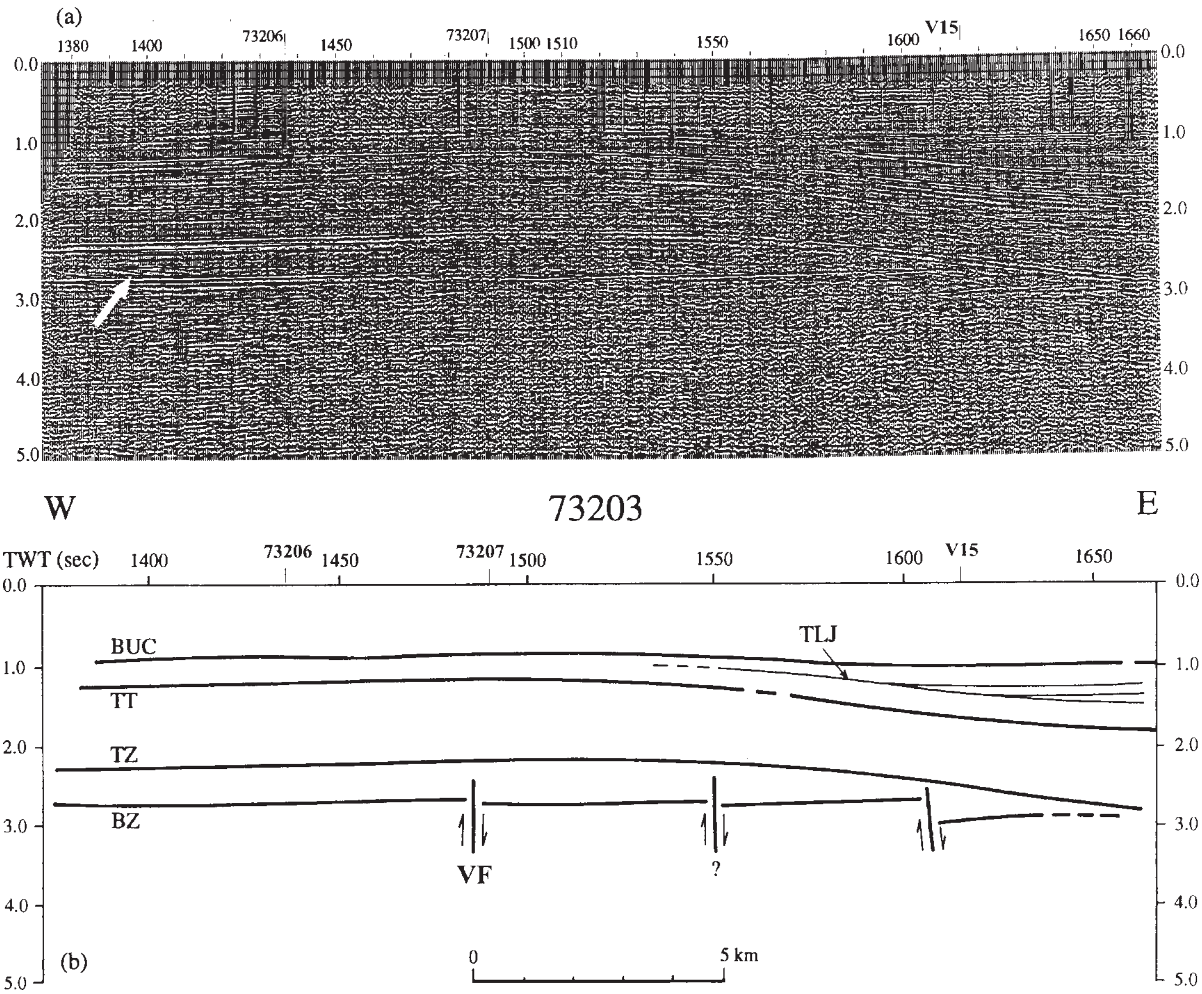


Fig. 13a. Reflection seismic section 73203 (courtesy of the Geological Survey of Denmark). For location, see Fig. 4. The arrow points to diffraction pattern(s) caused by fragmentation/faulting of a competent layer within the salt.

Fig. 13b. Seismic line drawing of the above section. Legend as in Fig. 12. VF = Voldum fault (see text).

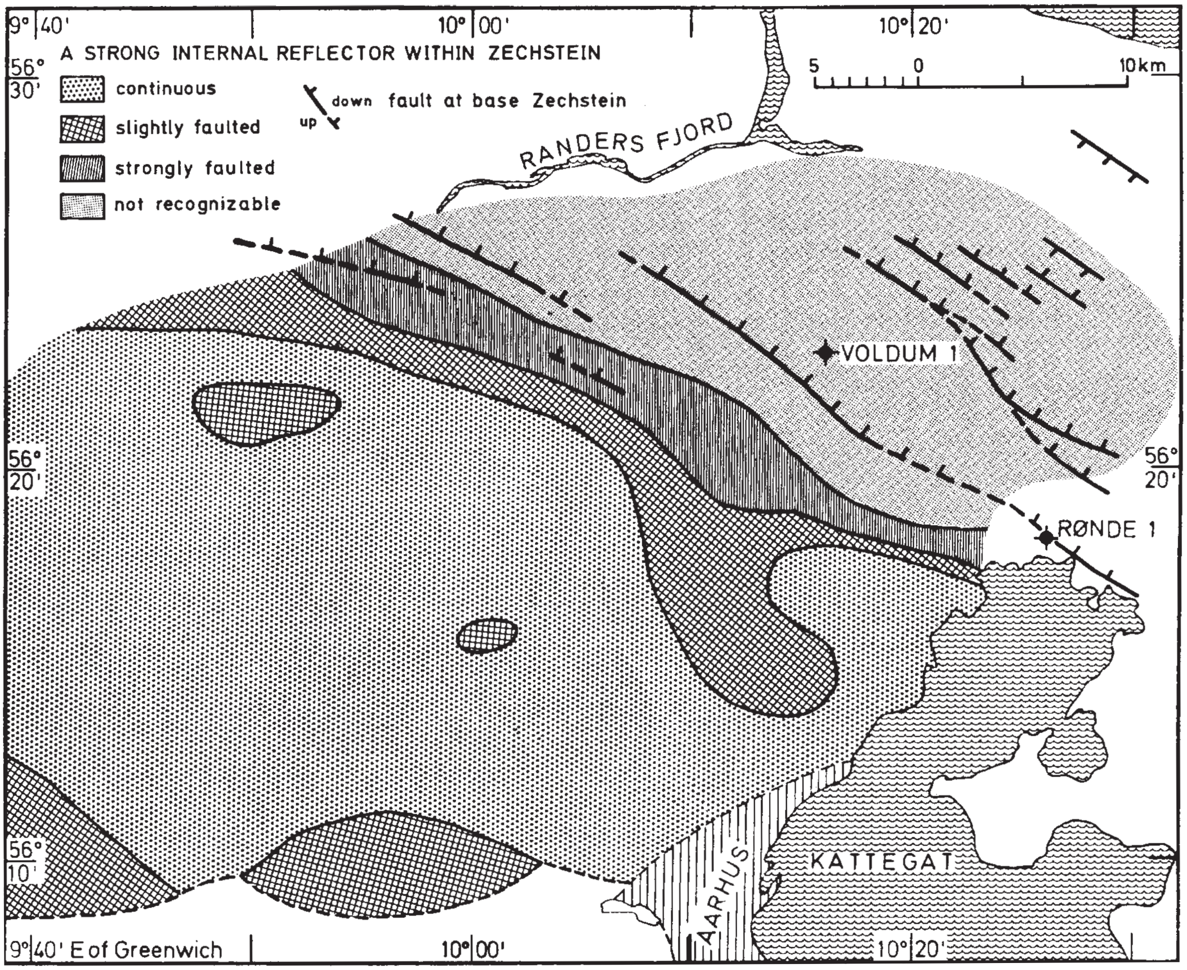


Fig. 14. Zones of varying degrees of disturbance of a strong internal reflector within the salt (from Sørensen, E.N. 1986, courtesy of the author). Faults at the base Zechstein horizon transferred from Fig. 6. For discussion, see text.

tive gravity anomaly trending northwest and where also the Jurassic/Lower Cretaceous sequence is thickest (up to about 1300 m). The top Lower Jurassic reflection, which can be traced through the greater part of this seismic section, parallels the top Triassic (Fig. 12). The faults below the Voldum salt accumulation, seen in Figure 8, delimit then the southwest side of a graben within which a synclinal structure consisting of Triassic and Lower Jurassic rocks, resting on thin Zechstein salt, has developed.

Reflection seismic section 73203

In the eastern part of the section 73203 (Figs 13a, 13b, for location see Fig. 4) the structural configuration on the east side of the salt pillow and the south side of the graben can be studied in more detail (this section, however, is highly oblique to the Voldum fault).

The top Lower Jurassic reflection, which is parallel to the top Triassic, marks the top (not necessarily in the stratigraphic sense) of the Lower Jurassic Fjerritslev Formation. As mentioned, this formation forms the bulk of the Jurassic/Lower Cretaceous sequence in both deep wells. It is uncertain whether the Middle Jurassic Haldager Sandstone, only 30 m thick in Voldum-1 and absent in Rønde-1, is present here. It is reasonable to assume, however, that the sediments which onlap the inclined surface of the top Lower Jurassic and thicken considerably in the graben area, i.e. away from the Voldum salt pillow, are predominantly of Late Jurassic age. These sediments represent the primary rim syncline of the pillow, and they also form the bulk of the graben fill.

Reflections within the Zechstein interval

On the seismic sections a strong reflection within, presumably, the lower part of the Zechstein sequence consistently appears. This reflection originates from a competent carbonate/sulphate layer within the salt. On the basis of the continuity of this reflector and the abundance of diffraction patterns indicating fragmentation/faulting of this layer embedded in the more plastic salt, Sørensen, E.N. (1986) has divided the area considered here into four zones, as shown in Figure 14. The reflection in question becomes gradually less continuous in the direction of Voldum pillow until it cannot be recognized any longer. In the western part of the seismic section 73203 (Fig. 13a), such diffraction patterns are marked by the arrow. The zones of varying degrees of disturbance of this layer are parallel to the faulting trend (Fig. 14). Some minor, isolated areas, designated as „slightly faulted“, occur within the parts where no faulting of the base Zechstein was observed. However, by comparison with the base Zechstein (Fig. 6), it is seen that these areas correspond to the more pronounced topographic rises in the basin floor, such as the high north of Aarhus.

Discussion and conclusions

The Triassic „thin“ (seen in Fig. 11) above the faults northeast of the Voldum fault is assumed to be caused by a Zechstein salt accumulation taking place during the deposition of the Triassic sediments. On the basis of the studies of Triassic faulting and the development of salt structures in this basin (e.g. Sorgenfrei 1969, Madirazza 1975, Bertelsen 1980, Boldreel 1985, Madirazza 1986, Madirazza et al. 1990), as well as in other parts of the North Sea (Ziegler 1978), it seems most likely that these faults were active during the Late Triassic (Keuper) when they triggered the salt movements resulting in the thinning of sediments of that age above the salt accumulation thus formed. However, no salt accumulation which could account for the Triassic thinning is present above the faults northeast of the Voldum fault. From the absence of an analogous Triassic thinning above the Voldum fault (Fig. 11), despite the presence of a very large salt accumulation above it, it follows that the movement along this fault is younger than along the faults to the northeast of it. Indirect evidence to that effect is also provided by seismic sections V15 and 73203 (Figs 12, 13) which show that the salt migration from the graben area did not begin before the Late Jurassic.

In the process of faulting along the Voldum fault in the Late Jurassic, and the resulting widening of the graben, salt movements were reactivated, and the original salt pillow has „moved“ up-dip leaving behind the Triassic „thin“ (Fig. 8). The Voldum fault may thus be regarded as a „causative“ fault (*sensu* Parker & McDowell 1955, Jenyon 1985) where the salt, due to differential pressure, has migrated laterally up-dip across the fault scarp(s). Due to the withdrawal of salt from the central parts of the graben, a synclinal basin, resting on thin Zechstein, has developed within the graben limits. The salt is thinnest below the axial part of the synclinal structure where the Upper Jurassic overburden is thickest (Figs 8, 12).

Based on the available data, it would be difficult to determine exactly the boundary between the Upper Jurassic and the Lower Cretaceous in the synclinal basin which could further constrain the age of these events. The wells Rønde-1 and Voldum-1, and also other wells in the Danish basin, show that the lithostratigraphy of the Upper Jurassic and, normally, rather thin Lower Cretaceous is quite similar, especially in the central parts of this basin (e.g. Michelsen 1978b). In both mentioned wells the thickness of the Lower Cretaceous is only 66 m. The sediments onlapping Lower Jurassic are not deformed as this could be expected had the salt continued to flow from the graben area after the deposition of these sediments (Fig. 13b). It appears then that the salt migration from the graben area into the Voldum pillow has virtually ceased at the close of the Late Jurassic, probably because very little salt remained within the graben area.

The regional development of the North Sea basin which was subjected to strong tectonism during the Late Jurassic (Late Cimmerian tectonic phase), especially during the Kimmeridgian-Portlandian (Ziegler 1978, 1981, 1982), supports the above interpretation concerning the time of the deepening of this graben and the salt withdrawal into the Voldum pillow.

The faults in the study area are sub-parallel and apparently arranged *en échelon*, and the throws along the individual faults change within relatively short distances. The faulting of the base Zechstein did not affect the base Triassic although the Zechstein interval across some faults is very thin. It is assumed that, in such cases, the salt acted as a deterrent to faulting of the overlying Triassic rocks. Under certain conditions such a phenomenon is indicative of a strike-slip movement (e.g. Jenyon 1986). All these characteristics suggest that a certain amount of horizontal component was involved in the process of faulting along this northeastern ”side” of the Zechstein basin corresponding to the Silkeborg Gravity High (as suggested in Madirazza et al. 1990). As mentioned above, in this relatively stable part of the basin the original topographic features of the basin floor are apparently preserved, and the intensity of salt movements decreases rapidly south and west of the Voldum fault. North of this fault the base Zechstein is strongly deformed, particularly along its strike (Fig. 6). The type of this deformation suggests that the downthrown block was moving southeast along the Voldum fault while the upthrown block, bordering onto the more stable part of the Zechstein basin corresponding to the Silkeborg

Gravity High, remained inactive. This means that the Voldum fault is dextral in nature.

At a maximum distance of about ten kilometres south of the Voldum fault the salt appears to have remained immobile (Fig. 14). The zones of diminishing degrees of disturbance are parallel to this fault indicating that here the salt movements were taking place at right angles to the faulting trend, i.e. up-dip the slight rise of the basin floor. Minor salt movements, which occured in isolated patches outside the faulted area, seem to have been governed solely by the topography of the basin floor (compare Figs 6 and 14). This could also explain why the outward narrow zone of disturbance, designated as „slightly faulted“ in Figure 14, widens and extends more to the south where it „onlaps“ the flank of the high in the base Zechstein (north of Aarhus).

The Upper Cretaceous sequence is 455 m thinner in Voldum-1, which is located "on top" of the salt pillow, than in Rønde-1 (Fig. 5). This indicates that considerable amounts of salt migrated into the newly forming pillow during the deposition of the Upper Cretaceous sediments. This post-Jurassic growth of the pillow is thought to be due primarily to the flow of salt from the part of the basin corresponding to the Silkeborg Gravity High. The average yearly rate of growth during the Late Cretaceous, calculated on the basis of the present thicknesses, was about 0.01 mm/year. Furthermore, the top of the Upper Cretaceous lies ca. 200 m higher in Voldum-1 than in Rønde-1 located outside the Voldum salt accumulation. This implies further growth of the pillow in post-Late Cretaceous times, but at a considerably slower average yearly rate of about 0.003 mm/year (a comparable rate of growth of 0.005 mm/year for the same time interval was estimated for the Thisted salt pillow (Madirazza 1981)). It may be said, then, that the Voldum salt pillow acquired its present form mainly in the Late Cretaceous. However, the speed of growth was slowing down in the Cenozoic, although there were still large amounts of salt available in the nonfaulted part of the basin. This suggests that the salt mass might have been close to establishing the isostatic equilibrium in post-Late Cretaceous times. A minor upwarping of the base Upper Cretaceous within the graben limits, seen in Figure 12, is indicative of a slight inversion of the graben basin. As mentioned, the post-Danian Tertiary sediments were deposited in the entire area of the Voldum pillow, but were later eroded. In the calculations of the rates of growth the compaction effects were not considered, which means that the present differences in thickness of the Upper Cretaceous in the two wells are partly due to compaction phenomena (see e.g. Sørensen 1986, Petersen 1991).

At the time of formation of the Voldum fault and the salt migration from the graben area, the post-Zechstein overburden was (at least) about 2400 m thick (the present thickness of Triassic and Lower Jurassic rocks). Gravitational instability thus induced was not sufficient to force the salt piercement of the Triassic strata which at the close of the Early Jurassic were probably compacted and lithified to a considerable degree. Furthermore, the movement along the Voldum fault had an appreciable horizontal component, and this type of faulting would not enhance the upward flow of salt.

Although the Voldum pillow continued to grow in Late Cretaceous and, at a slower rate in the Cenozoic times, uplifting the post-Zechstein strata, the gravitative disequilibrium alone without extensional faulting of the basin floor was not sufficient to cause the salt piercement and further development of this pillow into a diapir. The reasons why the Voldum pillow did not develop into a diapir may also apply to the few other structures in this basin, which started to grow in the Jurassic, but did not develop beyond the pillow stages.

Acknowledgements

The author wishes to express his gratitude to Bo Holm Jacobsen, Department of Earth Sciences, Århus, for fruitful discussions in the cource of writing this paper and his help in preparing the illustrations. The journal referee, Tanni Abramovitz, Geological Institute, Copenhagen, is thanked for critical and constructive comments on the manuscript.

Dansk sammendrag

Dannelsen af Voldum saltpuden på Djursland diskuteres på baggrund af refleksionsseismiske og tyngdemæssige data samt oplysninger fra to dybdeboringer (Rønde-1 og Voldum-1). Oprindeligt blev en mindre pude dannet i Trias på sydsiden af en graben i Zechstein bassinets bund. Under udvidelsen af denne graben (på grund af dannelsen af Voldum forkastningen i Sen Jura) pressedes saltet op langs grabens sydlige flanke. Her dannedes en ny og større saltpude, mens tykke Øvre Jura sedimenter blev aflejret inden for grabenområdet. Under denne udvikling forsvandt den oprindelige mindre pude, som kun efterlod et tyndt Trias lag som "vidne" om sin eksistens. De primære årsager til, at den nye pude ikke kunne udvikles til en diapir, skønnes at være vægten af tykke (2400 m+) og konsoliderede Trias og Nedre Jura sedimenter, samt at Voldum forkastningen havde en betydelig sideværts komponent. Puden voksede videre i Kridt og Tertiær, hvor saltet blev tilført hovedsageligt fra sydsiden af grabenområdet.

References

Abrahamsen, N. & Madirazza, I. 1986: The enigma of the Silkeborg gravity and magnetic anomalies, central Jutland, Denmark. In Møller, J. T. (ed.) Twentyfive years of geology in Aarhus. Geoskrifter 24, 45–59.

Arrhenius, N. & Lachmann, R. 1912: Die physikalisch-chemischen Bedingungen bei der Bildung der Salzlagerstätten und ihre Anwendung auf die geologische Probleme. Geologische Rundschau 3, 34–49.

Barton, D. C. 1933: Mechanics of salt domes with special reference to Gulf coast salt domes of Texas and Louisiana. American Association of Petroleum Geologists Bulletin 17, 1025–1083.

Bertelsen, F. 1980: Lithostratigraphy and depositional history of the Danish Triassic. Geological Survey of Denmark, series B, no. 4, 59 pp.

Boldreel, L. O. 1985: On the structural development of the salt dome province in NW Jutland, Denmark, based on seismic studies. First Break 3, 15–21.

Christian, H. E. 1969: Some observations on the initiation of salt structures of the southern British North Sea. In Hepple, P. (ed.) The exploration for petroleum in Europe and North Africa. Adlard & Son, Ltd. London, 231–248.

Harrison, T. S. 1927: Colorado-Utah salt domes. American Association of Petroleum Geologists Bulletin 11, 111–133.

Jackson, M. P. A., Vendeville, B. C. , Cramez, C. & Duval, B. 1993: Accommodation, space, extension and salt withdrawal: examples from the North Sea (extended abstract). American Association of Petroleum Geologists Bulletin. Hedberg Research Conference on Salt Tectonics (Bath, England) 1993.

Jackson, M. P. A. & Vendeville, B. C. 1994: Regional extension as a geologic trigger for diapirism. Geological Society of American Bulletin 106, 57–73.

Jacobsen, F. L. 1971: Zechstein i Rønde nr. 1 (with English summary). In Rasmussen, L. B. (ed.) The deep test well Rønde No. 1 in Djursland, Denmark. Geological Survey of Denmark, III series, 39, 108–113.

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

Jenyon, M. K. 1986: Salt Tectonics. Elsevier, London, 191 pp.

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

Lotze, F. 1957: Steinsalz und Kalisalze, Teil I. Gebrüder Borntraeger, Berlin, 465pp.

Madirazza, I. 1975: The geology of the Vejrum salt structure, Denmark. Bulletin of the Geological Society of Denmark 24, 161–171.

Madirazza, I. 1981: Mere om Thisted saltstrukturen (with English summary). Dansk Geologisk Forening, Årsskrift for 1980, 83–87.

Madirazza, I. 1986: The development of salt structures in the North Danish basin. In Møller, J. T. (ed.) Twentyfive years of geology in Aarhus. Geoskrifter 24, 226–233.

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.

Michelsen, O. 1978a: Report on the Jurassic of the Hobro No. 1 and Voldum No. 1 borings, Denmark. Geological Survey of Denmark, Årbog 1978, 141–149.

Michelsen, O. 1978b: Stratigraphy and distribution of Jurassic deposits of the Norwegian-Danish basin. Geological Survey of Denmark, B2, 28 pp.

Nettleton, L. L. 1943: Recent experimental and geophysical evidence of mechanics of salt dome formation. American Association of Petroleum Geologists Bulletin 27, 51–63.

Parker, T. J. & McDowel, A. N. 1955: Model studies of salt dome tectonics. American Association of Petroleum Geologists Bulletin 39, 2384–2470.

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, vol 1 text, 114 pp., vol. 2 Figs.

Petersen, K. 1991: The effect of gravitational compaction on estimation of vertical salt structure growth. Tectonophysics 194, 35–48.

Prisholm, S. & Christensen, S. 1985: Assessment of geothermal resources and reserves in Denmark. Geological Survey of Denmark C2, 54 pp.

Rasmussen, L. B. (ed.) 1971: The deep test well Rønde No. 1 in Djursland, Denmark. Geological Survey of Denmark, III series, 39, 123 pp.

Sannemann, D. 1968: Salt-stock families in northwestern Germany. In Braunstein, J. & O´Brien, G. D. (eds) Diapirism and diapirs. American Association of Petroleum Geologists Memoir 8, 261–270.

Seni, S. J. & Jackson, M. P. A. 1983a: Evolution of salt structures, East Texas diapir province, part 1: Sedimentary record of halokinesis. American Association of Petroleum Geologists Bulletin 67, 1219–1244.

Seni, S. J. & Jackson, M. P. A. 1983b: Evolution of salt structures, East Texas diapir province, part 2: Patterns and rates of halokinesis. American Association of Petroleum Geologists Bulletin 67, 1245–1274.

Sorgenfrei, T. 1964: Denmark. In Tectonics of Europe, Publishing House "Nauka", Moscow, 194–197.

Sorgenfrei, T. 1969: A review of petroleum development in Scandinavia. In Hepple, P. (ed.) The exploration for petroleum in Europe and North Africa. Adland & Son, Ltd. London, 191–248.

Sorgenfrei, T. & Bertelsen, O. 1954: Geologi og vandboring (with English summary). Geological Survey of Denmark, III series, 31, 106 pp.

Stille, H. 1925: The upthrust of the salt masses of Germany. American Association of Petroleum Geologists Bulletin 9, 417–441.

Sørensen, E. N. 1986: Seismisk kortlægning af Himmerland-Djursland området med særlig vægt på dybdekonvertering. Unpublished M.Sc. thesis, Department of Earth Sciences, University of Aarhus, vol. 1, 142 pp, Appendix A.

Sørensen, K. 1986: Rim syncline volume estimation and salt diapirism. Nature 319, 23–27.

Sørensen, K. 1998: The salt pillow to diapir transition: evidence from unroofing unconformities in the Norwegian-Danish Basin. Petroleum Geoscience 4, 193–202.

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

Trusheim, F. 1957: Über Halokinese und ihre Bedeutung für die strukturelle Entwicklung Norddeutschlands. Zeit-

schrift der deutschen geologischen Gesellschaft 109, 111–151.
Trusheim, F. 1960: Mechanism of salt migration in northern Germany. American Association of Petroleum Geologists Bulletin 9, 1519–1540.
Zhou, S. & Thybo, H. 1996: Calculation of residual gravity anomalies in Northern Jutland, Denmark. First Break 14, 129–134.
Ziegler, P. A. 1978: North-western Europe: tectonics and basin development. Geologie en Mijnbouw 57, 589–626.
Ziegler, P. A. 1981: Evolution of sedimentary basins in north-west Europe. In Illing, L. V. & Hobson, G. D. (eds) Petroleum geology of the continental shelf of north-west Europe. Heyden & Son, Ltd. London, 3–39.
Ziegler, P. A. 1982: Geological atlas of western and central Europe. Elsevier, Amsterdam, 130 pp. (with enclosures).