The geology of the Vejrum salt structure, Denmark

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Madirazza, I.: The geology of the Vejrum salt structure, Denmark. *Bull. geol. Soc. Denmark*, vol. 24, pp. 161–171. Copenhagen, November, 17th, 1975.

In 1963, Shell Denmark Ltd recorded a reflection seismic profile (SV 3) in the western part of Jylland. This profile crossed a Zechstein piercement salt dome named Vejrum. Several exploratory wells (maximum depth 1000 m) also were drilled in the area of this salt structure. On the basis of the seismic time-section of the mentioned profile and a number of geological data of both regional and local nature, a geological profile crossing the Vejrum structure was prepared. It was then possible to reconstruct the main stages in the development of this salt diapir.

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The reflection seismic line SV 3 was shot for many kilometres in a south-north direction through the western part of the Jylland peninsula. The various reflector horizons in the time-section of the profile were defined by J. C. Baartman (Geological Survey of Denmark) who has kindly given permission to use this section in the preparation of the present article.

It ought to be pointed out that the various horizons in a reflection seismic section represent the boundaries between the geological formations with different seismic velocities, i. e. those formations which are lithologically different. Therefore these reflectors are not necessarily identical with the geological boundaries in the chronostratigraphic sense. In the seismic profile in question this seems to be the case particularly with the top of the Middle Triassic (Muschelkalk). Here this reflector probably corresponds only approximately to the chronostratigraphic limit in the geological sequence.

On the residual gravity anomalies map of Denmark (surveyed and interpreted by Gulf Research & Development Co., Pittsburgh, 1947) this complex E–W trending salt structure was subdivided into an elongate western part ('D' Vejrum) and a directly adjoining eastern part ('C' Vejrum) which has a circular outline (for this map see Rasmussen, fig. 5 in 'Dybdeboringen Nøvling nr. 1 i Midtjylland', 1973). Currently, however, the name Vejrum is used for the whole structure which is located in a region of Miocene sedimentation.

The location of the seismic line SV 3 with respect to the outline of the structure 'D' Vejrum, as it appears on the mentioned map of the residual gravity anomalies, is shown in fig. 1. In fig. 2 the northernmost (about 22 km long) part of the time-section, relevant to the discussion of the Vejrum salt diapir, is shown.

The present writer has suggested earlier (Madirazza 1968) that the salt domes at Mønsted, Sevel, Vejrum and Linde, occurring in a string from east to west and located very close to each other, have grown from a common salt wall having a westerly trend. This conclusion was also reached by Baartman (see especially figs 7, 8, 9 in 'Dybdeboringen Nøvling nr. 1 i Midtjylland', 1973) who has interpreted the geological structure in this part of Jylland on the basis of a number of intersecting reflection seismic time-sections.

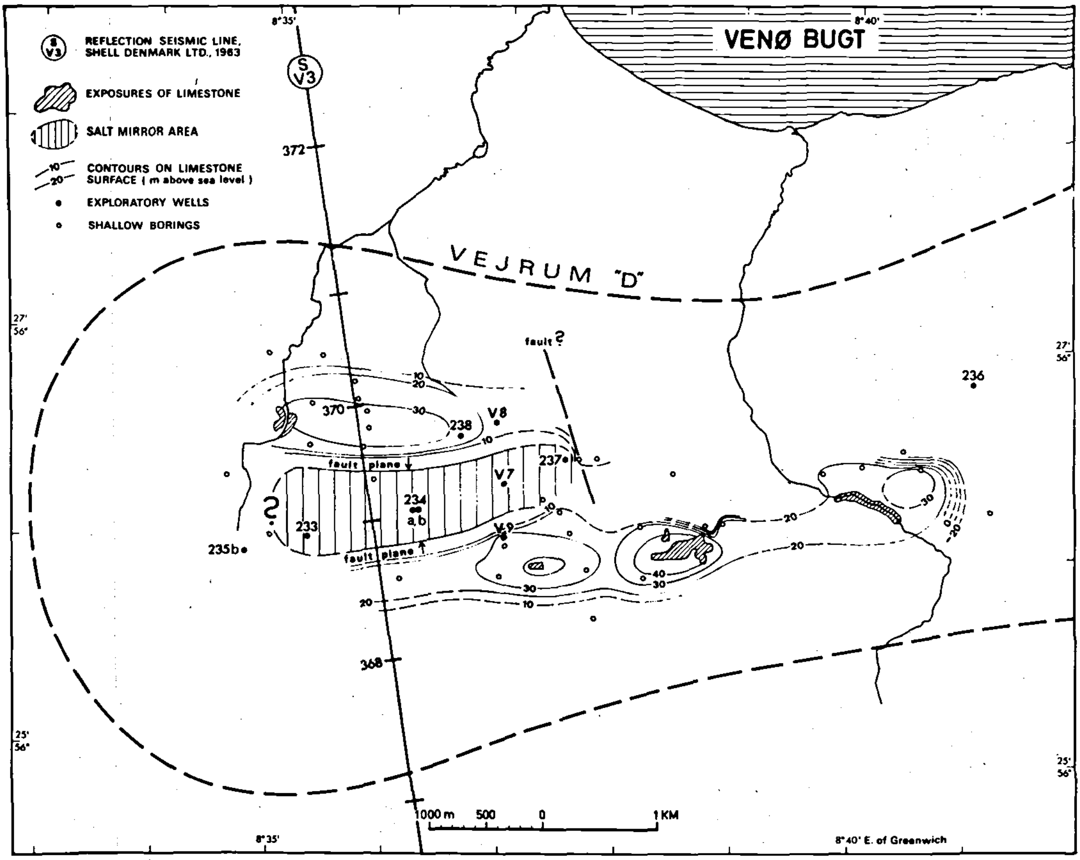

Fig. 1. Map of the limestone surface in the area of the Vejrum salt diapir. The limits of the salt structure, determined by geophysical methods, are indicated by the heavy broken line.

Sources and procedures

Based essentially on the time-section of fig. 2, which at its northern end crosses the axis of the western part of the Vejrum salt structure at virtually a right angle, a geological cross-section through this part of the salt structure was prepared. Subsequently the most important events in the development of this part of the diapir were reconstructed, as illustrated in the geological profiles (figs 2–8). Note that there is no vertical scale exaggeration in these profiles.

Apart from the reflection seismic profile numerous other data, derived primarily from the logs of borings drilled in this area, were used in the preparation of the geological profiles. In 1946 The Danish American Prospecting Co. drilled eight exploratory wells (to a maximum depth of 640 m) within the structurally highest parts of the Vejrum salt diapir. In 1973 three wells, V7, V8, V9, each 1000 m deep, were drilled by The Elsam Co. These three wells, which are the deepest in the area, are located along a N-S line some 1200 m east of the reflection seismic line, and parallel to it (fig. 1).

A total of six wells, all but one located east of the seismic line, were terminated in the Zechstein evaporites. These consist predominantly of halite with subordinate amounts of anhydrite and/or gypsum. In the present article the term "salt" will be applied to these evaporites.

In addition to the just discussed deeper exploratory wells, the logs of a large number of shal-

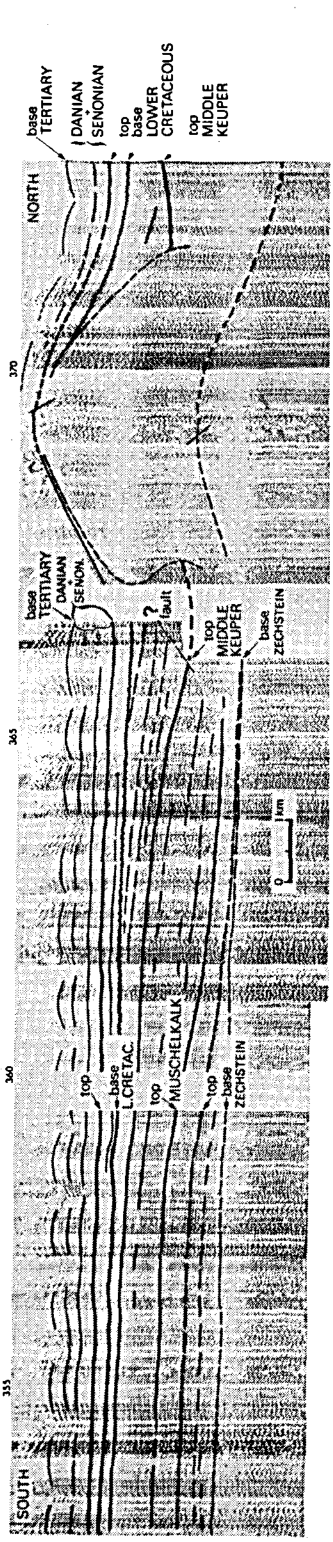

Fig. 2. A part of the reflection seismic time-section SV 3, recorded by Shell Denmark Ltd in 1963, which at its northern end crosses the axis of the Vejrum salt structure (cf. fig. 1).

lower borings, drilled mainly for water, were studied. The locations of all the exploratory wells together with their respective D. G. U. (Geological Survey of Denmark) file numbers are shown on the map of fig. 1. Many of the shallower borings relevant to the understanding of the geology in this area were also plotted on this map. In table 1 the D. G. U. file numbers, coordinates and final depths of all the borings plotted in fig. 1 are listed.

Very valuable information concerning the limestone structure, published by Ødum (1926), was considered in the preparation of the geological profiles. In two of the quarries, at present abandoned, Ødum (1926) determined the age of the limestone as Late Danian, Zone D.

The present writer has worked in the field in the area covering the entire Vejrum salt structure and collected a number of data, particularly relating to the limestone rocks and the Quaternary deposits. Several limestone pits were mapped in the process. Based on this work, combined with the information obtained from the bore logs, it was possible to draw the map of the limestone surface in the area of the salt structure, as shown in fig. 1.

Finally, the logs of all important exploratory wells drilled in Denmark were studied, particularly in order to arrive at a distribution of different geological formations and their representative thicknesses in this part of the sedimentary basin of northern Jylland.

In the seismic section of fig. 2 several normally reliable and persistent reflectors of the Danish sedimentary sequence (see e. g. Sorgenfrei & Buch 1964) are poorly defined or missing along the flanks and over the top of the salt structure. This is due to the fact that at shallower depths the seismic reflections are usually unclear. However, on the basis of the geological information obtained from all the above named sources it was possible to reconstruct the higher parts of the Vejrum diapir, as shown in the profile of fig. 8.

Before discussing the geological history of this part of the structure, it ought to be pointed out that the differences in thicknesses, as well as dips, of the geological formations in the seismic time-section (fig. 2), as compared to the geological profiles (figs 3–8), are due

TABLE 1.

D.G.U. file no.	Longitude E of Greenwich	Latitude N	Final depth in m
64.9	8°35′24″	56°26′53″	28
64.20	8°38′10″	56°26′06″	27
64.27	8°38′27″	56°26′22″	5.7
64.62	8°35′19″	56°26′40″	5(+)
64.88	8°35′47″	56°26′27″	14
64.91	8°35′49″	56°26′33″	13.5
64.92	8°35′48″	56°26′38″	5(+)
64.93	8°35′44″	56°26′41″	10.5(+)
64.112	8°37′48″	56°26′25″	10(+)
64.113	8°37′38″	56°26′25″	8(+)
64.116	8°37′20″	56°26′13″	27
64.117	8°37′28″	56°26′10″	14.5(+)
64.118	8°37′34″	56°26′04″	15(+)
64.120b	8°37′00″	56°25′59″	24
64.121	8°36′58″	56°25′51″	18(+)
64.128	8°37′48″	56°25′39″	24.5
64.131	8°38′13″	56°25′52″	1(+)
64.133	8°37′43″	56°25′53″	7.5(+)
64.150	8°38′53″	56°26′08″	13(+)
64.151b	8°41′11″	56°26′13″	31(+)
64.152	8°40′04″	56°26′25″	19.5(+)
64.158	8°40′35″	56°26′25″	7(+)
64.173	8°35′42″	56°26′46″	19
64.206	8°35′19″	56°26′47″	38
64.209	8°34′57″	56°26′54″	38
64.210	8°35′53″	56°26′18″	38
64.212	8°39′45″	56°26′23″	37.5
64.217d	8°40′26″	56°26′30″	52
64.233 Vejrum 1	8°35′18″	56°26′01″	462.5
64.234a Vejrum 2	8°36′12″	56°26′09″	302.5
64.234b Vejrum 2A	8°36′17″	56°26′10″	36.5
64.235b Vejrum 3A	8°34′49″	56°25′57″	218
64.236 Vejrum 4	8°41′01″	56°26′49″	556.5
64.237 Vejrum 5	8°37′31″	56°26′25″	640
64.238 Vejrum 6	8°36′37″	56°26′31″	548
64.269	8°34′36″	56°26″18′	30.5
64.357	8°36′06″	56°25′50″	80
64.385	8°38′44″	56°26′07″	37
64.405	8°34′59″	56°26′02″	34
64.468 (V7) Vejrum 7	8°37′00″	56°26′18″	1000
64.469 (V8) Vejrum 8	8°36′55″	56°26′35″	1000
64.470 (V9) Vejrum 9	8°37′00″	56°26′02″	1000

to differences in velocities of the seismic waves in different formations. Similarly, the large fold in the base Zechstein reflection, seen in fig. 2 directly below the structurally highest parts of the diapir, is an apparent deformation. Such a strong upward bending of this reflector in this particular place is most likely entirely produced by different seismic velocities in the salt mass and in the neighbouring sediments (see e. g. Tucker & Yorton 1973, pp. 18, 19) and it was, therefore, disregarded in the geological profiles. This apparent fold is cut by a normal fault downthrown to the north. The existence of this fault, cutting the base of the Zechstein horizon, is doubtful (J. C. Baartman personal communication, 1974) and it has therefore been omitted from the geological profiles.

It should be emphasised, however, that it is entirely possible that the flowage of the Zechstein evaporites and subsequent halokinetic movements, at Vejrum as well as elsewhere in the sedimentary basin of northern Jylland, were initiated by tectonic impulses in the pre-Zechstein rocks (see e. g. Sorgenfrei 1969).

Geological history

Pillow stage

At Vejrum the accumulation of salt into a pillow structure began after the deposition of the Middle Triassic (Muschelkalk) sediments. The formation of the primary peripheral sinks, corresponding to the pillow stage, took place during the Late Triassic, essentially the Middle Keuper (see figs 3 and 4). The pillow stage probably persisted during the deposition of the Rhaetic sediments, but these cannot be recognised in the seismic section since lithologically they differ little from the overlying Jurassic sediments. On the other hand, the top of the Middle Keuper is always a reliable reflector in this part of Jylland.

Diapiric stage

The piercement of the Triassic sediments and the transition to the diapiric stage occurred as a result of the pressure exerted by the newly deposited Jurassic sediments. The growth of the diapir and the upward flow of the plastic salt from the pillow into the diapir is reflected in the development of the secondary peripheral sink along the edges of the salt plug (fig. 5). Here, the abnormally thick Jurassic sediments, dipping towards the salt plug, were being laid down simultaneously with the collapse of the Triassic sediments that was caused by the flowage of the underlying salt into the diapir.

The Jurassic must have been considerab-

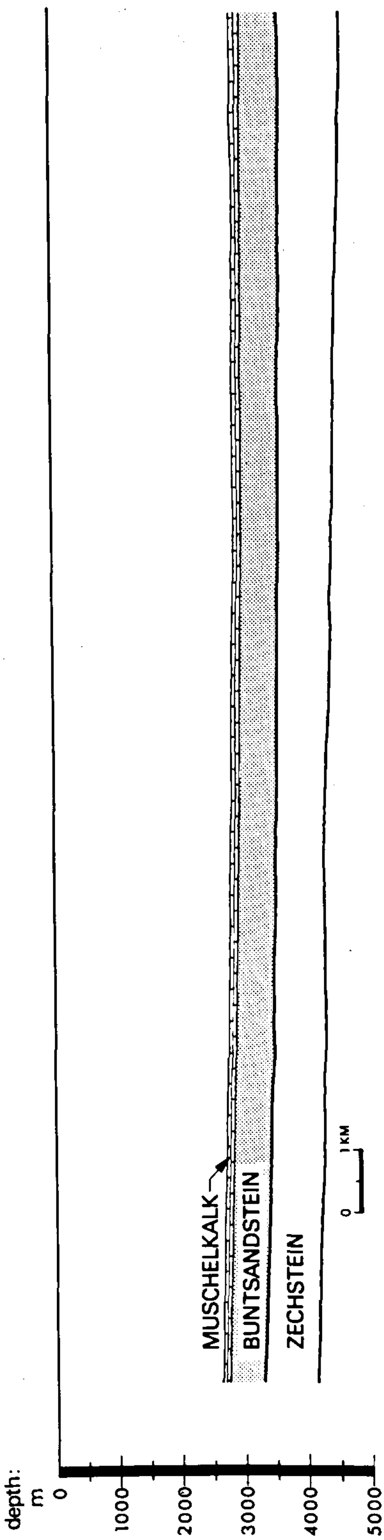

Fig. 3. The Zechstein (Upper Permian) evaporites at the close of Middle Triassic sedimentation.

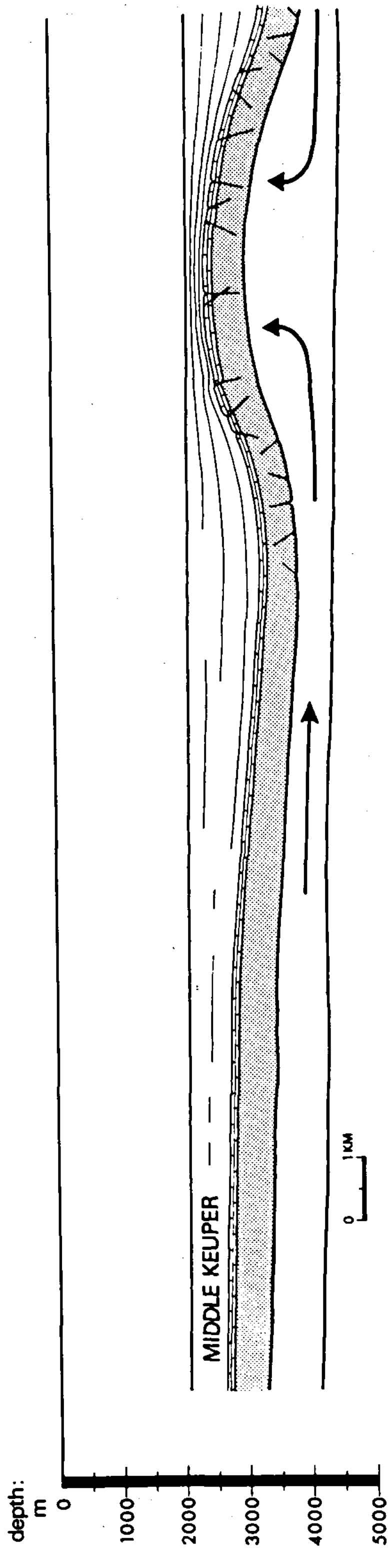

Fig. 4. Pillow stage. The formation of the pillow structure, recorded by the primary peripheral sinks, took place during the Late Triassic, mainly Middle Keuper.

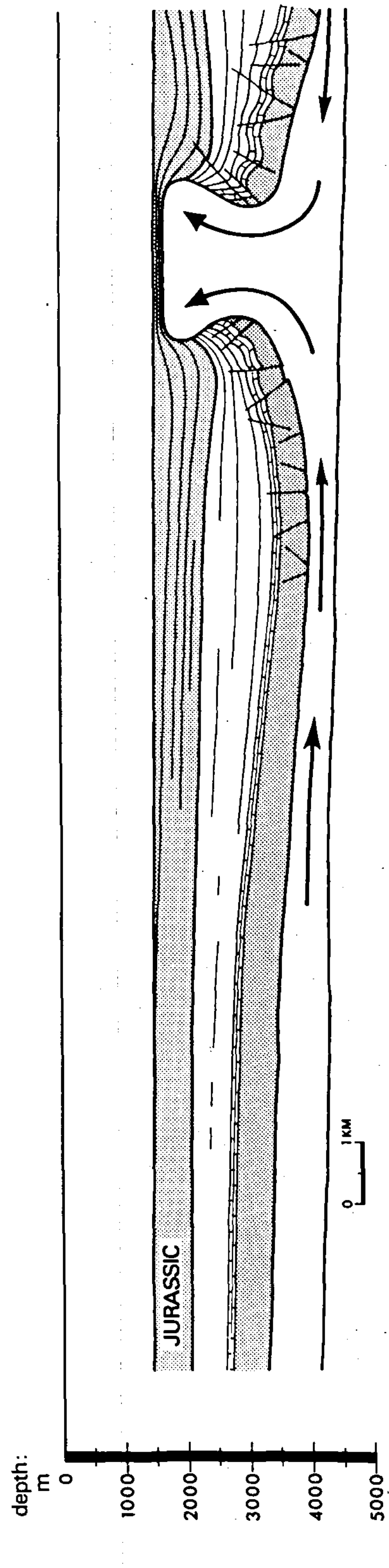

Fig. 5. Diapiric stage. The piercement of the Triassic sediments and the growth of the diapir, recorded by the secondary peripheral sink, took place during the Jurassic.

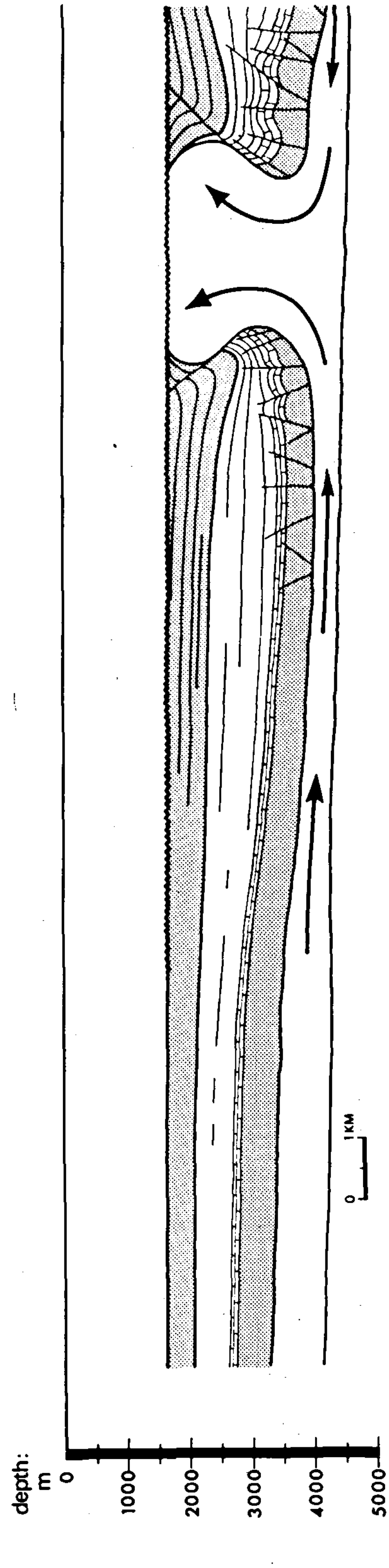

Fig. 6. In the course of the Lower Cretaceous transgression a part of the Jurassic sediments was eroded and the top of the salt plug probably exposed.

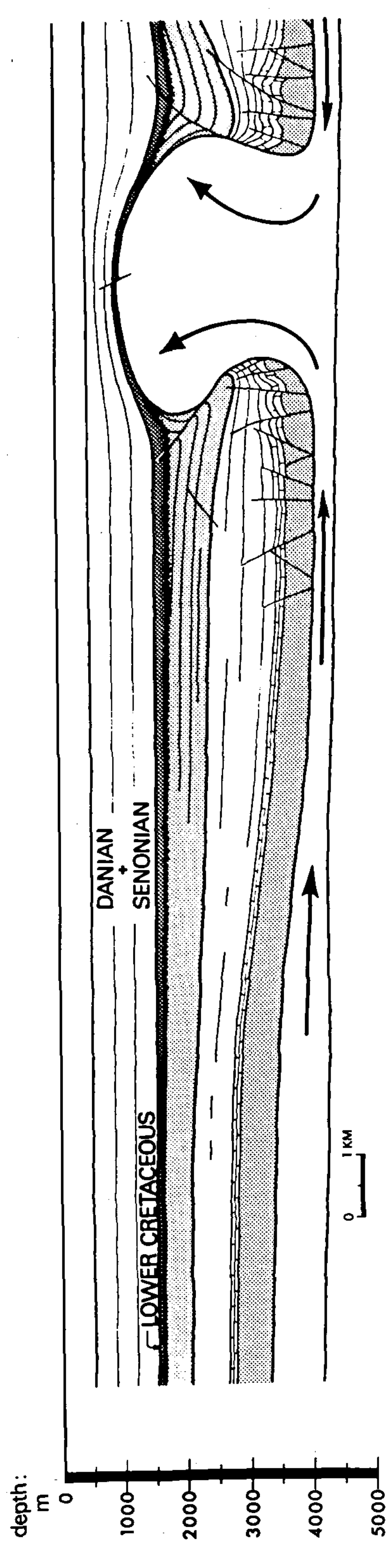

Fig. 7. The salt continued to rise simultaneously with the deposition of the Senonian and Danian limestones, as evidenced by thin sequences of these rocks over the diapir. The diapiric stage proper ended some time during the late Cretaceous.

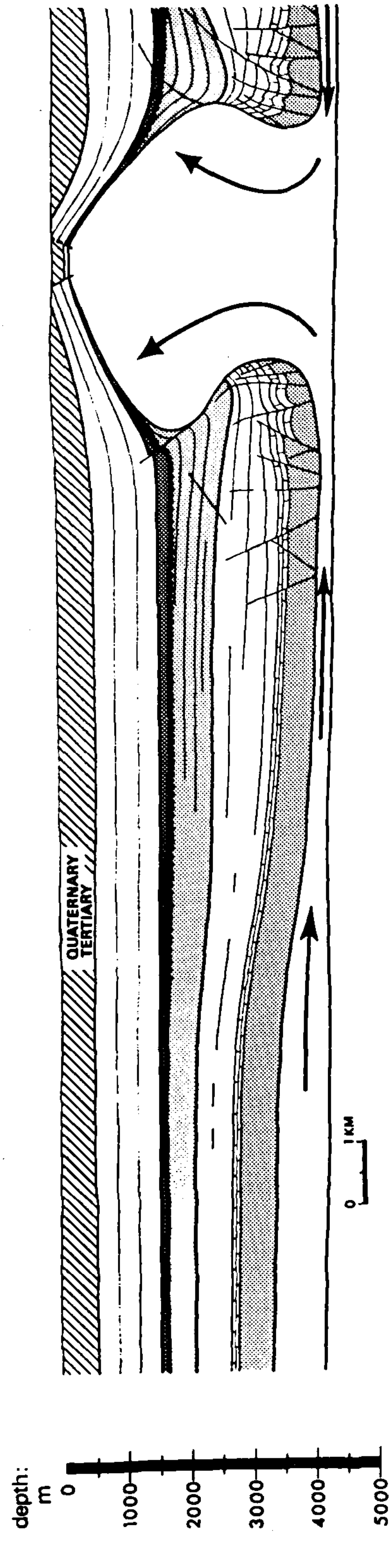

Fig. 8. Post-Danian Tertiary sediments were also uplifted by the halokinetic movements. A central E-W trending graben developed on the very top of the salt structure. The graben was active also during the Pleistocene.

ly thinner, or possibly missing in part, over the top of the diapir which now stood at shallow depths or which was conceivably a positive area during parts of Jurassic time. In this connection it ought to be noted that in the well no. 64.233 sediments of Jurassic age were identified for the first time in Denmark proper by Nørvang (1946). On the basis of their foraminiferal fauna they were determined as Lower Lias. The rest of the Lias and, for that matter, of the Jurassic, was missing in this well.

Unconformities

In the course of the transgression which took place at the beginning of the Early Cretaceous, a part of the Jurassic was eroded and thus the top of the salt mass was probably exposed (figs 5,6). In the southern end of the profile the Lower Cretaceous sediments are separated from the underlying Jurassic by an erosional unconformity which, in the direction of the salt structure, gradually develops into an angular unconformity (marked with a wavy line in the profiles). This unconformity is particularly well developed in the area where the Jurassic is thickest, i.e. in the secondary peripheral sink (figs 6, 7).

Post-diapiric movements

The presence of some unusually thin Lower Cretaceous sediments over the salt diapir and an upwarping of the angular unconformity indicate that the rise of salt continued during, and after, deposition of the Lower Cretaceous (figs 7, 8). But the salt has only in places perforated sediments of this age. According to information derived from several deeper wells, some of which are located quite close to the seismic section of fig. 2, it is known that the Senonian chalk rests either directly on the salt (or the caprock) or that it is separated from the salt only by a few metres of Lower Cretaceous rocks. It may therefore be surmised that the actual diapiric stage at Vejrum came to a close at some time during the late Late Cretaceous.

Both the seismic profile and the logs of several wells indicate that the Senonian, as well as Danian, chalks and limestones are abnormally thin over the highest parts of the diapir and also over its sloping surfaces both on the north and south sides (figs 7, 8). This means that as a result of the deposition of the regionally very thick Upper Cretaceous strong upward movements in the salt mass were reactivated. Similar thinning of the Upper Cretaceous and Danian rocks over the higher parts of other salt structures in northern Jutland is known to occur, as for instance over the Mønsted salt dome (Madirazza 1968). This phenomenon has been also reported from the Dan structure in the offshore Denmark in the North Sea (Childs & Reed 1975).

The entire post-Danian Tertiary sequence at Vejrum is also deformed and, apparently, concordant with the underlying Danian and Senonian limestone formations (figs 2, 8). These Late Cretaceous and later movements may be designated as post-diapiric.

Graben

The appearance of normal faults in the rocks topping a diapir is usually related to an imminent end of the diapiric stage. The weakening of the isostatic forces responsible for the upward flow of the lighter salt results in a change in the shape of the salt mass, its upper part assuming a wider form. The tensile stresses in this part of such a structure become much stronger, resulting in the development of normal faults. At this stage of its growth the Vejrum salt diapir developed a broader, slightly asymmetric upper part, creating a mild overhang on the south side. The faults, such as the north-dipping normal fault seen in the seismogram of fig. 2, probably appeared as early as during the Early Cretaceous, since rocks of this age seem to be thicker on the north (downthrown) side than on the south side of this fault.

As the map (fig. 1) shows, limestone rocks at relatively shallow depths occur in two narrow, E-W trending belts, which are located centrally with respect to the limits of the salt structure (compare this map with the profile of fig. 8). Apparently, the southern belt is considerably longer and extends farther east than the northern limestone belt which is confined to the western part of the Vejrum structure.

The three deepest wells (V7, V8, V9) were, as mentioned above, drilled along a N-S line approximately 1200 m east of the seismic profile. The preliminary logs of wells V8 and V9, which are about one kilometer apart, are similar. They both record thin (maximum 19 m) Quaternary cover, below which the Upper Cretaceous chalk was encountered, possibly topped by the Danian limestone. However, the middle well V7, drilled about half way between the other two, penetrated relatively thick (130 m) Quaternary, underlain by 70 metres of Tertiary sediments which were missing completely in the other two wells. The Tertiary section here included ash beds of Early Eocene age, overlain by sticky clays. A part of these clays is probably of Oligocene age while the Miocene is entirely lacking.

From the logs of these and other wells in this area, and from the map of fig. 1, it is evident that, apart from the north-dipping faults, south-dipping normal faults were also formed on the very top of the salt diapir. Thus an E-W trending graben developed. There are reasons to believe that the southern fault (or fault zone) is older, and that the movements along it were of greater magnitude than along the northern fault (or fault zone). A situation where (as in the well V7) relatively thick Quaternary and Tertiary are present within the graben limits is represented in the profile of fig. 8.

Farther west, and closer to the seismic section, comparatively thick (as e. g. in the well no. 64.234a) limestones of Senonian, as well as Danian, age occur within the depressed graben block. Furthermore, in that area the limestones are encountered at considerably higher levels, and the Quaternary and, the remaining part of, the post-Danian Tertiary are much thinner than in the area of the well V7.

These differences could mean that the sinking throughout the graben block was not uniform, or that the graben was cut by transverse faults and separated into minor blocks which each had a different tectonic, and thus sedimentological, history.

The geological picture, then, appears to be quite complex within the graben limits and, on the basis of the information at hand, no attempt has been made to draw the contours on the surface of the limestone rocks within the graben block itself.

It is of interest to note that in a single quarry within the northern belt, located some 500 m west of the seismic line, the limestone strikes east-west and dips northwards at 20°-22°. But in a quarry within the southern belt, according to Ødum (1926), the limestone dips about 22° to the south-south-east. From this latter locality Ødum also described three, more or less parallel, north-dipping normal faults and he was able to measure the displacement along the southernmost of these faults (ca. 1.2 m) by correlating flint layers across the fault plane. Along the other two faults the displacements were greater than the height of the limestone outcrop, i. e. minimum ca. 14 m. All these observations are in accordance with the existence of the central graben, with the rocks on both sides of it having been tilted in opposite directions (cf. fig. 8).

In general, the Danian limestone should be expected to occur in the outer, and the Senonian chalks in the inner, parts of the two limestone belts, the Danian-Senonian boundary being roughly parallel to the trends of these belts. Whether rocks of Danian or Senonian age are found below the Quaternary cover at a particular place depends on the relative thicknesses of these two types of rocks, their dips, and the amount of later erosion to which the highest parts of the salt structure were subjected. It appears, for instance, that immediately south of the graben block and in the vicinity of the seismic line, the Danian rocks are not present, while, according to Ødum, they are exposed in the mentioned quarry on the north side of the graben.

The salt mirror

In the discussion it has thus far been assumed that the central graben corresponds to the area limited by the two belts where the limestones occur at shallow depths. However, in four deeper wells (nos. 64.233, 64.234a, 64.237, V7), all apparently drilled within the graben block, the top of the Zechstein salt was reached at practically the same levels, that is at about – 206 m, or at depths of about 240–245 m. This means that the surface of the present salt mirror is very even and covers an area at least 2.5 km long and 800–1000 m wide (see fig. 1). This area, or at least a large part of it, also underlies the graben block.

It would be reasonable to suppose that as a result of at least the most recent solution of the salt by the ground water, a settling of the graben block above the area of the salt mirror has taken place (consult fig. 8). Such movements would preferably take place along pre-existing zones of weakness, in this case along the graben faults. The graben block and the zones where the salt, prior to its most recent solution, had reached the highest levels did not necessarily coincide. Actually, it appears certain that some parts of these two areas did not overlap. This would most likely be the case along the northern and southern limits of the salt mirror area, and also in the westernmost part of the structure where a more circular outline of the shallow limestone zone is distinguishable. Thus the steep faults, shown in fig. 1, which delimit the graben along the north and south sides, do not necessarily represent the original graben faults, but rather the surfaces along which the latest settling of the graben took place.

Caprock

The thickness of the caprock above the salt mirror surface varies greatly within short distances. For instance, in the well no. 64.234a, ca. 350 m east of the seismic line, the thickness of the caprock was found to be ca. 67 m, while in the well no. 64.233, ca. 600 m west of this line, the caprock was only about 10 m thick. Caprock of varying thicknesses is also present at depths far greater than the level of the salt mirror, i. e. along the sloping surfaces of the salt body. This suggests that salt mirrors, other than the present one, existed previously, leaving behind their own residual caprock.

The structure during the Pleistocene

The Vejrum salt structure occupied a very marginal position with respect to the last ice sheet (Madirazza 1970). The boundary of the Würm glaciation in this area runs just south of, and parallel to, the southern limit of the salt structure. This boundary bends sharply northwards at the western end of the structure.

It is evident from fig. 8 that at the beginning of the Pleistocene, or possibly even later, the top of the salt structure was a morphological high. This high, consisting of the Tertiary and Upper Cretaceous rocks, was subjected to strong erosion and levelling-off, especially by the glaciers which repeatedly covered this area during the Pleistocene. In several pits in the salt structure area moraine deposits, sometimes only 2–3 m thick, covering a fresh appearing and even limestone surface, can be observed. The amount of relative sinking of the graben block during the Pleistocene would correspond to the (maximum) thickness of the Pleistocene deposits within the graben limits which, according to the available information, is approximately 130 m.

Once the Würm ice started to stagnate and the area became free of ice, several late glacial streams, flowing north into Venø Bugt (bugt = bay), cut their valleys across the area of the salt structure.

Summary and conclusions

A map of the surface of the limestone in the area of the Vejrum salt structure has been prepared (fig. 1). These rocks are of Danian (Ødum 1926), but possibly also of Senonian, age.

On the basis of geophysical data, mainly the reflection seismic time-section SV 3 (fig. 2), and geological information from various sources including several exploratory wells, the geological history of this salt structure has been reconstructed. This history can be summarised as follows:

The primary peripheral sinks, corresponding to the pillow stage, were formed during the Late Triassic, essentially the Middle Keuper (figs 3, 4). The piercement of the Triassic sediments by the Zechstein salt and the growth of the diapir is recorded by the secondary peripheral sink, in which abnormally thick Jurassic sediments, dipping towards the salt plug, accumulated (fig. 5). A part of these sediments, which were very thin over the diapir, was eroded in the course of the Lower Cretaceous transgression (fig. 6). In the area of the secondary peripheral sink a marked angular unconformity separates the Jurassic from the Lower Cretaceous (figs 6, 7). The halokinetic rise of salt continued also during Early

Cretaceous sedimentation. According to the seismic profile and several wells, the Senonian, as well as Danian, limestones are abnormally thin over the structurally highest parts of the diapir, indicating that strong synsedimentary uplift continued during the Late Cretaceous and early Tertiary (fig. 7), but none of these sediments were perforated by the salt. Thus the actual diapiric stage came to a close at some time during the early Senonian.

The post-Danian Tertiary sequence, which is apparently concordant with the underlying limestone formations, was also bent upward by the rising salt (fig. 8).

Towards the close of the diapiric stage, probably already in the Early Cretaceous, significant normal faults appeared over the highest parts of the diapir resulting in the development of a central graben (compare figs 1 & 8). Apparently, the downward movements of this E-W trending graben did not take place at a uniform rate throughout the length of the graben block. In the well V7 (fig. 1) relatively thick Quaternary and Tertiary were encountered, indicating that in that area the graben block was active during the Tertiary and, at least a part of, the Quaternary.

As a result of the solution of salt by the ground water, a salt mirror was formed which is presently an even surface at a level, of ca. – 206 m. Thus a collapse of the part of the graben block overlapping the salt mirror area occurred.

During the Pleistocene the Vejrum salt structure area was subjected to strong erosion by glaciers. With respect to the last, Würm ice sheet this structure occupied a very marginal position. Moraine deposits, sometimes only 2–3 m thick, covering the limestone surface can be observed in several pits.

Acknowledgements. The writer wishes to thank the Geological Survey of Denmark (D. G. U.) for permission to use the unpublished information from their well records. Elsam Co., of Fredericia, and A. V. Joshi in particular, have kindly placed at the writer's disposal the preliminary logs of the three wells (V7, V8, V9) drilled by the Company in the area of the Vejrum salt structure. Carlsbergfondet has financially supported the writer's field work in this same area. The writer is indebted to Niels Schrøder, Department of Geophysics, Aarhus University, for his suggestions and comments particularly regarding the geophysical aspects of this article. Richard Wilson, Institute of Geology, Aarhus University, has kindly improved the English text. Torben Riis has most ably drafted the illustrations.

Dansk sammendrag

Ved hjælp af dels geofysiske, hovedsageligt refleksionsseismiske, dels geologiske metoder, har det været muligt at rekonstruere hovedtræk i udviklingen af Vejrum saltstrukturen.

Akummulationen af saltet i en pudestruktur, svarende til dannelsen af den primære randsænke, skete i Øvre Trias, i det væsentlige under aflejringen af Mellem Keuper. Gennembruddet af de triassiske sedimenter og væksten af saltdiapiren fandt sted i Jura. Diapirstadiet afspejles i den sekundære randsænke, hvor usædvanligt tykke jurasiske sedimenter aflejredes. Dette stadium afsluttedes engang i begyndelsen af Senon, men stærke halokinetiske bevægelser fortsatte i resten af Senon, og i Danien, idet disse yngste kretasiske og ældste tertiære bjergarter er betydeligt tyndere over saltstrukturen end udenfor.

Mod afslutningen af diapirstadiet udvikledes en graben på toppen af saltdiapiren; visse steder er der her bevaret relativt tykke tertiære og kvartære sedimenter.

Toppen af saltet blev opløst af det cirkulerende grundvand, og dermed dannedes et saltspejl ved ca. ÷206 m. Som resultatet deraf fandt en indsænkning af de overliggende bjergarter sted, svarende nogenlunde til grabenområdet. Denne indsænkning skete delvis i Kvartær.

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