ZECHSTEIN SALT DENMARK
Salt Research Project EFP-81

Volume II
Stratigraphy

DGU
Geological Survey of Denmark
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PREFACE

Volume II is part of four volumes elaborated in the course of Salt Research Project EFP-81.

The volume deals with the lithostratigraphy of Zechstein domal evaporites and a geochemical study of Zechstein 1 and 2 rock salt.

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CHAPTER 1

LITHOSTRATIGRAPHY OF THE ZECHSTEIN SALTS IN THE NORWEGIAN-DANISH BASIN

By Fritz Lyngsie Jacobsen

CONTENTS

LITHOSTRATIGRAPHY OF THE ZECHSTEIN SALTS IN THE NORWEGIAN-DANISH BASIN.

ABSTRACT.

In the Danish part of the Norwegian-Danish Basin 4 cycles of Zechstein evaporites are described. The oldest cycle Z1 is composed of bituminous shale, carbonates, anhydrite, rock salt and, in one well, a potassium mineralization. The older cycle Z2 is composed of bituminous shale, carbonate, anhydrite, rock salt and magnesium - potassium minerals. These latter minerals make up the Veggerby zone, which resembles the German Flöz Stassfurt. The younger cycle Z3 is composed of shale, fine sand, subordinate anhydrite and reddish coloured rock salts with two minor potassium mineralizations. The youngest cycle Z4 is composed of shaly sands, subordinate anhydrite and rock salt. No younger cycles are observed.

The depositional history of the Danish Zechstein evaporites is given. A strong subsidence of the Norwegian-Danish Basin was initiated at the end of the Rotliegendes and the beginning of the Zechstein. During Zechstein the basin was filled with relatively deep sea sedimentated evaporites in Z1 and in the major part of Z2. From the termination of Z2 to the end of Z4 shallow sea sediments were the dominating type.

In connection with the general description is given an outline of the movements of the salt with pillow stage in Late Bunter and with the diapiric movements from Jurassic to recently. Cap rocks are shortly discussed. A summary of the drilling practise is given. The economic geology in relation to the Zechstein is discussed with respect to hydrocarbons, potash and different uses of rock salt.

INTRODUCTION.

From 1932 onwards the salt exploration in the Danish area has progressively been intensified. This has lead to an increasing amount of information concurrently with which the need for a detailed stratigraphy has become more and more apparent.

Drilling was started by the Danish American Prospecting Co. (DAPCo) in 1935. In June 1946 the first Zechstein salt was described from the well Vejrum no. 1. In the period up to 1952 a total of 56 salt wells were drilled, 34 of which terminated in salt. In 1959 DAPCo abandoned the concession, Ødum 1960.

From 1959 to 1961 four exploration wells for potassium minerals were drilled in the Suldrup Saltdome, Boreudvalget 1962. Two wells were drilled in 1964, one in 1972 and one in 1974 by Dansk Salt I/S and used for solution mining of NaCl. In the year 1973 three exploratory wells were drilled by ELSAM at the Vejrum salt structure to test the possibilities for construction of air caverns for an Air Storage Energy Transfer plant.

In 1978 Dansk Olie & Naturgas A/S (D.O.N.G.) drilled its first eksploratory well in a campaign with the purpose to construct a gas cavern field in the Tostrup dome. In 1983 the solution mining of the first cavern was initiated. In the years 1979 - 1980 ELKRAFT/ELSAM, the cooperative electrical power plants for respectively Sjælland and Fyn-Jylland, drilled one well at Linde and two on Mors in order to investigate these domes as repository sites for high level radioactive waste.

In connection with the extended use of the Danish Zechstein salt the Ministry of Energy sponsored the present study of the grey halitic salt. The ambition of the project is to find a method to distinguish between the oldest and the older grey salt and to develop a geological model describing the relationship between the texture of rock salt and its mechanically tested strength.

In the appendix a summary of the events in Danish salt exploration is given year by year.

BASIN DEVELOPMENT

The Norwegian - Danish Basin is a broad and deep basin between the Ringkøbing-Fyn High and the Scandinavian Border Zone. The development of the basin is not yet fully understood but several authors have given a general description of its history of the evolution, e.g. Derumaux 1980, Hamar 1982, Michelsen & Andersen 1981.

After the termination of the Rotliegendes volcanism the subsidence accelerated and the local part of the Northwest-European Basin was turned into the Norwegian-Danish Basin. The knowledge concerning the basin floor is sporadic, it is based on a compilation of data from the surrounding areas and from the few wells that penetrated the rocks of the Zechstein Group, Rasmussen 1974, Ziegler 1981, Olsen and Strass 1982.

The volcanic rocks within the area in the Danish wells C-1, D-1 and L-1 are of Rotliegendes age, Larsen 1972, and are downfaulted remnants of a much larger cover, J.G. Larsen in Michelsen 1982.

The Rotliegendes sediments are scarsely known from the North German Basin, from British wells and from a few Danish wells, J.G. Larsen op. cit., Marie 1976, Rasmussen 1974, Ziegler 1981. The thickness of these sediments is 100-200 m and generally the coarser sediments are found towards the north and northeast. This indicates that Scandinavia was the major source area during Rotliegendes.

In the Danish part of the Norwegian-Danish Basin Rotliegendes silt and claystones are penetrated by the wells Nøvling 1: Christensen, 1973, Rønde 1: Christensen, 1971 and Slagelse 1: Poulsen, 1974. Despite that no fossils are found in these sections both authors are of the opinion that the data favour a Rotliegendes age for these sediments. The change from Rotliegendes to Zechstein is in the North German Basin defined by the presence of a conglomerate followed by the Kupferschiefer in Germany and the Marl Slate in England, overlain by limestones and dolomites. This succession reflects the major transgression of the North European Zechstein Sea. The opening of the sea to the north between Norway and Scotland was caused by rifting in connection with opening of the Atlantic Rift, Derumaux, 1980. This Zechstein Sea occupied an area consisting of the present North Sea area, Denmark, North Germany and Poland, Osika, 1975, and herein limestone, dolomite, anhydrite, halite and magnesium-potassium salts were depostied in 4 major cycles, Richter-Bernburg, 1955.

During the oldest part of the Zechstein period the Norwegian-Danish Basin was enclosed to north and northeast by the Fennoscandian Craton. To the south the basin was bordered by the Ringkøbing-Fyn High, which formed a peninsula or an island during the entire Zechstein period.

Strong subsidence in the Norwegian-Danish Basin continued throughout the Zechstein and Triassic while a sediment thickness up to maximum 5000 m was accumulated in the North Jutland area. The post Triassic rate of deposition has varied through time whitout reaching the previous level.

In Late Triassic time the weight of the overburden and differential movements in Pre-Zechstein rocks triggered movements in the Zechstein salt so that huge masses of salt formed pillows and even diapirs. Still more research is needed before it is possible to evaluate the complete history of the diapiric movement in this province. On figure 1 the Norwegian-Danish Basin with the described wells and the dome area are shown. The different domes mentioned are shown on the special map of North Jutland Dome Province (figure 2).

STUDY OF THE DANISH ZECHSTEIN SALT.

A total of 56 wells has been drilled in the salt domes

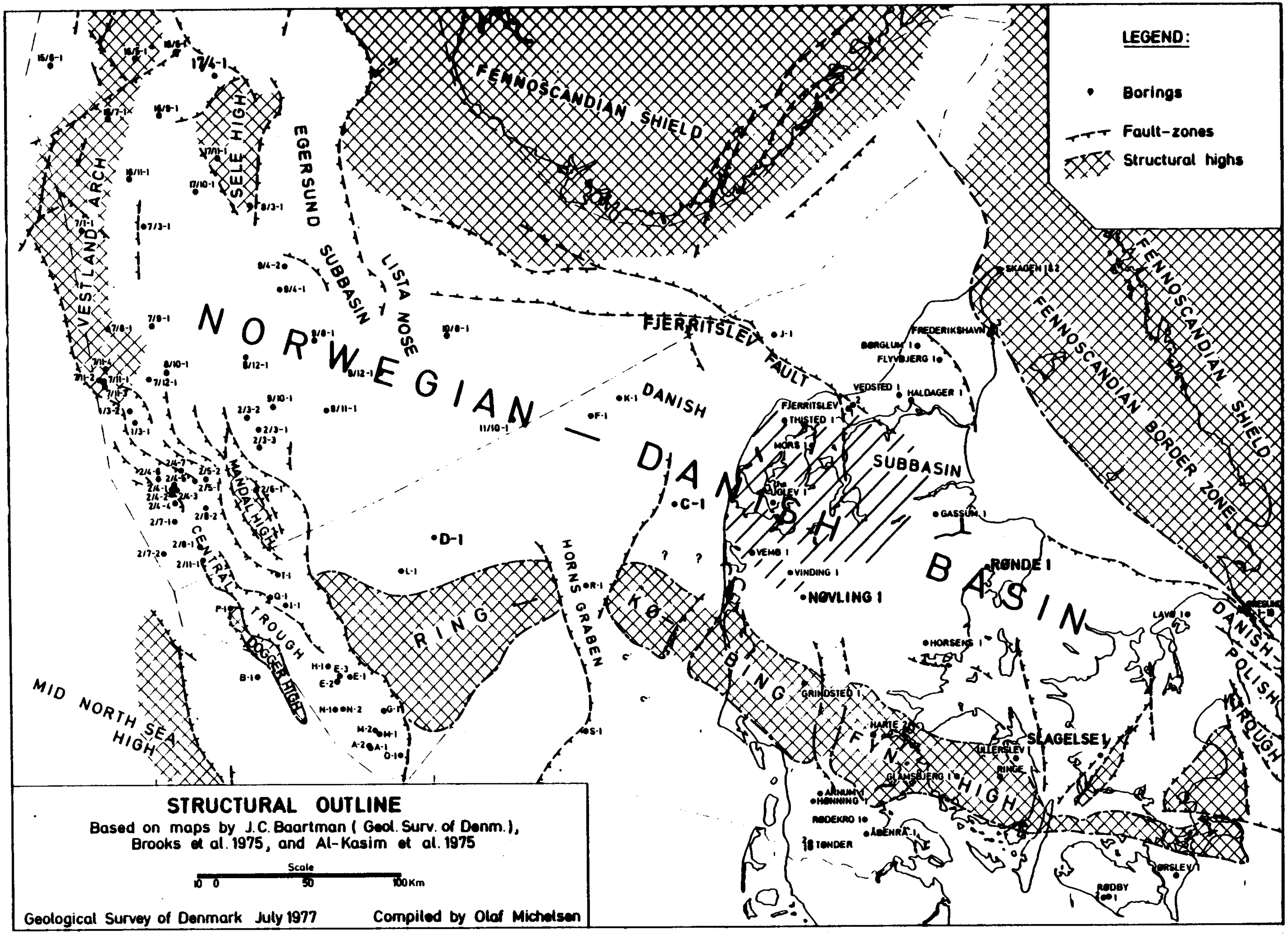


Fig. 1. Structural outline of the Danish Area, Michelsen 1978. The wells used in this paper are underlined and the dome province is shadowed. The more precise locations of the domes are demonstrated on fig. 2.

(table 2) and 5 deep wells in the bedded salt (table 1). The latter 5 wells were drilled as wild cats in connection with the exploration for oil in the Danish area. The D-1 well is drilled at a pillow structure, the other 4 on faulted but flatlaying structures which have preserved the bedded character of the salt.

The Geological Survey of Denmark has performed a detailed examination of cores, cuttings, logs etc. during and after the drilling campaigns. All the cores, i.e. from the first salt dome well to the last completed, have been described at the Geological Survey and thin sections have been prepared in a sufficient number to allow description of the texture of the different salt types. Chemical analyses have been carried out in connection with each drilling campaign and totalling a number of about 18000.

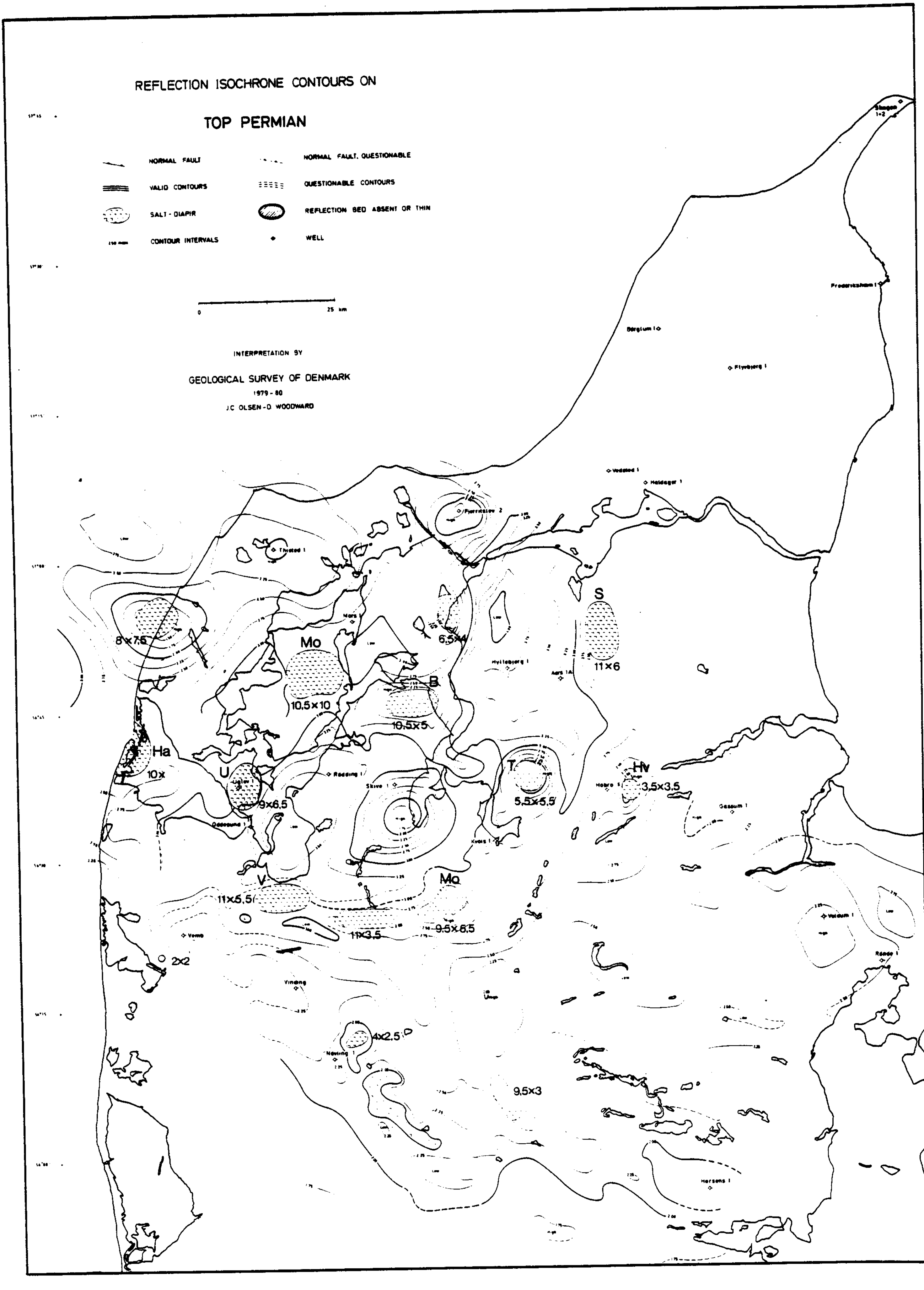
All the wells and all the chemical analyses will be published in condensed form in the Well Data Summary Sheet, Salt Wells.

DESCRIPTION OF THE ZECHSTEIN GROUP AND THE ADJOINING FORMATIONS.

Pre-Zechstein rocks.

Only five wells in the Danish part of the Norwegian-Danish Basin have penetrated the Zechstein rocks and given information concerning the older formations. The D-1 well in the central part of the North Sea penetrated a siltstone (3320-3468 m), coarse-grained, red-brown, bedded, non calcareous, varying clayey and a claystone (3468-3508 m), red-brown to chocolate brown with layers of reddish sandstone, Rasmussen 1974. Below this a basal eruptive sequence (3508-3520 m T.D.) was dated by O.Larsen 1972 to 237 +/- 16 mill. years (K/Ar).

The C-1 well, Rasmussen 1974, about 30 km W of the western inlet to Limfjorden encountered an acid effusive rock


REFLECTION ISOCHRONE CONTOURS ON
TOP PERMIAN
NORMAL FAULT
NORMAL FAULT, QUESTIONABLE
VALID CONTOURS
QUESTIONABLE CONTOURS
SALT - DIAPIR
REFLECTION BED ABSENT OR THIN
CONTOUR INTERVALS
WELL
0
25 km
INTERPRETATION BY
GEOLOGICAL SURVEY OF DENMARK
1979 - 80
J.C OLSEN - D WOODWARD
Skagen 1+2
Frederikshavn 1
Børglum 1
Flyvbjerg 1
Vedsted 1
Haldager 1
Fjerritslev 2
Thisted 1
Mors 1
Hyllebjerg 1
Aars 1A
Hobro 1
Gassum 1
Rødding 1
Skive 1
Uglev 1
Oddesund 1
Kvols 1
Vemb
Vinding
Nøvling 1
Voldum 1
Rønde 1
Horsens 1
8×7,5
Mo
10,5×10
6,5×4
B
10,5×5
S
11×6
Ha
10x
U
9×6,5
T
5,5×5,5
Hv
3,5×3,5
V
11×5,5
Mo
9,5×6,5
11×3,5
2×2
4×2,5
9,5×3

(3159-3169 m T.D.) directly below the Zechstein rocks. This rock is light greyish to reddish, banded with flow textures and with phenocrysts of alkalifeldspar. The rock is dated by O.Larsen 1972 to be 281 +/- 8 m.y., (K/Ar).

Danish North Sea D-1	1633 m
Danish North Sea C-1	629 m
Nøvling 1	111 m
Rønde 1	230 m
Slagelse 1	373 m

Table 1. Five deep wells in the Danish area of the Norwegian-Danish Basin with the total nos. of meters drilled in Zechstein Rocks in each well mentioned from west to east. The well Nøvling 1 is not included in this paper because only a part of Z2 is present, Jacobsen 1973.

Onshore in the Nøvling 1 well Zechstein rocks overlay the Nøvling Formation of Upper Ludlowian Age, Christensen 1973. This formation is composed of clay- and siltstone, red-brown, interbedded with effusive basalt, Jacobsen 1973.

The rocks below Zechstein in the well Rønde 1 is a sandstone, fine-grained, light reddish at top, gradually changing downward into darker reddish brown, silty with intercalated claystone, Jacobsen 1971. This rock is believed to be of Rotliegendes age, Christensen 1971.

←

Fig. 2. Top Zechstein, the Danish Salt Dome Province, onshore. The map demonstrates the two-way-time (TWT) contours in the western part of North Jutland. The salt domes, which have pushed their way through the overburden, are marked with salt symbols. Domes mentioned in the paper are marked as followes: B Batum, Ha Harboøre, Hv Hvornum, Mo Mors, Mø Mønsted, S Suldrup, T Tostrup, U Uglev and V Vejrum.

	Depth to cap rock	Depth to salt	Nos. of wells to salt	Meters drilled in salt	Approximate size in km
Batum	158	206	14	2323	10,5 x 5
Harboore	82	166	2	775	10 x ?
Hvornum	192	294	5	5049	3,5 x 3,5
Mors	582	608	2	5542	10,5 x 10
Monsted	213	317	1	445	5,5 x 5
Suldrup	103	200	15	10003	11 x 6
Tostrup	145	236	10	11296	5,5 x 5,5
Uglev	964	973	1	274	9 x 6,5
Vejrum	174	226	6	2574	11 x 5,5

Table 2. Nine salt domes in the Danish Dome Province were drilled from 1946 up to now. The data given in the table give an impression of the knowledge on the salt in each dome. Two of the domes are used today: Hvornum Dome with solution mining for NaCl in production and Tostrup Dome with a gas storage cavern plant under construction.

In the Slagelse 1 the Lower Permian is described in detail by Poulsen 1974. He believed that this dark red, silty and noncalcareous claystone, is of Rotliegendes age.

The knowledge concerning the Rotliegendes rocks is moderate but it is in general agreement with the common impression of the Norwegian-Danish Basin as part of a volcanic province. Remnants of this province are still exposed in the Oslo Region, where weathering of the effusive volcanic rocks produces red beds.

Zechstein 1. (Z1).

In none of the five wells, which penetrate the Zechstein in the Danish part of the Norwegian-Danish Basin, are there evidence of a conglomerate initiating the Zechstein sequence. But in four of the five wells dark brown to black bituminous marl or slate resembling the British Marl Slate or the German Kupferschiefer is present. These four wells (D-1, C-1, Rønde 1 and Slagelse 1) are all situated on the Northern Flank of the Ringkøbing-Fyn High. The development of the salt varies slightly between the wells. As no cores were cut in this interval all descriptions are based on cuttings and log analyses (table 3, fig. 3).

	Gamma ray GR	Density logging FDC
K-Mg-salts	Medium-high	Very low-medium
Rock salt	low	low
Anhydrite	low	very high
Dolomite	medium	high
Limestone	medium	medium high
Clay	medium-very high	medium-low
Sand-, siltstone	low-medium	medium

Table 3. In the outline of the lithostratigraphy of the Zechstein rocks Gamma Ray and Formation Density log are used as the generally most convenient logs describing the evaporites and their associated rocks. The general readings of the logs are given in the table.

Kupferschiefer/Marl Slate.

D-1	C-1	Rønde 1	Slagelse 1
1,5 m	1 m	1 m	?

The slate is overlayn by limestone-dolomite in varying thicknesses, which was deposited under a variety of environmental conditions.

Limestone-dolomite.

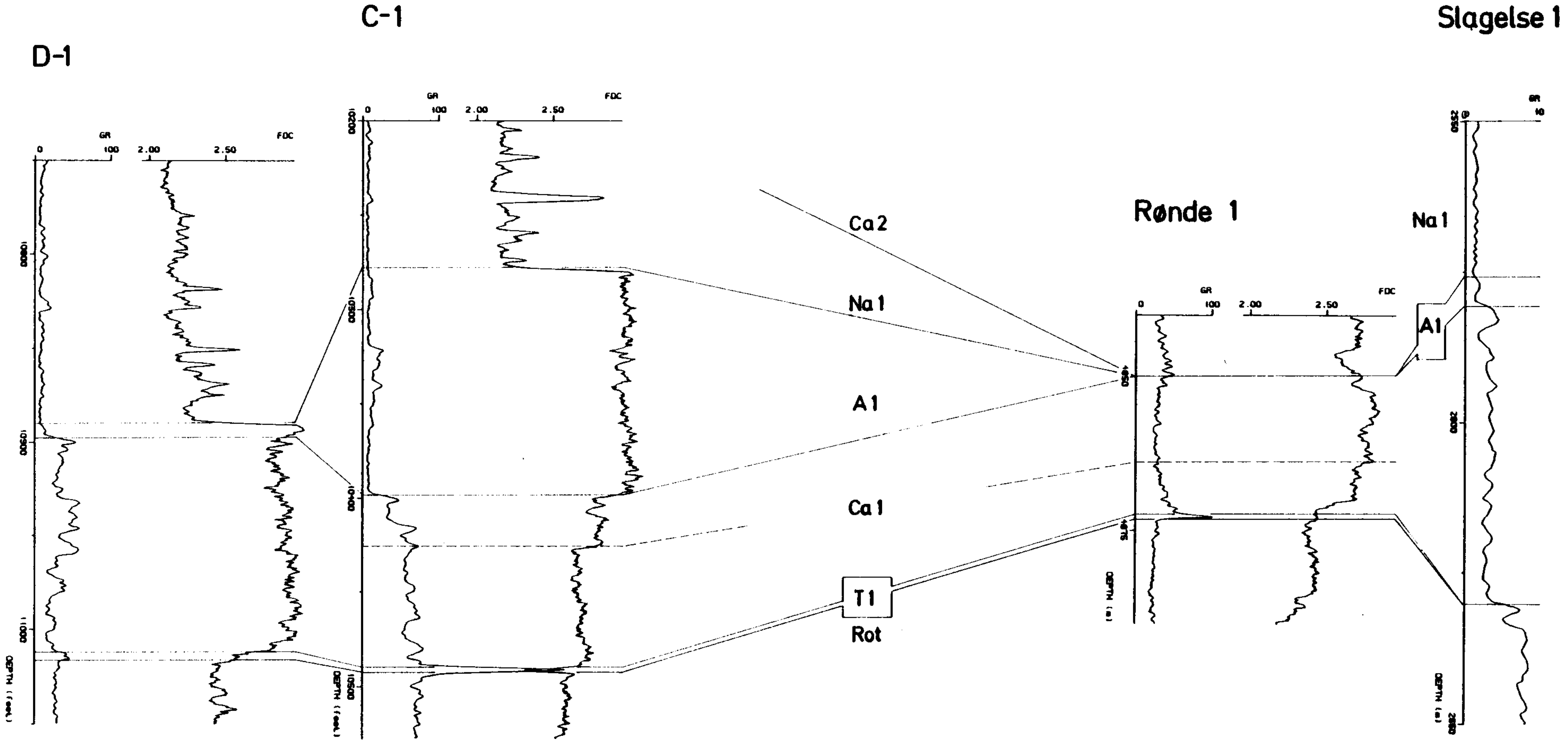
D-1	C-1	Rønde 1	Slagelse 1
35 m	28 m	22 m	49 m

18 m of dominantly dolomite is cored in the 35 m carbonate section in the well D-1. The lower part of the section is a 5 m thick limestone, light grey with light ferruginous staining, granular to finely crystalline and sandy at the base. This is overlayn by an 11 m thick dolomite-anhydrite rock. The dolomite is grey to greyish brown, dense and with nodules of greyish anhydrite. Thin layers of shale, black, with coal fragments, are dispersed through these rocks. Disseminated traces of oil cuts are seen in the core.

→

Fig. 3. Outline of the oldest part of the Zechstein Group in the Danish part of the Norwegian-Danish Basin. Rot: Rotliegendes as clay-, silt- and sandstones in D-1, Rønde 1 and Slagelse 1 and as volcanics in C-1. T1: Kupferschiefer with high uranium content in C-1 and Rønde 1. Ca1: The carbonate facies, which can be divided in to a lower limestone and an upper dolomite sequence in the wells C-1 and Rønde 1. Younger parts of Zechstein 1 are missing in the Rønde 1 well. A1: The anhydrite facies is thin in D-1, relatively huge in C-1, absent in Rønde 1 and thin in Slagelse 1. Na1: The lower part of the oldest rock salt. The salt is rich in anhydrite, which is clearly demonstrated by the FDC-log. Depth scale is about 1:1000.

ROTLIEGENDES / ZECHSTEIN 1



This sequence is followed by an 8 m thick dolomite, dark grey to greyish brown, which is bedded by layers of more clayish rock, which in turn contains thin undulating layers and lenses of clay. Dispersed nodules of anhydrite are present as eyes in the rock Anhydritkotenschiefer. There are traces of oil cut in this part of the core as well.

Above the "Anhydritknotenschiefer" follows 11 m of fractured dolomite-anhydrite rock. It is a dark grey dolomite with stylolites, shale fragments and anhydrite cement in fractures. A little oil is observed in the fractures.

In the C-1 well the lower carbonates are developed as interbedded limestone, marl and shale. The clay content decreases upwards. The colours are brown to brownish grey to grey. This section is 19 m thick and only cuttings are available.

Above this succession a 9 m thick bed of bedded, light grey to greenish grey and slightly calcareous dolomite with thin layers of clay is deposited.

The Rønde 1 well is drilled through a 22 m thick bed of dolomitic, marly, grey to dark grey limestone. The cuttings material from this rock was very poor.

In the Slagelse 1 well, the easternmost of the wells, the Zechstein 1 carbonate is described as limestone by Sorgenfrei and Buch 1964, and as dolomite by Poulsen 1974. It is impossible to distinguish between limestone and dolomite on the wireline logs as only a gamma ray and a neutron log were run. It is believed, however, that the lower part of this 49 m thick sequence consists of limestone, marl and shale. The upper part of the sequence, in which two cores were cut, consists of dolomite and shale. 14.5 m was recovered in the cores. These rocks consists of rythmically sedimented grey, fine to very fine grained dolomite and dark grey, thinly laminated shale. The whole cored sequence contains plant remains representing three members of the class Hepaticopsida and gymnosperm-pollen of the genus Leuckisporites. The latter is extremely dominating and is also well-known from other Zechstein sediments.

The carbonates are followed by a sedimentation of anhydrite. In the Rønde 1 well sulphates are lacking. In the other three wells the anhydrite is developed as a fine grained, white to grey to yellowish grey, almost monomineralic rock with no or a very small clay content. Only in the center of the C-1 succession an increase in the GR-log indicates a somewhat higher clay content. No cores are cut in these sections.

Anhydrite.

D-1	C-1	Rønde 1	Slagelse 1
2 m	36 m	0	5 m

The next rock sequence in this oldest cycle of the Zechstein consists of rock salt. This rock salt is known from the dome area of Northern Jutland as well, but in most cases it is not possible to tell the exact thickness.

Z1 rock salt.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
102 m	31 m	c. 400 m	0 m	137 m

The rock salt was cored to a greater extent in the dome area. Therefore it is possible to give a more definite description of its appearance and to analyze the behavior of the salt in stressed environments.

In the D-1 well the rock salt is clear to light greyish with disseminated anhydrite. All information is related to log analyses combined with study of cuttings. In the lower 11 m of the section five thin layers of anhydrite are encountered in the salt. But in contrast to the other wells drilled in the oldest Zechstein rock salt, the D-1 well encountered potassium salts in three levels.

Potassium salts in the Zechstein 1 rock salt sequence in meters above its bottom:

97-99 m Potassium mineralization, carnallite? High GR-reading in dissolved cavity.

66-69 m Potassium mineralization associated with anhydrite and/or kieserite.

44 m Anhydrite with potassium mineralization.

The rock salt drilled in the C-1 well is anhydrite-rich, clear to light greyish.

In the dome area it is generally the upper part of the oldest rock salt, which is seen in the wells. Due to halokinesis movements this salt has a gneissic appearance (figs.4, 5, 6). It is medium-coarse grained, more or less translucent and with disseminated euhedral anhydrite. There is a diffuse bedding in the rock salt. Each bed is 5 to 20 cm thick and the colour is grey to dark grey. The alternating translucent salt varies in thickness from few centimeters to several meters.

In the Rønde 1 well no Z1 rock salt is encountered.

The Z1 rock salt in Slagelse 1 is clear to greyish to light reddish. 8.7 m of the upper part of the member is cored. The rock salt contains disseminated anhydrite and anhydrite in thin beds. The lowermost 1.5 m of the core is reddish coloured and contains traces of disseminated carnallite and polyhalite.

The general appearance of the Z1 salt is very similar to the grey to greyish rock salt belonging to the Z2 cycle. This stratigraphic problem is one of the major tasks for the

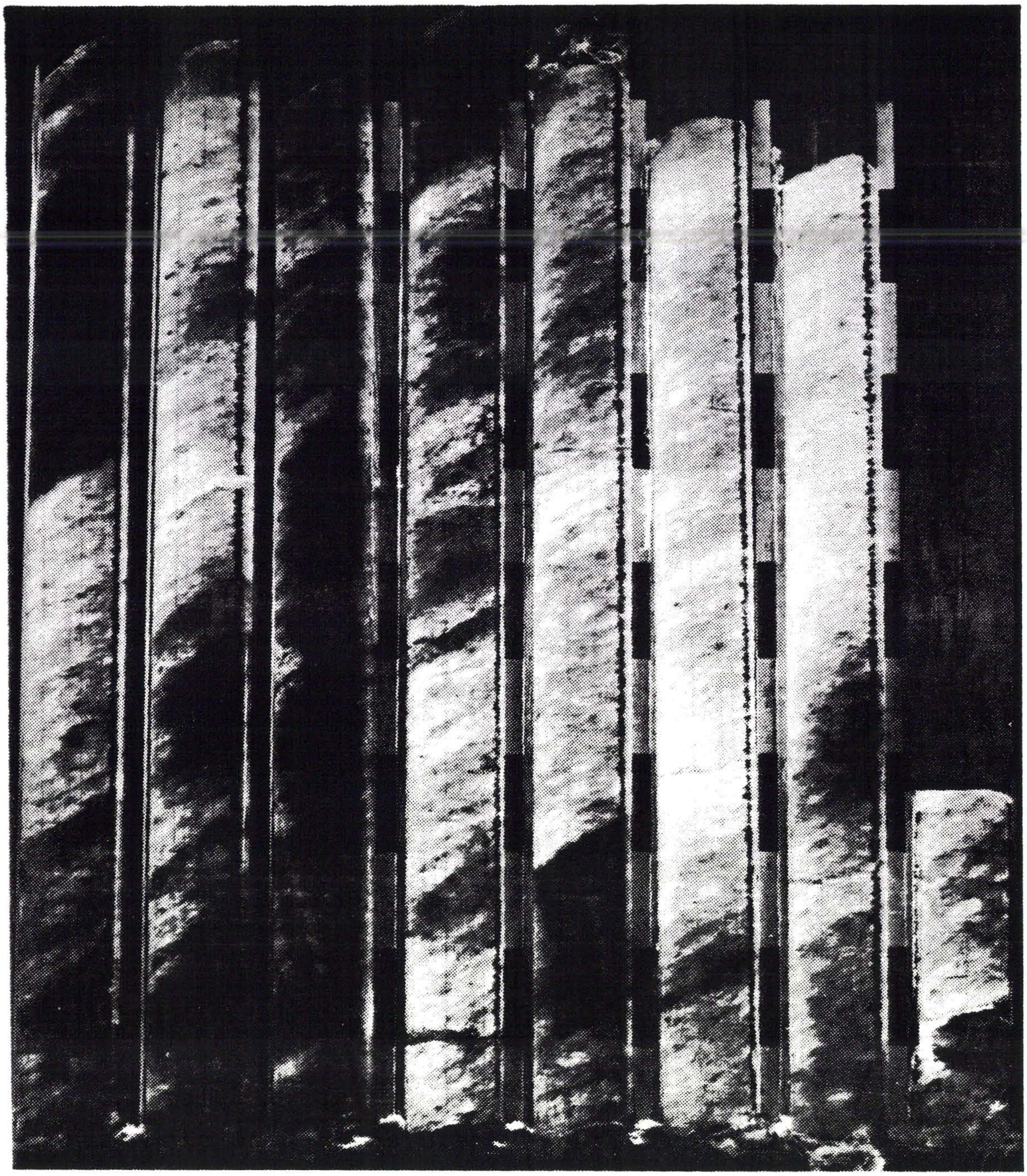


Fig. 4. Erslev 2, core no. 22, 2848.14-2856.18 m below ground level. Photo with translucent light. Nal-rock salt, grey to light grey to greyish, more or less translucent, coarse grained and foliated with gneissic texture with eyes up to 8 cm. The nontranslucent parts of the core contain disseminated clay, anhydrite as disseminated crystals and as fine grained tectonized nodules. The average mineralogical composition of the core is calculated from the chemical analyses Quist's lab. and Laier, 1980: Halite 97%, anhydrite 3%, clay, quartz and pyrite in total 0.2%. The measure marks are 10 cm each. The groove on the core is cut by the orientation knife in the core barrel.

present project to solve, see Springer 1984, (chapter 3, this volume).

Zechstein 2. (Z2).

The sequence between the two huge series of grey rock salts, commonly called the transition zone or the anhydrite-dolomite zone, is almost identically developed in all wells in which it is encountered. In the dome area 14 wells transsect the zone, in some wells several times due to folding or faulting. Therefore only a detailed description, related to the GR-log, of the transition zone from one well, Batum 13, is presented, see Sønderholm 1984, (chapter 2, this volume).

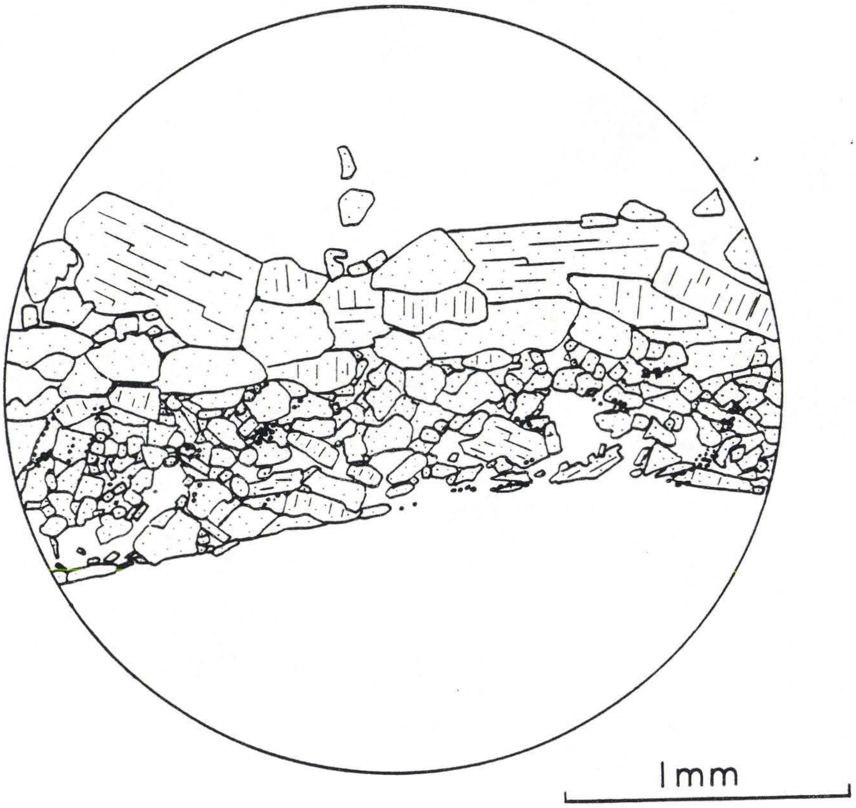


Fig. 5. Batum 1A, 466,6 m below ground level. Detail of the front illustration. Thin layer of anhydrite in clear halite. The figure probably shows solution of rock salt with a sedimentation of residual anhydrite from the dissolved salt. On the front illustration it is possible to recognize brine inclusions as droplets and as negative crystal forms.

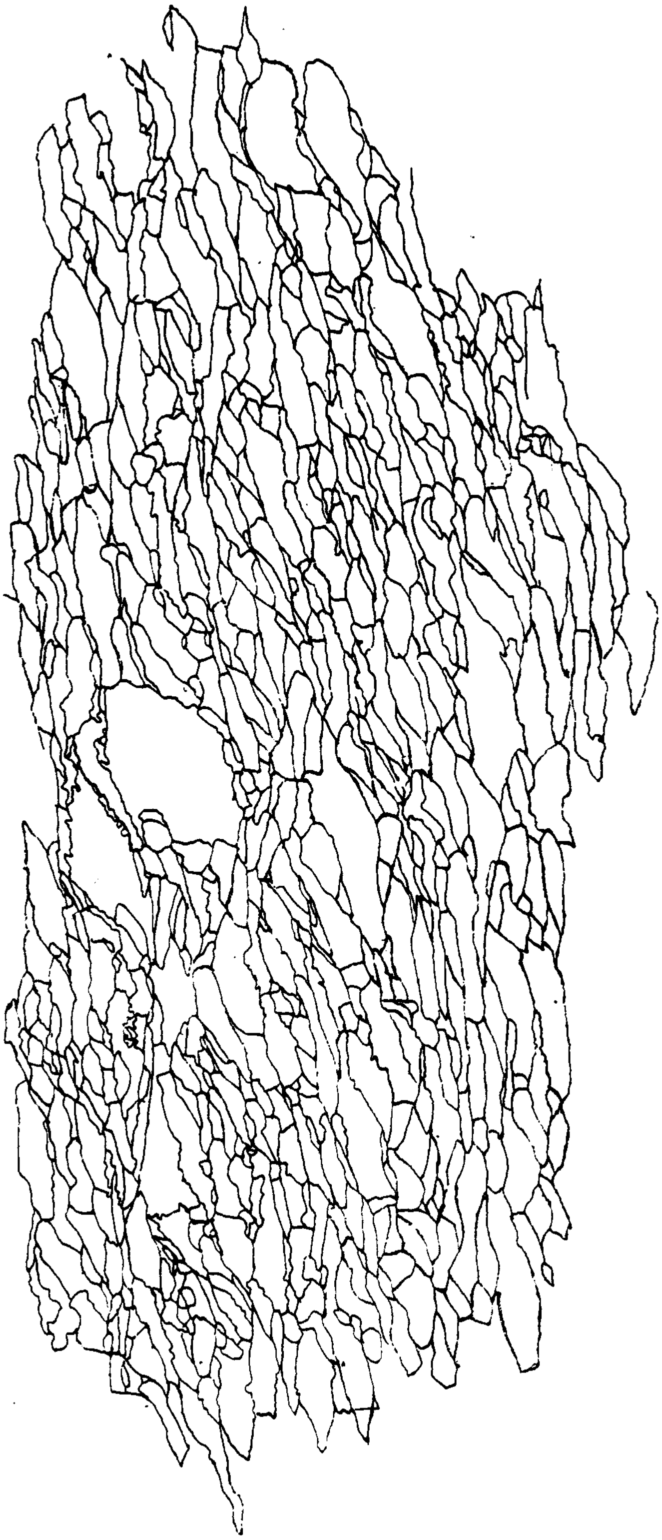


Fig. 6. Tostrup 6, core no. 10, 1216.50 m below KB. Replica on acetate film of a cut and polished core piece 1:1. Rock salt strongly foliated with a medium to coarse grained heteroblastic gneissic texture. The salt is probably NaI. Drawing by Gert Grønning.

The transition zone Z1/Z2.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
9 m	66 m	15 m	23 m	37 m

Fig. 7 demonstrates the accordance between log motifs from the different wells. The sequences from D-1 and the dome area represent a deep-sea sedimentation. The other wells exhibit facies originating from locations nearer to the shore. The paleogeographic significance of the transition zone will be discussed later in this paper.

The summarized description of the transition zone, as given below, is based on core descriptions from the dome area and Slagelse 1, and log correlations to the other wells.

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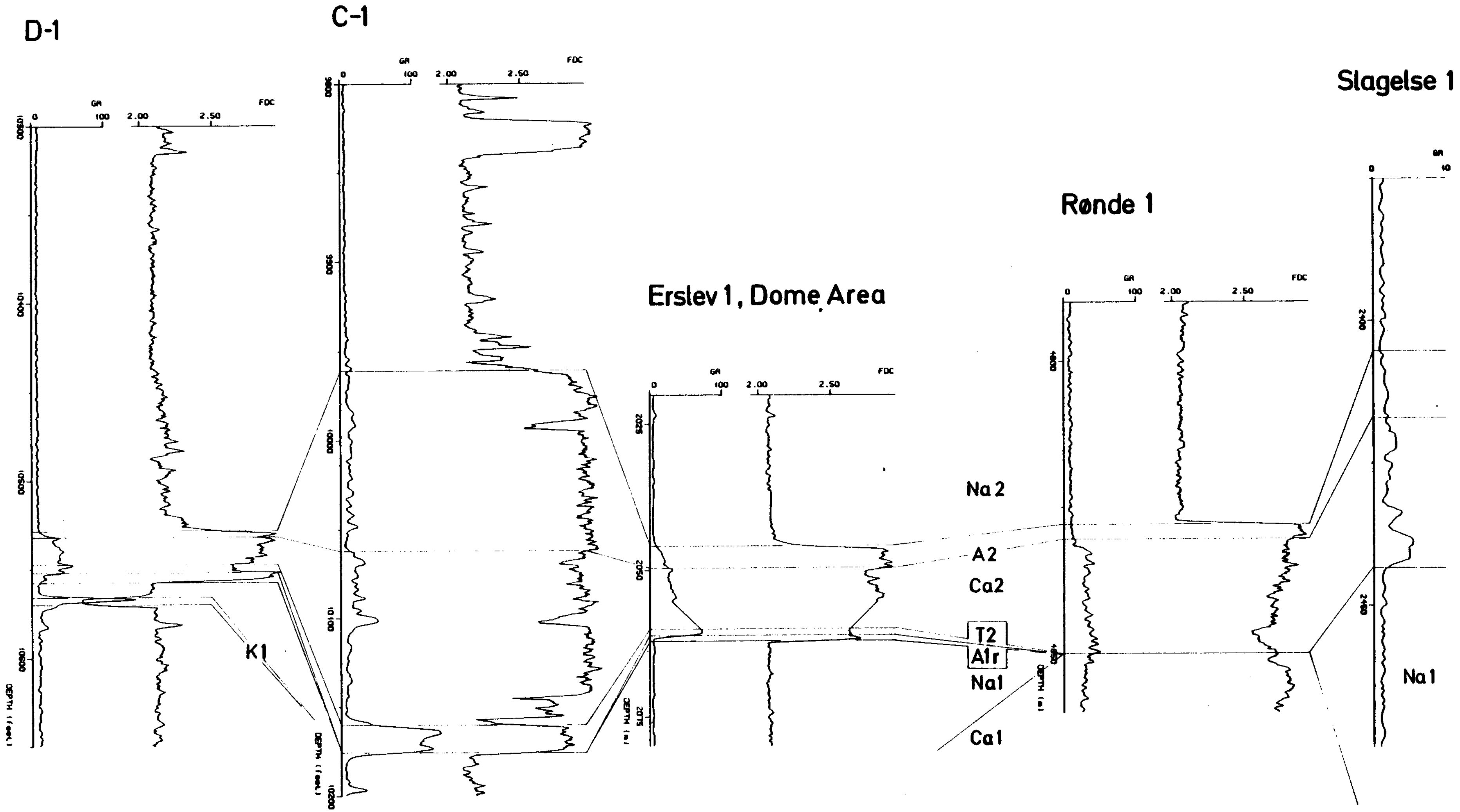
Fig. 7. Outline of the transition zone between Zechstein 1 and 2 in the Danish part of the Norwegian-Danish Basin. Na1: Top of the oldest rock salt, absent in Rønde 1 well. K1: Potassium bed in the D-1 well. A1r: Anhydrite bed developed during the influx of the Zechstein 2 Sea. T2: Clay bed with organic matter resembling the Stinkschiefer. Ca2: The carbonate facies developed as Anhydritknotenschiefer, Schwaden - and Wolkenanhydrit. In the Dome Area, where the zone has been cored several times, it is possible to determine the lower part as the most lime-rich part. A2: The anhydrite facies developed as Flaseranhydrit. Na2: The lower part of the older rock salt, which in D-1 and C-1 are richer in anhydrite than in the Dome area and in the Rønde 1 well. Depth scale is about 1:1000.

ZECHSTEIN 1/2



The oldest rock, which is present in the D-1 well and in the dome area, is a max. 1 m thick pure anhydrite, greyish blue to light grey, diffusely layered and massive. The next layer is a carbonate-clay rock, brownish black, finely laminated and rich in organogenic matter, which overlies the above anhydrite and constitutes the bottom of the transition beds in the other wells. The dominating carbonate rock types are calcite and dolomitic calcite. High contents of petroleum gasses are commonly encountered in these rocks.

Thereafter follows a part of the section which varies slightly from well to well. In the dome area many cores are drilled in this interval. Therefore it has been possible to give a detailed description of the sequence as mentioned

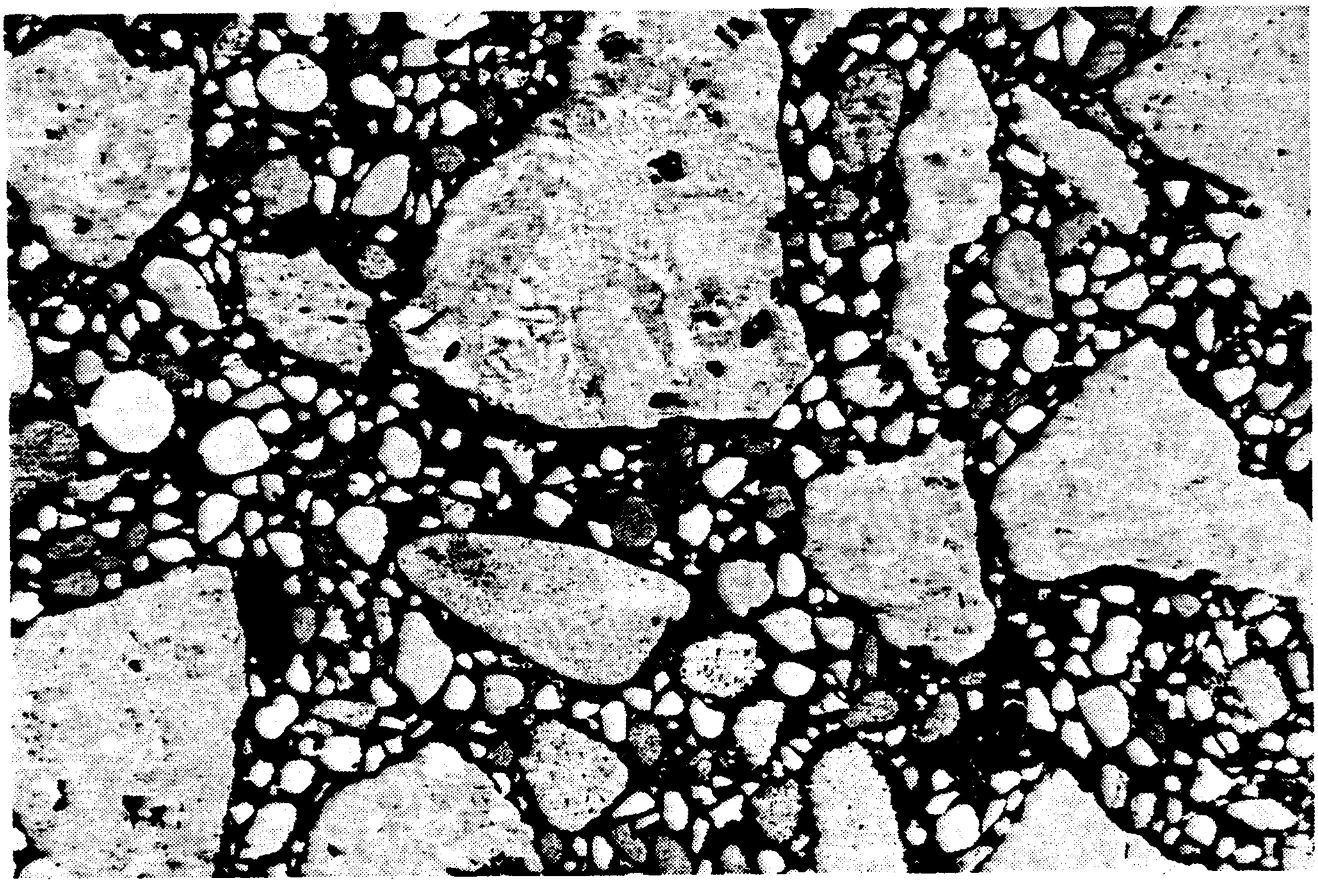


Fig. 8. Slagelse 1, core no. 2, 2426-2435 m below rotary table. Sample 30-36 cm below top of core. Agglomerate, reddish brown, vesicular, with greenish xenolithes, max 1 cm across. The xenolithes are fine grained granodiorites with xenomorph granular myrmekitic texture. The feldspars are partly altered. Furthemore different xenolithes of limestones, greenish siltstone and well rounded quartz grains are observed. The groundmass is nearly opaque and made up of small rust aggregates.

above. It has also been possible to interprete the ancient environment on the basis of core descriptions and log evaluation. The sequence comprises a carbonate dominated section, which immediately overlies the clayee carbonate rock. In the lower part calcite is the major constituent, but upwards it changes gradually to a fine grained dolomite. The entire interval has a varying content of clay and/or anhydrite. The rock types entcountered in the upper part are: Anhydrit, Wolken- and Schwadenanhydrit, Anhydritknotenschiefer and finely bedded dolomite.

The most pronounced log motif close to the top of the section is caused by finely bedded, brown and clayish dolomite, which gives medium high values on the GR and density logs. In Slagelse 1 this clayish dolomite section includes a 6 cm thick volcanic agglomerate (fig. 8). This is of granodioritic composition and is an evidence of volcanism in relation to the subsidence of the basin.

All logs and the described cuttings from the wells gives the same impression of the uppermost rock type of the transition zone. It is a rather pure anhydrite developed as a Flaseranhydrit.

The Zechstein 2 rock salt sequence, which follows the transition zone is in its lowermost part anhydrite-rich,. Upwards the anhydrite content decreases rapidly to 2-5% in the major part of this salt sequence. Towards the top of the greyish rock salt sequence it changes gradually via a light brownish to a nearly colourless type, poor in anhydrite and with traces of sylvine and kieserite. These salts are followed by an orange coloured rock salt with 1-2% sylvine and 1-2 % kieserite which forms the transitional salt to the K-Mg-zone.

Z2 rock salt.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
1124 m	264 m	c. 600 m	55 m	90 m

The huge rock salt sequence in the D-1 well is believed to be caused by flowing of the rock salt during the development of the local pillow structure. The lowermost 20 m in this well have a slightly higher content of anhydrite than the corresponding intervals in other wells. An exceptional feature of the rock salt in D-1 is a 12 m thick K-Mg-mineralization 169 m above the base of the section. Scattered thin beds of anhydrite, which are less than half a meter thick, are also encountered.

A high content of anhydrite in layers and as disseminated crystals is the most marked feature of the lower 78 m of the Z2-rock salt in the C-1 well. 37 m above the base of the section a 6 m thick bed of anhydrite is observed. The remainder of the salt is pure with an anhydrite content of 2-4% (log-evaluated). In the upper 40 m an increase in kieserite is observed.

In the dome area, where many cores have been cut, it is impossible to give a definite thickness of the Z2 rock salt. The anhydrite-rich lower part is about 5 m thick. The major part of the sequence is a more or less translucent, light greyish rock salt with 1 to 3% disseminated anhydrite. This rock has a grey to dark grey diffuse layering caused by beds with a small clay content and an anhydrite content of 2-6%. Small lumps of thin, commonly rotated, layers of anhydrite, are recognized in these beds. Pyrite, authigenic quartz and clay are seen as traces. The rock salt has a gneissic texture and is medium to coarse grained. Commonly there is a strong foliation and/or lineation. In the upper part of the sequence it changes into a more brownish and in the very top a clear rock salt type (fig. 9). In many intervals of the greyish, brownish and clear salt types, kieserite is observed as a trace mineral.

The sequence in Rønde 1 consists of more or less translucent greyish rock salt with disseminated anhydrite as aggregates or sub- to euhedral crystals.

In Slagelse 1 the light greyish rock salt is generally low in anhydrite. Only in the bottom of the section an increase of the anhydrite content is encountered.

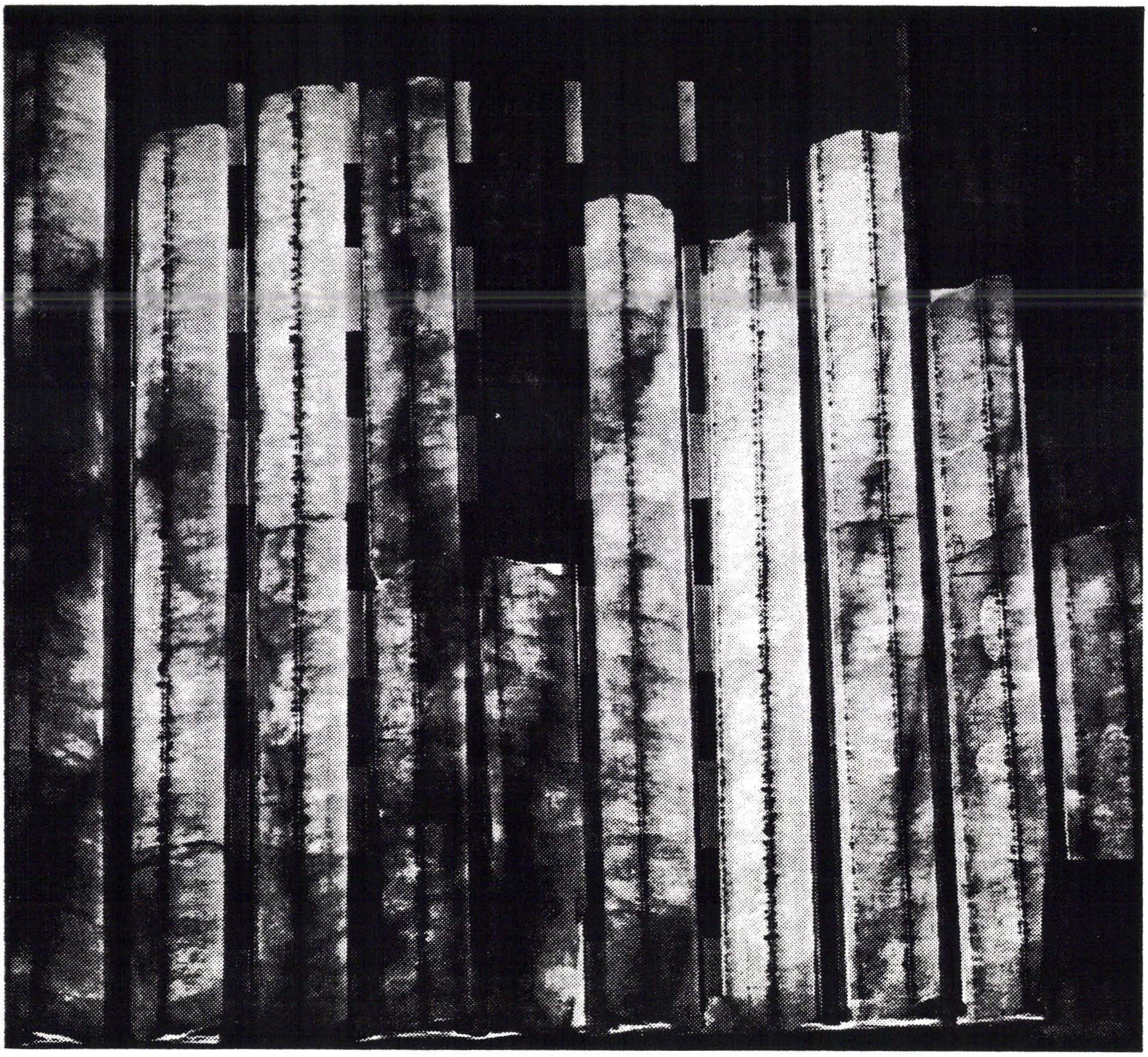


Fig. 9. Erslev 1, core no. 26, 2600-2609 m below ground level. Photo with translucent light. Na2-rock salt, colourless, translucent to light grey, semitranslucent, heteroblastic, coarse crystalline (max. 15 cm) with fine disseminated anhydrite, kieserite and sylvine. The average mineralogical composition of the core is calculated from the chemical analyses Quist's lab. and Laier, 1980: Halite 97,5%, anhydrite 1%, kieserite 1%, sylvine 0,5% and insoluble matter 0.03%. Note the dark layers, which are richer in anhydrite, having a dip of c. 60° in top of the core, vertical in the middle and 75°-80° in the bottom, demonstrating the original bedding of the salt, which is superimposed by a slightly dipping foliation. The latter one caused by differential movements during the upthrust of the salts, illustrating the complexity of the folding patterns in a salt dome. The measure marks are 10 cm each. The groove on the core is cut by the orientation knife in the core barrel.

Above the greyish Z2 rock salt follows a light orange rock salt, which constitutes a transition zone to the K-Mg-zone, called the Veggerby zone (fig. 10).

Transition zone to the Veggerby zone.

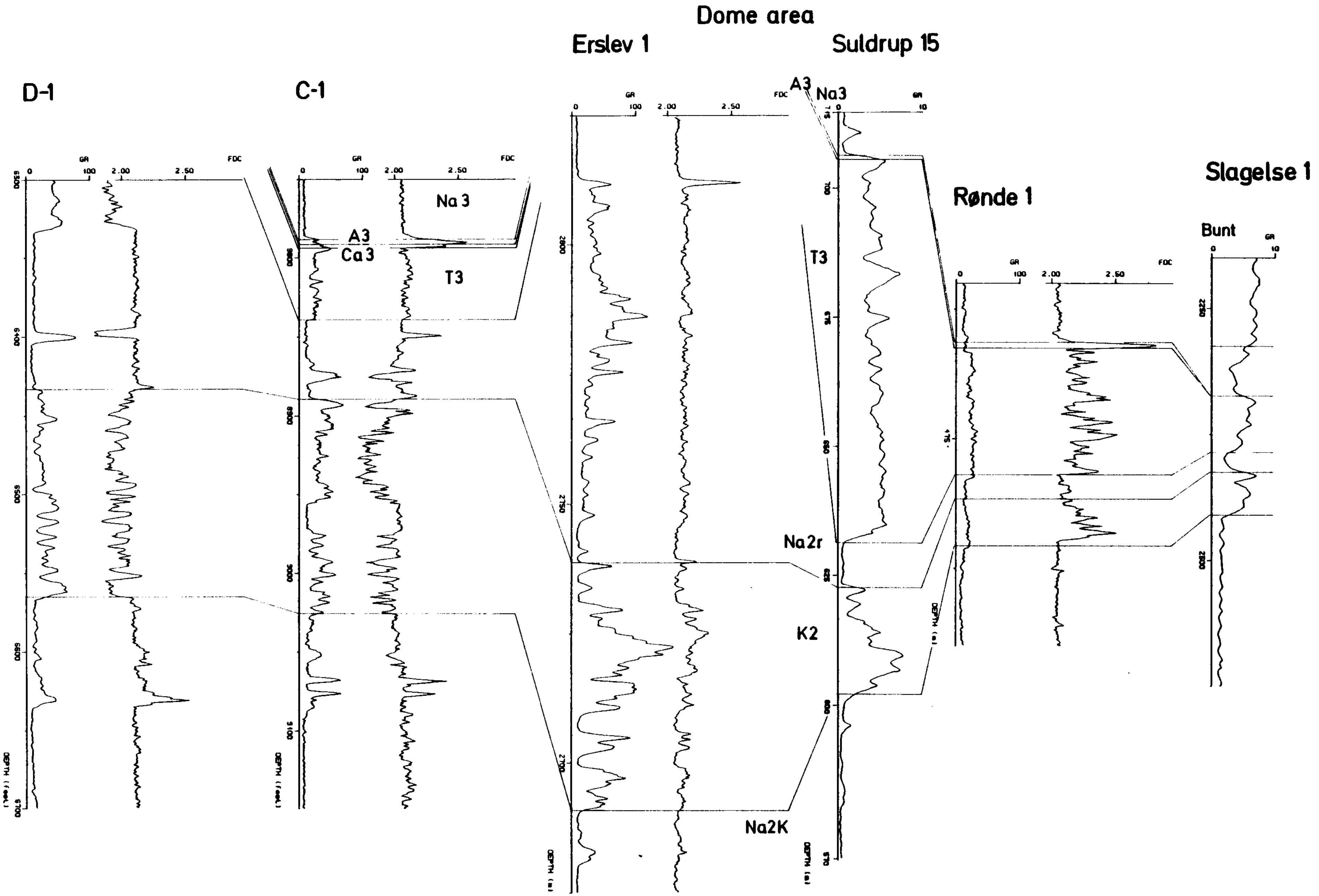
D-1	C-1	Dome area	Rønde 1	Slagelse 1
84 m	20 m	c. 20 m	3 m	24 m

As in the other wells the orange salts in D-1 are characterized by a slight increase in the GR-reading. One 1 m thick anhydrite layer with K-mineralization is found 21 m below top of the section.

→

Fig. 10. Outline of the younger part of Zechstein 2 and the older part of Zechstein 3 in the Danish part of the Norwegian-Danish Basin. Na2K: Rock salt, light orange, with disseminated kieserite and sylvine. Several thin anhydrite beds are observed. In the Suldrup 15 are 3 beds observed in the cores. K2: The Veggerby zone, K-Mg-zone resembling Flöz Stassfurt in NW-Germany. The section 2700-2745 m in Erslev 1 is cored and the lower part is obviously folded. Na2r: Decksteinsalz. In Erslev 1 is a part of the Veggerby zone refolded together with the Na2r. T3: Clay-, silt- and sandstones. The T3 in D-1 is shown on fig. 18. Ca3: This carbonate is only observed in C-1. A3: Anhydrite facies is thin and black. The Suldrup 15 observation is from a core. A3 is present in Erslev 1 too, but not illustrated in this paper. A3 in D-1 is on fig. 18. Na3: The younger rock salt with a tectonized potash bed in Suldrup 15, thin in Slagelse 1, where it is clayish and covered by Buntsandstein (Bunt). Depth scale is about 1:1000. In the Rønde 1 well is noted the high density in K2, which is caused by high baryte content in the dissolved area from the potash bed.

ZECHSTEIN 2 / 3



In the transition zone in C-1 two layers of anhydrite are included in the salt. Each layer is about 1/2 m thick and contains K-mineralizations. These beds are located 12 and 14 m below top of the section.

In the dome area the transitional salt to the Veggerby zone has been studied to a greater extent. The salt is orange to reddish brownish and divided in layers with alternating darker and lighter colour. Each dark layer is about 2 cm thick. The texture is in general equidimentional homeoblastic (fig. 11). The following minerals are observed: Sylvine, 1-3%; Carnallite, 1-5%; Kieserite, 1-2%; Anhydrite about 1% and Polyhalite 0-2%. 3 1/4-1/3 m

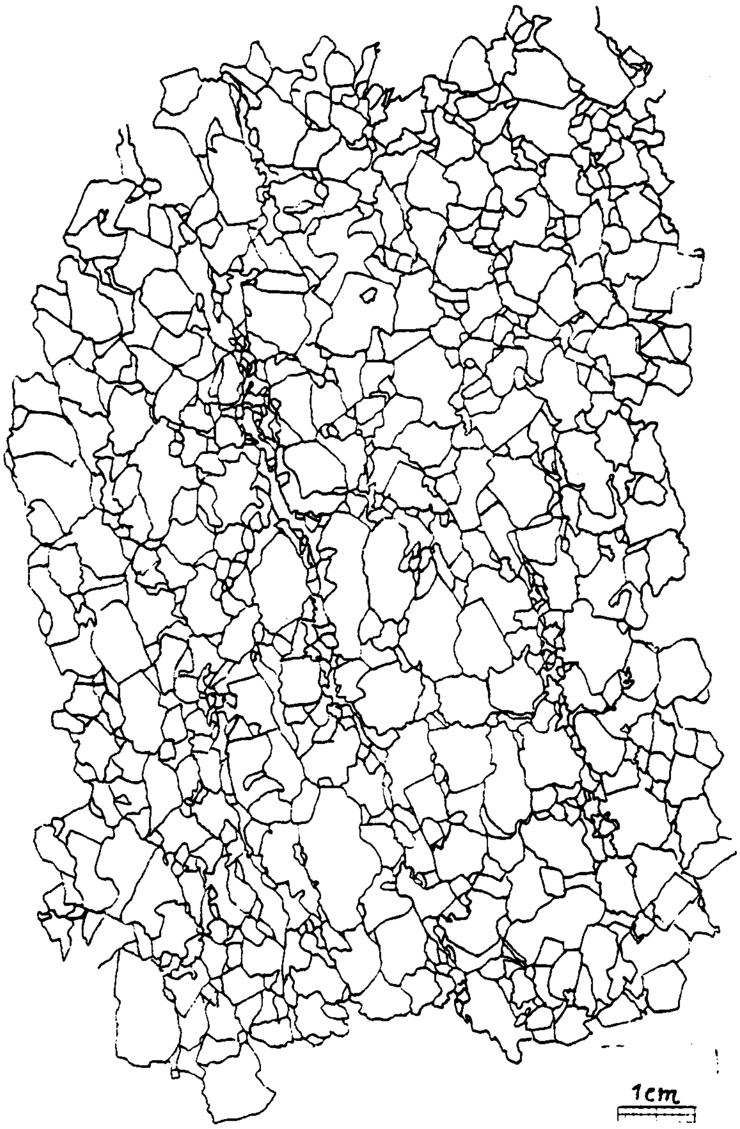


Fig. 11. Tostrup 8, core no. 14, 1402.87 m below KB. Replica on acetate film of a cut and polished core piece 1:1. Rock salt with a medium to coarse grained heteroblastic interlock texture. The fine to medium grained streaks are kieserite-richer parts of the salt, which is Na2K. Drawing by Gert Grønning.

thich layers of fine bedded anhydrite, commonly containing K-mineralization, are recognized at 19 m, 12 m and 5 m below top of the section.

In Rønde 1 a few cuttings with sylvine and kieserite have been encountered.

One core has been drilled in the lower part of the section in the Slagelse 1 well. The rock salt is red-brownish to orange to greyish, translucent and with disseminated anhydrite and polyhalite. Small ammounts of sylvine and kieserite are observed. The texture is gneissic interlobal.

Above the orange rock salt follows the K-Mg-zone, named the Veggerby zone in the Danish dome area and resembling the German Flöz Stassfurt. The zone is drilled and cored in several wells in the dome area. Many logs have been run and a large number of chemical analyses have been carried out by Boreudvalget and the Survey. Most analyses were performed during the potash exploration campaign 1959-1961.

The Veggerby zone.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
42 m	43 m	10-15 m	7 m	9 m

The K-Mg-zone in the D-1 well is 204 m thick. A part of it is recrystallized during the halokinetic pillow stage. The rock types between the 42 m K-Mg zone and the clay formation consist of 30 m Deckhalite and 132 m recrystallized and secondarily enriched rock salt.

The scarcity of samples from this zone renders a further correlation with the Veggerby zone in the dome area impossible.

It is possible to make a good correlation from the dome area to the C-1 well and to refind the 4 sections of the Veggerby zone, which are described below from the dome area, in the C-1 well.

The Veggerby K-Mg-zone has been drilled and/or cored several times in 4 domes. In the Suldrup dome, where the potash prospecting was carried out in 1959-1961, one nearly undisturbed, overturned sequence was cored 100%. This sequence was analysed chemically and mineralogically during the campaign, Boreudvalget 1961. This descriptional profile fits well with other more or less disturbed profiles in the Suldrup Dome. Due to the close ressemblance to the corresponding profiles from the Tostrup and Hvornum domes this profile from Suldrup has become a standard profile for the Veggerby zone. A slightly different lithologic column, which was also nearly undisturbed by the halokinetic movements, was encountered in the Mors dome. Both profiles are demonstrated on fig. 10.

The lower part of the Veggerby zone shows a gradual change from the orange coloured salt to a bedded "Hartsalz". Three types of salt alternate randomly: 1) Brownish to greyish halite with sylvine and kieserite is dominating, while carnallite and anhydrite are subordinate minerals, 2) White, nontranslucent halite-kieserite-sylvine (Hartsalz). 3) Greyish to black halite-anhydrite-clay with sylvine. A small amount of boracite is disseminated in this salt and it is further characterised by a moderate high K-content.

The lower part of the Veggerby zone is followed by a section dominated by halite. This section contains relatively less potssium and is hence easily recognoized on the GR-log. The rock types resemble the underlying rocks but for the low content of K- and Mg-minerals. This part of the succession is best developed on Mors, where the content of halite decreases upwards, while the content of sylvine and kieserite conversely increases.

In the next sequence is the content of kieserite increasing upwards, where the rock is white and fine grained. The kieserite dominated rock alternates with salt with less kieserite and salt with quartz (silt), clay and anhydrite (fig. 12, 13, 14). This part of the zone is characterised by a varying moderate to high K-content and a low halite content. The dominating potassium mineral is sylvine whereas carnallite is subordinate. The upper part of this

Fig. 12. Erslev 1, core no 28. 2718.96-2727.30 m below ground level. Photo with reflected light. The central part of Veggerby K-Mg-zone. Three types of salt occure in this part of the zone: 1. Rock salt, light grey to grey, sylvinitic and kieseritic, 2. Kieserite-halite-sylvine rock, white to light grey, fine grained and 3. Rock salt, clayish, anhydritic, sylvinitic and with a variable content of kieserite. Type 2 and 3 have the highest K-%. The average mineralogical composition of the core is calculated from the chemical analyses Quist's lab. and Laier, 1980 Halite 54%, kieserite 34%, sylvine 8%, anhydrite 1%, clay and silt 2%. The average of the five core pieces in the middle of the photo is: Halite 44%, kieserite 43%, sylvine 12%, anhydrite traces, clay and silt 1%. Close to the top of core piece no. 3 boracite is seen as a white streak. The measure marks are 10 cm each.

section contains occasionally clay-rich, greyish black, thin layers. These are from few centimeters to 15 cm thick and show an irregular folding pattern, (fig. 15).

The upper part of the Veggerby zone is dominated by rocks with halite-silt-clay-anhydrite-kieserite-carnallite and a varying amount of sylvine (fig. 16). The sylvine is more intensely bluish to bluish grey and has a stronger smell of mercaptane than elsewhere in the Veggerby zone. White kieserite and grey halite-rich layers alternate with the dominating clayish rock. The content of halite and silt in this part of the Veggerby zone is higher in the Mors dome than in the more eastern domes.

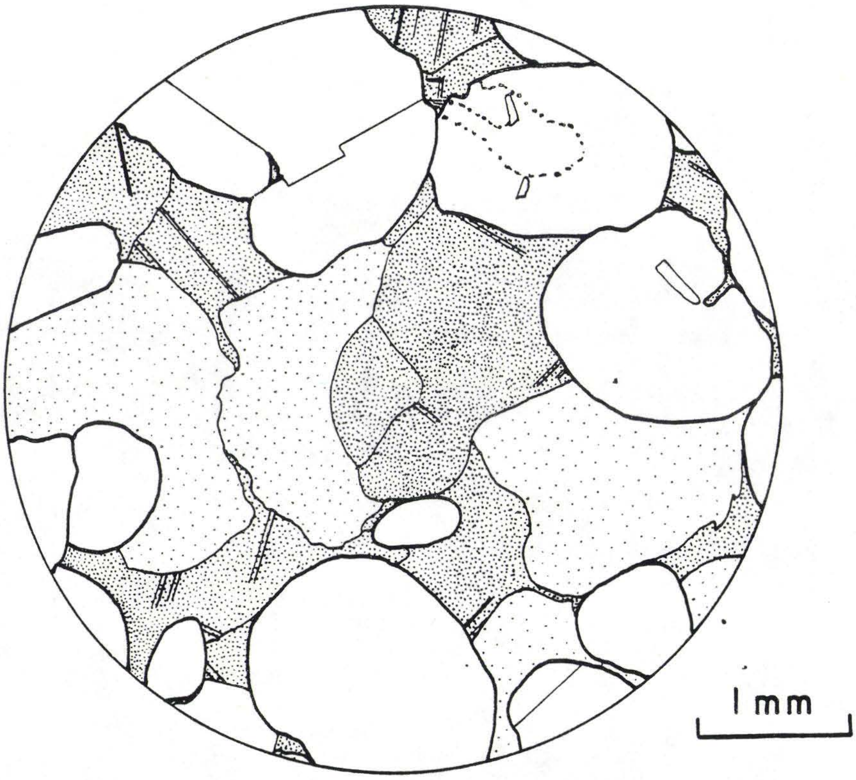


Fig. 13. Suldrup 15, 608.32 m below ground level. Drawing from a thin section of "Hartsalz" from Veggerby zone. The rock is a kieserite-sylvine-carnallite rock with xenomorphic to hypautomorphic texture. The rounded grains are kieserite, the light stippled is sylvine and the dense stippled is carnallite.

In the Rønde 1 well it is, due to the drilling method, only possible to located the top and bottom of the Veggerby zone and to find its mineralogical constituents: halite, kieserite, sylvine, carnallite, polyhalite and anhydrite.

The Slagelse 1 well gives no information regarding the mineral assemblage of the Veggerby zone. The only indication of the K-Mg-zone is seen on the GR-log.

Above the Veggerby zone follows a sequence of rock types, which resemble the German term "Decksteinsalz", deckhalite. These rocks are well known from the dome area are described in detail below.

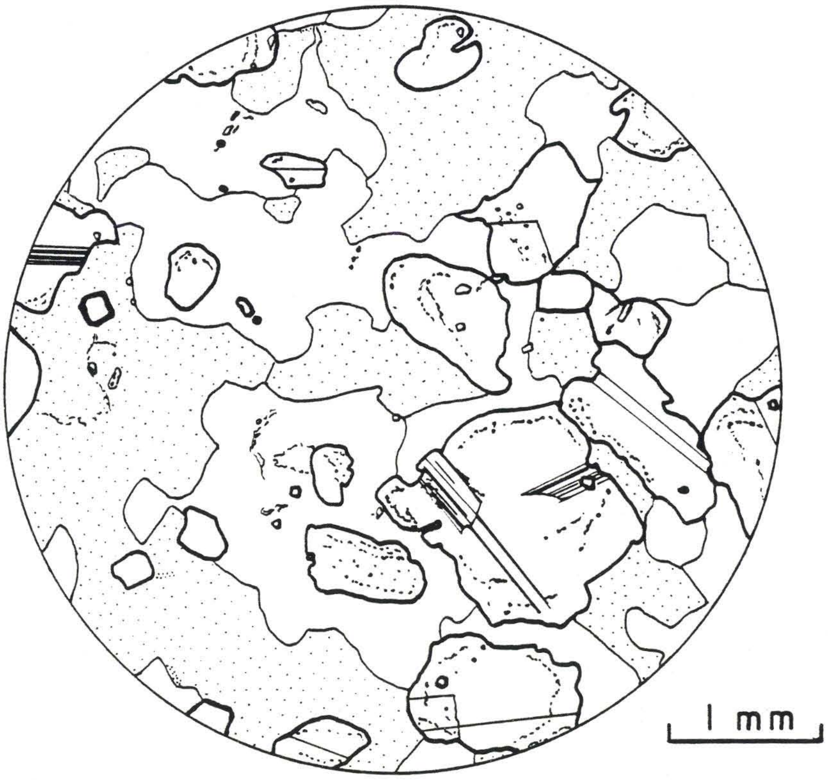


Fig. 14. Suldrup 15, 609.44 m below ground level. Drawing from a thin section of "Hartsalz" from Veggerby zone. The "Hartsalz" is a halite-sylvine-kieserite rock with xenomorphic texture. The halite is clear, the sylvine light stippled, and kieserite is in rounded forms with twins and rims inside the crystals, indicating a step in the crystallization. Boracite is present as idiomorphic crystals, generally as traces, but in a few samples up to 1.2%.

Decksteinsalz, deckhalite.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
162 m	18 m	15 m to c. 30 m	5 m	4 m

Fig. 15. Suldrup 15. 612.58-612.85 m. Intensive folding pattern of a fine bedded grey, clayish, silty, anhydritic Hartsalz and a white kieseritic Hartsalz from the upper part of the Veggerby zone. The average composition is: Halite 25%, kieserite 47%, sylvine 3%, carnallite 15%, anhydrite 6% and clay-silt 4%. Boracite is present as trace and recognized as white straks in the left side of the core piece.

The 162 m thick deckhalite succession in the D-1 well is composed of 30 m proper deckhalite covered by 132 m carnallitic salt. The lower 30 m of the section are composed of rock salt, clear to reddish-brownish, with a 2 m thick potassium mineralization 9 m above the bottom. The upper 132 m of the section are composed of a halite-carnallite rock with some kieserite. Cuttings of halite have a varity of colour from clear, yellowish, greyish to orange. It is impossible to veryfie whether this salt is of primary origin, or whether it is recrystallized or secondarily enriched.

In the C-1 well a 15 m section is recorded: rock salt, colourless, yellowish, orange and red-orange. There are cavities in some of the cuttings from this section, which indicates the presence of a K-Mg-mineralization. Other cavities contain clay. 3 m above the bottom of the section there is a 2 m thick K-Mg-zone and 12 m above the bottom there is a 1 m thick layer of anhydrite.

The deckhalite is nearly undisturbed in the Suldrup 15 well and here the salt is recovered 100% during the coring. In other domes the deckhalite is strongly tectonized, poorly recovered in cores and therefore sometimes only logged by petrophysical methods. The rock salt is generally brownish to brownish grey to dark brownish grey and it contains disseminated streaks and angular fragments of clay (greenish black) and siltstone (greenish grey). The salt is orange or with light coloures, coarsely crystalline in some parts, which indicates a secondary origin. These salts are in connection with a 0.2 m bedded, halitic K-Mg-zone, 4 m above the bottom and a 0.1 m bed of bluish grey anhydrite 7 m above the bottom of the section.

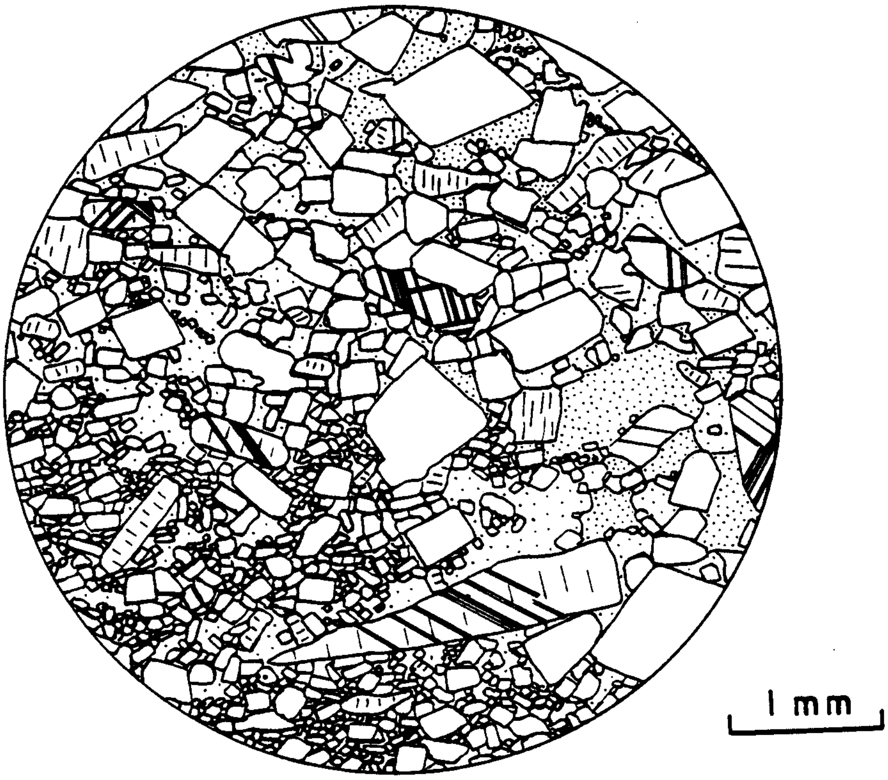


Fig. 16. Suldrup 15, 615.67 m below ground level. Drawing from a thin section of the upper part of the Veggerby zone. The rock is an anhydrite-sylvine-halite rock with automorphic texture. The anhydrite is clear,occasionally with cleavage and twins, sylvine is dense stippled and halite light stippled.

Data collected from other wells in the eastern domes seem to correspond very well to the rather complex zone found in the Suldrup 15 well.

In the Rønde 1 well only few cuttings of rock salt are collected. These are reddish brown and contain irregular thin layers of silty, greyish green clay.

Neither logs nor cuttings are available from this sequence in the Slagelse 1 well.

Zechstein 3. (Z3).

The gradual onset of the next cycle is indicated by the upward increasing clay content in the deckhalite. The gradually increasing clastic content changes the rock type from deckhalite into saltclay.

Saltclay.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
24 m	16 m	15 m - 60 m	25 m	11 m

These thicknesses include the dolomite and anhydrite layers which overlie the Saltclay, used in the sense of the German term of clay, silt and rock salt.

Information from the D-1 well concerning this rock suite is poor: only few cuttings to compare with the reasonably good logs. The lowermost 17 m consist of siltstone and clay, and the uppermost 6 m consist of silty clay. These sections are followed by streaks of dolomite and a 1 m layer of anhydrite.

A succession resembling that from the D-1 well is drilled in the C-1 well. Here the lower part is 12 m thick and has a slightly higher clay content than the corresponding interval in the D-1 well. This bed is succeeded by 2 m silty clay, 1 m dolomite and 1 m anhydrite.

In the western part of the dome area, which is represented by the Erslev 1 well (fig. 17), the saltclay suite is not developed exactly like in the eastern part. The section has been drilled 4 times, but is only partly cored. Due to the high quality of the logs it has been possible to make a coherent description. The lowermost 7 m consist of siltstone, light grey to olive grey with euhedral crystals of halite. This rock is interbedded with dark brownish red rock salt. The uppermost 7 m consist of clayish rock salt,

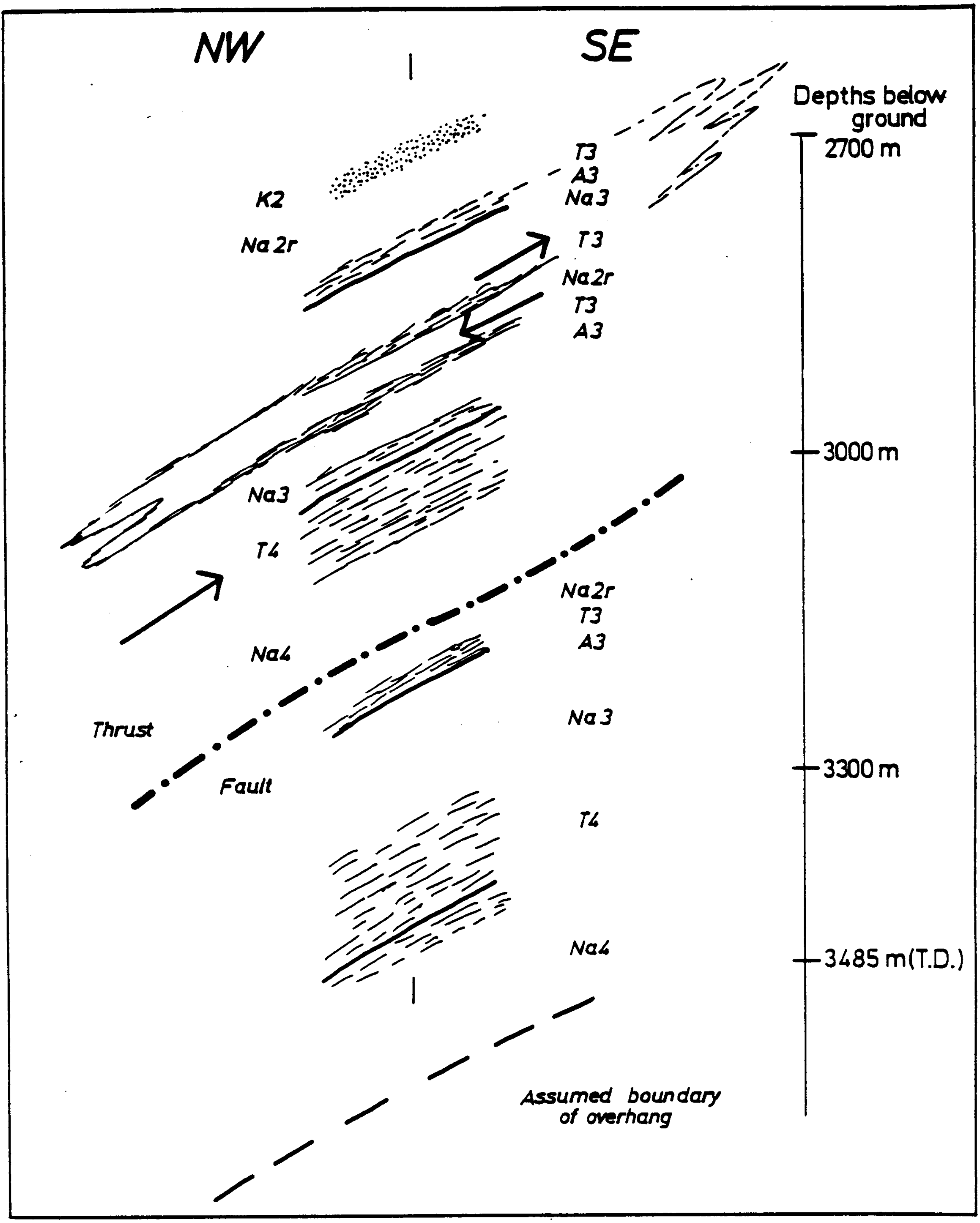


Fig. 17. Tentative model of the lower part of the Erslev 1 well situated at Mors Island. This model is based on informations from 4 cores, cuttings and petrophysical logs. It is believed that the deepest part of the well is close to bottom of the southern overhang of the Mors Saltdome.

black to violet brown, with occassional layers of clay, silty, brownish grey to dark brownish grey. As in the section below also a few layers of siltstone are present. In the upper part, a few streaks of brown dolomite are observed. Layers of grey to bluish grey anhydrite, 1/2 to 1 m thick, are found on top of the clay series. It is worthy of mentioning that the log feature of this section resembles the corresponding feature in the C-1 well and partly that of the D-1 well.

In the eastern part of the dome area the Z3 saltclay is developed otherwise . The clay has been drilled in several wells in the Suldrup, Hvornum and Tostrup domes, but only in the Suldrup 15 well, the section is nearly tectonically undisturbed. This saltclay falls in 3 sections. The lower is dominated by clay, greenish grey to black and silty with thin layers of clayish and greenish grey silt. The middle part is composed of fine light greyish green, crossbedded silty sand with interbeds of black and sticky clay or of fine sand, redbrown with a purple tint and with subordinate light greyish green beds. Few streaks of brown dolomite, separate the clay-fine sand section from the overlying 20 cm grey black and clayish anhydrite.

All the mentioned sedimentary rock types, both in the eastern and the western domal area, contain cracks and joints filled with blood red haematite-stained carnallite, brownish rock salt and orange coloured fibrous halite crystals. The fibres are perpendicular to the joints. The youngest joints also contain yellowish carnallite, rinneite and halite.

In the Rønde 1 well the Z3 saltclay section is developed as a bedded sequence of fine grained sandstone, siltstone and claystone, (varicoloured brick-red, grey, brown and light green). This section is capped by 1 m of fine grained, greyish black to grey, anhydrite.

The saltclay in the Slagelse 1 well are sparsely repressented by cuttings. They seem to indicate, however, the presence of a silty, red and green coloured shale.

The Z3 salts are complex and have a variety of colours in the areas where they have been drilled. They contain mineralizations of K-Mg-salts and beds of anhydrite. The Z3 salts vary from area to area and they resemble the German salts only to some degree (fig. 18).

Z3 rock salt.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
34 m	109 m	c. 100 m	61 m	10 m

No observations regarding the colour of the Z3 rock salt in the D-1 well are recorded. On the logs it is possible to identify a one meter thick bed of anhydrite with a potassium mineralization 20 m above the bottom of the section.

Wireline logs and the sparse cuttings are the basis for the revelation of the section in the C-1 well. The rock salt is colourless with disseminated anhydrite. 5 anhydrite layers are encountered, which are all potassium mineralized. The locations of these five layers, in meters above the base of the salt, are:

1 m	thick	layer	30 m	above	bottom
2 m	-	-	72 m	-	-
1 m	-	-	89 m	-	-
1 m	-	-	100 m	-	-
1/2 m	-	-	103 m	-	-

In the dome area the Z3 salt has been drilled in the Mors, Tostrup, Suldrup and Hvornum domes, but it has not been possible to give a definite stratigraphy of the different salt types. The colours of the rock salts vary from faint yellowish and brownish to yellow to orange and reddish brown to redbrown with purple tint and even to bloodred.

In the Z3 salt the content of anhydrite is variable. The anhydrite may be found as disseminated crystals in the rock salt, as diffuse dark bands (as known in the German salts), or as fine layers with a thickness of a few mm to some cm. Primary as well as secondary potassium minerallizations are observed. Richter-Bernburg (1962) correlates this Suldrup potassium zone, drilled in the wells Suldrup 12 and 16, with the German Flöz Ronnenberg. He also correlates the underlying rock salts with the Liniensalz and the overlying beds as Bandersalz and Anhydritmittel-salz. Secondary 10-50 cm thick K-Mg-mineralizations are common in the anhydrite layers.

In the Rønde 1 well two rock salt sections are encountered. At the bottom of the section there is 32 m clear rock salt with anhydrite and with a potassium mineralization 3 m below its top (log-identification). Overlying this salt there is 32 m reddish brown rock salt with irregular thin beds of reddish brown clay and aggregates of anhydrite.

No samples are available from the Slagelse 1 well so the identification of rock salt and shale is exclusively based on wireline logs.

Zechstein 4. (Z4).

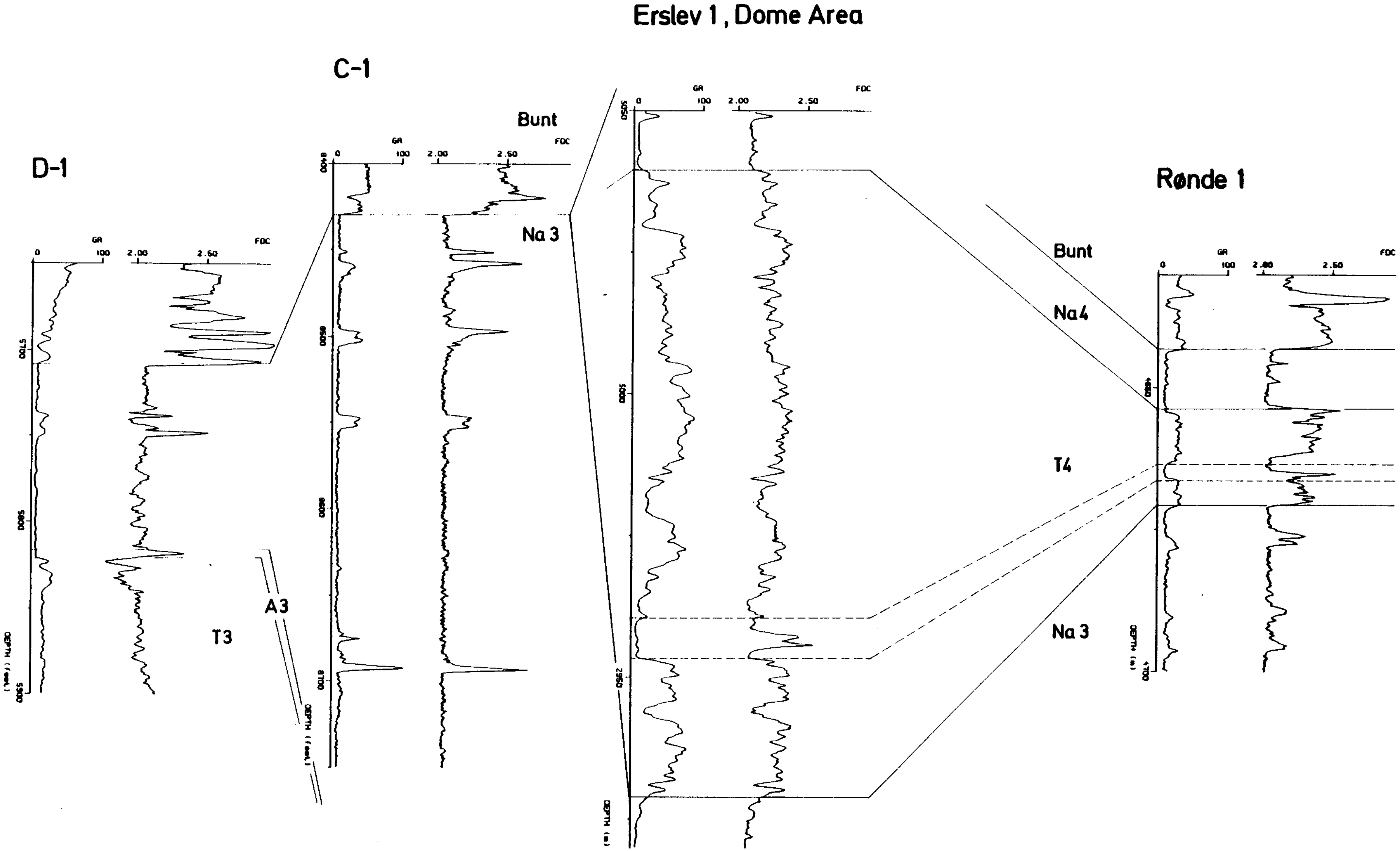
The possible presence of the Z4 clastics and evaporites is difficult to verify due to the lack of information regarding the rock types (fig. 18).

The Z4 cycle.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
20 m?	2 m?	50-60 m	15 m	0 m

Fig. 18. Outline of the top part of the Zechstein Group in the Danish part of the Norwegian-Danish Basin. T3 and A3 are described on fig. 10. Na3: Younger rock salt with beds of anhydrite, which are more or less mineralized by potassium. T4: Clay-, silt- and sandstone observed in Erslev 1 and Rønde 1. Note the rock salt and the anhydrite- rich part one third from bottom. The thickness of the section in Erslev, the Dome Area, is caused by inclination of the bed. Na4: The youngest rock salt. Bunt: Buntsandstein developed as clay-, silt- and sandstone with anhydrite beds. Depth scale is about 1:1000.

ZECHSTEIN 3/4 / BUNTSANDSTEIN



In the D-1 well a sequence of interbedded clay and anhydrite overlies the Zechstein salt. The clay content increases upwards. There is nothing to suggest the presence of younger rock salt in this well.

The Z4 cycle in the C-1 well is developed almost identically as in the D-1 well, only the bed thickness seems to be smaller.

According to my interpretation the Erslev 1 and Suldrup 4 wells in the dome area penetrate the clay section of the Z4 cycle. A new evaluation of logs and samples from the lower part of Erslev 1 is demonstrated in fig. 17.

The evaluation of Suldrup 4 has been carried out by Richter-Bernburg, 1962: The lower, about 10 m, of the saltclay section is composed of siltstone, caly and silt, which is medium olive brown to olive grey to greyish black. This is overlayn by an about 1 m thick, dark grey to greyish black anhydrite layer together with yellowish red clayey rock salt. This layer is further followed by light brownish grey to greyish black silty clay and claystone. The entire section is more or less brecciated with colourless to light reddish orange rock salt intruded into the breccia. The saltclay sequence in Suldrup 4 resembles the Erslev 1 saltclay section, except for the missing anhydrite.

The saltclay section in the Rønde 1 well is composed of 5 m reddish brown claystone with silky luster, which is overlayn by dark reddish brown claystone, siltstone and sandstone with a certain resemblance to the Lower Triassic sediments. Like the Erslev 1 well the Rønde 1 well encountered an anhydrite bed in the saltclay section.
None of these rocks are encountered in the Slagelse 1 well.

Rock salt sections belonging to the Z4 cycle are drilled in the Rønde 1 well and in the dome area. In both cases the identification is questionable.

Z4 rock salt.

D-1	C-1	Dome area	Rønde 1	Slagelse 1
0 m	0 m	> 20 m	11 m	0 m

The rock salt in the dome area is found in the Erslev 1 and Suldrup 4 wells. It is light grey to pale reddish orange and contains a few layers of clayey rock salt.

The Rønde 1 rock salt is clear and contains thin beds of brick-red clay.

There are no indications of the presence of rocks belonging to the Zechstein cyclic deposits which elsewere overlie the Z4 beds.

Bunter Shale Formation.

Above the Zechstein cycles follows the Bunter Shale Formation, Bacton group, which consists of claystone interbedded with minor siltstone. These rocks are varicoloured red-orange, brown with greenish spots, greenish greyish or reddish and have as minor constituents a varying content of calcite, dolomite and/or mica, Bertelsen, 1980.

DEPOSITIONAL HISTORY OF THE DANISH ZECHSTEIN EVAPORITES

The sedimentation of the Zechstein deposits in Northern Denmark must be considered in the context of the development of the Norwegian-Danish Basin but the entire North West European Zechstein Basin.

The tectonical frame is given, in the introduction. Here a brief account of the depositional history based on well data is given.

The influx of sea water to the Zechstein sea came from north through the channel between Norway and Scotland, Derumaux, 1980. This channel was probably open in Late Rotliegendes. The sedimentary sequence is very much the same in the whole basin, the lower beds beeing conglomerates, Kupferschiefer (Marl Slate), anhydrite and dolomite. In the Werra area of the basin as well as in the Norwegian-Danish area rock salt sedimentation was initiated. During Z1 the subsidence of the Norwegian-Danish Basin seems to have been stronger than in other parts of the major basin. In the dome area 400-500 m of grey rock salt was deposited under reducing (anaerobic) conditions. During the final sedimentation K-Mg- minerals were deposited in the central part of the basin (the D-1 well).

The lower part of the Z2 beds consists of anhydrite, which originate as insoluble residues after a phase of dissolution of the oldest rock salt (Z1). Above this anhydrite the sedimentation of a very uniform sequence of clay, calcite, dolomite and anhydrite has taken place. This latter sequence is about 15 m thick and has a very characteristic log motif, which can be recognized all over the basin as well as in the well 17/4-1 in the Wiking Graben, Olsen 1978 and Ormåsen et al. 1980. This sequence is a splendid marker bed.

From the beginning of the sedimentation of the Z2 beds the sediments were practically identical to those in the major part of the basin in Germany, despite that the Ringkøbing-Fyn High was still a peninsula or a row of islands.

The evaporites which were sedimented during Z2 to begin with of a type quite similar to the Z1 rock salt. The upper part of this salt is purer as reflected in the change of colour from greyish, more or less translucent salt to slightly brownish to clear to light orange. This upper rock is finely banded and has a minor content of K-Mg-minerals. All these features indicate the change to an oxidizing sedimentary environment, which in turn was caused by a stabilized influx from the sea to the Zechstein basin.

Z2 terminates with K-Mg-evaporites which are called the Veggerby zone in the Norwegian-Danish Basin. They resemble the Stassfurt potash zone in the German Basin, Richter-Bernburg 1962. The zone is followed by a reverse sedimentation of deckhalite.

From the termination of Z2 the development of the

Norwegian-Danish Basin has its own individuality, which differs from that of the major basin. This is probably caused by a decreasing rate of subsidense. Green and red clastic sediments become proportionally more important although dark clays still occur. The amount of sedimented dolomite and anhydrite is very small. All the rock salts in Z3 are coloured (light yellowish grey to orange to blood red to brown red with violet tint) reflecting oxidicing conditions during their formation. One primary K-Mg-bed, resembling Flöz Ronnenberg, in the Suldrup dome, and several 1/2 - 1 m beds of anhydrite, commonly with secondary potassium mineralization, are encountered.

The final sedimentary cycle in the Zechstein is the Z4, which to a still higher degree than Z3, consists of red and green clastic deposits. On top of these there are reddish brown rock salts the clay and silt content of which reflect their precipitation under oxidicing conditions in a shallow sea. This sea was restricted to the central area of the Norwegian-Danish Basin.

The present knowledge about the Norwegian-Danish Basin during the Zechstein period is sufficient to establish its general and undetailed history. Particularly in the basin rim area the Zechstein may deviate from the general. Here, like in the German Basin, a series of rocks such as the dolomites and anhydrites in the Z1 and Z2 successions. More clastic dominated sediments are present in the Z3 and Z4 cyclic deposits as a reflection of relatively reduced rate of subsidence.

MOVEMENTS OF THE SALTS.

As mentioned in the section "Basin Development" it is generally believed that the halokinetic pillow stage was initiated in the Late Bunter and the onset of the diapiric stage is of Jurassic and Lower Cretaceous age. These movements continued during the Late Cretaceous and Tertiary. The movements produced faults in the sediments, which overly the halokenetic structures. Such faults are documented at Mønsted (Madirazza, 1968a), on DGU maps of the Suldrup dome

(Sorgenfrei, 1958) and over the Vejrum dome (Madirazza, 1975). Major faults are located above the cap rock in Suldrup (striking N-S) and Vejrum (striking E-W). Domes which exemplify structures with a major ringfault system in the overlying strata are Mors (Larsen & Baumann, 1982), and Mønsted and Tostrup (Petersen, 1983). Rim synclines are another expression of late halokinetic movements.

The movements in the salt, as deduced today, are a result of all previous events in the pillow and the diapiric stages as well as in the mature stage of the domes. The total movements are, as pointed out by e.g. Trusheim 1957, Seni and Jackson 1983, a function of salt inflow, solution of salt and depression in the rim syncline.

In the Danish area the Quaternary glaciations also affected the salt, Madirazza 1968b, 1978. Such effects may be caused by movements of the ice caps. The difference in heat conductivity of salt and the surrounding sediments, may influence the depth of the permafrozen zone during glacial periods. Differences in the compressibity of salt with overburden and the surrounding younger sediments affect the speed of halokinetic movements during glaciation and deglaciation. Hydration and dehydration of the anhydrite-gypsum system may likewise be affected to during and by glacial climatic changes, Madirazza, 1977.

The rate of salt solution has varied due to alternations in the water supply as demonstrated by the difference between the level of the marine postglacial deposits and the level of the regional Holocene isostatic upheaval. Locally the upheaval of the centre of salt pillows is documented to be 2.5 mm/year over the last 4000 years (Hansen & Håkansson, 1980, 1981, Madirazza, 1981).

In connection with solution mining in the Hvornum salt dome leveling has been carried out in the area. The repeated local levelling has been performed during 15 years and reveals small movements of less than 0.1 mm/year except in one area, the rim syncline, which has a rate of subsidence of 0.9 mm/year. No further investigations have been carried out in the area. It is believed that these movements of the ground surface are also late effects of deglaciation.

CAP ROCK

During the upthrust of a diapir and when the diapir has developed natural solution of the salts commences. This may happen in different ways and with different speed depending on the character of the accessible water, the permeability of the surrounding rocks, etc. (Wouch and Martinez 1983). The K-Mg-salts which are precipitated last in an evaporitic cycle are the first to be dissolved followed by halite. This halite generally contains 1.2-1.6% anhydrite (by weight) in relation to the amount of halite, Tomkins 1981.

On this basis it is possible to make a rough estimate of the mass of cap rock to be produced from a certain amount of rock salt with a known content of impurities, and vice

		Batum	Harboere	Hvornum	Mors	Mensted	Suldrup	Tostrup	Uglev	Vejrum
Nos. of wells in cap rock		19	3	6	2	1	15	10	1	6
Covering rocks		Ch	Ch	TQ	Ch	Ch	C + TQ	Ch	J	Ch + TQ
Depth to cap rock in m		158	82	192	582	213	103	145	964	174
Thickness of cap rock	min	33	83	48	20		7	33		0
	average	45	108	72	23	104	71	62	29	18
	max	58	132	115	26		114	99		66
Mineral assemblages in cap rock		A + G	A + G	A + G	A	A + G	A + G	A + G	A	A + G
Nos. of "lost circulation"		5		4			5	1		2

Table 4. Summary of informations on the cap rocks and the younger covering rocks of the Danish salt domes. The Quarternary is included, when they are a substantial part. J = Jurassic claystone, Ch = chalk and limestone, TQ = Tertiary and Quarternary clay and sand. The thicknesses of the cap rocks are given together with the mineral assemblage and nos. of "lost circulation". A = anhydrite and G = gypsum.

versa. Calculations of dissolved halite are strongly dependant on sufficient well information about the thickness of the cap rock.

Nine of the Danish salt domes, which consists of Zechstein salt, have developed a cap rock. The character of these cap rocks dependon the cover rock above them. Four of the domes (Batum, Mors, Mønsted and Tostrup) are covered by Cretaceous chalk and four domes (Harboøre, Hvornum, Suldrup and Vejrum) by Quaternary or Tertiary sediments. The last dome (Uglev) is covered by Jurassic clay, Table 4.

The mineral content of the cap rocks has not been determined in the same way in the old and new wells. The old wells (wells drilled before 1955 by DAPCo) have to some extend been cored through the cap rock, but the recovery has normally been poor. In the new wells the cap rock is not cored and commonly only a part of it is logged.

The deep seated cap rocks in the Mors and Uglev domal structures consist of anhydrite, which is the residue from the dissolving of the rock salt by saturated brines at a favourable temperature. In all the other domes the cap rock consists of mixed anhydrite and gypsum in its upper part, anhydrite in the central and in the top of the lower part, and anhydrite and gypsum (even pure gypsum) in the lower part. This indicates dissolving of the salt by non-saturated water, which is in hydrodynamic contact with the salt mirror. These circumstances cause the development of a high porosity along the upper surface of the salt, which in turn is recorded during drilling as "lost circulation", i.e. no mud return to the surface due to a relatively low pressure of the formation water. The gypsum which is drilled in this section is often well crystallized. Data concerning the cap rocks are summarized in table 4.

DRILLING PRACTICE.

Depending on the character of the drilled succession different precautions are to be taken during the drilling operation. As a consequense of this it is important for a skilled well site geologist to be aware of the rock characteristics so that he is able to advice the drilling supervisor properly.

Both bedded and domed rock salt is in general fast and easily drilled. Here the attention is only drawn to the specific problems with the Danish dome salt. As in other domes the salt is strongly folded, commonly as curtain folds, Richter-Bernburg, 1980, but in many cases this fold system is succeeded by an even more complex system. In practice this means that a change in the drilled rock may happen abruptly within a short period of time.

"Lost circulation" commonly appears in the lower part of the cap rock, just above the salt mirror. Frequently cuttings of well crystallized gypsum are observed just before the circulation is lost. The gypsum looks like broken glass on the shale shaker. The geologist or the logger is hereby given the opportunity to call the drilling supervisor before the circulation loss is a reality.

Drilling problems in the salt may be caused by: Brine accumulations, gas accumulations, and strongly foliated rock salt.

Gas blowouts have occured in two wells, Batum 13 and Tostrup 1. The blowouts lasted 90 min. and 20 min. respectively, and both holes were hereby emptied for drilling mud. One small gas occurrance was noticed at the Tostrup 3 well and some also were encountered during the drilling of the Suldrup 8 and 10 wells. The gas in the Suldrup dome was in connection with bittern brine (see below). The source rock of the gas is the shale in the lowermost part of the Z2 sequence. The gas is commonly detected during the drilling. Because the salt has moved up from below the gas, which is captured in it has a pressure equal to the lithostatic pressure or even higher. A normal precaution to prevent severe blowouts is to use a suitable blowout preventer, and, if a high mud weight is used, to make sure that the equipment is easily handled.

Pressurized bittern brine accumulations, which gave rise to overflow, were present in the Suldrup 8 and 10 wells. The

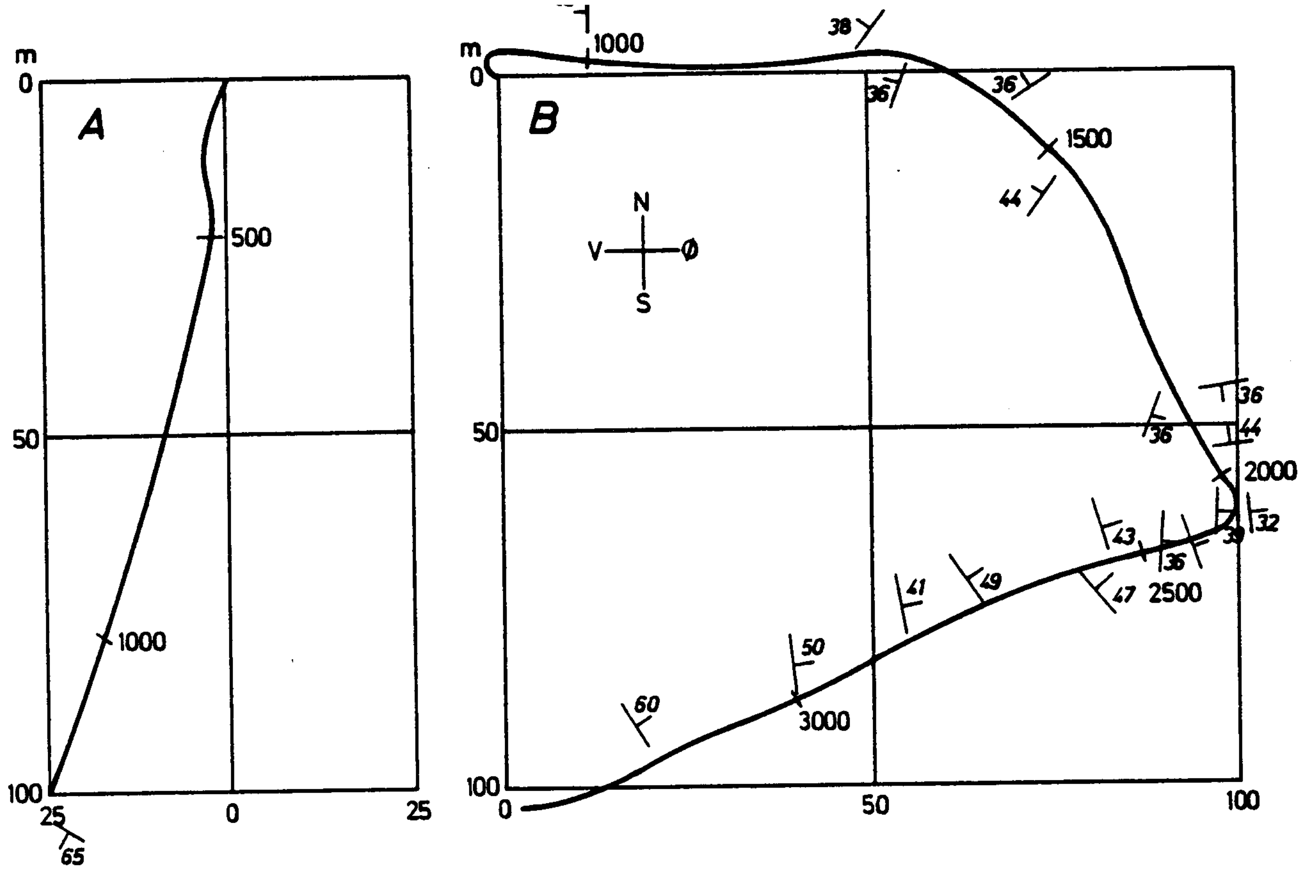


Fig. 19. In two Danish wells, Suldrup 4A drilled 1959-1960 and Erslev 2 drilled 1980, the influence of the structure of the salt is demonstrated by the track of the boreholes.

A. Suldrup 4A demonstrates the influence of a steep dipping potassium-bed, which caused the well to deviate in the direction of the dip. At total depth an oriented core was cut.

B. In the Erslev 2 well a number of oriented cores were cut in the foliated grey rock salt during the drilling with a gentle dip. It is clearly seen that the drilling direction is perpendicular to the strike and opposite the dip direction (drilling up-dip), and how the direction is changed through the folded area to the deep part of the well with an opposite dip.

Suldrup 10 well produced minimum 200 cubic meters of calcium-magnesium-sodium-potassium bittern. The bittern was analyzed and discussed by Dinesen 1961. Also smaller accumulations of magnesium-potassium chloride solutions have been struck. Such fluids may cause the viscosity of the drilling mud to rise. If the viscosity rises too much it is possible to follow the mud cake build-up (coagulation of Mg-bentonite) in the fluid zone by logging it with a resistivity-tool.

As described by Larsen 1984, (volume III, chapter 1), some of the Danish salts are strongly foliated. This influences the results of uniaxial compression tests. Salt with dipping foliation is affected by the drilling operation.

This is demonstrated in the Erslev 2 well (fig. 19B), where the bit tended to drill perpendicular to the foliation. Another example is the Suldrup 4A well, where the bit was caught by a hard bed, which it followed almost without deviations for hundreds of meters (fig. 19A).

The normal precaution against the foliation effect on the drilling direction is to decrease the weight on bit and if necessary to change the configuration of the stabilizers in relation to the drill collars. A maximum deviation of 1.5 degrees, which is recommended for cavern constructions, can be obtained with no difficulties.

A variety of drilling fluids have been used in the Danish area and in general only small problems, which were easily solved, have been recorded. It is advisory to add some gypsum to the mud during the drilling and to cement the casing in the cap rock to prevent solution around the casing shoe. In the case of deep drilling it is necessary to have the mud conditioned for rising the mud weight. In the Erslev 1 and 2 wells oil-based mud, with a weight of 1.65 and 1.74 g/cc respectively, was used in order to counterbalance the salt creep in these deep wells, which terminated at depths of 3485 and 3400 m.

It is worthy of mentioning, that it is possible to drill cores of the entire Veggerby potash zone, if the drilling is carried out with saturated sodium chloride mud with sufficient yield strength and with bentonite added. This was done in e.g. the Hvornum and Tostrup wells.

ECONOMIC GEOLOGY.

In this paragraph attention is given to the present and future use of the Zechstein evaporites. This includes their oil and gas potential, salt as a mineral source, salt as a storage medium, etc.

The oil and gas potentials depend on the presence of source rocks and a permeable and sealed reservoir rock within the evaporites themselves. At present only thin but high grade source rocks have been drilled in the Norwegian-Danish Basin: the Kupferschiefer and the bituminous clay in the Transition Zone Z1/Z2. Both these beds are thin all over the entire basin and they are of no commercial value, but the latter has caused blowouts in the dome area.

Live oil has been cut in the D-1 well in the Z1 dolomite. This hydrocarbon occurence was recorded as a trace, and the rock was impermeable.

The possibility of finding oil and gas in the Zechstein sequence depends on the presence of reefs with a reasonably good permeability, which are in connection with bitumen rich sediments in a basin marginal facies. This it is the case in Germany, Botz et. al. 1981.

Halokinetic movements may produce hydrocarbon traps in the strata, which surround the salt structures. This is certainly the case in the Danish part of Central Graben, Michelsen 1982, and is a secondary effect of the flow of salt.

A potassium mineral prospect in the Suldrup dome has been investigated with four wells in the years 1959-1961. The objective of the investigations was to evaluate the Veggerby zone (K_2O = 8,5%), the Suldrup zone (K_2O = 5%) and a third, thin potash zone: Højris zone (K_2O = 12%), Boreudvalget 1962. All the zones were drilled several times and were in no case commercially exploitable. The value of the sylvine in the Veggerby zone is given in connection with the figs. 12 and 15.

The Veggerby zone was drilled in the Hvornum and the Tostrup domes. This was done in connection with testing for solution mining of rock salt and for gas storage caverns. In general the K-Mg-salts are strongly tectonically disturbed. They resemble each other and are relatively low in K_2O.

The Veggerby zone is also present in the Mors dome. Here the zone differs slightly from the corresponding interval in the more eastern domes. A manual and a spot analysis of the

Veggerby zone in the Mors dome (Quists lab., and Laier, 1981) suggests the zone to be thicker and to have a higher content of sylvine and kieserite at this location than in the Suldrup wells. Unfortunately the Mors dome is very deep seated with the top of the salt at a depth of about 500 m. Only 2 wells with 1100 m between them were drilled and they encountered the potassium bed at a depth of 2680-2813 m, Jacobsen and Christensen 1980. It is impossible with the few available data to evaluate the structure of the dome in order to demonstrate where to drill for testing of the K-Mg-salts at a reasonable depth. But the data can be used for a provisional evaluation of the future mining potential.

The major objectives for the Danish investigations of the Zechstein in the Norwegian-Danish Basin have up to now been the use of the grey Z1 and Z2 rock salts for solution mining, construction of caverns for storage of liquid and gaseous hydrocarbons, and suitability for the disposal of highly active solid radioactive waste.

For all these purposes pure rock salt with only minor impurities are required. The demands to the characteristics of the salt differ slightly with respect to the use. The major demands for each purpose concern the relative locations of the Z1 and Z2 rock salts, the transition zone Z1/Z2, the Veggerby zone, the Z3 salts and the disclosed brines and hydrocarbon gasses.

In this paper no attempt is made to evaluate the safety risk related to simultaneous use of the same salt mass for the different purposes, but this will be a major problem, which calls for a future solution.

As a qualified estimate about 100 square km dome area with grey rock salts is available. They are not proven to consist of pure salts but rather as salts with minor impurities of anhydrite, brines, gaseous matters, etc. The calculation is carried out on the basis of a close packing of the caverns and with a center-to-center distance of 200 m between each well in a plant of 8 wells for solution mining, 300 m for liquid hydrocarbons, 400 m for gaseous hydrocarbons, and 200 m, as proposed by the power plant corporations, ELKRAFT and ELSAM 1981, for highly active solid radioactive waste (HLW).

	Solution mining	about	3200	caverns
or	Caverns for liquid hydrocarbons	-	1400	-
or	Caverns for gaseous -	-	800	-
or	Plants for HLW from 6x1000 MW nuclear power plants in 25 years	-	400	plants

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APPENDIX

APPENDIX

Events related to salt exploration in the Danish part of the Norwegian-Danish Basin.

SUMMARY.

1938-1948: Gravimetric surveys, interrupted in the years 1940-1946.

1939-1953: Seismic surveys, interrupted in the years 1940-1946.

1946-1952: Drilling in the dome province of North Jutland. Following wells were drilled: Batum 1 to 16A, Harboøre 1, Hvornum 1, Mønsted 1, Suldrup 1 to 12, Tostrup 1 and 2, Uglev 1 and Vejrum 1 to 6.

1957-1958: Seismic surveys.

1958-1959: Drilling of Harboøre 2 and 3. Brine production to the Cheminova chemical plant.

1959: Drilling of Slagelse 1.

1959: Report from Saltudvalget concerning production of salt (NaCl) and potash from the salt domes.

1959-1961: Prospecting for potash and drilling Suldrup 4A, 15, 16 and 17 and reported by Boreudvalget. Conclusion: The potassium seams were not commercial.

1963-1966: Seismic surveys.

1964: Drilling of Hvornum 2 and 3. Production wells for solution mining of NaCl for Dansk Salt I/S.

1965-1966: Drilling of Rønde 1 and Nøvling 1.

1966: Dansk Salt I/S began production of NaCl from Hvornum 2 and 3.

1968: Drilling of C-1 and D-1.

1971: Drilling of Hvornum 4 and 4A, the last one as production well (NaCl).

1972-1973: Investigation of the Vejrum Salt dome with seismic surveys and drilling of Vejrum 7, 8 and 9 to investigate the possibility of constructing a compressed air power plant for ELSAM.

1973-1974: Seismic surveys in the dome area.

1976: Report from a working group to the Danish Atomic Energy Commission concerning geological disposal in Denmark of high-level waste from nuclear power plants. Conclusion: Argillaceous Eocene clays, rock salt of Z1 and Z2 and crystalline rocks are all expected to be suitable. The costs of a research program is believed to be cheapest for the clay investigation and is recommended as the first choice.

1978: Conceptual study for storage of liquid and gaseous hydrocarbons carried out for Dansk Salt I/S and D.O.N.G. A/S respectively.

1978: Drilling of Tostrup 3 as exploratory well for storage of gas.

1978: Storage of high-level waste from Danish nuclear power plants, phase I conceptual study on storage in rock salt by ELKRAFT and ELSAM (Corporations of electric power plants).

1978-1979: Drilling of Hvornum 5 as production well for solution mining for Dansk Salt I/S.

1979: Seismic surveys related to the research programme dealing with storage of high-level waste.

1979: Drilling of Tostrup 4 as exploratory well for storage of gas.

1980: Drilling of Erslev 1 and 2 at the Mors salt dome as exploratory wells for storage of high-level waste.

1980-1981: Drilling of Tostrup 5 to 10 as production wells for solution mining of caverns for storage of gas for D.O.N.G. A/S. Additional gravimetric and seismic surveys were carried out.

1981: Storage of high-level waste from Danish nuclear power plants, phase II report by ELKRAFT and ELSAM. Conclusion: Safe waste disposal is possible in 8 deep boreholes or in a mine in pure rock salt with disseminated anhydrite and less than 0.1% water, e.g. in the Mors salt dome (Explored by the Erslev 1 and 2 wells).

1983: Solution mining of the gas storage caverns at Tostrup was initiated.

1984: Evaluation of the report on salt dome investigations by ELKRAFT and ELSAM carried out by the National Agency of Environmental Protection. Conclusion: The results of the investigations wof a safe waste disposal proves, that suitable salt is present in the Mors salt dome, but the investigations which have been carried out do not suffice to establish the size of the area, where this salt quality is present.

Remark: Only geophysical investigations, which are connected with the general salt exploration, are mentioned in this summary. Through the considered period other geophysical explorations were carried out in connection with search for oil and gas traps.

CHAPTER 2

DESCRIPTION OF THE DOLOMITE-ANHYDRITE TRANSITION ZONE (ZECHSTEIN 1 - ZECHSTEIN 2) IN THE BATUM-13 WELL, NORTHERN JUTLAND, DENMARK

By Martin Sønderholm

CONTENTS

DESCRIPTION OF THE DOLOMITE-ANHYDRITE TRANSITION ZONE (ZECHSTEIN 1 - ZECHSTEIN 2) IN THE BATUM-13 WELL, NORTHERN JUTLAND, DENMARK

INTRODUCTION

Batum-13 was drilled on the Batum saltdome from the 2/4 to the 9/5 1952 by DAPCO.
In the following the applied rock names are the same as those used by Ricther-Bernburg (1955), as these are the ones traditionally most used in Denmark, whereas the structural and textural classification correponds with the one proposed by Maiklem et al.(1969).

In the accompanying log the rock has been assessed visually and is shown as percentage of carbonate (s.l.)/anhydrite and anhydrite/halite. These visual assessments can be expected to diverge from chemical analyses by up to approximately 25%. A visual assessment of the clay content is not possible, and this is therefore not included in the lithological log.

The relative content of clay and organic material can be read in the Gamma-Ray log, as 40K is bound to clay minerals and uranium to bitumen.

GAS COMPOSITION IN THE TRANSITION ZONE

During the drilling of Batum-13, a gas blowout occured at 418.6m (1375´). After a duration of 90 mins. through a 7" casing pipe, it died out by it self.

The original analysis of the gas, a description of the blowout and a description of the testing procedure is included in appendix 1.

FOSSILS

In the interval 436.35-436.55 m a fossiliferous carbonate rock (sparse bio-micrite) was encountered, containing several species of unidentified foraminiferas and bivalves, and at 435.5 m a very sparse fauna of foraminiferas is present.

POLLEN

The core intervals 431.7-436.3m (1418´-1433´) and 436.3-442.4m (1433´-1453´) where studied for pollen as a part of the geological description of the core material in connection with drilling (Batum-13 reports).

These studies were negative, as it was impossible to identify primary pollen.

CORE DESCRIPTION

The following description covers the core interval 415.0-442.6m (1360´-1453´) which corresponds with the core boxes PKV 003.442-003.459 of the Survey.

A lithographic log is attached at the back of this volume.

The depths given below in meters are not in accordance with Driller´s depth (Batum-13 reports). The depths given here are adjusted to the Gamma-Ray log because these measurements are more accurate. This gives depths 0.5 m higher than Driller´s depth, which is given in English feet below.

In the interval 414.9-431.2m thin sections used for textural determinations have been produced in connection with the drilling. Furthermore 6 thin sections have been made at different levels throughout the zone. Between 431.2 and 437.8 m it has not been possible to determine the texture visually.

Lack of recovery is discussed during the course of the description.

Depth:	Description:
414.0-414.9 m (1360.0´-1362.9´)	ROCK SALT, grey, translucent, medium to coarse grained, anhedral. Dip: 60°

414.9-417.3 m
(1362.9′-1370.7′)

FLASER-ANHYDRITE , light grey to bluish grey, sligthly banded, fine grained to dense, non-parallel bedded, distorted, nodular-mosaic anhydrite, which downwards changes to parallel bedded, distorted mosaic/nodular-mosaic anhydrite. At the top the nodules are 5->50 mm in size, downwards smaller, 3-40 mm; the texture is subfelted.

Carbonate matrix dark grey, clayey,micritic, in bands and layers with thicknesses at the top of < 1-5 mm, at the bottom < 1-10 mm. In the lowermost 50 cm there are intercalations of slightly banded, nearly massive anhydrite in layers of 5-10 cm thickness.

At the bottom thin (< 1 mm), anhydrite filled joints, that cut the anhydrite nodular and the matrix.

Dip: 40 - 55°.

417.3-418.6 m
(1370.4′-1374.6′)

Lack of recovery is gathered in the bottom of the core.

418.6-420.1 m
(1375.0′-1379.9′)

FLASER-ANHYDRITE and SCHWADENANHYDRITE, ligth grey, slightly banded, fine grained to dense, nonparallel bedded, distorted, mosaic anhydrite; the texture is subfelted. The anhydrite masses are 5->30 mm in size.

Carbonate matrix, dark greyish black, clayey with traces of organic material, micritic.

There is a smooth transition downwards into highly distorted anhydrite with carbonate bands. From 419.2 m very irregular, partly bedded carbonate layers (as matrix) common, thicknesses of 5-25 mm.

Dip: 40 - 50°.

420.1-420.9 m (1379.9´-1382.5´)	CARBONATE SHALE, clayey with organic material, laminated, alternately grey and black, thicknesses of <0.1-1 mm. Some thicker layers (up to 4 mm) show microfolding (isoclinal folds) within the layer. A few anhydrite nodules up to 2 mm in size with a subfelted texture. Dip: 40 - 50°.
420.9-424.7 m (1382.5´-1394.6´)	Lack of recovery which might be due to the disintegration of the core caused by the gas blow-out is gathered at the bottom of this.
420.9-427.0 m (1382.5´-1402.6´)	ANHYDRITE-KNOTENSCHIEFER, light grey, fine grained to dense, bedded nodular anhydrite; the texture is lathshaped to subfelted. The nodules are isolated or intergrown, they are 1-10 mm in size and contained in a dolomite matrix, dark grey to black, clayey with traces of organic material, micritic. The laminae are either conform with the nodules or intensely deformed.
425.5-426.6 m (1397.6´-1398.3´)	Two big high-angular joints (Dip 75-85) with widths up to 15 mm, infilled with anhydrite at the sides, medium grained, sub- to euhedral. When the joints are more than 5 mm wide they have a core of HALITE, grey medium to coarse grained, anhedral. From 425.7 m the CALCITE-content increases. Thin anhydrite filled joints. Dip: 40 - 45°.
427.0-428.6 m (1402.6´-1408.0´)	SCHWADEN- and WOLKENANHYDRITE with irregular CARBONATE layers, the upper 40 cm are light grey to light blue, slightly banded, fine grained to dense, nodular-mosaic anhydrite

with a subfelted texture. Isolated anhydrite nodules, 1-20 mm in size, or intergrowths of these can form almost coherent, very irregular layers in a carbonate matrix, dark grey to greyish brown, clayey with traces of organic material, micritic, intensely folded lamination. Below this 6 sequenses (1-6 from top), 10-40 cm thick, are to be seen. At the bottom they all consist of massive/nearly massive anhydrite with diffuse carbonate bands. Sequence 1 is terminated by mosaic anhydrite (core material is missing at the top), while sequences 2-6 develop into nodular-mosaic anhydrite (nodules 5-20 mm in size). Sequences 3, 4 and 6 are terminated by nodular anhydrite (nodules 2-7 mm in size) in a laminated chaotically folded, micritic carbonate, clayey with organic material. Sequence 2 is terminated by bedded nodular anhydrite while sequence 5 is terminated by laminated, chaotically folded, micritic carbonate with a few anhydrite nodules. Sequence 5 is not complete, as some core material is missing in the middle.

The pores and joints in the matrix do not cut the anhydrite nodules/bodies. These joints are empty or infilled with anhydrite, and at the top, with some euhedral FLUORITE crystals.

Dip: 45°.

428.6-437.8 m
(1408.0´-1417.3´)

Strong smell of hydrogen sulphide and hydrocarbons when the core is broken.

428.6-431.5 m
(1408.0´-1417.3´)

ANHYDRITE-KNOTENSCHIEFER, greyish blue, fine grained to dense, bedded and distorted bedded nodular anhydrite with isolated nodules and intergrowths of these. At the top there are

	very irregular coherent layers, and bottommost there are irregular bodies of distorted mosaic and nearly massive anhydrite 1-10 cm in size. The texture is subfelted to lathshaped. Carbonate matrix greyish brown to black, clayey with traces of organic material, micritic, crinkly laminated or chaotically folded.
429.3-429.6 m (1409.7′-1410.7′)	LAMINATED CARBONATE, nearly black, clayey with organic material, very finely laminated (lamination <0.3 mm) with greyish brown 1-5 mm long lenses of cleaner carbonate within the individual lamina. Very few subangular anhydrite nodules. In the lowermost 10 cm single, big (2-6 cm), very irregular, not stratabound anhydrite bodies. Many open joints and pores, partly filled with anhydrite, in the matrix. Joints >5 mm wide with HALITE in the center and anhydrite with a little euhedral FLUORITE at the sides. Dip: 40 - 50°.
430.6-431.1 m (1414.4′-1415.7′)	Lack of recovery is gathered in this interval as the core pieces above and below are fitting.
431.5-432.4 m (1417.3′-1420.3′)	SCHWADEN- and WOLKENANHYDRITE with irregular CARBONATE layers; 3 sequences (1-3 from the top), bottommost consisting of mosaic anhydrite and terminated by laminated carbonate. Sequence 3 is the most complete, as the mosaic anhydrite is associated with nodular-mosaic anhydrite and nodular anhydrite. In sequence 2, the endmembers are solely seperated by nodular anhydrite, whereas sequence 1 only consists of these. Dip: 55 - 60°.

432.4-432.8 m (1420.3´-1421.6´)	ANHYDRITE-KNOTENSCHIEFER, light grey to bluish grey, nodular anhydrite, the upper 10 cm with big nodules (5-15 mm) and very big intergrowths or very irregular layers, downwards smaller nodules (3-5 mm) in a carbonate matrix, greyish brown to brownish grey, crinkly laminated. Dip: 30 - 45°. Smooth transition to:
432.8-433.5 m (1421.6´-1423.9´)	ANHYDRITE with CARBONATE, streaks, light grey to greyish blue, slightly banded, highly distorted massive anhydrite with many intensely folded and very irregular carbonate streaks, dark brown to brownish black, clayey with traces of organic material.
433.5-434.1 m (1423.9´-1425.9´)	LAMINATED CARBONATE, greyish brown, micritic practically lacking anhydrite nodules.At the top bedding is very steep(80-90) and strongly folded. Many pores and joints up to 5 mm wide, which are totally or partly infilled with anhydrite. Dip: 35 - 45°. Smooth transition to:
434.1-435.0 m (1425.9´-1428.8´)	ANHYDRITE-KNOTENSCHIEFER, bedded nodular anhydrite, nodules 2-10 mm in size, downwards up to 20 mm, else the same as the Anhydrite-Knotenschiefer at 420.9-427.0 m, though it contains more clay and organic material. Many rather thin joints infilled with anhydrite. Dip: 45 - 50°.

Smooth transition to:

435.0-435.6 m
(1428.8′-1430.8′)

SCHWADEN- and WOLKEN ANHYDRITE, light grey to greyish blue, streaky, slightly distorted bedded nodular-mosaic anhydrite which downwards changes into a slightly distorted mosaic anhydrite.

Carbonate matrix, dark brown to brownish black, clayey with organic material, micritic. At 435.4 m a 5 cm thick layer of distorted, bedded nodular anhydrite, with a fissility that is due to parting along laminae rich in clay and organic material.

A very sparse fauna of foraminiferas is present in the bottom.

Dip: 40 - 50°

435.6-437.3 m

CARBONATE MUDSTONE, silty, brownish black, diffusely laminated, in the top with some weakly distorted anhydrite nodules (15-25 mm). Contains beds, 1-10 cm thick of carbonate mudstone with intraclasts.

The laminated carbonate is dolomitized and contains silty clastic material (10-15%), organic material (approx. 15) and pyrite. The laminae are 0.1-1mm thick but diffuse because of the formation of micro-stylolites.

The intraclastic beds are ungraded or show a faint coarse-tail grading. The bedding planes are irregular (load and flame structure in the bottom, water escape structures in the top). The intraclasts are matrix supported and can be protruding.

The laminated mudstone begins with a 10 cm thick bed of grey mudstone with intraclasts. The matrix contains up to 40% silty clastic material. The intraclasts are from o.2-5mm, rounded to angular, and consist of the same material as the matrix.

In the interval 436.35-436.65 m 1-5 cm thick beds of greyish brown-brown, partly dolomitized, silty biogene mudstone with intraclasts are seen. The content of clastic material is less than 10%. The content of biogene material is 5-15% and is made up at whole or fragmented shells of foraminiferas (Nodosarius sp. and Clomospira sp.) and unidentified bivalves (ostracods or brachiopods).

The intraclasts are <1mm and up to 3 mm and consist of the same material as the matrix. They are rounded and have micritized rims (algal borings?).

In the bottom of the laminated mudstone (437.1 m) dedolomitized (calcificated) lenses and layers up to 5 mm thick are seen.

Joints <5 mm wide are partly infilled with calcite.

Dip: 50°.

437.3-437.8 m
(1436.4′-1438.0′)

ANHYDRITE, greyish blue to light grey, massive, diffuse bedding.

Dip: 35 - 50°

437.8-442.4 m
(1438.0′-1453.0′)

ROCK SALT, pink, translucent, coarse grained.

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CHAPTER 3

A GEOCHEMICAL STUDY ON ZECHSTEIN SALT AND ANHYDRITE FROM THE BATUM 1A WELL.

By Niels Springer

CONTENTS

A GEOCHEMICAL STUDY ON ZECHSTEIN SALT AND ANHYDRITE FROM THE BATUM 1A WELL.

ABSTRACT

This preliminary study was initiated in an attempt to distinguish between grey salt of the Danish Zechstein 1 and 2 series, respectively. Anhydrite and bulk halite rock samples were recovered from core material of two small sections representing each series. The sample material was analyzed by X-ray fluorecence analysis for the major elements S, Cl and Ca, and the traces Mg, K, Ti, Mn, Fe, Cu, Zn, Br, Rb, Sr, Y, Ba, La and Pb. Additionally, B was analyzed by an automated spectrophotometric method. It was found that the elements Ti, Mn, and Sr as well as the ratios S/Cl, Mn/Fe, Ca/Mg and Ca/Sr displayed very significant differences between the two sections. If this is a systematic difference characterizing the whole evaporite series, a geochemical stratigraphy can be established for the Zechstein salt.

Evidence is presented that the evaporation cycle episodically passed into potash-magnesia facies. This is recorded in anhydrite but not seen in the associated halite. The halite analyses also showed a very homogeneous distribution of Br through both sections. It is suggested that the very soluble K-Mg facies minerals were dissolved and carried away by a migrating fluid phase during metamorphic recrystallization of the rock salt. This event probably also homogenized the Br distribution throughout the evaporite sequence.

The regular distribution of many elements in the anhydrite, which is believed to reflect the conditions in the brine at the time of deposition, suggests that evaporite generation took place in a large marine evaporite basin.

INTRODUCTION

This report is a reconnaissance study on a small section of the evaporite series. It was initiated to obtain the first information on the trace element geochemistry of the Danish Zechstein salt. Additionally a major goal of this study has been to try to detect any differences in geochemistry between the two evaporite cycles Z 1 and Z 2 in order to establish a stratigraphic division between the grey salt of the two cycles. There is no obvious

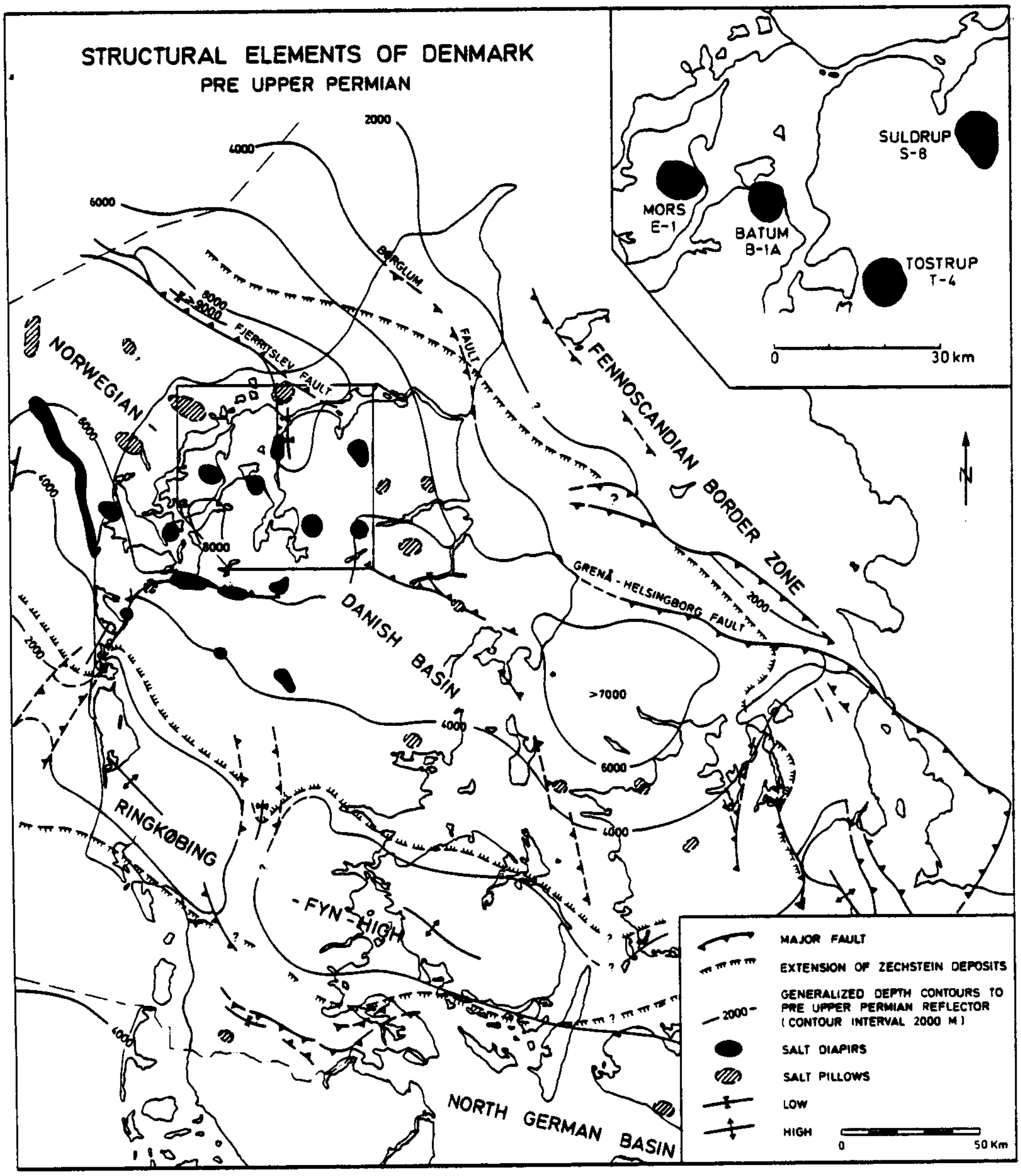


Figure 1. Map of the halokinesis area in Northern Jutland, Denmark. The location of the Batum salt dome is shown inserted. After Michelsen et al. (1981).

differences between rock salt from the two cycles, and even refined petrographic methods have failed to detect any significant differences (J.Fabricius, pers.comm.). The study focused primarily on the geochemistry of anhydrite separated from rock salt, because anhydrite is known to resist metamorphic recrystallization in the rock salt, and is believed to reflect the primary chemistry at the time of precipitation from the brine.

GEOLOGICAL SETTING

During Zechstein time more than 1000 m of evaporites were deposited in the Norwegian-Danish Embayment, fig. 1. Three main cycles have been recognized with intercalation of dolomite, anhydrite, potassium salt, clay-, silt-, and sandstone. It is believed that the evaporite sequence was deposited from a large volume of brine in an extended marin basin (F.L.Jacobsen, pers. comm.). The Danish Zechstein has been correlated with the German Zechstein cycles Z1-Z3 (Richter-Bernburg, 1960; Jacobsen, 1971).

The material included in this study was recovered from well no. 1 A in the Batum salt dome, fig. 1. The section, which is inverted, covers only the lower part of the Zechstein 2 series and the upper part of the Zechstein 1 series. The lithostratigraphy of the Batum 1 A well is shown in fig. 2.

ANALYTICAL METHODS AND PRESENTATION OF DATA ON STANDARDS

Sampling

Samples were prepared from core material exclusively. Halite samples were cut from the central part of the core and washed in demineralized H_2O. Anhydrite samples of high purity were obtained by solution of halite in hot water, followed by mineral separation in heavy liquids (Fabricius, 1983). The washed and dried samples of halite and anhydrite were crushed for a few minutes in a wolfram carbide swing-mill to reduce grain size below 50 µm, which is suitable for X-ray fluorescence (XRF) analysis. The final grain size distribution was checked using an optical microscope equipped with a micrometre grid.

Instrumental

Powder pellets of 1.5 g weight were prepared for each sample applying a few drops of poly vinyl alcohol (PVA, 5 %) as a binder. All samples and standards were analyzed for 15 elements within a period of 7 days on a fully automated Philips PW 1400 XRF spectrometer, recently installed at the Institute of Petrology, University of Copenhagen. Two elements, S and Cl were measured on an older Philips PW 1410/20 spectrometer. The measuring procedure followed normal practice as described, e.g. in Bailey & Sørensen (1976). All relevant instrumental settings are given in the appendix, table 1.

Principles

The concentration of a trace element X in an unknown sample can in general be determined from the expression

$$X \text{ ppm} = A \times \mu/\rho \times k$$

where A is the count rate measured in counts/second, μ/ρ is the mass absorption coefficient and k is a machine constant. k is determined from suitable standards with a well known concentration and mass absorption coefficient. For the unknown sample the mass absorption coefficient μ/ρ can be found experimentally or more precisely determined from the major element composition of the sample. Also, the availability of suitable blank materials, free of the analyzed trace element, is of major importance in XRF trace analysis. The determination of many element ratios by XRF analysis is especially favourable because the ratio between the mass absorption coefficients is virtually constant for all materials between absorption edges.

When analyzing pressed powder pellets, the determination of elements at high concentrations (major elements) and with low atomic number ($Z<26$) is less precise due to interelement and grain size effects (Bailey & Sørensen, 1976).

Boron analysis

Boron were analyzed by DGU Geochemical Laboratory. For anhydrite c. 50 mg of crushed sample was dissolved in 5 ml 2% hydrochloric acid. For halite samples 500 mg was dissolved in 5 ml distilled water. The boron concentration was measured in these solutions by an automated azomethine-H method (Edwards, 1980). The detection limit of boron concentration in the solution is 0.1 mg/l corresponding to 1 ppm and 10 ppm B in the solid samples of halite and anhydrite, respectively. The precision of the method is within ± 1 ppm B for halite and ± 10 ppm B for anhydrite.

Preparation of standards

The problem of analyzing evaporites is rarely presented to the geochemical laboratory. This is reflected in the nearly complete lack of international geochemical evaporite standards. Only one international standard anhydrite, ZGI-AN, have been prepared, and this standard is not certified for trace elements. No international standard halite is available.

Thus, to accomplish the analytical program it was necessary to prepare synthetic standards. From specpure and analytical grade chemicals two different synthetic multi element standards were produced, one intended for anhydrite analysis and the other designed for halite analysis. Useful blank pellets were prepared from pure $CaSO_4$, $2H_2O$ and NaCl respectively.

It was attempted to produce waterfree $CaSO_4$ from chemically pure gypsum by heating to 300°C, but the experiment failed because of rapid water uptake when the sample was again subjected to normal atmospheric conditions. It was also found that gypsum ($CaSO_4$, $2H_2O$) was unstable to machine conditions. During measurement varying amounts of water were lost from the sample due to the heating up from the X-ray emission and the vacuum in the machine. This caused uncontrollable variation in mass absorption, and the synthetic gypsum standard yielded machine constants which differed significantly from the other standards. Thus, unfortunately, it was necessary to discard the synthetic gypsum standard. The synthetic halite standard happened to be reliable, and as there is no big differences between the mass absorption for anhydrite and halite for most elements (table 2 in the appendix), it was decided to use the synthetic NaCl standard for both anhydrite and halite analyses. The element concentration as well as the variation found between two pellets of this standard are given in table 1. It is seen that the homogeneity of this standard is better than 2% for all elements except Mn.

Standard results

As a check on the accuracy of the measurements, two international rock standards were also measured against the synthetic NaCl standard. The results and the recommended values are given in table 2.

For the anhydrite standard ZGI-AN, all major elements and Sr are within 95 % limits of the certified values. However, gross deviations occur for the trace elements. The trace contents are not certified, and a quick examination of the data sheet issued by the distributor reveals an extremely large scatter in trace element concentrations as determined by different laboratories, implying that the standard is inhomogeneous and can not be used as a reliable international standard for trace elements.

Element	Conc., ppm	cov. % *
Na	290 502	not analyzed
Ca	49 990	<0.1
Mg	4986	1.7
K	1000	<0.1
Br	2044	1.7
Rb	508	0.4
Sr	1018	0.6
Y	200	0.4
Ba	2014	not analyzed
Fe	1002	0.9
Mn	205	2.4
Cu	986	0.4
Zn	1007	0.4
La	505	0.6
Pb	505	1.2

* cov: coefficient of variation = relative standard deviation. The standard were prepared from suprapure NaCl spiked with accurately weighted amounts of pure chemicals, which were crushed to fine power in a WC swing-mill. Homogenization was performed in a small high-speed blender.

Table 1. Data for NaCl, Synthetic Multi Element Standard.

Due to its completely different composition and the previously mentioned troubles with major elements, no precise determination was attempted for major elements in the BCR-1 standard. Trace elements are generally in good agreement with the recommended values.

Element or oxide	ZGI-AN		USGS-BCR 1	
	meas. conc.	recom. conc.	meas. conc.	recom. conc.
MgO	0.34 %	0.32 ±0.08 %		
K_2O	0.011 %	0.014±0.004 %		
CaO	40.22 %	40.73 ±0.27 %		
Fe_2O_3	0.010 %	0.014±0.004 %		
Mg	2038 ppm			
K	91 ppm			
Ca	28.74 %			
Ti	12 ppm	18 ppm *		
Mn	5 ppm	46 ppm *	1118 ppm	1410±90 ppm
Fe	71 ppm			
Cu	<lld	11 ppm *	18 ppm	19±4 ppm
Zn	2.3 ppm	8 ppm *	127 ppm	129±1 ppm
Br	4.6 ppm		<lld	< 1 ppm
Rb	<lld	7 ppm *	47.5 ppm	47±1 ppm
Sr	1464 ppm	1451±440 ppm	333 ppm	330±5 ppm
Y	<lld	6 ppm *	35 ppm	39±7 ppm
La	<lld	0.4 ppm *	17 ppm	25.0±0.1ppm
Pb	<lld		17 ppm	13.6±0.1ppm

*Values not certified by the manufacturer.
lld = lower limit of detection.

Table 2. Results obtained on two international rock standards. The recommended values (±1 standard deviation) for anhydrite AN were issued by Zentrales Geologisches Institut, Berlin. Data for the basalt BCR - 1 were tabulated from Gladney et al. (1983).

DATA REDUCTION AND STATISTICAL PRINCIPLES

Determination of absolute concentration and estimation of errors.

Due to lacking facilities and the unusual character of the analyzed material, data reduction was done off line on an advanced handheld calculator. Calculation of mass absorption coefficients followed normal practice using the major element composition of the samples and the tables published by Heinrich (1966). Anhydrite and halite are close to pure $CaSO_4$ and NaCl respectively, so the error in assuming a fixed composition for natural samples is negligible (< 1 % of the true mass absorption coefficient). Calculated mass absorption coefficients

Element	Precision, %		Detec. limit
	Anhydrite anal.	Halite anal.	ppm
B			10, 1
Mg	1 - 4.5	20 - 75 (40)	44
K	0.2 - 5 (1)	0.8 - 1.5	1.8
Ca	0.2	0.5 - 1.5	41
Ti	3 - 8	20 - 70 (40)	2.6
Mn	8 - 45 (20)	60 - 90	1.7
Fe	0.3 - 0.8	5 - 16	1.4
Cu	7 - 80 (45)	14 - 35	1.6
Zn	4 - 70 (25)	20 - 70 (45)	1.0
Br	6 - 40 (25)	1	0.8
Rb	*	*	0.7
Sr	0.5	1 - 7	0.8
Y	*	*	0.7
La	*	*	4.7
Pb	*	*	2.3
S/Cl	4 - 16 (6)	1 - 2	
Mn/Fe	1 - 30 (10)	15 - 100 (50)	
Ca/Mg	0.5 - 5	5 - 75 (40)	
Ca/Sr	0.1	0.5 - 4	

* most samples were below the detection limit.

Table 3. Presentation of errors and detection limits given at the 95 % confidence level. In brackets are given the mean error for elements with a large range in errors.

for standards and samples as well as the estimated composition of natural samples are shown in the appendix table 2 A + B.

The precision on the measurements was determined from counting statistics as well as from repeated counting on the samples. An estimate of the precision as well as the detection limit for each element can be found in table 3. The precision depends on the number of counts per second, i.e. the X-ray signal for the element in the sample and the total counting time. It should be noticed that the accuracy of the S/Cl ratio is hardly better than 10-15 % due to the lack of suitable standards at the time of analysis, i.e. the numbers could deviate systematically but the overall trend is preserved. However, in general, the error in element ratios is lower than would be expected from the error on the single elements.

Statistics

One of the major goals of this study have been to detect any differences in element distribution between Z 1 and Z 2 series, respectively. However, most statistical treatments place constraints on the distribution of the population from which the samples were drawn. The distribution of a major element between a solid phase and the solution is described by Rayleigh´s distribution law, and the distribution of trace elements is governed by Berthelot - Nernst´s homogeneous distribution law and Doerner - Hoskins logarithmic distribution law. Application of these laws assumes equilibrium conditions in the system, which can not in general be guaranteed during evaporite deposition (Dean, 1978). In conclusion, there is little reason to expect a normal distribution of elements through an evaporite sequence, and in fact a closer examination of data from this study has shown skewed distributions for some elements/element ratios.

In consequence, distribution-free statistical methods should be applied. In the case of two independent samples, as examplified in this study by Z 1 and Z 2 the

Mann - Whitney U test is a powerful test to detect any differences in distribution (Siegel, 1956). The U statistic is calculated from the formula:

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1$$

where n_1 and n_2 are the number of observations in each sample, and R_1 is the sum of ranks assigned to sample 1. An equivalent formula can be written for sample 2. For samples larger than 20 observations the probability distribution of U approaches the normal distribution. Therefore the null hypothesis of no significant difference between the two sample distributions can be tested by calculation of the z statistic:

$$z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}}$$

Rejection values are 1.96 and 2.58 for the 5 % and 1 % significance level.

RESULTS

Eighteen elements were measured of which S, Cl and Ca were major elements and the rest were the traces B, Mg, K, Ti, Mn, Fe, Cu, Zn, Br, Rb, Sr, Y, Ba, La, and Pb. Some of the trace elements Rb, Y, La and Pb could not be detected in most samples, and Ba were not calculated because a quick check showed the Ba concentration to be below detection limit in all samples. These elements are excluded from tables 4 and 5 in which the analytical results for anhydrite and halite are presented.

A total of 43 anhydrite samples was analyzed of which 22 were known to be taken from the Z 1 part and 21 from the Z 2 part of the core. 10 samples of halite rock, 5 from within each of the sampled sections, were selected for comparison with the associated anhydrite mineral phases. The two Zechstein halite series are recognized in fig. 2 by the abbreviations Na 1 and Na 2.

At present only a limited number of publications deal with the trace element geochemistry of anhydrite and halite. However, comparison with published results shows that the analyses in tables 4 and 5 fall within normal ranges, except for Ti and Zn which are high in both anhydrite and halite (Moore, 1971; Dean, 1978).

The results of the statistical analysis are shown in table 6. Cu is not included in the table because too many samples fell below the detection limit. It was found that there are significant differences ($p < 0.05$) between anhydrite from the Z 1 and Z 2 series for the elements Mg, Ti, Mn, Zn, and Sr as well as for the four element ratios given in the last part of the table. Some distributions are extremely significant, e.g. Ti, Mn, Sr and S/Cl having $p < 0.0001$ (p denotes the probability that the two distributions were drawn from the same population, i.e. that they are equal. When the chance is less than 5 % ($p < 0.05$) it is normal practice to accept that the samples/distributions are in fact different). No significant differences were found between the halite analyses in table 5.

Applying the most significant elements/element ratios, a classification scheme for Z 1 and Z 2 anhydrites can be established, table 7. Because some of the distributions are skewed it was decided to use the median as a measure of central tendency instead of the more widely used arithmetic mean. Also included in the table is the 50% confidence interval (Q25-Q75). The median and the confidence interval were determined from a cumulative frequency distribution plot. In some cases there is a very slight overlap between the intervals, but this will not invalidate the use of the classification table.

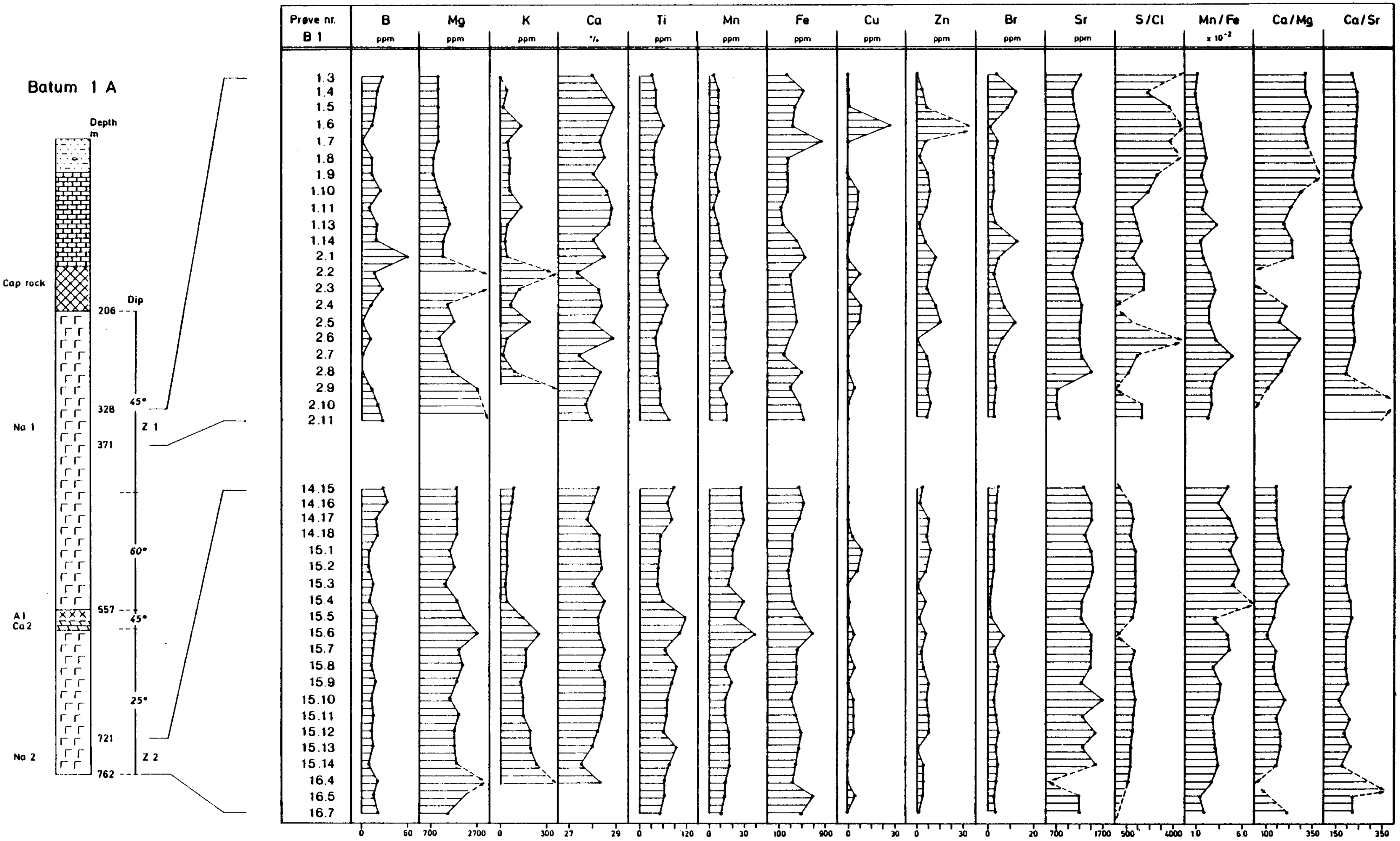


Fig. 2. This column diagram shows the element variation through the investigated sections as well as the lithology of the Batum 1A well. Abbreviations: Na1 = Z1 = Zechstein 1 rock salt; Na2 = Z2 = Zechstein 2 rock salt; Ca2,A1 = dolomite-anhydrite transition zone.

Sample	B ppm	Mg ppm	K ppm	Ca %	Ti ppm	Mn ppm	Fe ppm	Cu ppm	Zn ppm	Br ppm	Sr ppm	S/Cl	Mn/Fe × 10^{-2}	Ca/Mg	Ca/Sr	
B 1.1.3	26	886	*	27.91	30	4	259	*	*	4	1237	6123	1.40	331	227	
B 1.1.4	20	917	43	28.48	46	6	521	*	3	13	1141	2106	1.10	326	251	
B 1.1.5	18	865	18	28.91	43	6	379	2	6	9	1151	3895	1.52	351	253	
B 1.1.6	14	938	136	28.62	59	6	332	26	32	1	1201	4337	1.93	320	240	
B 1.1.7	*	903	44	28.31	44	5	871	*	6	5	1170	3614	0.58	329	244	
B 1.1.8	14	773	58	28.53	36	7	282	*	2	3	1216	$>10^4$	2.37	388	236	
B 1.1.9	13	828	47	28.02	40	5	270	*	4	3	1200	2843	1.92	356	235	
B 1.1.10	24	1005	44	28.63	38	6	271	6	8	3	1208	2217	2.23	299	239	
B 1.1.11	11	1286	141	28.82	32	3	137	5	6	2	1084	809	1.85	235	267	
B 1.1.13	19	1503	47	28.72	36	6	186	3	2	4	1285	1189	3.02	201	225	
B 1.1.14	17	1216	31	28.06	44	7	415	*	4	13	1265	1301	1.77	242	223	Z1
B 1.2.1	59	1219	44	28.50	75	11	552	*	12	5	1149	875	1.98	245	250	
B 1.2.2	15	4846	4272	27.31	50	8	304	7	7	3	1036	1609	2.57	59	265	
B 1.2.3	28	3751	121	28.25	56	10	327	*	6	5	1116	1597	3.03	79	255	
B 1.2.4	13	1357	67	28.38	72	9	376	9	13	7	1259	414	2.48	219	227	
B 1.2.5	*	1749	191	28.04	54	11	460	8	15	12	1208	886	2.45	168	234	
B 1.2.6	13	1042	42	28.86	44	10	309	*	*	6	1206	5876	3.18	291	241	
B 1.2.7	*	1292	18	27.40	48	10	228	*	6	3	1275	1187	4.47	223	216	
B 1.2.8	*	1628	90	28.34	49	15	497	*	8	17	1438	642	3.05	183	198	
B 1.2.9	11	2694	2838	28.04	57	8	322	4	6	4	742	120	2.50	109	380	
B 1.2.10	22	4436	1546	27.67	53	11	426	*	8	3	717	1511	2.68	65	388	
B 1.2.11	27	3475	2124	27.93	79	12	580	*	4	3	802	1309	2.06	84	350	
B 1.14.15	29	1796	95	28.29	92	21	453	*	3	5	1296	424	4.56	165	220	
B 1.14.16	32	1839	74	28.04	74	21	567	*	2	4	1471	691	3.71	160	192	
B 1.14.17	17	1792	65	27.74	81	22	460	*	7	4	1443	767	4.67	163	193	
B 1.14.18	20	1752	49	28.28	59	19	362	3	5	3	1361	676	5.22	169	209	
B 1.15.1	10	1490	47	28.33	56	15	346	9	8	3	1430	989	4.19	200	199	
B 1.15.2	10	1687	43	28.43	47	15	260	5	4	3	1468	905	5.87	177	195	
B 1.15.3	16	1340	28	28.00	46	13	299	*	*	2	1405	975	4.45	219	201	
B 1.15.4	10	1795	45	28.49	60	22	328	2	4	1	1280	982	6.74	167	224	
B 1.15.5	19	2133	157	28.21	118	16	547	*	2	2	1298	819	2.86	139	219	
B 1.15.6	17	2778	263	28.27	106	29	745	4	5	7	1445	489	3.93	107	197	Z2
B 1.15.7	14	1919	170	28.50	65	15	385	*	2	3	1419	954	3.99	156	202	
B 1.15.8	12	2092	172	28.26	95	11	414	4	3	5	1449	704	2.53	142	196	
B 1.15.9	18	1768	137	28.52	84	15	396	*	7	4	1349	776	3.68	169	213	
B 1.15.10	12	1455	150	28.52	70	11	353	3	5	3	1690	902	3.00	206	170	
B 1.15.11	16	1796	153	28.42	71	10	412	3	7	4	1305	796	2.53	166	219	
B 1.15.12	11	1668	183	28.24	63	13	492	4	7	5	1514	785	2.63	178	188	
B 1.15.13	16	1663	196	28.02	97	13	464	*	*	4	1301	667	2.78	177	217	
B 1.15.14	10	1783	240	27.54	77	12	396	*	3	5	1524	668	3.11	162	182	
B 1.16.4	22	5746	1148	28.27	65	9	359	*	3	4	661	552	2.46	52	431	
B 1.16.5	15	2249	1489	28.43	65	10	702	4	3	3	1240	213	1.42	133	231	
B 1.16.7	22	1355	65	28.24	52	8	476	*	1	4	1229	255	1.77	219	231	

* Analysis below detection limit.

Table 4. Chemical analyses of anhydrite, Batum 1A

	Sample	B ppm	Mg ppm	K ppm	Ca %	Ti ppm	Mn ppm	Fe ppm	Cu ppm	Zn ppm	Br ppm	Sr ppm	S/Cl	Mn/Fe x 10^{-2}	Ca/Mg	Ca/Sr
	B1.1.1 H	4.0	200	255	2.15	13	2	28	13	5	205	97	0.063	8.12	97	197
	B1.1.3 H	3.6	116	227	1.18	10	*	19	10	*	219	52	0.034	*	95	204
	B1.1.5 H	3.7	144	340	0.83	8	*	9	7	*	221	37	0.020	*	53	200
	B1.1.7 H	3.2	*	152	0.16	6	2	13	8	2	217	10	0.004	1.30	*	140
Z1	B1.1.9 H	3.3	*	198	0.30	8	3	16	10	7	207	16	0.008	17.20	*	166
Z2	B1.15.12 H	3.0	*	204	0.50	4	2	9	7	2	208	31	0.014	21.20	*	146
	B1.15.14 H	3.4	68	538	0.66	9	*	26	15	6	194	38	0.014	*	41	153
	B1.16.3 H	3.3	*	319	0.49	4	*	5	9	2	218	22	0.011	*	*	197
	B1.16.4 H	3.4	107	251	0.61	8	*	9	5	3	210	30	0.017	*	73	179
	B1.16.5 H	3.0	*	255	0.30	7	2	17	13	5	214	14	0.007	13.70	*	189

* Analysis below detection limit.

Table 5. Chemical analyses of rock salt, Batum 1A.

Element	Statistics		
	U	z	p
B	228	1.10	> 0.05
Mg	346	2.79	< 0.01
K	297.5	1.62	> 0.05
Ca	254.5	0.57	>> 0.05
Ti	398.5	4.07	<< 0.01
Mn	417	4.52	<< 0.01
Fe	304.5	1.79	> 0.05
Zn	315	2.04	0.01<p<0.05
Br	281.5	1.23	> 0.05
Sr	418	4.54	<< 0.01
S/Cl	387	3.79	<< 0.01
Mn/Fe	373.5	3.46	<< 0.01
Ca/Mg	346	2.79	< 0.01
Ca/Sr	412	4.40	<< 0.01

Table 6. Mann - Whitney U - test on element distributions in anhydrite (table 4) from Z 1 and Z 2.

Element/ elem. ratio	Z1 Series M	 Q25-Q75	Z2 Series M	 Q25-Q75
Ti ppm	47	37.5-57.0	70	57.0-86.0
Mn ppm	7.5	5.8-9.2	14	12.0-18.4
Sr ppm	1201	1116-1246	1405	1335-1470
S/Cl	1554	830-2400	767	600-830
Mn/Fex10^{-2}	2.30	1.82-2.78	3.68	2.80-4.45
Ca/Mg	239	180-305	166	148-180
Ca/Sr	241	229-254	202	196-216

Table 7. Classification table for anhydrite from Batum 1 A well. Each series is characterized by the median M and the 50 % confidence interval.

DISCUSSION

In the following discussion readers are requested to refer to tables 4 and 5 and fig. 2 which is a "log" type diagram depicting the variation in chemistry through the two sections studied from the Batum 1A core.

In trying to establish a geochemical division between the two Zechstein evaporite series, it seems wise to restrict attention to a discrete evaporite facies, as very significant changes occur in chemistry when passing from one evaporite facies till the next (cf. Holser, 1979a). An investigation of the halite analyses does not show any deviation from halite facies chemistry. However, an inspection of the anhydrite analyses reveals 3 levels with strongly increased Mg and K values as well as low Sr values. This probably indicates that evaporation passed into the potash-magnesia facies at the sampling levels B1.2.2, B1.2.9-1.2.11 and B1.16.4. The reason for the decrease in absolute Sr concentration is not obvious, and seems to be in conflict with the distribution coefficient being less than 1 for Sr in the system anhydrite/brine. However, a possible explanation could be the synchronous precipitation of celestite in the later stages of the evaporation cycle (Holser, 1979b), thereby removing large amounts of Sr from the brine.

It is somewhat surprising that the K-Mg anomaly is not visible in the associated halite samples B1.16.4-1.16.5. Although this point needs further confirmation, it is tentatively suggested that the very soluble K-Mg minerals were removed by circulating fluids during metamorphic recrystallization of the halite after deposition.

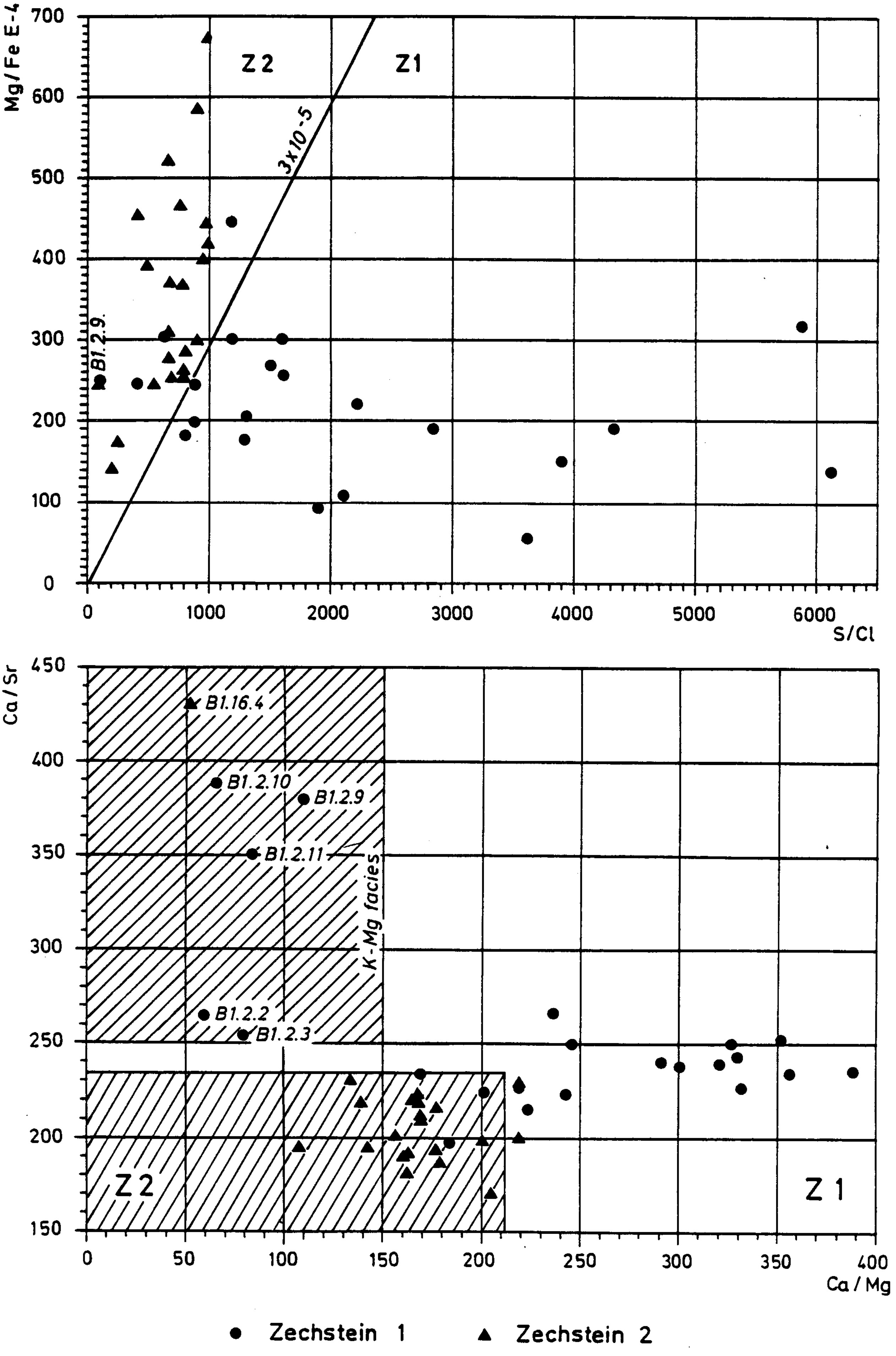
Two scatter diagrams which can be used for classification of the samples are presented in figs. 3 and 4. The best discrimination between Z1 and Z2 samples is obtained in the diagram Mn/Fe as a function of S/Cl, in which a line through the origin with the slope 3×10^{-5} completely divides Z2 samples from the Z1 area, but 4 samples of the Z1 section fall within the Z2 area. One of these (B1.2.9) probably belongs to the potash-magnesia facies and should be excluded from the diagram which is only recommended for halite facies samples. The second diagram showing Ca/Sr as a function of Ca/Mg also displays a fair division between Z1 and Z2 samples. The small Z2 area is delimited by lines having Ca/Mg = 210 and Ca/Sr = 232. Besides, this diagram has the advantage of yielding a very clear division of the potash-magnesia facies from the halite facies. Anhydrite precipitated during K-Mg facies is characterized by low Ca/Mg and varying but relatively high Ca/Sr. The samples which are supposed to belong to the K-Mg facies fall in an array along the ordinate, while samples belonging to the halite facies fall in a second array along the abscissa.

No simple variation diagram can secure a complete division of Z1 and Z2 samples. There is still about 10% chance that a single sample would fall into the wrong field in figs. 3 and 4. If the chemical analyses are to be used for stratigraphic classification, a different procedure must be followed. It is suggested that at least 5 anhydrite samples from the section considered should be analyzed and the mean values computed. By using table 7 a safe classification is expected because the means with a very high probability will fall inside the confidence limits given in the table. The procedure should only be applied to anhydrites belonging to the halite facies.

The statistical analysis has demonstrated greater mean concentrations of Mg, K, Ti, Mn and Sr in halite facies anhydrites from the Z2 section (see tables 4, 6 and 7). It is known from experimental studies (Holser, 1979b) that the distribution coefficient is less than 1 for Mg, K and Sr in the system anhydrite/brine. This would tend to increase concentration of these elements in the brine as evaporation proceeds, thereby also increasing the absolute concentration of Mg, K and Sr in late stage anhydrites. The observed differences between Z1 and Z2 could then be explained by assuming the Z2 section to represent a slightly later stage in a halite evaporation cycle. In both sections the evaporation evidently went close to or probably crossed the border to the potash-magnesia facies.

The two elements B and Br should also concentrate in the brine during evaporation, but this is not seen in the present study. The very significant difference in S/Cl ratios between the two series can only be explained by a greater volume of fluid inclusions in anhydrite from Z2. Fluid inclusions trapped in halite and quartz crystals during deposition have been shown to be Na-Mg-Ca-chloride rich brines (Fabricius, 1983), which could probably also explain the higher Mg content found in Z2 anhydrites.

It was pointed out above that the salt series could have been subjected to late stage alteration by circulating fluids during metamorphic recrystallization. This is further supported by the apparent absence of Mg in half of the halite analyses, table 5. From the point of view of stratigraphic correlation, analyses on halite are not expected to be of much value. However, from a genetic point of view it could be useful to consider the Br content in halite, because Br is used as an indicator of



Figs. 3 & 4. Variation diagrams used for discrimination between Zechstein 1 and 2 samples.

palaeo salinity. The Br analyses in table 5 shows a surprisingly regular distribution with Br falling in the range 200-220 ppm in both sections. This is a high Br concentration indicative of halite precipitation just at the limit to potash-magnesia facies conditions. This is in agreement with observations from the anhydrite analyses. The very regular distribution of Br is equal to the development described from part of the German Zechstein (Raup & Hite, 1978) and, considering also the homogeneous distribution of many elements in the anhydrite, could be said to favour the idea of evaporite generation in a large deep-water marine basin that was little affected by minor changes of the influx-reflux balance of the basin. Nevertheless, it is still surprising to find such similar Br contents in two random sections from the Z1 and Z2 series. Only a complete geochemical profile through the Danish Zechstein salt could rule out the possibility that metamorphic recrystallization homogenized the Br distribution through the whole evaporite series.

CONCLUSIONS

Between two sections of grey salt from the Batum 1A well, representing the Zechstein 1 and 2 series, statistically very signigicant differences have been observed for the elements Mg, Ti, Mn, Sr and the element ratios S/Cl Mn/Fe, Ca/Mg and Ca/Sr. This could be due to a characteristic geochemical difference between the two evaporite cycles, or it could be explained by the investigated section of Z2 representing a different stage in the evaporation cycle.

The anhydrite analyses suggests the occurrence of K-Mg facies conditions in both sections, which is not always found in the associated halite. It is proposed that, during metamorphic recrystallization of the evaporite series, circulating fluids removed the highly soluble K-Mg minerals leaving no anomaly to be detected in the halite. This event could also be responsible for the very homogeneous Br distribution found in halite from both sections.

The regular distribution of many elements (Ti, Mn, Fe, Zn, Br and Sr) in the anhydrite, which is not affected by recrystallization of the enclosing rock salt, supports the idea of a large marine deep-water evaporite basin.

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APPENDIX

Table 1, 2A to 2B.

Appendix, table 1. Instrumental settings

Element	Line	Col.	Det.	Xtl.	Tube	Power		Energy Discrimination			Measuring positions , °2θ		
						KV	mA	UPL	%	LWL	Top	UBg.	LBg.
Mg	Kα	C	F	1	Rh	50	50	52		24	45.30	48.56	44.14
S	Kα	C	F	3	Cr	50	50	60		28	110.75	115.00	104.00
	Kβ										100.85	104.50	96.50
Cl	Kα	C	F	3	Cr	50	50	60		28	92.85	96.50	91.00
	Kβ										84.90	104.00	81.00
K	Kα	C	F	4	Rh	50	50	72		26	136.89	139.59	133.69
Ca	Kβ	C	F	4	Rh	50	50	64		24	100.40		96.12
Ti	Kα	C	F	4	Rh	50	50	66		26	86.33	89.05	84.57
Mn	Kα	C	F	4	Rh	50	50	62		34	63.13	67.39	60.17
Fe	Kα	C	F	4	Rh	50	50	62		34	57.67	60.17	55.27
Cu	Kα	F	F+S	4	Rh	80	30	70		24	45.12	46.62	44.08
Zn	Kα	F	F+S	4	Rh	80	30	68		22	41.88	44.08	41.08
Br	Kα	F	S	4	Rh	80	30	70		30	30.00	32.10	29.20
Rb	Kα	F	S	4	Rh	80	30	70		30	26.65	29.20	26.08
Sr	Kα	F	S	4	Rh	80	30	70		30	25.18	26.08	24.40
Y	Kα	F	S	4	Rh	80	30	70		30	23.82	24.40	23.24
Ba	$L\alpha_1$	C	F	4	Rh	50	50	66		26	87.31	89.05	84.57
La	$L\alpha_1$	C	F	4	Rh	50	50	70		30	83.09	84.57	82.21
Pb	$L\beta_1$	F	F+S	4	Rh	80	30	70		24	28.32	29.28	26.06

Col. = collimator, Det. = detector,

C = coarse
F = fine

F = flow det.
S = scintillation det.

Xtl. = crystal, UPL = upper level, LWL = lower level

1 = TlAP
3 = Ge
4 = LiF (200)

Element	line	BCR-1	ZGI-AN	NaCl, SMES
		μ/ρ (Element, line)		
Mg	$K\alpha$	2293	2294	2893
S	$K\alpha$	1014	413.4	552.4
S	$K\beta$	845.8	344.7	460.7
Cl	$K\alpha$	711.7	709.2	466.0
Cl	$K\beta$	584.3	582.3	382.6
K	$K\alpha$	371.5	371.2	773.9
Ca	$K\alpha$	229.7	218.6	456.1
Ti	$K\alpha$	200.6	360.7	366.9
Mn	$K\alpha$	101.2	172.7	176.4
Fe	$K\alpha$	80.59	137.7	140.7
Cu	$K\alpha$	68.93	73.54	74.98
Zn	$K\alpha$	56.66	60.44	61.58
Br	$K\alpha$	23.44	24.95	25.31
Rb	$K\alpha$	17.16	18.13	18.42
Sr	$K\alpha$	14.64	15.51	15.79
Y	$K\alpha$	12.60	13.32	13.61
La	$L\alpha_1$	184.3	331.5	337.1
Pb	$L\beta_1$	19.93	21.25	21.54

Appendix, table 2A. Calculated mass absorption coefficients for natural and synthetic standards.

Tables of mass absorption coefficients

Mass absorption coefficients μ/ρ (Element, line) for samples and standards were calculated according to normal practice using published major element analyses and the coefficients of Heinrich (1966). Errors in assuming a fixed composition for the samples are less than 1%. See text for further information.

Element	line	Anhydrite	Halite
		μ/ρ (Element,line)	
Mg	Kα	2224	3051
S	Kα	412.2	562.7
S	Kβ	343.7	469.2
Cl	Kα	712.3	403.3
Cl	Kβ	584.9	331.1
K	Kα	372.9	865.7
Ca	Kβ	219.5	509.9
Ti	Kα	362.1	372.7
Mn	Kα	173.4	177.9
Fe	Kα	138.3	141.7
Cu	Kα	73.83	75.48
Zn	Kα	60.68	61.98
Br	Kα	25.06	25.45
Rb	Kα	18.20	18.47
Sr	Kα	15.57	15.82
Y	Kα	13.38	13.65
La	$L\alpha_1$	332.8	342.4
Pb	$L\beta_1$	21.34	21.65

Appendix, table 2B. Calculated mass absorption coefficients for natural samples, assuming a constant composition of 99.9% $CaSO_4$ + 0.1% Sr for anhydrite samples and 98% NaCl + 2% $CaSO_4$ for halite samples.

SALT RESEARCH PROJECT EFP-81

Volume I. Sammendrag af Saltforskningsprojekt EFP-81. (English summary).
Editor: J.Fabricius.

Forord.

Historisk oversigt.

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Kapitel 3. Mikrotermometri.

Volume II. Stratigraphy.

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Fritz Lyngsie Jacobsen.

Chapter 2. Description of the Dolomite-Anhydrite Transition Zone (Zechstein 1 - Zechstein 2) in the Batum-13 well, Northern Jutland, Denmark.
Martin Sønderholm.

Chapter 3. A geochemical study on Zechstein Salt and Anhydrite from the Batum-1A well.
Niels Springer.

Volume III. Fabric analyses of Domal Rock Salt.

Chapter 1. Textural and Petrofabric Analyses of Rock Salt related to Mechanical Test Data - a quantitative Approach.
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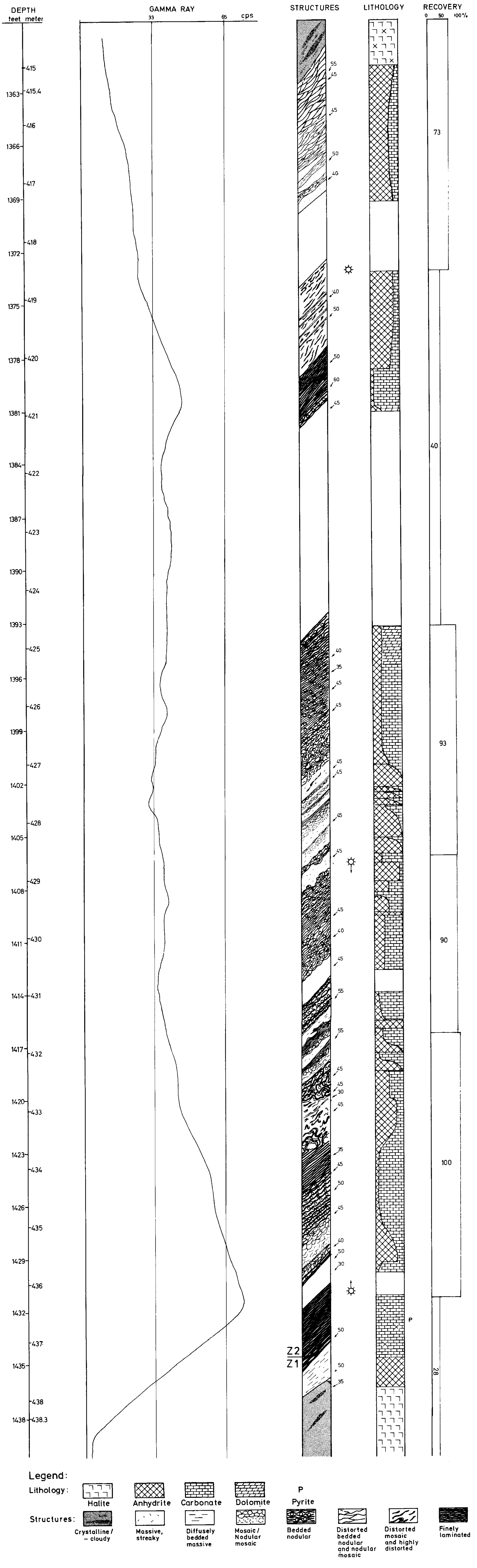
Johannes Fabricius.

Chapter 2. Formation Temperature and Chemistry of Brine Inclusions in euhedral Quartz Crystals from Permian Salt in the Danish Trough.
Johannes Fabricius.

Chapter 3. The Thermal Stability of Natural Carnallite in Cognate Geological Environments.
Johannes Fabricius.

BATUM 13



DESCRIPTION

ROCKSALT, grey, translucent, with lumps of anhydrite

—

FLASERANHYDRITE, light grey - bluish grey, with carbonate, brownish black, clayey, with trances of organic material.

1375′ Gas blow - out, duration: 90 min.

—

CARBONATE SHALE, greyish brown and black, clayey, finely laminatet, with traces of organic material

—

ANHYDRITE - KNOTENSCHIEFER, greyish brown from carbonte, clayey with nodule of anhydrite (1-10 mm) and trances of organic material. Upper part dolomite.

—

WOLKEN- and SCHWADENANHYDRITE, light grey - bluish grey with irregular layers of CARBONATE, brownish black, clayey with traces of organic material.

—

ANHYDRYTE – KNOTENSCHIFER, brownish black carbonate, clayey with nodules of anhydrite (3-10mm.) with traces of organic material. Strong smell of hydrocarbons when core is broken.

—

WOLKE-and SCHWADENANHYDRITE, light grey - bluish grey with irregular layers of CARBONATE, brownish black, clayey; finely, laminated, with traces of organic material.

— ANHYDRYTE-KNOTENSCHIFER, brownish black from carbonat, clayey lamination strongly curled, with nodules of anhydrite (1-10mm) and traces of organic material

—

ANHYDRITE, massive with irregular layers and streaks of brownish black CARBONATE.

—

CARBONATE, light greyish brown, clayey, finely laminated.

— ANHYDRITE – KNOTENSCHIFER, brownish black from carbonate, clayey with nodules of anhydrite (2-10mm) and organic material.

—

WÓLKENANHYDRITE, light grey - bluish grey with irregular layers and streaks of brownish black CARBONATE, smell of hydrocarbons when core is broken.

—

LAMINATED CARBONATE MUDSTONE, silty, brownish black with organic material and pyrite. Contains 1-10cm tick beds of carbonate mudstone with intraclasts, some of them fossiliferous.

—

ANHYDRITE, greyish blue - light grey, massive, diffusely layered

—

ROCKSALT, reddish, translucent

^{45}DIP ☼ HYDROCARBONNICH INTERVAL F FOSSILIFEROUS

In connection with and as a part of the EFP-81 research program are 3 papers which describe the evaporites of the Danish Zechstein and specific problems in this relationship collected in this volume. Fritz Lyngsie Jacobsen gives a description of the lithostratigraphy of the rocks in the Danish Part of the Norwegian-Danish Basin. The development of the Basin specially in relation to the Zechstein rocks, movements of the salt, problems related to the cap rocks and drilling practise in the Danish Area and a consideration on the economic geology are treated as a part of this subject. Martin Sønderholm gives a description of the transition zone between Zechstein 1 and 2 together with the adjoining petrogas and brine.
Niels Springer has studied the variance in the geochemical composition of the upper part of Zechstein 1 and the lower part of Zehstein 2 rock salts.

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