

Studies of Fluid Inclusions in Halite and Euhedral Quartz Crystals from Salt Domes in the Norwegian-Danish Basin

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ABSTRACT

Microthermometric studies have been carried out on fluid inclusions in halite and in euhedral quartz from salt domes in the dome area of N. Jutland, which is a part of the Norwegian-Danish Basin. The investigated salt is of Zechstein age.

Euhedral quartz crystals have been extracted from selected core material from wells in different domes at various depths from 200 m to 3485 m. The homogenization temperature and the melting temperature of the ice and the different hydrates have been measured on fluid inclusions in the quartz crystals. The salinity and the Ca:Mg ratio have been determined from the various phase diagrams of the system $\text{CaCl}_2\text{—MgCl}_2\text{—NaCl—H}_2\text{O}$. Sa-

linity: 30–40 weight% brine, Ca:Mg ratio: 3:1–1:4. In a few cases both the trapping and the homogenization temperature were measured and the prevailing pressures during the crystallization of the quartz have been calculated. The maximum P and T values may indicate thermal convection in the salt pillow, causing initiation of the diapiric penetration phase. A parallel study of fluid inclusions in the corresponding halite has shown that the physical and chemical conditions of halite in connection with the brine give rise to inaccurate temperature measurements and too low salinity determination.

INTRODUCTION

Several workers have studied fluid inclusions in bedded salt, e.g., Dreyer et al. (1949); Roedder (1963); Powers et al., ed., (1978); Roedder and Belkin, (1979a). To the best of the author's knowledge only Roedder and Belkin, (1979b), have performed a study of dome salt. It is obvious from these studies that P-T-X results from such studies are ambiguous. For this reason the present study is focused on the fluid inclusions occurring in the small euhedral quartz crystals found in the rock salt. The P-T-X data obtained from these crystals are compared with data from the fluid inclusions in the halite and the genesis of the rock salt and the quartz crystals will be discussed.

GEOLOGICAL SETTING

In the Norwegian-Danish Basin (Figure 1) evaporites were precipitated during Zechstein time in three main cycles, which are believed to correspond to the North German Zechstein 1, 2 and 3 cycles (Richter-Bernburg, 1960).

The stratigraphy of the Danish Zechstein evaporites is given in Table 1 and Figure 6. All the thicknesses mentioned are approximate because they originate from wells in strongly deformed sequences within domes. From geo-

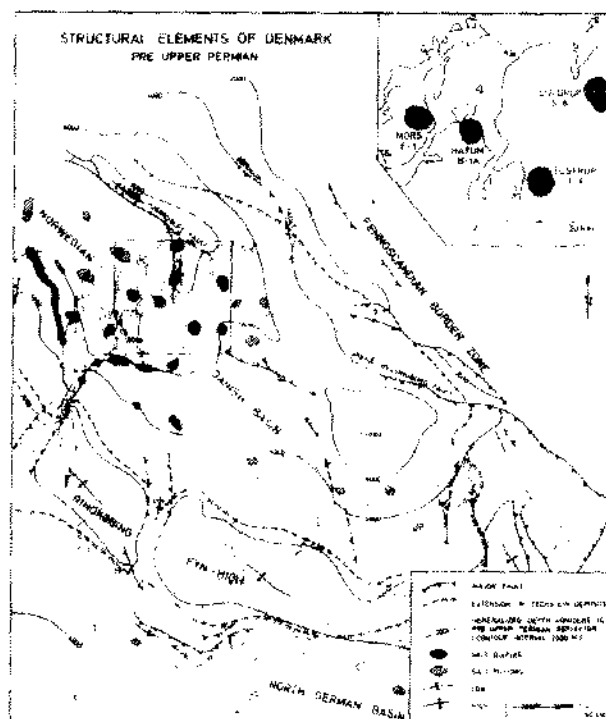


Figure 1. Map of the halokinesis area in Northern Jutland, Denmark. After Michelsen et al. (1981).

TABLE 1
The Stratigraphy of the Danish Zechstein

Cycle	Symbol	Depth m	Lithology
Z3	Na3	100—	<i>rocksalt</i> , red to brownish to greyish, coarse crystalline, with disseminated anhydrite and two thin zones of potassium and one thin bed of anhydrite
		200	
	T3	60	" <i>saltclay</i> ", consolidated sandstone, siltstone, claystone, red and green colours, with <i>rocksalt</i> .
Z2	Na2r	15	" <i>deckrocksalt</i> ", yellowish red to orange red, <i>kieseritic</i> , potassic with clay and anhydrite.
		10	
	K2	10	<i>hardsalt</i> , <i>kieserite</i> , halite carnallite, sylvite and clay. (Veggerby K-zone corresponding with Kaliflöz Stassfurt)
	Na2 (K)	20	<i>rocksalt</i> , reddish to brownish red, potassic and <i>kieseritic</i> .
	Na2	500	<i>rocksalt</i> , light to medium grey, occ. colourless, coarse crystalline with disseminated small crystals of anhydrite.
Z1	Ca2	9	<i>anhydrite-dolomite</i> , alternating layers of anhydrite, dolomite and limestone, medium-grey.
	A1	1	<i>anhydrite</i> , brownish, compact.
	Na1	500	<i>rocksalt</i> , light to medium grey, occ. colourless, coarse crystalline with disseminated small crystals of anhydrite.

physical evidence it is believed that the diapirism (the pillow phase) was initiated in Late Triassic. The penetration phase is regarded to be of Middle Jurassic-Early Cretaceous age and the postdiapiric phase commenced in Late Cretaceous (Richter-Bernburg, 1981). Figure 1 exhibits the dome area in N. Jutland and the insert map shows the sites and the names of the domes with the names of the wells mentioned in this paper.

METHODS AND MATERIALS

In the fluid inclusion study an Olympus petrographic microscope BHA with 10×, 20×, and 40× LWD objectives was used in connection with a CHAIXMECA microthermometry apparatus, 1980 model. The heating-freezing stage is controlled by an electronic manual/automatic controller and temperature read-out.

The *rocksalt* test samples were prepared from cleavage pieces of large colourless halite crystals from selected cores of the Mors E1 well. The pieces were double polished and had the dimensions of approximately, 1 × 4 × 4 mm.

The quartz crystals and other water insoluble minerals were separated from 500 g of core material by dissolving

the salt in hot water. This residue, containing more than 99% anhydrite, was then separated by heavy liquids and the quartz crystals were eventually separated manually. The quartz crystals were counted and measured and their crystal type was established. The normal procedure of freezing followed by heating was performed upon the fluid inclusions in the quartz crystals. This procedure is unsuitable in halite because the inclusions leak during the freezing period; therefore, the reverse procedure was used.

The salinity and the Ca:Mg ratio of the inclusion fluids were estimated by combining the phase diagrams $\text{CaCl}_2\text{--MgCl}_2\text{--H}_2\text{O}$ and $\text{NaCl--CaCl}_2\text{--H}_2\text{O}$ (Janat'eva, 1946) and $\text{NaCl--MgCl}_2\text{--H}_2\text{O}$ and the three diagrams ($\text{CaCl}_2 + \text{MgCl}_2$)— $\text{NaCl--H}_2\text{O}$, Ca:Mg ratio 3:1, 1:1, 1:3 (Figure 2) (Luznaja & Verescetina, 1946).

FLUID INCLUSIONS IN HALITE

The Inclusions

The fluid inclusions used are believed to be primary, because they are either isolated or form short trains of a few small inclusions (Roedder, 1976, 1979). The great majority of the inclusions are negative cubes with a length of the edges averaging 10–12 μm . Small cubes are abundant, but cubes with edge lengths more than 50 μm are rare. Normally even the smallest inclusions contain one or more crystals of anhydrite, which is not a daughter mineral or a pseudomorph after gypsum. Irregular large inclusions are always found in connection with clusters or tight rows of anhydrite crystals.

After freezing many of the inclusions have developed plane joints parallel to the walls of the inclusions which are artifacts. These are caused by the formation of ice and the different hydrates. The joints are filled with very small fluid inclusions during the heating period, presumably by diffusion (Gerlach and Heller, 1966), or the liquid is forced out in the joints when heated above the homogenization temperature.

Thermometry

Interestingly, several of the smaller inclusions have not nucleated a gas phase at room temperature because of an apparent metastability, "stretched" fluid (Roedder, 1963). But a slight cooling to -15°C to 20°C invalidates this apparent metastability and a gas phase is formed. The solubility of NaCl in $\text{CaCl}_2\text{--MgCl}_2$ solution increases with rising temperature (Stewart and Potter, 1979; Jenks, 1979). Because of this it becomes important that the inclusion has sufficient time to dissolve NaCl from the walls during the heating period and is close to the homogenization temperature T_h .

If the inclusion homogenizes in the fluid phase, i.e., the enclosed gas bubble disappears and the inclusion is heated beyond T_h , the pressure in the inclusion increases with

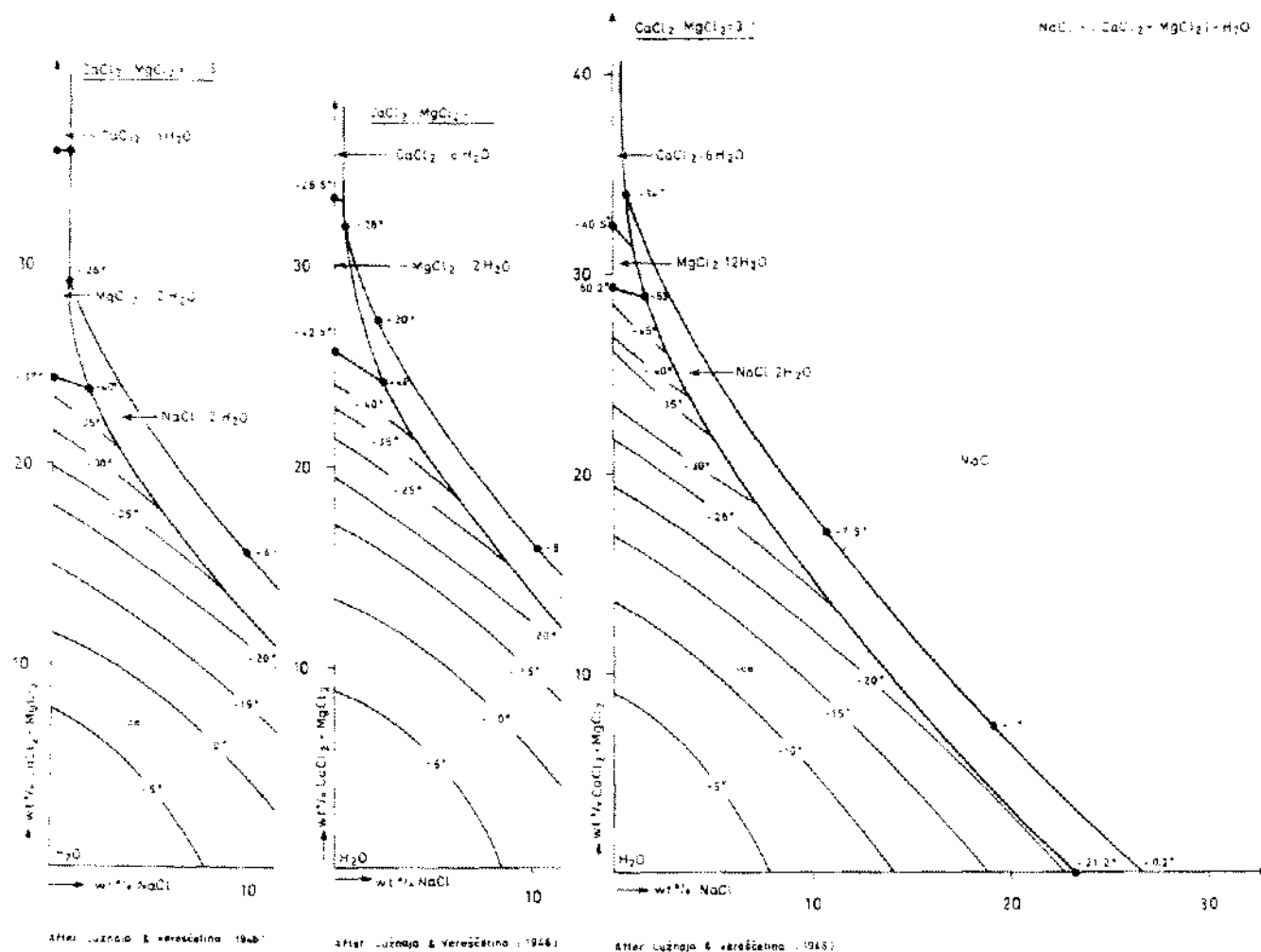


Figure 2. Phase diagrams in the system $\text{NaCl}-(\text{CaCl}_2 + \text{MgCl}_2)-\text{H}_2\text{O}$, the Ca: Mg ratio 3:1, 1:1, 1:3.

about 11 bars per $^{\circ}\text{C}$ above T_h valid for a 30 weight % NaCl solution (Potter, 1977). The inclusion expands, if it doesn't decrepitate, resulting in a higher T_h . This indicates that an "annealing" of the inclusion has occurred (Roedder & Belkin, 1979b). As far as possible the lowermost homogenization temperatures should be measured first. The homogenization temperatures have been measured in the following two intervals:

28.5 $^{\circ}\text{C}$ -124.8 $^{\circ}\text{C}$, $n = 68$, mean $T_h = 72.6^{\circ}\text{C} \pm 5.9^{\circ}\text{C}$
 189.8 $^{\circ}\text{C}$ -223.2 $^{\circ}\text{C}$, $n = 23$, mean $T_h = 203.2^{\circ}\text{C} \pm 2.5^{\circ}\text{C}$.

Some few inclusions showed a T_h above 300 $^{\circ}\text{C}$, obviously due to stretching.

Cryometry

In order to measure the freezing-point depression, and hence determine the chemistry of the fluids, the inclusions were cooled down to -90 $^{\circ}\text{C}$ to 110 $^{\circ}\text{C}$. By a slow rise of the temperature the majority of the inclusions nucleated ice

and, later on, hydrate. The formation of ice was often spontaneous, sometimes from a single nucleus.

The melting point of the ice— T_m , ice—was measured. This temperature cannot be verified by lowering the temperature to the point of recurring ice formation, because a part of the liberated liquid instantaneously reacts with the walls, forming NaCl hydrate. The new T_m , ice will then be lower than the first one, giving a falsely lowered freezing-point depression. Because at least three different hydrates are present, of which NaCl·2H₂O optically dominates by furrowing the inclusion walls, it is impossible as a rule to measure the melting points of the other hydrates such as MgCl₂·12H₂O and especially of CaCl₂·6H₂O. In a few cases the melting point of MgCl₂·12H₂O could be measured, because a comparatively large amount of liquid suddenly is released.

The melting point of the ice— T_m , ice—is measured in the interval -51 $^{\circ}\text{C}$ -25 $^{\circ}\text{C}$, $n = 75$, mean temperature -37.6 $^{\circ}\text{C} \pm 1.8^{\circ}\text{C}$. In the cases shown in Table 2, T_m , ice

and the melting point of $\text{MgCl}_2 \cdot 12\text{H}_2\text{O}$ in advance of the $\text{NaCl} \cdot 2\text{H}_2\text{O}$ destroying the walls could be measured:

TABLE 2
Salinity and Ca:Mg Ratio

T_m , ice	T_m , hyd.	Salinity min.	Ca:Mg appr.
-40.6°C	-34.6°C	30 wt%	1:1
-50.6	-33.6	32	2:1
-38.8	-28.9	29	1:3
-40.1	-36.6	32	1:1
-42.0	-33.8	32	1:1
-32.7	-29.8	29	1:3
-44.5	-34.5	33	2.5:1

The salinity and the Ca:Mg ratios are determined from the reference phase diagrams (Figure 2). The melting point of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ was not measured, hence the true salinity is presumed to be 5–10 wt% higher than the above noted. The NaCl content is less than 2 wt% at 20°C.

DISCUSSION

Because of the problems mentioned, above, the results of the thermometry and the cryometry are of only fair validity. They can only indicate the conditions *in situ*.

Thermometry

In order to find the trapping temperature T_i of the inclusions the homogenization temperatures T_h have to be corrected for the prevailing pressure in the salt domes. For T_h less than 50–60°C, the pressure correction is negligible. An estimate of the pressure prevailing during the formation of inclusions with T_h higher than 60°C is impossible, because they may have formed at any stage between the bedded salt phase and the post-diapiric phase or even later.

The homogenization temperatures that were measured might only represent an approach to equilibrium volume relations at the pressure and the temperature of the sample site (Roedder and Belkin, 1979b). In spite of the unacceptably high T_h values it should be noted that they are comparable to the highest values obtained on inclusions in the quartz crystals.

Cryometry

The amount of supercooling shows that the fluids are very clean and free from submicroscopic freezing nuclei. This may indicate that clay material may have settled in advance of the halite crystallization. The fluids in the inclusions may represent seawater, trapped within the original salt, which has coalesced during flowage (Roedder and Belkin 1979b). In the present work the cryometric results exclude the possibility of any source other than seawater, which is highly concentrated in the halite facies.

FLUID INCLUSIONS IN QUARTZ CRYSTALS

The Quartz Crystals

Euhedral quartz crystals in saline sediments may have stratigraphical significance in local areas (Shettler, 1972). Since the formation of the crystals depends on many factors within saline environments and because the crystals are very sensitive to facies changes, they may be useful as facies indicators (Nachsel, 1966).

The stratigraphical significance is based on the number of crystals (in 500 g of cuttings or core material), their colour, the axis ratio $c:a$, the crystal habit and the enclosures in the crystals (Shettler, 1972). Tarr (1929) has set up a growth series from the pseudocubic positive rhombohedron r to the doubly terminated long prismatic form $r + z + m$. This growth series has been named type I–VI by Grimm (1962) (Figure 3), and he suggests an authigenic postsedimentary or early diagenetic formation of the crystals. Nachsel (1966) points out that a syndimentary origin must be very rare and a silica transport during the salt-metamorphosis seems impossible, thus he interpreted the crystallization to have taken place during the diagenesis.

The quartz crystals contain a considerable number of anhydrite inclusions, which as a rule are prismatic automorphic microcrystals. This poikilitic structure indicates that the formation of the quartz crystals began in the very moment of incipient anhydrite precipitation (Demangeon, 1966). Demangeon also finds that anhydrite precipitation begins when the volume of the seawater is reduced to 1:22.

The present investigation is based mainly on the Batum 1A well, which was drilled in 1951 with continuous coring from the salt mirror at a depth of 206 m to a total depth of 762 m (Figure 4). The core recovery in the uppermost, approximately 120 m of the salt, was zero. As the salt in the

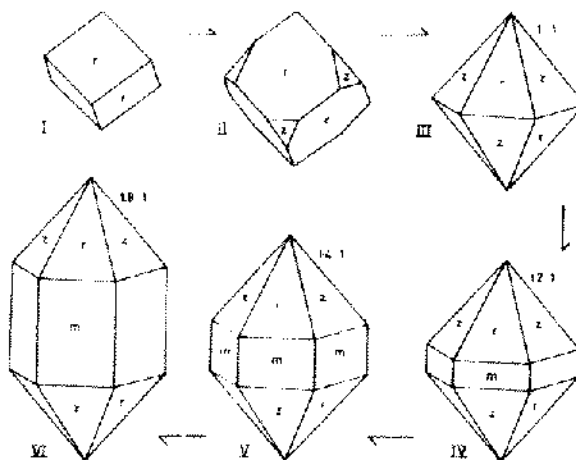


Figure 3. The quartz crystal growth series. After Grimm (1962).

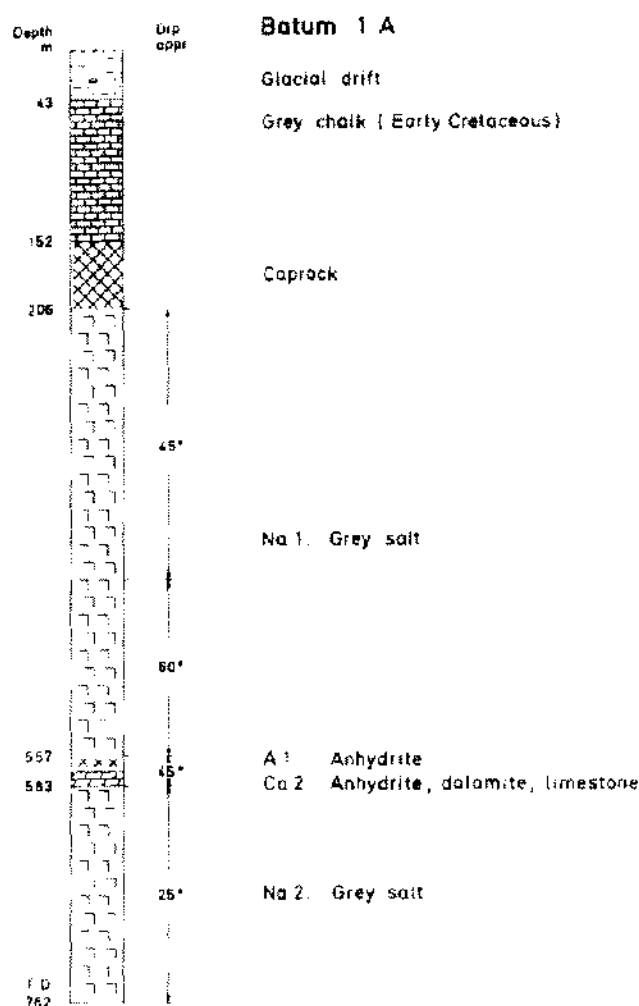


Figure 4. The Batum 1A well. The Z1 and Z2 layers are inverted.

well is referred to the Na1 and Na2 salt units, cores from the Mors and the Tostrup domes were selected in such a way that the entire stratigraphic column was represented.

The extracted quartz crystals from the Batum 1A well are all perfect euhedral crystals with sharp edges and smooth crystal faces with practically no lineage or mosaic structures. The habit are of type III-VI (Figure 3). Generally the *r* faces are larger than the *z* faces and on type III crystals one or two *m* faces may be developed. Some of the crystals are slightly distorted. Intergrown twin crystals with parallel *c*-axes and with four or three pyramids are common. In this study crystals of type I and II have not been found.

The crystals are colourless and transparent but a few are light yellow to light red with yellow tint though still transparent. The length of the crystals ranges from less than 63 μm to 1.4–1.6 mm regardless of the crystal type and the width corresponds with the *c*:*a* ratio noted on Figure 3.

The number of the crystals per 500 g core material ranges from very few up to some few hundreds with an average number of 50–60. None of the morphologic types are dominant, though type VI is slightly more abundant than the other types. In relatively few crystals the solid enclosures are poikilitic distributed minute anhydrite crystals. This occurrence is regardless the crystal type. In the majority of the crystals the number of anhydrite crystals is moderate to scarce. The anhydrite crystals are larger than the above mentioned poikilitic anhydrite and they are better crystallographically developed. The quartz crystals generally contain one or more nuclear clastic grains of quartz, which are small and well rounded. Around these grains a very thin film of brine is found. The film becomes visible when frozen and it splits up into vermicular branching inclusions of fluid and gas at room temperature. The characteristics mentioned are valid for quartz in both the Na1 and the Na2 salt.

The Fluid Inclusions

Two types of inclusions are found: isolated regular ones (negative crystals) and families of very thin irregular inclusions situated on an *m*, *r* or *z* crystallographic interface (Figure 5). The irregular inclusions are by far the most common. All the inclusions studied are primary (Roedder, 1976, 1979). Secondary inclusions are extremely rare.

The inclusions usually contain a fluid phase and a gas phase. Also in very few inclusions one or two daughter minerals are present (Figure 5). The daughter minerals are halite and rarely sylvite.

Quartz Crystals from Other Stratigraphic Levels

The Na2(K) salt has been sampled from the Mors E1 well at a drilled depth of 2715 m. The salt, which is

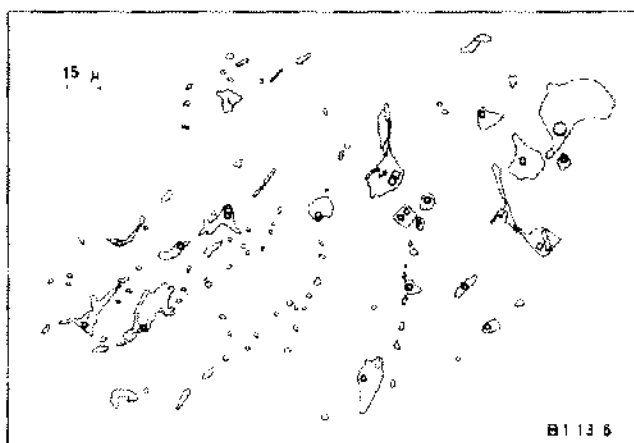


Figure 5. Irregular thin fluid inclusions containing liquid, gas and a thin "cube" of halite in some of the inclusions. The inclusion family is situated on an *m* interface approx. 100 μm below the crystal face.

potassic and strongly kieseritic (hardsalt), is devoid of quartz crystals.

The potassium zone K2 and the "deckrocksalt" Na2r were studied in the Mors E1 well from drilled depths of 2800 m and 2883 m. The quartz crystals in this zone are all long prismatic (type VI) crystals. The crystal faces are practically all developed with a tight mosaic structure, which rarely allows any microthermometrical measurements. The number of crystals is very large compared to other lithostratigraphical units. The salt clay T3 of the Tostrup 4 well from a depth of 525 m is correlated with the clay at 2802 m in the E1 well. The correlation is based upon the content and type of quartz crystals, the large number of well developed small pyrite octahedrons and of perfectly developed small brownish rhombohedrons of a carbonate mineral. The quartz crystals are identical with the above mentioned, with exception of a red-coloured patchy coating on several of the crystals.

The Na3 salt, taken from the Tostrup 4 well at a depth of 1012 m is very deficient in quartz crystals, and these few are of the same types as found in the Na1 and Na2 salt. These crystals have not been studied.

Crymometry on Quartz Inclusions

None of the inclusions in quartz crystals from K2, Na2r and T3 nucleated ice or hydrate during the freezing procedure, though the temperature was held below -125°C for long periods. Many of the inclusions in the crystals from Na1 and Na2 acted in the same manner, especially the smaller ones. But some of the larger inclusions with a length of more than $10\text{ }\mu\text{m}$ nucleated either hydrate alone or ice plus hydrate during the freezing period.

Using the phase diagrams (Figure 2) combined with the other diagrams of Janat'eva (1946) and Luznaja and Verescetina (1946) the salinity and the Ca:Mg ratio is determined. As it is known that the brine under all conditions must be saturated with respect to NaCl, the melting point of $\text{MgCl}_2 \cdot 12\text{H}_2\text{O}$ on the freezing point depression curve of the phase diagrams (Figure 2) can be used in determining the Ca:Mg ratio. The melting point of $\text{MgCl}_2 \cdot 12\text{H}_2\text{O}$ is established when much brine suddenly is released after melting of the ice, if any. The salinity is determined by using the melting point of the CaCl_2 -hydrate on the freezing point depression curve, assuming that no halite crystal is present.

If a halite crystal is present the determination of the true salinity is too low due to the lack of isotherms in the NaCl-field of the diagrams. Using the isotherms at the CaCl_2 -NaCl- $2\text{H}_2\text{O}$ diagram a rather inaccurate estimate of the NaCl content can be established. The results of the cryometry study are shown in Figure 6 in the column headed SALINITY.

Thermometry on Quartz Inclusions

The homogenization temperature T_h corresponds to the disappearance of the gas phase, also if the inclusion con-

tains a solid phase (a daughter mineral) at T_h . Homogenization temperatures of various stratigraphical levels are illustrated in Figure 6. The mean T_h is indicated by the black triangle and the spread of the T_h values is illustrated.

The two histograms in the column DISTRIB. T_h show the distribution of the homogenization temperatures measured in Zechstein 1 and Zechstein 2, respectively. The mean temperature \bar{T}_h with 5% confidence limits and the standard deviation σ are noted. Five crystals only contain inclusions with halite cubes, which dissolve at a higher temperature T_i than the corresponding T_h (see the column CRYSTALLIZATION CONDITIONS). Based upon the difference $T_i - T_h$ the pressure P has been calculated by the method of Potter (1977).

In order to compare the results obtained on inclusions in halite with the corresponding inclusions in quartz crystals, the crystals were extracted from the rocksalt in question (Mors E1.19) Two populations of T_h were observed:

$$\begin{aligned} 35^{\circ}\text{C}-68^{\circ}\text{C}; \bar{T}_h &= 51.2^{\circ}\text{C} \pm 3.5^{\circ}\text{C}; n = 32 \\ 70^{\circ}\text{C}-105^{\circ}\text{C}; \bar{T}_h &= 87.8^{\circ}\text{C} \pm 2.7^{\circ}\text{C}; n = 42. \end{aligned}$$

DISCUSSION

In 1948 the Suldrup 8 well was drilled through Na1 salt, A1, Ca2 and Na2 salt. In a depth of 408 m, when the A1 anhydrite was reached, a brine pocket was hit, resulting in an artesian well. According to Dinesen (1961) the brine had the following composition (weight%): Salinity, 31%; NaCl, 3.95%; KCl, 3.55%; CaCl_2 , 15.15%; MgCl_2 , 8.10%; Ca:Mg ratio, 1.9:1; pH, 3.18 (20°C). The salinities and the composition of the brines measured in the present study are in good agreement with this. However, the Suldrup 8 brine has a higher Ca:Mg ratio, which corresponds fairly well with the samples Nos. 8.4 and 8.9 close to the A1 layer (Figure 6, SALINITY). The brines trapped in the quartz crystals and in the halite as well must be concentrated seawater with no contamination of foreign brines (Figure 7).

In practically all the samples of Na2 and in the majority of the samples of Na1 from Batum 1A, small grains or perfect crystals of authigenic kieserite were found in various quantities from one grain to more than fifty grains/crystals. This observation indicates a seawater concentration within NaCl facies ranging into Mg,K facies (Figure 7). Some few inclusions with a cube of NaCl also have a cube of KCl.

The solubility of NaCl in a CaCl_2 - MgCl_2 brine increases rather strongly at temperatures above about 100°C (Stewart and Potter, 1979). As the *in situ* brine, from which the quartz crystals have been precipitated, must be saturated with respect to NaCl, the dissolving temperature T_s , higher than T_h , of a cube of NaCl present in the inclusion is the true trapping temperature T_t .

Knowing T_i and T_h , the pressure prevailing on the brine *in situ* during the crystallization can be calculated, if the salinity is established. Using the diagrams of Potter (1977)

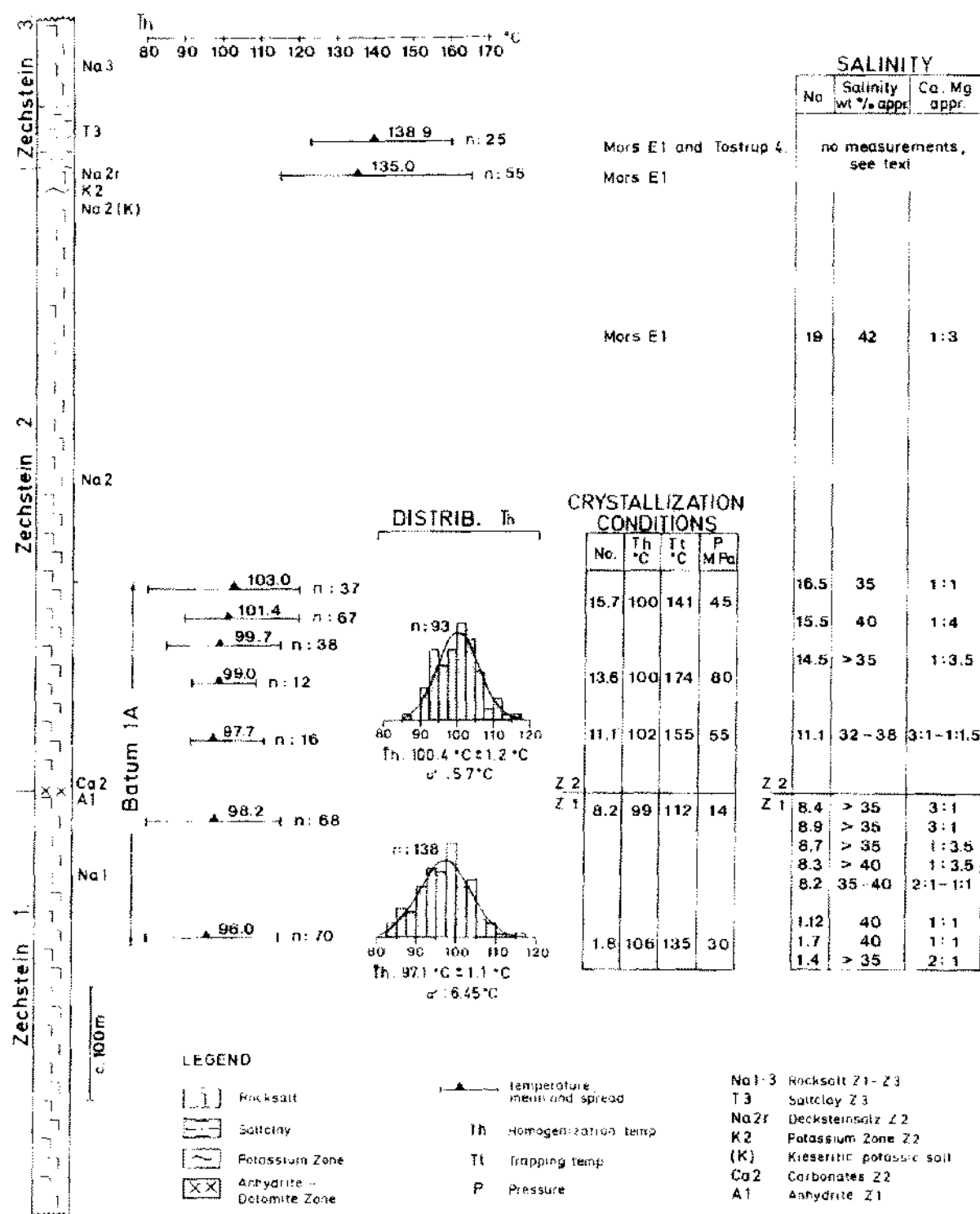


Figure 6. The three Zechstein evaporite cycles in North Jutland and the results of the microthermometrical study.

and salinity of 35 wt%, a factor of 1 MPa per °C above T_h is estimated. The mean $T_t = 175^\circ\text{C}$ corresponding to the pressure $P = 80$ MPa were the crystallization conditions, when the quartz crystal No. 13.6 precipitated (Figure 6). A pressure of 80 MPa corresponds to c.3.5 km consolidated sediments having an average density of 2.3 g/cc. The cor-

responding geothermal gradient is approximately 20 m per °C.

In Early Jurassic times the sedimentary sequence above this particular crystal included 600-700 m Z2 and Z3 salt and saltclay (Figure 6) followed by 3500-3800 m consolidated and unconsolidated sand and clay of Triassic

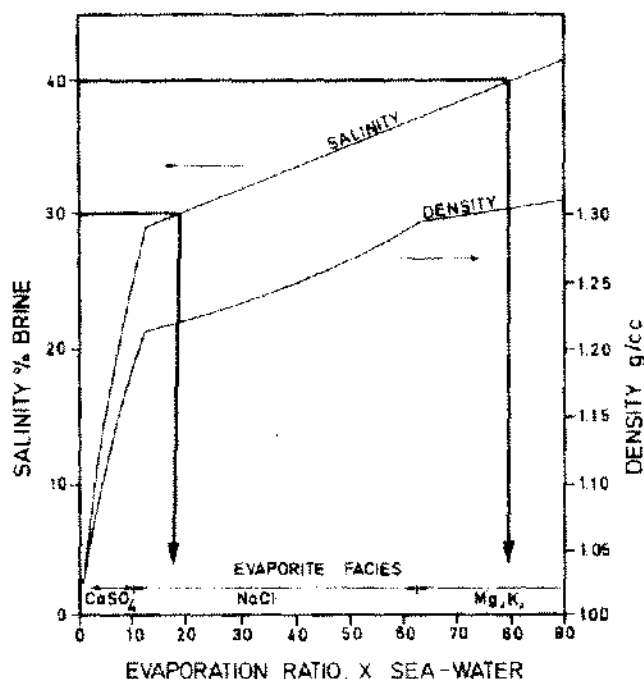


Figure 7. Density and salinity of concentrated seawater. The approximate limits of salinity, this study, are given. After Holser (1979).

and Jurassic age (Michelsen *et al.*, 1981). Due to the high thermal conductivity of salt, the geothermal gradient is supposed to be higher in the salt than in the sandy and clayey sediments.

The quartz crystal in question is proposed to have been precipitated in Early Jurassic, outside or inside the salt pillow developed. The crystal is not authigenic, i.e., a synsedimentary or diagenetic crystallization, but formed 35–45 million years later than the diagenesis of the Na2 salt. The diagenetic stage is here taken to equvalate conditions of low temperature and low pressure, (Braitsch, 1971).

The majority of the inclusions studied having T_h higher than about 100°C contain no cube of NaCl at 20°C. Keeping in mind that the inclusion brines are saturated with respect to NaCl, this discrepancy can be explained either by a certain metastability or by a small fluid volume. Compared with the quartz crystal No. 8.2 (Figure 6) it is presumed that the pressure correction added to T_h in order to obtain T_i is of the order of magnitude of 10–12°C. All of the crystals studied, except some of the crystals of Mors E1.19, are crystallized much later than the diagenesis, i.e., they are not authigenic. The Mors E1.19 crystals with the T_h interval 35°C–68°C may be of diagenetic origin and due to this they are true authigenic crystals. The T_h interval 28.5°C–124.8°C measured at inclusions in the halite coincide very well with the corresponding intervals measured at the Mors E1.19 quartz crystals.

In Figure 6, it is seen that the mean T_h values in Batum

1A are increasing slightly from Na1 up through Na2. It is believed that this trend has no stratigraphical significance, because the temperature differences are small and the temperatures are not pressure corrected. The differences may be due to statistical inadequacy.

The high T_h values measured in Na2r and T3 indicate a late crystallization and the large number of crystals make it probable that the crystallization happened after the compaction of the saltclay. The porewater (concentrated seawater) of the clay must have been involved in the formation of the quartz crystals. These T_h values are of stratigraphic significance.

The T_h , T_i and P values for crystal No. 13.6 (Figure 6) are mean values of six observations. The maximum T_i measured is 179.7°C, which combined with the corresponding $T_h = 92.3^\circ\text{C}$, indicate a maximum pressure $P = 87$ MPa. This pressure corresponds to a post-Zechstein overburden more than 3800 m.

According to Talbot (1978) and Talbot *et al.* (1982) these conditions may cause thermal convection in the salt pillow instead of thermal conduction. An estimate of the Rayleigh number R , using the parameters mentioned, gives a value well above the critical $R_c = 656$, indicating thermal convection. The diapiric penetration phase may have been triggered by these conditions.

The crystal morphologies (Figure 3) probably do not represent a growth series in the salt studied. The reason is that no ghost crystals or thermal zonation within the crystals have been found. Large type III crystals are found in connection with very small type VI crystals. Twins consist always of the same type as do intergrown crystal aggregates.

CONCLUSION

Fluid inclusion studies in halite are impeded by the physical and chemical conditions of halite. The results obtained are fairly inaccurate and they give a tendency only. The majority of the quartz crystals found in the Zechstein 1 and 2 salt are not authigenic *sensu stricto*, but they may have crystallized millions of years later than the diagenesis of the salt. The crystals have no stratigraphic significance. A growth series of the crystals from a pseudocubic type to a long prismatic type is believed not to exist. The fluid inclusion work performed upon the quartz crystals has shown that the crystallization took place in highly concentrated seawater at temperatures between approximately 75°C and 180°C. The salinity ranges from 30 to more than 40 weight% salt composed of CaCl_2 , MgCl_2 and less than 2 weight% NaCl. The CaCl_2 : MgCl_2 ratio ranges from 3:1 to 1:4. The mean homogenization temperatures show an increase from the lowest level studied in Zechstein 1 to the highest level studied in Zechstein 2. The obvious stratigraphical significance is believed to be invalid due to statistical inadequacy.

The maximum pressure calculated (87 MPa) in connection with the maximum formation temperature (179.7°C) indicates thermal convection in the salt pillow phase. These conditions may have initiated the diapiric penetration phase in Early Jurassic times.

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REFERENCES

- Braitsch, O. 1971. *Salt Deposits, Their Origin and Composition*. 297 p. Springer-Verlag, Berlin, Heidelberg, New York.
- Demangeon, P. 1966. A propos des quartz authigènes des terrains salifères: *Bull. Soc. franc. Minér. Crist.*, v. 89, p. 484-487.
- Dinesen, B. 1961. Salt Mineralvand fra Danmarks dybere Undergrund: DGU. IV. Række. Bd.4.Nr.6. 20 p.
- Dreyer, R. M., R. M. Garrets, and A. L. Howland, 1949. Liquid inclusions in halite as a guide to geologic thermometry: *Am. Min.*, v. 34, p. 26-34.
- Gerlach, H. and S. Heller. 1966. Über Künstliche Flüssigkeitseinschlüsse in Steinsalzkristallen: *Ber. Deutsch. Ges. Geol. Wiss. B. Miner. Lagerstättenf.*, v. 11.2, p. 195-214.
- Grimm, W.-D. 1962. Idiomorphe Quarze als Leitminerale für salinare Fazies: *Erdöl und Kohle.*, v. 11, p. 880-887.
- Holser, W. T. 1979. Mineralogy of Evaporites: Marine Minerals, Mineralogical Society of America, In: *Short Course Notes*, Burns, R. B. (ed.), 380 p.
- Janat'eva, O. K. 1946. Polytherms of solubility of salts in the tropic system $\text{CaCl}_2 - \text{MgCl}_2 - \text{H}_2\text{O}$ and $\text{CaCl}_2 - \text{NaCl} - \text{H}_2\text{O}$: *Jour. Appl. Chem.* v. 19, p. 709-722. (in Russian).
- Jenks, G. H. 1979. Effects of temperature, temperature gradients stress and irradiation on migration of brine inclusions in a Salt repository: ORNL-5526, 73 p.
- Luznaja, N. P. and I. P. Verescetina. 1946. Sodium, calcium and magnesium chlorides in aqueous solutions of -57 to +25 (polythermic solubility): *Jour. Appl. Chem.* v. 19, p. 723-733. (in Russian).
- Michelsen, O. et al. 1981. Kortlægning af potentielle geotermiske reservoirer i Danmark: *Geol. Surv. Denmark. Series B*, No. 5, 96 p.
- Nachsel, G. 1966. Quarz als Faziesindikator: *Zeitschr. angew. Geol.* v. 12, 6, p. 322-326.
- Potter II, R. W. 1977. Pressure corrections for fluid-inclusion homogenization temperatures based on the volumetric properties of the system $\text{NaCl} - \text{H}_2\text{O}$: *Jour. Research U.S. Geol. Survey.* v. 5, No. 5, p. 603-607.
- Powers, D. W., S. J. Lambert, S.-E. Shaffer, L. R. Hill and W. D. Weart. 1978. Geological characterization report: Waste Isolation Pilot Plant (WIPP) site, Southeastern New Mexico. Chap. 7.5 p. 7.47-7.70.
- Richter-Bernburg, G. 1960. *Geologischer Bericht über Ergebnis der Bisherigen und Planung der weiteren Exploration auf Kalisalze in Nord-Jütland: Kaliboringerne ved Suldrup 1959-1961*, v. 1, 175 p. Rapport, udarbejdet af Egnsudviklingsrådets Boreudvalg. København 1962.
- _____. 1981. Geological remarks about the North Jutland salt domes in respect of their suitability for radioactive waste disposal. Unpublished report. ELSAM & ELKRAFT, Denmark.
- Roedder, E. 1963. Studies of fluid inclusions II: Freezing data and their interpretation: *Econ. Geol.* v. 58, No. 2, p. 167-211.
- _____. 1976. Fluid-inclusion evidence on the genesis of ores in sedimentary and volcanic rocks: *Handbook of strata-bound and stratiform Ore Deposits* (Wolf, K. H. ed.), v. 2, p. 67-110. Elsevier, Oxford.
- _____. 1979. Fluid-inclusions as samples of ore fluids: *Geochemistry of hydrothermal ore deposits*. 798 pp. John Wiley & Sons.
- _____. and H. E. Belkin. 1979a. Application of studies of fluid inclusions in Permian Salado Salt, New Mexico, to problems of siting the Waste Isolation Pilot Plant: *Scientific Basis for Nuclear Waste Management*, v. 1, p. 313-321. Plenum Press.
- _____. 1979. Fluid-inclusions in salt from the Rayburn and Vacherie domes, Louisiana: *U.S. Geological Survey Open File Report 79-1675*, 25 p.
- Shettler, H. 1972. The stratigraphical significance of idiomorphic quartz crystals in the saline formations of the Weser-Ems area, North-Western Germany: *Geology of saline deposits. Proc. Hannover Symp.* 1968. UNESCO, 1972. *Earth Sciences*, v. 7, p. 111-127.
- Stewart, D. B. and R. W. Potter. 1979. Application of physical chemistry of fluids in rock salt at elevated temperature and pressure to repositories for radioactive waste: *Scientific basis for Nuclear Waste Management* v. 1, p. 297-311. Plenum Press.
- Talbot, C. J. 1978. Halokinesis and thermal convection: *Nature*, v. 273, No. 5665, p. 739-741.
- _____. Tully, C. P. and P. J. E. Woods. 1982. The structural geology of Boulby (Potash) mine, Cleveland, United Kingdom: *Tectonophysics*, v. 85, p. 167-204.
- Tarr, W. A. 1929. Doubly terminated quartz crystals occurring in gypsum: *Jour. Min. Soc. Am.* v. 14, p. 19-25.