

Structural Studies of a Danish Salt Dome Optimize Construction of Six Gas Storage Caverns

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ABSTRACT

A total of 11 deep wells have been drilled for gas storage purposes in the Tostrup salt dome in Denmark. The dome is structurally and compositionally complicated and layers of K, Mg-salt, clay, anhydrite and dolomite occur in large isoclinal folds in the upper part of the dome. Six storage caverns have been completed up to the present. The total storage volume is 2.8×10^6 m³. About 15 drill cores, half of them oriented, were cut in each well. The cores formed the basis for a detailed stratigraphic and structural analysis of the upper part of the dome. The structural model was developed step-wise during the successive exploration stages, and this enabled optimal positioning of the new wells with respect to prediction of the rock salt distribution at cavern depths. In cases where K, Mg-salt or anhydrite-dolomite was encountered during leaching of the cavities, it was possible to modify the leaching strategy on the basis of the structural model and thereby complete all the scheduled caverns successfully.

INTRODUCTION

The Danish salt dome province is situated within the Danish-Norwegian Basin, which in turn forms part of the Northern Permian Basin in Europe (Fig. 1). A total of 38 deep wells were drilled within the salt dome province in the period from 1946 to 1952. The wells were drilled by the Danish American Prospecting Co. as a part of a regional investigation of the potential for hydrocarbons and for rock salt within the Danish area. Information from these wells and from 4 subsequent wells, drilled for potassium salts during 1959-1961, made it possible to establish the stratigraphy of the Zechstein in the Danish part of the Permian Basin (Table 1: see Jacobsen, 1984). Wells drilled between 1966 and 1981 in the Central Graben in the North Sea and in the North German salt dome province subsequently formed the basis for regional correlations, and a revised stratigraphic model was developed to conform with the North German Zechstein stratigraphy (Michelsen, 1982).

In 1979, the Danish Government decided to introduce natural gas from the North Sea as a major domestic energy source. A transmission system was constructed onshore and linked with the gas fields in

the North Sea and with the German gas net. A gas storage facility was to be created in one of the salt domes. The Tostrup dome in North Jutland was selected for the cavern field (Figs. 1 and 2) as this dome was already deemed suitable on the basis of two deep wells, TO-1 and TO-2, from the early drilling period. These wells were followed by 9 more wells in the period up to 1987 (Petersen, 1986), and in six of these, TO-5, TO-6, TO-7, TO-8, TO-9 and TO-10, gas storage caverns have now been completed. The leaching of a seventh cavern is presently being planned. The stepwise expansion of the storage field, along with the sequential positioning of the wells, enabled the greatest possible flexibility during the exploration phase. This was necessary in order to take full advantage of the geological and structural information from each successive well within the structurally complex framework of the salt dome. The structural data and their evaluation are presented below.

DATA ACQUISITION

Approximately 15 conventional cores were cut in each well. Every second core was oriented and, by careful coring, recovery rates of close to 100% were

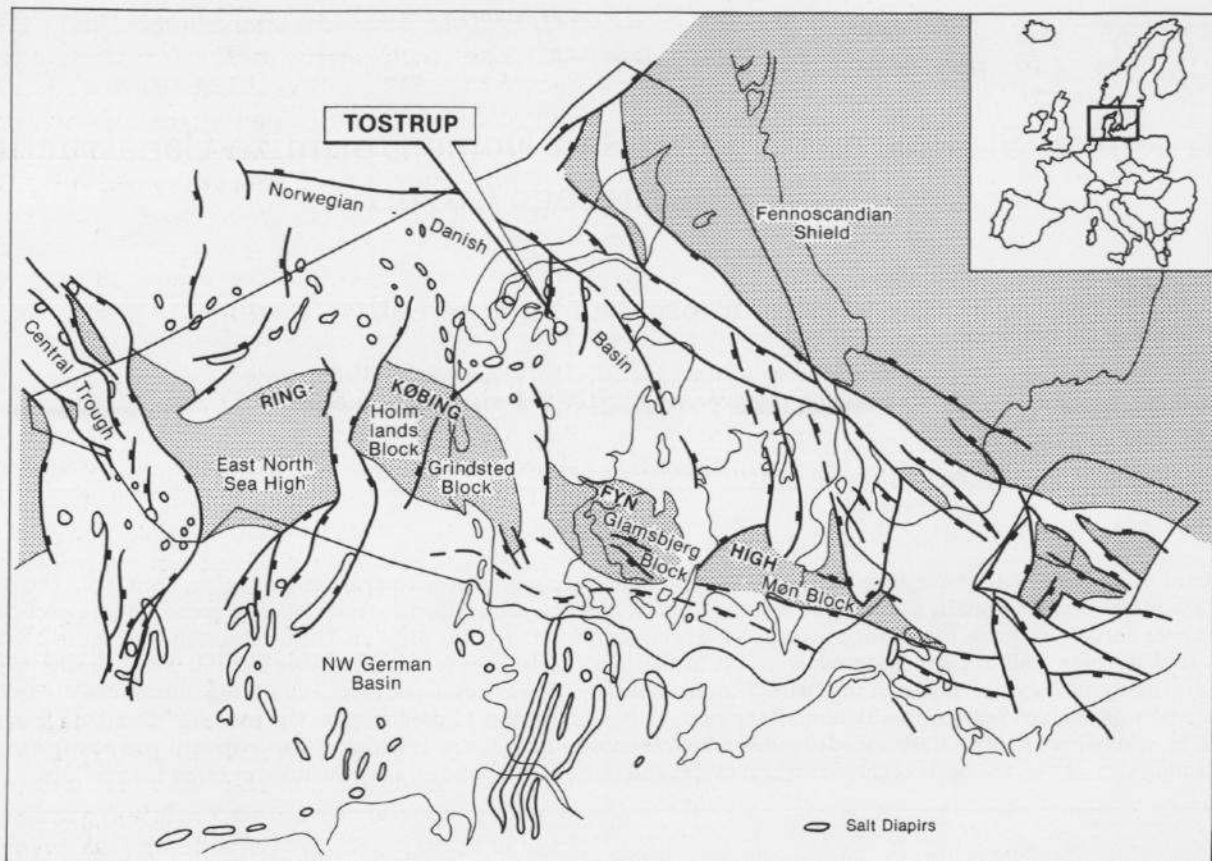


Fig. 1. Location of the Tostrup Salt Dome and the major structural elements in Denmark.

TABLE 1

Stratigraphy of the Zechstein in the Norwegian–Danish Basin

Cycle, symbol	Thickness (m)	Lithology
Z4 Na4	20	Rock salt, light grey to orange
T4	30–40	Salt clay, silty olive brown to greyish black
Z3 Na3	C. 100	Rock salt, reddish varicoloured with two thin K-Mg-beds and one thin bed of anhydrite
T3	60	Salt clay, silty, red to green to greenish black
Z2 Na2r	15	Deck halite, silty brownish with K-Mg-salt
K2	10	Hard salt, kieseritic, Veggerby Potash zone
Na2(K)	20	Rock salt, kieseritic and potassic, orange
Na2	C. 600	Rock salt, anhydritic, light to medium grey
A2	4	Anhydrite with flaser texture
Ca2	10	Dolomite, light to dark brown
T2	0.2	Shale, brownish black
Z1 A1r	1	Anhydrite, compact, bluish grey
Na1	C. 400	Rock salt, anhydritic, light to medium grey

In this paper Ca2A2 is used as joint designation for rock sequence A1r, T2, Ca2 and A2. The index of the cycles and symbols are from Richter–Bernburg (1953).

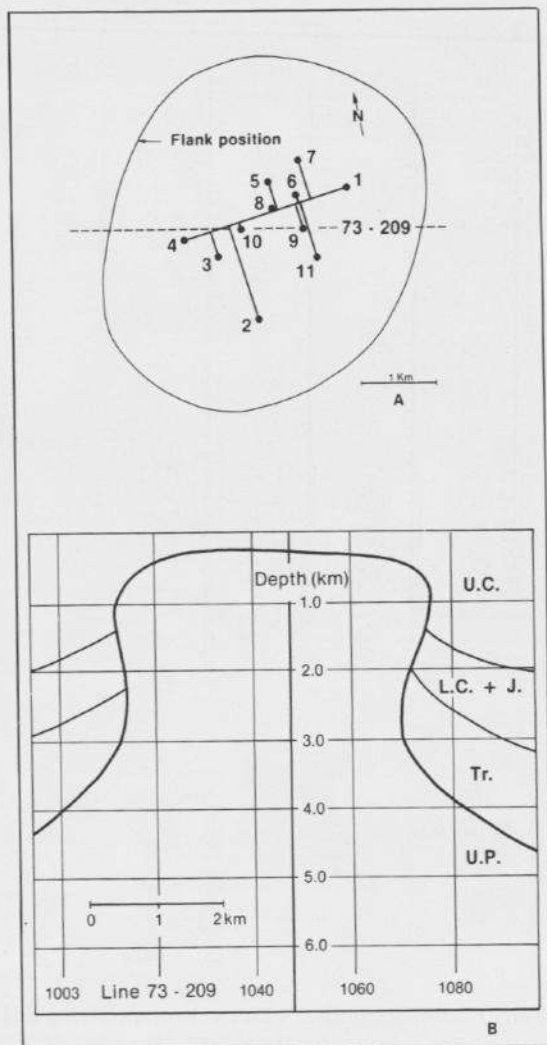


Fig. 2. Tostrup Salt Dome. A. Distribution of wells in the Tostrup Dome. The flank position corresponds to a depth of 1500 m below mean sea level. The wells are shown only with their series TO numbers. B. Cross section along the seismic line 73-209. U.C.: Upper Cretaceous; L.C.+J.: Lower Cretaceous and Jurassic; Tr.: Triassic; U.P.: Upper Permian.

obtained for all cores. Immediately after recovery and cleaning, all cores were photographed, the orientation of foliations and grain fabric were marked and recorded, and the cores were described and sampled for chemical analysis, rock mechanical analysis and leaching tests. The core data are shown in Fig. 3. The vertical distance between the cores at cavern level (1100–1500 m below mean sea level) was normally 50 m. From the top of the salt to the top of the caverns (300–1100 m below mean sea level) the cores were cut with a spacing of about 150 m.

RESULTS AND EVALUATION

The results of the structural measurements on each core are presented in Fig. 3. The orientation of both the foliation and the bedding was recorded relative to the azimuth of fiducial groove marks in the cores. Occasionally distorted or twisted groove marks had to be corrected for. No corrections for borehole deviation were applied as the deviation was usually less than 1.5 degree. The azimuth core ring and the attached clinometer used in these measurements are shown in Fig. 4. Typically, a foliation could be measured and the basic assumption was that the foliation represents the latest plastic deformation of the salt. When bedding was present in addition to the foliation, they frequently appeared to be parallel or subparallel. This is probably due to the fact that differences in competence between individual beds govern the flow pattern and the strain rates of the salt during halokinesis. It is in agreement with the observations of Talbot (1979) who described how bedding planes rotate into parallelism with the foliation planes during continuous flow in a salt glacier.

The bedding planes in the cores were made visible by colour variation in the salt enhanced by inter-layered impurities. For each core, the foliation

TABLE 2

Typical analyses of salt at the cavern level in TO-6 given in percentages

TO-6 depth mbrt*	Chemical analyses									Major minerals (calculated)		
	Na	K	Ca	Mg	Cl	SO ₄	Insol	H ₂ O	Sum	NaCl	CaSO ₄	Insol
1156.8	38.0	0.01	0.50	0.00	59.8	1.24	0.15	0.03	99.7	98.1	1.7	0.2
1212.1	37.0	0.01	1.28	0.00	58.6	3.22	0.10	0.15	100.4	95.5	4.4	0.1
1269.7	38.0	0.01	0.26	0.00	60.6	0.63	0.11	0.05	99.7	99.0	0.9	0.1
1338.5	39.0	0.01	0.63	0.00	59.6	1.07	0.09	0.00	100.4	98.4	1.5	0.1
1380.2	38.0	0.01	0.95	0.01	59.3	2.10	0.14	0.00	100.5	96.9	3.0	0.1
1461.8	38.0	0.01	0.63	0.00	59.7	1.46	0.14	0.05	100.5	97.8	2.1	0.1

*mbrt = m below drilling rotary table.

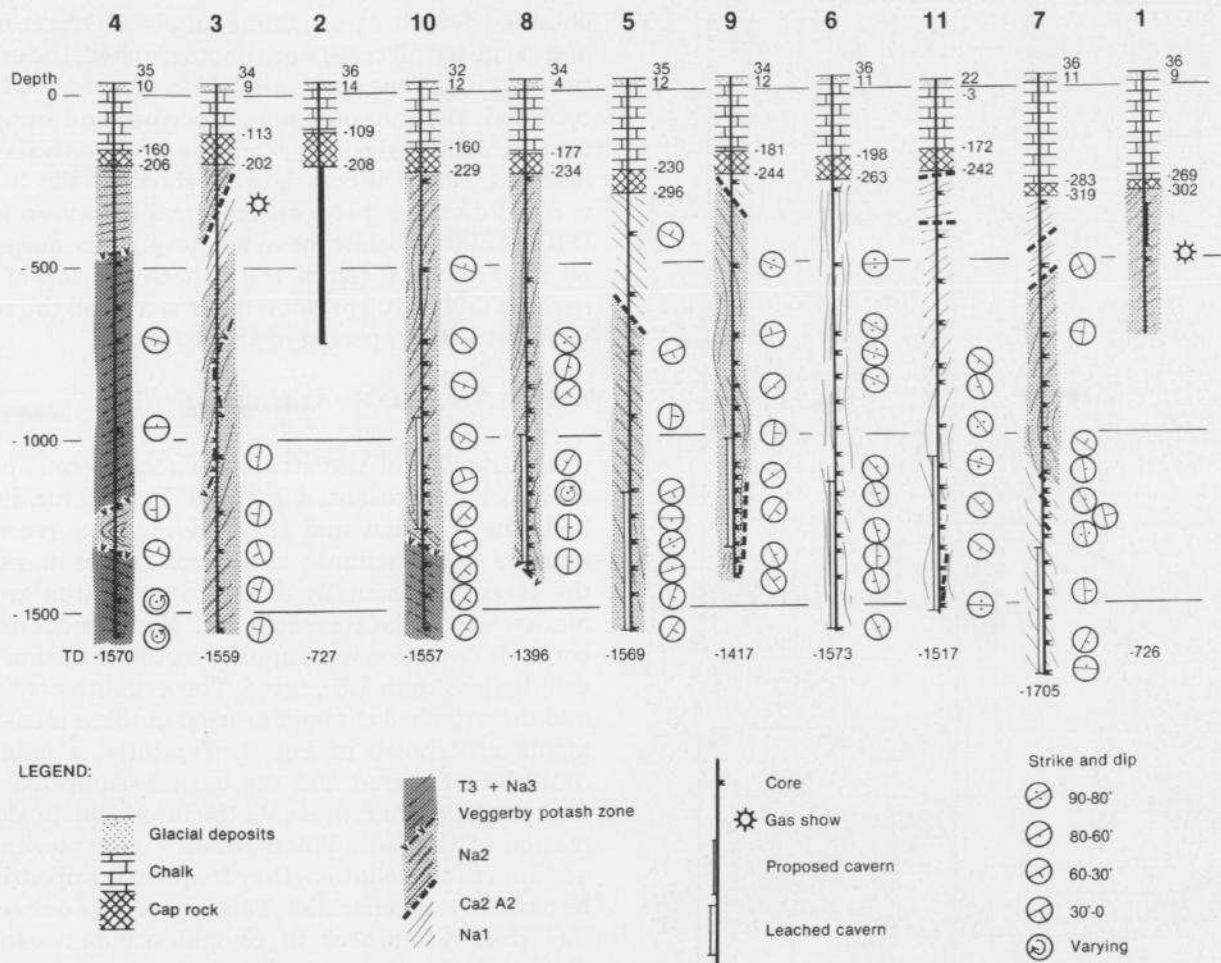


Fig. 3. Profile of the eleven Tostrup wells. The stratigraphy and composition are shown together with the average strike and dip of the foliation seen in the cores. Well locations are shown on Fig. 2. Mean sea level is datum for the wells.

planes and their poles were plotted on a Wulff stereographic net (lower hemisphere). The core orientations were subsequently combined vertically for each well (Fig. 5) and horizontally (Fig. 6) in selected depth slices. This enabled 3-dimensional control of the fold axes within the salt volume lying between the base of the wells and the base of the cap rock. Figure 7 shows how insight into the structure of the dome developed during the drilling campaign.

After completing TO-5, it became clear that the potassium salts from the Veggerby potassium zone (K2) were found towards the west, whereas the stratigraphically older rocksalts, Na2 and Na1 were to be found further to the east at cavern depth. Consequently, the suggestion was made to locate the subsequent wells towards the east. The Veggerby potassium zone has a high content of sylvite, kieserite and carnallite. Compared with the halite, these K, Mg-salts are highly soluble, and, if present within the projected cavern volume, the leaching process becomes difficult to control.

In addition to the Veggerby potassium salts (K2), the presence of the anhydrite-dolomite sequence (Ca2A2) between the Na1 and Na2 rocksalt will influence and possibly prevent the leaching of a regular cavern. The anhydrite-dolomite zone, which on average is 15 m thick, is almost insoluble. It has a much higher rock mechanical competence than the surrounding salt and, as a result, the zone will be boudinaged where the salt was folded during the diapiric stage. If situated within the cavern interval, such blocks might be released from the cavern walls during leaching and may damage the leaching string when sinking through the leaching brine.

As regards the composition of the salt, this was determined by a large number of chemical analyses of the cored salt, which together with the rock mechanical analyses and dissolution tests, constituted critical data for the solution model applied in the cavern leaching project (Kavernen Bau- und Betrieb-GmbH, KBB solution mining model). During the leaching period, the composition of the brine from

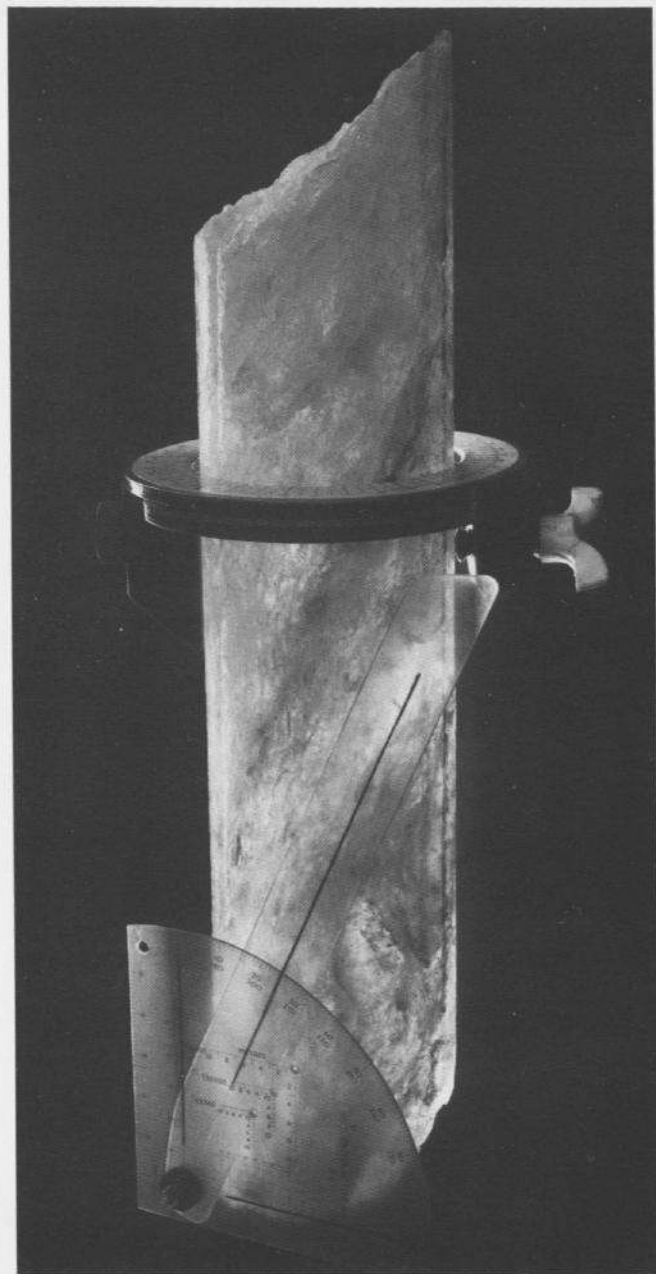


Fig. 4. Core of rock salt showing the strike and dip measuring device. The 360° azimuth scale ring is placed in relation to the azimuth of the groove marks engraved during the coring process. The dip of the foliation relative to the side of the core is recorded by the clinometer. Well TO-11, core no. 12,, 1365.36–1365.76 m below drilling rotary table.

each cavern was analyzed daily. Typical chemical data are shown in Table 2.

The final structural model of the dome, encompassing the cavern field and the salt volume around the caverns, is illustrated in Fig. 8. A major anticline opening to the south with a east south-easterly plunging fold axis is seen in the eastern part of the cavern field. The change in the direction of the axis

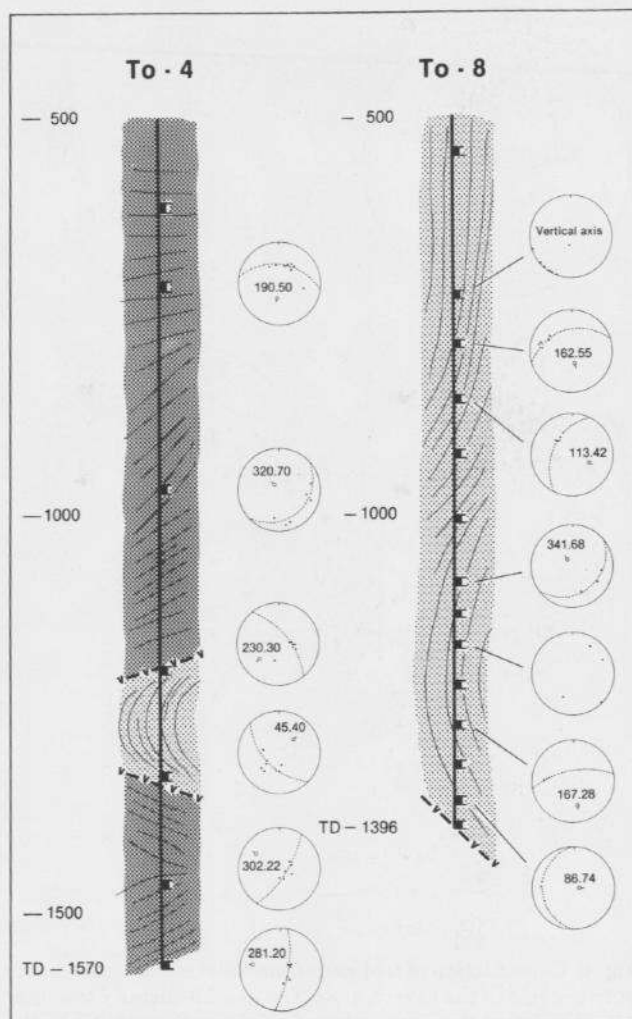


Fig. 5. Examples of the use of Wulff's net analyses on vertical sections in TO-4 and TO-8. The stereographic projections show the foliation and the constructed fold axes in Z3 salt at TO-4 and in Z2 salt at TO-8.

and its plunge is shown in Fig. 6. Towards the west, the anticline is followed by a syncline which, in its core, contains salt-clays from the Z3 evaporation cycle.

CASE HISTORIES

The structural model was applied in resolving leaching complications during the development of the cavern field. Three different leaching situations are presented below i.e. for TO-6, TO-8 and TO-9. A technical review of the construction of these caverns is presented by Quast (1986).

TO-6 is located in the anticline core where there is a steeply dipping axial plane (Fig. 8). The cavern was leached in Na1 salt (Z1 evaporation cycle) and developed into a perfectly circular sectioned cavity

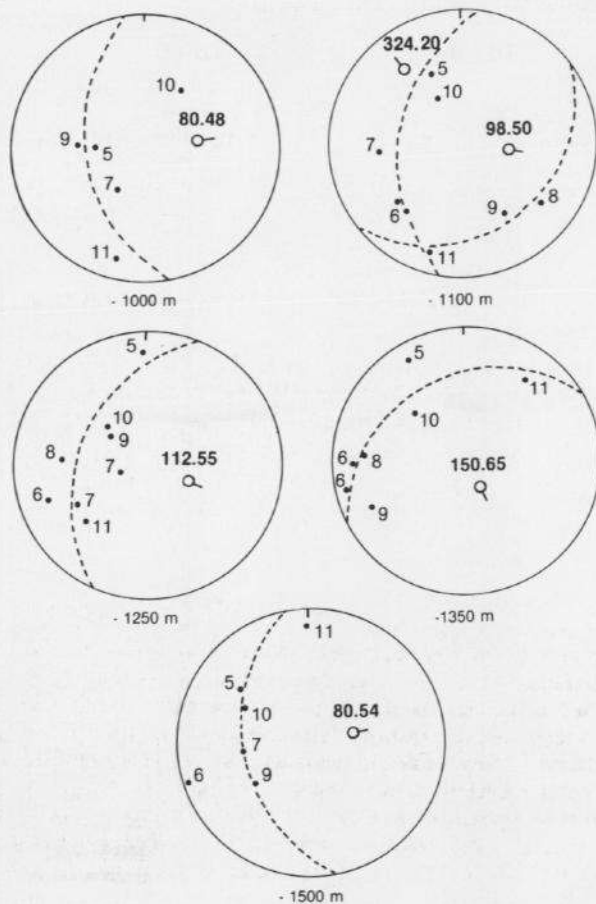


Fig. 6. Construction of fold axes from foliation measurements at five levels in the cavern area. The overall easterly to south-easterly dip of the axes is noted. The numbers refer to the individual wells (e.g. 11) and to the direction and dip of the fold axes (e.g. 80.48).

with a diameter of 55 m and a height of 429 m, corresponding to a cavern volume of $520,000 \text{ m}^3$ (Fig. 9). It is currently one of the largest gas storage caverns in Europe.

TO-8 is situated in Na2 salt (Z2 evaporation cycle) in the overturned flank between the anticline and the syncline (Figs. 5 and 8). Here, the foliation strikes N-S and dips 70 degrees towards the east. The TO-8 well initially intersected the Veggerby potassium zone at its base, so prior to the onset of leaching, it was decided to locate the cavern floor about 30 m above the top of the potassium zone. It was realized that there was a risk of leaching into tectonized potassium-bearing salt at a higher level on the western flank of the cavern. The composition of the discharged solution brine was continuously monitored during leaching, and an increase in the K and Mg concentration was in fact observed after 80 days (Fig. 10). After a sonar survey had proved an excess diameter on the western side of the cavern, the shoe of the leaching string was raised 21 m and indirect leaching was adopted, i.e. inflow of fresh water at the top of the cavity and outflow at the new level of the string. The anomalous K, Mg-levels persisted and after a period of 306 days, a new sonar survey showed that it was necessary to raise the leaching string an additional 33 m. Thereafter, sedimentation of released impurities of anhydrite gradually sealed the potassium salt which had been exposed below. With time, the K, Mg-content of the brine decreased to the level, expected for the Z2 halite (Fig. 10). No additional potassium zones were met during leaching at higher levels, and the TO-8 cavern was completed with a final volume of $460,000 \text{ m}^3$.

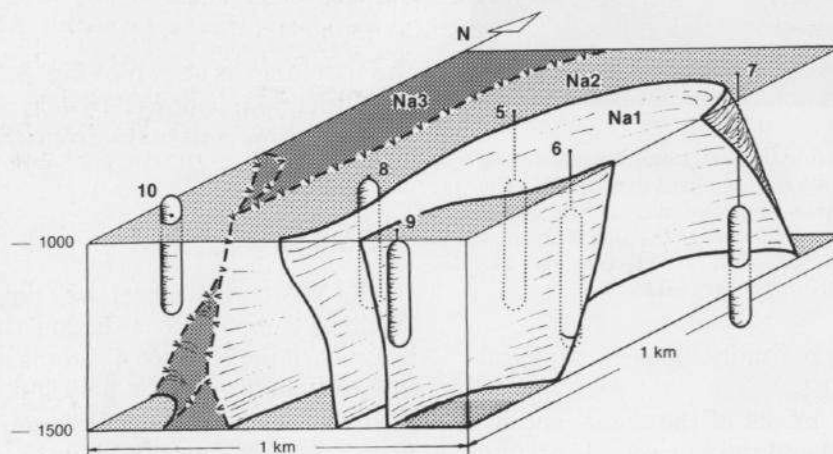


Fig. 8. Structural model of the cavern area. The anticline to the east (refer to Fig. 7) encompasses Na1 and cavern no. 6 in its core. The anticline is bounded to the west by a syncline with a steeply dipping axial plane. The TO-10 cavern to the south-west is situated in an anticline of Na2 salt. The entry point of the cavern or the wells into the block diagram is marked with a dot.

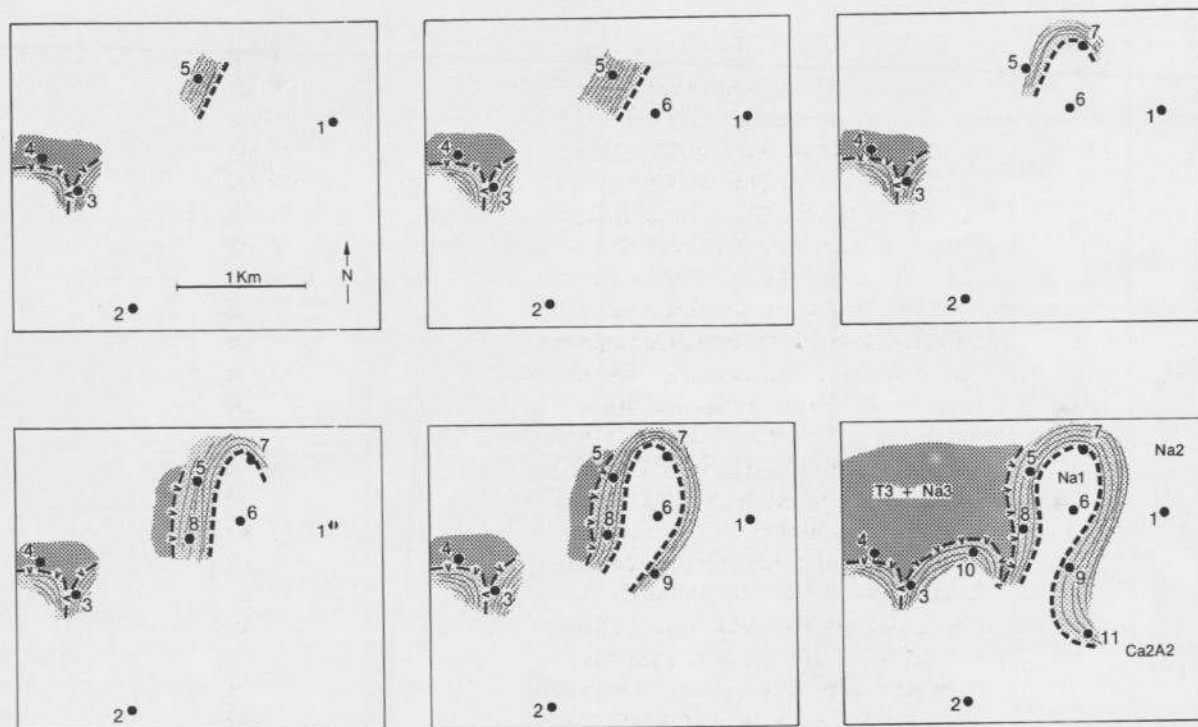


Fig. 7. The development of the geological model based on the structural analyses of the new wells (cavern level -1250 m).

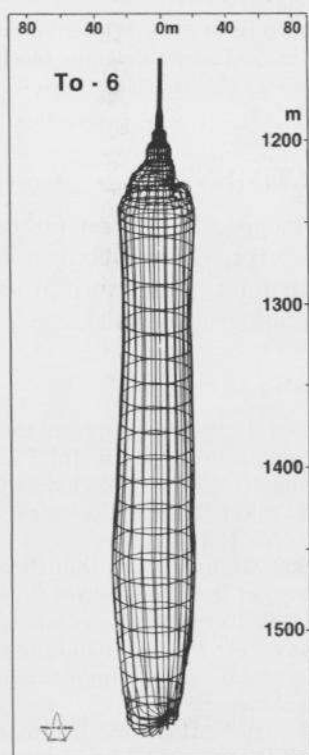


Fig. 9. 3-Dimensional representation of the results of the sonar survey of the completed TO-6 cavern. The cavern was leached in Na1 and is extremely regular.

TO-9 is situated in Na2 salt at the eastern flank of the central anticline not far from the trend of the anhydrite-dolomite zone (Ca2A2) (Fig. 7). One of the regular sonar surveys, performed during the leaching period, showed the presence of a large block protruding from the eastern wall of the cavern (Fig. 11). The risk of encountering anhydrite-dolomite blocks was also predicted on the basis of the structural interpretation (Fig. 8). Part of the block broke off between the third and fourth sonar survey and damaged the lower part of the leaching string. No more blocks of the boudinaged anhydrite-dolomite zone were encountered during the later leaching stages, and by applying step leaching for the upper cavern levels it was possible to complete a cavern with a total volume of 356,000 m³.

CONCLUSIONS

The close cooperation between the technical departments of Dansk Olie og Naturgas A/S, Kavernen Bau- und Betrieb- GmbH, the regulatory authorities and the numerous service companies involved during the drilling and leaching stages proved to be successful. Within a structurally complicated salt dome, detailed structural analysis facilitated the construction of a cavern storage field comprising six caverns with a total leached volume of 2.6×10^6 m³.

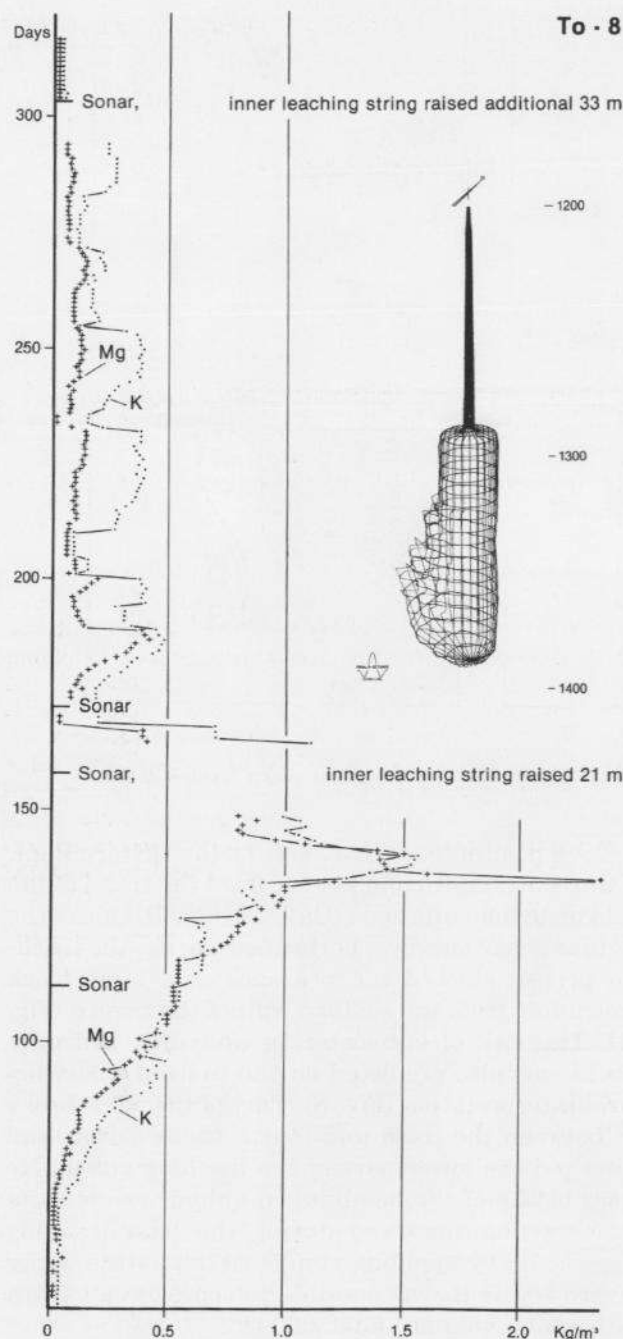


Fig. 10. K, Mg content of the leaching brine from TO-8 versus leaching time. The increase in K and Mg after approximately 80 days was due to leaching of K, Mg-salt from the upper Z2 evaporation cycle. The 3-dimensional representation of results from the sonar survey, run after 157 days, demonstrates the excess diameter and the dip of the K, Mg layers on the west side of the leached cavity.

The aim was to attain a high degree of flexibility both in the exploration phase and in the development stage; the development history outlined has proved this applied working strategy to be, not only necessary, but also successful.

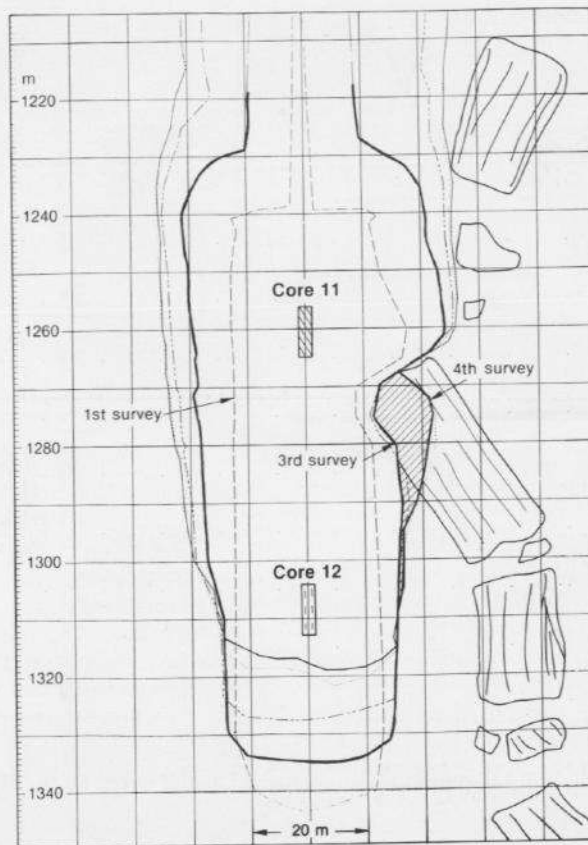


Fig. 11. Sonar cross section of the TO-9 cavern with conceptual representation of the anhydrite-dolomite block (Ca_2A_2) in the wall. The hatched part of this block broke off between the 3rd and 4th sonar surveys.

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