

## SEDIMENTOLOGY AND RESERVOIR PARAMETERS OF THE CHALK GROUP IN THE DANISH CENTRAL GRABEN<sup>1</sup>

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### ABSTRACT

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The Chalk Group is subdivided into Chalk Units. The regional development of these is the basis for a depositional model implicating a high degree of redeposition and resulting in a geographic zonation of the Danish Central Graben into 'Deposit Zones'.

Wireline log interpretations suggest good reservoir-intervals to coincide with specific lithologies. These are proximal allochthonous deposits, i.e. debris flows, which are found to be most common in the Chalk Units 6 Upper Part, Unit 5 and locally in Unit 2.

The matrix permeability is best developed in the highly porous intervals. In the most favourable reservoirs fracturation has enhanced the permeability up to hundred times.

### INTRODUCTION

Since the DAN field discovery in 1971 by the Danish Underground Consortium the knowledge about chalk has increased drastically and new concepts have been added. This has led to extensive development of chalk fields in the North Sea. Through development of these fields knowledge about chalk deposition has become much greater. Results are published by, among others, KENNEDY (1980) and WATTS ET AL. (1980).

Reservoir studies in the North Sea have been published by CHILDS & REED (1975), HARDMAN & EYNON (1977), D'HEUR (1980), MICHELSEN (1982) and many others. The regional development has been outlined by DAY ET AL. (1981) and recently by ZIEGLER (1981).

The present study on released material is an application of part of this new knowledge on the Late Cretaceous-Danian Chalk Group (DEEGAN & SCULL, 1977) in the Danish Central Graben, extended with the concepts developed through our research. This paper is an intermediate report on a current chalk project at the Geological Survey of Denmark. The study is based on core investigations and evaluation of wireline logs.

All the basic data have been submitted by DUC (Danish Underground Consortium). Investigations and evaluations were carried out by the staff of the Geological Survey of Denmark.

### SETTING

The westernmost part of the Danish offshore includes a section of the Central Graben, which is a complex trough with a long history of differential subsidence (ZIEGLER, 1981). Mesozoic rifting controlled the major structural pattern overprinted by younger tectonics, which have greatly influenced the sedimentation.

The Danish part of the Central Graben is limited by the Ringkøbing-Fyn High to the east and the Dogger and Mid North Sea Highs to the west (cf. MICHELSEN & ANDERSEN, 1983, this volume).

During the Late Cretaceous and Early Tertiary, strike-slip faulting took place in the Graben, giving rise to inversion tectonics (MICHELSEN, 1982). These movements and halokinesis initiated the development of the chalk structures, which have been drilled today (Fig. 1).

The Chalk Group is generally less than 250 m thick in a northwest-southeast trending area along the southern part of the Ringkøbing-Fyn High and on the Dogger High. The greatest thickness exceeding 1200 m is found in three northerly basins which parallel the Graben axis, as well as locally in rimsynclines in the vicinity of saltpiercement structures and along major fault zones (see MICHELSEN & ANDERSEN, 1983, this volume).

The Chalk Group thickness is inversely related to the thickness of the Early Cretaceous deposits reflecting the Mid Cretaceous inversion phase.

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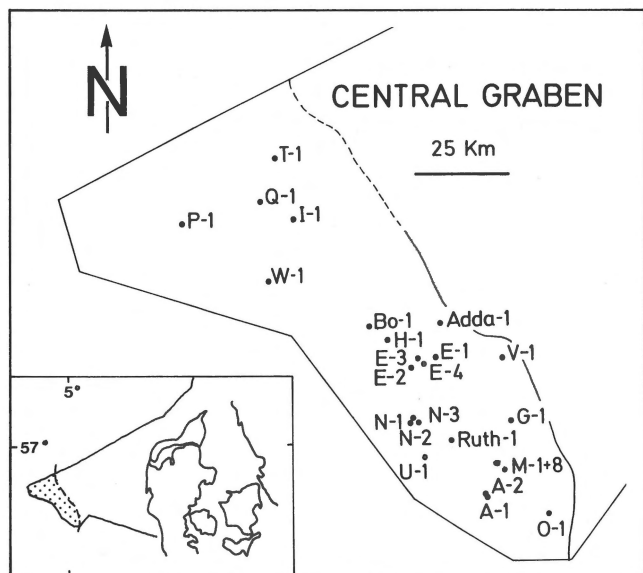


Fig. 1  
Locality map.

The Top Chalk surface (Fig. 2) is at a shallow level of approximately 2000 m depth in the southern part, gently dipping into a shallow plateau in the central area, from where it deepens steeply into a northern and western basin with depths exceeding 3000 m. Minor high areas are found along the Norwegian boundary and above halokinetic structures (Fig. 2).

Based on wireline logs the Chalk Group in the Central Graben is subdivided into 6 Units which tentatively can be correlated to the Norwegian Chalk Group formations (Fig. 3). Only the lack of detailed correlation between Unit 6 and 5 and the Ekofisk and Tor formations, respectively, hinders a direct application of the formal lithostratigraphy at present. It

is also possible to recognise the Plenus Marl Formation, although its marly upper part is missing in the Danish area.

The Chalk Units are unequally developed in different parts of the Central Graben, as exemplified on figure 4. A thin chalk section may be caused either by thinning of the individual Units, as in the BO-1 well, or by thinning as well as absence of Units, as in the I-1 well. In general, the thinnest chalk is found in the structurally highest located areas, where also entire Units may be missing.

The available biostratigraphic data tentatively suggest the upper Chalk Units to be time-stratigraphic ones, see MICHELSEN (1982, fig. 31). This is especially true for the Units 6 and 5, where biostratigraphic control is good. The deeper parts of the Chalk Group, Unit 2 and 3 and the base of Unit 4, seem to be somewhat diachronous. In the eastern part, along the Ringkøbing-Fyn High, Unit 1, which is of Cenomanian age, conformably overlies Early Cretaceous strata. Further towards the west gradually younger chalk unconformably overlies older strata, and sedimentation in the basin east of the Dogger High, where the wells Q-1 and W-1 are located, seems not to have commenced until Santonian.

Based on presence/absence and variation in relative thickness of the Units in drilled sections, the Graben area is divided into elongated areas, 'Deposit Zones', which roughly parallel the Graben axis (Fig. 5). Each Deposit Zone includes and is characterized by wells with similar thicknesses and thickness successions of the various Units present.

Deposit-Zone 1, the Ringkøbing-Fyn High area, is not included in this paper. Deposit-Zone 2 is situated along the Ringkøbing-Fyn High and is characterized by dominance of Units 1 to 3, a thin Unit 5 and a thick Unit 6 (V-1 well on figure 4). Deposit-zone 3 is characterized by a well developed Unit 2 and 4 relatively to the other Units (E-3 and BO-wells on figure 4). In Deposit-Zone 4 the Units 1 to 3 are absent. Unit 4 and 6 are thick, and Unit 5 relatively thin (I-1 well on figure 4).

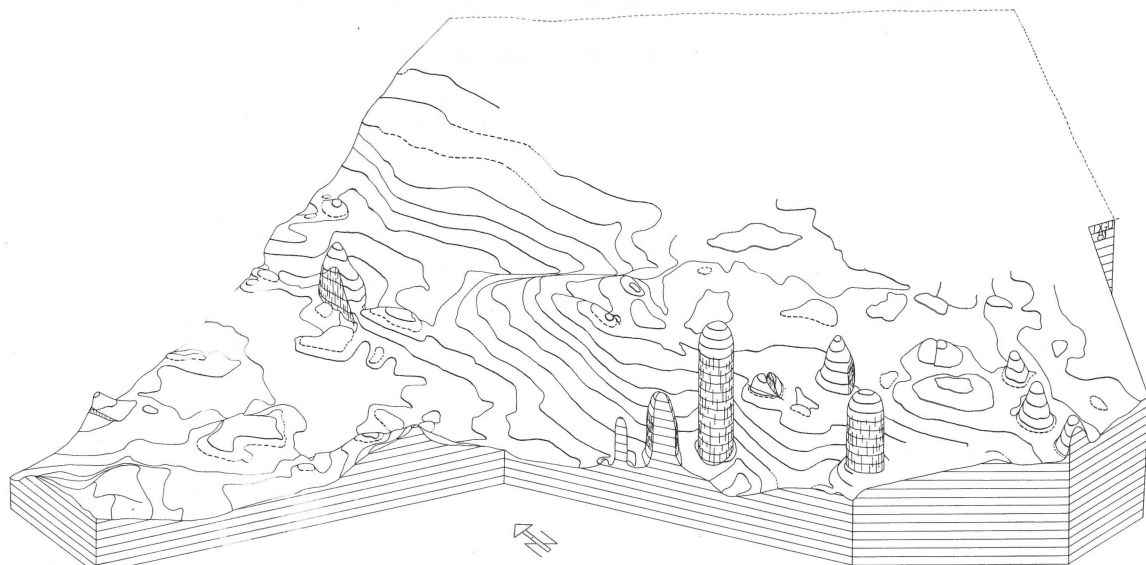


Fig. 2  
Block-diagram of the Top Chalk surface.

NORWAY CENTRAL GRABEN	DENMARK CENTRAL GRABEN
Ekofisk Form.	Unit 6 <span style="float: right;">Upper Lower</span>
Tor Formation	Unit 5
U	Unit 4
Hod Form. M	Unit 3
L	Unit 2
Plenus Marl Form.	
Hidra Formation	Unit 1

Fig. 3  
Correlation between the Norwegian and the Danish subdivision of the Chalk Group.

Deposit-Zone 5 like Zone 3 has a dual development, with relatively thick Units 2 and 4, but with the general thickness of all Units substantially greater than in the other Deposit Zones (Q-1 well on figure 4). Deposit-Zone 6, which represents the Dogger High and the areas northwest and west of it, is only penetrated by the P-1 well. Deposit-Zone 6 is therefore liable to future changes (P-1 well on figure 4).

### SEDIMENTOLOGY

The chalk is composed of skeletal calcium carbonate of planktonic origin. The bulk of the rock consists of coccolithic debris and coccoliths. Allochems are dominantly planktonic foraminifera and calcispheres, but skeletal material from benthic organisms (e.g., echinoderms, inocerams and sponge spicules) are locally important. The siliciclastic content is

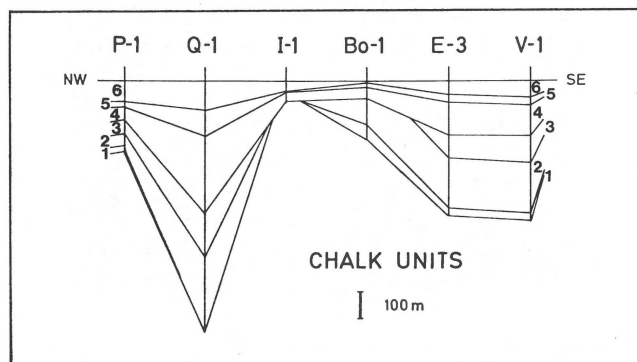


Fig. 4  
Correlation and thickness variation of the Chalk Units in selected wells.

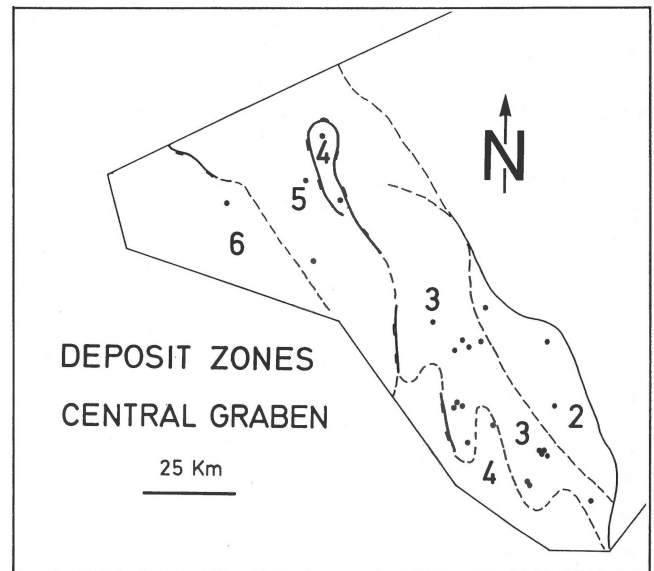


Fig. 5  
Subdivision of the Chalk Group in the Danish Central Graben into Deposit Zones. See text for explanation.

usually low and dominated by clay minerals.

The planktonic carbonate was produced in the upper part of the water column from where it settled to the bottom, probably in the form of faecal pellets produced by larger planktonic organisms, such as copepods (BROMLEY, 1979).

Upon primary settling on the sea floor the chalk was subjected to bioturbation. Since the chalk was rich in organic matter it was an ideal substrate for infaunal deposit feeders, which continuously ingested and mixed the upper sediment layer (EKDALE, 1978; BROMLEY, 1979). Therefore, bioturbation destroyed bedding and left the rock without any primary physical sedimentary structures. The bioturbation stimulated early diagenesis, especially dewatering of the sediment (HARDMAN & KENNEDY, 1980).

This so-called 'pelagic' chalk was very porous (up to 70%) and thus very susceptible to lateral mobilisation. The resulting allochthonous chalk has been known onshore for long time and is described by BROTZEN (1945), VOIGT (1962), and STEINICH (1967, 1972 a, b). Allochthonous chalk was not accepted as a common chalk sediment type, however, until the many descriptions from the North Sea were published by PERCH-NIELSEN ET AL. (1979), WATTSET AL. (1980), KENNEDY (1980), HARDMAN & KENNEDY (1980) and HARDMAN (1982) and also for the onshore by NYGAARD & FRYKMAN (1981).

When siliciclastic sediments are redeposited, sorting of the sedimentary components may take place, but the single components generally retain their character, i.e. a pebble in a debris-flow does not undergo any significant change from the initiation as a slump or slide to the deposition after flow. Thus, the travel distance has little impact on the constituents of the deposits, except for sorting.

MIDDLETON & HAMPTON (1976) suggested a scheme for flow processes in clastic sediments (Fig. 6). The degree of lithification in the pelagic chalk determines whether its remobilisation results in soft sediment deformation or brittle deformation. But even in the case of brittle rock behavior, the rock usually is comparatively soft, so that transport causes considerable wear on the rock fragments. Hereby the rock fragments, the intraclasts (Fig. 7), become rounded and gradually smaller. In case the bedload flow continues long enough they finally disappear or give rise to planar features, creating a secondary layering (Fig. 8). The quantity and size of soft intraclasts in a chalk bed is thus suggestive for the travel distance relative to adjacent allochthonous units in the sequence.

Mass flow will cause suspension of the finer chalk particles, whereby the remaining bedload is enriched in larger skeletal grains. The distal part of the flow might end up as a turbidite. This is comparable to processes suggested by DAVIES (1977) and KRAUSE & OLDERSHAW (1979), for some Palaeozoic carbonates.

Inspired by MIDDLETON & HAMPTON (1976) we have illustrated the bedload processes that occur in chalk during redeposition (Fig. 9). Depending on the travel distance, the same type of source material may end up as rock types usually described as:

- Deformed beds, such as slides and slumps,
- Debris flows, with intraclasts,
- Mudflows, with diffuse often contorted layering, or
- Turbidites, rich in allochems, laminated and graded.

This allows chalk sequences to be interpreted with regard to proximity to the source area, depending on travel distance and gradient. Therefore, the same source material can be redeposited by a sequence of processes, which are transitional to one another.

Settling after cessation of flow can result in development of an early, so-called 'shredded structure' with small scale folding and micro-faulting which deforms layering (Fig. 10).

When interpreting deposits formed by gravity flow processes, we rely on physical sedimentary structures, including intraclasts, secondary layering, shredded structures and lamination. But transportation causes also suspension of the sediment fines; redeposition of these creates a rock poor in sedimentary structures.

The interpretation of a rather homogeneous chalk se-

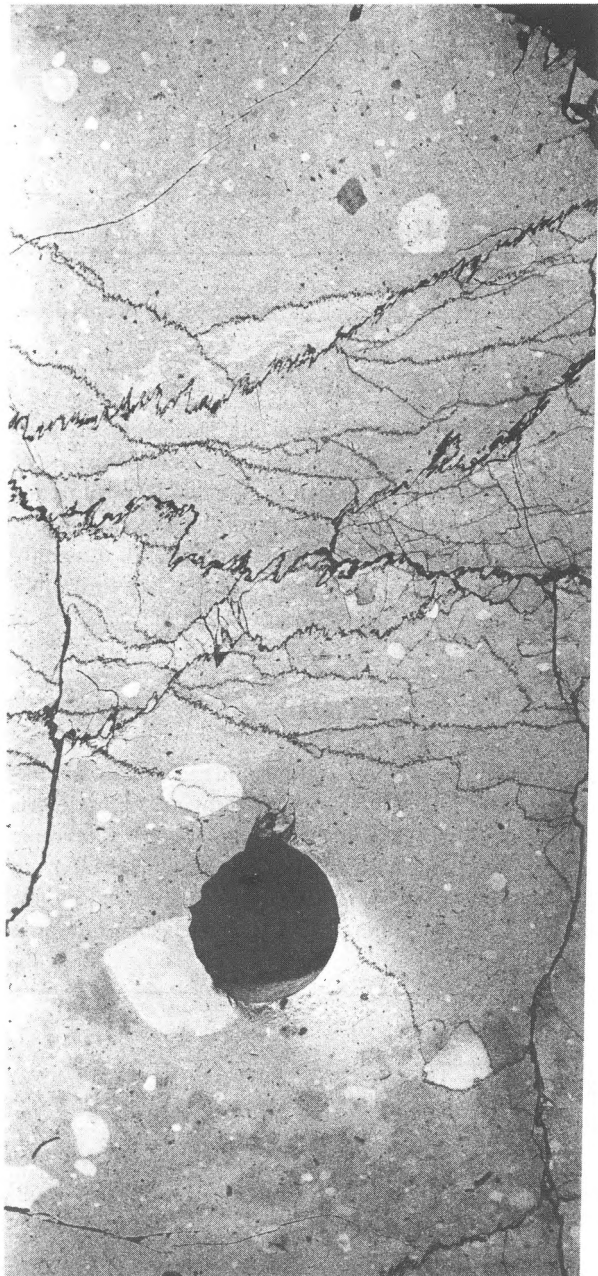
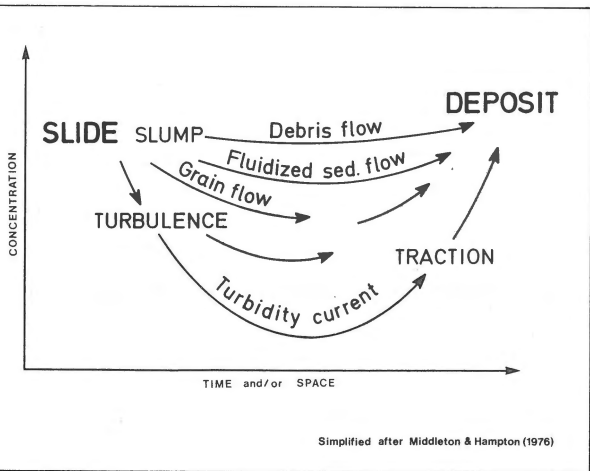


Fig. 7  
Chalk of debris flow origin with rounded intraclasts. Note the intraclast size and colour variation. Dark spots at bottom are oil-stains. The core is dissected by stylolites with dark clay seams. Core from T-1 at 7472' (BKB), core diameter 10 cm.



Simplified after Middleton & Hampton (1976)

Fig. 6  
Hypothetical evolution of a single gravity flow.

quence with some bioturbation is critical to the depositional model, since it may be taken as either 'pelagic' or 'resuspended' chalk. We recognize trace fossil assemblage and density as the key to the macroscopic distinguishment (Fig. 11). Chalk sediment surfaces are subjected to bioturbation. In pelagic chalk a continuously overlapping sequence of trace fossils is found (Fig. 11). In the thick-bedded, proximal alloch-

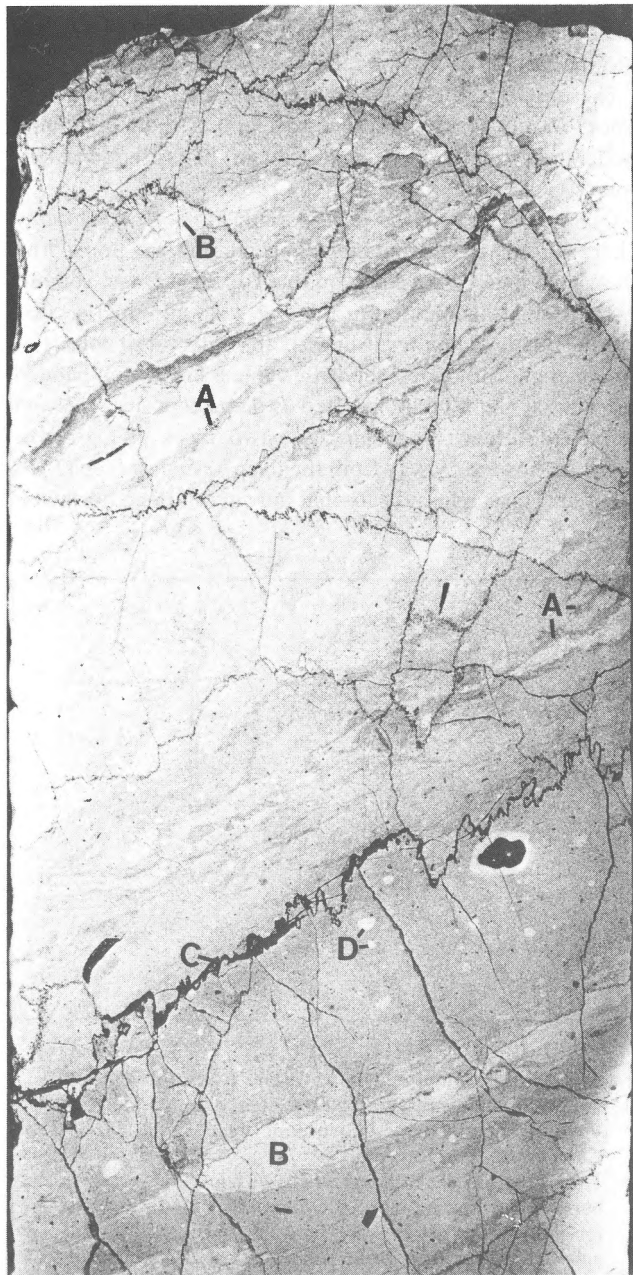


Fig. 8  
The figure shows several examples of flow-induced lamination (A). Drawn-out lightcoloured clasts occur at (B), whereas other smaller chalk intraclasts are undeformed (D). The thick inclined stylolite (C) indicates a boundary between two flows. Core from T-1 at 7521' (BKB), core diameter 10 cm.

thonous units, the traces are related to bed surfaces, except for escape traces (NYGAARD, 1982). Escape traces, however, may be found throughout a rapidly deposited sequence while surface related traces are found on the successive bed boundaries. When no physical structures are present, this trace fossil distribution can indicate an episodic nature of sedimentation. The frequency of the sedimentary episodes and the rate of deposition of pelagic chalk can be implied by the trace fossils. Often *Chondrites* is the only trace fossil (Fig. 12). The diameter of a single *Chondrites* burrow is constant within a single burrow system, which suggests the burrower to have stayed for a short time, and to have produced more than one burrow system through life. *Zoophycos* is found in association with other trace fossils (Fig. 13). It is a complicated burrow and often the diameter of the dwelling tube as well as the operational radius is increasing downwards, reflecting a rather sessile burrower, which stayed in a burrow system over considerable time.

*Chondrites* and *Zoophycos* are traces formed in relation to sediment surfaces. Based on the above behaviouristic considerations we, therefore, interpret chalk intervals where *Chondrites* is the only trace fossil, as continuously and rapidly deposited. *Chondrites* and *Zoophycos* together, in well defined horizons, are taken to indicate episodic depositional events with very little intermediate sedimentation.

While physical structures are essential for the interpretation of the most proximal and distal allochthonous deposits, trace fossils might replace these as indicators of depositional processes in the intermediate allochthonous settings. Based on these criteria, intervals of allochthonous origin are found in the Danish Central Graben which would otherwise have been interpreted as pelagic chalk.

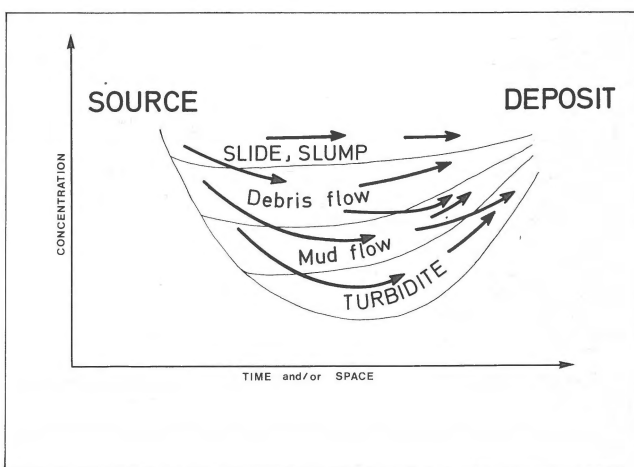


Fig. 9  
Diagram showing hypothetical evolution of a gravity flow of chalk type sediment. The transition from one flow type to another is a function of (1) the degree of coherence of the source sediment (2) the mixing of water into the flow and (3) the travel speed. Mud clouds of suspended fine-grained material probably form as an accessory deposit to all the shown flow types but is not shown on the diagram.

The clastic content in the chalk is usually low but at the base of Unit-2 in the Turonian shale the clay minerals locally dominate. This interval was cored in the BO-1 well and consists of finely laminated, dark shale alternating with chalk in 2 to 10 cm thick beds. Few compacted clay-filled *Planolites*-type trace fossils are found in the chalk beds, whereas the shale seems to be barren (Fig. 14). *Zoophycos* is present



Fig. 10  
Shredded structure in flow-induced lamination. Shredding is small-scale folding and microfaulting (A). Small light-coloured chalk intraclasts are present in the matrix (B). Core from T-1 at 7535' (BKB), core diameter 10 cm.

where two thin chalk beds are found in succession. The *Zoophycos*, which has extremely close spaced windings, is present within the lower chalk bed (Fig. 15). This suggests the benthic fauna to have preferred the chalk substrate. A likely interpretation of the shale-chalk sequence is that the shale represents the constant accumulation of clastic fines, which during part of the Turonian was the only sediment to be primarily deposited at the Graben floor. The chalk interbeds are interpreted as episodically deposited from relatively dense suspended gravity flows, bringing material from shallow areas into the basin.

These examples give the impression of a common occurrence of redepositional processes, and a sedimentational model involving these seems to explain the present distribution of Chalk Group sediments.

Dipmeter logs may be used as indicators of allochthony where core material is missing. This method was applied by R. LEONARD and J. W. KENNEDY on the Tor Field (pers. comm., 1982). Using this method in the Q-1 well, an upper section with a chaotic log pattern suggests this interval to consist of proximal allochthonous deposits, while a lower well-bedded log interval might be interpreted as distal deposits. The well defined difference between these two types of log-motifs vanishes, however, away from the deep basin in which Q-1 is situated. This might indicate that only in this deep northwest-

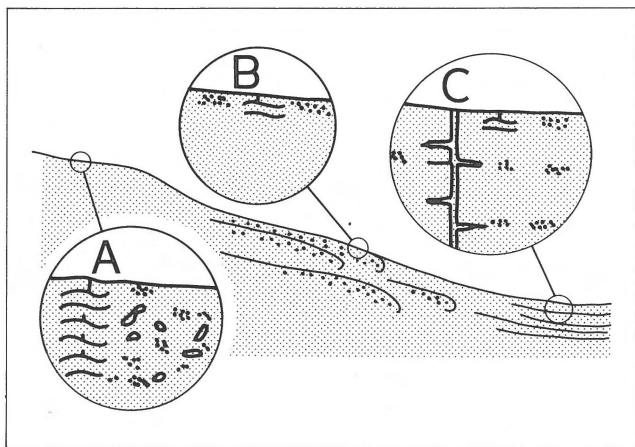


Fig. 11

Trace fossil distribution related to various types of chalk beds.

- A: Authochthonous 'pelagic' chalk is densely transsected by a continuously overlapping sequence of trace fossils (*Zoophycos*, *Chondrites*, *Planolites*, etc.).
- B: Thick proximal allochthonous beds such as debris flows are only burrowed in their topmost part. Depending on the available time for burrowing activity in between successive depositional episodes, either *Chondrites* alone or also *Zoophycos* may be present.
- C: Thin distal allochthonous beds, such as turbidites, are characterised by traces (made by organisms able to escape episodic burial) such as *Trichichnus* (Frey, 1970) and *Bathichnus* (Bromley et al., 1975; Nygaard, 1981). The same type of bed surface traces are found as in the case of B, rendering the lithological sequence into an alternation of burrowed and unburrowed intervals.

terly part of the Danish Central Graben Chalk Basin the routes of transportation were long enough to develop a distal allochthonous sequence. In the remaining part of the Danish sector, short distance redeposition seems to have been the most common process, giving rise to abundant debris and mud flow deposits. Based on this sedimentologic concept we suggest the areas, where the Chalk Group is thin, to have supplied

material to the adjacent areas, where it is thicker.

The thickness distribution of Chalk Unit 2 is taken to exemplify the depocentres, where the lower part of the Chalk Group was accumulated (Fig. 16). Figure 16 is based on drilled thicknesses and, therefore, mainly represents the chalk development on top of structures. Therefore, also the significance of any single measurement is dubious, but we believe



Fig. 12  
Cluster of *Chondrites* (C) in homogeneous chalk. The trace is slightly deformed. The position of the cluster and the faint bedding indicate the boundary between two sedimentary units is located just above the cluster. Note also the escape trace *Trichichnus* (T). The darker colour in the upper part of the core piece is caused by oil-invasion. Core from T-1 at 7269' (BKB), core diameter is 10 cm.



Fig. 13  
*Zoophycos* showing gradually larger burrow-tube diameter down through the section. Note the presence of other trace fossils *Chondrites* (C) and *Planolites* (P), and the general biomottled appearance. Core from T-1 at 7269' (BKB), core diameter 10 cm.

that the distribution shown by all the data together has some validity. It is also stressed that the datings of the Unit Boundaries are somewhat inaccurate.

Despite these limitations we still find Unit 2 related to two depocentres in which we expect to find allochthonous deposits. The first one is an east-west trending basin in the ADDA-1/BO-1 area, whereas the other is a northwest-southeast trending basin in the Q-1/W-1 area. Around the Q-1 and W-1 wells a depocentre is still present during deposition of Unit 4 (Fig. 17), whereas in the southern area the drilled thicknesses are smaller and nearly uniform. Therefore, 'pelagic chalk' is likely to dominate in Unit-4 in the southern area.

The depositional model suggested above is concerned with regional trends in sedimentation and transportation. Surely detailed investigations will reveal many local deviations from the regional model, although the basic way of interpretation may still be applicable on and around structures.

### RESERVOIR PARAMETERS

In the following paragraphs we will try to exemplify variations in reservoir characteristics in relation to Chalk Units and Deposit Zones. Some preliminary explanations will be given that have been reached based upon the depositional model.

Core material and log-pattern studies from a number of

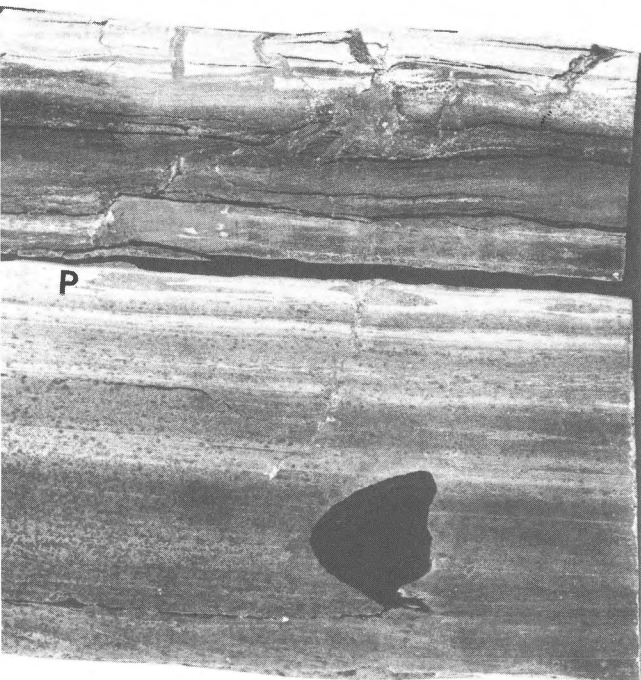


Fig. 14  
Thin chalk bed with *Planolites* type traces (P), interbedded with very clayey intervals. The trace fill is marly. Note also the marly fracture fill at top of the figure. The Turonian Shale (Plenus Marl Formation) from BO-1 at 7271' (BKB), core diameter 10 cm.

wells reveal a common occurrence of allochthonous chalk. Log patterns in transported intervals have relatively low undulation frequency and high amplitude. Combined with formation evaluation on wireline logs these studies show that proximal allochthonous beds – the debris flow deposits – are seemingly preferentially oil-saturated compared to other types of allochthonous deposits and pelagic chalk (Fig. 18). However, this does not exclude other chalk types from acting as reservoirs.

The type of chalk influences the oil-saturation and other reservoir parameters, such as porosity and permeability. This is exemplified in the T-1 well (Fig. 19), where porosity values

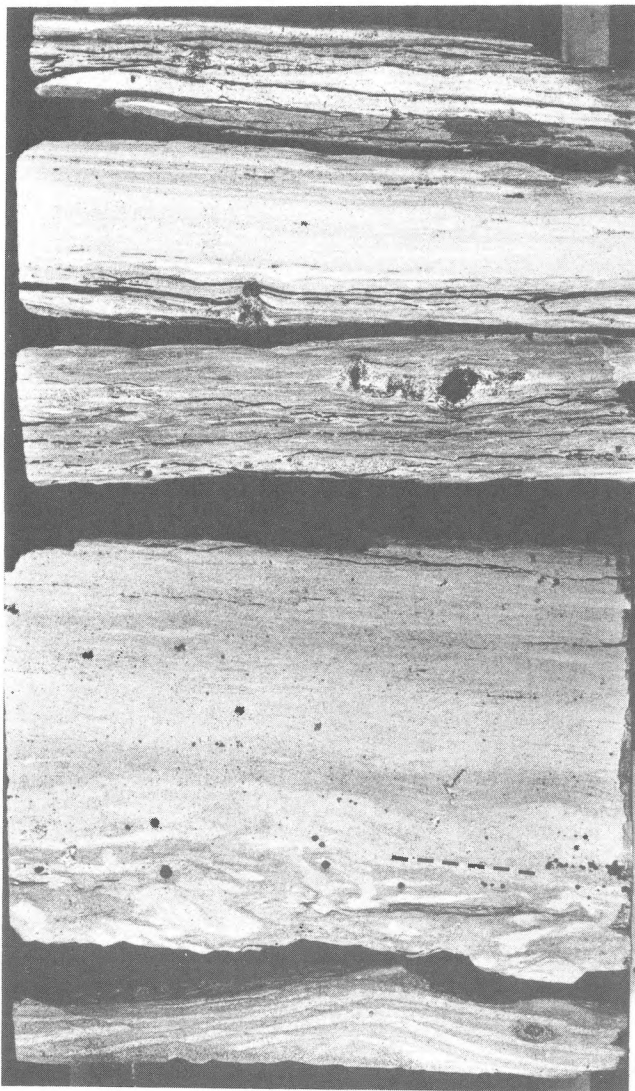
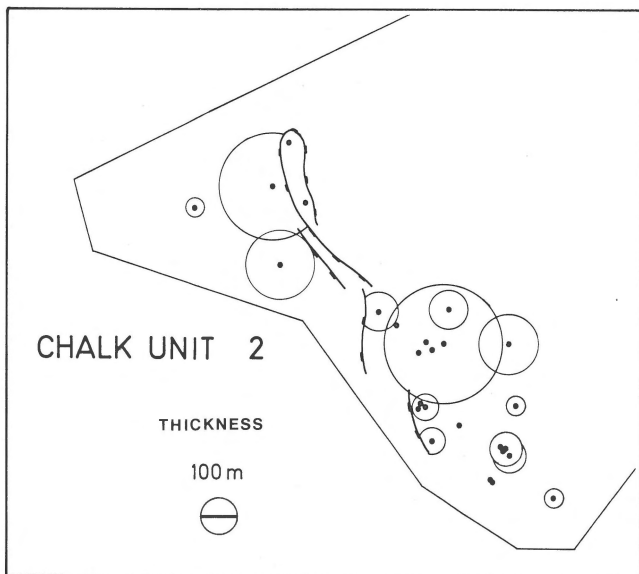
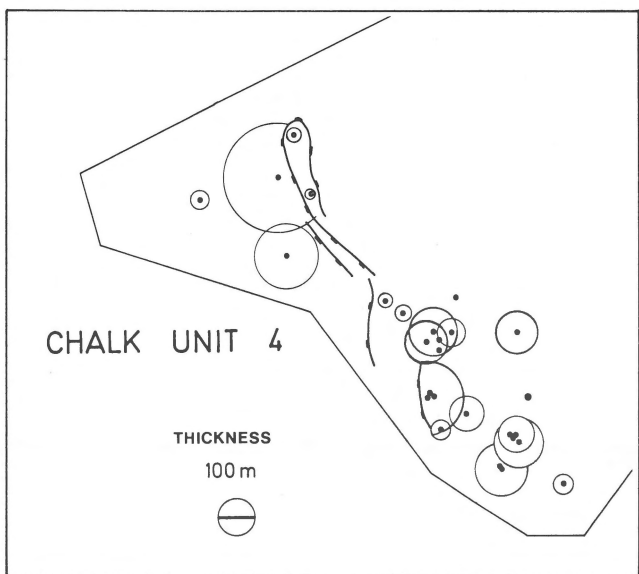


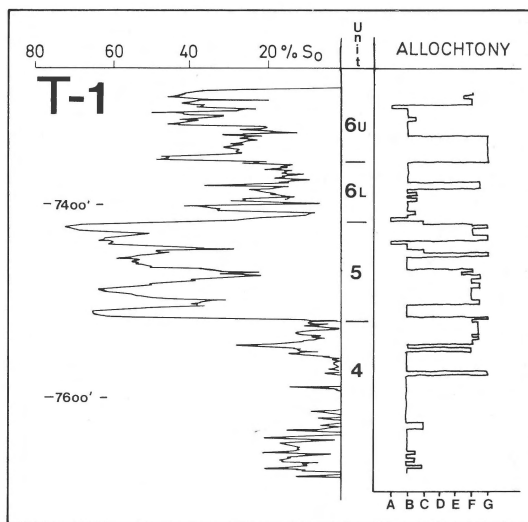
Fig. 15  
Turonian shale (Plenus Marl Formation) interbedded with chalk. Two chalk beds are in superposition to each other along the dashed line. In the lowermost chalk bed a *Zoophycos* with very closely spaced windings is seen. The deformed biomottled interval above the *Zoophycos* is caused by traction in connection with the deposition of the chalk bed above. Core from BO-1 at 7274' (BKB), core diameter 10 cm.



**Fig. 16**  
Thickness of Chalk Unit 2, as found in drilled sections, shown as circles. Black dots alone indicate wells where the Unit is absent. Areas with great thickness, as found in the northern and in the middle areas of the Central Graben, are interpreted as depocentres, where allochthonous chalk is likely to be found, derived from the surrounding areas, where the Unit is thin or even absent.

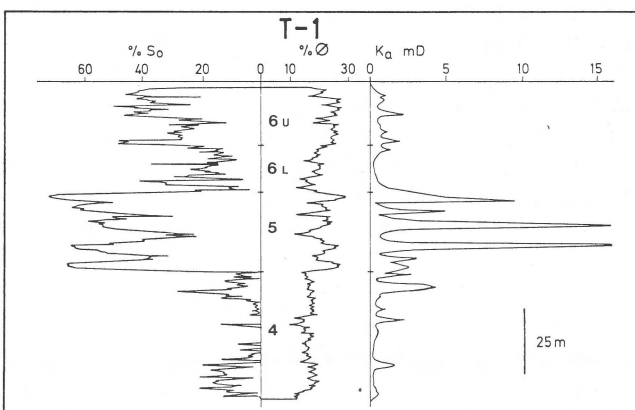


**Fig. 17**  
Thickness distribution of Chalk Unit 4 in drilled sections. The circle diameters correspond to thicknesses. Black dots alone represent wells where the Unit is absent. The northern area, with great thicknesses, is interpreted as a depocentre, where allochthonous chalk is likely to be found, derived from the surrounding areas. In the middle and southern part of the Central Graben nearly equal thicknesses are found. This is interpreted as an area, where 'pelagic' chalk is likely to dominate.



**Fig. 18**  
Diagram of the cored interval in the T-1 well showing log-derived oil-saturation ( $S_o$ ) compared to sediment-type. The scale A to G expresses the degree of allochthony as interpreted from core descriptions. Criteria for subdivision of the scale:  
A: Homogeneous chalk without structures and trace fossils.  
B: Chalk with trace fossils (= 'pelagic' chalk).  
C: Trace fossils deformed, showing signs of ooze-creep or sliding.  
D: Horizontal shear-planes and fracturation of layers.  
E: Intraclasts common.  
F: Small intraclasts and associated shredded lamination.  
G: Clasts strongly deformed, shredding and shear- or flow-lamination of sediment.

On the diagram intervals with debris flows and mud flows can be correlated with higher oil-saturation compared to the adjacent intervals.



**Fig. 19**  
Log-derived oil-saturation and porosity calculated for the Chalk Group in the T-1 well and displayed together with air-permeability measured on cores. The oil-saturation and permeability seem to follow the porosity variation. The high porosity encountered in Chalk Unit 6, Upper Part, and in Unit 5 has also the highest oil-saturation and permeability values. The remaining part of the Chalk Units, having lower porosity values, exhibits a low saturation and permeability. This causes an anomalous saturation pattern with the pay zone situated in the middle of the reservoir. This indicates that the T-1 discovery might be a combination of both a structural and a stratigraphic trap.

and especially core derived air permeability values are much higher in the debris flow deposits present in Chalk Unit 5 and Unit 6, Upper Part.

Based on the depositional model, allochthonous chalk is to be expected in Chalk Unit 2 in the middle part of the Central Graben. This assumption is supported by log patterns for the ADDA-1 well, where log evaluation shows the Chalk Unit 2 to have a relatively high oil-saturation, despite average porosity values not exceeding those of the other Units in this well (Fig. 20).

The differences in reservoir quality between 'pelagic chalk' and allochthonous chalk is exemplified by the E-2 well (Fig. 21). From log patterns and regional thickness variations of the Chalk Units, the Chalk Unit 4 is interpreted as 'pelagic chalk' and the Chalk Unit 5 as redeposited chalk. The gas preferentially saturates the allochthonous chalk in Unit 5. In Chalk Unit 4 both porosity and especially the gas-saturation are substantially lower, although the upper part of Unit 4 is included in the pay-zone.

It has been argued that the relatively good reservoir characteristics in chalk of the debris flow type are due to early lithification of the rock prior to redeposition. The source for early cement is found in aragonitic sediment constituents (HARDMAN, 1982) and good reservoir quality after redeposition is then maintained, as no aragonite was left to cement the rock at a later stage. We agree that an early lithification is a prerequisite to a good reservoir quality in transported chalk, but we mainly attribute this quality to the degree of disintegration of the matrix structure.

Disintegration of a chalk rock by redeposition forms intraclasts of a wide size range. The smallest of these are tiny matrix platelet aggregates. Such aggregates are supposed to give the deposit the character of a micro-clast-supported structure, causing high porosity and matrix permeability. In chalk, which has been transported over relatively long distances, the microclasts are further disintegrated. This rock is, therefore, likely to have poorer reservoir quality, caused by a denser packing of individual matrix grains. Proximal allochthonous intervals seem to have relatively good reservoir characteristics, but also other factors, such as diagenetic effects, depth of burial, overpressuring and early oil-invasion, affect the original depositional features.

The influence of burial depth is illustrated on figure 22. The porosity decreases drastically with depth within a single well but gently on a regional scale. This is illustrated by the porosity variations between the Deposit Zones (Fig. 23), where the highest porosity values are found at the structurally shallowest level, i.e. in the Deposit Zone 3. The variations in porosity between the neighbouring Chalk Units (Fig. 24) seem to be more closely related to depositional characters, as debris flows are commonly found in Chalk Unit 6 (Upper Part), Unit 5, and locally in Unit 2.

In the Central Graben the porosity values lie considerable above the 'normal' chalk compaction curve. This anomaly is in literature explained by overpressuring and partly by early

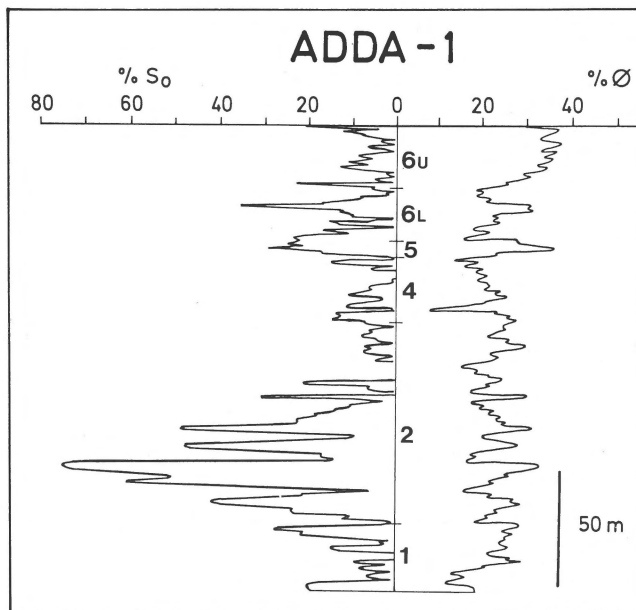


Fig. 20 Log-derived porosity and oil-saturation calculated for the Chalk Group in the ADDA-1 well. High oil-saturations are found in the porous zones in the lower part of the Chalk Unit 2. The chalk in this interval is interpreted as consisting of debris flows. Substantially lower saturation values are found in the chalk above, in spite of its similar or even higher porosity values. The oil zone in the Chalk Unit 2 is situated far below spillpoint at Top Chalk level, indicative of an intra-chalk, stratigraphic trap. Test data indicate the oil zone to be highly fractured.

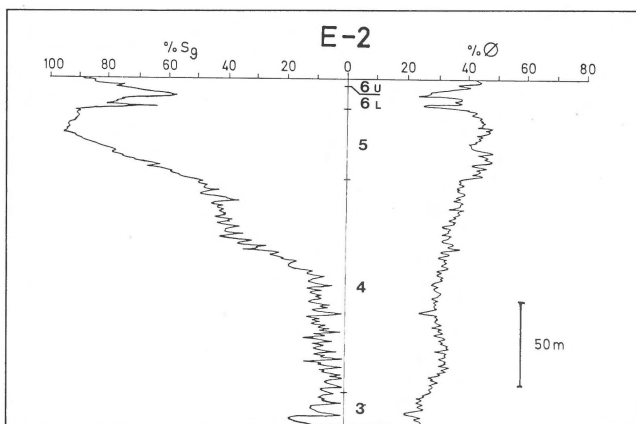


Fig. 21 Log-derived porosity and gas-saturation for the Chalk Group in the E-2 well. This well did not penetrate the entire Chalk Group. Highest porosity and gas-saturation are found in Chalk Unit 5, which from log-patterns, in accordance with the depositional model, is interpreted as an allochthonous interval of debris flows. Lower values of porosity and gas-saturation are found in the Chalk Unit 4, where the chalk is interpreted as a 'pelagic' deposit. In spite of the lower values the upper part of Unit 4 still contributes to the pay-zone. The Chalk Unit 6, Lower Part, has a lower porosity and gas-saturation than the over- and underlying Units, thus representing a poorer reservoir quality. This pattern is often found in the Danish Central Graben.

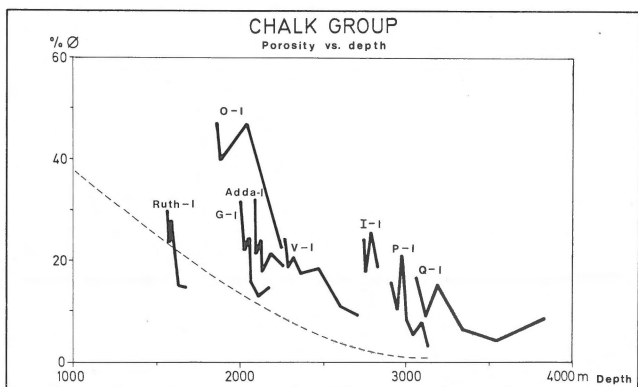


Fig. 22  
The distribution of log-derived porosity versus depth for the Chalk Group in selected wells. The porosity is averaged for each Chalk Unit and plotted against the intermediate depth level for the Unit concerned. The porosity values are calculated from FDC-CNL logs and corrected for borehole, gas, and clay-effects. The dashed line is the 'normal' compaction curve from SCHOLLE (1977). The porosity varies within each Chalk Unit and decreases drastically with depth in the single well. On average, however, the porosity decrease with depth is less pronounced. Relatively high average porosities are maintained even at a great depth, where zero porosity should be expected. This might indicate that there is no porosity barrier to reservoir development, even at great depths.

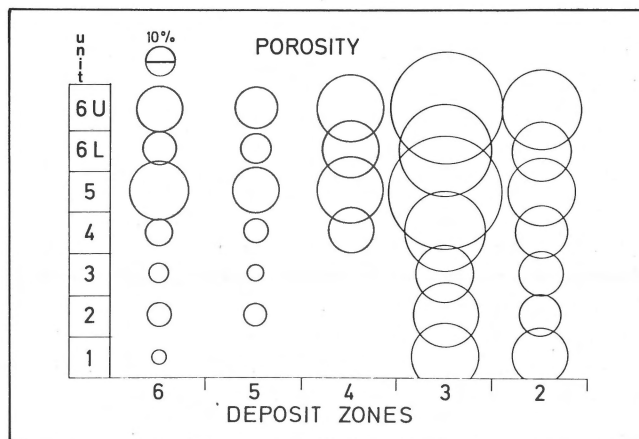


Fig. 24  
Log-derived porosity averaged on Chalk Unit level for each Deposit Zone. The values are corrected for borehole, clay, and gas-effects. On Chalk Unit level the highest porosity values are found in Unit 5 and Unit 6, Upper Part; the lowest values are found in Chalk Unit 3. Geographically, Deposit Zone 3 has the highest porosity values, with decreasing values towards east in Deposit Zone 2, and towards west and northwest in the Deposit Zones 4 to 6.

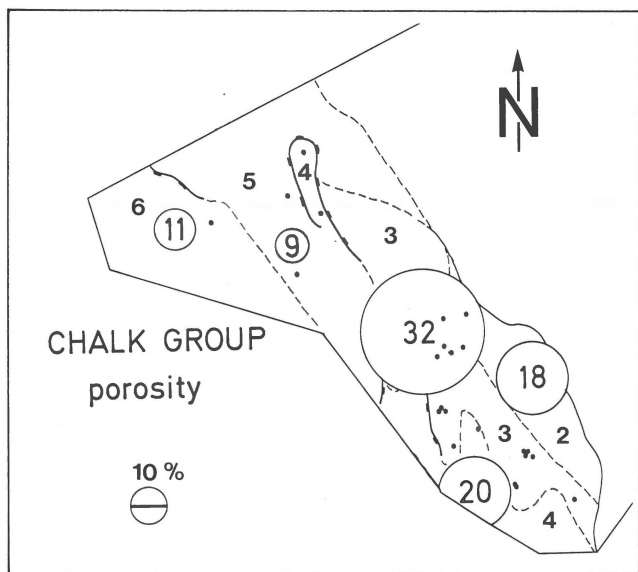


Fig. 23  
Log-derived porosity calculated for the total Chalk Group and averaged for Deposit Zones. The porosity values are calculated from FDC-CNL logs, and corrected for borehole effect, gas effect, and clay-effect. Highest porosity values are found in Deposit Zone 3, situated at a shallow depth level, while the porosity values are low in the Deposit Zones 5 and 6, situated at the greatest depth (Fig. 2). The intermediate porosity values found in Deposit Zone 2 might partly be explained by depth of burial and partly by the higher clay-content (Fig. 26).

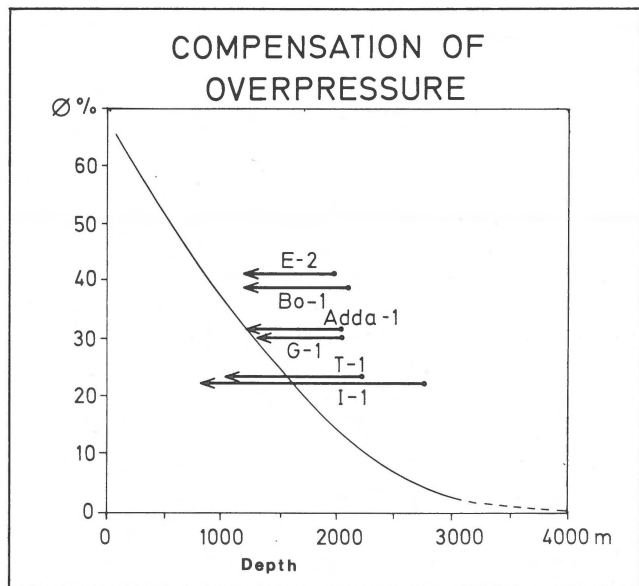


Fig. 25  
Average porosity values for the Chalk Unit 6, Upper Part, compensated for overpressure. By compensation of the overpressure, the porosity values in the ADDA-1 and G-1 wells, in Deposit Zone 2, are displaced to the 'normal' compaction curve (from Scholle, 1977). The E-2 and BO-1 wells, in Deposit Zone 3, still exhibit porosities that are relatively high. This might be explained by early invasion of hydrocarbons, combined with overpressure. After compensation, the T-1 and I-1 wells, in Deposit Zone 4, have very low porosities, which might indicate, that depth of burial has been greater than at present.

oil-invasion (SCHOLLE, 1977; HARDMAN, 1982). Examples from the Danish Central Graben seem to favour overpressuring as the main factor (Fig. 25), as individual Chalk Units at the same depth level have the same porosity range in both hydrocarbon-saturated and water-wet wells.

The clay content is generally low (less than 10%) for the Chalk Group in the Danish Central Graben (Fig. 26). High porosity is related to a low clay content, as in the Deposit Zone 3 and on Unit level in the Chalk Unit 5 (Fig. 27). But certainly also deviations from this simple relationship are found as exemplified by comparison of the Lower and Upper Part of Chalk Unit 6 (Fig. 27). Problems in distinguishing between sedimentary and authigenic clay is considered to be the main hindrance for the attempt to explain these variations.

Permeability data are only available from cored intervals in the wells. The scattered data show a general decrease with depth (Fig. 28). The measured air-permeability may have a logarithmic correlation to porosity reflecting true matrix permeability (Fig. 29), but often this relationship is not too clear. Notable deviations from the good correlation are taken as evidence for microfracturing (Fig. 30). Although no clear relationship is found, good matrix permeability seems to some extent to be related to low clay content. This is evident in Deposit Zone 3 (Fig. 31). Extensive fracturing of hydrocarbon-bearing chalk reservoir rock allows production in spite of the low matrix permeability normally found in these reservoirs.

CONCLUSIONS

The Chalk Group is subdivided into Chalk Units based on wireline log characteristics. The thickness variations of the Units forms the basis for a geographic zonation of the Danish Central Graben into Deposit Zones.

Investigations of core material and the regional development of the Chalk Units suggest a depositional model that includes common redeposition processes. These processes have worked locally on the salt-induced structures giving rise to proximal gravity flows, such as debris flows and mud flows. More distal redeposition of some of the material has given rise to mud cloud and turbidite deposits.

The distribution of reservoir characters is to some degree reflected in the Chalk Units and Deposit Zones. Log evaluation and sedimentological interpretation suggest some of the most favourable chalk reservoirs to be of allochthonous origin. Proximal allochthonous beds, such as debris flow deposits, have been found in Chalk Units 6 (Upper Part), 5 and locally in Unit 2, and seem to be correlated with relatively high oil-saturation. Investigations of reservoir parameters indicate these to be affected by interaction of several factors.

The deposit type, especially in combination with overpressuring, is the main key to a good matrix porosity and permeability. Depth of burial seems to affect porosity at only very

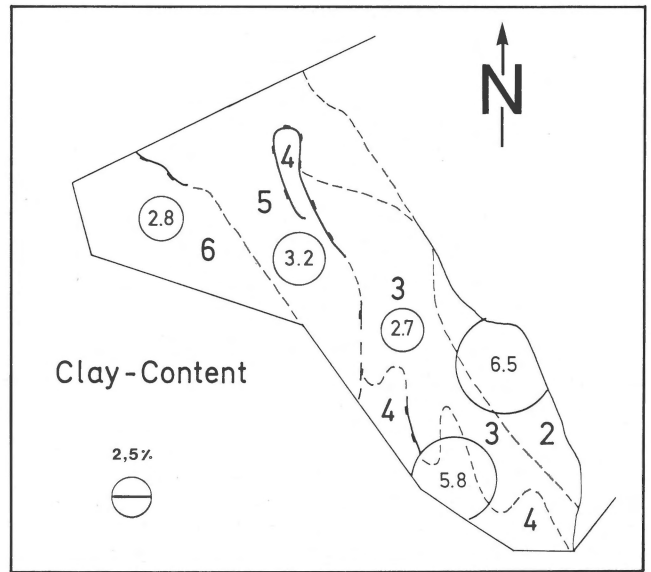


Fig. 26 Log-derived clay-volume calculated for the total Chalk Group and averaged for Deposit Zones. The clay-volume is calculated from Gamma-Ray logs and corrected for borehole effect. The lowest content of clay is found in the Deposit Zones 3, 5 and 6. Deposit Zone 2 has the highest average clay-content in the Danish part of the Central Graben. The clay-content in Deposit Zone 4 is caused by anomalous high values in the I-1 well. When neglecting the I-1 well, the remaining values in this Deposit Zone are similar to those in Deposit Zone 3.

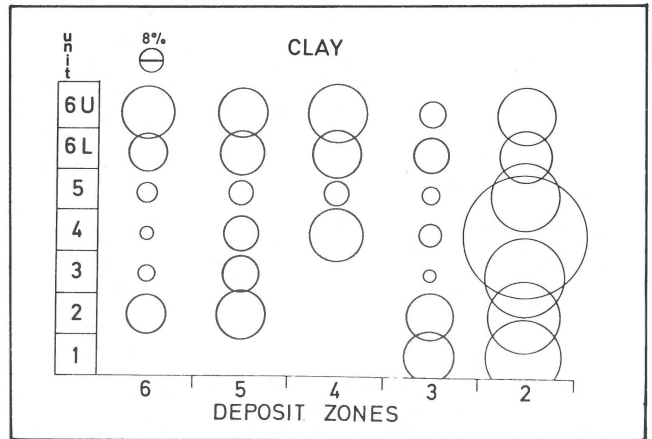


Fig. 27 Log-derived clay-volume averaged on Chalk Unit level for each Deposit Zone. The clay-volume is calculated from Gamma-Ray logs, corrected for borehole effect. The lowest clay-content is found in the Chalk Unit 5, with increasing values upwards and downwards. The opposite pattern is, however, found in Deposit Zone 2. The regional distribution shows the lowest clay-content for Deposit Zone 3, with slightly increasing values towards west and northwest in the Deposit Zones 4 to 6. An extremely high clay content is found in Deposit Zone 2. The relatively high amount of clay in Deposit Zone 4 is mainly caused by the I-1 well. When neglecting the I-1 well, the remaining values in this Deposit Zone are similar to those of Deposit Zone 3.

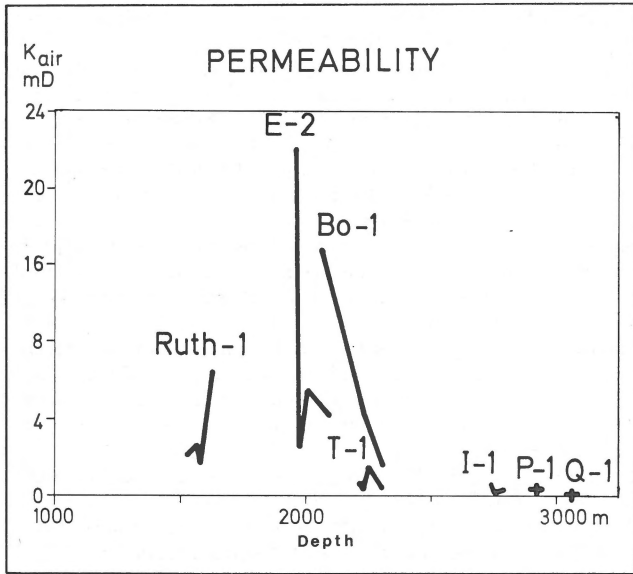


Fig. 28  
Core-measured air-permeability averaged for each Chalk Unit in selected wells. Not all Units are represented and some of the averaged permeability values are based on rather few measurements. The permeability data generally represent chalk matrix values. These are generally low in the Chalk Group and decrease with depth. Exceptions from this pattern are found in the upper Chalk Units in the E-2 and BO-1 wells in Deposit Zone 3, where the permeability is extraordinarily high, whereas the deeper parts of these wells contribute to a general low permeability trend.

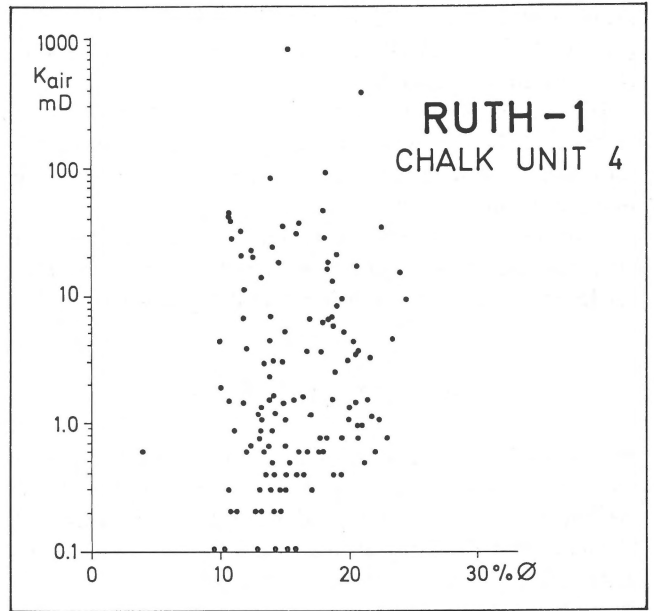


Fig. 30  
Core-derived air-permeability versus core-porosity for the Chalk Unit 4 in the RUTH-1 well. The deviation from a logarithmic relationship between porosity and permeability (cf. Fig. 29) is caused by microfracturing. The cluster of points in the lower right of the figure indicates porosity dependent matrix permeability, which does not exceed 25% porosity and 1.5 mD, respectively.

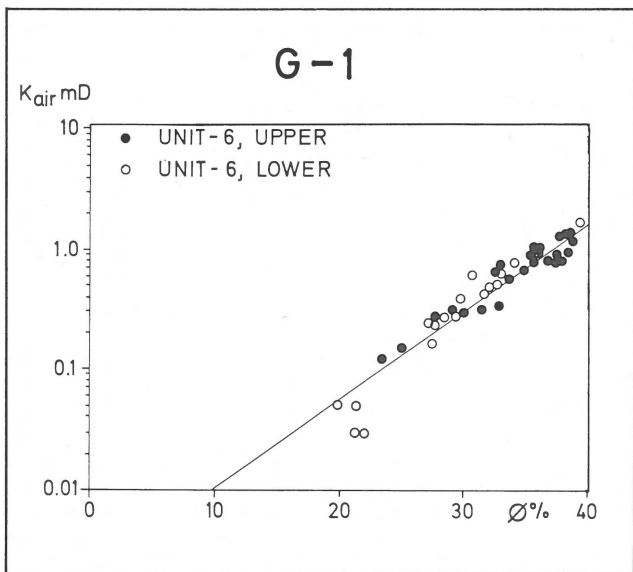


Fig. 29  
Air-permeability versus porosity measured on cores from the G-1 well shown for Chalk Unit 6, Lower and Upper Part, respectively. The data suggest a logarithmic relationship (regression line) between permeability and porosity, reflecting that the true chalk matrix permeability has been measured.

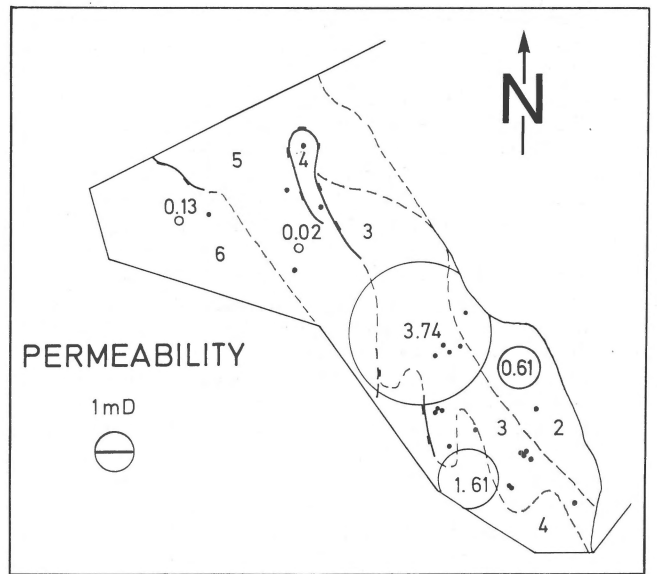


Fig. 31  
Core-measured air-permeability values in the Chalk Group, averaged for Deposit Zones. The measurements are matrix permeabilities. Deposit Zone 3 has the highest values, which is in accordance with the high porosity and low clay-content in this area (Figs. 23 and 26). The lower permeability found in Deposit Zone 2 might be caused by the high clay-content. The matrix permeability value in Deposit Zone 4 is overprinted by high fracture permeability in the RUTH-1 well, whereas the extremely low permeability values in the Deposit Zones 5 and 6 are caused by the great depth of burial in these areas.

great depth, while the clay content is only in the Chalk Unit 6 (Lower Part) and locally elsewhere high enough to restrict reservoir quality severely.

The allochthonous chalk deposits of debris flow origin are supposed to be located somewhere down regional and structural slopes. Amongst the latter type, both salt- and fault induced features can be included.

If allochthonous chalk has those favourable reservoir characteristics as outlined at this preliminary study, the interest for stratigraphic traps will certainly be enhanced.

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