DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/56

The Chalk at Stevns Klint

Field trip guidebook, Stevns, Denmark

Arranged for:
Phillips Petroleum International Company Denmark and
Licence 5/95 partners

Peter Frykman and Finn Jakobsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

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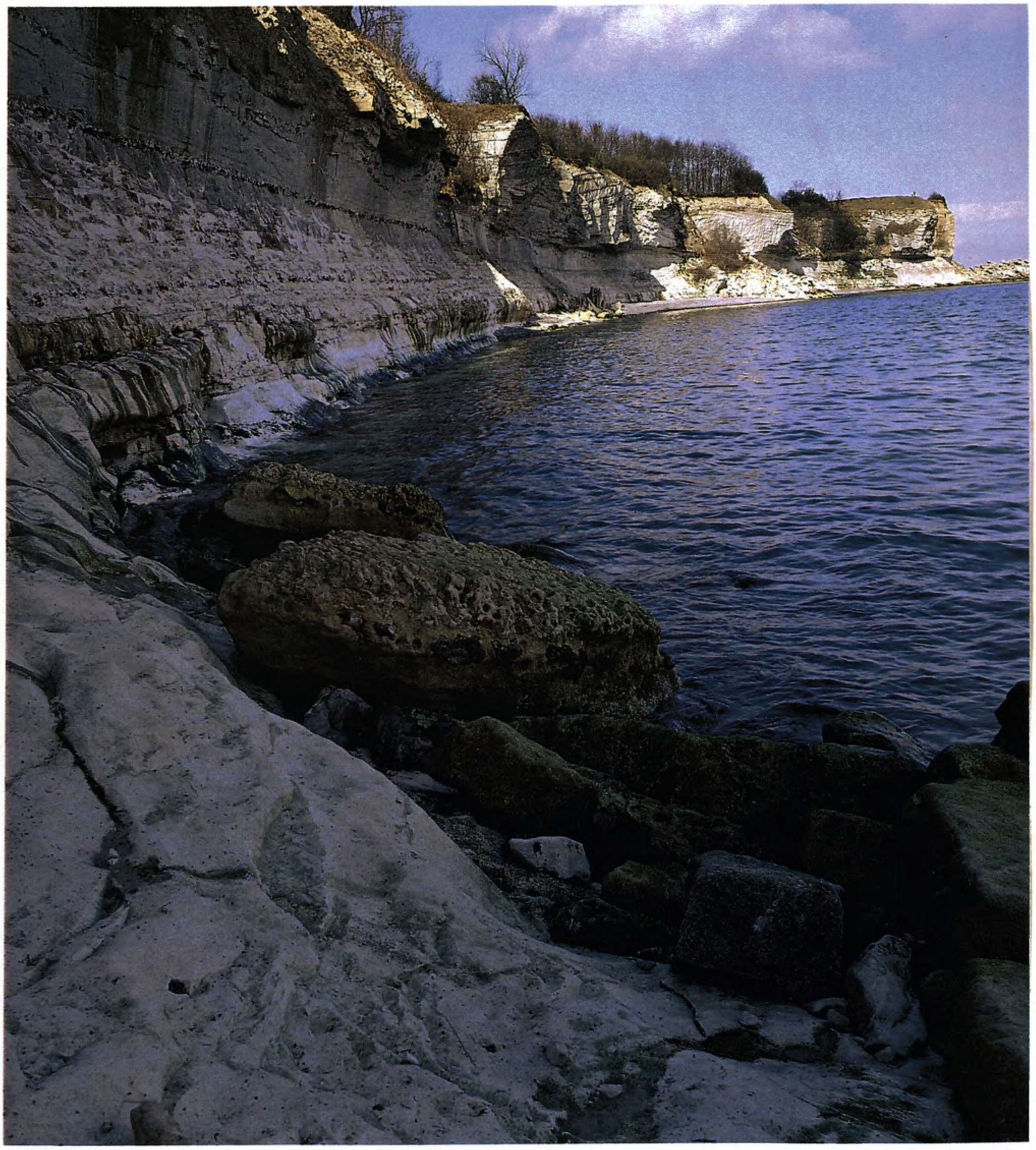
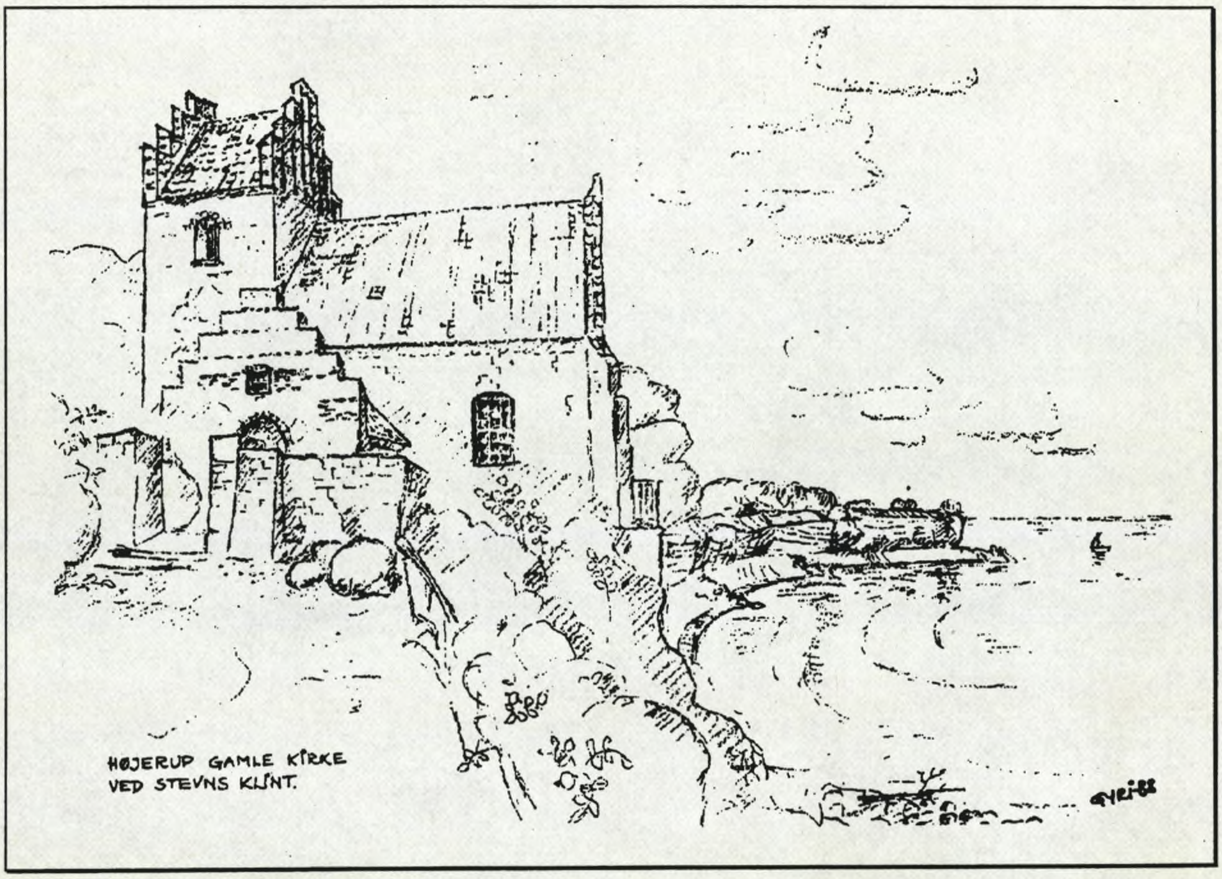
The Chalk at Stevns Klint - Field trip guide

Field Trip arranged for Phillips Petroleum International Company Denmark and 5/95 license partners, by the Geological Survey of Denmark and Greenland (GEUS).

15. May 1997



Old Højerup Church.



In Højerup, at the very edge of the cliff, stands the ancient church, which together with the cliff itself is one of the best known sights in Sealand.
Tradition says that a seafarer in distress at sea promised to erect a chapel on the cliff, if he was saved. Luckily he was, and in 1250 the chapel was erected, built of stones from the white lime cliff. About 100 years later, during the reign of Valdemar Atterdag, the building was enlarged. On september 11th 1358 the church was reconsecrated.
In the centuries that followed the cliff, however, was undermined by the sea. As early as 1675 drawings show the inland removal of the eastern church yard wall. It was obvious that the church was in danger but century after century people found consolation in the tradition, which said that the Old Højerup Church would survive by moving a cock's stride further inland every Christmas night. But a cock's stride was not enough and on march 16, 1928 its choir and altarpiece tumbled into the sea. The church was then anchored and today still stands on the edge of the cliff.

The church contains several frescoes and a pulpit from 1605.

The Chalk at Stevns Klint - Field trip guide

Guide prepared by Peter Frykman and Finn Jakobsen,
Senior Research Geologists at the Geological Survey of Denmark and Greenland.

This field trip guide is aimed at supplying background material for discussion of the chalk outcrops at Stevns, and contains some unpublished information, as well as preliminary statements and conclusions. The guide is not suited for referencing of this material.

Programme:

This excursion is arranged for: Phillips Petroleum International Company Denmark and 5/95 license partners, by the Geological Survey of Denmark and Greenland (GEUS).

The chalk exposures will be visited at the cliff at the village of Højerup at Stevns Klint (Fig. 1), approximately 40 km south of Copenhagen, a bus-drive of ca. 1h.20min .
The chalk outcrops stretch approximately 12 km along the coastline of the peninsula of Stevns and reaches ca 40 m in height.

Warning notice:

The visit to the cliff and the beach is at the participants own risk. Rocks at the beach may be slippery, the cliff is in some places overhanging - so, both watch your steps and look up, and please be careful.

Participants:

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Nigel Bramwell
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Richard Bowe
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Danish Energy Agency (DEA)
Niels Balslev

Stevns Chalk Field Trip

The object of this excursion is an outcrop at the chalk cliffs that stretch approximately 12 km along the coastline of the peninsula of Stevns and reaches ca 40 m in height. The chalk cliffs represent one of the most prominent exposures of the Cretaceous/Tertiary transition in the world. The exposed chalk corresponds in age approximately to the upper Tor to lower Ekofisk Formation in the North Sea chalk fields (Fig. 2), and is in some aspects an analogue to the chalk formations in the oil/gas reservoirs in the North Sea.

Introduction.

Stevns Klint is situated at the peninsula of Stevns, Zealand (Sjælland), Denmark, approximately 40 km south of Copenhagen (Fig. 1). At Stevns Klint, a section of 20-40 m of chalk/limestone of Latest Cretaceous (Maastrichtian) to Early Palaeocene (Danian) age is exposed in a 12 km long coastal cliff (Figs. 3, 4). At Højerup, the locality visited during the field trip, approximately 30 m of chalk and limestone is exposed.

Geological setting.

Stevns Klint is situated over a fault limited structural high between the eastern end of the Ringkøbing-Fyn High and the Fennoscandian Border Zone (Fig. 5). The Maastrichtian facies types at Stevns are of more shallow water types than in the majority of exposures in Denmark according to Surlyk (1979). The same general facies pattern is also detected in the Early Danian deposits, where pelagic chalk occurs only in the westernmost part of Jylland (Håkansson & Thomsen, 1979). At Stevns the Danian is developed as fossiliferous limestone deposited partly as bryozoan mud mounds.

The Upper Cretaceous chalk reaches a maximum thickness of ca. 1800 m. in the Danish Sub-basin, of which the Maastrichtian accounts for ca. 700 m. (Stenestad, 1972)(Fig. 6). General considerations on the sedimentation rate for the Maastrichtian chalk have been presented by Håkansson et al. (1974), who arrived at an average around 0.15 mm/year. For much of the sequence this average is meaningless, since single thick units may have been deposited as slurry flows or other abrupt processes. Conversely, periods with very slow sedimentation and non-deposition is shown by existence of hardgrounds and omission surfaces (Bromley 1979).

At the Fennoscandian Borderzone north and north-east of Stevns much of the Maastrichtian and Danian near-shore facies are lacking due to the uplift in the areas to the NE. Considerable thicknesses of chalk/limestone sediments could have existed here into Sweden prior to uplift of the craton margin and erosion.

According to Japsen (1993), the chalk on Stevns has been buried to at least to a depth of 1000 meters prior to the alpine uplift. This is deduced from the investigation of the sonic velocities from wells drilled nearby. However, this conclusion is not in keeping with estimates of the former thicknesses of the overlying Tertiary formations, which most likely allow no more than approximately 400-500 m burial.

The chalk in the Stevns area is exposed due to gentle, large-scale alpine deformations (Fig. 7); in the uppermost part of the exposures, modest glacially induced deformations are locally seen. Large scale faulting is not an important element in the deformation pattern, but sub-vertical joints and horizontal cleavage surfaces are very prominent in the whole section.

The lithological succession.

The Maastrichtian section at Stevns Klint consists of white to light-grey, friable, coccolithic chalk, dominantly representing autochthonous sedimentation.

The Maastrichtian is represented by different subfacies of chalk and a total thickness of c. 35 m is exposed along the Stevns Klint itself. The different lithofacies at this locality are presented following the description by Surlyk (1979) and the sequence at Højerup is summarised on Figure 3. The general sequence is shown on Figure 4.

The lowest exposed 5-10 metres of chalk along Stevns Klint, comprises a sequence of white chalk with a large content of bryozoans. It was deposited as low mounds, with geometry outlined by the flint bands. Some of the mounds show a slight overlap. Above this a sequence of c. 20 m of white chalk with apparent horizontal bedding. The bedding is indistinct, except for being outlined by horizons with scattered flint nodules and trace fossils. Generally there is a low fossil content and the unit is characterised by a high density of *Zoophycos* burrows (Fig. 8). The flint bands generally outline a near horizontal layering. At Højerup only the top of this chalk interval is exposed. In the top part of this unit, c. 3-4 meters below the Cretaceous/Tertiary boundary, a prominent nodular flint layer occurs. This layer can be traced along most of Stevns Klint. In many places this flint layer in the top part is succeeded by two omission surfaces with incipient hardgrounds with weakly lithified chalk below. These two surfaces are easily picked out by their yellow-brownish tint.

These two omission surfaces at the top of the white Chalk, ca. 10 cm apart, mark temporary interruptions in the sedimentation. These hardgrounds form the separation to the overlying unit of grey chalk, c. 2.5 to 3.5 m thick, having a relatively high content of small benthic fossils (up to 20%), mostly bryozoans. The sediment is classified as bryozoan wackestone. The colour of the Grey Chalk is due to the presence of small amounts of carbon black (soot!) (Hansen et al., 1987). The grey chalk was deposited as low asymmetric, slightly overlapping biohermal ridges or mounds. The southern flank is steepest and shortest (the stoss-side) and prominent flint bands are only found within the less steep northern flank (lee-side). The growth of the bioherms is probably comparable to the processes interpreted by Thomsen (1976, 1977) for asymmetric Danian bioherms, where the mounds grew under the influence of unidirectional currents which facilitated growth in the upcurrent direction. The bioherms in the grey chalk is characterised by *Thalassinoides* trace fossils, and these are sometimes internally burrowed by *Chondrites*. Small scale synsedimentary slumping and mass flows occurred on the flanks involving beds only a few tens of cm. thick and 1-2 m. long. This unit of Grey Chalk is terminated by the Cretaceous/Tertiary (K/T) boundary.

The Grey Chalk is overlain by dark, marly clay of Danian age, which drapes the undulating topography created by the tops of the bryozoan mounds in the Grey Chalk. The clay bed, termed the Fish Clay, is thickest (up to 25 cm) in the depressions and wedges out upslope of the mounds (Figure 4). In detail the Fish Clay has been divided into four discrete layers; a basal grey marl bed followed by a black, silty, and marly clay bed with pyrite concretions, interlaminated black clay and light grey marl, which only is present in the central parts of the depressions, and a light grey marl bed with fragments of chalk (Christensen et al., 1973). The K/T boundary at Stevns Klint has been investigated in great detail, and still holds the world record for Iridium anomaly, found in the Fish Clay immediately above the boundary.

The Fish Clay is overlain by up to 0.5m of *Cerithium* Limestone which fill the depressions between the mounds of the grey chalk (figure 3). The *Cerithium* Limestone is also denoted the "dead layer" due to its scarcity in biogenic material (Ødum, 1926). The lack in biogenic material has caused Hansen (1990) to suggest a predominant inorganic origin of this layer. The *Cerithium* Limestone is also found in outcrops in Northern Jylland, where its thickness reaches several meters.

The top of the *Cerithium* Limestone is marked by an unconformity. Erosion at this level also has removed the highest parts of the Maastrichtian mounds in the Grey Chalk. The unconformity is developed as a hardground, with prominent *Thalassinoides* burrows, which pierce both the *Cerithium* limestone and the Grey Chalk (Rasmussen, 1971; Surlyk, 1979; Ekdale & Bromley, 1984). Above the hardground the Danian Bryozoan Limestone tops the succession. The Bryozoan Limestone is developed as up to 20 m thick biohermal structures with east-west elongations, steep southern, and more gentle northern slopes. The internal structure of the bioherms is outlined by numerous flint bands and occasional thin hardgrounds, mostly found on the northern leesides (Surlyk, 1979). The combined progradation and aggradation pattern of the mounds shows adequate accumulation-space for the mounds that seems to have been deposited well below wave-base, at water-depths in the order of 100 meters (F. Surlyk, pers.comm.).

The development of the Danian sequence as dominated by bryozoan mounds is probably a result of the near-shore or shallow-water situation. In the North Sea reservoirs the Danian is developed more as chalk mudstone with less macrofossils and less flint. The onshore Danian therefore seems not to be a direct analogue to the North Sea Ekofisk Formation.

The boundary dispute.

Stevns Klint is a prominent exposure of the K/T boundary. This boundary coincides with one of the most dramatic mass-extinction events among plants and animals in the geological record. A sometimes very intense debate has in recent years been going on between supporters of different theories regarding the events taking place on and around the Cretaceous/Tertiary transition.

The debate was initiated by the discovery in 1980 of an anomalous enrichment of the rare element iridium in the Fish Clay at Stevns Klint and other boundary localities around the world. The presence of iridium, being a relatively more frequent constituent in extraterrestrial material, along with other indications, caused several authors to suggest the instantaneous effect of a major meteor impact to be the direct reason for the mass-extinctions at the K/T boundary (e.g. Alvarez et al., 1980, 1982, 1984; review in Danish in Rasmussen, 1993).

The impact theory was opposed with arguments stemming from a.o. the documentation of the gradual character of the mass-extinction (Birkelund & Håkansson, 1982, Ekdale & Bromley, 1984). An alternative explanation for the events at the K/T boundary has been suggested by e.g. Hansen (1990) who explains the gradual mass-extinction to be the effect of a series of

volcanic eruptions, which gradually influenced and changed the ecological conditions, to which the Cretaceous flora and fauna had been adapted. The carbon content in the grey chalk and the iridium anomaly are interpreted as derivatives of the volcanic outbursts (Hansen, 1990).
Indications of sea-level fall at the K/T boundary and possibly immediately before (F.Surlyk, pers.comm.) adds to the complexity in interpreting the sedimentological and faunistic changes at this horizon.

Petrophysics of outcrop chalk

Investigation of petrophysical properties has been carried out in the uppermost Maastrichtian and lowermost Danian sequence (Frykman, 1994). The area in which these investigations have been carried out is the quarry at Sigerslev (Fig. 1) operated by Faxe Kalk A/S, ca. 5 km north of Højerup. The Sigerslev quarry exposes the uppermost 25 meters of the Upper Maastrichtian chalk as well as a few meters of the overlying Danian limestone. In the northern end of the quarry the white chalk of the uppermost Maastrichtian was sampled by drilling tightly spaced, one inch plugs from the wall (Figures 9, 10, 11). A total of 141 samples were obtained representing a vertical section of 8 m. At one horizontal level a total of 234 samples represents a lateral section of 27 m. Measurements of porosity and permeability were obtained in the laboratory by conventional core analysis methods.
The chalk sequence at this locality has not been described previously in any detail, but it compares closely to the classical Stevns Klint section only 5 km away. The results of porosity and air permeability measurements for the different sample suites in the Maastrichtian chalk are shown as histograms and logs in Figures 9-11.
The crossplot of porosity and permeability (Fig. 10) shows a tight clustering of the Sigerslev-1 data from the Upper Maastrichtian white chalk. The results from the additional section covering the Maastrichtian/Danian transition outline an expected difference between the Maastrichtian and Danian samples, and also show deviations in the very uppermost Grey chalk Maastrichtian samples compared to the samples from the main suite below (Fig. 10).

Allochthony?

For some time there has been a direct association between reservoir quality of chalk reservoirs and the occurrence of allochthonous facies. The most obvious allochthonous deposits, in which intraclast of chalk, shear structures and contorted bedding occur, have been coupled with high porosity and high permeability (Brasher & Vagle 1996, and references therein). This view has been opposed by Maliva & Dickson (1992), who argue that the content of insoluble residue, clay, silica etc. is the dominating factor for the diagenetic and compactional pathway and thereby the development of reservoir quality.

It would have been optimal to have good exposures of both types of deposits in order to compare their petrophysical properties. However, the difficulty in finding onshore parallels to allochthonous chalks limits the investigations of this problem.
The only onshore example described from Denmark is the finding of a minimum 1.25 meter thick allochthonous unit in a well (Erslev 3S) penetrating the chalk on top of the Mors Saltdome in Jylland (Figure 12)(Nygaard & Frykman, 1981). This lends support to the idea of allochthony being mostly of a local nature associated largely with the

synsedimentary movement of the salt structures. Most reservoirs have been drilled on such structures and are supplying data for our view on the allochthony.

Other examples of onshore possibly allochthonous chalk have been reported by Brotzen (1945) from the Höllviken well onshore Sweden in the Maastrichtian sequence, in a region certainly not associated with salt tectonics.

A report of textures interpreted as allochthonous chalks from Rügen, Germany, has been published by Steinich (1972), but the published description does not allow a detailed interpretation of the origin of the structures.

An example of synsedimentary rupture of a hardground at Stevns is reported by Surlyk (1979) and by Bromley & Ekdale (1987) - Figure 12.

Magnificent large-scale examples of allochthony in chalk-related facies are exposed at the Normandy coast in France and have been described by e.g. Quine & Bosence (1992). The depositional regime for these allochthonous beds seems to be connected with the sloping sides of a broad channel structure running east-west into Normandy. The sediment is generally wacke- to pack-stones with a higher content of macrofossils than the Maastrichtian chalks in the North Sea reservoirs, and the Normandy sequence is therefore probably not a good analogue to the chalks in the North Sea. However, the structures are beautifully outlined by flint bands, and can be interpreted in light of redepositional processes, and the geometries might be helpful for the interpretation of possible sizes and geometries of allochthonous chalks.

Reports on the size of debris flows and slump deposits in clastic sediment systems exist, but it is doubtful whether the mechanical properties can be considered comparable for the chalk carbonate deposits.

Stevns Klint - An analogue to the chalk of the North Sea?

The Maastrichtian chalk and Danian limestone at Stevns Klint are correlatives of the North Sea hydrocarbon reservoirs in the Tor and Ekofisk Formations respectively. Palaeogeographically Stevns Klint was located relatively close to the coastline, while the North Sea chalks were deposited near the centre of the basin (Figure 13). This is reflected in the generally relatively high content of coarse skeletal grains from benthic organisms in Stevns Klint, as well as in the number of omission surfaces, and the dramatic coarsening and shallowing upwards, as compared to the North Sea counterparts. The basal white coccolithic Chalk section at Stevns Klint may, however, be considered a close analogue to the autochthonous deposits in the North Sea. The porosity in the white Chalk section of Stevns Klint varies between 42-53% while gas matrix permeabilities range between 4-14 mD (Frykman, 1994). Comparable North Sea values are generally lower, and they vary over a broader range. This probably reflects differences in the postdepositional diagenetic and burial history.

The Danian limestone at Stevns is developed as bryozoan wacke- to -packstones in biohermal facies, and is therefore not a good analogue to the more micrite dominated chalk in the Ekofisk formation of the North Sea. The different petrophysical aspect of Ekofisk compared to Tor chalk could be linked with a dominance of coccoliths with small platelets, which is shown to gain abundance from the Middle Danian (E.Thomsen, pers.comm).

The results of the core analysis of the Maastrichtian outcrop chalks have been compared to core analyses from wells in the uppermost Maastrichtian chalk reservoir zone in the Dan Field (Figs. 14, 15), which shows that a trend of porosity and permeability for reservoir chalks can be seen leading towards the very high values from the outcrops. The diagenesis and burial history of the compared samples are of course different, and further investigations outline the exact comparison of these data from outcrops to data from high-porosity reservoirs. Trends for the changes of porosity correlated with burial depth have been discussed by Scholle (1977), but the trends are generally complicated by the presence of overpressure in many of the reservoirs. For the Dan Field the reservoir depth of ca. 1800 m. is reduced to an effective burial of only 1150 m. if the amount of overpressure is accounted for.

Fractures

For the North Sea reservoirs, the fracture network is very important for the production characteristics. It is therefore necessary to evaluate if analogous patterns in faulting and fracturing can be studied in outcrops and utilised for the reservoir analysis.

The fracture system seen in the Stevns area and in the Sigerslev quarry consists of a combination of a few small faults with little offsetting, subvertical joints in a complex system, very-low-angle fractures, and horizontal cleavage surfaces. When viewing this fracture system and looking for an analogue to the reservoir fracturation, it must be remembered to filter out the features that are associated with late tectonic processes, not relevant for reservoir conditions. What is to be filtered out at Stevns is the two near-horizontal features. The very-low-angle fractures are only occurring in the topmost of the sequence, and are in some cases filled with platy flint. These fractures are interpreted to have formed during glacial dragging of the uppermost layer of the chalk sequence.

The horizontal cleavage surfaces are interpreted as unloading fractures originating from the postglacial uplift phase. In most places they form a sub-horizontal pattern, and also follow closely the flint bands which are assumed to outline the original bedding plane orientations. It therefore seems natural that the cleavage fractures to some extent are guided by the small lithological differences existing in the otherwise homogeneous chalk. Thus the position of the fractures results as a compromise between lithological contrasts and the stress field.

The tectonic history of the Stevns area with the gentle Alpine uplift probably excludes the locality from being used as an analogue for the fractured reservoirs that are developed on top of salt induced structures. For these cases must be found other outcrops, like the North Jylland Thisted area, where an underlying salt structure has brought Maastrichtian and Danian to the surface (Thrane & Zinck-Jørgensen 1997). Likewise the data from the Lägerdorf Quarry in Germany also on top of a salt structure could have a potential as analogue (Koestler & Reksten 1995).

Cyclicity

Outcrop studies have demonstrated a clear porosity layering within the chalk sequence. High porosities are encountered in all outcrop lithologies but low porosities are associated with an increase in the clay content or early diagenetic cementation. The thickness of the cycles is dependant of depositional environment. Thick cycles are found associated with event stratification and in the case of a series of rapidly succeeding periods of sedimentation, no early cementation takes place. This allows the formation of thick uniform high porosity chalk sequences.

The cyclicity recognised in the outcrop sequences is comparable to the porosity layering recorded in the off-shore wells, and all mostly in the range of 1 to 2 meter thickness (see example Figure 16). The comparison between well data and outcrops shows a distinct difference in absolute porosity but also clearly illustrates that both the relative variation in porosity and the cyclicity is the same in both outcrops and wells. The outcrop studies can be used to more clearly outline which depositional or diagenetic processes have given rise to the resulting cyclic pattern in the porosity signal.

The Dan field Maastrichtian chalk exhibits a chalk affected by compaction associated with depth of burial and according to Scholle et al. (in prep.) the tight intervals of the cycles are associated with solution seams and stylolites. From other fields it is shown that within clay-rich/clay-poor alternations, the concentration of solution seams and stylolites indicates more intense compaction in the clay rich intervals (Herrington et al. 1991). In outcrop chalk there is no evidence of compaction of the individual layers but still it exhibits the same cyclicity. It is therefore assumed that the compaction related to increase depth of burial do not amplify the porosity variation severely. Instead the porosity is reduced in a dual way where the chemical compaction related to the clay rich intervals are associated with calcite dissolution subsequent recrystallised in the pores of the clean chalk.

More on analogy of outcrops

Different investigations on reservoir chalk show that there are no distinct differences in porosity distributions between autochthonous and allochthonous chalk, and they also indicate that there is no distinct difference in permeabilities between the two depositional modes. This scheme is in accordance with the conclusion from the work made on the Eldfisk field (Herrington et al. 1991, Maliva & Dickson 1992).

Porosity reduction is found in offshore reservoir chalks affected by early diagenesis and chalks with a high content of clay (clay content of both primary sedimentary and secondary diagenetic origin (pressure dissolution))(Herrington et al. 1991). It is therefore assumed that the original porosity of the chalk is not related to mode of deposition but to the content of insoluble residue and early diagenetic cementation.

Variations in the packing of the matrix constituents and in the degree of intergranular cement are observed on samples from the Dan field (Dons et al. 1995). These variations are indicative of a dual porosity reduction. However, the data are derived from several wells and not from a continuos well section, and it has not been possible from the available data to associate the SEM analysis explicitly to intervals dominated by compaction and intervals dominated by cementation.

The effect from compaction, pressure dissolution, and the associated recrystallisation are reduced in case of overpressure in the reservoir and the overpressured chalk most probably represents preservation of a chalk at a very early diagenetic stage. The overlap in porosities between outcrop chalk and overpressured chalk is interpreted to represent the same degree of diagenetic alteration, and outcrop data is therefore expected to be considered as a close analogue to the high-porosity reservoir chalks.

Outcrop chalk with intensive early diagenetic cementation may comprise porosity values similar to late diagenetic chalk. However, to consider these as analogue for low porosity off-shore chalk are dependant on the similarities in the diagenetic alteration of the poresystem i.e. similarities in cementation related to early diagenesis and late diagenesis.

Given that the view of Japsen (1993) of Stevns having experienced 1000 meter burial, a comparison of effective burial depth for Stevns chalk and e.g. the Dan Field reservoir chalk illustrates that the two sediment packages could have experienced nearly the same effective burial depth (same effective stress) (Figure 17). Therefore compositional differences and diagenetic processes could be responsible for the developed petrophysical differences between the two types of chalk.

The chalk at Stevns only displays very few of the lithotypes present in other outcrops and in the North Sea reservoir chalks, and the one dominant lithotype - the burrowed chalk mud- to wacke-stone - is represented in the compilation of outcrop lithotypes in Table 1, which again is a subset of the full lithotype range for reservoir chalks as described in the JCR Classification Scheme (Joint Chalk Research 1996).

The similarities between outcrop data and reservoir chalk as discussed above is only valid to a certain limit. Some restrictions are to be set before postulating that early and late diagenesis have the same impact on chalk. Especially when comparing data from different formations comprising different lithologies or differences in the content of insoluble residue. The petrophysical data from outcrop chalks and reservoir chalks indicate a link between the two diagenetic different chalk types. The change in petrophysical properties seems to be controlled by clay content and texture. It may, however, also be seen that in case of similar origin and composition there is a close relationship between the petrophysical properties.

This is illustrated in Figure 18 where data from different sources associated with the pure chalk of the Tor Formation and time equivalent intervals are plotted. The data are gathered closely along the Maastrichtian trend. The outcrop data representing a low diagenetic stage (mechanical compaction) are located in the upper part of the porosity range, whereas data from the Dan field representing a high diagenetic stage (chemical compaction) are located in the lower part. In the transition zone the Valhall field data are located illustrating the impact of overpressure. Due to the high level of overpressure, the reservoir chalks have avoided chemical compaction and actually represent a low diagenetic stage where only mechanical compaction has taken place. In sequences of clean autochthonous chalks, information from outcrop investigations can potentially be used in fine-scale geomodels for upscaling exercises (Frykman 1997).

Petrophysical and petrographical analyses on both outcrop chalk and reservoir chalk show a number of similarities with respect to the diagenetic alteration. The type of cementation seems to be similar and both data sets follow the same permeability vs. porosity trend, indicative of comparable changes in the pore systems due to diagenesis. Petrographical and petrophysical analyses of outcrop chalk are therefore expected to be transferable to reservoir chalk, especially in the case of high porosity/high permeability chalks e.g. in the Valhall field. The similarities may also include rock-mechanical aspects, although this will require further investigation focusing on this subject.

With respect to chalk fields with relatively low porosities and permeabilities (e.g. the Dan field), outcrop data may still be beneficial, but some additional assumptions have to be made. In particular, the influence of non-comparable aspects such as pressure dissolution and stylolitisation, migration and presence of hydrocarbons, and overpressuring, need further examination.

Sealing capacity of chalk

Intra-chalk traps have been considered viable exploration targets for some time, although limited success has been reported. To illustrate the sealing capacity of a chalk rock, the capillary pressure curves for clean Maastrichtian outcrop chalks from Stevns and Hillerslev have been considered (Figure 19). The entry pressure of around 14 Bar for the Air/Hg measurements corresponds to ca. 1 Bar oil/water capillary pressure. This pressure can withstand a 40 meter thick oil column before breakthrough. However, correlating this to the sealing capacity is probably irrelevant, since any fractures most likely will allow a much earlier breakthrough of the chalk bed in question. The capillary pressure is probably more relevant when the saturation of different chalk layers in the reservoir have to be considered.

Conclusion

The Upper Maastrichtian Chalk sequence at Stevns is developed as burrowed chalk mudstone to wackestone, with some specific similarities to North Sea reservoir chalks.

1. the outcrop chalk is comparable to autochthonous burrowed chalk mudstone reservoir lithotype.
2. the diagenesis has had low impact on the outcrop chalk as in the overpressured high-porosity reservoir chalks.
3. a low content of insoluble residue matches that of the clean reservoir chalks.
4. fracturation pattern in outcrop might resemble that in reservoirs for some selected types of fractures (healed hairline, joints).
5. petrophysical properties (porosity, permeability) closely match similar high-porosity reservoir chalks, and forms part of the general trend shown by the reservoir chalks.
6. pore geometry seems to be comparable from outcrop chalk as deduced from the capillary pressure curves, although the mean pore size may vary.

Investigation of outcrop chalks and their layering aspect (cyclic?) can be utilised for outlining the processes behind cyclic development, and for constructing fine-scale geomodels that describe the heterogeneity pattern.

TABLE 1.

Compilation of Lithotypes for use on outcrop examples.

The table has been adopted from the JCR nomenclature scheme, and is here commented and related to depositional mode and diagenesis.

Lithotype no.	Autochthonous chalk	Allochthonous chalk	Chalk dominated by early diagenetic processes	Chalk dominated by late diagenetic processes	Comments
1	**Burrowed Massive Chalk Mudstone/ Wackestone**				The degree of bioturbation varies from very low burrow density (and diversity) to extremely high burrow density and diversity. Bioturbation may be related to severe alteration of the sediment giving rise to a structureless (massive) appearance
2	**Laminated Argillaceous Mudstone**				Is considered of autochthonous origin when associated with a rhythmically bedded chalk sequence.
3		**Burrowed Massive Chalk Mudstone/ Wackestone/ Packstone**			Is associated with episodic bedding and high energy chalk. The lithotype covers a wide range of textures and constituent of biogenic fragments.
4		**Laminated Argillaceous Chalk.**			The lithotype is associated with deposits of primary sedimentary origin. In case of clear indication of pressure dissolution the chalk was determined under the late diagenetic lithotypes.
5		**Laminated Chalk Mudstone**			
6		**Pebbly Massive Chalk Mudstone/ Wackestone.**			Clast size ranges from less than 0.5 cm to more than 10 cm.
7		**Pebbly Laminated Argillaceous Chalk Wackestone**			This lithotype is only seen in the Normandy chalk but differs severely from the lithotype with pure chalk matrix and is therefore listed individually.
8		**Deformed Chalk Mudstone**			Described in Bromley & Ekdale (1987)
9		**Massive chalk Mudstones.**			Chalk associated with episodic bedding and massive chalk demonstrating a fining upward gradation is considered as allochthonous chalk
10			**Incipient hardgrounds**		Described in Kennedy & Juignet (1974)
11			**Nodular hardgrounds**		Described in Kennedy & Juignet (1974)
12			**Massive (true) hardgrounds**		Described in Kennedy & Juignet (1974)
13				**Flaser Chalk**	Described in Bromley & Ekdale (1987)

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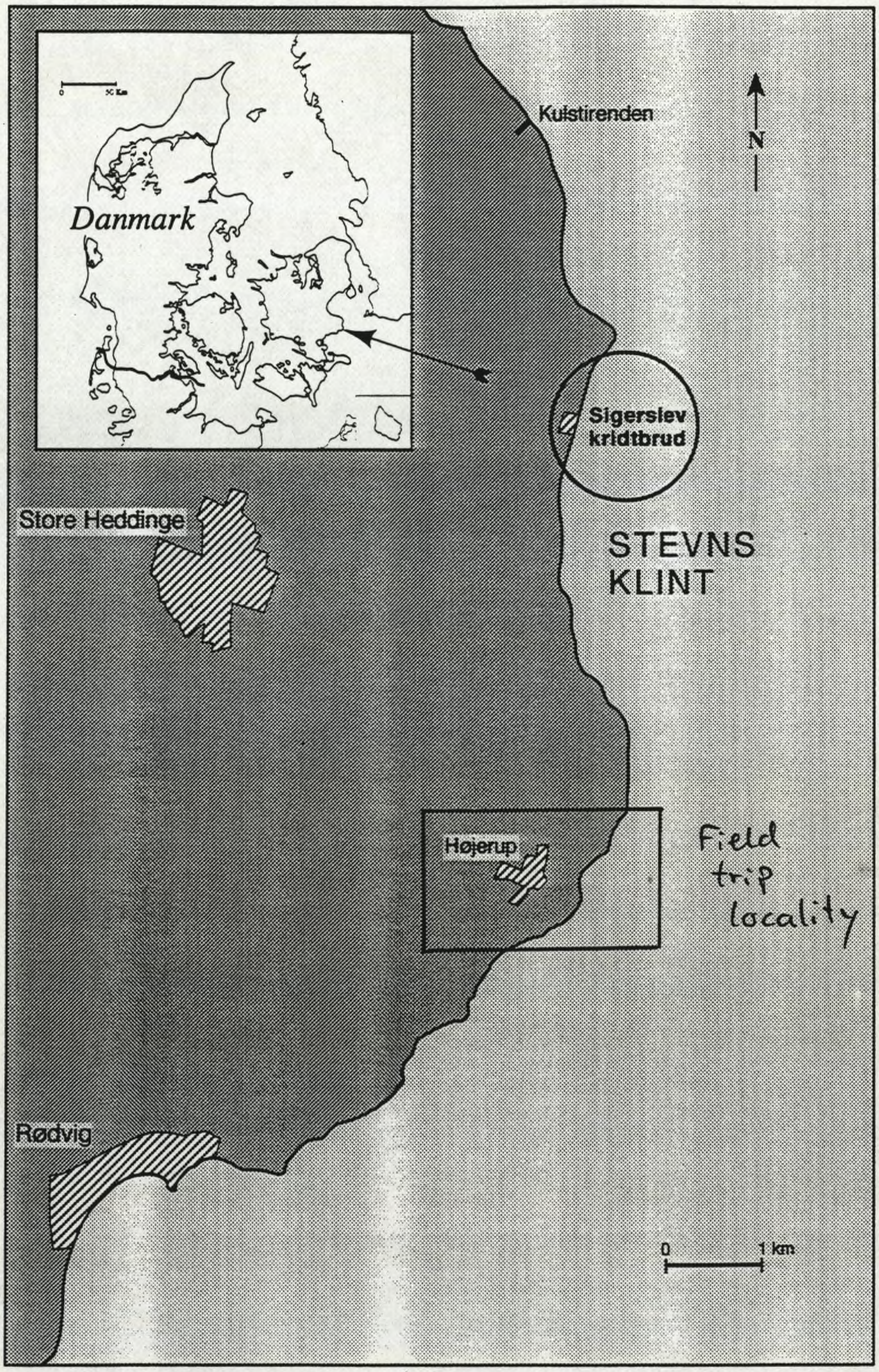
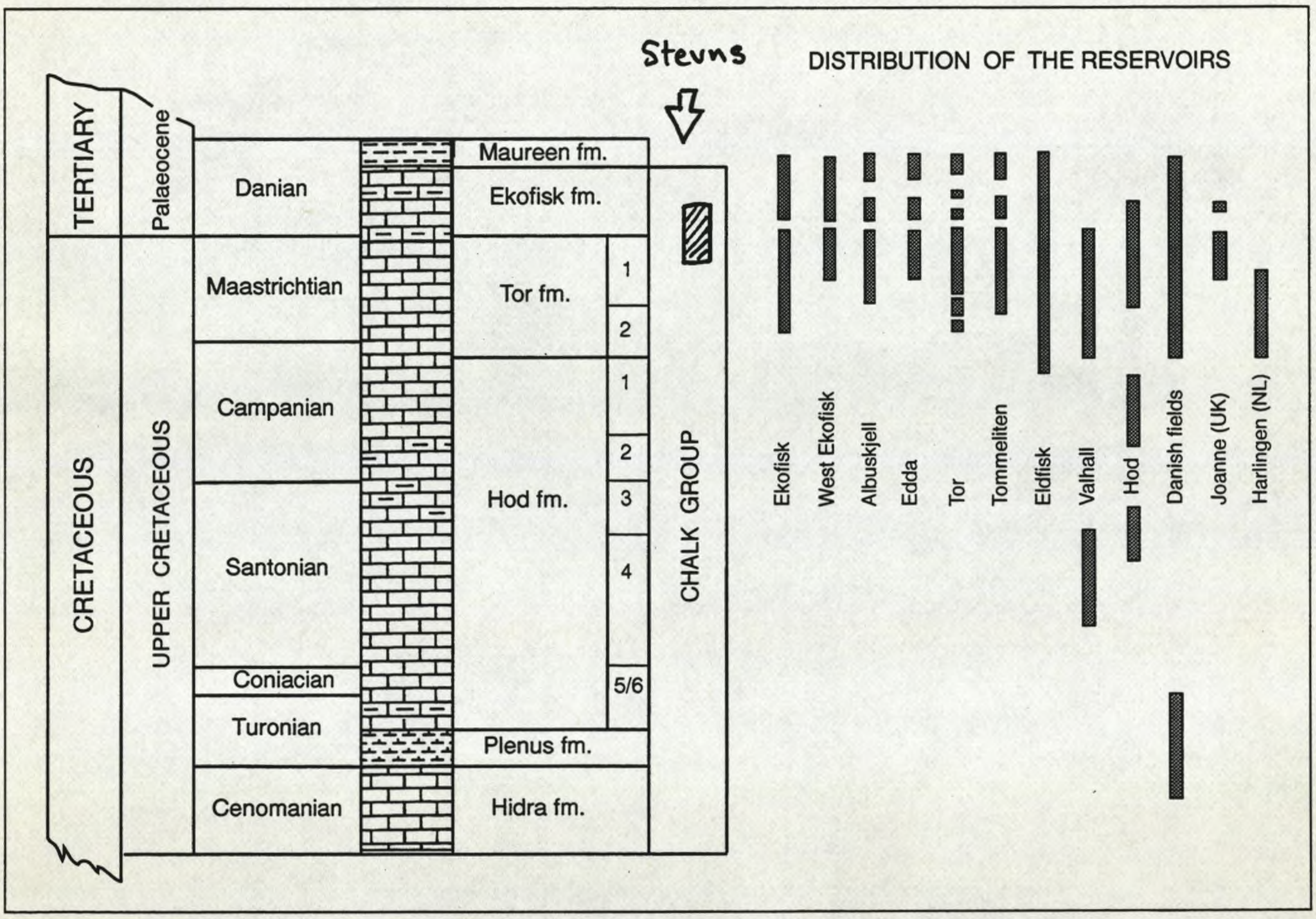


Figure 1
Location map for Stevns Klint and the visited locality at Højerup. Sigerslev is a nearby active chalk quarry.



Modified from D'Heur (1993)

Figure 2
Stratigraphic scheme showing the position of the chalk succession at Stevns compared to the North Sea reservoir sections.

Danian Biohermal Bryozoan Limestone

Above the hardground formed in both the Grey Chalk and the *Cerithium* Limestone, the Danian Bryozoan Limestone tops the succession. The Bryozoan Limestone is developed as up to 20 m thick biohermal structures with east-west elongations, steep southern, and more gentle northern slopes. The internal structure of the bioherms is outlined by numerous flint bands and occasional thin hardgrounds, mostly found on the northern leesides. The combined progradation and aggradation pattern of the mounds shows adequate accumulation-space for the mounds that seems to have been deposited well below wave-base, at water-depths in the order of 100 meters.

Cerithium Limestone

The Fish Clay is overlain by up to 0.5m of *Cerithium* Limestone which fills the depressions between the mounds of the grey chalk (figure 5). The lack in biogenic material has caused Hansen (1990) to suggest a predominant inorganic origin of this layer. The top of the *Cerithium* Limestone is marked by an unconformity. Erosion at this level also has removed the highest parts of the Maastrichtian mounds in the Grey Chalk. The unconformity is developed as a hardground, with prominent *Thalassinoides* burrows, which pierce both the *Cerithium* limestone and the Grey Chalk.

Fish Clay

Dark, marly clay of Danian age, which drapes the undulating topography created by the tops of the bryozoan mounds in the Grey Chalk. The clay bed, termed the Fish Clay, is thickest (up to 25 cm) in the depressions and wedges out upslope of the mounds (figure 5). The K/T boundary at Stevns Klint has been investigated in great detail, and still holds the world record for Iridium anomaly, found in the Fish Clay.

K/T boundary

Grey Chalk

ca. 2.5 to 3.5 m thick bryozoan wackestone. The grey chalk was deposited as low asymmetric, slightly overlapping biohermal ridges or mounds. The southern flank is steepest and shortest (the stoss-side) and prominent flint bands are only found within the less steep northern flank (lee-side). The bioherms in the grey chalk is characterised by Thalassinoides trace fossils, and these are sometimes internally burrowed by *Chondrites*. Small scale synsedimentary slumping and mass flows occurred on the flanks involving beds only a few tens of cm. thick and 1-2 m. long., having a relatively high content of small benthic fossils (up to 20%), mostly bryozoans. The colour of the Grey Chalk is due to the presence of small amounts of carbon black (soot!).

Omission surfaces

These two omission surfaces at the top of the white Chalk, ca. 10 cm apart, mark temporary interruptions in the sedimentation. These two surfaces are easily picked out by their yellow-brownish tint. These hardgrounds form the separation to the overlying unit of grey chalk

Flint layer

In the top part of this unit, c. 3-4 meters below the Cretaceous/Tertiary boundary, a prominent nodular flint layer occurs. This layer can be traced along most of Stevns Klint.

White Chalk

The lowest exposed 5-10 metres of chalk along Stevns Klint, comprises a sequence of white chalk with a large content of bryozoans. It was deposited as low mounds, with geometry outlined by the flint bands. Some of the mounds show a slight overlap.

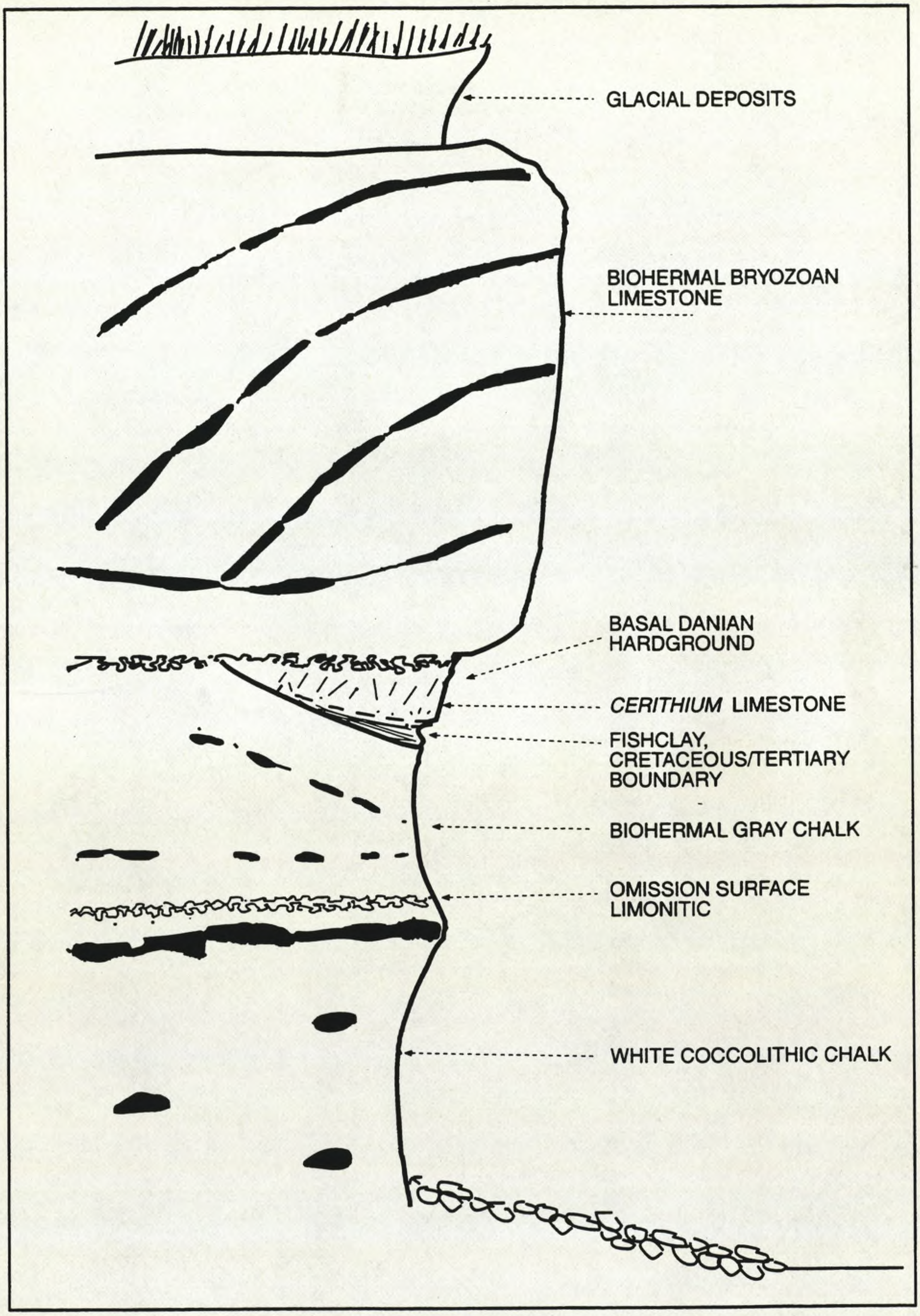


Figure 3
The lithological succession at Højerup, Stevns Klint (not to scale).

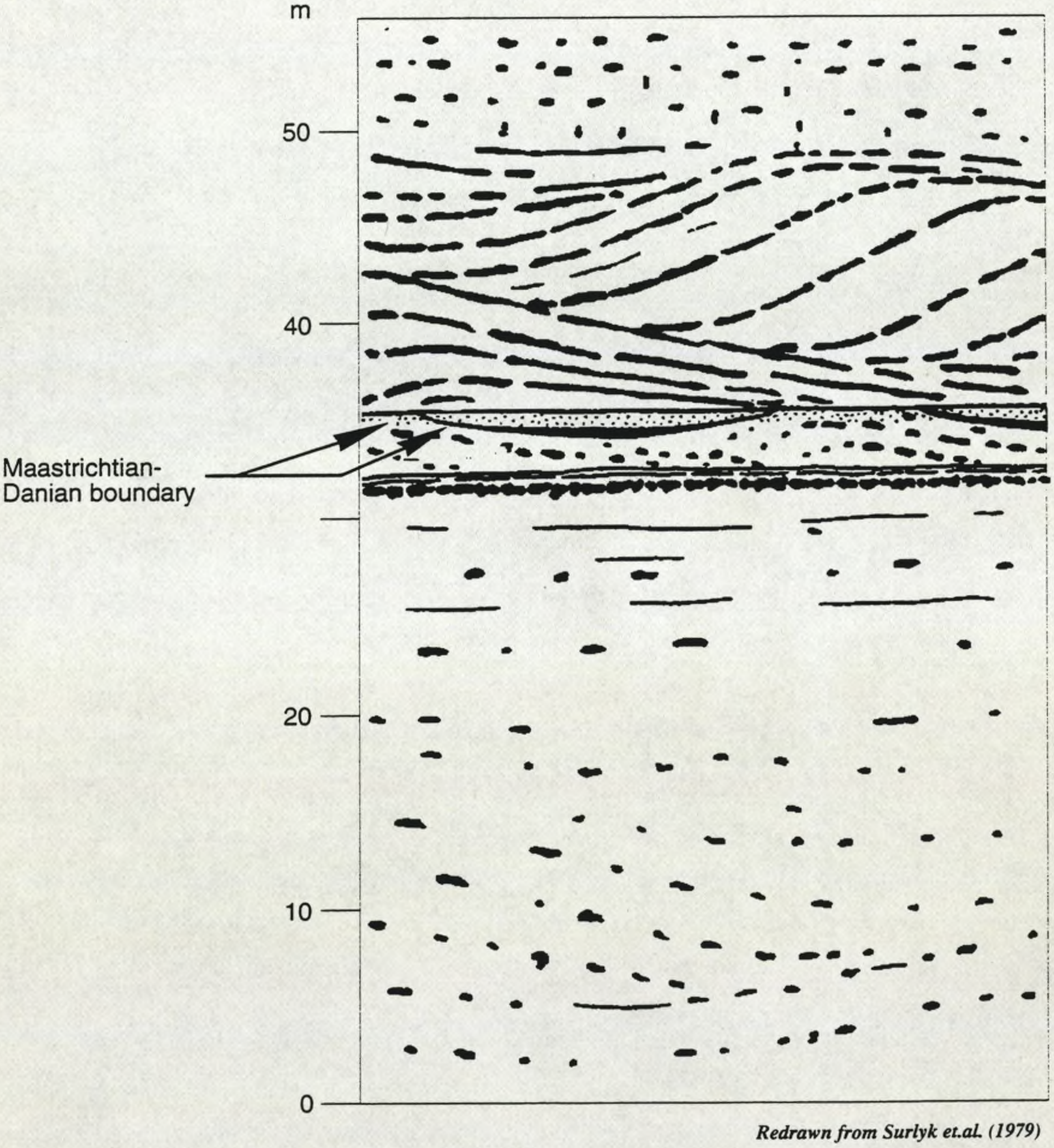


Figure 4
The lithological succession at Stevns Klint showing general bedding aspect and the position of the developed mounds in both the Maastrichtian and Danian section.

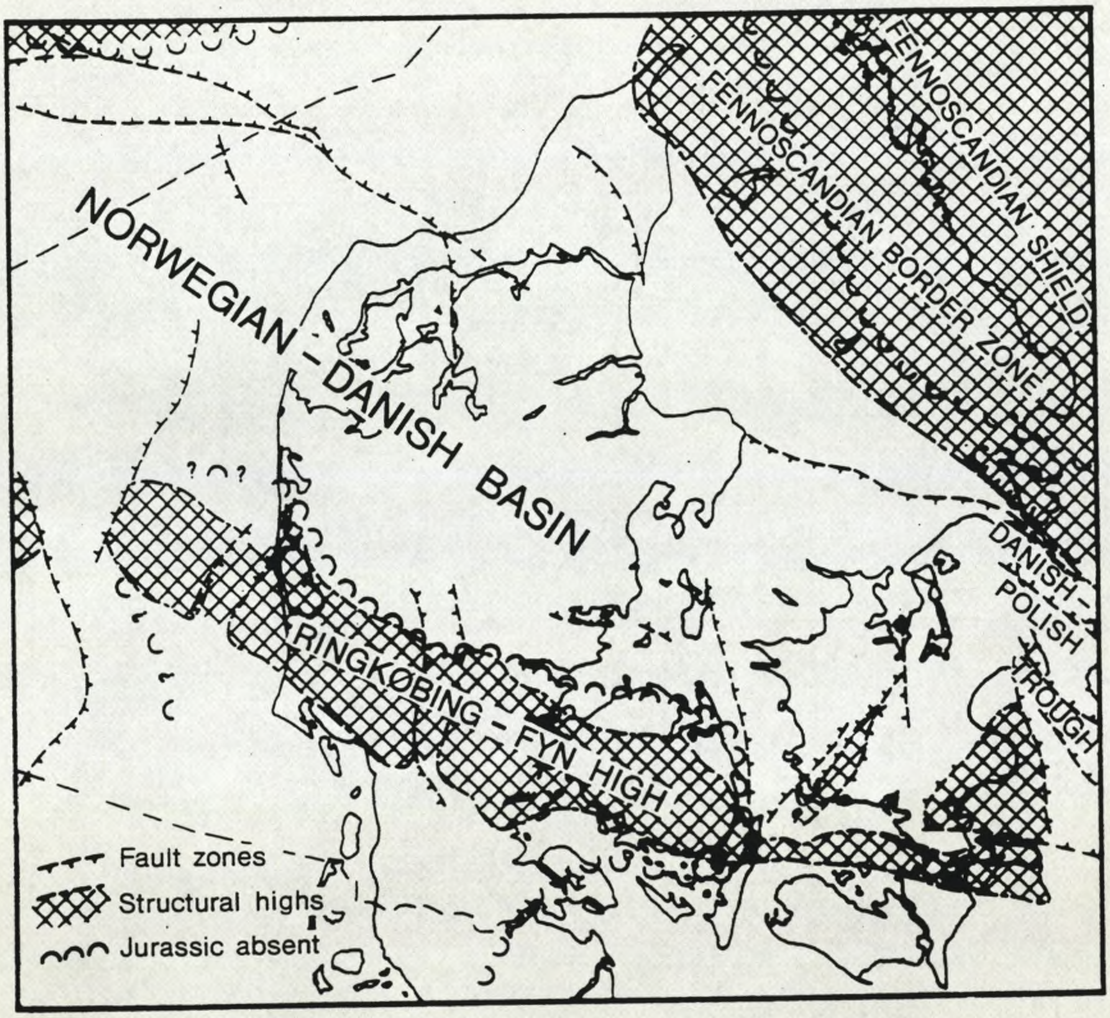
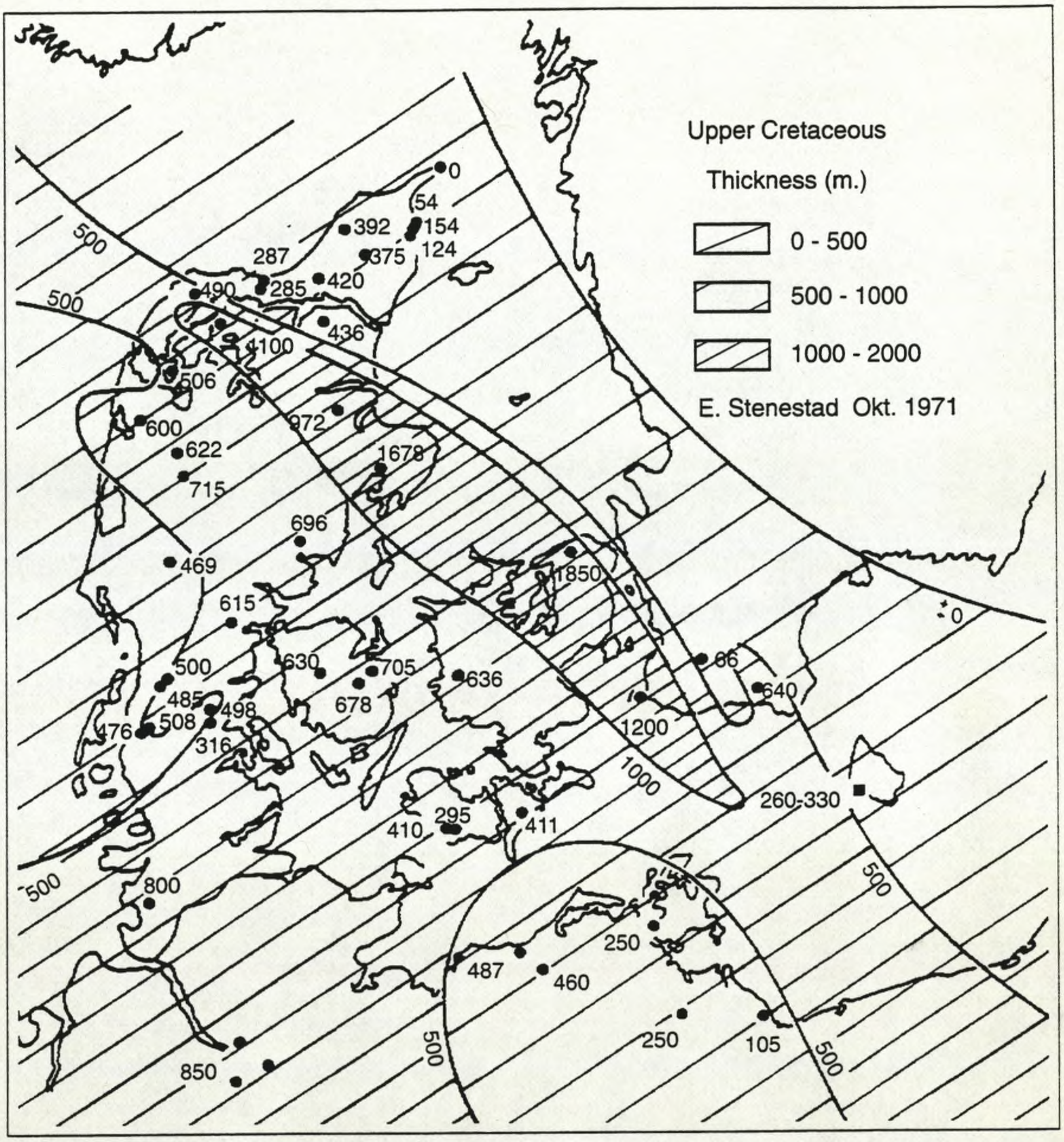


Figure 5
Map showing the main structural elements around the Norwegian-Danish Basin.
(From Rasmussen 1978)



Redrawn from Stenestad (1972)

Figure 6
Map showing thickness of the Upper Cretaceous deposits.
(From Stenestad 1972)

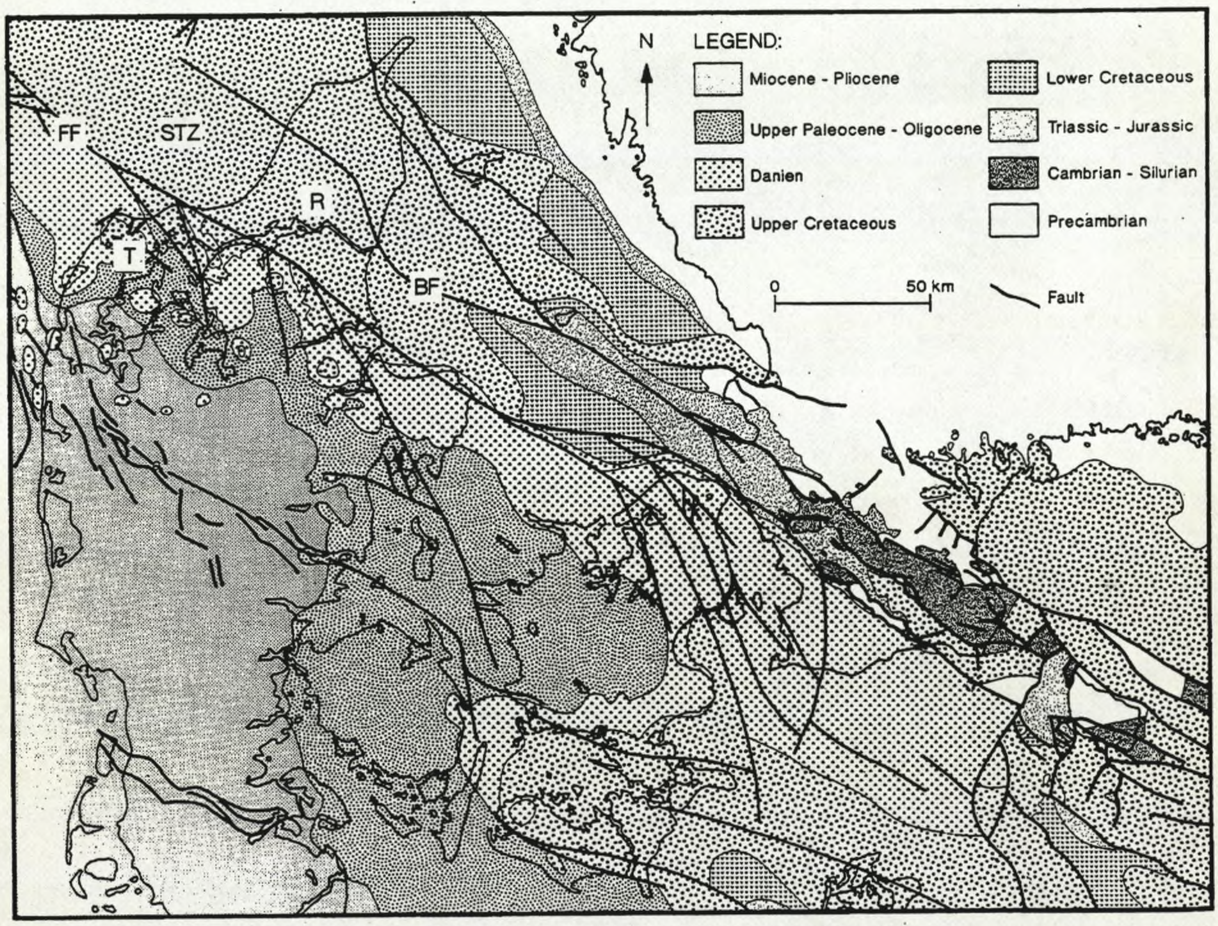


Figure 7
Sub-Quaternary geological map of Denmark. FF: Fjerritslev Fault; STZ: Sorgenfrei-Tornquist Fault Zone; BF: Børglum Fault; R: Rørdal Quarry. (From: Håkansson & Surlyk, in press)

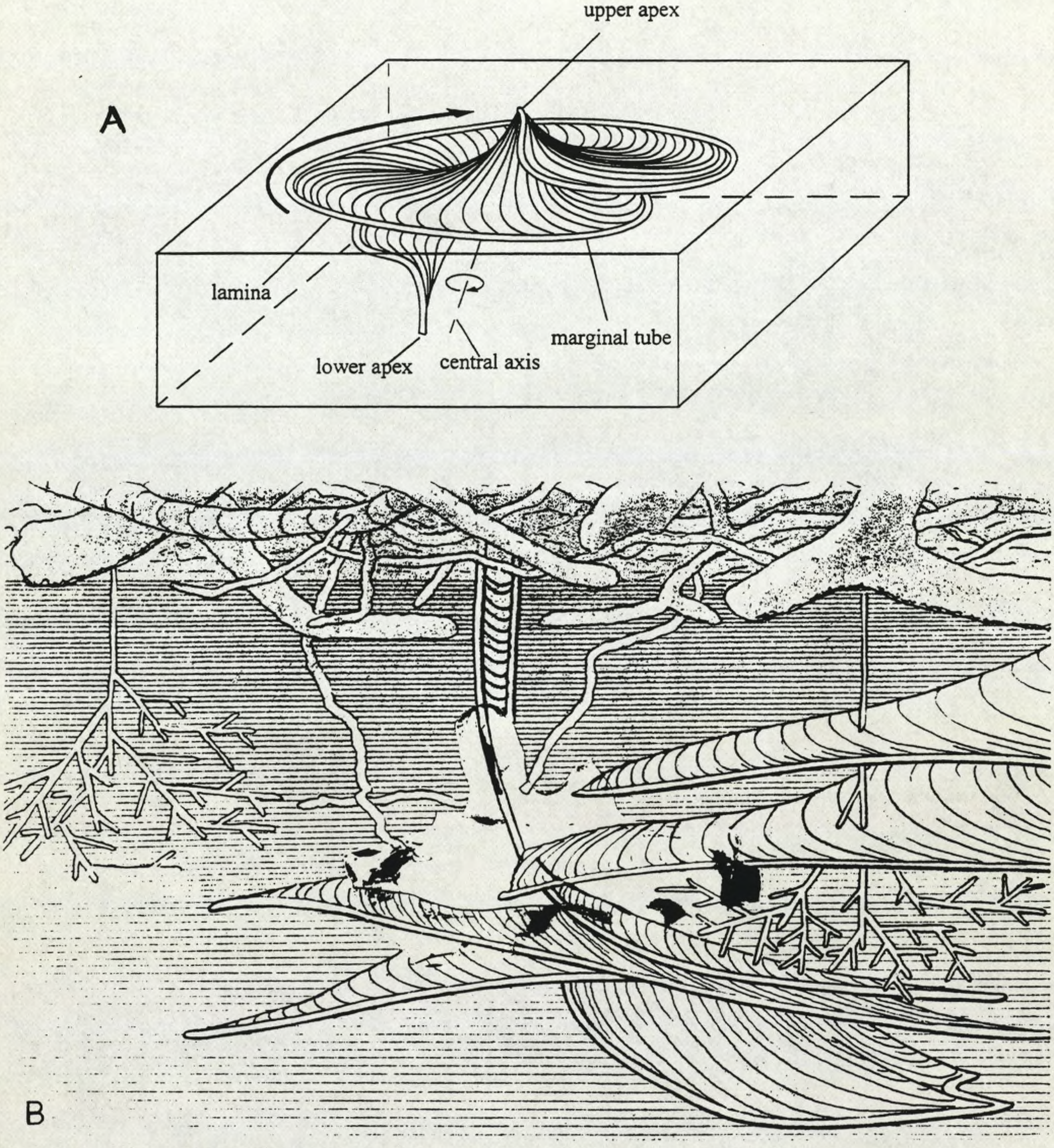


Figure 8
(A) ***Zoophycos.*** The "spreiten burrow" is constituted by a lamina spirally coiled around a central axis, not materialsed by a tube. The whorls are bound by an open tunnel, the "marginal tube", which represents the last tunnel built by the organism. The lamina is constructed upwards in the sediment following the direction indicated by the arrow. (From Olivero, 1996).
(B) Interpretation of the ichnofabric of the chalk around a flint nodule (center) in which trace fossils were found preserved. In the top part *Thalassinoides* (thick branching) and *Planolites* (thin) is found. Extending lower down is the *Chondrites* (thin branching) and *Zoophycos*.
(From Bromley and Ekdale 1984)

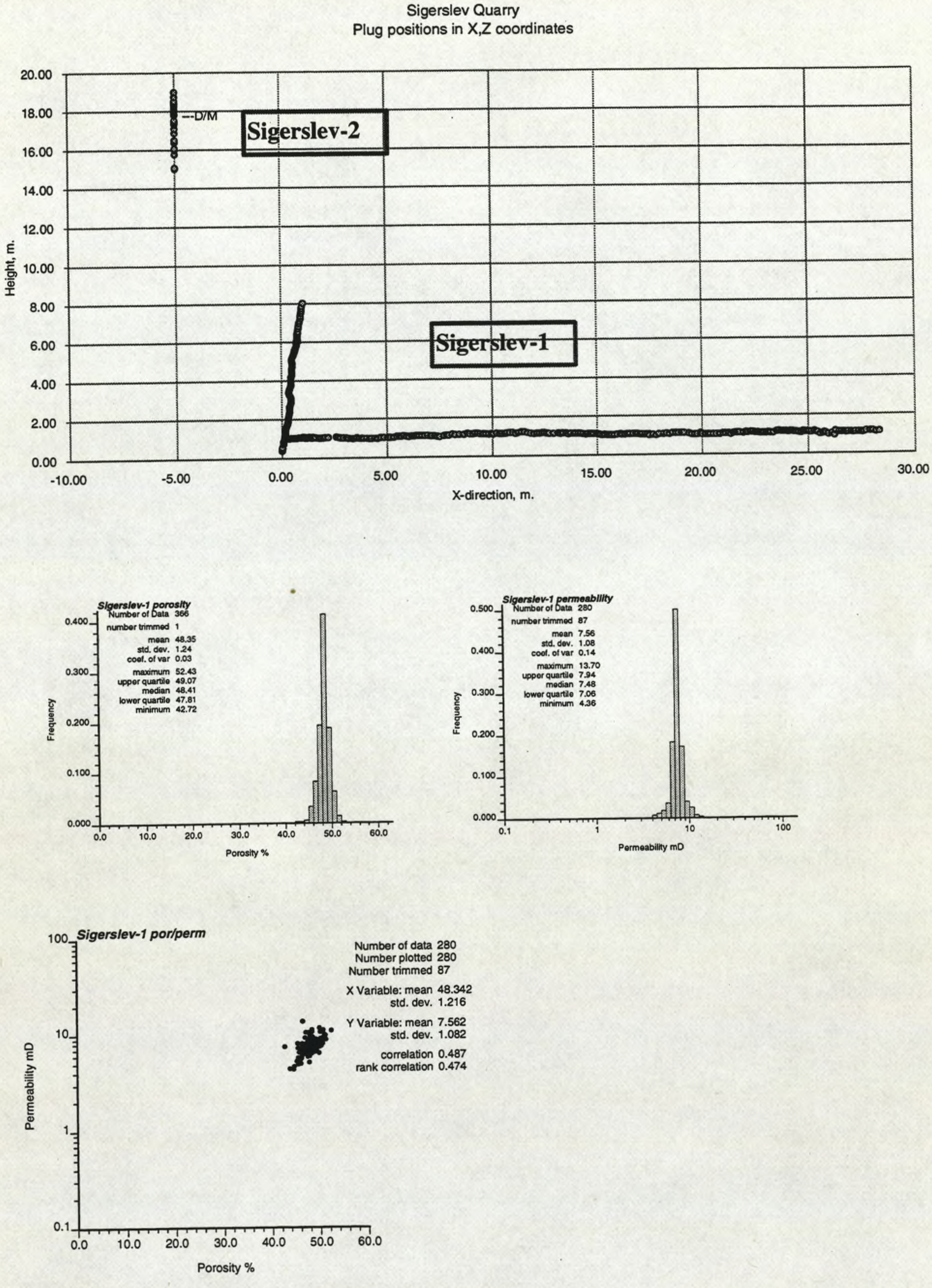


Figure 9
Diagram showing the position of plug data from the two subsets Sigerslev-1 and -2 from the Sigerslev Quarry wall section. The Maastrichtian/Danian boundary is within the Sigerslev-2 set. Histograms and crossplot of porosity and permeability data from the Sigerslev-1 data set.

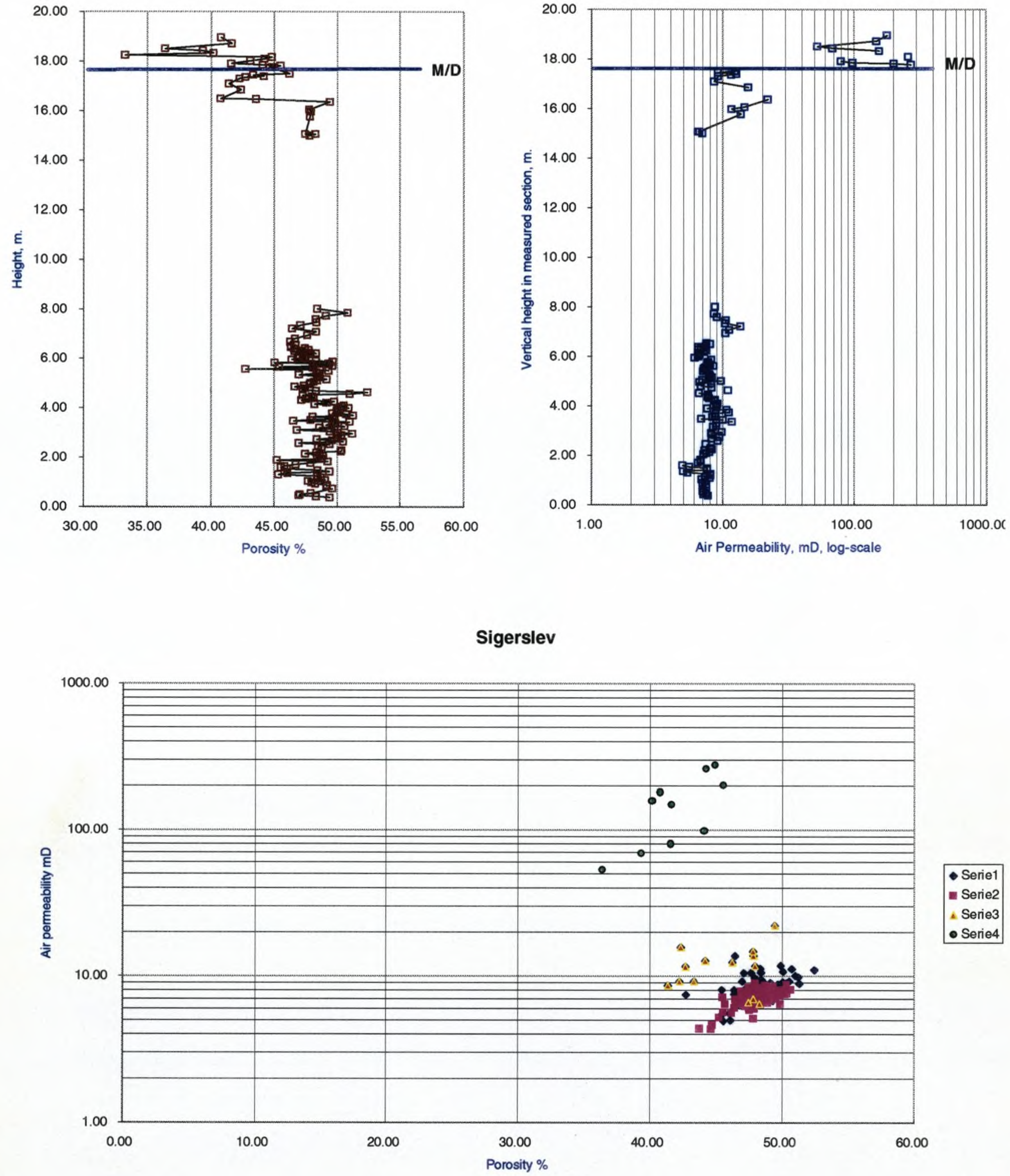


Figure 10
Plots of porosity and permeability data from the vertical section in Sigerslev showing the abrupt change at the Maastrichtian/Danian boundary. The crossplot outlines the distinct difference between the Maastrichtian (serie1,2,3) and the Danian (serie4) samples. The uppermost Maastrichtian samples from just below the boundary (serie3) deviate slightly from the main cluster of Maastrichtian chalk.

Figure 10

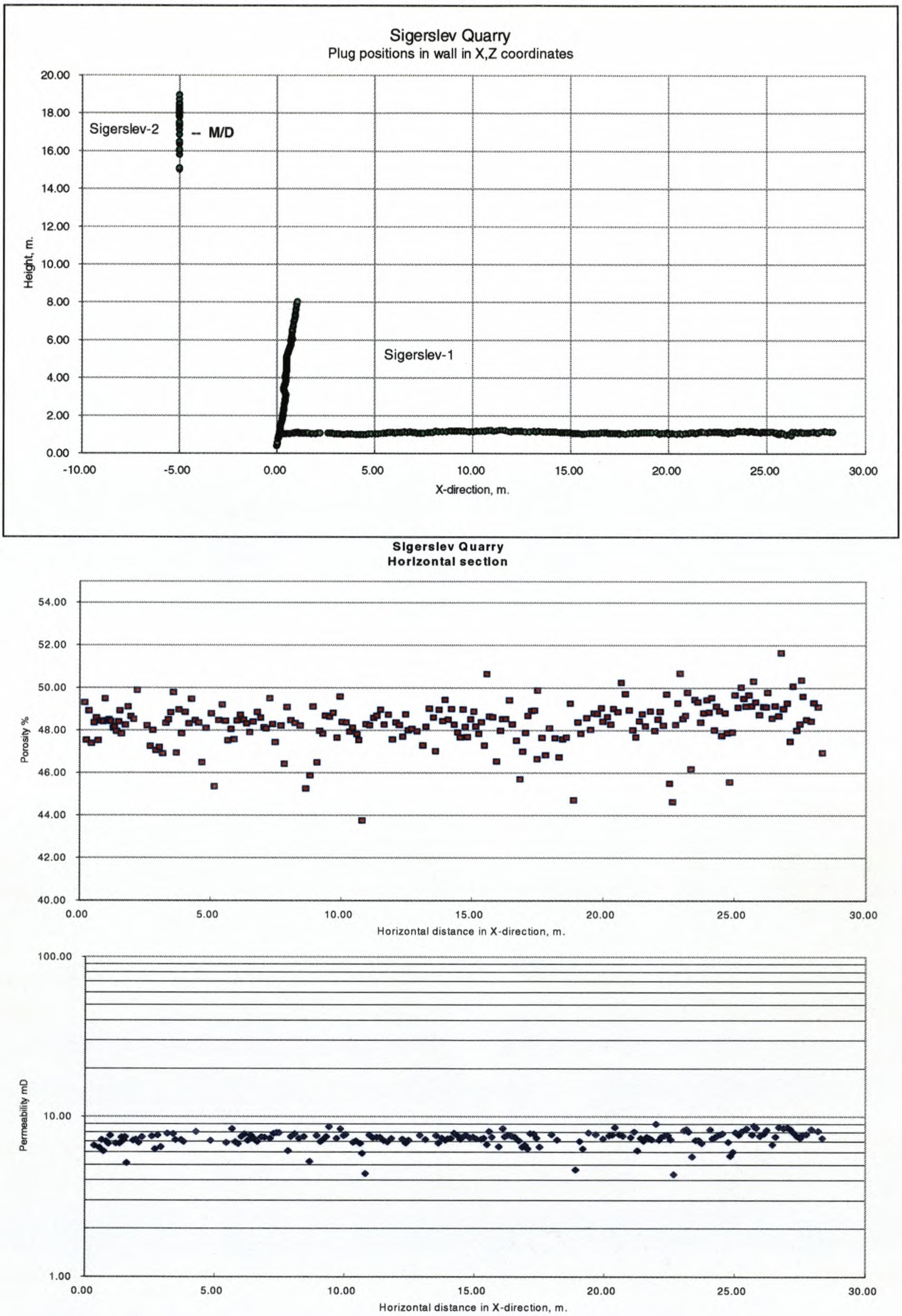


Figure 11

A: Diagram showing the position of plug data from the two subsets Sigerslev-1 and -2 from the Sigerslev Quarry wall section. The Maastrichtian/Danian boundary within the Sigerslev-2 set is indicated.

B: Porosity data from the horizontal section following one single bed of chalk in the Sigerslev-1 profile. C: Permeability data from same section.

Figure 11

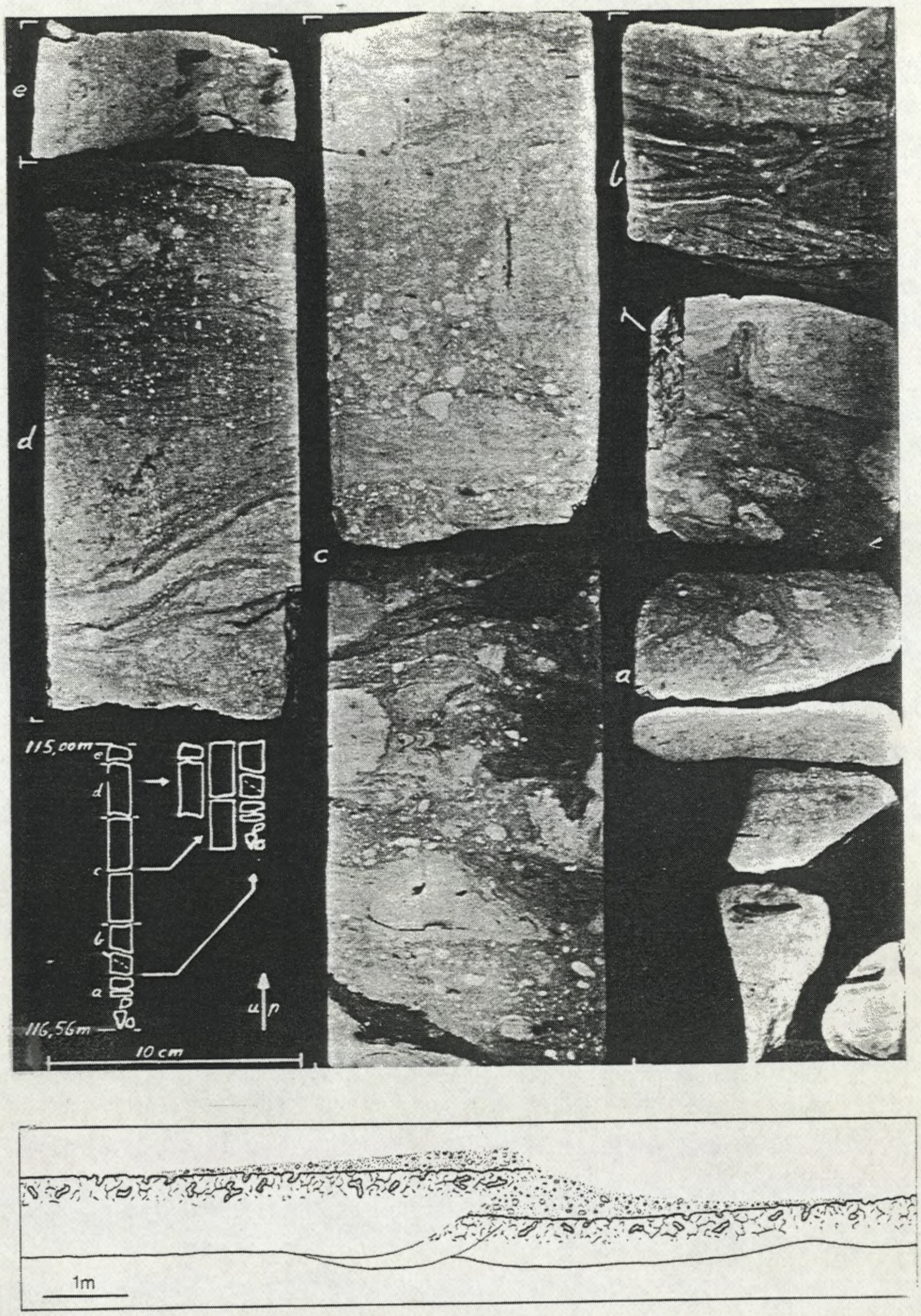


Figure 12
(A) Characteristic sections of the allochthonous chalk found in the Maastrichtian core from the well Erslev 3S on the island of Mors, Northern Jylland, Denmark. Note the chalk intraclasts and the shear deformed layers. (From Nygaard & Frykman 1981).
(B) Sketch of hardground ruptured by slide. Maastrichtian/Danian boundary hardground at Kulsti Rende, Stevns Klint, Denmark. (From Bromley & Ekdale 1987)

Figure 13
Palaeogeographic map of Central Europe and the North Sea area showing the maximum extension of the sea during Late Cretaceous. The map also shows the present-day extra-Alpine outcrops of chalks and related facies and areas with Late Cretaceous inversion. (Modified from Scholle, 1974; Hancock, 1975 and Ziegler, 1990).

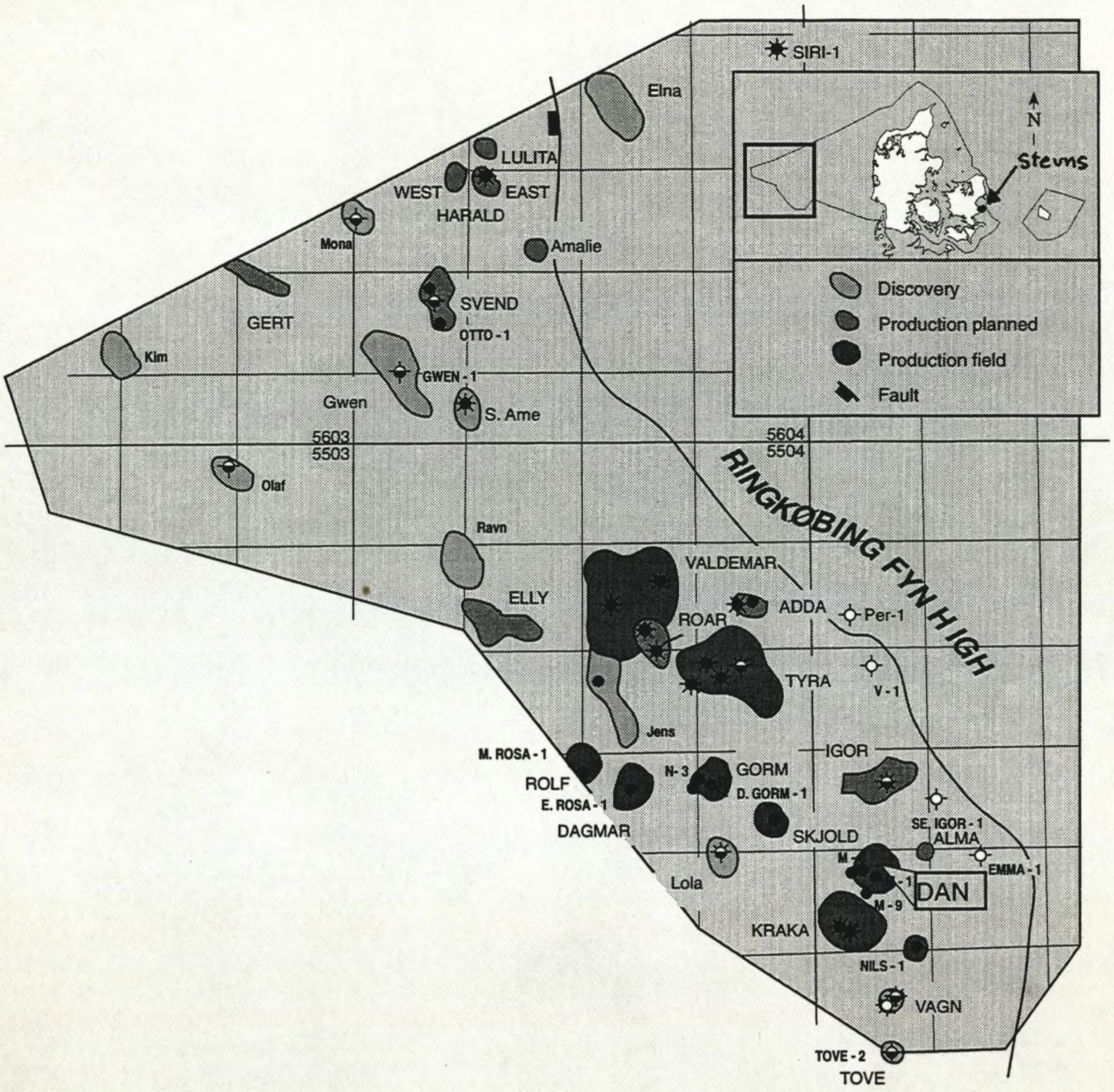


Figure 14
Map of the Central Graben area showing oil/gas fields and selected wells. Dan Field location is marked.

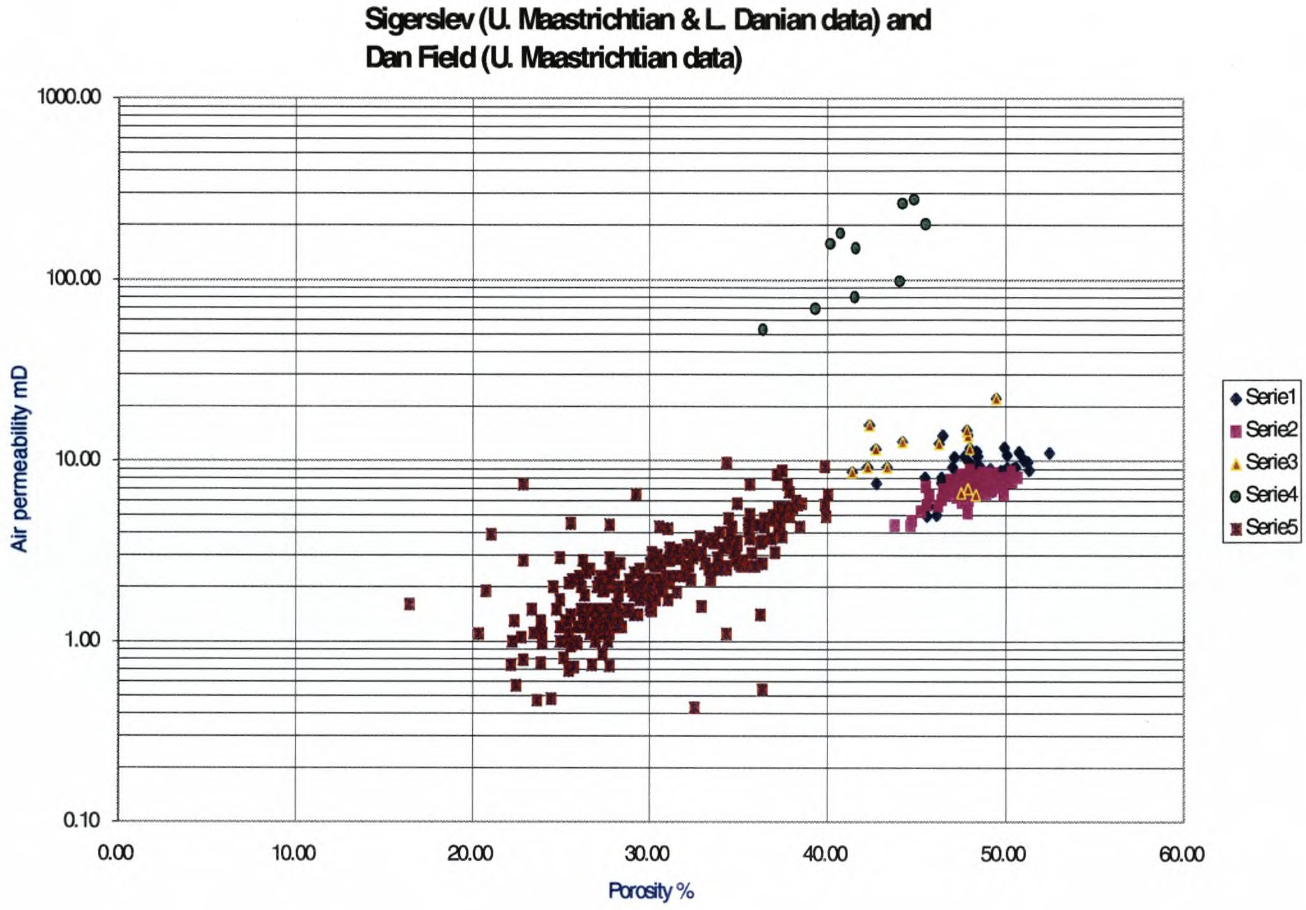
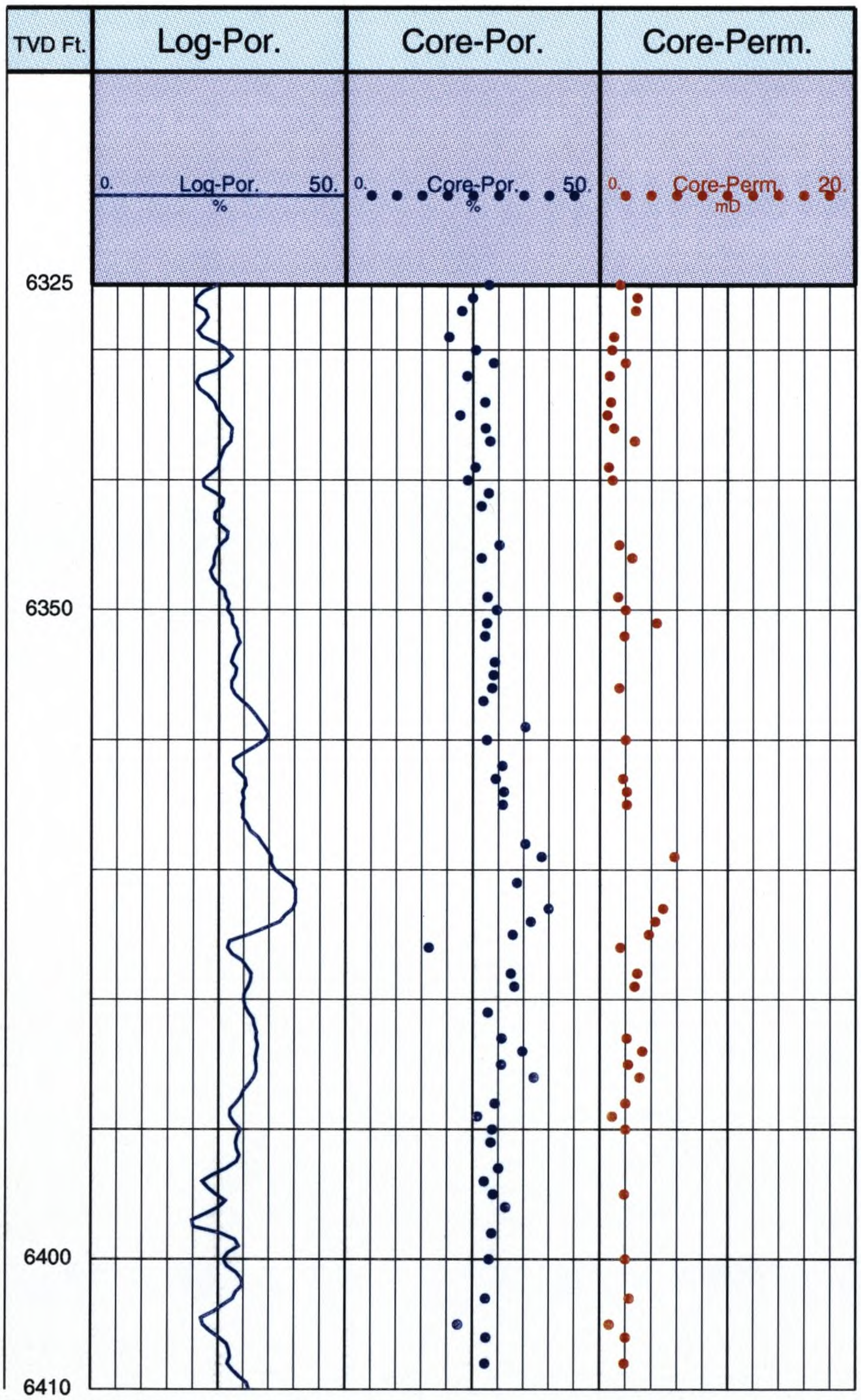


Figure 15

Crossplot of porosity and permeability for core-analysis data from wells in the uppermost Maastrichtian in the Dan Field Chalk reservoir (red serie5) compared with the data suite from the Sigerslev chalk outcrop (serie1,2,3,4).

Figure 15



M10x, Dan Field, U. Maastr. TVD plot

(c)X.(Frank)Liu 1993

Figure 16

Section through the uppermost Maastrichtian (unit M12) section from the well M10x from the Dan Field showing log-interpreted porosity, core-porosity and core-permeability data. The regular variations (cyclic?) in porosity with ca. 8 p.u. difference between high-low layers are seen.

Figure 16

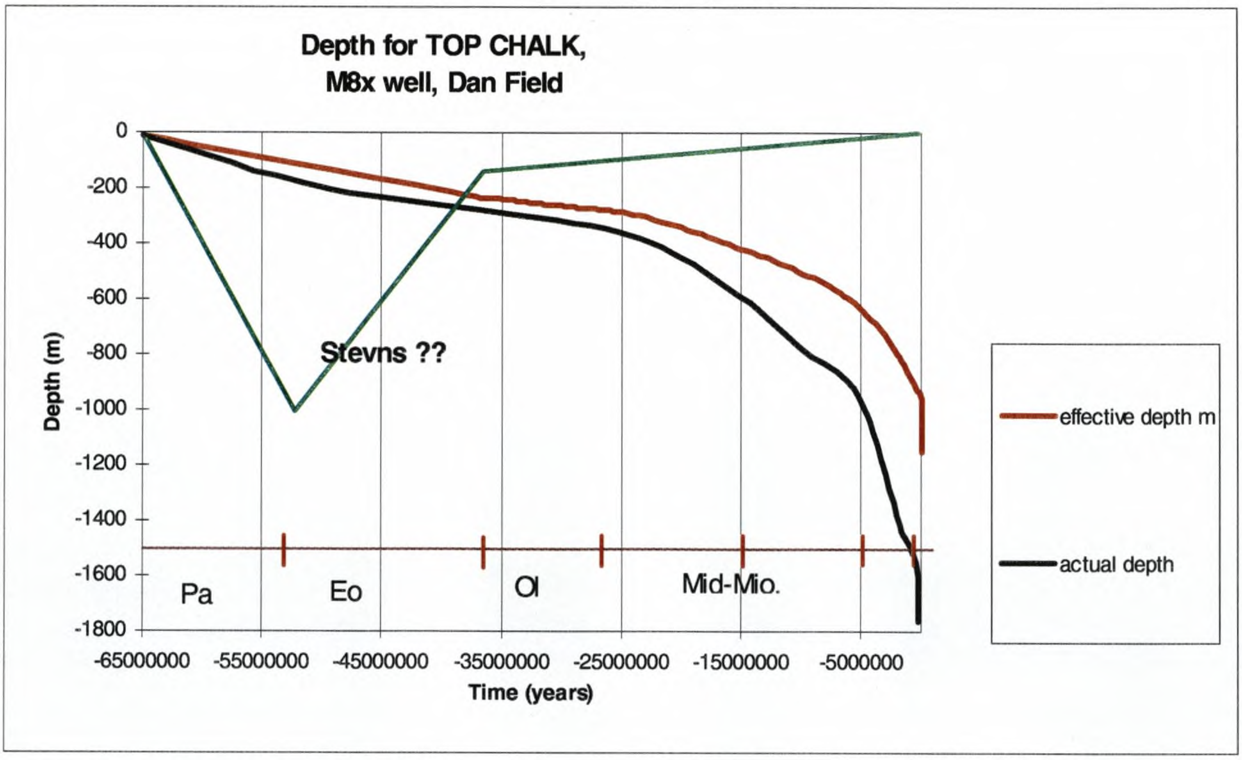


Figure 17.

Tentative comparison of burial history for a well on the Dan Field and the Stevns area. Accepting the view by Japsen (1993) means that the two examples have been buried to nearly the same effective burial depth, however, at different rates and duration.

Figure 17.

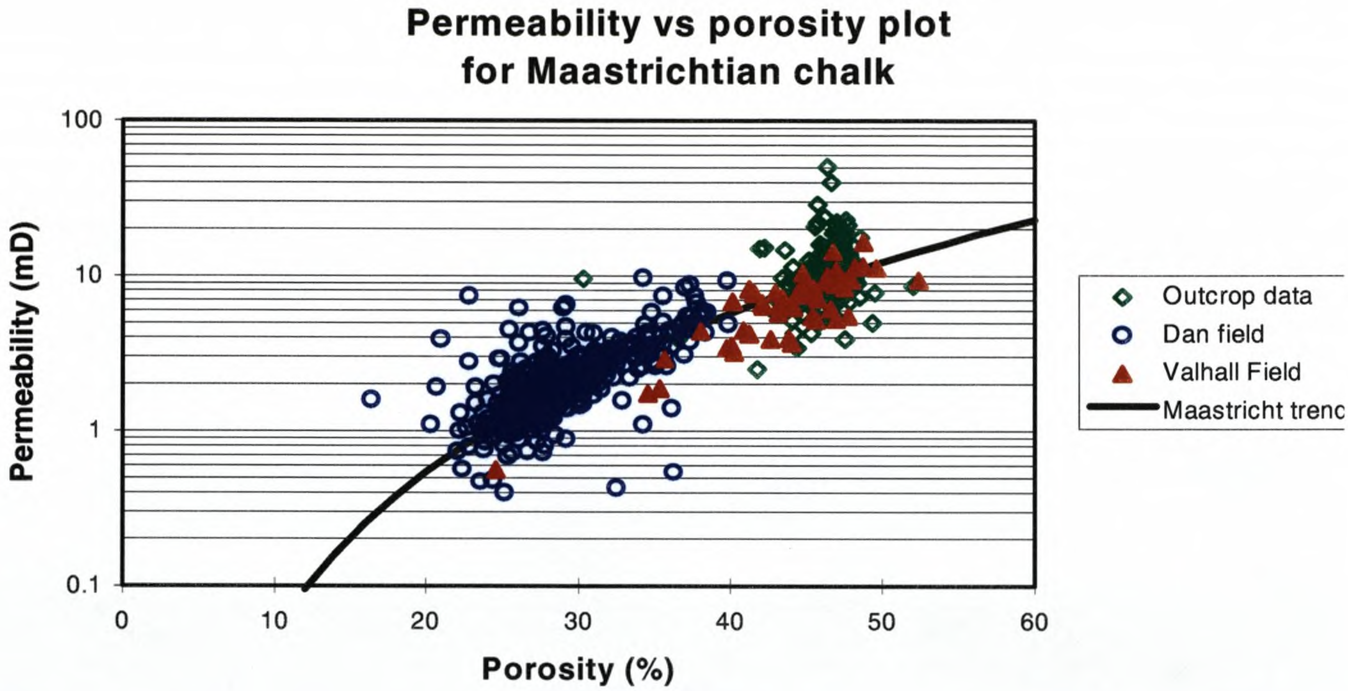


Figure 18

Porosity versus permeability plot of outcrop and reservoir chalk data related to the Tor 1 formation and time equivalent intervals. The data set includes data from outcrops on Rügen and North Jutland, and from the Dan and Valhall fields.

Figure 18

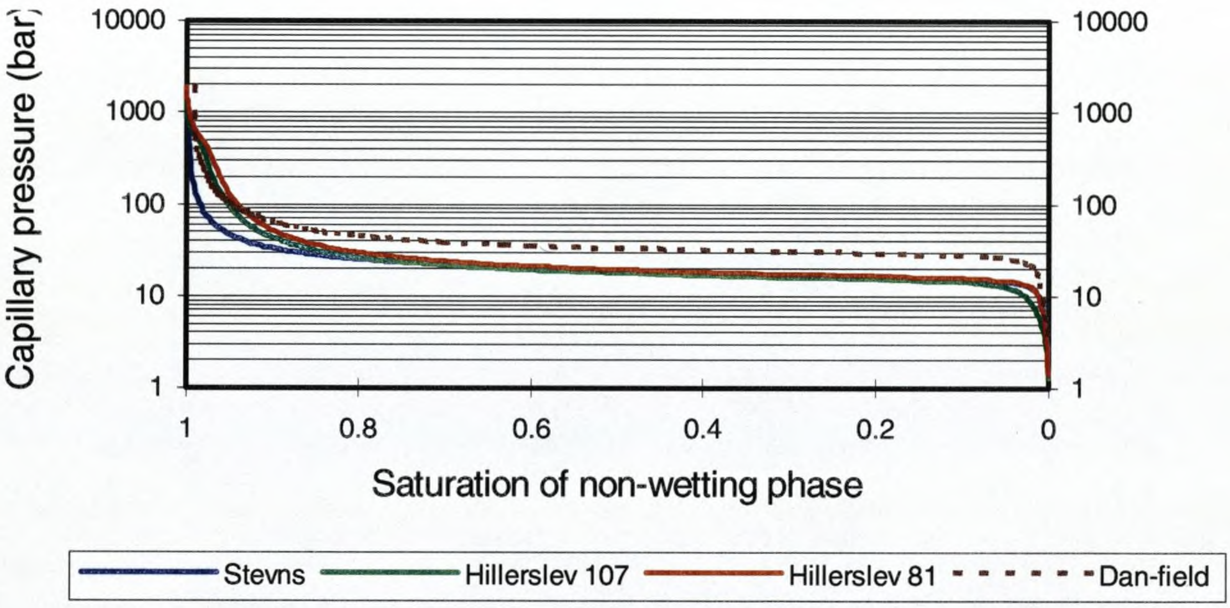


Figure 19

Capillary pressure curve (Hg/air) for reservoir chalk from the Dan Field compared to curves from three samples of Maastrichtian outcrop chalk from Stevns and Hillerslev (North Jylland).
The pore geometry seems very regular and well-sorted, which gives rise to the flat plateau. The entry pressure for the outcrop chalk is ca. 14 Bar, which corresponds to ca. 1 Bar oil/water Pc, equivalent to ca. 40 m. oil-column. The entry pressure for the Dan Field sample is slightly higher, indicating smaller pores.

Figure 19