DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/56

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Field trip guidebook, Stevns, Denmark

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G E U S

The Chalk at Stevns Klint

This field trip guide is aimed at supplying background material for discussion of the chalk outcrops at Stevns, and is mainly a compilation of existing material. The guide also contains some unpublished information, as well as preliminary statements and conclusions.

Location

The classical and most visited chalk exposures along the coastal cliffs of Stevns Klint are located at the village of Højerup, approximately 40 km south of Copenhagen, a bus-drive of ca. 1 hour and 20 min (Fig. 1). The chalk outcrops stretch approximately 12 km along the coastline of the peninsula of Stevns and reach up to ca 40 m in height.

Fig. 1. *– Location Map.*

Warning notice:

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

The classical cliff profile at Stevns

Stevns Chalk Field Trip

The object of this field guide is to examine the Upper Cretaceous – Danian chalk and bryozoan limestone exposed in the coastal cliff Stevns Klint (Stevn is an old Danish word for an anvil or stern-like topographic profile, and klint means cliff). The outcrop extends for about 14 km along the coastline of the peninsula of Stevns and reaches ca. 30–40 m in height and shows one of the most prominent exposures of the Cretaceous–Tertiary boundary in the world. The exposed carbonates corresponds in age approximately to the upper Tor to lower Ekofisk Formations in the North Sea chalk fields, and can in some aspects be used as a field analogue to the chalk formations in the oil/gas reservoirs in the North Sea. What is also important to capture from these outcrops, are the aspects that are **not** analogous to features in the chalk reservoirs.

For the introduction to the chalk reservoirs in the North Sea, a recent overview has been presented in the Millennium Atlas (Surlyk *et al.* 2003).

Introduction

Stevns Klint is situated at the peninsula of Stevns, on the island of Sjælland (Zealand), Denmark, approximately 40 km south of Copenhagen (Fig. 2). At Stevns Klint, a succession comprising 20–40 m of chalk and bryozoan limestone of latest Cretaceous (Maastrichtian) to Early Paleocene (Danian) age is exposed over 12 km. At Højerup, which is the classical locality visited during most field trips, approximately 30 m of chalk and limestone is exposed.

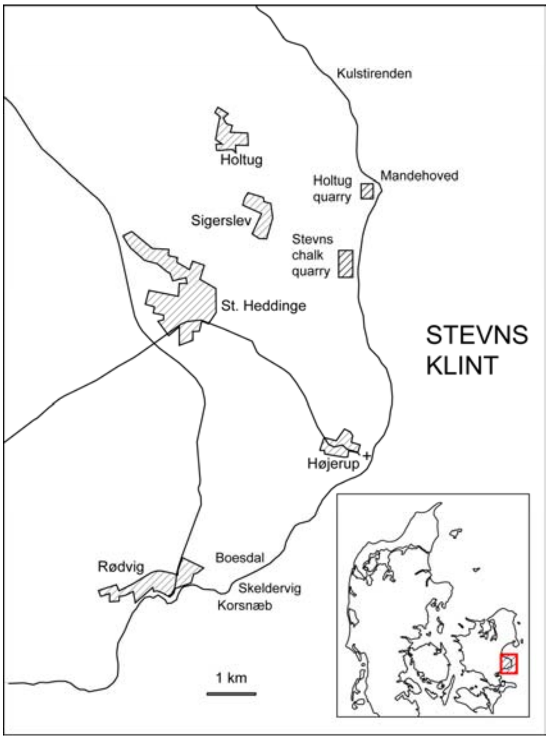


Fig. 2 – *Map of the Stevns Klint area.*

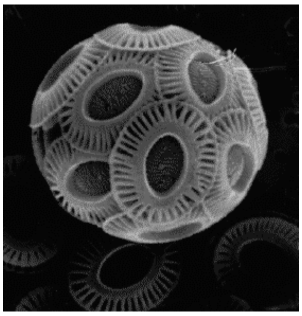
Old Højerup Church and the cock's stride

Fig. 3 – *Airphotograph of Højerup old church with the classical chalk localities to both sides of the stairs descending to the left (south) of the church.*

Just outside the village of Højerup, at the very edge of the cliff, stands the old church, which together with the cliff itself is one of the best known sights in Sjælland.
Tradition says that a seafarer in distress at sea promised to erect a chapel on the cliff, if he was saved. Luckily he survived, and in 1250 the chapel was erected, built of stones from the white limestone cliff itself. About 100 years later, during the reign of King Valdemar Atterdag, the building was enlarged and on September 11th 1358 the church was reconsecrated.
In the centuries that followed, the cliff was gradually undermined by the sea. As early as in 1675, contemporary drawings show the removal of the eastern churchyard wall due to erosion of the cliff. It was obvious that the church was in danger, but for centuries people found consolation in the tale, which said that the Old Højerup Church would survive by moving a cock's stride further inland every Christmas night. But even all the cock's strides were not enough, and on March 16th 1928 the choir and altarpiece tumbled into the sea. The church was then anchored, the cliff reinforced with concrete and today still stands on the edge of the cliff.
The church contains several frescoes with the oldest from late 1300, and a pulpit from 1605. Is open to the public at certain hours.
The murals: The oldest date from late half of 1300. The star under the tower arch is from ca. 1500, the acanthus in the choir and tower from ca. 1600. From SE the murals depict Peter and Paulus, then Christ and his resurrection as a gardener. Over the choir arch the women at Christ's grave with sleeping guard. To the north on the east wall the child murder in Betlehem. On the north wall: St. George's fight to save the princess, who on the next picture has the dragon on leash. Under this, Christ with the cross.
The best preserved murals are as follows: Holy Olav with axe, Holy Christoffer carrying the Jesus child over a river. By the way, if you have seen a picture of Kristoffer, you will not die the same day!. Over the large northern window, Tobias with the fish, and far to the west the offering of Isac. Above is depicted different human burdens: Anger (two fighting men), lust (an embracing couple).
On the west wall a fortune wheel that takes people to power and honour, and soon after to poverty and grief.
(From: Poulsen, H. 1985: Værd at vide om Stevns Klint. Stevns Museum).

The chalk

Most chalks are composed of micron-sized coccolith debris composed of low-magnesium calcite. The ring-shaped coccoliths are parts of a larger skeleton (coccosphere) produced by a group of pelagic marine algae “Coccolithophorids” that flourished in the upper part of the water column. This group of algae is still part of the oceanic biota, and can form blooms in the Atlantic which can be seen on satellite images.


a)

b)

Fig. 4 – *a) Recent coccosphere - Emiliania huxleyi.*
b) Coccospheres have even been depicted on a stamp. Calcidiscus leptoporus.

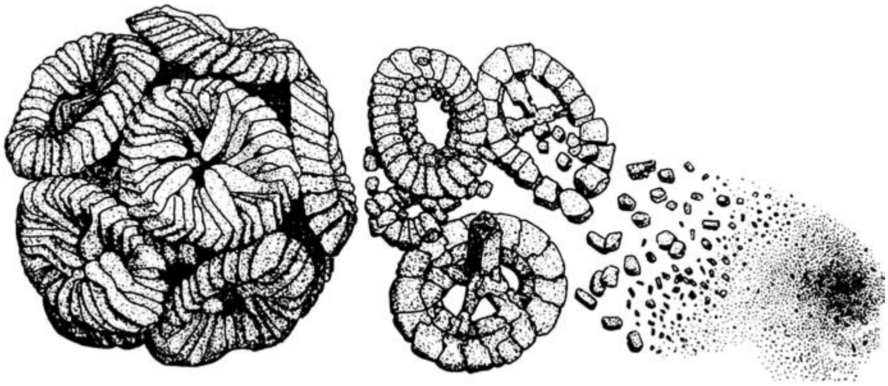
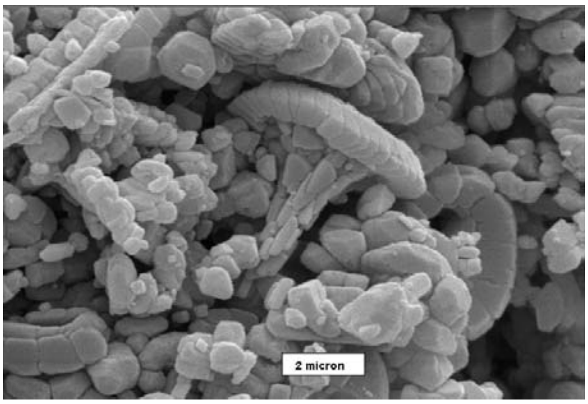
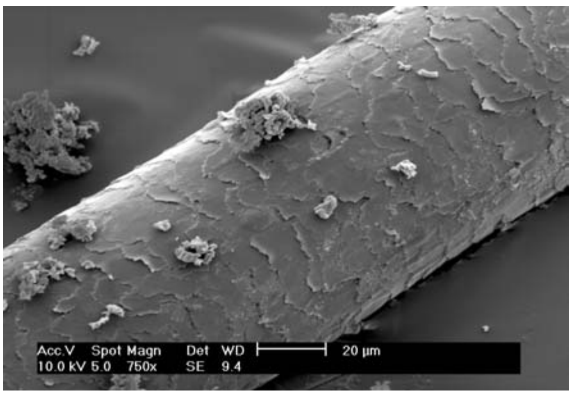


Fig. 5 – *The disintegration of a coccosphere into coccoliths and ultimately into individual platelets and crystallites. (Slightly modified from drawing in Bromley 1979).*





a) ***b)***

Fig. 6 – *SEM images of (a) chalk with whole and fragmented coccoliths from Stevns Klint; sample with porosity 48%, permeability 7 mD, showing, ½–2μm size calcite crystallites. (b) Chalk dust on a human hair. A single coccolith is seen in the dust particle in the upper central part of the picture.*

Chalk characteristics in brief

Chalk reservoirs are recognised as a special type with specific behaviour, that requires specific development schemes and time perspective for reservoir management (Frykman 2002). Some general but unique features of chalk are:

1. Usually very pure carbonate, at Stevns generally only 1–2% insoluble residue (IR).
2. Low diagenetic potential due to the composition of 95% stable low-magnesium calcite.
3. High porosity, low permeability, high capillary forces, all due to the small grain size.
4. Pelagic to hemipelagic sediment. Therefore layering is commonly the main heterogeneity. The layering can be cyclic, e.g. as marl–limestone cycles (documented in both outcrop and reservoir chalks).
5. Silica content is represented by flint nodules, and also occurs as nano-silica in reservoir chalk.
6. A detailed sequence stratigraphic interpretation can be made of the Cretaceous–Paleogene boundary strata, whereas it is less straightforward in older parts of the chalk

Geological setting

Stevns Klint is situated over a fault-bounded structural high situated between the eastern end of the Ringkøbing–Fyn High and the Sorgenfrei–Tornquist Zone (Fig. 7).

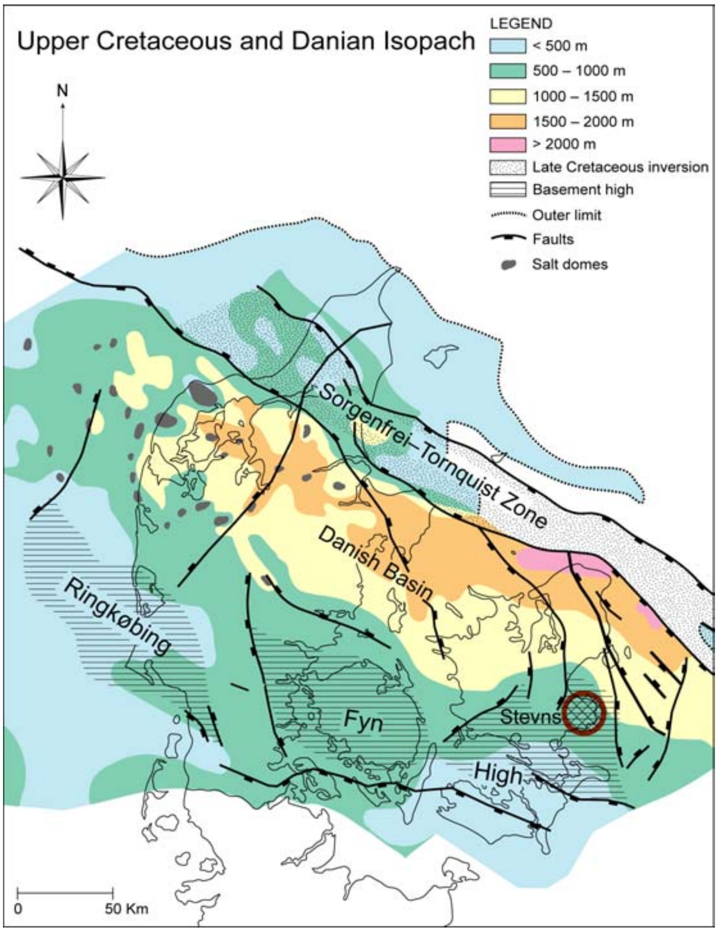


Fig. 7 *– Map of the Danish area showing the main structural features and the Stevns area (encircled).*

Maastrichtian and Danian near-shore facies are generally lacking in the areas north-east of Stevns due to the regional uplift and erosion (Fig. 8). Considerable thickness of chalk/limestone probably existed prior to the uplift.
Evidence of erosion of chalk exposed during the Eocene is shown by the findings of erratic flint nodules in the diatomite deposits of the Fur Formation in Northern Jylland, the flint having been carried from the former coast of Norway or Sweden embedded in driftwood tree roots (Heilmann-Clausen 2000; Madsen 2001).

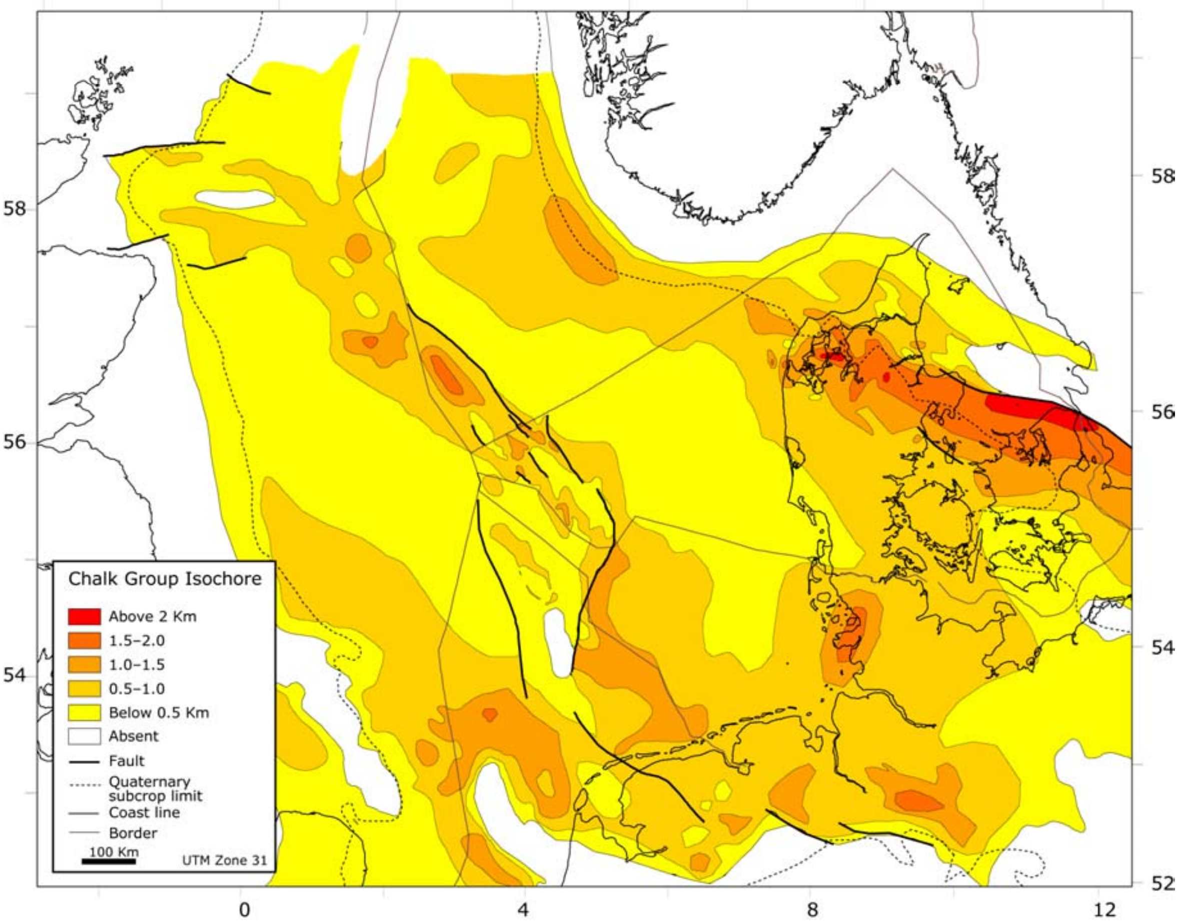


Fig. 8 *– The thickness of the Chalk Group (Upper Cretaceous – Danian carbonates) in the North Sea Region. (From Japsen 1998).*

In the uppermost part of cliff, minor glacially induced deformations are locally seen, and sub-vertical joints and horizontal cleavage surfaces are very prominent in the whole section.
The chalk at Stevns has been buried to at least a depth of 500 metres prior to Neogene uplift, as interpreted from sonic velocities in nearby boreholes (Japsen & Bidstrup 1999)

The short story

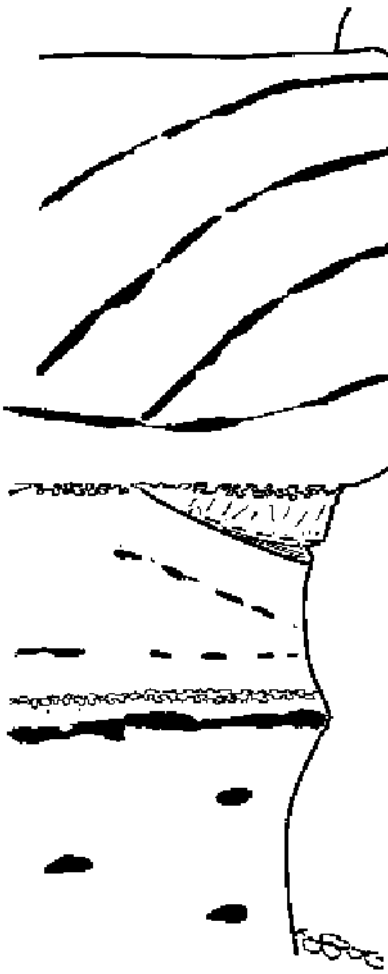


Fig. 9 *– Sketch of the typical cliff profile at Stevns.*

The profile of the coastal cliff at Højerup, Stevns Klint has a characteristic shape with the overhanging
Danian Bryozoan Limestone forming the top part of the cliff with only a thin Quaternary cover. The underlying Maastrichtian chalk is less resistant and is eroded back. The boundary strata between the mounded bryozoan-rich Maastrichtian grey chalk and the Danian bryozoan limestone comprise shallow basins with the characteristic
Fish Clay overlain by **Cerithium Limestone**: The crests of the chalk mounds and the Cerithium Limestone are truncated by an erosional hardground.
The **K–T boundary** (Cretaceous–Paleogene) with the famous Iridium anomaly at the base of the Fish Clay is nicely accessible at this locality. The anomaly forms the basis for the meteorite impact hypothesis and the debate over the causes for the extinction of the dinosaurs and many other faunal and floral elements. From the top of the cliff surviving "dinosaurs" – sea gulls and cormorants – are normally seen. **The "Grey Chalk"** owes its colour to a small amount of dispersed carbon black, and overlies a distinct pair of incipient hardgrounds with an underlying prominent flint layer. **The White Chalk** at the base of the cliff contains only scattered flint nodules.

Fig. 10
Beach locality just North of the Højerup church staircase access. Seashore to the right in the picture. The white chalk forms the lower part of the cliff, and is overlain by the grey chalk with the prominent flint band and incipient hardgrounds separating the two units. The flints in the grey chalk outline small mound structures. The overhanging brownish parts are the Danian Fish Clay, Cerithium limestone and mounded Danian bryozoan limestones.

The lithological succession in more detail

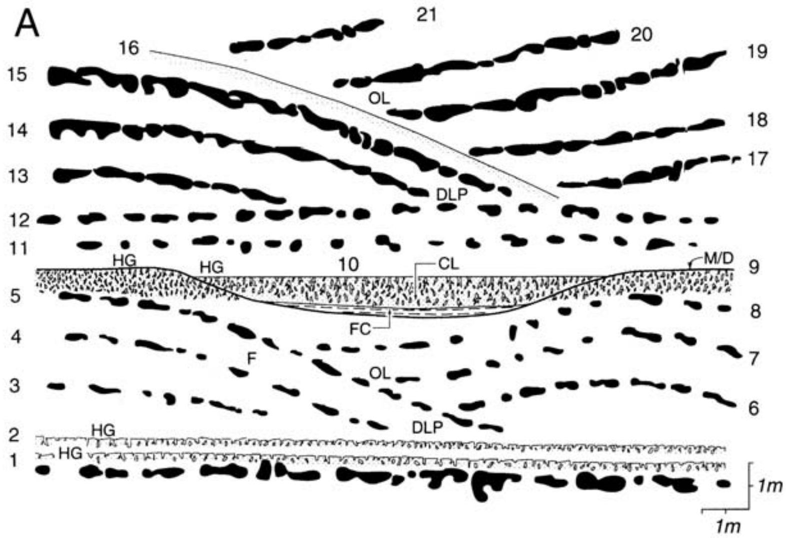


Fig. 11
Schematic stratigraphic section of the Maastrichtian–Danian boundary succession at Stevns Klint: Lines 1–21 indicate time lines. FC = Fish Clay; CL = Cerithium Limestone HG = Hardground, M/D = Maastrichtian–Danian boundary. (From Surlyk 1997).

The Maastrichtian succession exposed 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 ca. 35 m is exposed along the Stevns Klint itself.

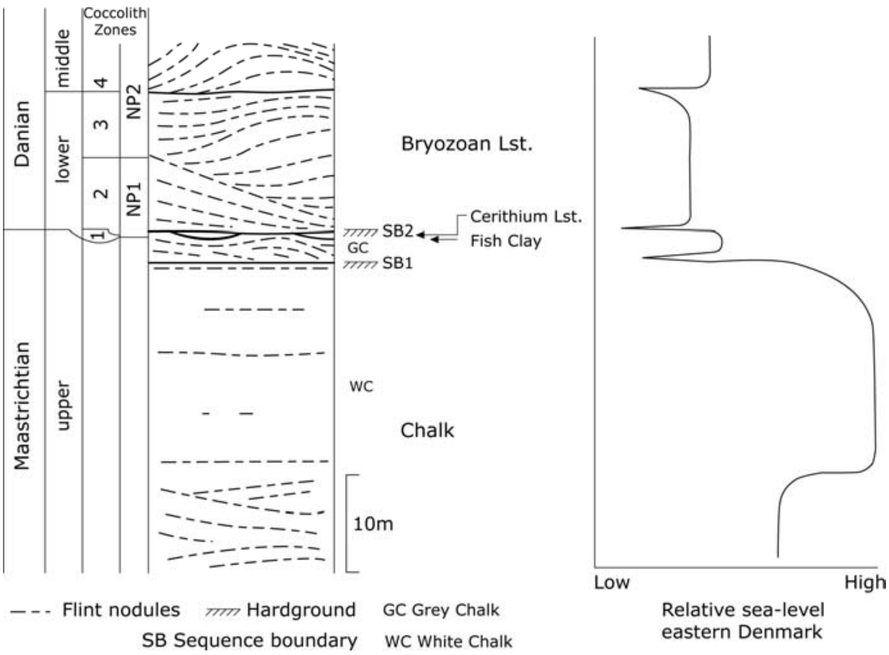


Fig. 12
The general succession exposed at Stevns Klint with a sequence stratigraphic interpretation of the sea-level fluctuations. (Slightly modified from Surlyk 1997).

The lowest chalk exposed along Stevns Klint, comprises ca. 20 m of **Maastrichtian white chalk**, showing indistinct horizontal to gentle wavy bedding, outlined by horizons of scattered flint nodules and trace fossils. The content of benthic fossils is generally low and the unit is characterised by a high density of *Zoophycos* burrows. It is topped by two closely spaced **incipient nodular hardgrounds** and a prominent layer of black nodular flint.

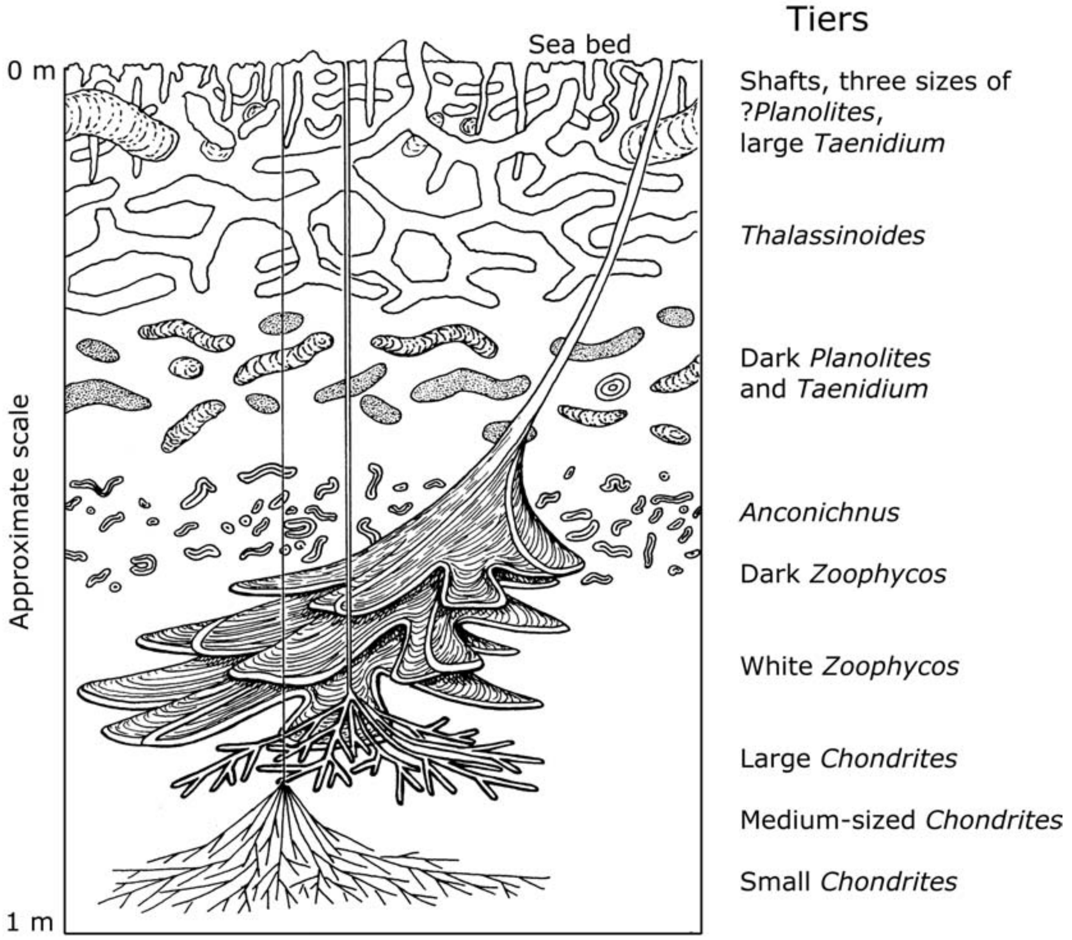


Fig. 13
Typical gallery (tier) of trace-fossils in chalk, where Zoophycos and Chondrites are interpreted to have reached 1 m below the sediment-surface (Bromley & Ekdale 1986; Surlyk et al. 2003).

The **prominent nodular flint layer** can be traced along most of Stevns Klint and the two hardgrounds represent omission surfaces at the top of the White Chalk, marking temporary interruptions in the sedimentation. The top hardground is overlain by uppermost Maastrichtian Grey Chalk.

The Grey Chalk is 2.5–4 m thick, and has a high content of small benthic fossils (in the range of 10% by weight), 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!) interpreted as having an origin from volcanic activity (Hansen *et al.* 1987). Besides the carbon black in the sediment, the soot is also found incorporated in bryozoan skeletal calcite, and is seen as a greyish colour. An interesting detail is that these grey bryozoans sometimes are overgrowing or is overgrown by purely white bryozoans (Hansen *et al.* 1987). The occurrence of greyish growth bands in pectinid bivalves, presumably caused by soot incorporation, may also suggest an episodic occurrence of the soot in the environment (E.

Håkansson, pers.comm. 2001). The Grey Chalk was deposited as low asymmetric, slightly overlapping biogenic mounds (Larsen & Håkansson 2000). The southern flank is steepest and shortest (interpreted as the up-current side) and prominent flint bands are only found within the less steep northern flank (down-current). The mounds are mostly 30–35 m wide in direction of migration. The length of the mounds is uncertain due to the orientation of the outcrop, but is estimated to be between 50 and 250 metres by comparison with the Danian bryozoan mounds.
The growth of the mounds probably followed the model proposed for the asymmetrical Danian bryozoan mounds (Thomsen 1976, 1977), where the mounds grew under the influence of unidirectional currents from the south, which facilitated growth in the up-current direction. The mounds in the Grey Chalk are characterised by *Thalassinoides* burrows, with fills commonly reburrowed by *Chondrites*. Small-scale synsedimentary slumping and mass flows occurred on the flanks involving beds only a few tens of centimetres thick and 1–2 m long. The Grey Chalk is topped by the **Cretaceous–Paleogene (K–T) boundary.**

The Fish Clay forms the basal Danian stratum. It is a dark-grey to black, marly clay, occurring in the troughs of the undulating topography created by the bryozoan mounds of the uppermost Maastrichtian Grey Chalk. The Fish Clay, deriving its name from the occasional fish scales and shark teeth, is mainly about 5 cm thick, but reaches 35 cm at the northern end of the cliff at Kulstirenden (Fig. 10). The K–T boundary at Stevns Klint has been investigated in great detail, and forms the basis for the famous meteorite impact hypothesis of Alvarez et al. (1980). It still holds the world-record for the highest K–T boundary abundance of Iridium of 185 ng/g (Hansen *et al.* 1986). The K–T boundary is by international agreement defined at the iridium-bearing layer at the base of the Fish Clay.

The Cerithium Limestone overlies the Fish Clay and is of earliest Danian age. It is up to 0.5 m thick, and fills the depressions between the mounds of the Maastrichtian Grey Chalk (Fig. 10). The name of the unit reflects the content of several species of the gastropod *Cerithium*. Detailed studies of the early cemented parts of the limestone have revealed a wealth of aragonite-shelled bivalves (Heinberg 1999).

The top of the Cerithium Limestone is marked by an erosional **unconformity**. Erosion at this level also has removed the crests of the Maastrichtian mounds of the Grey Chalk. The unconformity is developed as a hardground, with prominent *Thalassinoides* burrows, which penetrate both the Cerithium Limestone and the Grey Chalk (Surlyk 1979, 1997; Ekdale & Bromley 1984). This originally caused some confusion concerning the distribution of the fauna preserved in the complex hardground layer, since it includes both Maastrichtian and Danian strata adjacent to each other, and thus fossils from both periods.

Above the hardground the **Danian Bryozoan Limestone** tops the succession exposed in the cliff. The biogenic mounds were 5–11 m high, 50–110 m long on the sea floor and oval in plan view with NNE–SSW elongation, steep southern flanks (15–25°), and more gentle northwestern slopes (5–15°). The bryozoan content is typically 20–45 %, and the internal structure of the mounds is outlined by numerous flint bands and occasional thin hardgrounds, restricted to the gentle northern lee side slopes (Surlyk 1997). The mounds migrated towards SSE by accumulating sediment on the up-current flanks due to increased growth and the baffling and filtering effect of the abundant bryozoan colonies that thrived on the nutrient supplying current. The down-current flanks were comparably condensed as indicated by the hardgrounds and densely spaced flints bands. The combined lateral migration and vertical aggradation pattern of the mounds shows that adequate accumulation-space existed for the mounds which were formed well below wave-base, at water-depths in the order of 100 metres. The biogenic nature of the Danian mounds is well documented, and they are not of similar origin as e.g. the superficially similar structures in the cliffs at Haute Normandy, France, which are interpreted as interchannel erosional ridges shaped by successive erosional events (Quine & Bosence 1991). The Danian mounds at Stevns are essentially accretionary build-ups, but they incorporate examples of similar erosional features as seen in the Normandy chalks (Surlyk 1997). The in-place deposition of the bryozoan colonies has been documented at the locality Karlby Klint showing large well-preserved colonies collapsed onto the bedding planes (Thomsen 1977).

The development of the Danian succession as bryozoan mounds probably reflects a relatively near-shore and more shallow marine environment compared to the central part of the Danish Basin or the Central Graben in the North Sea, where the reservoirs in the Danian Ekofisk Formation are developed as chalk mudstones with only sparse macrofossils. The onshore Danian therefore is **not** a useful analogue to the presently known North Sea Ekofisk Formation. Coarse bryozoan debris and flint fragments are reported from a well in the Norwegian Stord Basin, indicating that the bryozoan-rich facies exists at least locally in the North Sea, and that more shallow-water deposits may occur over palaeo-structural highs at specific locations in the North Sea. Comparable facies of bryozoan limestones and mound complexes could be discovered – with expected good reservoir properties.

Palaeo-positions of selected chalk outcrops and reservoirs

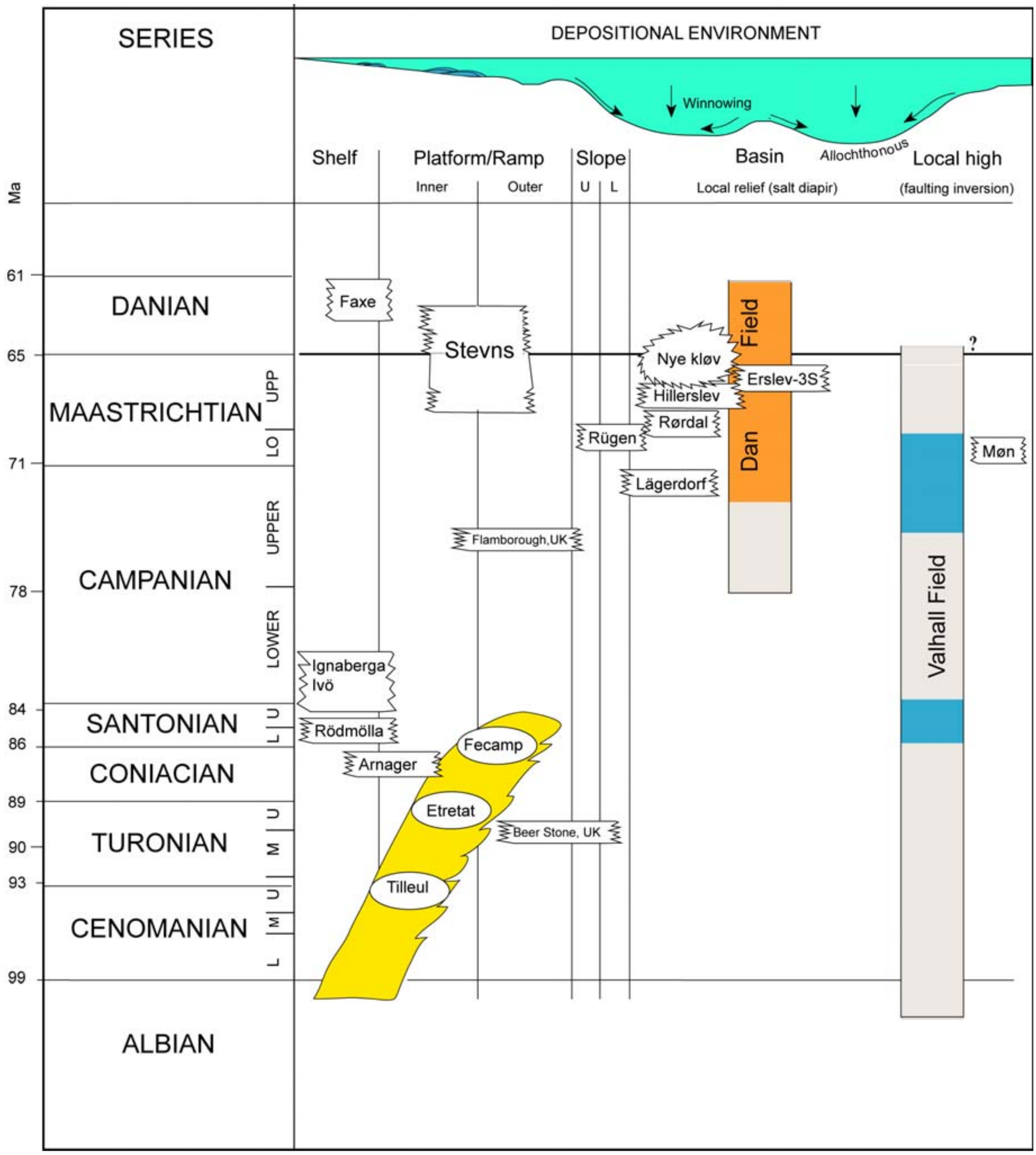


Fig. 14

Schematic presentation of the facies distribution of selected different chalk/carbonate types in Northwest Europe. (Modified from Jakobsen 1996 with updated time-scale from Hardenbol et al. 1998).

Flint

Flint nodules are common in the chalk and are products of chemical segregation of dissolved silica originally derived from the dissolution of biogenic silica in the chalk deposits, primarily sponges.

A minority of flint nodules are associated with body fossils of echinoids, oysters, sponges etc. and found scattered in the chalk section. However, apart from these scattered occurrences and the occasional *Paramoudra* flint (barrel-shaped flint) (Bromley *et al.* 1975), black flint nodules are normally concentrated in discrete bands or layers. The flint bands characteristically occur at irregular intervals, approximately at 0.5–2 metres apart. The flint bands present a wide array of morphological variations. In some the nodules are sparsely scattered along single planes or within a finite unit of chalk. Other levels are heavily silicified. The morphology of the flint nodules commonly mirror the initial silicification in burrows, most commonly found as galleries of *Thalassinoides* burrows (Bromley & Ekdale 1983). In layers with low silica content the flint may occur as slender finger-like nodules in isolation. In layers with higher silica content the nodules may interconnect as a network or boxwork or may fuse into massive nodules. In rare cases massive platy flint layers about 10–20 cm thick may be developed.

Origin of flint

The formation of flint takes place over a long period of time and can be divided into several phases. The first phase starts very soon after deposition, where an embryonic situation is found immediately below the sea floor (0.2–0.6 m) where redox conditions prevail and organic matter provides adsorption nuclei for silica. The depth of the redox boundary is quite variable and depends on the sedimentation rate and the main development of flint nuclei may respond to the duration of time for non-deposition periods. The longer the period of non-deposition the deeper the zone is located. No rigid nodules are formed in this early phase, but only nucleation sites for subsequent silica accumulation and reprecipitation are formed. At a later stage, dissolution of silica from the matrix takes place and silica migrates to the embryonic zone where it precipitates and initiates a fine scale replacement of skeletal calcite. This process continues in the main stage of growth by intense precipitation of opal-CT lepispheres. Reworking of the flint at this stage serve only to disaggregate the lepispheres because these are not firmly cemented until the phase of interstitial opal-CT chalcedony precipitation (Clayton 1983). During late diagenesis the opal-CT protoflint recrystallises to its present state with alpha-quartz mineralogy (Clayton 1983).

The origin of flint is primarily associated with the silica released from disintegrated silica sponges. In outcrops there seems to be an inverse relationship between number of flint nodule layers and presence of preserved sponges, as seen in the Coniacian Arnager Limestone on Bornholm (Noe-Nygaard & Surlyk 1985). The appearance of flint seems to be controlled by depositional environment and it is dominant in the more basin marginal deposits where silica sponges are assumed to have been abundant. In more basin central deposits flint nodules also occur, but are much less common and generally smaller.

Outcrop observations

A flint band from the Stevns Klint has been measured in detail over a distance of 10 m., and represents a preliminary attempt to quantify the volumetric occurrence of flint (Fig. 15). The thickness of the layer is about 15–20 cm and comprises up to 80% flint nodules. Both finger-like nodules and larger fused nodules are observed. This particular flint band is the prominent layer formed in connection with the omission surface associated with the change from the white to the grey chalk lithology at Stevns – the boundary between the White Chalk and the Grey Chalk. The immediately overlying incipient double hardground is interpreted as a sequence boundary (Surlyk 1997). It is also seen from figure 15 that the size and the connection of nodules are highly variable in lateral direction.

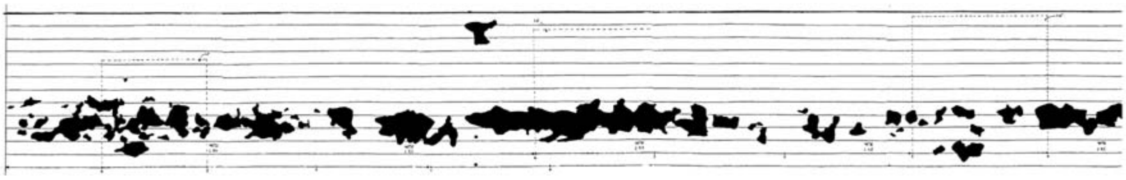


Fig. 15
Vertical section in the flint layer ca. 3–4 m below the Maastrichtian–Danian boundary at Stevns Klint. The total lateral section covers 9.5 m, and shows the highly variable distribution of nodules as well as the variable size of the individual nodules. (Flint layer measured and drawn by Jens Jacob Gørtz, Anne Kristensen og Christian Uttenthal 1999, DTU).

In the flint nodules virtually no porosity and permeability will be present. However, from outcrop observations it seems that the chalk between the flint nodules is generally of higher porosity than the chalk outside the flint band.

The permeability effect of flint

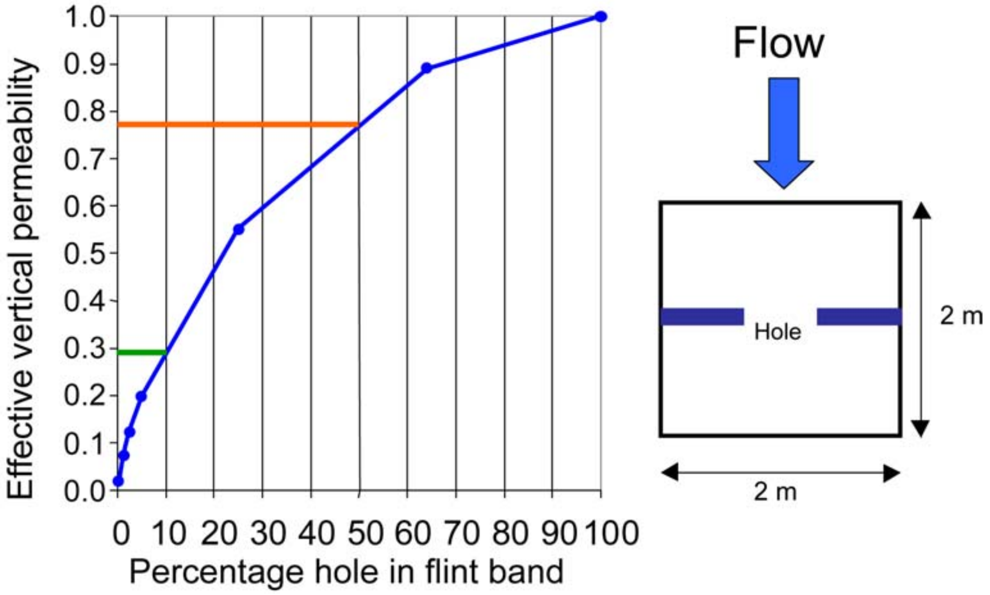


Figure 16
The effective permeability of a chalk volume of 2x2 m decreases as the percentage of hole area in the flint band decreases.(Modified from Frykman et al. 1999).

Sequence stratigraphic outline

A sequence stratigraphic interpretation was presented by Surlyk (1997). Recognition of key surfaces, notably erosion surfaces associated with hardgrounds and abrupt seaward shifts in facies, allow identification of a number of sequences separated by well-defined sequence boundaries. The uppermost Maastrichtian – Danian succession comprises four sequences (Fig. 17).

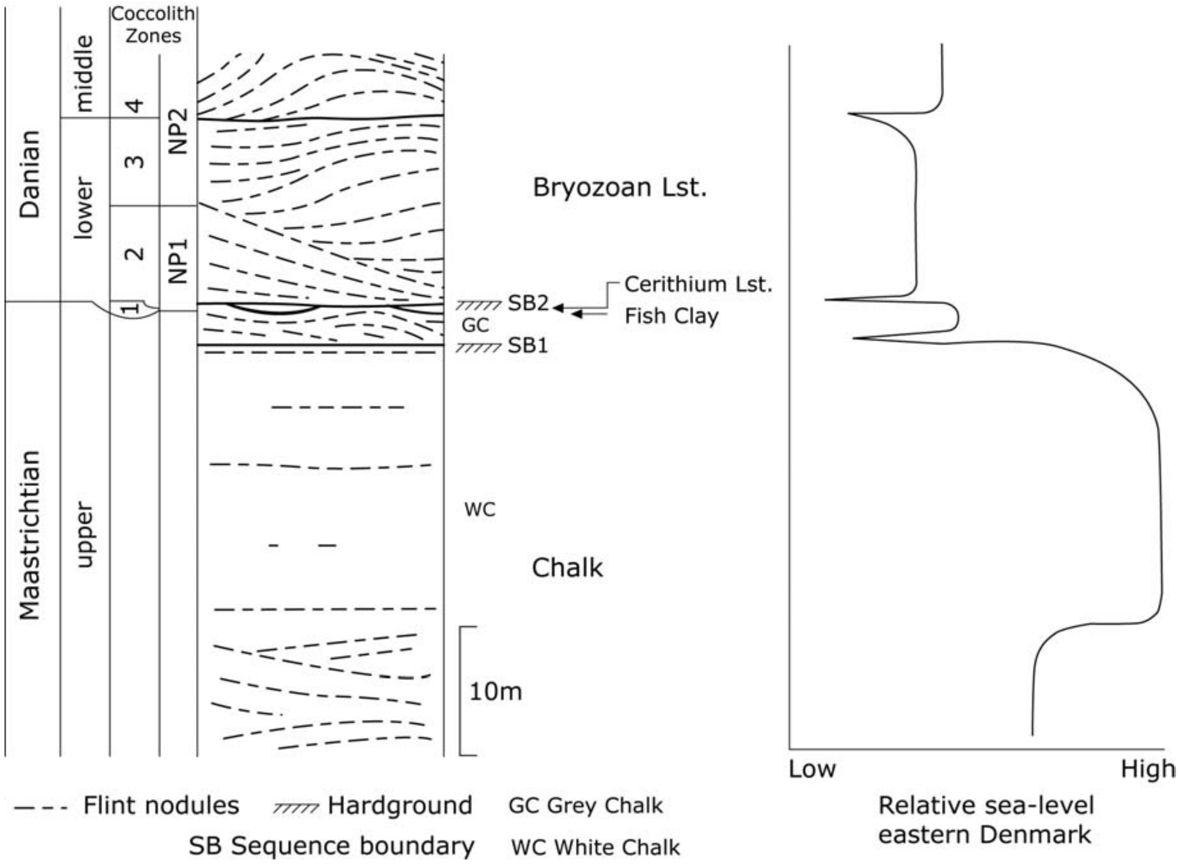


Fig. 17

Interpretation of the sea-level fluctuations related to the uppermost Maastrichtian–Danian succession. (Slightly modified from Surlyk 1997).

An important sequence boundary occurs at the base of the uppermost Maastrichtian mounded Grey Chalk (SB1 on Fig. 17). It represents an abrupt seaward shift in facies from deep-water chalk to relatively shallow-water bryozoan wackestone, and is interpreted as caused by a eustatic sea level fall. Renewed rise created accommodation space for development of the bryozoan mound succession of the Grey Chalk. Benthic diversity appears to decrease in the topmost part of this unit probably reflecting increasing water depth. The omission surface and the double-layer of flint associated with the sequence boundary at Stevns are not recorded in the time-equivalent but more basinal Kjølbygård outcrop section in northern Jylland.

The Grey Chalk at Stevns is overlain by the K–T boundary beds.
The Fish Clay would normally be considered the maximum flooding level, but the boundary events were complex and a simple sequence stratigraphic interpretation is considered impossible at the moment. The Fish Clay passes gradually into the Cerithium

Limestone, which is topped by a regional erosion surface (SB2 on Figure 17) that reflects a major probably eustatic sea-level fall.
Succeeding sea-level rise created accommodation space for the lower Danian mounded bryozoan limestones. A high order cyclicity is represented by the rhythmic flint bands, which record variations in sedimentation rate. This is interpreted to be linked to carbonate productivity, climate fluctuations, and therefore probably within the Milankovitch frequency band. The duration of the cycles is difficult to estimate due to the complex mounded architecture (Surlyk 1997).

Chalk stratigraphy and sea level

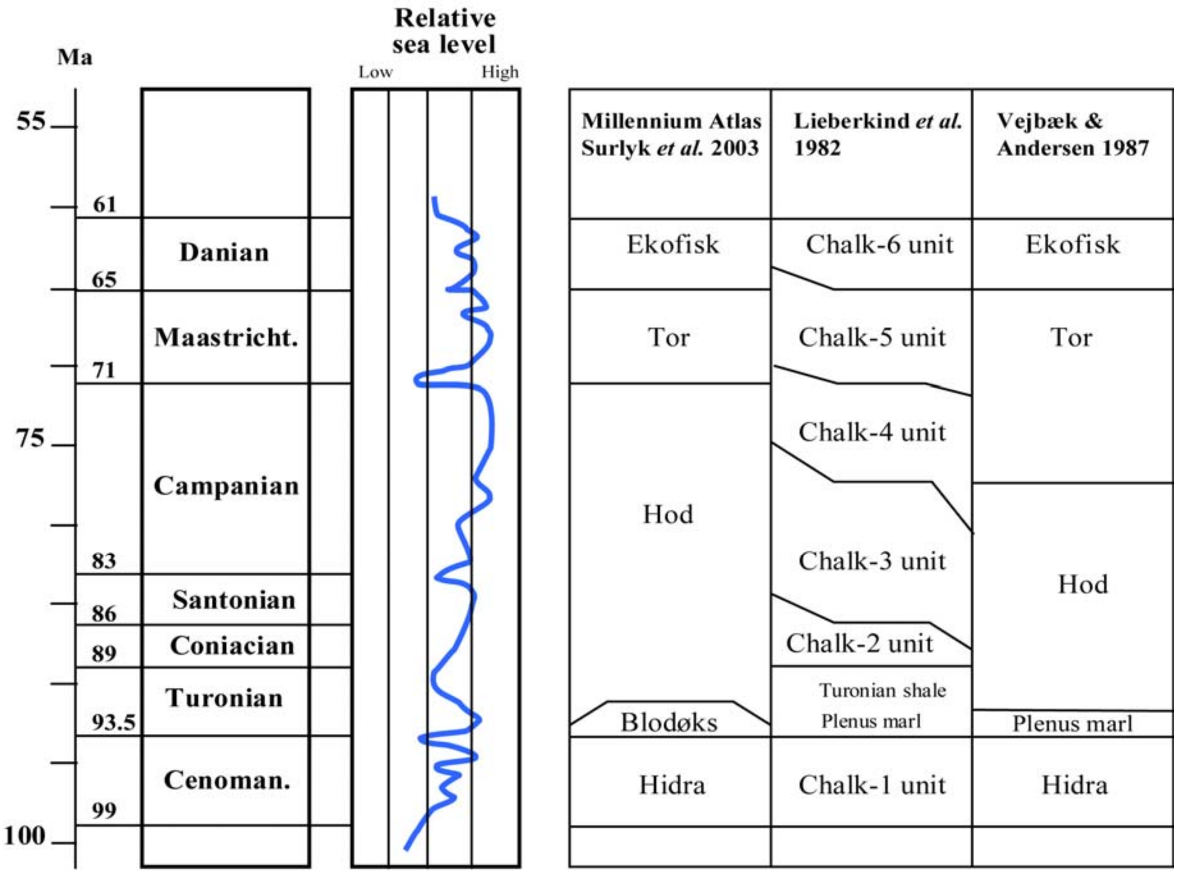


Figure 18
Chalk stratigraphy in the Danish Central Graben. The relative sea level curve is compiled from Haq et al. (1988), Hancock (1993) and Surlyk & Lykke-Andersen (2004). Time scale from Gradstein et al. (1995) and Hardenbol et al. (1998).

Petrophysics of outcrop chalk - an example from Stevns

Investigation of petrophysical properties has been carried out in the uppermost Maastrichtian and lowermost Danian succession (Frykman 2001). The intention was to investigate two different aspects of the chalk: a) possible analogy to North Sea reservoir chalk, and b) possible cyclic pattern in the petrophysical properties.
These investigations were carried out in the quarry at Sigerslev operated in 1992 by Faxe Kalk A/S, 5 km north of Højerup (Fig. 19). The Sigerslev quarry exposes the uppermost 25 m of the upper Maastrichtian chalk and a few metres of the overlying Danian limestone. In the northern end of the quarry the white chalk of the uppermost Maastrichtian was sampled by tightly spaced drilling of one inch plugs from the wall (Figs 20, 21).

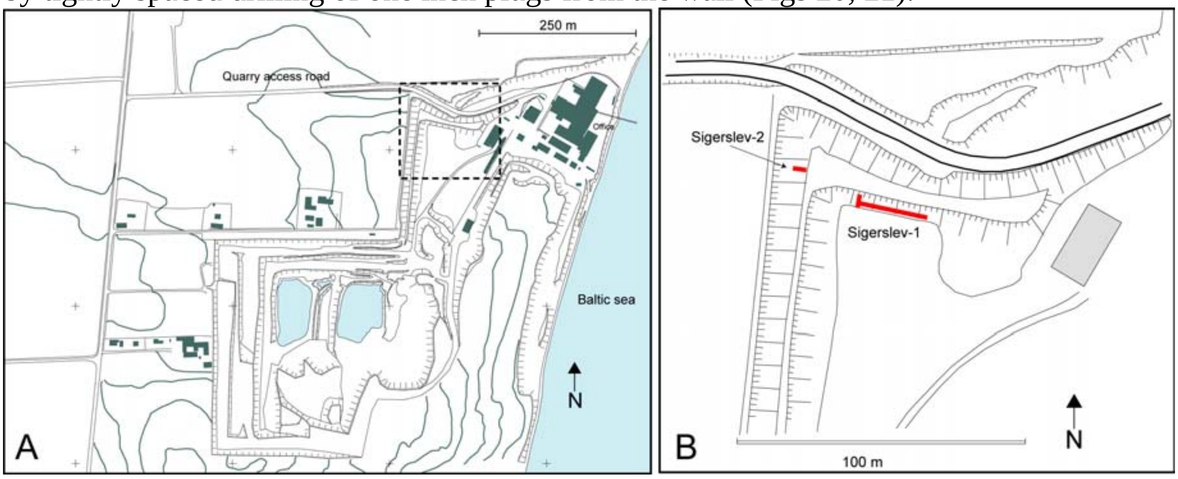


Fig. 19
A: Map of the quarry at Sigerslev (1992-extent) with the study area outlined. B: map showing the north wall, which was examined in detail.

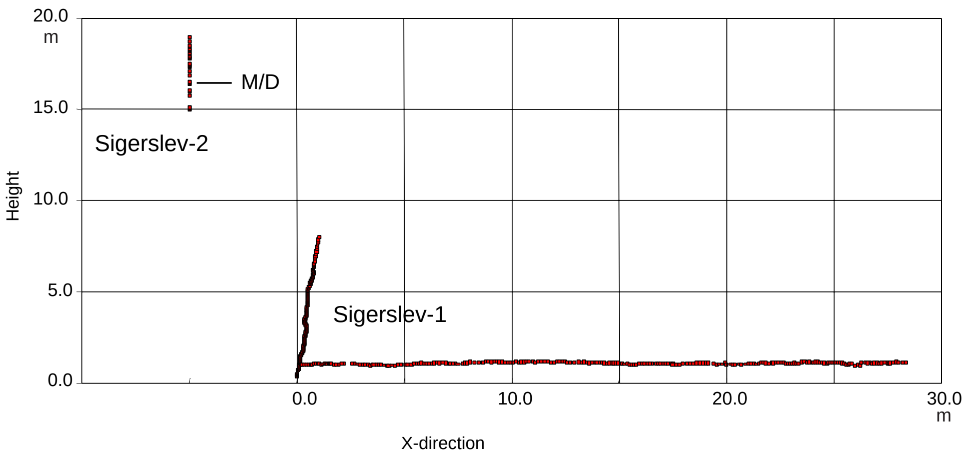


Figure 20
Schematic vertical section showing position of the extracted samples.

In the Sigerslev-1 section 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. In the Sigerslev-2 section the Maastrichtian–Danian boundary interval is represented. Measurements of porosity and permeability were obtained in the laboratory by conventional core analysis methods.

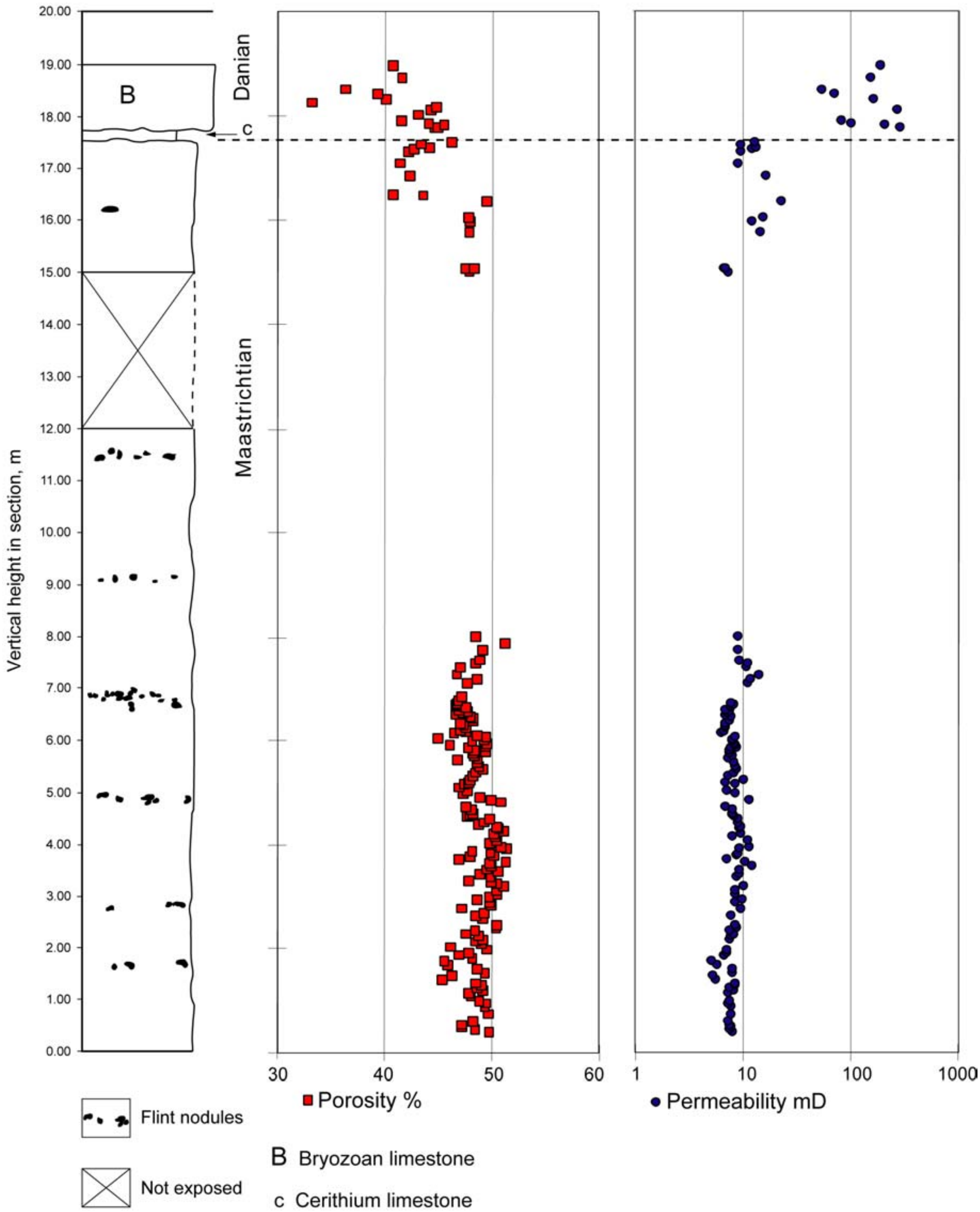


Fig. 21
Section through the Maastrichtian and Danian chalk and limestones showing the variations in the porosity and permeability.

The chalk at this locality has not been described previously in any detail, and it is difficult to discern the Grey Chalk in this local area.

The cross plot of porosity and permeability shows a tight clustering of the Sigerslev-1 data from the upper Maastrichtian white chalk (Fig. 22).

Additional sampling in the bryozoan limestone at the southern part of Stevns Klint has added to the knowledge of variability in porosity and permeability in the Danian. Generally the bryozoan limestones have higher permeabilities than the chalk due to the larger grain size and poorer sorting (Fig. 22).

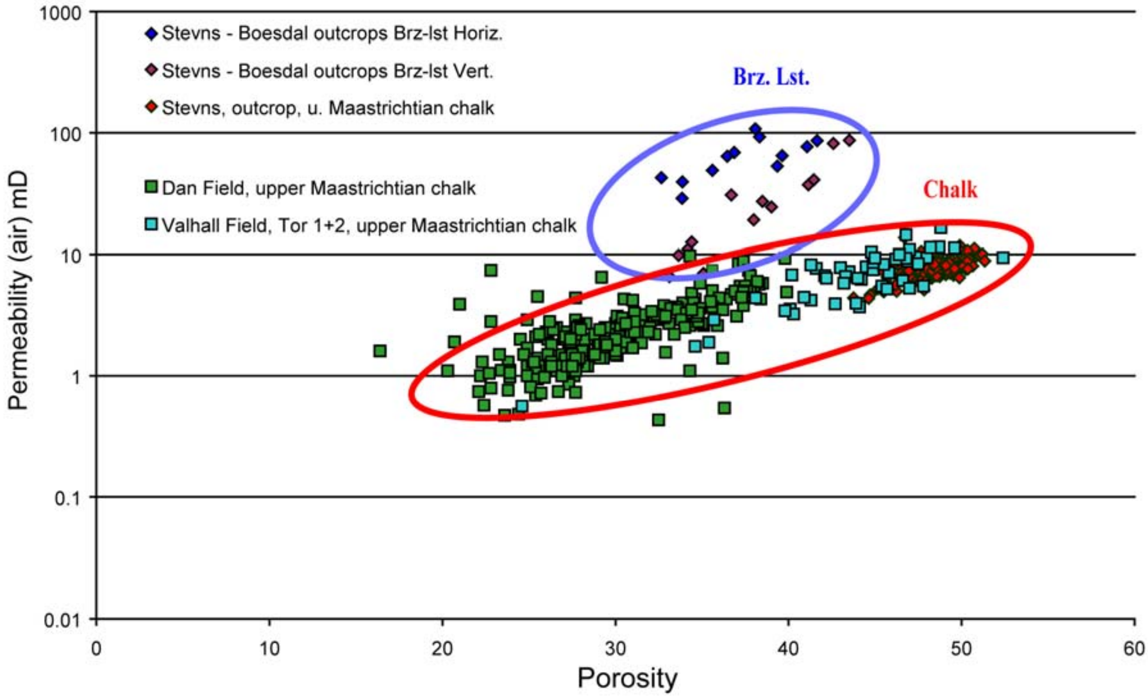


Fig. 22
The porosity–permeability relations for the samples from different types of upper Maastrichtian chalk (framed in red) and the Danian bryozoan limestones sampled at Korsnæb (framed in blue).

Stevns Klint – Analogue for North Sea reservoir chalk?

Chalk reservoir characteristics:

The reservoir chalk shows the following characteristics:

1. Large capillary forces causes high imbibition potential and very long transition zones
2. Silica can occur as nano-silica
3. Fractures are important for reservoir performance
4. Field life-time is much longer than for siliciclastic reservoirs
5. Overpressure development in the reservoirs causes porosity preservation and exotic rock-mechanical behaviour
6. Compaction during production is an important drive mechanism
7. Fluid-contacts may be in non-equilibrium and non-horizontal

The Maastrichtian chalk and Danian bryozoan limestone at Stevns Klint are stratigraphic correlatives of the North Sea hydrocarbon reservoirs in the Tor and Ekofisk Formations, respectively (Fig. 23)

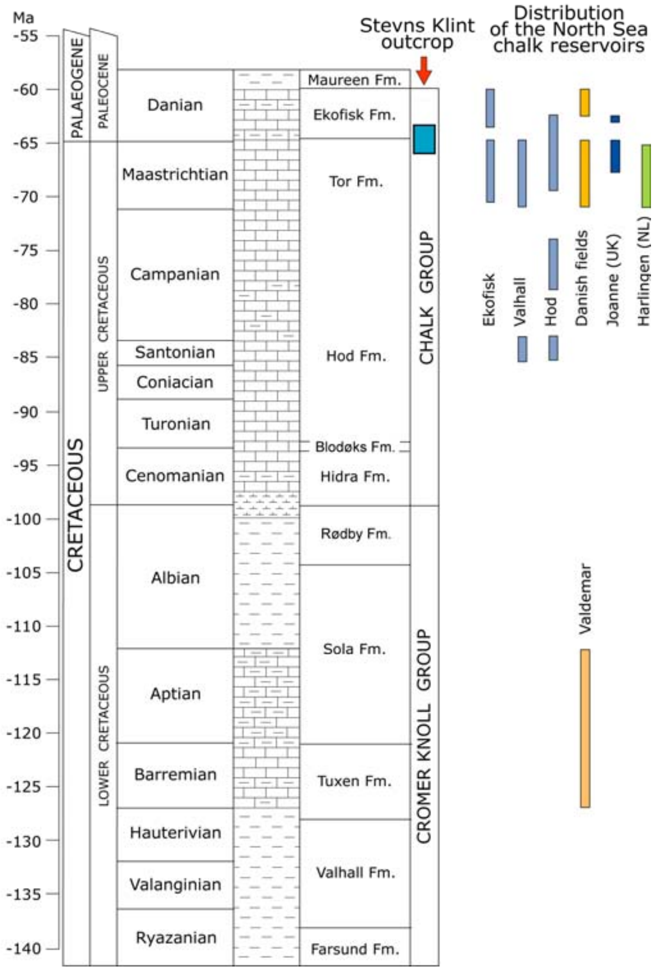


Fig. 23

Scheme showing the stratigraphic distribution of different reservoir chalks in the North Sea and at the Stevns Klint . Slightly modified from D'Heur (1993) and time-scale after Gradstein et al. (1995).

Palaeogeographically Stevns Klint was located relatively closer to the coastline, than the North Sea chalks which were deposited near the centre of the greater North Sea Basin in much deeper water. This is reflected in the generally relatively high content of coarse skeletal grains from benthic organisms, the number of omission surfaces, and in the step-wise overall coarsening and shallowing upwards succession at Stevns Klint. The basal white coccolithic chalk at Stevns Klint may, however, be considered as an analogue to the autochthonous high-porosity chalks in the North Sea. The porosity of the white chalk at Stevns Klint varies between 42–51%, while gas matrix permeabilities range between 4–14 mD (Frykman 2001). Typical North Sea chalk values are generally lower (except for extreme cases as in e.g. the Valhall Field), and they vary over a broader range. This reflects differences in the burial history and post-depositional diagenesis.

The Danian bryozoan limestone at Stevns Klint is developed as bryozoan wackestone to packstone in biohermal facies, and is not a good analogue to the more micrite-dominated chalk in the Ekofisk Formation of the North Sea. The possibility exists, however, that similar shallow-water bryozoan mound deposits exist over palaeo-highs in the North Sea.

The core analyses of the Maastrichtian outcrop chalks are compared to core analyses from wells in the uppermost Maastrichtian chalk reservoir zone in the Dan Field, and a trend of porosity and permeability for reservoir chalks can be seen leading towards the very high values found in outcrop (Fig. 24). The diagenesis and burial history of the compared samples are of course different, and further investigations are needed to evaluate the comparison of outcrop and high-porosity reservoir data. Trends for the changes of porosity correlated with burial depth were described 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 c. 1800 m is reduced to an effective burial of only 1150 m if the amount of overpressure is accounted for (see Fig. 31).

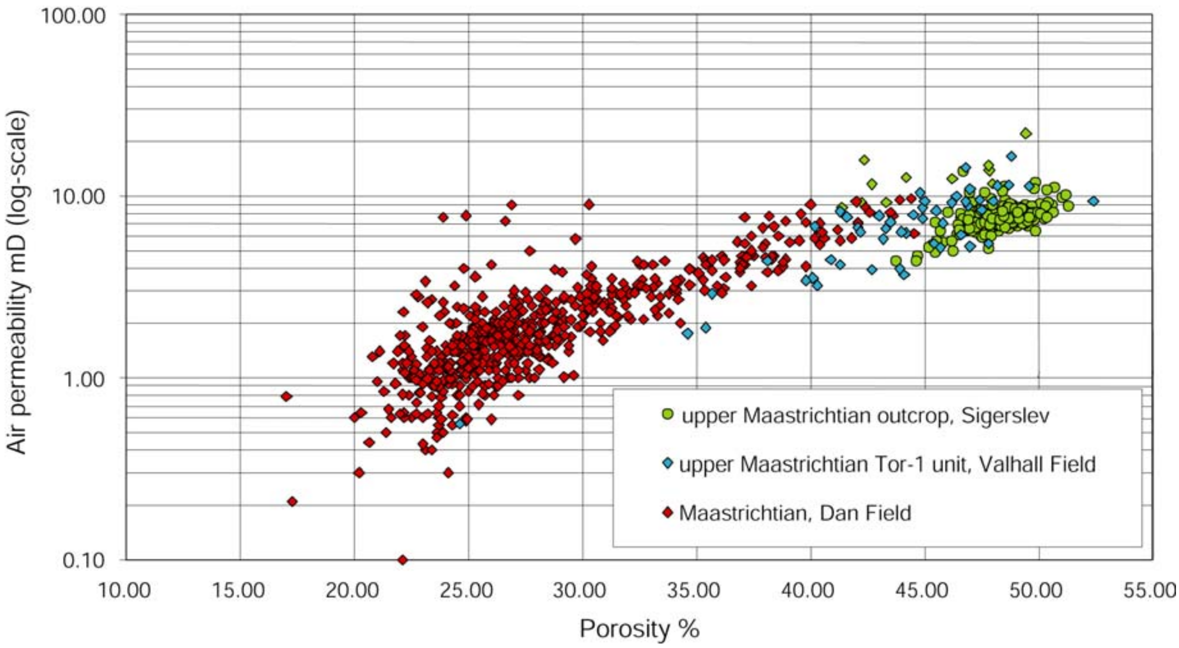


Fig. 24
*Porosity–permeability (**air**) relations for the reservoirs in the Dan and Valhall fields and outcrop samples of Maastrichtian chalk from Sigerslev Quarry.*

The different petrophysical aspects, mainly the lowered permeability in relation to porosity, of Ekofisk chalk compared to Tor chalk (Fig. 25) may reflect a stratigraphic increase in dominance of coccoliths with comparatively smaller platelets, which became abundant from the middle Danian (E. Thomsen, pers. comm). It has also been suggested that a generally higher content of clay and silica in the Ekofisk chalk is responsible for the lower permeability (Røgen & Fabricius 2002).

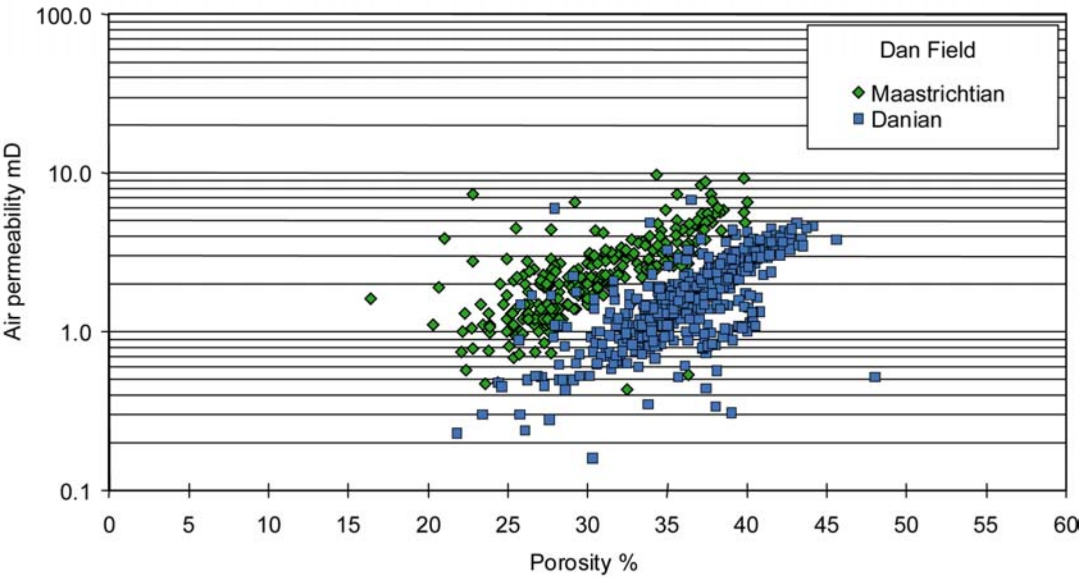


Fig. 25
*Porosity–permeability (**air**) relation for the Maastrichtian and the Danian chalk of the Dan Field.*

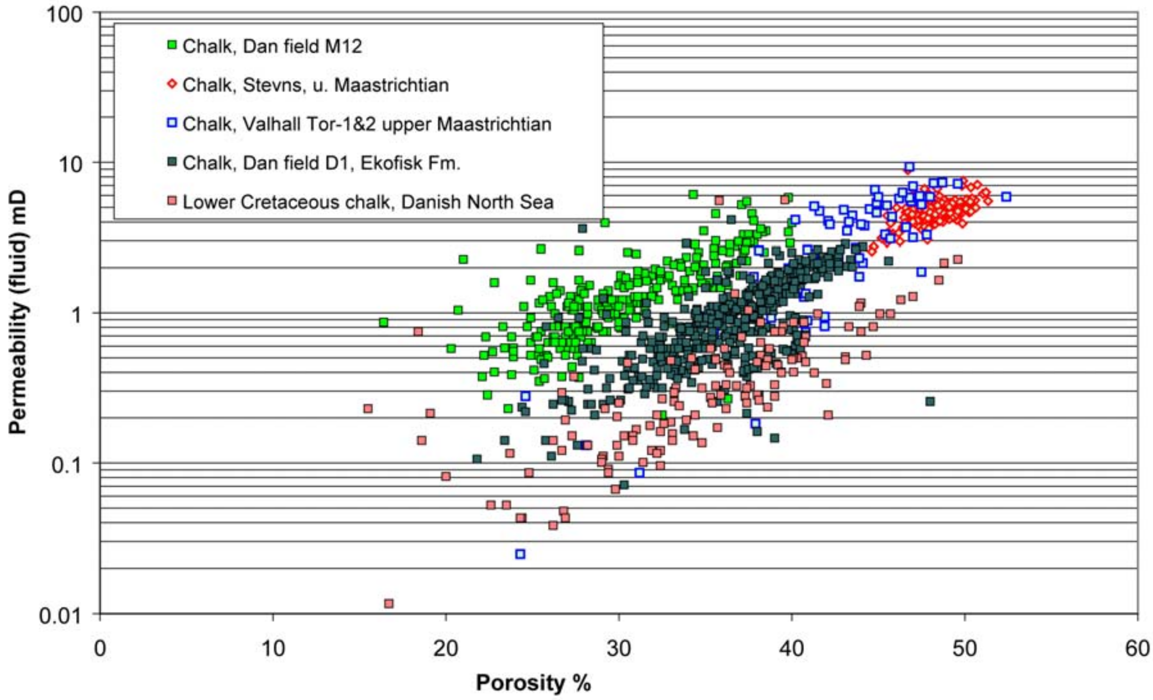


Fig. 26
*Porosity–permeability(**fluid**) relation for the Maastrichtian, Danian and additional data from Lower Cretaceous chalk in the Valdemar field (Jakobsen et al. 2004).*

Silica

In off-shore wells flint nodules are found scattered in the chalk with dominance in the Danian. Very little flint and only few flint layers are observed in the clean chalk, such as the Maastrichtian. The flint nodules are relatively small and are found as isolated rounded elements in the cores. In the tight lower part of the Danian chalk, the flint layers occur at intervals ranging from 15 to 30 cm and are interbedded with a chalk matrix with a relatively high content of clay and dispersed silica. The flint nodules can be larger than the core diameter, but this does not necessarily mean that a massive flint interval in a core represents a platy flint layer. From outcrop data it is more likely that the observed flint is only associated with a nodule of limited lateral extension.

In addition to the layers of black flint, discrete intervals with nano-silica are found in the Danian. The silica occurs as nm-size particles of α–quartz interpreted to have precipitated and flocculated directly in the free water phase and sedimented together with the coccolith material (Jakobsen *et al.* 2000). Visually the intervals with nano-silica appear as chalk but it contains up to 80% silica, affecting dramatically the bulk density and mechanic properties. Conventional petrophysical measurements indicate a slight decrease in porosity and also indication of decrease in permeability as compared to the surrounding chalk intervals.

Cyclicity

Outcrop studies in the chalk in the UK and Germany have demonstrated a well-developed cyclicity at several levels (Gale *et al.* 1999; Niebuhr 1999). The variability is clearly outlined by the varying clay content in the succession of marly and more pure chalk beds. High porosities are encountered in all outcrop lithologies but lower porosities are associated with an increase in the clay content or early diagenetic cementation.

The cyclicity recognised in outcrop is comparable to the porosity layering recorded in some off-shore wells, and is mainly in the range of 1 to 2 m thick (Stage 1999).

Comparison between data from wells and outcrop shows a distinct difference in absolute porosity and also illustrates differences in the relative variation in the porosity. 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.

From the assumed duration of the different cycle-periods during the Cretaceous period (Berger & Loutre 1989), the expected thickness of the cycles can be estimated, assuming a rock accumulation rate of 2–3 cm/kyr.

Table Orbital cycles	Duration of periods in the Upper Cretaceous	Assuming 2 cm/kyr
	(after Berger & Loutre (1989))	Expected thickness of cycle bed in outcrop
Long eccentricity	400 ky	8 m
Short eccentricity	115 ky (= ca 100 ky)	2 m
Obliquity	51.1 + 39.3 ky (= ca 40 ky)	0.8 m
Precession	22.4 + 18.6 ky (= ca 20 ky)	0.4 m

This assumption leads to an estimated bed thickness of 0.4 m for the shortest cycle, the precession cycle. This is a very crude estimate of expected bed thickness given the large uncertainty of the deposition rate.

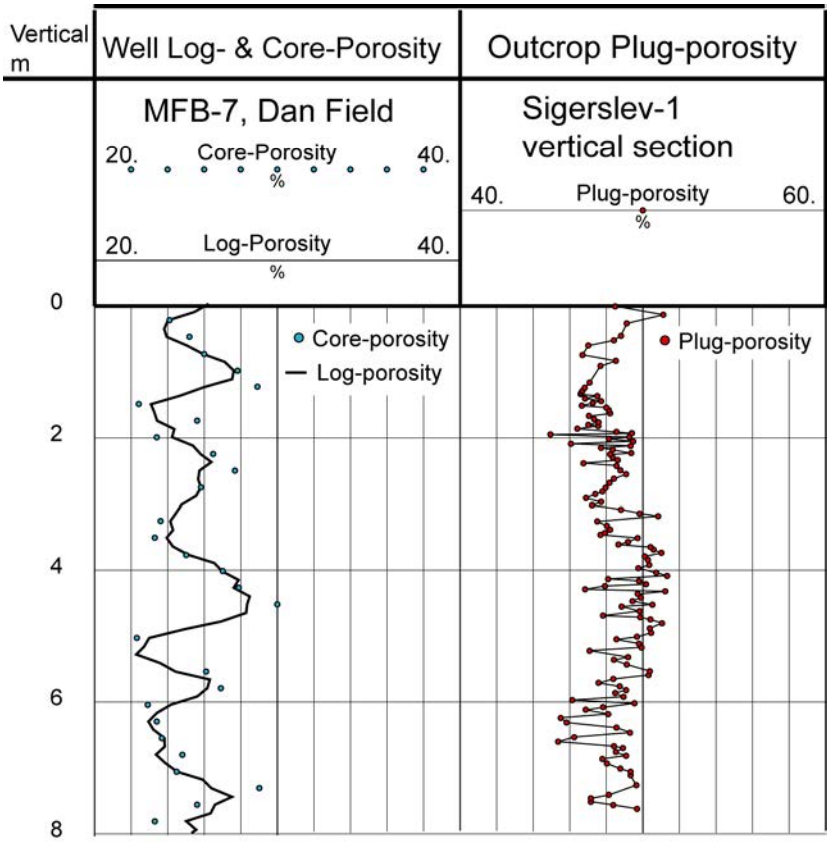


Fig. 27
Comparison of the porosity variations in the cyclic section in MFB-7 (Dan field) and the section in Sigerslev-1.

The Maastrichtian chalk of the Dan field is affected by compaction associated with depth of burial and the relatively tight intervals of the cycles are associated with solution seams and stylolites (Scholle *et al.* 1998). An interval in the MFB-7 well in the Dan Field has been investigated in more detail and shows a clear cyclicity in porosity variations and in magnetic susceptibility (Stage 1999). The interval has also been used to illustrate the technique for upscaling and relation between different volume scales for a cyclic chalk section (Frykman & Deutsch 2002).

Allochthony?

For some time a direct association between reservoir quality of chalk reservoirs and the occurrence of allochthonous facies has been postulated. The most obvious allochthonous deposits, with chalk intraclasts, shear structures and contorted bedding, have been coupled with high porosity and high permeability by Brasher & Vagle (1996), and references therein. This view was opposed by Maliva & Dickson (1992), who argued that the content of insoluble residue, clay, silica etc. is the dominating factor for the diagenetic and compactional pathway and thereby for the development of reservoir quality.
Investigations of reservoir chalk show that there are no distinct differences in porosity or permeability distributions between autochthonous and allochthonous chalk. This is in accordance with the conclusion from the work made on the Eldfisk field (Herrington *et al.* 1991; Maliva & Dickson 1992).
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 an at least 1.25 m thick allochthonous unit in a well (Erslev 3S) penetrating the chalk on top of the Mors salt dome in Jylland (Nygaard & Frykman 1981). Allochthony is mainly of local nature associated with syndepositional movements of the salt structures or faults. Most reservoirs have been drilled on such structures and are supplying data for this view on the allochthony.
Other examples of allochthonous chalk in onshore locations have been reported from Maastrichtian chalk in the Höllviken well onshore Sweden (Brotzen 1945), in a location not associated with salt tectonics but within an important fault zone.
Allochthonous Maastrichtian chalk of debris flow origin was described from Rügen, Germany by Steinich (1967, 1972).
An example of synsedimentary thrusting has been described from a hardground at Stevns Klint, but is not part of larger scale allochthony (Surlyk 1979).

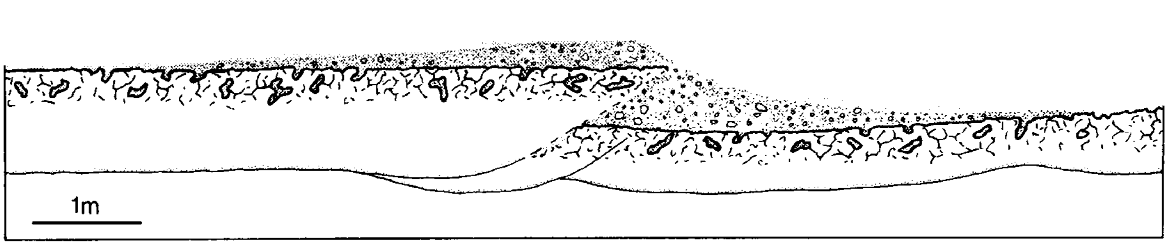


Fig. 29
Ruptured hardground at Stevns Klint. (Slightly modified from Surlyk 1979).

Magnificent large-scale examples of erosional features, redeposition and allochthony in chalk-related facies are exposed on the Normandy coast in France (Quine & Bosence 1991). The succession shows examples of multiple depositional and erosional events forming valleys or channels and complex interchannel ridges connected with the sloping sides of a broad channel structure running east–west into Normandy. The sediment comprises mainly chalk wacke- and packstone with a higher content of macrofossils than the Maastrichtian or Danian chalks in the North Sea reservoirs. Despite the diversity of erosional phenomena, the Normandy succession is **not** a good analogue to the chalk sediment and to the processes described from the North Sea allochthonous chalks. However, the structures are beautifully outlined by flint bands, allowing interpretation of depositional and erosional processes, and the geometries and their scale may serve as inspiration for the interpretation of allochthonous reservoir chalks.

Lithotypes

The chalk at Stevns Klint shows some of the lithologies present in other outcrops and in the North Sea reservoir chalks, and the one dominant lithology – the burrowed chalk mud- to wacke-stone - is represented in the compilation of outcrop lithologies in Table 1, which contains a subset of the full lithotype range for reservoir chalks as described in the JCR Classification Scheme (JCR 1996).

Petrophysical analogy of outcrops

Porosity reduction is found in offshore reservoir chalk affected by early diagenesis and in chalk with a high content of clay of both primary sedimentary and secondary diagenetic origin, concentrated by pressure dissolution (Herrington *et al.* 1991). It is therefore assumed that the porosity of the chalk is not related to the exact mode of deposition but rather to the content of insoluble residue and early diagenetic cementation. The principles for burial diagenesis of chalk sediments and their sonic velocity response have recently been outlined by Fabricius (2003).

Variations in the packing of the matrix constituents and in the degree of intergranular cement are observed in samples from the Dan field (Dons *et al.* 1995). These variations are indicative of a dual porosity reduction by compaction and cementation. However, the data were derived from several wells and not from a continuous 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 effects from compaction and pressure dissolution are reduced in case of overpressure in the reservoir, and the overpressured chalk therefore causes preservation of porosity. The overlap in porosities and permeabilities between outcrop chalk and overpressured reservoir chalk is interpreted as a similarity in pore geometry and flow characteristics.

Burial history and diagenesis

Given that the chalk at Stevns has experienced 500 m burial (Japsen & Bidstrup 1999), a comparison of effective burial depth for Stevns chalk and e.g. the Dan Field reservoir chalk illustrates that the two sediment units have experienced a 600–700 m difference in effective burial depth (= effective stress) (Fig. 30). From analysis of deep-sea chalk units and their petrophysical evolution, the burial depth interval from 500 to 1200 m is shown to be associated with minor change in porosity, but significant change in sonic velocity (Fabricius 2003). Diagenetic processes could be responsible for the petrophysical differences between outcrop and reservoir chalks.

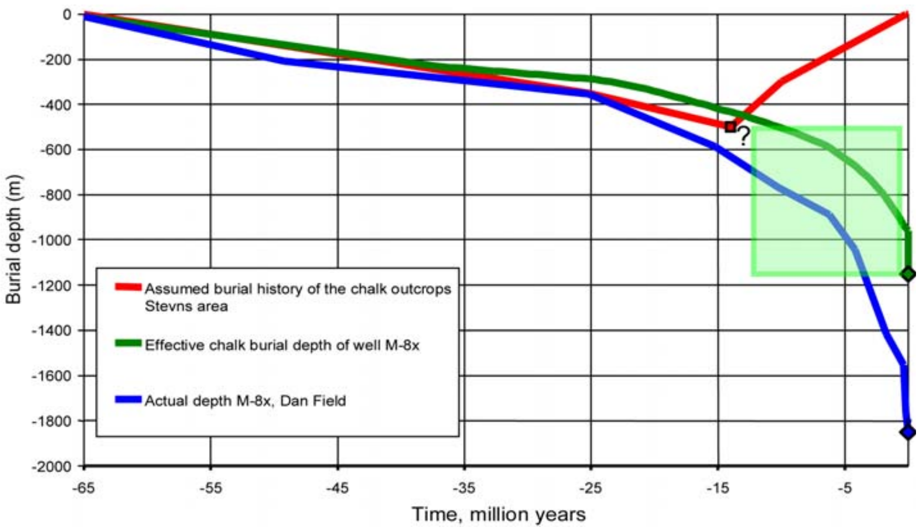


Fig. 30

Burial history for a well at the Dan Field compared to the interpreted burial history for the Stevns area. The shaded area is the effective depth- and time-window for additional diagenesis of the reservoir chalk in this well.

Most chalk reservoirs have attained a certain amount of overpressure during their burial history, which will cause the effective stress at present to be reduced compared to actual burial depth (Fig. 31). For example the South Arne field is at a present depth of 2800 m, but has approximately the same effective stress as the Dan Field corresponding to an effective depth of 1300 m.

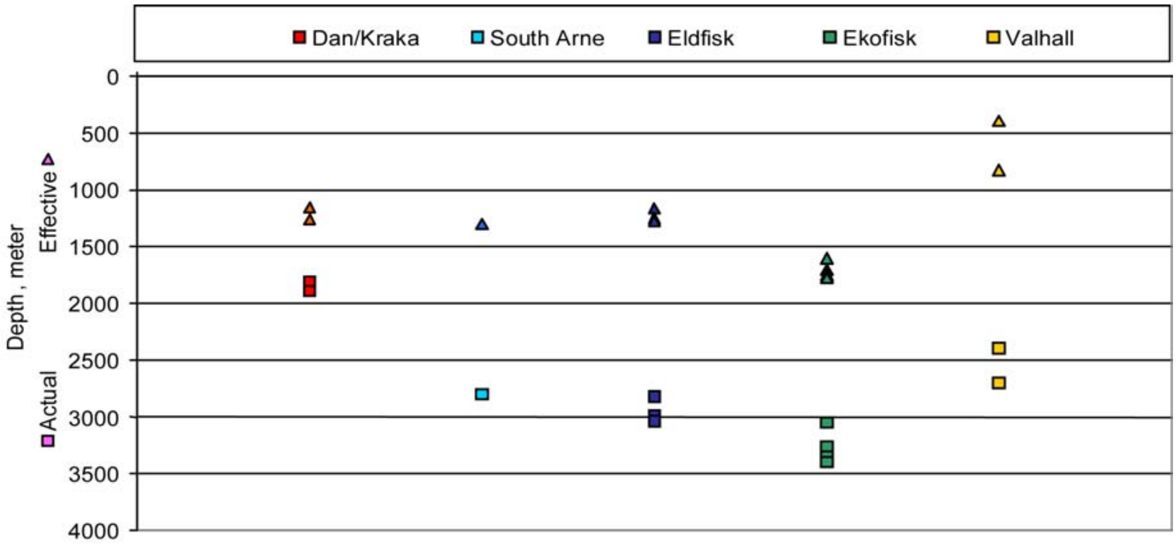


Fig. 31

Burial (actual and effective) for the reservoir section in different chalk fields, calculated from published pressure data and other information (Andersen 1995; Fabricius 2003).

Capillary pressure and 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 Maastrichtian reservoir chalk from the Dan field have been considered and compared to a reservoir sandstone (Fig. 32). The entry pressure of around 200 psi (14 Bar) for the Air/Hg measurements corresponds to c. 15 psi (1 Bar) oil/water capillary pressure. This pressure can withstand a 40 m thick oil column before breakthrough. However, correlating this directly to the sealing capacity is probably uncertain, since any fractures most likely will allow a much earlier breakthrough of the chalk bed in question.

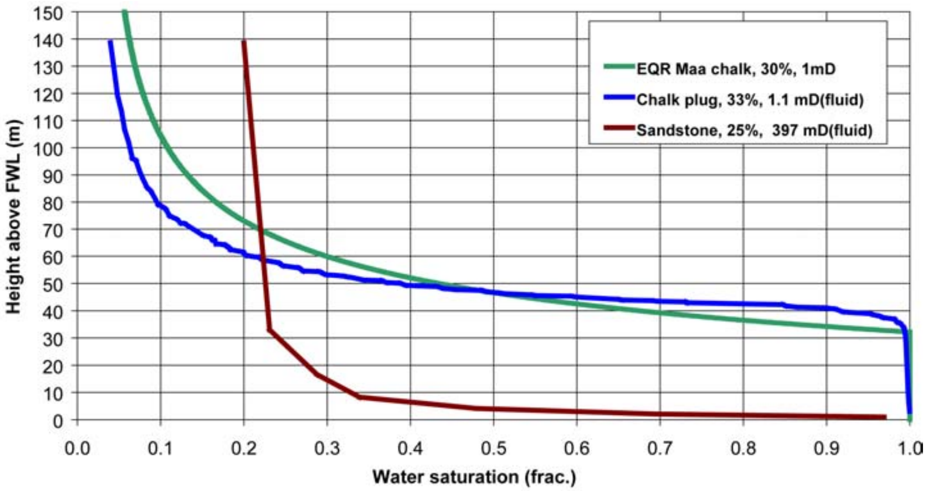


Fig. 32

Capillary pressure curve from a reservoir chalk and a sandstone.

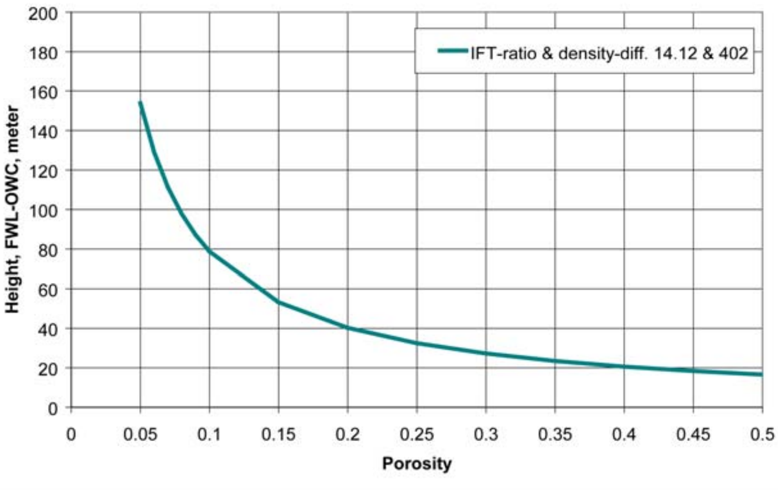


Fig. 33

Sealing capacity of chalk, shown as oil column height necessary for breakthrough for a Maastrichtian type chalk at the given reservoir conditions.

The low permeability and the entry pressures in the reservoir chalks are responsible for the slow migration and filling of chalk reservoirs, and also contribute to the irregular distribution of the oil during the filling history Vejbæk *et al.* (in press).

Fractures

The fracture network is very important for the production characteristics in North Sea reservoirs. It is therefore necessary to evaluate if analogous patterns in faulting and fracturing can be studied in outcrops and utilised in reservoir analysis and modelling.
The fracture system seen in Stevns Klint and in the Sigerslev quarry consists of a combination of 1) a few small faults with little offset, 2) subvertical joints in a complex system, 3) very-low-angle fractures, and 4) horizontal cleavage surfaces. When looking at this fracture system and seeking an analogue to the reservoir fracturation, the features that are associated with late tectonic processes should be filtered out, as they are not relevant for reservoir conditions. At Stevns the two near-horizontal features have to be filtered out. The very-low-angle fractures only occur in the topmost part of the sections, and are in some cases filled with platy flint. These fractures are interpreted to have formed during sub-glacial drag on the uppermost layer of the chalk during the Pleistocene.
The horizontal cleavage surfaces are suggested to be unloading fractures, originating from rapid postglacial ice-sheet melting and succeeding isostatic uplift. In most places they form a sub-horizontal pattern, and generally follow closely the flint bands, which are assumed to outline the original bedding, but may cross-cut the flint bands (Fig. 34)

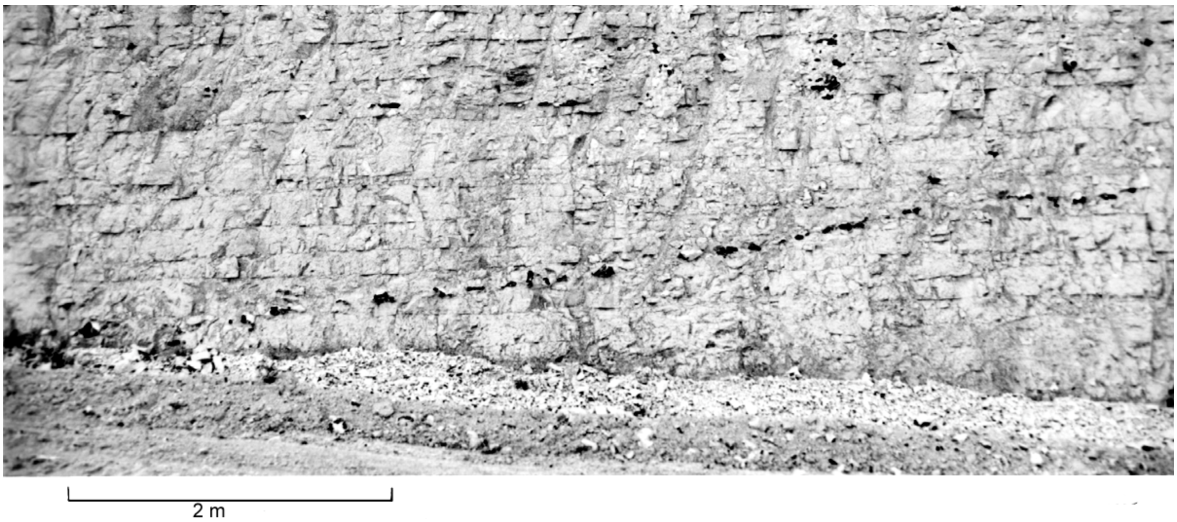


Fig. 34
Illustration of the geometry of the horizontal fractures and their crosscutting relation to a flint band in the Sigerslev quarry.

The tectonic history of the Stevns area with important Cenozoic uplift probably excludes the locality from being used as an analogue for the fractured reservoirs that are developed on top of salt-induced structures. Analogues for these cases must be found other outcrops, such as the Thisted area in northern Jylland, where an underlying salt structure has brought Maastrichtian and Danian chalk to the surface (Thrane & Zinck-Jørgensen 1997). Likewise the data from the Lägerdorf Quarry in Germany (Figs 35,36) also on top of a salt structure have been promoted as a potential analogue (Koestler & Reksten 1995).

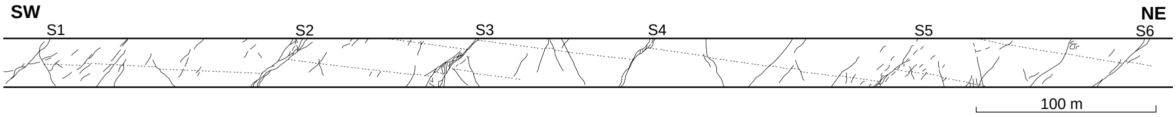


Fig. 35
Long section in the Lägerdorf quarry, indicating the major fault zones and associated fractures. (From Koestler & Reksten 1995).

Fig. 36
Map of the fractures in wall 09 in the Lägerdorf quarry. Profile is 225 x 40 m.

Flow in fractures

The permeability effect of a fracture in 1 m^3 of chalk (Fig. 37) can be calculated, assuming a fracture aperture of 100 µm. This results in an effective permeability of 85 mD for the chalk block along the fracture strike and vertically.

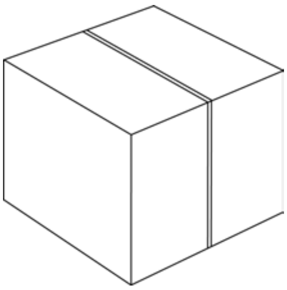


Fig. 37
Schematic illustration of 1 m^3 chalk with a vertical fracture.

The fracture network in Sigerslev quarry has been investigated qualitatively for flow by using infrared thermography. This illustrates the channelised flow pattern in the fracture network, where only a few very conductive pathways carry the main part of the flow. In Sigerslev, the flow channels seem to be located at the intersection between the horizontal fracture set and some of the subvertical fractures (Fig. 38).

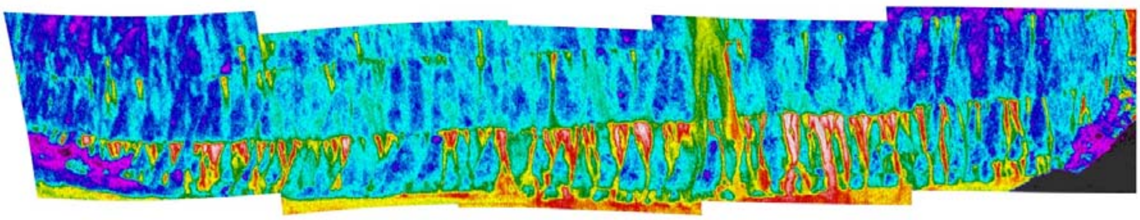


Fig. 38
Thermographic photo of a vertical wall showing in red colours the outflow of ca. 8˚C "hot" groundwater on a very cold day (Courtesy of the FracFlow project at GEUS).

Hairline fractures

A distinct type of fractures has been recognised both in many reservoir chalks and in outcrops in addition to tectonic fractures. The fractures appear as irregular, steeply inclined very thin lines, commonly in clusters with a near-parallel orientation. In outcrop chalk, the hairline pattern is only visible if the oil-staining Bushinsky technique is used to enhance the visibility of the features (Bromley 1981), and applied to an outcrop chalk from the uppermost Maastrichtian it clearly brings out a complex pattern of hairline fractures (Fig. 39). This type of fractures has also been illustrated in Campanian outcrop chalk in the Paris Basin (Mettraux *et al.* 1999).

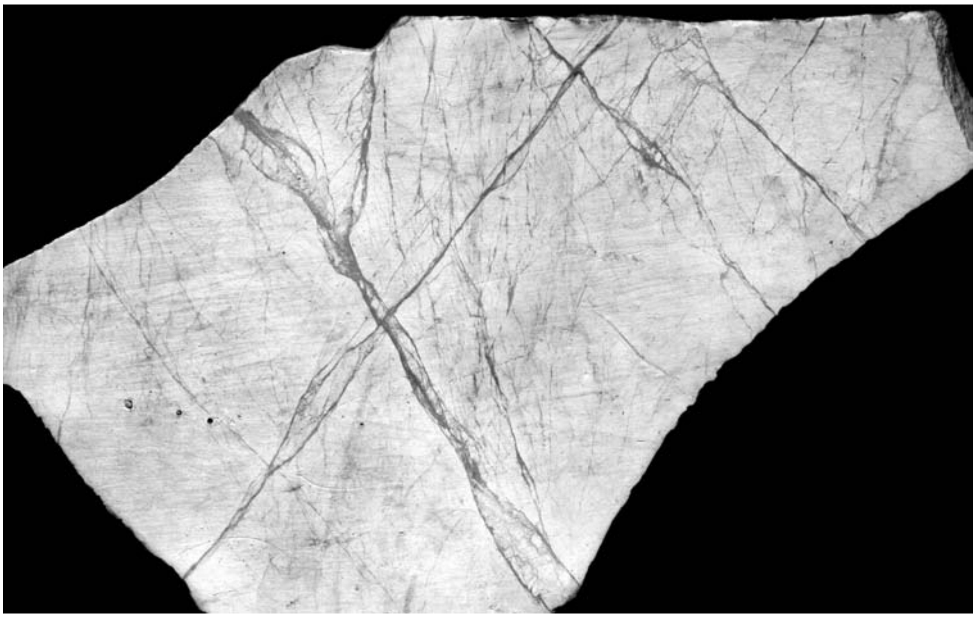


Fig. 39
Vertical slice 16 cm across in outcrop chalk from Stevns Klint from the uppermost Maastrichtian clean chalk. The Bushinsky technique has been applied using a light handyman oil. The complex pattern of hairline fractures includes thin brecciated zones with small chalk intraclasts.

The prediction that hairline fractures show lower porosity than the surrounding matrix is in some cases confirmed by backscatter electron imaging (BSE) of polished samples (Dons *et al.* 1995). A decrease of about 10% in the area representing pore space is observed when the interior of hairlines is compared to the surrounding matrix. The grains of the hairline fractures are obviously more densely packed compared to the grains of the surrounding non-fractured chalk. The lower porosity of the hairlines is not due to a precipitation of calcite cements, as there is apparently no variation in cementation of the hairline and the surrounding matrix. This speaks in favour of a very early formation of the hairline fractures, being related to early dewatering of the sediment, after the original lime ooze was somewhat consolidated and had undergone gentle mechanical compaction.

Rock mechanical properties

Analysis of the rock mechanical properties of reservoir chalk is an active area in chalk research. The general conclusions and guidelines have been hampered by the lack of systematics in laboratory testing conditions and unspecified relation to the rock types and diagenetic characteristics of the specimens tested. However, some conclusions have appeared. The yield and failure surface seems to show a clear relation to porosity. Two reservoir samples conform to the general trend for this system (Fig. 40). The outcrop sample from Hillerslev has a comparably much lower failure surface. The Valhall and Hillerslev chalk have similar porosities, no visible cementation when investigated with SEM, and similar Pc characteristics, so the pore network generally is similar for the two chalk samples. The matrix material is highly similar in composition, the only difference being that the Valhall chalk contains a few stylolites, indicating some limited amount of pressure solution during the burial diagenesis. One interpretation of the reservoir chalk rock strength is that the diagenesis for the reservoir sample, including the available carbonate in solution has caused a very localised cementation of the grain contacts. This works like a welding of the small grains, thereby reinforcing the overall skeleton in the rock. This explanation conforms with the description of hydrocarbon-bearing chalks having maintained high porosity and concurrently relatively high sonic velocity (Fabricius 2003).

The rock mechanical data therefore show a signature of the diagenesis that is not readily observable with other tools.

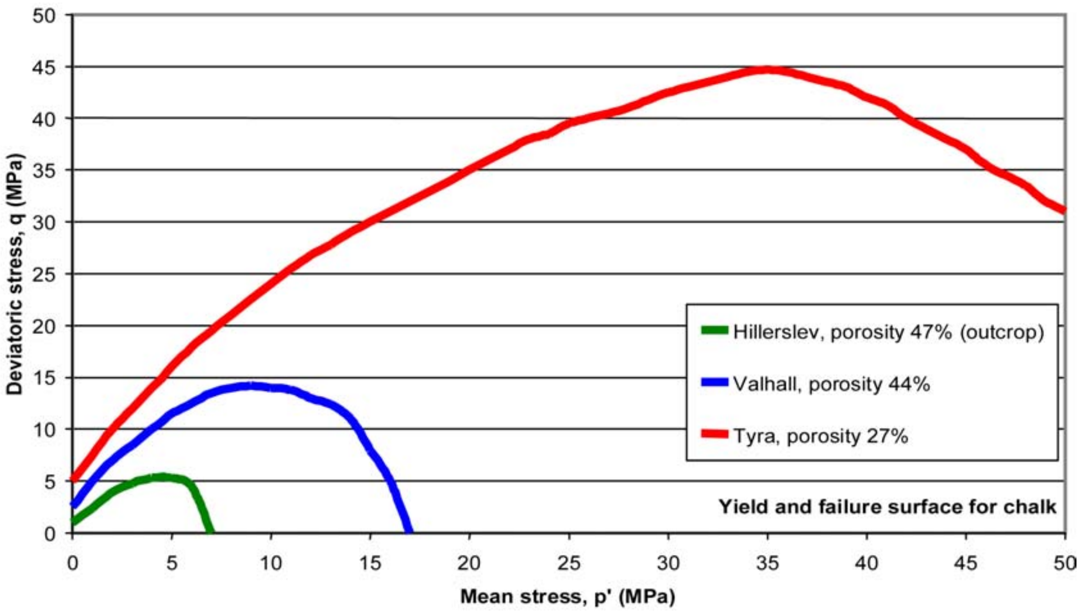


Fig. 40

Failure envelopes for three different chalk samples. The normal relation is a porosity dependency as is shown by the Valhall and Thyra samples. The Hillerslev outcrop chalk shows additional weakness compared to the Valhall sample with same porosity, which must be caused by diagenetic differences. Chalk samples from Stevns show similar characteristics as the Hillerslev samples.

Analogy potential of Stevns outcrop chalk

Focus on the Maastrichtian clean chalk

+ good analogy	- limited/no analogy
Initial **material** – mostly coccolith debris	
Dominant **mineralogy** – low Mg-calcite Very clean, <1-2% IR	
Similar **porosity/permeability relation** linked to the similar grainsize and texture	**Rock mechanical properties** are different due to the difference in diagenetic cementation and grain-welding
Similar **Capillary pressure** characteristics and pore-throat distribution indicate a similar pore-network	**Sound velocity and rock physics properties** are different due to the difference in rock frame resulting from diagenetic cementation
Pelagic sedimentation of the autochthonous chalk is similar and trace-fossil assemblages are similar, although slightly shallower water at Stevns	**Hemipelagic** (winnowing) processes are more common in offshore locations
	Allochthonous (redeposited) chalk not common in outcrop chalk, and of limited abundance in the southern Danish North Sea chalk, but abundant in northern part and in the Norwegian chalk reservoirs
	Biogenic **mounds** only seen in outcrop sections; possibly a shallower water feature
	Reservoir chalk is more **heterogeneous** with varying clay content and diagenetic enhancement of contrasts
Hardground developed in uppermost Maastrichtian	
Cyclicity detected in lower upper Maastrichtian onshore chalk	
Silica present as **flint** nodules and layers, seems to be much more abundant in onshore chalk	Occurrence of **nano-silica** only found in the reservoir chalk, and mainly in the Ekofisk Fm.
	Burial history is different Onshore chalk uplifted in the Neogene
	Diagenetic history is different Deeper burial and much higher temperature
	Hydrocarbon filling and **overpressure** development of reservoirs influence the diagenesis
The large-scale **fault and fracture** pattern may be similar in analogous structural settings (not at Stevns, but e.g. at Lägerdorf)	**Horizontal fractures** only present in outcrops and related to Quarternary burial history. Some glacial impact on top part

Conclusions

The upper Maastrichtian chalk of Stevns Klint is developed as burrowed chalk mudstone to wackestone, with some specific similarities to North Sea reservoir chalks.

1. Stevns outcrop chalk is similar to autochthonous burrowed chalk mudstone reservoir lithotype with low content of clay and insoluble residue.
2. A low content of insoluble residue matches that of the clean reservoir chalks.
3. Diagenesis has had low impact on the outcrop chalk, and the flow properties therefore are similar to the chalk in the hydrocarbon-filled overpressured high-porosity reservoir chalks.
4. Pore geometry is similar as deduced from the capillary pressure curves and pore-throat distributions.
5. Due to differences in diagenesis, the sound velocity and rock mechanical properties may not be similar.
6. The fracturation pattern seen in the Stevns outcrops may resemble that in reservoirs for some selected types of fractures (healed hairlines, conjugate joint sets), but other outcrop localities are better analogies concerning structural position.
7. The porosity/permeability trend closely matches that of the high-porosity reservoir chalks, and forms part of a general trend shown by the reservoir chalks.

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 to extremely high burrow density and diversity. Bioturbation may have caused strong alteration of the sediment resulting in 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**			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 must be posted under the late diagenetic lithotypes.
5		**Laminated Chalk Mudstone**			Damholt & Surlyk (2004)
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 strongly from the lithotype with pure chalk matrix and is therefore listed separately.
8		**Deformed Chalk Mudstone**			Described in Bromley & Ekdale (1987)
9		**Massive chalk Mudstones**.			Chalk associated with episodic bedding and massive chalk showing normal grading is considered as allochthonous chalk
10			**Incipient hardgrounds**		Described in (Kennedy & Garrison 1975)
11			**Nodular hardgrounds**		Described in (Kennedy & Garrison 1975)
12			**Massive (true) hardgrounds**		Described in (Kennedy & Garrison 1975)
13				**Flaser Chalk**	Described in Bromley & Ekdale (1987)

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