Mapping of the Maastrichtian-Danian boundary in the coastal area of Køge Bugt by gamma- and resistivity logging

OLE LARSEN

Larsen, O.: Mapping of the Maastrichtian-Danian boundary in the coastal area of Køge Bugt by gamma- and resistivity logging. *Bulletin of the Geological Society of Denmark,* Vol. 44, pp. 101–113. Copenhagen, 1998-02-28. https://doi.org/10.37570/bgsd-1998-44-06

The Maastrichtian-Danian boundary surface has been mapped by geophysical logging of water supply borewells in the coastal area of Køge Bugt south of København. The transition from bryozoan limestone of Danian (earliest Palaeogene) age with a variable apparent resistivity between 100 and 250 Ohmm to chalk of Maastrichtian (latest Cretaceous) age with a relatively stable apparent resistivity in the range 60–80 Ohmm is easily detected on most resistivity logs. Gamma logs show a characteristic anomaly with two peaks in the uppermost Maastrichtian chalk approximately 8–10 meters below the Maastrichtian-Danian boundary. This gamma anomaly is caused by a layer of marl, which is found persistently in the whole area between København and Køge. The marl is probably equivalent to the Kjølby Gaard Marl, known from outcrops of uppermost Maastrichtian chalk in northwest Jylland.

A preliminary contour map has been prepared displaying the elevation of the boundary surface between the Danian limestone and Maastrichtian chalk below. This map shows that the limestones are weakly folded with structures very simi-lar to those observed in the outcrops of Stevns Klint and also detected by recent seismic studies of the limestone basement in Øresund. The structures can be interpreted without introducing major vertical displacements along faults.

Key words: Resistivity logging, gamma logging, bryozoan limestone, chalk, Cretaceous, Danian.

Ole Larsen, Geologisk Institut, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K., Denmark. 23 May, 1997.

In the region between København and Køge, on the east coast of the island of Sjælland, Maastrichtian chalk and Danian bryozoan limestones form the pre-Quaternary basement. These rocks are outcropping along Stevns Klint, the coastal cliffs of Stevns peninsula (Fig. 1). Danian bryozoan limestones form large biohermal mounds above Maastrichtian chalk (Rosenkrantz 1938, Surlyk 1997). The Maastrichtian-Danian boundary surface is nearly horisontal, but viewed on a large scale it is weakly folded with wavelengths of kilometer scale. Maastrichtian chalk and Danian limestone are met in deep water supply wells on the Stevns peninsula and in the coastal region between København and Køge. Lower Danian bryozoan limestones are exposed in the walls of a now abandoned limestone quarry at Karlstrup (Gravesen, 1983). Chalk was earlier to be seen below the Danian limestones at Karlstrup quarry, but this part of the section is now hidden below the surface of a quarry lake.

From well logs it is known that Maastrichtian chalk forms the pre-Quaternary basement along a considerable part of the coastline between København and Køge (Fig. 1). Approximately 2 km inland from the coastline, Danian bryozoan limestone appears above the chalk, and the chalk is only reached in deeper wells. The occurrence of chalk immediately below the Quaternary deposits near the coast is mainly due to the combined effect of a westward dip of the strata and a deeper level of erosion towards the east (Nejrup, Breddam, Johansen & Korsbæk 1993).

Previous studies of lithological well logs suggested that a more complex tectonic framework would be needed in order to explain the variation in levels, at which the boundary between chalk and bryozoan lime-

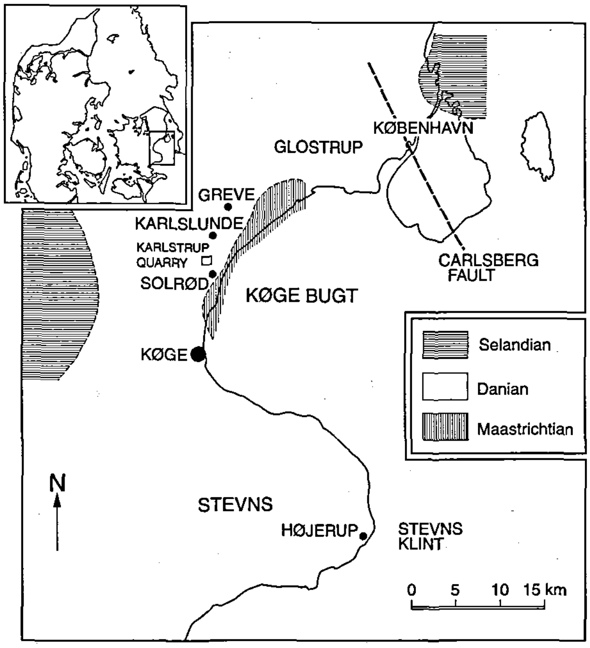


Fig.1. Pre-Quaternary map of eastern Sjælland, south of København.

stone is located. Rosenkrantz (1925) was the first who attempted to compare stratigraphical information from wells in the area between København and Køge. He suggested that a NNE-SSW trending fault west of Karlstrup quarry separates younger Danian limestones west of the fault from an uplifted eastern block with lowermost Danian limestones and Upper Cretaceous chalk. Rosenkrantz suggested that the uplifted coastal block and the eastern part of the Stevns peninsula were parts of the same structure, and he called the uplifted block the "Valby-Stevns Horst". This interpretation was later supported by Ødum (1932, 1935). In a presentation to the Geological Society in March 1937 Rosenkrantz introduced a new fault trending NNW-SSE from Køge, but at the same time he omitted the NNE-SSW-trending fault west of Karlstrup (Rosenkrantz 1938). Hansen (1941, 1943) opposed Rosenkrantz, and he pointed out that the observations could be interpreted just as well assuming weak fold structures in the limestone basement. He placed the Stevns peninsula on an E-W trending antiform and the Karlstrup area on a another WNW-ESE-trending antiform with the town of Køge centered on a synform separating the two antiforms.

More recently Christensen (1979) and later the consulting engineering companies I. Krüger A/S (1987) and N&R Consult A/S (1989) suggested several fault lines separating individual blocks of limestone basement. In all three studies a NE-SW trending fault was placed between the quarry at Karlstrup and the town of Karlslunde following closely the fault line, which Rosenkrantz had suggested in 1925. This fault was now termed "the Køge Bugt Fault". These interpretations were based primarely on lithological logs from a constantly increasing number of wells registered at The Geological Survey of Denmark and Greenland (GEUS), but topography of the limestone surface and directions of surface water streams were also considered. In the opinion of the present author the indicated fault lines seem to be founded on very meager evidence, and none of the faults have yet been proven to exist. With the aim of putting further constraint on the interpretation of the basement structure the present author has attempted to check the recorded lithological information by geophysical logging of existing wells in the Køge Bugt area.

Geophysical methods have been employed extensively during the recent years in connection with geotechnical and hydrogeological studies in the København area. Important lithological boundaries have been identified by the combined use of several geophysical logging methods (Klitten, Plough & Olsen 1994). Gamma logs often show anomalies connected to boundaries between major depositional units, while resistivity logs and induction logs show anomalies that are well-correlated with variations in porosity and density in the Upper Danian limestones. Individual anomalies can be identified and correlated between wells in large parts of København. Based on experiences from logging investigations of borewells at different locations in the København area: Søndersø (Klitten 1993), Dragør (Klitten 1994) and Glostrup (Andersen & Klitten 1995) K. Klitten, senior geologist at GEUS, suggested to the present author the resistivity log as useful for identification of the boundary between chalk and bryozoan limestone.

This paper reports the results from resistivity and gamma logging carried out in 1995 and 1996. This work confirms that the resistivity log is a useful tool to destinguish between chalk and bryozoan limestone, because of the very different resistivity characteristics of the two rocks. In limestones the gamma log is useful for pinpointing marker horisons enriched in radioactive elements. Glauconite, phosphorite and organic material may be concentrated in hardgrounds, and their enrichment in radioactive elements may cause gamma anomalies. In the Køge Bugt area it has not been possible to relate any gamma anomalies to hardgrounds. However, characteristic gamma anomalies in the chalk do occur, and these are clearly related to layers of marl seen as minima in the resistivity logs.

Logging techniques

Resistivity logging was carried out using a conventional 32" (40 cm) spacing normal log. In our experience a 16" spacing is generally too sensitive to variations in borehole diameter, screen material and gravel pack, while the 64" spacing tends to even out variations, that may prove useful in the interpretation of the resistivity curves. The use of the resistivity log is limited to filtered well sections and open sections below the casing. In the Køge Bugt area the older wells have free-standing rock walls below an iron casing, while wells drilled more recently are fitted with casings and screens made of PVC or PEH. In this case only the filter interval will produce a log, and the recorded resistivities are generally above those obtained from wells without screen. For that reason the values shown on the resistivity logs of Figs 3, 5 and 9 are "apparent resistivities" and no attempt has been made to present the data as "formation resistivity". Corrections for the influence from variable borehole diameter and variation in the conductivity of the well fluids proved to be insignificant compared to the influence of the screen and the gravel pack.

Gamma logging was carried out using conventional equipment for integrated gamma counting. Scintillation probes with a 38 mm outer diameter and an uncalibrated counting rate in the chalk and limestone of 200–300 cpm (counts per minute) were used. Attempts to use a thin probe measuring only 10 mm in outer diameter in order to bypass installed water supply pumps were generally not successful. Counting rates have not been calibrated against a known standard source, nor has any correction been applied for variations in borehole diamater.

Geophysical logs from a reference well at Højerup, Stevns

The reference well 218.764 at Højerup, Stevns, is located only 400 m inland from the coastal cliffs at Stevns Klint (Fig. 1). Therefore the resistivity and gamma logs from this well both were expected to display the main characteristics of the stratigraphy at the transition from Maastrichtian chalk to Danian limestone (Fig. 2).

The resistivity curve (Fig. 3) shows a marked change at a depth corresponding to an elevation of 13 m above sea level (a.s.l.). Above this level the apparent resistivity is approximately 140 Ohmm, and below this level the resistivity curve flattens out at 80 Ohmm. Between 9 and 12 m a.s.l. slightly higher resistivity values approaching 100 Ohmm are recorded. In the gamma log a narrow peak more than 800 cpm was recorded 12 m a.s.l.

These observations may be compared with what is seen in outcrops along the cliffs of Stevns Klint (Fig. 2). The lithology at Højerup has been described by several authors, including Rosenkrantz (1938) and Surlyk (1997). At Højerup the Maastrichtian chalk is truncated by an undulating erosion surface (M–D) 10–11 m above sea level. The upper 3.5 meters of the chalk above two closely spaced hardgrounds (HG) is slightly darker coloured than the deeper parts of the chalk and is known as the Grey Chalk (GC). Hansen, Rasmussen, Gwozdz & Kunzendorf (1987) demonstrated that the darker colour is caused by small amounts of evenly distributed carbon black. The Grey Chalk has a considerable content af bryozoans. During the deposition of the Grey Chalk low bryozoan bioherms developed on the sea floor. The bedding is today outlined by flint nodules (F). The eroded top surface of the Grey Chalk is covered by a marly clay, called the Fish Clay (FC) due to the sparse occurrence of fish scales and teeth. The Fish Clay reaches its greatest thickness in the centres of the basins between the low bioherms. The maksimum thickness recorded along Stevns Klint is 20-30 cm, but at Højerup it is only a few centimeters thick. The geochemistry of the Fish Clay has been studied by numerous authors in order to support or oppose extraterrestrial impact theories (e.g. Alvarez, Alvarez, Asaro & Michel 1980), but of particular interest in this context is the several-fold enrichment of uranium and thorium in the Fish Clay over the background concentrations in the chalk and limestones (Engell-Jensen, Korsbech & Madsen 1984, Kunzendorf, Gwozdz & Hansen 1990). The *Cerithium* Limestone (CL), which covers the Fish Clay, is a yellowish white chalkstone composed mainly of silt-size, rounded particles of crystalline calcite (Thomsen 1995). The *Cerithium* Limestone is the lowermost unit of the Danien limestone. At Stevns Klint Fish Clay and *Cerithium* Limestone are only preserved in basins between the biohermal mounds of Grey Chalk due to erosion following the deposition of the *Cerithium* Limestone. A hardground (HG) has developed along this erosional surface. Approximately 16 m of Danian bryozoan limestone (BL) is outcropping in the upper part of the cliff section. Layers of flint nodules demonstrate that the limestones were deposited in large biohermal mounds. The internal

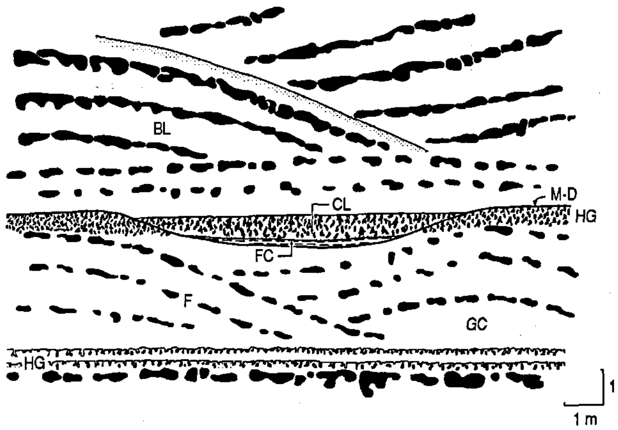


Fig.2. Schematic stratigraphic section across the Maastrichtian-Danian boundary at Stevns Klint (from Surlyk 1997). GC: Grey Chalk, F: Flint layers, M/D: Maastrichtian-Danian boundary, FC: Fish Clay, CL: *Cerithium* Limestone, BL Bryozoan limestone, HG Hard grounds (shown dotted).

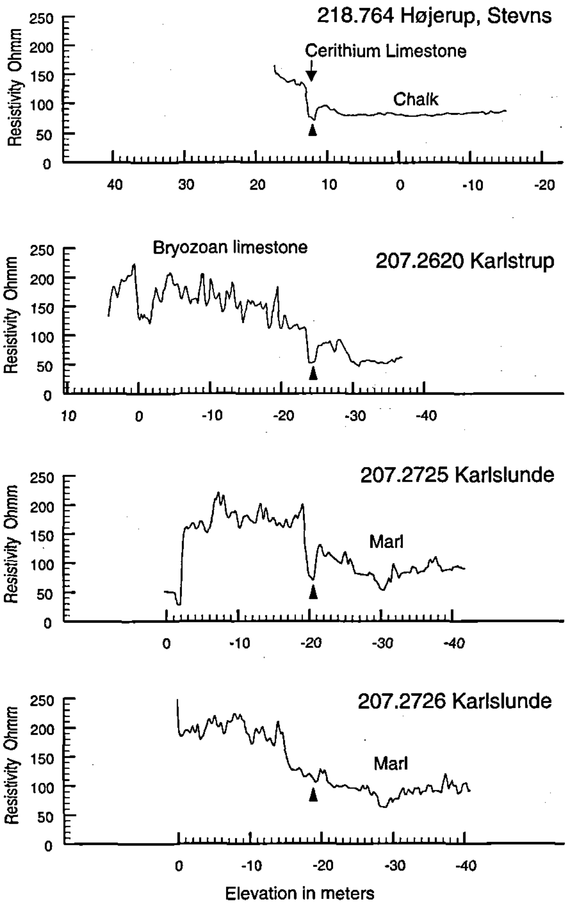


Fig. 3. Resistivity logs from Stevns, Karlstrup and Karlslunde.

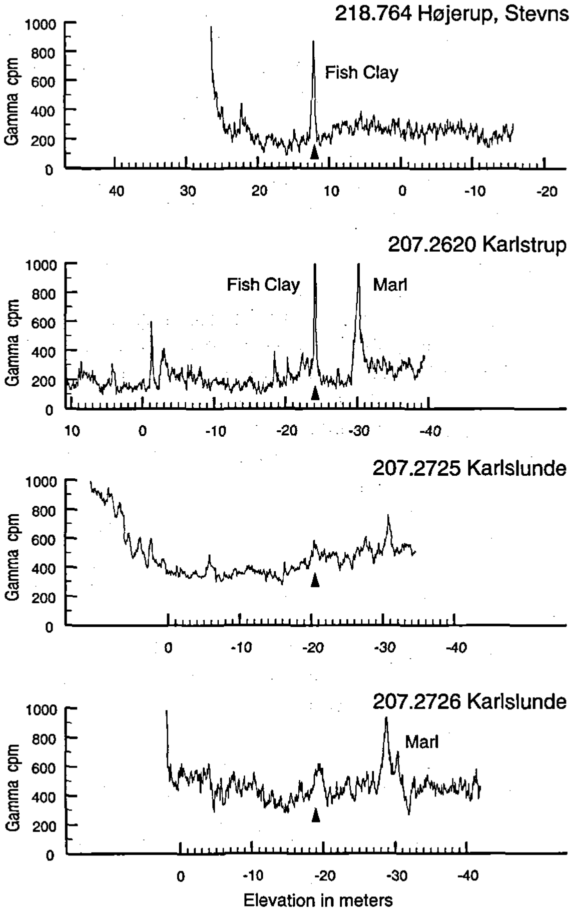


Fig.4. Gamma logs from Stevns, Karlstrup and Karlslunde.

structure of the mounds is important when interpreting resistivity logs from the bryozoan limestone, because anomalies are related to the lithology of units that have considerable variation of dip. Resistivity anomalies are thus not correlatable between wells separated more than a few tens of meters.

In view of the observations from the cliff outcrops, we can reach the following interpretation of the geophysical logs obtained from well 218.764:

1. Maastrichtian chalk at Stevns Klint has a relatively low apparent resistivity around 80 Ohmm, and displays very little vertical variation below the level of the Grey Chalk. Since the chalk was formed by the accumulation of mainly calcitic ooze, the sediment has undergone only very slight diagenetic alteration, and has preserved much of its primary porosity. This would account for the low resistivity.
2. The Grey Chalk displays intermediate resistivity values in the range 80–100 Ohmm.
3. At Højerup the boundary between Maastrichtian chalk and Danian limestones is marked by a well-defined resistivity minimum. The recorded width of the resistivity minimum is about 1.3 m. The maximum thickness of the Fish Clay is commonly less than 10 cm in the center of the depositional basins at Stevns Klint (Kunzendorf et al. 1990). A layer of clay less than 10 cm thick would not be sufficient to produce a resistivity minimum of the recorded thickness. This suggests that the resistivity anomaly is caused by high porosity in the *Cerithium* Limestone, which is mainly composed of silt-size calcitic grains (Thomsen 1995).
4. The bryozoan limestone at Stevns Klint has an apparent resistivity above 120 Ohmm. The Danian limestone has been altered much more by diagenetic processes than the chalk. Layers of hardened limestone with layers or large nodules of flint are seen to alternate with soft, less recrystallised limestone, that has retained more of its primary porosity. These lithological characteristics account for the higher and more variable resistivity recorded in the bryozoan limestone.

5. The gamma intensity is 250–300 cpm in the Maastrichtian chalk and at Højerup 200 cpm in the Danian limestones (Fig. 4). This observation agrees with measured uranium concentrations: 500–700 ppb U in Maastrichtian chalk and 200–300 ppb U in Danian limestone from Stevns Klint (Kunzendorf et al. 1990). According to Engell-Jensen et al. (1984) the Th content of Maastrichtian chalk from Sjælland is equally low (<800 ppb Th), and the K content is also very low (<0.05%). In Danian bryozoan limestones and coralline limestones these authors consistently found extremely low U-contents (<250 ppb U), variable, but low Th-contents (<800 ppb Th) and K values similar to those recorded in the chalk.
6. The gamma anomaly recorded at a depth of 22 m at Højerup is very narrow and positioned at the bottom of the resistivity anomaly (Fig. 4). The gamma anormaly is believed to be the responce of the Fish Clay. The Fish Clay is not only enriched in noble metals such as iridium, but also shows considerable enrichment in U (5000 ppb), Th (3000 ppb) and K (0.2%) (Engell-Jensen et al. 1984, Kunzendorf et al. 1990). The combined effect of this enrichment is sufficient to explain the gamma anomaly. The hardground topping the *Cerithium* Limestone and cutting the low bryozoan mounds of Maastrichtian chalk could have been sufficiently enriched in radioactive trace elements to cause a gamma anomaly, but this anomaly would be located at the top and not at the bottom of the resistivity anomaly of the *Cerithium* Limestone. Furthermore, no gamma anomalies are seen below the Grey Chalk, despite the fact that two hardgrounds may be located in the wall of the outcropping cliffs.

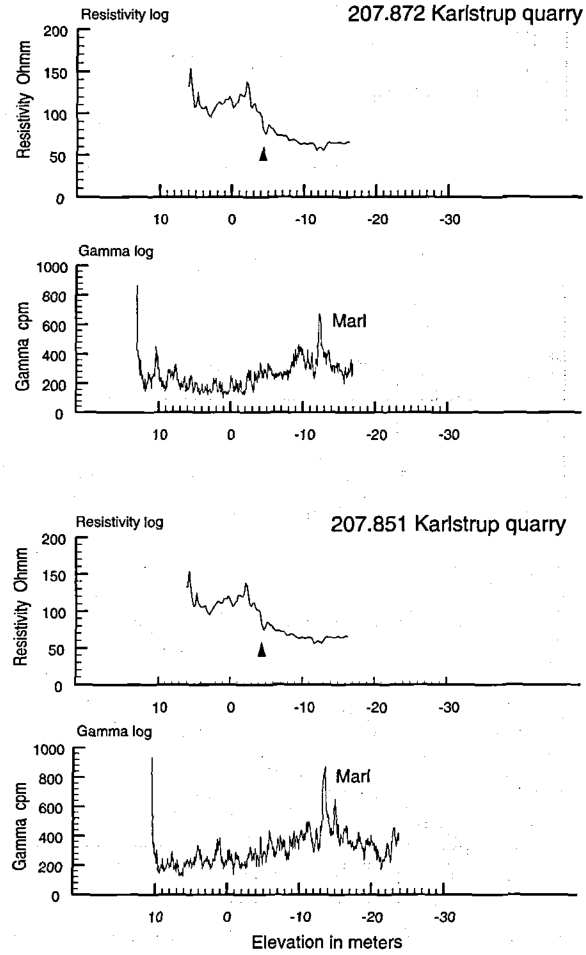


Fig. 5. Resistivity- and gamma logs from two wells at Karlstrup limestone quarry.

Interpretation of logs from the Køge Bugt area

It is now possible to interpret the geophysical logs obtained in the Køge Bugt area using the interpretation obtained from the reference well at Højerup. Five selected wells demonstrate, how logs may be correlated. Resistivity logs and gamma logs from well 207.2620 from Karlstrup and wells 207.2725 and 207.2726 from Karlslunde are shown in Figs 3 and 4 together with logs from the reference well, and logs from wells 207.851 and 207.872 from Karlstrup Limestone Quarry are shown in Fig. 5. The logs are arranged with the boundary between chalk and bryozoan limestone in vertical alignment. Well locations are shown on a detailed map of the Karlstrup-Karlslunde area (Fig. 6).

All wells in Fig. 3 display the same resistivity pattern: High and variable resistivity in the range 150–250 Ohmm typical of bryozoan limestone is recorded above sections with a lower resistivity interpreted as chalk. The anomaly pattern observed in the bryozoan limestone cannot be correlated from one well to the next, because they generally reflect variations in porosity within the mound structures. Wells 207.2620 and 207.2725 both display a destinct minimum separating the high-resistivity section from the low-resistivity section below, and samples retrieved from well 207.2725 confirm that this minimum separates bryozoan limestone from chalk.

In the resistivity log of 207.2725 a second minimum is clearly seen 9.5 m below the boundary between bryozoan limestone and chalk. This minimum is present also in well 207.2726, located nearby. Both minima correspond to destinct gamma maxima (Fig. 4). In well 207.2620 a similar anomaly occurs in the chalk, but here the vertical distance up to the Maastrichtian/Danian boundary is only 6 m compared to 10 m in the Karlslunde wells. This difference may be due to variable levels of erosion of the Maastrichtian

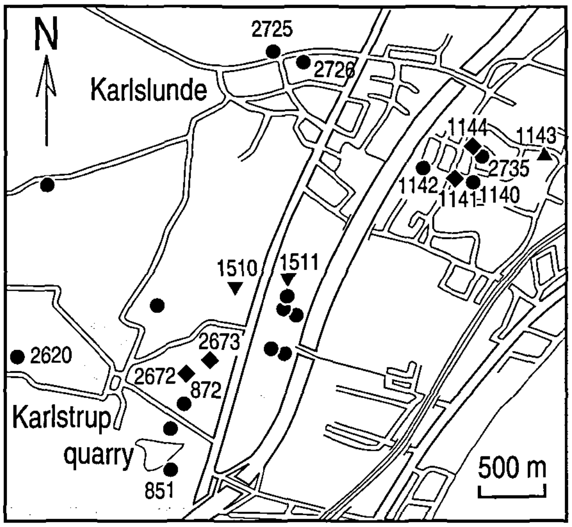


Fig.6. Detailed map of the Karlstrup-Karlslunde area showing locations of wells referred to in the text. Filled circles mark wells, where the boundary between chalk and bryozoan limestone is located by geophysical logging. Diamond-shaped markers indicate wells with lithological data indicating the elevation of the boundary. Resting triangles mark wells, where the boundary has been removed by erosion, and inverted triangles mark wells, where the boundary must be below the well bottom.

sediments before deposition of the Fish Clay and *Cerithium* Limestone.

The gamma log of well 207.2620 displays a very sharp anomaly at the boundary between chalk and bryozoan limestone. This anomaly must be caused by the Fish Clay, with its enrichment in radioactive elements. The occurrence of Fish Clay in well 207.2620 and in the Karlstrup Quarry (Gravesen 1983) proves that the Fish clay was originally deposited in the Karlstrup area. However, this sharp gamma peak is seldomly observed in logs from the Køge Bugt area, so apparently the Fish Clay has generally been removed by erosion before the deposition of Danian limestone.

Logs from wells 207.851 and 207.872 at Karlstrup limestone quarry are shown Fig. 5. Well 207.872 is located outside the quarry at a distance of 250 m from the northern shore of the quarry lake. This lake now covers the Maastrictian chalk up to base of the Danian limestones. The elevation of the boundary is 4 m below sea level (b.s.l.) at the quarry. The boundary may still be observed at the northeastern corner of the quarry lake, but at the southeastern corner, where well 207.851 is located, the boundary is hidden below the surface of the quarry lake.

Gravesen (1983) studied in detail the transition sequence from Maastrichtian chalk to Danian limestone exposed at lake surface level. Fish Clay, up to 10 cm thick, was observed in depositional basins between low mounds of Maastrichtian chalk. The limestone above the Fish Clay contains fine laminae of clay and was described as "Streaky Chalk". This unit is up to 1 m in thick and is followed by 20–40 cm of hard indurated limestone. The "Streaky Chalk" contains only few macrofossils, but foraminifera indicate that the layer corresponds to the *Cerithium* Limestone at Stevns Klint. Above the indurated limestone follows bryozoan limestone in large mound structures similar to those seen at Stevns Klint.

Both resistivity logs from Karlstrup limestone quarry (Fig. 5) have small well-defined minima, where the resistivity curve crosses the 75 Ohmm resistivity level. These resistivity minima, although smaller than the minima on Fig. 3, are believed to mark the position of the "Streaky Chalk". No gamma anomalies are seen at this level. Fish Clay was not mentioned in the lithological well logs from Karlstrup quarry, so the Fish Clay may be thin or missing in these wells.

In both wells at Karlstrup quarry a second depression in the resistivity curve is seen 8 m below the top of the chalk. At the same level the gamma logs show two destinct anomalies. The uppermost peak, displaying the highest gamma intensity, is located at the resistivity minimum. The same was observed in well 207.2726 at Karlslunde.

The observations on well logs from Karlslunde and Karlstrup quarry allow us to draw the following conclusions:

1. The transition layers between chalk and bryozoan limestone may be located, if the resistivity curve shows a minimum at the point, where the resistivity curve drops from variable high resistivity to nearly constant low resistivity. If no minimum is seen, but the drop in resistivity occurs abruptly, the boundary between chalk and limestone may be located with an accuracy of 1–3 m on the basis of resistivity curves alone.
2. The boundary may be reflected in the gamma log, if Fish Clay with a significant enrichment in U and Th is preserved. However, in may places the Fish Clay has been removed by erosion before the deposition of the transition layers and the bryozoan limestone, and then the boundary cannot be located on a gamma log.
3. In the Karlstrup-Karlslunde area a pair of gamma peaks are recorded in all wells penetrating the top 10 m of the chalk. A minimum may be seen in the resistivity log at the position of the uppermost gamma peak. This anomaly has the highest peak intensity and is found at depths of 6–10 m below the Maastrichtian/Danian boundary. The two peaks are approximately 2 m apart, but in some logs only one peak is seen. This peak is then asymmetrical hiding the low-intensity peak as a shoulder on its lower side. In wells that only penetrate the chalk the identification of this characteric gamma anomaly may give an indication of the elevation of the Maastrichtian-Danian boundary.

Occurrences of marl in uppermost Maastrichtian chalk

Ålborg Portland and Cement Factory (APCF) has drilled many cored test wells in and around the Karlstrup quarry. From one of these wells, 207.2672 (APCF well E10, location: Fig. 6), a sample of marl was recovered from a depth of 9-10 m below the transition from bryozoan limestone to chalk (22 m b.s.l.). In a similar test hole 207.2673 (APCF well G12, location: Fig. 6) samples of marl were recovered from two different levels, 14.5 m b.s.l. and 19 m b.s.l.. The lower marl layer presumably corresponds to the marl recovered from 207.2672. These test wells are no longer accessible for logging, but it seems justified to relate the characteristic pair of gamma anomalies recorded in wells 207.615 and 207.872 to the lower marl layer found in the cores of the test wells. It seems that the upper marl layer has so far not been detected by logging.

In northern Jylland at the farm Kjølby Gaard (Fig. 7) a 35 cm thick layer of marl was described already many years ago (Troelsen 1937). The marl is located in chalk 11.5 m below the Maastrichtian-Danian boundary. It was originally described as the Cumula Clay. Troelsen (1955) renamed it the Kjølby Gaard Marl, and this term will be used in the following. The

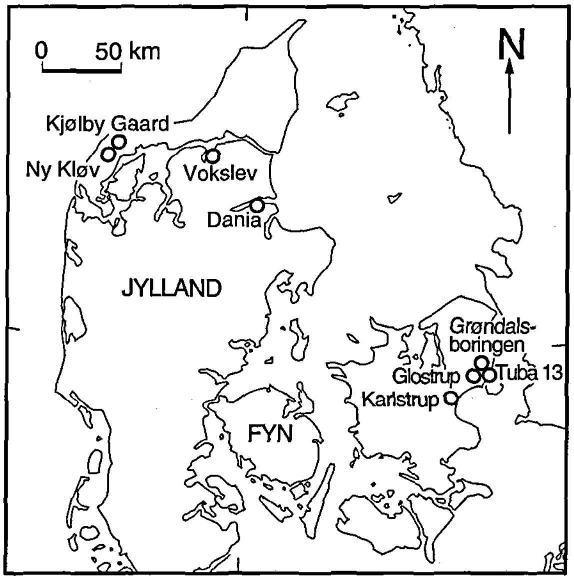


Fig. 7. Map showing occurrences of the Kjølby Gaard Marl.

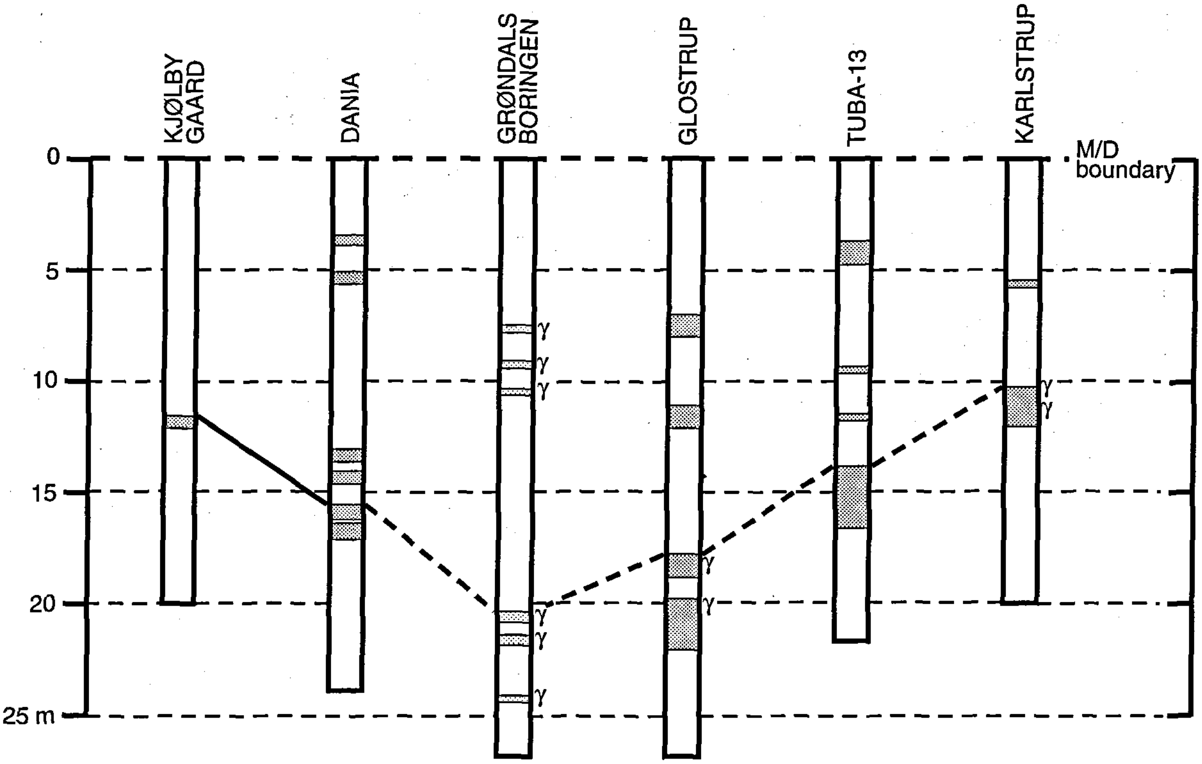


Fig. 8. Correlation of uppermost Maastrichtian marls in northern and eastern Denmark (partly based on Hansen et al. 1987). "γ" marks the location of gamma anomalies.

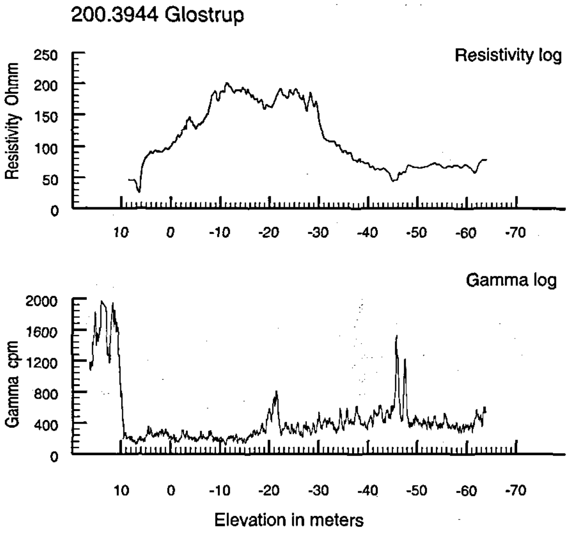


Fig. 9. Resistivity- and gamma logs from Glostrup, west of København.

marl is characterised by an abundance of the large planktonic foraminifera species *Globotruncana contusa.* These foraminifera have never been observed in the ordinary chalk facies. Ekdale and Bromley (1983) studied the Kjølby Gaard Marl in detail. The clay content in the marl reaches 15–25% as opposed to the surrounding upper Maastrichtian chalk, which in northern Jylland contains less than 10% clay.

Troelsen (1955) reported that the Kjølby Gaard Marl also occurs at Nye Kløv, 1.4 km south of the type locality, at the limestone quarry at Erslev on the island of Mors and at the limestone quarries of Vokslev and at Dania Cement Factory, both in northeastern Jylland (Fig. 7). A 30 m thick section from the Dania quarry including the Maastrichtian-Danian boundary was described by Jørgensen (1975). Layers of argillaceous limestone (marl) are seen in the chalk at various levels (Fig. 8). The marly beds are up to 0.75 m thick and contain up to 30% non-dissolvable residue. The marl layer 16 m below the Maastrichtian-Danian boundary also contains *Globotruncana contusa,* the same planktonic foraminifera, which characterise the Kjølby Gaard Marl. Therefore, based on microfossil evidence, Hansen et al. (1987) suggested a correlation of this marl unit at Dania with the Kjølby Gaard Marl of northwestern Jylland.

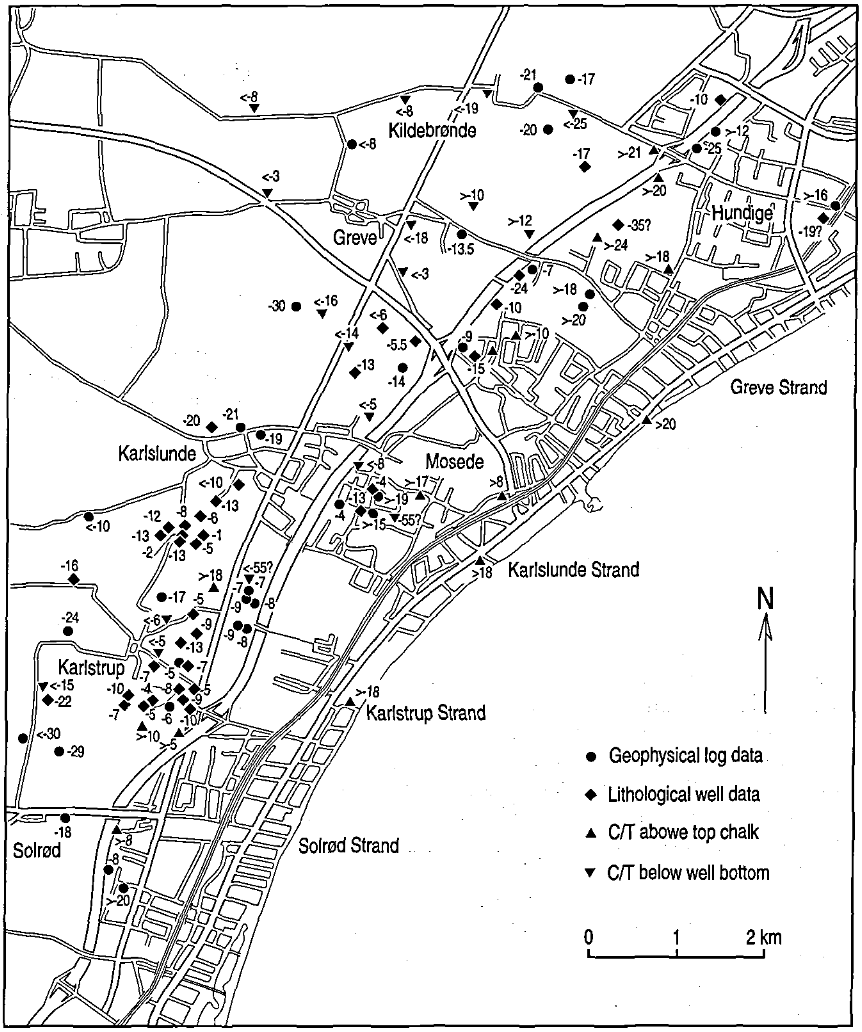
Moving east to the København area (Fig. 7) several units of marl were found in the core from well 210.3080 ("TUBA13") drilled during a previous site investigation campaign for an underground railway in København City (Stenestad 1976). The thickest layer of marl 14.5–16.5 m below the Maastrichtian-Danian boundary (Fig. 8) probably corresponds to the Kjølby Gaard Marl (Hansen et al. 1987). This marl from "TUBA13" does not contain the characteristic large planktonic foraminifera found in the Kjølby Gaard marl in northern Jylland, so this cannot be used for correlation. However, a horizon with the nannofossil *Palludinium grillator,* found less than 1 m below the Kjølby Gaard Marl at Nye Kløv and Kjølby Gaard, has been located in "TUBA13" 19 m below the Maastrichtian-Danian boundary. This supports a correlation of the thick marl layer in "TUBA13" with the Kjølby Gaard Marl in Jylland (Hansen et al. 1987).

Grøndalsboringen (Fig. 7) is a deep test well drilled between 1894 and 1907 in the northwestern part of København. According to Bonnesen et al. (1913) the chalk was reached 37.7 m below surface. Another 800 m were drilled below this level without reaching the bottom of the Senonian. Layers of clay/marl were described from deeper parts of the chalk section, but none were recovered from the uppermost Maastrichtian. However, this well was recently reopened for geophysical logging by GEUS. The deeper parts of the well have caved in and are now inaccessible, but the top 200 m, fitted with an iron casing, could be gamma logged. This log shows several gamma anomalies within the uppermost 25 m of Maastrichtian chalk (the anomalies are marked "γ" on Fig. 8). Two gamma peaks at 20.8 m and 22 m are of particular interest. The peak at 20.8 m shows higher gamma intensity than the peak at 22 m, and this suggests that the anomaly might be correlated with the similar anomaly recorded in the Køge Bugt area.

Recently a test well (200.3944) was drilled to a depth of 80 m at Egeparken in Glostrup appromately 12 km west of central København (Fig. 7). Stringers of clay were noted at depths of 51 and 55 m (7 m and 11 m below the top of the chalk), while thicker layers of marly clay were sampled between 18 and 22 m below the assumed boundary (Fig. 8). This well has been geophysically logged by Hansen (1997), and the logs are shown here as Fig. 9. The gamma log from this well has a very distinct set of two gamma peaks at 46 m b.s.l., which obviously relates to the marl recovered at 18 m below the top of the chalk. The resistivity log shows a minimum at the same depth reflecting the elevated clay content in the marl. The Glostrup log also shows the characteristic decline from 150–200 Ohmm to an apparent resistivity of 50–100 Ohmm, but the decline occurs only 15 m and not 18 m above the marl marker. Either the top 3 m of the Maastrichtian here has an unusual high apparent resistivity, or the first occurrence of chalk was erroneously registered 3 m too high.

By combining lithological descriptions of outcrops and recovered drill cores with geophysical well logs and fossil evidence it seems justified to correlate the Kjølby Gaard Marl in Jylland with uppermost Maastrichtian marls in København and in the Køge Bugt region. This marl appears to be an important marker horison which is easy to identify in geophysical logs. This marl marker was not recorded in the well at Højerup, Stevns.

Fig. 10. Map of the Køge Bugt area between Solrød and Hundige showing lithological and geophysical data indicating the elevation of the Maastrichtian-Danian boundary surface relative to sea level. Filled circles mark wells, where the elevation of the boundary is based on geophysical logging. Diamond-shaped markers are used for wells with lithological data indicating the elevation of the boundary. Resting triangles mark wells, where the boundary has been removed by erosion, and inverted triangles mark wells, where the boundary is located below the well bottom.



Structural interpretation of well data from the Karlstrup area

Lithological data based on material collected by drillers and described by geologists of the Geological Survey are available from the Zeus database at GEUS. Out of 244 wells reaching either Danian limestone or Maastrichtian chalk, 137 wells end in Danian limestone. 48 wells report some sort of information concerning the transition from bryozoan limestone to chalk. 34 wells were placed in areas, where chalk was met immediately below Quaternary sediments.

Wells penetrating both Danian limestones and Maastrichtian chalk are naturally of prime importance for the interpretation of the position of the Maastrichtian-Danian boundary. However, deep wells with bryozoan limestone continuing to the bottom may be used to place an upper limit to the elevation of the boundary in places, where more direct information is lacking. Similarly, wells in which Maastrichtian chalk occurs immediately below thin Quaternary deposits may be used to indicate a minimum elevation for the boundary.

The location of a major part of the wells from which information concerning the boundary between bryozoan limestone and chalk can be obtained are indicated in Fig. 10. Resting triangles mark wells with only Maastrichtian chalk, inverted triangles mark wells with only Danian limestone, diamond-shaped marks indicate wells, where both rock types are recorded. Assumed elevations of the boundary are shown only, where the information has significance for the interpretation. Boundary elevations determined from geophysical logs are marked with a filled circle. All elevations relate to sea level. A contoured map of the boundary surface is shown as Fig. 11. Contouring was made manually and is based on a subjective evaluation of the available data. The information from some

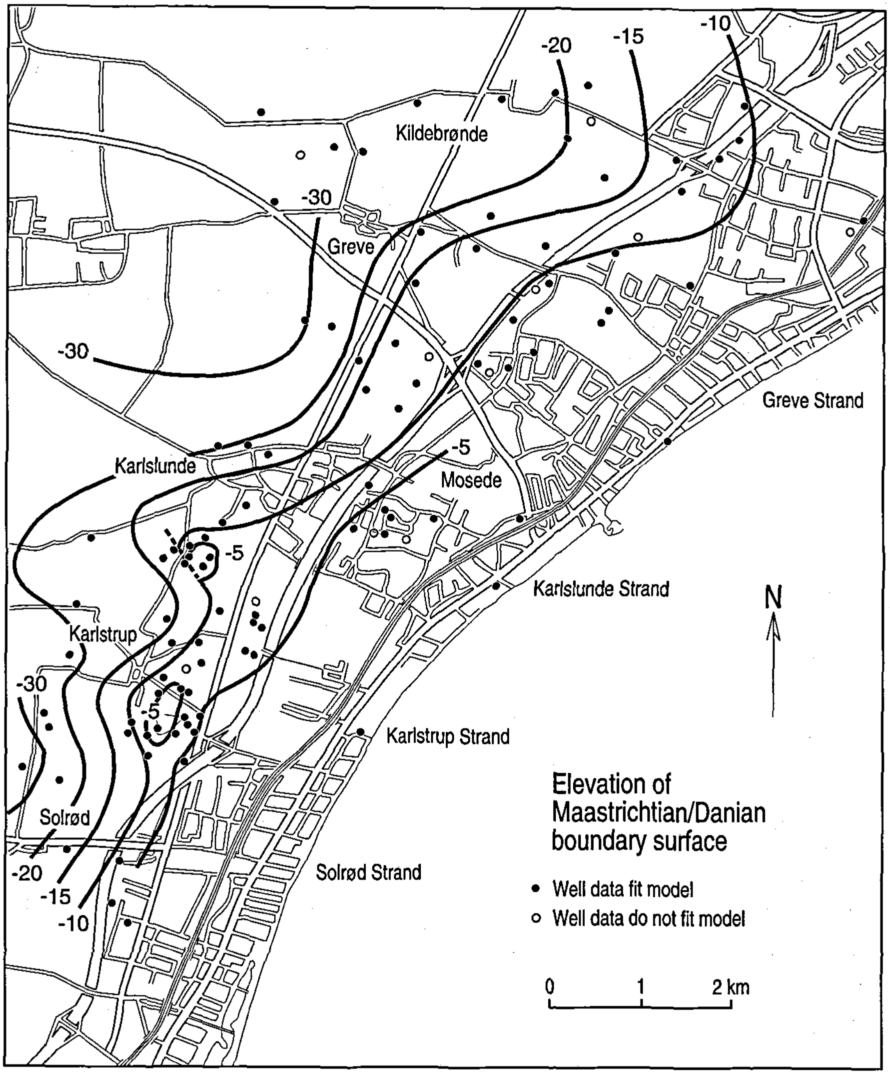


Fig.11. Preliminary map with contoured elevation of the Maastrichtian-Danian boundary surface displaying the structural interpretation of the area between Solrød and Hundige. This map suggests that the limestones are weakly folded, but not faulted.

wells seems to be in conflict with data from neighbouring wells, unless one is willing to cut the area into a number of individual fault blocks. The author is inclined, at the present stage of this work, to accept a certain amount of conflicting data in order to obtain a simple structural model. The main reason for this is that one cannot always rely on the information from drillers logs, and neither on the lithological logs based on samples described at GEUS. A number of well samples were retrieved from storage at GEUS, and the lithology and stratigraphical position was reinterpreted. A few of the samples were checked by examining their microfossil contents. It appears, that the Maastrichtian-Danian boundary in the Køge Bugt area is very difficult to locate on the basis of lithological criteria alone. Bryozoan sceletal remains are common in the uppermost meters of the chalk and may give samples the characteristic appearence of a Danian bryozoan limestone. On the other hand fine-grained calcitic muds are not restricted to the Maastrichtian chalk. The deposition of planktonic ooze continued for some time into the Lower Danian, until the bryozoans invaded the sea floor, and biohermal mounds started to grow. Samples derived from Danian calcilutites could easily be misinterpreted as Maastrichtian chalk. This limitation is also relevant in relation to the interpretation of resistivity logs, because this log reflects lithological characteristics and does not provide us with a chronostratigraphical marker. The resistivity log may at best give information about the depth of the transition from bryozoan limestone (wackestone and packstone, in the classification of Dunham 1962) into porous mudstone, but it cannot distinguish between Danian and Maastrichtian mudstones.

The contoured map of the Maastrichtian-Danian boundary (Fig. 11) clearly demonstrates that surface declines from a level above 5 m b.s.l. east of the freeway leading into København from the southwest to levels deeper than 10 m b.s.l. west of the freeway. Two structural domes appear, one at the Karlstrup limestone quarry and the other midway between the village of Karlstrup and the town of Karlslunde. These two structural domes are separated by a synform trending E-W. According to the original log files at GEUS wells 207.1510 and 207.1511, located in this synform (Fig. 6), should have Danian limestone down to a depth of 50–60 m b.s.l. For this to be true, a fault or a steep flexure with a vertical displacement of approximately 50 m would have to be placed along the southeast side of the synform. In order to test this, samples from these wells were reexamined at GEUS. A sample from the bottom of well 207.1510, previously marked as "Danian", is now considered as "Maastrichtian", while a sample from the bottom of well 207.1511 came out as "Probably Danian". In Karlslunde Strand immediately east of the freeway (wells 207.1140–207.1144, location: Fig. 6) all lithological logs previously reported bryozoan limestone to 50 m b.s.l. A reevaluation of samples from 4 wells demonstrated that chalk is present at moderate depth in all 4 wells. It thus appears that there is no impelling evidence for a fault with major vertical displacement in order to separate these wells from the adjoining area where chalk occurs less than 10 m b.s.l. A synform with a 10–15 m depression of the boundary surface trending E-W between Karlstrup and Karlslunde seems to explain the observations. However, the nose of the antiform, immediately north of this synform, seems to be very steep according to the well logs. A fault line has been drawn NW-SE between wells with the bryozoan limestone/chalk boundary almost at sea level and nearby wells with the boundary 12–13 m below sea level. At present these wells are all fitted with pumps, and are not accessable for resistivity logging.

North of Karlslunde the boundary surface descends into a trough, where it reaches a depth of about 30 m b.s.l., before it slowly rises again to about 20 m b.s.l. in the vicinity of the village of Greve. East of the village of Kildebrønde depths of about 15–20 m appear to extend eastwards almost to the freeway. These depressions of the boundary surface north of Karlslunde appear to be elongated in an E-W direction.

Although folds with steepened flanks are present in the Karlstrup area, there seems to be no evidence for extended faults with major vertical displacements.

Seismic studies of the limestone basement between København and Limhamn, Sweden, have demonstrated folds in the Danian limestone. On the flank of a first order synclinal structure between København and the island of Saltholm several NW-SE -trending minor fold structures have been recognized (Knudsen 1994, Knudsen, Jakobsen, Andersen, Larsen & Foged 1994). The wavelenghts and amplitudes of these deformations correspond to those observed along the cliffs at Stevns Klint and similar structures appear to occur also in the limestones of the Karlstrup area.

One major fault ,"the Carlsberg fault", shows a displacement of Danian limestone of up to 80 m in the central København area (Fig. 1). This fault, early recognized by Rosenkrantz (1925), is oriented NW-SE, and it was recently confirmed by shallow seismic studies (Fallesen 1995, Knudsen & Klitten 1995). Another major fault, the Roskilde fault, trending north from Køge towards Roskilde, was also recognised by Rosenkrantz (1938). Deep seismic studies show considerable vertical displacements of Upper Cretaceous and older Mesozoic sediments along this fault (Bidstrup 1984). Although the present study offers no evidence for major vertical fault movements within the limestones of the Køge Bugt area minor displacements cannot be excluded. The abrupt western termination of the structural dome between Karlstrup and Karlslunde could be related to displacements occurring at greater depth, possibly the Roskilde fault.

Summary

Geophysical logging using resistivity and natural gamma techniques have been used to locate the boundary surface between Danian bryozoan limestone and Maastrichtian chalk. Bryozoan limestones display variable apparent resistivity values between 100 Ohmm and 250 Ohmm, while the chalk has a constant apparent resistivity around 60–80 Ohmm. A gamma anomaly reflecting Fish Clay at the boundary itself is normally not visible. However, a set of two gamma peaks, 1–2 meters apart, is commonly seen in the chalk with the most intensive peak located about 6–10 m below the boundary surface. These gamma peaks are caused by layers of marl. These marls are correlatable with similar layers in the center and west of København and are probably equivalent to the Kjølby Gaard Marl of northern Jylland. This marl, where it occurs, may be used as a marker horison indicating with an accuracy of 2–3 m the position of the Maastrichtian-Danian boundary. These two gamma anomalies are therefore particularly useful where the Danian limestones and transition rocks have been removed by erosion in Tertiary or Quaternary time.

The Maastrichtian-Danian boundary surface is interpreted as a weakly undulating surface displaying antiforms and synforms alternating on a kilometer scale. Synforms appear to have axes trending E-W. At present there seems to be no evidence of faulting with large vertical displacements. In the Karlstrup area structural domes have steepened western flanks indicating flexural movements that could be related to faulting at depth.

Acknowledgements

Senior geologist Kurt Klitten at the Geological Survey of Denmark and Greenland (GEUS) suggested the use of resistivity logging for mapping the boundary between chalk and bryozoan limestone and also on behalf of GEUS provided us with instrumentation for borehole logging. During the project the instruments were serviced by GEUS. Geologist Allan Gramboe-Rasmussen at GEUS helped this project by kindly retrieving a number of samples from storage and reinterpreting the lithology and stratigraphy in the wells represented by these samples.

Dansk sammendrag

Der er benyttet resistivitetslogging og gammalogging til at fastlægge koter på grænsefladen mellem bryozokalk fra Danien og det underliggende skrivekridt fra Maastrichtien. Med en 32″ normallog elektrodekonfiguration viser bryozokalken varierende resistiviteter mellem 100 Ohmm og 250 Ohmm, mens skrivekridtet har en ret konstant lav resistivitet omkring 60–80 Ohmm. Ved gammalogging er det kun i sjældne tilfælde muligt at finde en anomali svarende til Fiskeleret. I Karlstrupområdet ses derimod ofte to anomalier ca. 2 m under hinanden, hvor den øverst registreres i en dybde omkring 6–10 m under grænsen mellem skrivekridt og bryozokalk. Disse gammaanomalier skyldes mergellag, der også findes i den centrale og vestlige del af København. Merglen svarer sandsynligvis til Kjølby Gaard Merglen i Nordjylland. Hvor dette mergellag genfindes i de geofysiske logs, kan det benyttes som en markerhorisont, der understøtter fastlæggelsen af beliggenheden af grænsefladen mellem Maastrichtien og Danien.

En tolkning af de undersøgte lithologiske og geofysiske borelogs er sammenfattet i et konturkort (isohypsekort) over skrivekridt-bryozokalk grænsen. Kortet viser, at kalken i Karlstrupområdet hælder 12–17 promille mod vest, men kalken er samtidigt svagt foldet omkring øst-vest-gående akser. Afstanden mellem antiklinalerne er 2–3 km, og foldernes amplitude er højst ca. 10 m. Der er ingen indikation for, at kalkbjergarterne i området er gennemsat af større forkastninger, således som det tidligere er foreslået. I området nord og syd for landsbyen Karlstrup findes de stejleste hældninger af grænsefladen. Årsagen kan være flexurbevægelser forårsaget af dybereliggende forkastninger, muligvis udløbere fra den dybtliggende Roskildeforkastning mellem Køge og Roskilde Fjord.

References

Alvarez, L. W., Alvarez, W., Asaro, F. & Michel, H. V. 1980: Extraterrestrial Cause for the Cretaceous-Tertiary Extinction. Science 208, 1095–1108.

Andersen, G. and Klitten, K. 1995: Borehulslogging, Boring H05, DGU nr. 200.3235, Glostrup. DGU kunderapport nr. 29.

Bidstrup, T. 1984: Geofysisk kortlægning af Sjælland. M.Sc. dissertation. Univerity of Århus, 200 pp.

Bonnesen, E. P., Bøggild, O. B. & Ravn, J. P. J. 1913: Carlsbergfondets dybdeboring i Grøndals Eng ved København 1894–1907 og dens videnskabelige resultater. Bianco Luno, København.

Christensen, O. W. 1979: Geologiske Data til Hydrogeologiske Modeller. Grundvandsmodel for Hovedstadsregionen. Dissertation, Danish Technical University, Lyngby, 150 pp.

Dunham, R. J. 1962: Classification of carbonate rocks according to depositional texture. In Ham, W. E. (ed.) Classification of carbonate rocks. Memoirs of the American Association of Petroleum Geologists 1, 108–121.

Engell-Jensen, M., Korsbech, U. & Madsen, F. E. 1984: U, Th and K in Upper Cretaceous and Tertiary sediments in Denmark. Bulletin of the Geological Society of Denmark 32, 107–120.

Ekdale, A. A. & Bromley, R. G. 1983: Trace fossils and ichnofabric in the Kjølby Gaard Marl, uppermost Cretaceous, Denmark. Bulletin of the Geological Society of Denmark 31, 107–119.

Fallesen, J. 1995: Danienkalkens stratigrafi og struktur på Amager belyst ved geofysiske undersøgelser – specielt med henblik på Carlsberg Forkastningen. M.Sc. dissertation, University of Copenhagen, 94 pp.

Gravesen, P. 1983: Maastrichtien/Danien-grænsen i Karlstrup Kalkgrav (Østsjælland). Dansk Geologisk Forening, Årskrift for 1982, 47–58.

Hansen, K. 1941: Tektoniske Retningslinier paa Sjælland. Meddelelser fra Dansk Geologisk Forening 10, 9–16.

Hansen, K. 1943: Tektonikken i Danmarks Undergrund endnu en Gang. Meddelelser fra Dansk Geologisk Forening 10, 367–373.

Hansen, K. C. 1997: Kortlægning af Danien-Skrivekridt grænsen i det sydvestlige København med hydrogeologiske og geokemiske aspekter. M.Sc. Dissertation, University of Copenhagen, 124 pp.

Hansen, H. J., Rasmussen, K. L., Gwozdz, R. & Kunzendorf, H. 1987: Iridium-bearing Carbon Black at the Cretaceous-Tertiary Boundary. Bulletin of the Geological Society of Denmark 36, 305–313.

I. Krüger A/S 1987: Saltvandsproblemer på Kildepladser i Køge Bugt området. Rapport til Roskilde Amt, 160 pp.

Jørgensen, N. O. 1975: Mg/Sr distribution and diagenesis of Maastrichtian white chalk and Danian bryozoan limestone from Jylland, Denmark. Bulletin of the Geological Society of Denmark 24, 299–325.

Klitten, K. 1993: Borehulslogging, Boring 19A, Søndersø Kildefelt. Udført for Københavns Vandforsyning. DGU Kunderapport nr. 73.

Klitten, K. 1994: Borehulslogging, 208.1527 og -.311, Dragør Kildeplads. Udført for Dragør Vandforsyning. DGU Kunderapport nr. 59.

Klitten, K., Plough, C. & Olsen, H. 1994: Geophysical log-stratigraphy of the København Limestone. Proceedings of the Eleventh European Conference on Soil Mechanics and Foundation Engineering, Copenhagen. Vol5.

Bulletin of the Danish Geotechnical Society 11, 127–134.

Knudsen, C. 1994: Geologien under Øresundsforbindelsen. DGU Information sept. 1995, 2–4.

Knudsen, C., Jakobsen, P. R., Andersen, C., Larsen, B. & Foged, N. 1994: Stratigraphy and Engineering Geology of København Limestone. Proceedings of the Eleventh European Conference on Soil Mechanics and Foundation Engineering, Copenhagen Vol. 5, Bulletin of the Danish Geotechnical Society *11*, *117–126*.

Knudsen, C. & Klitten, K. 1995: Bybane i København Kalken. DGU Information 3, 8 pp.

Kunzendorf, H., Gwozdz, R. & Hansen, H. J. 1990: Uranium at the Cretaceous-Tertiary boundary in Denmark. Terra Nova 2, 79–86.

Nejrup, D., Breddam, T., Johansen, Th. & Korsbæk, H. 1993: Grundvand i Greve. Dissertation, Roskilde University Centre, 94 pp.

N&R Consult A/S 1989: Vandressourceundersøgelse i Køge Bugt Kommunerne. Fase 1: Statusbillede. 43 pp.

Ødum, H. 1932: Mindre Meddelelser fra D.G.U.'s Borearkiv. Meddelelser fra Dansk Geologisk Forening 8, 185–195.

Ødum, H. 1935: Træk af den prækvartære Undergrunds Geologi paa Sjælland m.v. Meddelelser fra Dansk Geologisk Forening 8, 516–524.

Rosenkrantz, A. *1925*: *Undergrundens tektoniske Forhold* i København og nærmeste Omegn. Meddelelser fra Dansk Geologisk Forening 6, 3–17.

Rosenkrantz, A. 1938: Bemærkninger om det østsjællandske Daniens Stratigrafi og Tektonik. Meddelelser fra Dansk Geologisk Forening *9*, *199–212*.

Stenestad, E. 1976: Københavnsområdets geologi især baseret på citybaneundersøgelserne. Danmarks Geologiske Undersøgelse III 45, 149 pp.

Surlyk, F. 1997: Cool-Water Carbonate Ramp with Bryozoan Mounds: Late Cretaceous-Danian of the Danish Basin. In James, N. P. & Clarke, J. D. A. (eds): Cool-water carbonates, SEPM Special Publication 56, 293–307.

Thomsen, E. 1995: Kalk og kridt i den danske undergrund. In Nielsen, O. B. (ed.): Danmarks Geologi fra Kridt til i dag, 30–67, University of Århus.

Troelsen, J. C. 1937: Om den stratigrafiske Inddeling af *Skrivekridtet i Danmark. Meddelelser fra Dansk Geolo*gisk Forening 9, 260–263.

Troelsen, J. C. 1955: Globotruncana in the White Chalk of Denmark. Micropaleontology 1, 76–82.