Structures and stratigraphy of Danian limestone, eastern Sjælland, Denmark

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West of København, the top of the pre-Quaternary limestone is found near the terrain surface. There is only a relatively thin cover of Quaternary deposits, which makes the limestone vulnerable to pollution. Region Hovedstaden, being responsible for treating polluted sites, therefore asked GEO and the Geological Survey of Denmark and Greenland to describe the geology and hydraulic characteristics of the limestone formations (Galsgaard *et al.* 2014). During this work new information and data were collected and a revised geological model established for the area between København and Roskilde (Fig. 1). The model is based on seismic sections, a revised map of the pre-Quaternary surface, biostratigraphy, borehole information and geophysical data. This paper presents the revised geological model.

Limestone formations

The uppermost 100 m of the pre-Quaterary deposits between København and Roskilde comprises Maastrichtian chalk, bryozoan limestone (Stevns Klint Formation), the København Kalk Formation and the Lellinge Grønsand Formation (Figs 1, 2).

Cretaceous (Maastrichtian) chalk is a carbonate mudstone. It is overlain by Danian deposits in the area between Roskilde and København, but occurs at the pre-Quaternary surface in the southern part of the area.

The early and middle Danian bryozoan limestone, defined as the Stevns Klint Formation by Surlyk *et al.* (2006), usually contains 20 to 45% bryozoan fragments, but the formation also comprises mudstone or calcarenite with scattered bryozoans. Usually the bryozoan limestone is deposited in mounds, which are strongly asymmetrical in the lower mound complex and less so in the middle and upper mound complexes (Fig. 2). Flint occurs as layers between the limestone layers and lenses of coral limestone also occur. The bryozoan limestone is 53–63 m thick in the København area (Stenestad 1976).

The København Kalk Formation is of late Danian age. It is a sandy and silty carbonate mudstone defined by Stenestad (1976). It has sub-horizontal layering with pronounced flint layers parallel to the layering. A log-stratigraphy was established in the København area by Klitten *et al.* (1995; Fig. 2). The formation is 40–45 m thick.

The youngest formation, the Lellinge Grønsand Formation, is of Selandian age and consists of glauconite and carbonate-rich sand with layers and lenses of sandy limestone. Glauconite-rich marl also occurs.

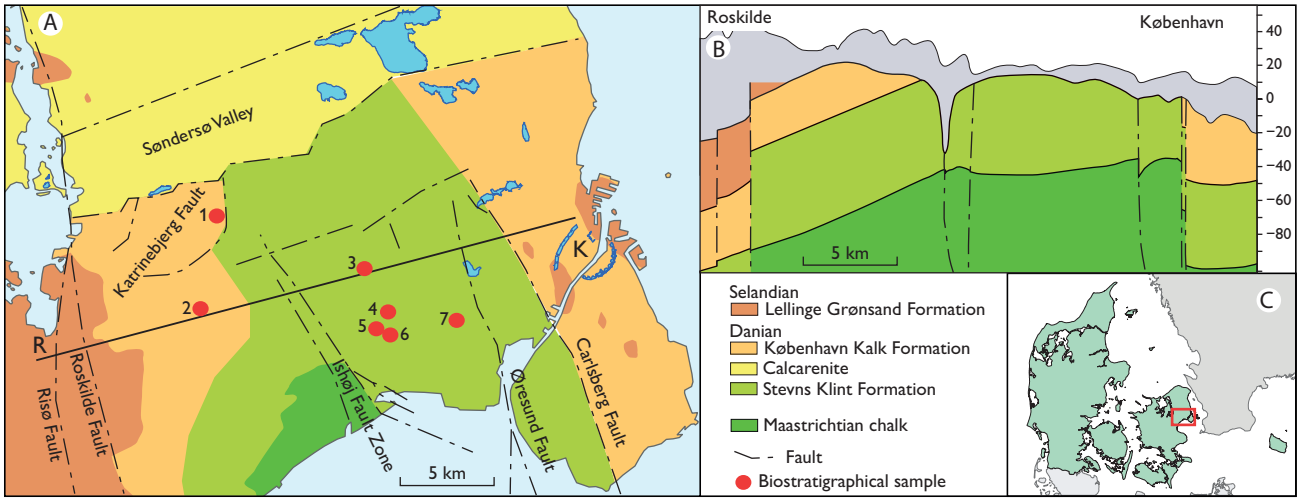

Fig. 1. **A**: A revised geological map of the pre-Quaternary surface in the København–Roskilde area. The numbered dots show the location of analysed samples. **R**: Roskilde. **K**: København. **B**: An east–west profile. **C**: Location of the study area.

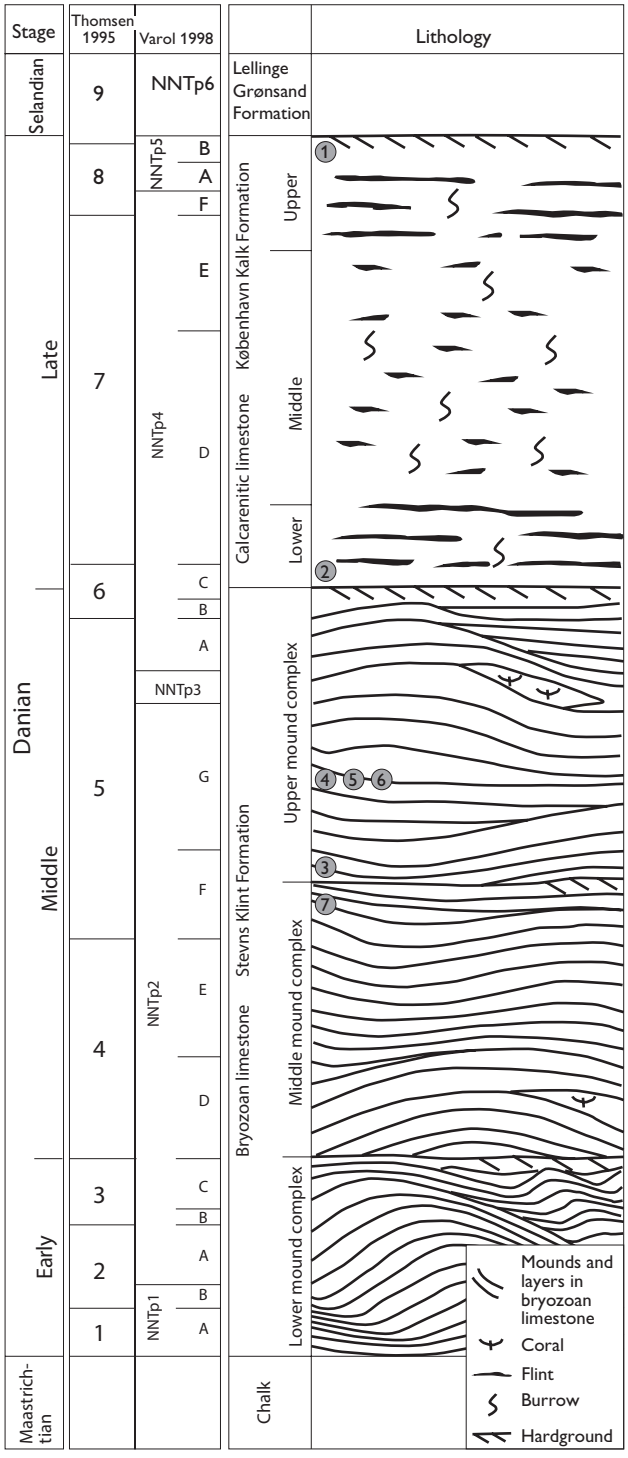

Fig. 2. Chronostratigraphy, biostratigraphy, lithostratigraphy and lithology in the greater København area (modified from Lund *et al.* 2002). Numbered dots are the numbered localities in Fig. 1A.

Biostratigraphy

Calcareous nannofossils are the main constituent of chalk deposits. Calcareous nannofossils are thought to be the remains of the principal calcareous nannoplankton group: the haptophyte algae (Bown & Young 1998). They are useful as biostratigraphic markers as they have a widespread distribution and are present globally in the photic zone of almost all marine habitats.

Table 1. Biostratigraphical results

Locality*	Nannofossil zone	Stage
1 Hove limestone pit	NNTp5B-6	Uppermost Danian – Selandian
2 Kallerup pit	NNTp4C	Early late Danian
3 Naverland 26, Glostrup	NNTp2F	Middle Danian
4 Kirkebjerg Parkvej 14	NNTp2G	Middle Danian
5 Dalager 7	NNTp2G	Middle Danian
6 Hesselager 17	NNTp2G	Middle Danian
7 Hvidovre Hospital	NNTp2F	Middle Danian

* locality numbers refer to localities marked on Figs 1, 2

The nannofossil biostratigraphic dating of the outcrops and wells from eastern Sjælland is based on the North Sea zonation scheme of Varol (1998) which, along with the Danish onshore nannofossil zonation scheme of Thomsen (1995) for comparison, is seen in Fig. 2. The zonation scheme of Varol (1998) was mainly based on North Sea wells, but sections from onshore Denmark were also used in its construction. As seen in Fig. 2, the zonation scheme of Varol (1998) allows for a higher resolution biostratigraphic breakdown than that of Thomsen (1995). Table 1 (youngest stratigraphy at the top) shows the biostratigraphic dating of samples taken from two outcrops and five wells (Fig. 1). The results show that samples from the more easterly localities are the oldest (middle Danian, subzones NNTp2F–G), and the samples become younger to the west (upper Danian–Selandian subzones NNTp4C and NNTp5B).

Faults and interpreted faults

The most pronounced tectonic feature in the subsurface of København is the SE–NW-trending Carlsberg Fault that separates the København Kalk Formation from the Stevns Klint Formation (Fig. 1). The fault is one of a number of relay faults related to the Tornquist–Sorgenfrei Wrench Fault Zone. The Carlsberg Fault can be regarded as a negative flower structure with a main offset between 50 and 100 m of the hanging-wall block down to the NE (Fallesen 1995; Jakobsen *et al.* 2002). The Carlsberg Fault may still be active as terrain movements have been detected across the fault (Jakobsen *et al.* 2013) and neo-tectonic faulting of the Quaternary cover is seen (Kammann *et al.* 2016). The Carlsberg Fault is recorded on the seismic profile HGS-002 (Fig. 3) along with the Øresund Fault and the Ishøj Fault Zone. The Øresund Fault is almost parallel to the Carlsberg Fault, but they merge about 12 km north of the

seismic profile. The Ishøj Fault Zone is a *c.* 5 km wide positive flower structure with folding between the faults and an over-all inversion across the zone. The inversion has caused the Maastrichtian chalk to be present at the pre-Quaternary surface in the Ishøj area.

One of the prominent continuous reflectors in the upper part of the seismic profile is outlined in Fig. 3, and it dips *c.* 50 m from the Ishøj Fault Zone to the eastern part of the area shown in the seismic section. The same dip is seen on the seismic section HGS-001 about 10 km north of HGS-002. The Roskilde and Risø Faults are the westernmost faults presented in Fig. 1; they form part of a series of N–S-trending relay faults in the Roskilde area (Pedersen & Gravesen 2016).

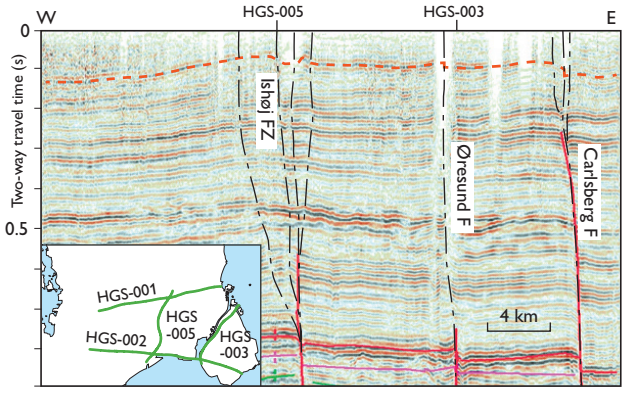

Fig. 3. Seismic section HGS-002. The inset map shows the location of the profile and some additional profiles used for the interpretation.

Pre-Quaternary surface

The Danian limestone forms the pre-Quaternary surface in eastern Sjælland and is the primary source of groundwater in the area. The large number of wells and well-logs and geological information recorded and stored in the national Jupiter database allow a detailed mapping of the limestone surface. Based on these well-logs and several geological models, a new map of the level of the pre-Quaternary surface was constructed (Fig. 4).

In the northern part of the map area, the Søndersø Valley has a valley bottom *c.* 40–30 m below sea level and strikes SW–NE. Several buried valleys have been identified and marked with red lines on the map (Fig. 4). The longest of these is the Herlev Valley that is oriented parallel with the Søndersø Valley *c.* 5 km south to the of it. Towards the west, the Herlev Valley almost intersects the smaller Katrinebjerg Valley. The general level of the pre-Quaternary surface is 5–10 m higher south of the Herlev and Katrinebjerg valleys compared with the area between these valleys and the Søndersø Valley.

Two narrow valleys, the Rådhus and Vibenhus valleys, situated below the city of København are generally well mapped based on borehole data. Several conspicuous depressions in the limestone surface are only identified from one or a few boreholes, e.g. in the northern part of Taastrup and the eastern part of the Herlev Valley. It is possible that these small depressions are un-mapped valleys similar to the clear buried valleys identified on the map in Fig. 4.

Geological model

The revised geological map and model are presented in Fig. 1. The map is based on interpretation of the map of the pre-Quaternary surface, seismic sections and biostratigraphic analyses. The biostratigraphic analysis of the middle part of the Stevns Klint Formation (Fig 1) shows that the limestone in this area, at the pre-Quaternary sur-

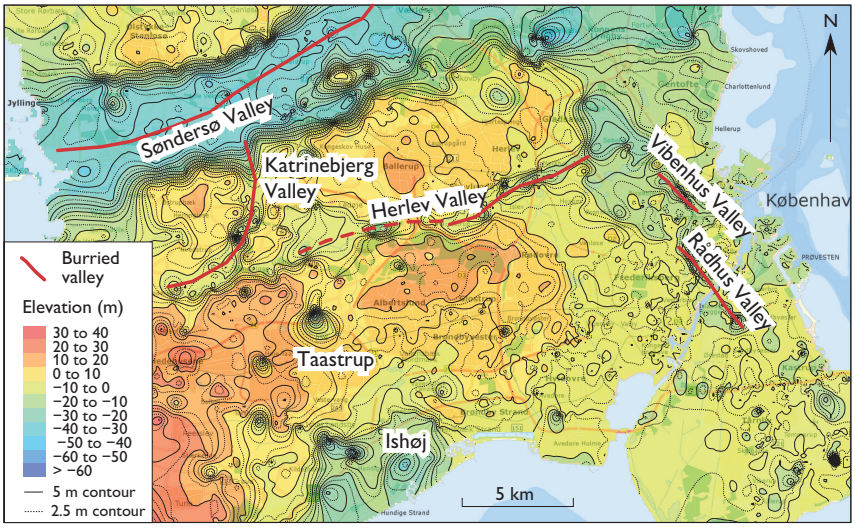

Fig. 4. Topography of the pre-Quaternary surface in the København–Roskilde area based on the latest data.

face, is of middle Danian age and belongs to the upper mound complex (Fig. 2). Compared with the depth to the Maastrichtian–Danian boundary, registered in adjacent boreholes, the thickness of the Stevns Klint Formation is fairly uniform and comparable with thicknesses known from the København area, and a uniform thickness of the limestone unit is consequently assumed. Previous maps do not show the presence of the København Kalk Formation between the Lellinge Grønsand Formation and the Stevns Klint Formation in the western part of the area (Stenestad 1976). With a dip of *c.* 50 m from the Ishøj Fault Zone to Roskilde, it is therefore expected that the København Kalk Formation is present between the Stevns Klint Formation and the Lellinge Grønsand Formation. This was confirmed by biostratigraphical analyses of samples from localities 1 and 2 (Figs 1, 2). However, the two samples representing København Kalk Formation are from the uppermost and lowermost parts of the formation, respectively. This means that the Katrinebjerg Fault (Fig.1), interpreted from the pre-Quaternary surface map, is in fact a fault, with an offset of *c.* 50 m. At Hove (locality 1, Fig. 1) a geophysical log from borehole DGU 200.5248 shows the same log pattern as it is known from the København area and shows the presence of the whole formation.

Many samples from boreholes within the western København Kalk Formation area are described as bryozoan limestone. This could represent a facies variation with a higher concentration of bryozoans than is usually seen in the København area. However, it is also possible that the tectonic conditions are more complex, with more faults than those documented so far.

Conclusions

The geological map of the pre-Quaternary surface is revised for the area between København and Roskilde. The revision is based on new seismic sections, a map of the pre-Quaternary surface and biostratigraphic analyses.

The Ishøj Fault Zone is a positive flower structure, and a prominent structural feature in this area. Between the Ishøj Fault Zone and the Roskilde Fault, the limestone dips westwards.

The Upper Danian København Kalk Formation is documented in the western part of the pre-Quaternary surface between København and Roskilde and may have a higher content of bryozoans than in the København area.

Acknowledgements

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