FIELD TRIP TO THE CHALK CLIFFS AT MØNS KLINT

Excursion guide prepared for geologist participating in the 3 D modelling conference May 2023 in Copenhagen

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6th European Meeting on 3D Geological Modelling

Geological Modelling for the Sustainable Society

FIELD TRIP PROGRAM MAY 2023

Participants for the field excursion will be picked up by bus in the center of Copenhagen at 8 a.m. The bus drive to Møns cliff is approximately 2 hours. An experienced geologist will guide the excursion on a walk from south to north. Midday we will stop for lunch at Geocenter Møns Klint. After lunch, we continue to the neoclassical palace at 'Liselund castle'. Here the bus will return and drive back towards Copenhagen.
We will arrive in Copenhagen in time to get ready for the ice-breaker event in the evening. The walk along the cliff is around 5 km (on the beach in uneven terrain) and includes a climb of 497 steps up the cliff. Therefore, please remember suitable shoes and clothes. The excursion will be completely at your own risk.
The field excursion guide involves a description of the geology at Stevns (pages 12-18), which is a UNESCO heritage site, due to the visibility of the famous Cretaceous/Tertiary boundary (C/T). A visit to Stevns cliff can be recommended as a half-day trip after the conference for people of special interest (self organized).

23TH OF MAY, MORNING:

08.00 – 10.00: Bus drive to Møn

10.00 – 12.00: Walk along the cliff - southern part of the glaciotectonic complex

23TH OF MAY, AFTERNOON:

12.00 – 12.15: Mounting the steps up to the Geocentre

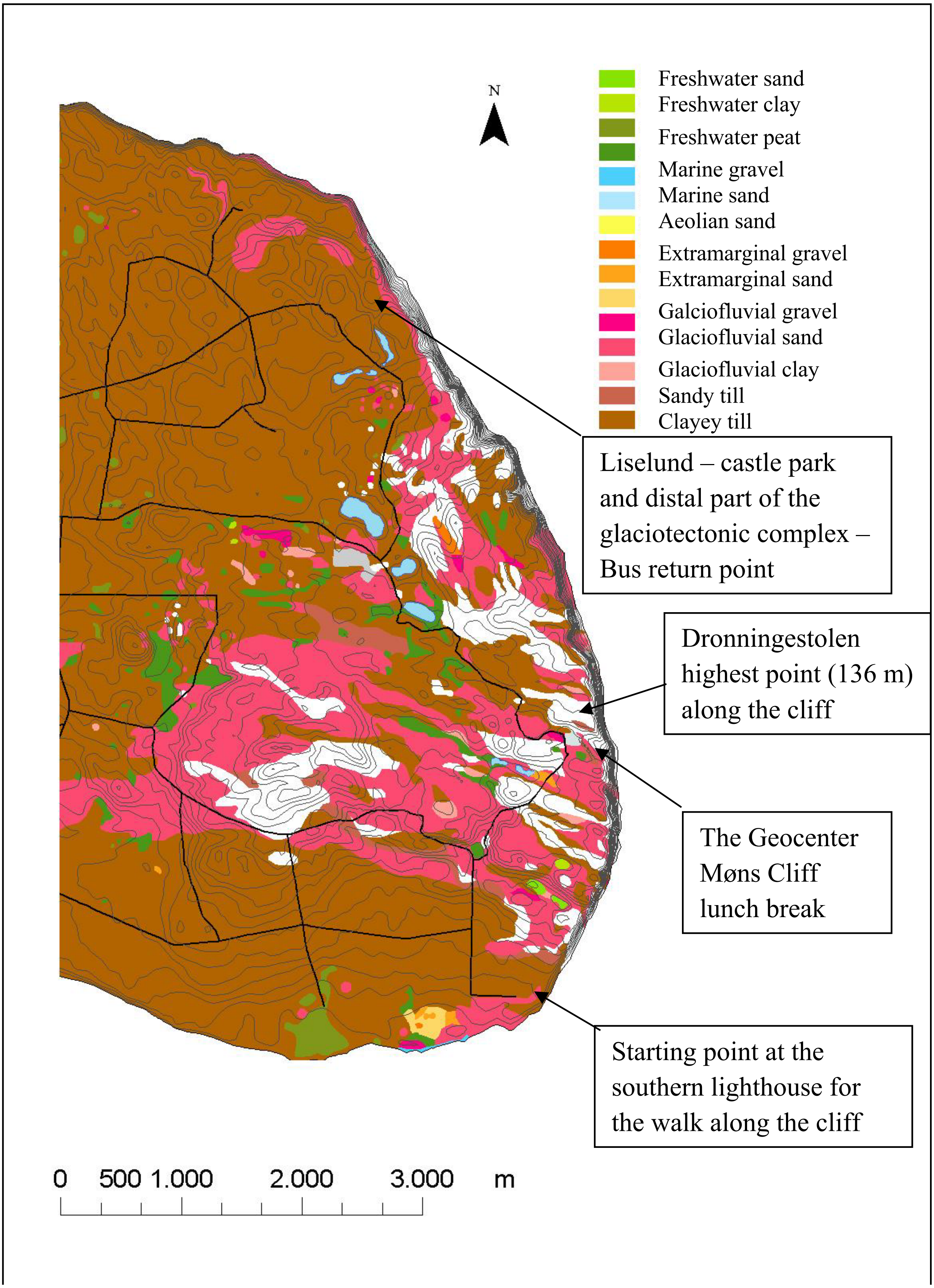
12.15 – 13.00: Lunch at the Geocentre café

13.00 – 14.00: Walk up to Dronningestolen and Forchhammers Point

14.00 – 14.30: Drive to Liselund

14.30 – 16.00: Walk down to the beach at Liselund Park

16.00 – 18.00: Bus drive back to Copenhagen


N
Freshwater sand
Freshwater clay
Freshwater peat
Marine gravel
Marine sand
Aeolian sand
Extramarginal gravel
Extramarginal sand
Galciofluvial gravel
Glaciofluvial sand
Glaciofluvial clay
Sandy till
Clayey till
Liselund – castle park and distal part of the glaciotectonic complex – Bus return point
Dronningestolen highest point (136 m) along the cliff
The Geocenter Møns Cliff lunch break
Starting point at the southern lighthouse for the walk along the cliff
0 500 1.000 2.000 3.000 m

ABSTRACT

Møns Klint is a beautiful coastal cliff bounding the hilly terrain Høje Møn situated in the eastern part of the island of Møn in south-eastern Denmark. A scenic cross section through this terrain is seen in the coastal cliff facing the Baltic Sea - an exceptional landscape of unique nature only seen very few places elsewhere in the world. The hills consist of white Cretaceous chalk only covered by a thin layer of black soil with beech trees. Along the coastal cliff the Cretaceous chalk crops out as 100 m high vertical, white cliffs separated by valleys with Quaternary sediments mainly covered by a rich vegetation.

The formation of Møns Klint has attracted scientific discussion for more than two centuries. The earliest view related its rough and peaked features to result from orogenic activity. Standing on one of the hill crests a similarity of mountain-like features comparable with the Jura Mountains may indeed be perceptible. Orogenic, activities were initially proposed before realisation of the occurrence of glaciations during the Quaternary period. From about 1880 to 1920 an alternative model for the formation of Møns Klint was formulated, involving generation of the hilly ridges by ice push, also referred to as a glaciotectonic thrusting and stacking of the chalk sheets to form a structural complex. With some modifications this is still the general opinion, and Møns Klint is arguably the most famous example of a glaciotectonic complex.

Meanwhile, the question about a deep-seated cause for the formation of the structural complex occasionally pops up. The idea of involvement of block-fault tectonics was brought forward in the years 1930–40 without having received much support. During the last 25 years new insights in the subsurface of Denmark have been acquired in connection with hydrocarbon exploration. Today, it is therefore known that Møns Klint is located in the junction of two marked tectonic elements in the Danish subsurface, namely the Ringkøbing–Fyn High and the fault splay on the west side of the faulted Sorgenfrei–Tornquist Zone. So the idea of a formation of the complex by a combination of tectonic, deep-seated deformation and glaciotectonics has been re-vitalised.

THE ORIGIN OF MØNS KLINT

Denmark is generally regarded as a lowland without dramatic topography. Møns Klint stands out as a marked exception with its impressive coastal cliff bounding the hilly terrain, Høje Møn on the eastern part of the island of Møn, SE Denmark (Fig. 1). The spectacular cliff has for centuries attracted people's attention, and the geological development of Møns Klint has been the target of much speculation and formulation of hypotheses. Today Møns Klint is regarded as a both classic and outstanding example of a glaciotectonic complex. The cliff exposes a 4 km long cross section through the structural complex, where a number of crucial details can be observed. However, it is still unproven, whether deeper seated geological features provided the background for the formation of Møns Klint and the hills of Høje Møn.

TERRAIN AND LANDSCAPE

The hilly terrain Høje Møn occupies the eastern part of the island of Møn, which comprises composite, parallel, elongated ridges reaching 130–140 m above sea level (Fig. 2). The terrain is bounded to the east by the coastal cliff of Møns Klint facing the Baltic Sea. The cliff presents a cross section through the hilly landscape and displays the internal tectonic structures. Some of the hill crests can be traced for more than 5 km inland towards the west, and the hills consist of white Cretaceous chalk, which crops out on the hill slopes in the wood. Lakes are common in the narrow valleys between the parallel-ridged chalk hills, and soft clay and sand are located in these depressions. At Møns Klint the Cretaceous chalk is exposed as 100 m high vertical, white rock faces separated by valleys with Quaternary sediments mainly covered by rich vegetation. Due to the erosion of the cliff two types of landslides are common: rock falls of the chalk cliff and clayey landslides in the valleys (Pedersen et al. 1989, Pedersen & Møller 2004, Pedersen & Gravesen 2009, Pedersen 2012).

Figure 1. Oblique aerial photograph of the 130 m high point Dronningestolen in the central part of Møns Klint. The inserted map show the location of Møns Klint in SE Denmark. Photo: SASP 2003.

THE DEVELOPMENT OF SCIENTIFIC HYPOTHESES FOR THE FORMATION OF MØNS KLINT

For more than two hundred years scientific speculation and discussion have addressed the origin of Møns Klint. Around 1825 the first professor in geology at the University of Copenhagen, Johan Georg Forchhammer, suggested a plutonic origin of Møns Klint. He interpreted the Quaternary sediments between the chalk cliffs as volcanic dykes and suggested that the plutonic activity was the cause of the elevation and deformation of the Cretaceous chalk, i.e. a combination of volcanogenic and orogenic formation (Forchhammer 1826, 1863). In the spring of 1834 the professors Charles Lyell and Johan Georg Forchhammer made a famous visit together to Møns Klint. On the way to Møn they also visited Stevns Klint and the Faxe limestone quarry, where

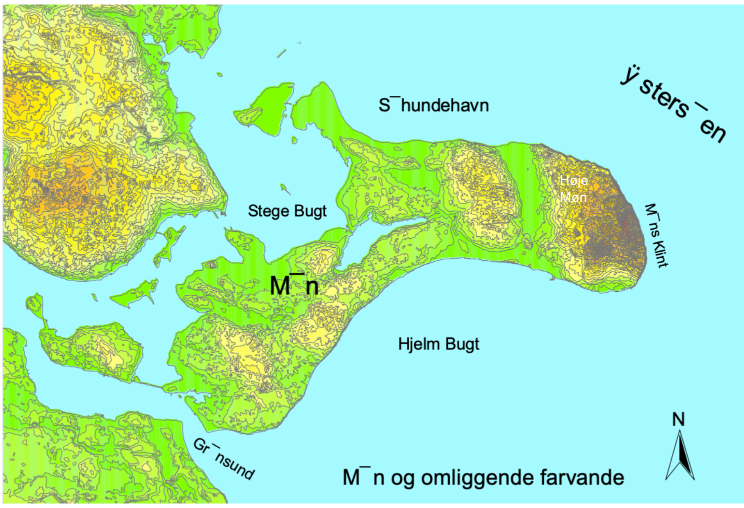


Figure 2. Topographic map of the island Møn and surrounding sea. The highest point in this part of Denmark is located in Høje Møn: Aborre Bjerg 143 m above sea level.

they more or less agreed on the Tertiary age of the limestone. Moreover they also agreed that the chalk of Møns Klint is of Cretaceous age (Lyell 1837). However, they strongly disagreed on the formation of the structure and uplift of Møns Klint. At that time Lyell had just finished the first editions of the renowned four volume work: Principles of Geology, in which the ice age concept and the considerable ice sheet coverage of the northern hemisphere were presented. Lyell´s initial interpretation was that the Quaternary sediments between the chalk sheets comprised drift deposits, i.e. boulder clay and outwash sand that had filled major fractures in the chalk. In accordance with subsequent works on the cliff he modified this opinion, but basically he advocated a drift origin (i.e. ice dynamic) in contrast to Forchhammer´s plutonic interpretation.

About 15 years after Forchhammer and Lyell's excursion to Møns Klint, Forchhammer proposed the formation of Møns Klint as the subject for a thesis, which might be rewarded with the gold medal of the University of Copenhagen. H.C.W. Puggaard was awarded the gold medal in 1851. His work contains the first structural description of Møns Klint including very detailed measurements and drawings of cross sections. The copper engraving of the entire cliff section produced by the artist W. Kyhn in the awarded- winning thesis presented by Puggaard has been reproduced and copied in nearly all publications since 1851 about the geology of Møns Klint. Puggaard was careful in expressing interpretations, which contradicted Forchhammer´s ideas, but his structural description clearly demonstrates that the cliff section is composed of thrust sheets of chalk separated by Quaternary deposits. At Puggaard´s defence of his doctoral degree in Bern in 1852 he fully supported Lyell´s idea of glacial impact during the formation of Møns Klint. His description was so convincing that Lyell devoted a full chapter to Puggaards description of Møns Klint in his famous work "The Antiquity of Man" (1863).

When Forchhammer died 1865 he was succeeded by J.F. Johnstrup, who fully supported the glaciation hypothesis and the impact of the extensive ice cover of northern Europe. It thus became generally accepted that push from the ice caused the dislocation of the chalk sheets. The push of the ice was furthermore regarded to be the effect of the Baltic Ice Stream, coming from the east. This resulted in chalk sheets with a top cover of till being displaced into the structural complexes at Møns Klint as well as in the German island Rügen at the south coast of the Baltic Sea (Johnstrup 1874).

Around 1900 a number of geological excursions were arranged to Rügen and Møns Klint by the Geographical Society of Greifswald. During these excursions the discussion of the geological development of the cliffs were continued. The glacial origin was challenged by arguments for a block fault deformation, which were brought forward with reference to tectonic features further south in Germany (Credner 1904). The last Danish supporter of a tectonic origin was V. Hintze, who compiled a map of the relief of Møn Klint and Høje Møn based on the concept of block faulting (Hintze 1937). However, the concept of glaciotectonics had already been settled, and G. Slater, who established the term glaciotectonism, appointed Møns Klint as one of the classic examples of a glaciotectonic complex (Slater 1927). This status was sustained in the first textbook on glaciotectonics by American and British Quaternary geologists, who presented Møns Klint as the type example of large composite-ridges in their glaciotectonic classification (Aber et al. 1989).

BEDROCK GEOLOGY OF THE CRETACEOUS CHALK AT MØN

The Late Cretaceous age of the chalk at Møns Klint was already realised by Lyell (1837). The detailed biostratigraphic position of the chalk is based on investigations of the brachiopods, which placed the chalk in the lower part of the Maastrichtian Stage (Surlyk 1984). The white chalk is well known all over NW Europe, where it is exposed in several beautiful coastal cliffs. It is also a target for hydrocarbon exploration (Surlyk et al. 2003), and a dense grid of seismic lines has been collected for the study of the chalk distribution and its underlying deposits in the North Sea. Formerly the Upper Cretaceous chalk was regarded as a relatively uniform marine deposit comprising skeletal fragments of minute single-celled coccolithophorid algae, but recent investigation of seismic sections from the Danish Basin have demonstrated that the sea-floor was highly dynamic with a great variety of ridges, valleys, channels and drifts on a variety of scales caused by the action of persistent bottom currents, so called contour currents, and the whole of the Danian Basin is now regarded as one of the oldest and largest ancient contourite complexes. (Lykke-Andersen & Surlyk 2004, Esmerode et al. 2006, Surlyk & Lykke-Andersen 2007).

The challenge of studying the bedrock geology below Møn is related to the important tectonic structures in the SE part of the Danish Basin. The Møn High is thus situated over the eastern end of the Ringkøbing-Fyn High. On the southern slope of this high salt tectonics disturbs the Cretaceous strata, and east of the Møn High the Sorgenfrei-Tornquist Zone forms a fanning fault pattern trending NW-wards into the Danish Basin (Thybo 2000).

UNDERSTANDING THE GLACIOTECTONIC ARCHITECTURE OF MØNS KLINT

Construction of a new cross section of Møns Klint has not been undertaken since the one produced by Puggaard (1851) (Fig. 3). Selected parts of the cliff have been studied since 1851, but a complete cross section based on new data with exact surveying has not yet been published. Photogrammetric data and computer supported stereometric recording of structural features was carried out in 1992–93 by cooperation between the Institute of Photogrammetry and Surveying (DTU), Geological Museum (KU) and the Geological Survey of Denmark (DGU). The photogrammetric survey formed the basis for a number of landslide investigations along the cliff section (Pedersen 1994, 2003, 2007, 2012; Pedersen & Møller 2004; Pedersen & Gravesen 2006, 2009). The cross section displayed in Figure 4 is based on the photogrammetric survey.

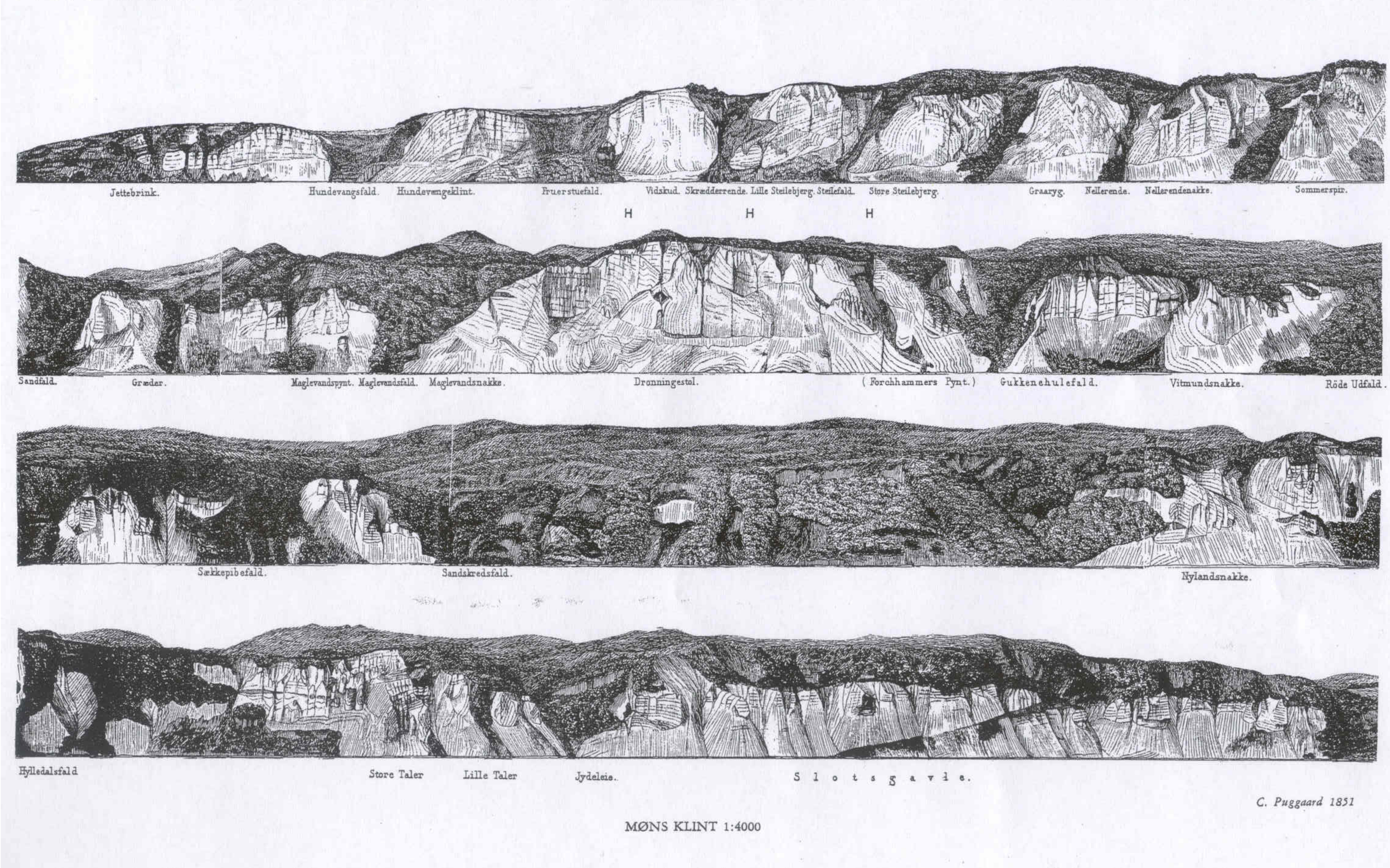
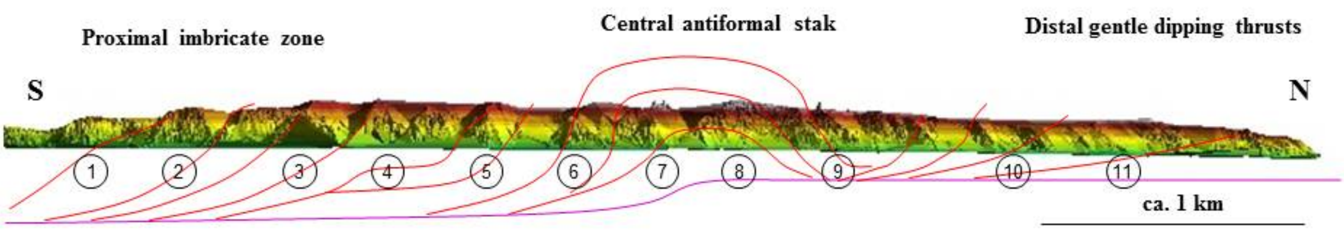


Figure 3. The famous structural cross section of Møns Klint produced as a copper engraving by the golden-age painter W. Kyhn and published by Puggaard (1851. Note that all the original names are indicated on the figure. The scale on the picture is a fake, each cross sections is about 1.250 km long. The sections are oriented S–N with the topmost cross section located furthest to the south and the lower section located in the northernmost part of Møns Klint.

There is a general consensus of a glaciotectonic formation of Møns Klint but different interpretations of the dynamics have been proposed over the years. The timing of the deformation is younger than the Eemian, interglacial, because sediments containing the bivalve Cyprina occur as the lowermost unit in the Quaternary succession involved in the glaciotectonic dislocation (Hintze 1937, Konradi 1973). Moreover two boulder clay units interlayered by glaciolacustrine clay occur on top of the dislocated Cretaceous chalk sheets (Pedersen & Gravesen 2006, 2009). The two boulder clay units are interpreted as representing the Ristinge Till Formation and the Mid Danish Till Formation of Houmark-Nielsen (1987, 1994), and according to the latest determination of the age of the Mid Dansh Till Formation the deformation took place during the Late Glacial Maximum about 20 000–17 000 years ago (Houmark-Nielsen & Kjær 2003, Houmark-Nielsen 2010) (Fig. 5).

The challenge in understanding the deformation at Møns Klint is the variation in the orientation of the bedding in the southern versus the northern part of the cliff section. In one model a deformation in an interlobate position during the Baltic Ice Advance has been suggested (Jensen 1993). However, an ice push from two divergent lobes is not necessary for formation of dips in opposite directions, which can be explained by thin-skinned thrust-fault tectonics (Pedersen 2005). The latest model based on a photogrammetric survey interprets a deep-seated ramp in the central part of the complex. Thrusting over this ramp resulted in the antiformal stack over the Dronningestol cliff (Fig. 3 and 4) (Pedersen 2000). An important verification of this model will be the documentation of the detachment surface below Møns Klint (Fig. 4). A combination of seismic and photogrammetric studies supported by detailed fieldwork is required in order to obtain this goal.



Cross section of **Møns Klint** based on a photogrammetric survey.
1: Jættebrinken, 2: Hundefangsklint. 3: Store Stejlbjerg, 4: Gråryg, 5: Sommerspir, 6: Græderen, 7: Maglevandspynt, 8: Dronningestol, 9: Vitmundsnakke, 10: Store Taler, 11: Slotsgavle.
The red lines shows the interpreted thrust faults, which are rooted down to the detachment surface marked with a violet coloured line.

Figure 4. Structural interpretation of the décollement level below Møns Klint. In the thin-skinned thrust-fault model the cliff section is subdivided into a proximal, a central, and a distal zone. The proximal zone is characterised by imbricate thrust sheets dipping steeply to the south. In the central zone the structures are characterised by the translation over the deep-seated ramp near the Dronningestol cliff creating an antiformal stack. This structure created the northward dip of beds. In the distal zone the beds are dipping very gently before the deformation fades out towards the foreland.

Stratigrafisk og strukturel opbygning af Møns Klint
Stratigraphy and structures of Møns Klint

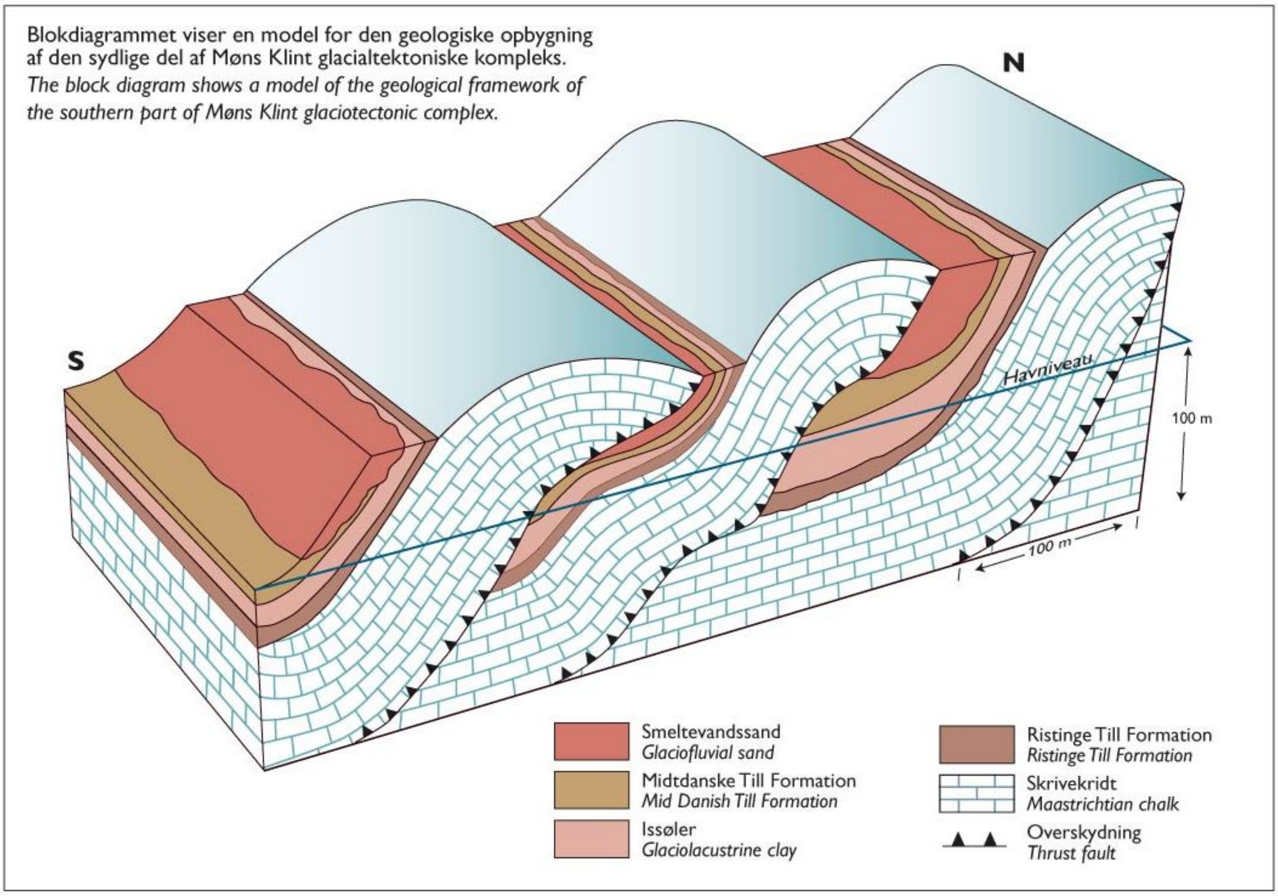


Figure 5. The block diagram illustrates the structure in the steeply imbricated thrust sheets in the proximal (southern) part of the Møns Klint glaciotectonic Complex. The décollement level is almost located at the base of the diagram. The stratigraphic and tectono-stratigraphic position of the four main Quaternary units deposited on the top unconformity of the chalk are indicated in the diagram

THE GEOLOGY OF STEVNS KLINT

All along the c.10 km long coastal cliff section Stevns Klint (Fig. 1) the Danian bryozoan limestone constitutes the upper part of the cliff, which is resting on the soft Maastrichtian chalk at the base (Surlyk, Damholt & Bjerager 2006). The Danian limestone is a hard lithology in which the internal framework of hardgrounds and flint bands mainly occurring in mound shaped features increases its resistance to erosion (Figs 2, 3). In the lower part of the cliff the soft chalk is easily eroded and excavated, while the Danian limestone forms an overhang, which occasionally breaks off or collapses. The presence of the marl and clay at the boundary between the chalk and the limestone, the Fiskeler Member (Surlyk, Damholt & Bjerager 2006), contributes to the planar base of the overhang. The impressive view of the most dramatic overhangs will commonly encourage visitors to think twice before they decide to pass below the overhang with its potential for collapse.

LITHOSTRATIGRAPHY OF STEVNS KLINT

The lithostratigraphical division of the geological units present in the Stevns Klint coastal cliff section is presented in Fig. 5. The lower part of the succession constitutes the Maastrichtian chalk (uppermost part of the Cretaceous), which at Stevns Klint is divided into two members of the Tor Formation, the Sigerslev Member and the Højerup Member (Surlyk et al. 2006). The boundary between the two members is situated 0.5 m above the prominent black, nodular flint bed in top of the Sigerslev Member. The Højerup Member comprises smaller bryozoan mounds in the depression of which the Rødvig Formation is located (Surlyk et al. 2006). In the diagram the lithology is indicated as clay referring to the Fiskerler Member (fiske-ler:: fish clay, the famous C/T boundary unit) . The clay grades up into a marl, which in the depressions is overlain by the Cerithium Limestone Member. The Rødvig Formation and the top of the mounds in the Højerup Member are truncated by a hardground at the base of the Stevns Klint Formation (Surlyk et al. 2006). The Stevns Klint Formation corresponds to the Danian bryozoan limestone, which at Stevns Klint is only represented by the up to 20 m thick Korsnæb Member. The unit is characterised by the flint beds outlining the bryozoan mounds that create the curved features of the hard, resistant limestone in the top of the cliff sections. The Korsnæb Member is truncated by an erosional unconformity upon which the Weichselian glacial deposits occur. Part of the truncation was formed during the glacial advance resulting in shearing and cataclastic displacement of the limestone resulting in the formation of a limestone-glacitectonite at the base of the till. The till unit is generally 3 m thick, but varies a lot and two beds may be recognised, which are related to the Mid Danish Till Formation and the East Jylland Till Formation (Houmark-Nielsen 2007) representing ice advances from central Sweden and the Baltic, respectively, during the Late Glacial Maximum at the termination of the Pleistocene.

Figure 2. Location map of Stevns Klint with the division into segments indicated by red numbers. The insert map in the upper left corner shows the distribution of landslides in Denmark, where the red triangles are most hazardous slides and blue ones refer to clayey landslides. Stevns Klint is red triangle no. 2, and Møns Klint mentioned in the text is no. 1. Also mentioned in the text is no. 4: Lønstrup Klint, where the highest rate of coastal erosion in Denmark, up to 1.25 m/y occurs.

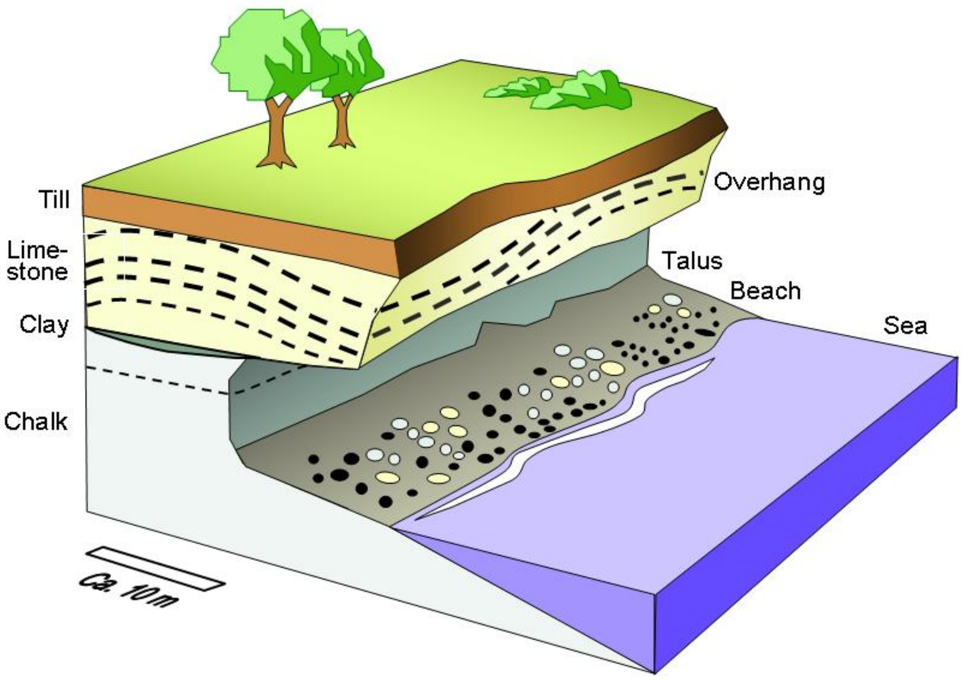


Figure 3. The block diagram illustrates the main geology and geomorphology of the coastal cliff at Stevns Klint. At the base of the geological succession the white chalk is soft and subjected to erosion. The hard Danian limestone forms the overhang above the Cretaceous/ Tertiary boundary (C/T) at the base of the clay. Details about the lithostratigraphy are given in Fig. 3.

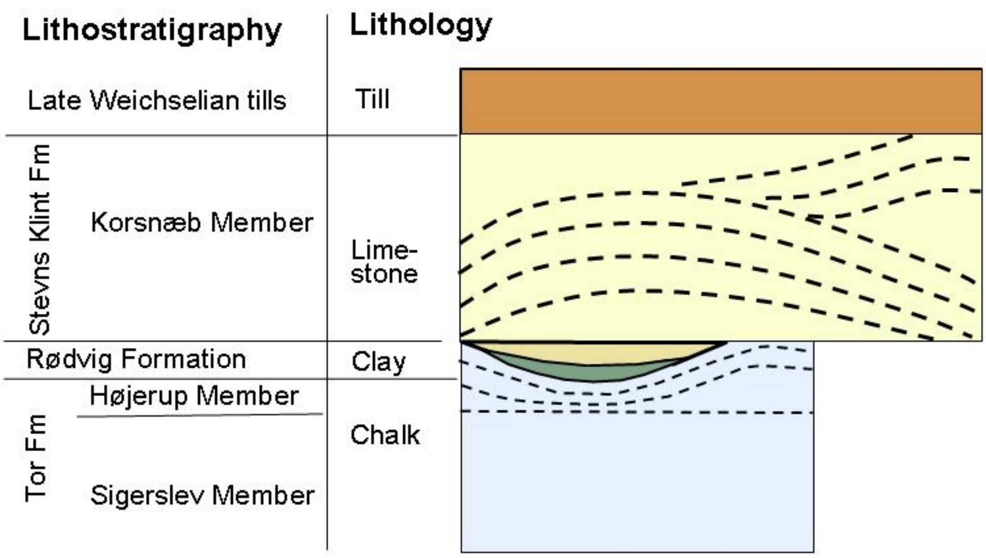


Figure 4. Lithostratigraphical division of the geological units present in the Stevns Klint coastal cliff section. The lower part of the succession constitutes the Maastrichtian chalk (uppermost part of the Cretaceous), which at Stevns Klint is divided into two members of the Tor Formation, the Sigerslev Member and the Højerup Member (Surlyk et al. 2006).

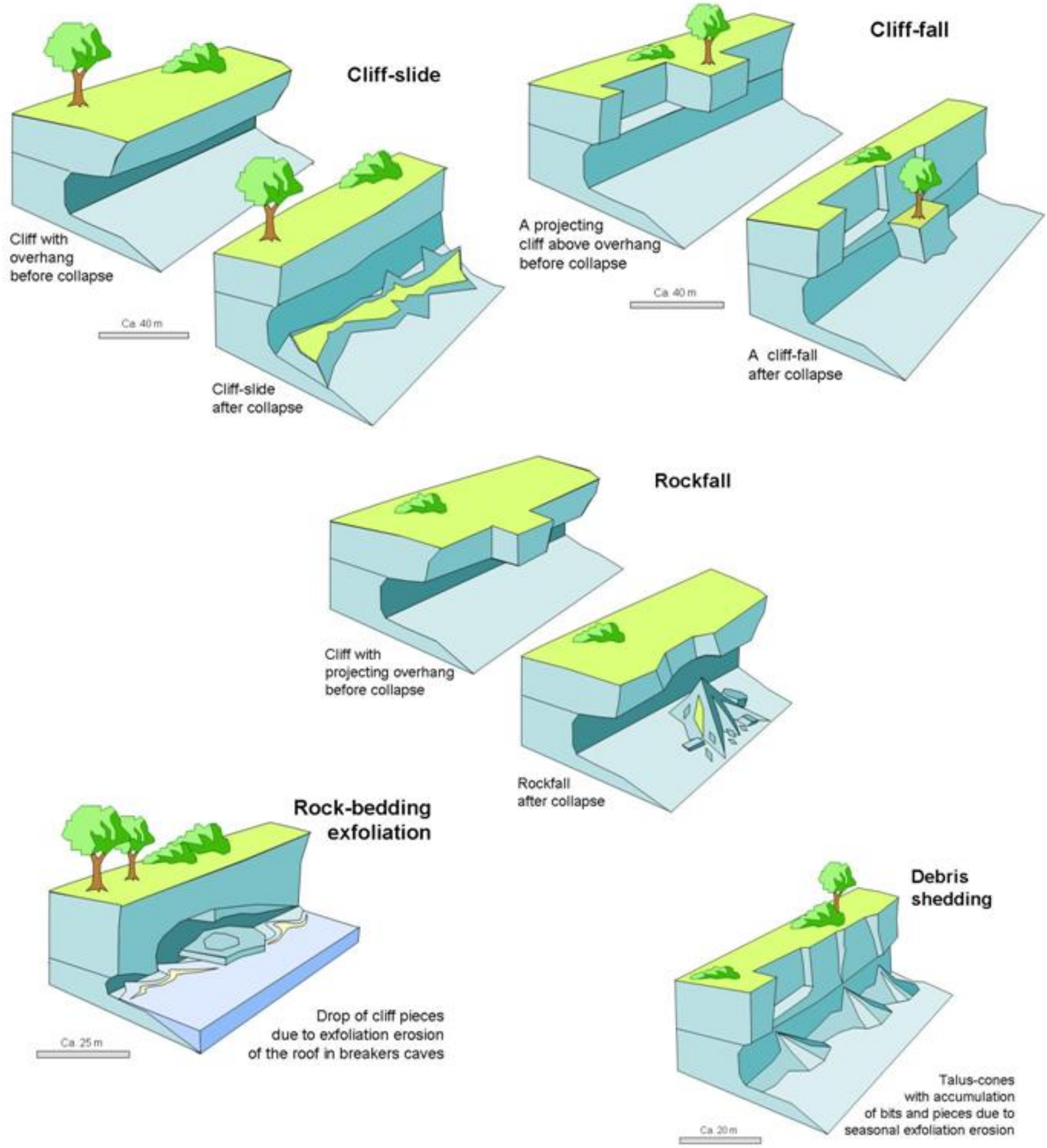


Figure 5. Characterisation of the rockfall types occurring at the chalk and limestone cliff along Stevns Klint. The most hazardous type is the cliff-slide involving volumes in the order of 5000 m3. The cliff-fall only includes volume in 500 m3 size, but it gives an impressive prospect with the bedding completely preserved in a displaced cliff. The rockfall is the general type of landslide with a pieces of the cliff translated into a debris cone. The rock-bedding exfoliation generates platy limestone blocks the size of 1–10 m3, which drop off from the roof below the overhangs. The main erosion along the cliff is due for debris shedding, which is responsible for the talus at the toe of the cliff.

Figure 5. Typical excavation marks in the bryozoan limestone at Boesdal. The K/T boundary is here located under sea level.

Figure 6. Photo of the cliff-fall and the large overhang at Stevns Fyr. The lighthous is located at the highest point along Stevns Klint, 41.5 m a.s.l. Below and north of the lighthouse the rectangular shaped small limestone quarries can be seen. Note that under the substantial overhang a small pile of blocks indicate a rock-bedding exfoliation of the roof below the overhang. This type of erosion contributes to the decrease in the thickness of the overhang, which decreases its strength and thus increases its tendency of a cliff-fall (or cliff-slide).

Figure 7. the photo shows an example of a cliff-fall, which is illustrated in the diagram below. Note that this type of rockfall typically affects a protruding point of the cliff due to former limestone quarrying along the coastal cliff.

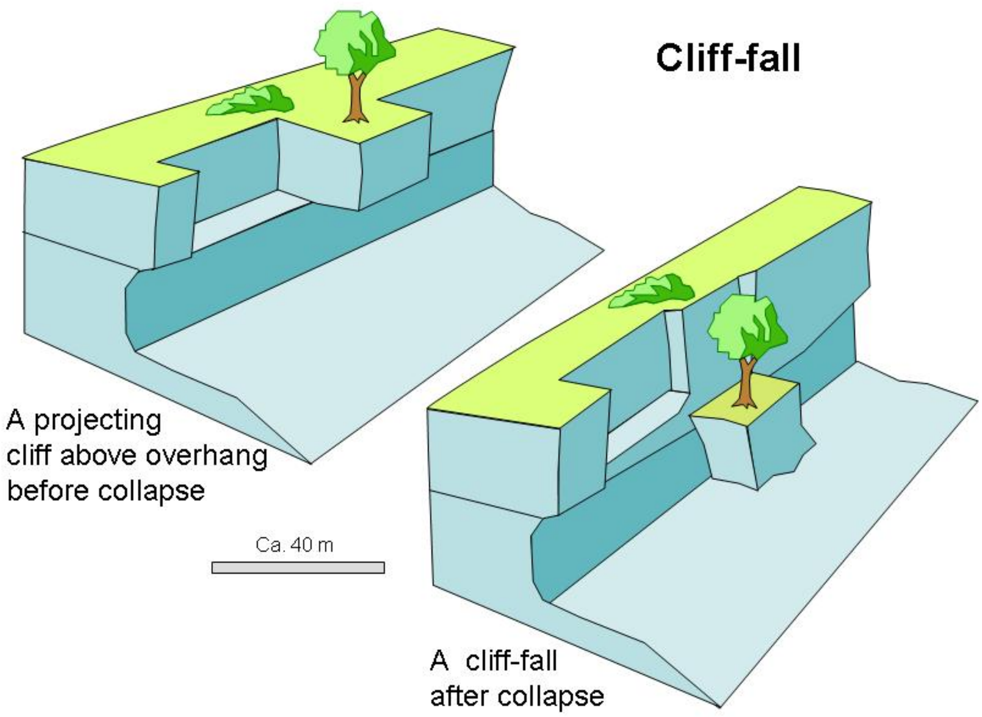


Figure 8. The landslide at Højerup old church. The top of the landslide body is c.15 m a.s.l. and the toe of the slide is protected against erosion with blocks and boulders. The new church in Højerup was built in 1913 due to the local fear for destruction of the old church by a landslide.

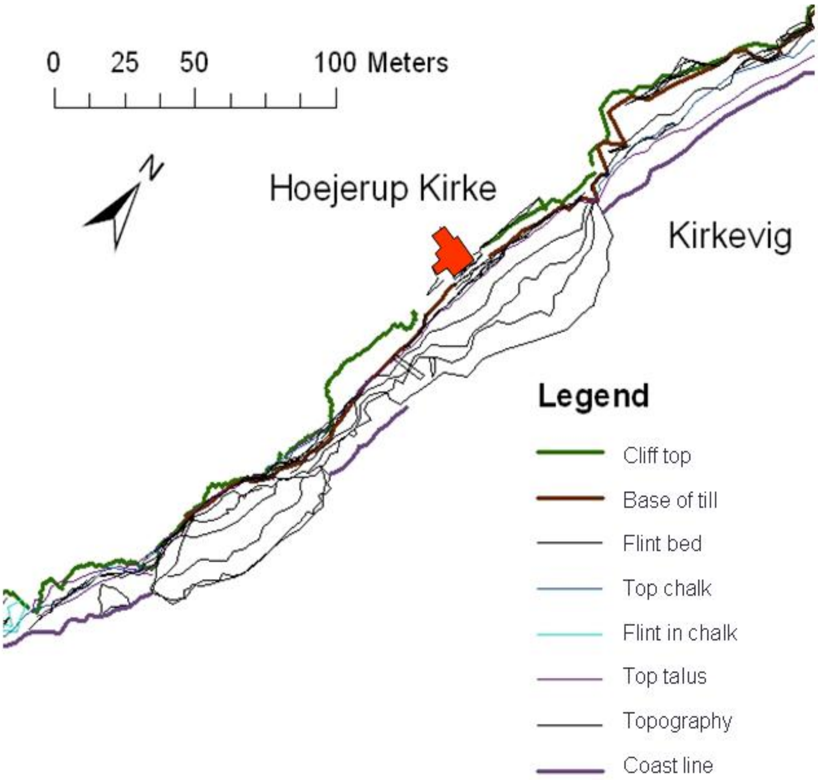


Figure 9. Photogrammetric traced contours which document the conditions at the coastal cliff along Stevns Klint. The cliff top is defined as the point of inflection from the more or less horizontal ground above the cliff and the steeply incline surface of the cliff. The base of the till outlines the boundary between the till and the Danian limestone. Flint bed represents the tracing of representative flint layers on the cliff surface. Top chalk is a mixture of line tracings, but it mainly represents the Rødvig Formation, which is indicative of the deepest erosion below the overhang. Flint in chalk may even represent a further undercutting of the chalk. It is mainly traced along the flint beds and hardgrounds at the boundary between Sigerslev and Højerup Members. Top of talus is the interface of the toe of the cliff and the talus cones. Topography outlines all other elements of interest. In the landslides 2.5 m contour intervals have been traced. On top of the cliff small quarries have been traced, and a few buildings and steps are also outlined with this line type. Finally the wave-breaking zone has been traced to give an indication of the width of the foreshore.

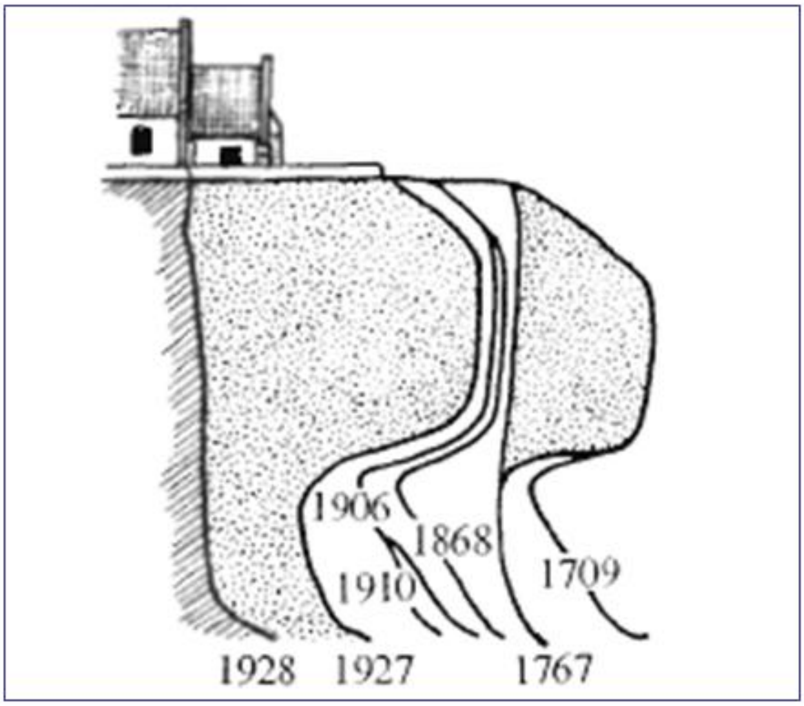


Figure 10. The recession of the cliff below Højerup old church from Rasmussen (1967). Note that the two large rockfalls occurred in 1767 and 1928. Since then the cliff below the church has been saved by coastal protection.

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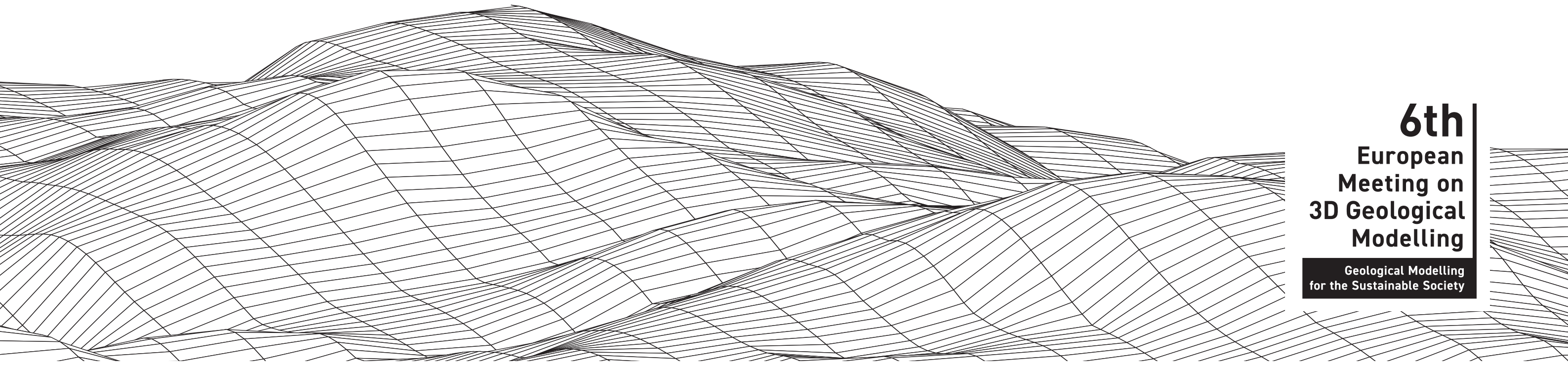

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