DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/93

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Landslide hazard assessment based on photogrammetrical supported geological analysis of the limestone cliff Stevns Klint in eastern Denmark

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Introduction

Occurrence of rockfalls along the coastal cliff Stevns Klint has been common knowledge since the famous landslide in 1928, which separated the choir of the old Højerup church from its nave. Landslides are regularly occurring along Danish coastal cliffs (Pedersen et al. 1989), but at Stevns Klint the outcropping geology provides a special geomorphologic framework prone to cliff collapse. 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 take decide to pass below the overhang with its potential for collapse.

The aim of this report

It has been decided to make an assessment of the risk of rockfalls along the Stevns Klint chalk and limestone cliff. The rockfall risk analysis has been initiated by Østsjællands Museum, who is responsible for compiling the application for Stevns Klint to be admitted to UNESCO's list of World Heritage Sites. Consequently, GEUS has been asked to make an analysis the rockfall risk of the Stevns Klint. The assessment is summarized in this report, which is based on a geological and geomorphologic analysis of overhang, cliff vulnerability and rockfall dimensions along the coastal cliff at Stevns Klint. The analysis is based on a photogrammetric investigation of a series of oblique photographs, which were taken of the cliff section in the end of April 2011. Subsequently, the cliff section was mapped in segments and detailed photogrammetric measurements were carried out by the application of the computer working station SOCESET in the photogrammetric laboratory at GEUS. The photogrammetric survey was saved in an ArcGis format, which in the future will be available for other projects and applicable for future comparison of the cliff-collapse development. Similarly the terrestrial photogrammetric investigation of the cliff with oblique photographs taken in 1992 (Surlyk et al. 2006) was applied for comparative analysis of the rockfall development during the past 20 years.

The analysis is divided into detailed investigations of 22 segments (Pedersen & Strunck 2011) (Fig. 1). A similar division into well known segments from south to north was also applied by Surlyk et al. (2006). Furthermore the general conditions of cliff erosion are described, and an introduction to the rockfall mechanisms is provided with a description of the characteristics of the various types of landslides.

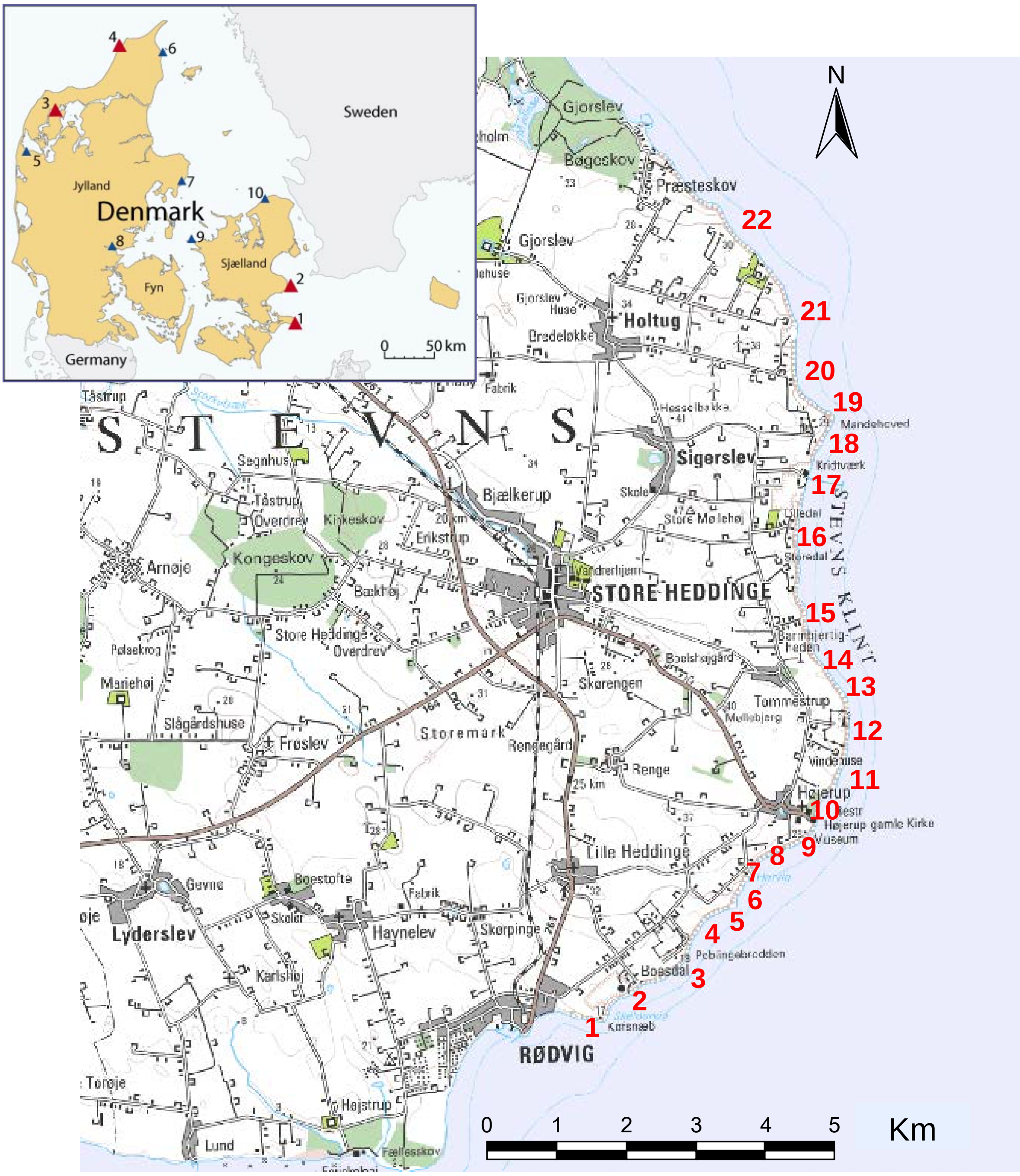

Figure 1. *Location map of Stevns Klint with the division into segments indicated by red numbers. The insert map in the upper left corner shows the distribution of landslides in Denmark, where the red triangles are most hazardous slides and blue ones refer to clayey landslides. Stevns Klint is red triangle 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.*

General erosional conditions at Stevns Klint

One of the essential factors for rockfall assessment is the rate of erosion. The general rate of coastal erosion at Stevns Klint is estimated to15 cm/year from comparison of the position of the coast line in 1891 with the coast line given by the National Survey and Cadastre in 2010. The highest rate is about 35 cm/year, which occurs at the coast segment between Storedal and Lilledal (Loc. 16 in Fig. 1). However, in some places the coast line also shows signs of progradation, partly due to accumulation of beach ridges and partly because old landslides remains preserved along the coast, where they act as wave breakers. The first case is especially pronounced at Korsnæb (Loc.1 in Fig. 1), where the accumulation rate amounts to 12 cm/year. The latter case is well illustrated by the landslides at Højerup old church, where the translated landslide body is still preserved as a 12 m progradation of the coast line (Loc. 10 in Fig. 1) partly stimulated by coastal protection. Furthermore, the landslides north of Kirkevig (Loc. 11 in Fig. 1) has also resulted in an progradation of the coast line about 7–9 cm/year, and a similar advance of the coast line is present south of Storedal (Loc. 15 in Fig. 1). In general the erosion rate of Stevns Klint must be regarded as modest, when it is compared to the highest rate of erosion along the Danish coast line, which is 1.25 m/year at Lønstrup Klint (Pedersen 1986) (for location see Fig. 1).

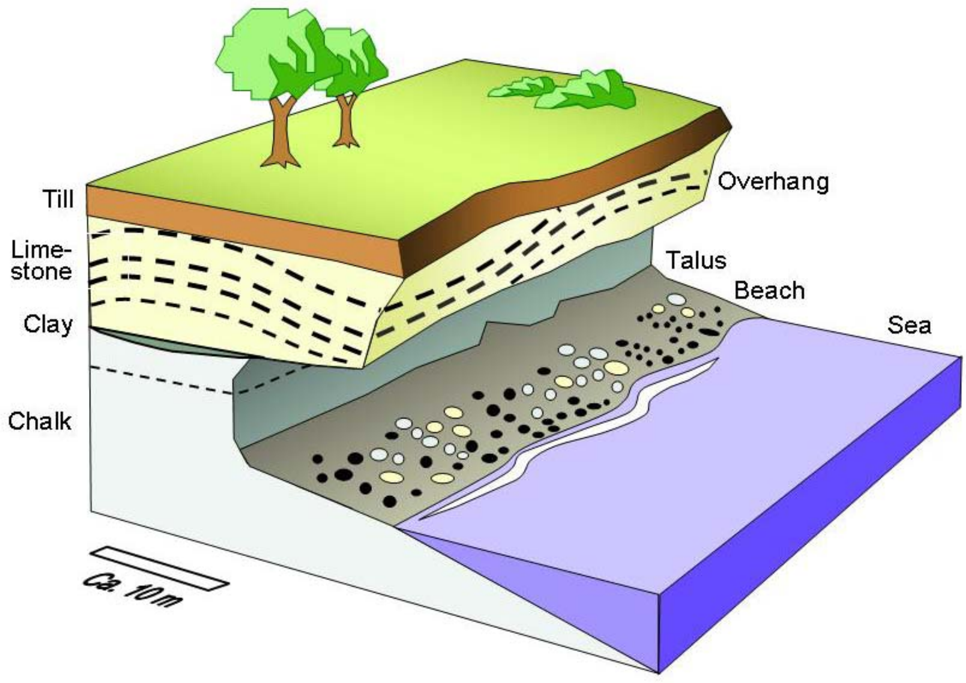

Figure 2. *The block diagram illustrates the main geology and geomorphology of the coastal cliff at Stevns Klint. At the base of the geological succession the white chalk is soft and subjected to erosion. The hard Danian limestone forms the overhang above the Cretaceous/Tertiary boundary (C/T) at the base of the clay. Details about the lithostratigraphy are given in Fig. 3.*

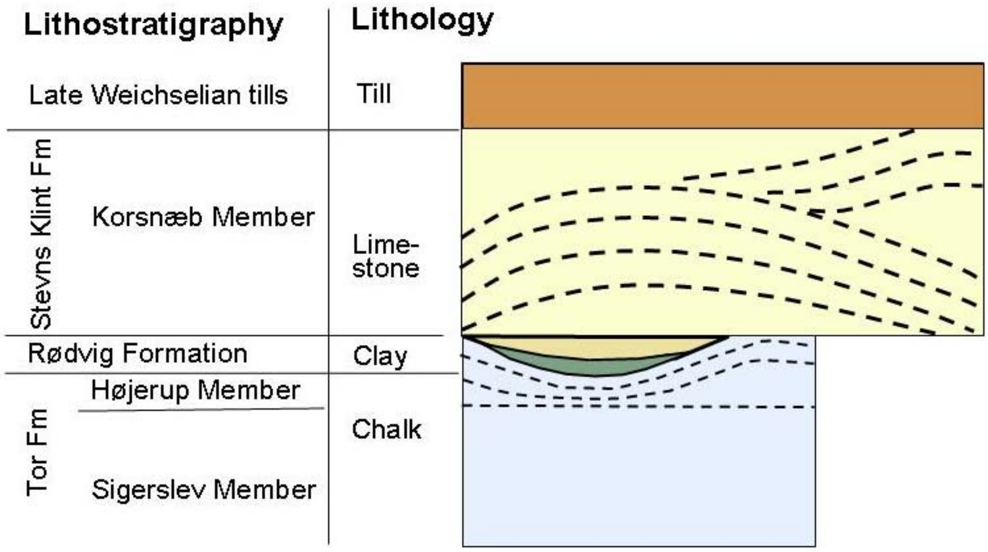

Figure 3. *Lithostratigraphical division of the geological units present in the Stevns Klint coastal cliff section. The lower part of the succession constitutes the Maastrichtian chalk (uppermost part of the Cretaceous), which at Stevns Klint is divided into two members of the Tor Formation, the Sigerslev Member and the Højerup Member (Surlyk et al. 2006). 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.*

It is not only the natural coastal erosion that affected the cliff disintegration. The traces of human activity over the past hundreds of years are recognized as square excavation marks in many places along the cliff. The small limestone quarries were excavated in rectangular pits with walls inclined towards the base resulting in considerable overhang. In 16 m high walls these overhang can be up to 6 m at the top jutting out over the floor of the pits. The excavation profiles may contribute to the cliff points projecting out above the beach.

Characterization of rockfalls at Stevns Klint

The rockfalls at Stevns Klint do not belong to the biggest and most hazardous class of landslides (Pedersen, Foged & Frederiksen 1989). An obvious reason for this is simply the height of the cliff, which is about 40 m at the highest point at Stevns Fyr (the lighthouse) in the central part of the coastal cliff (Loc. 12 in Fig. 1). From this point the height of the cliff decreases towards the north and south where the cliff height is only 15–20 m. Thus rock avalanches does not occur at Stevns Klint in contrast to those occurring at Møns Klint (Fig. 1), where the latest landslide took place in January 2007, and resulted in the collapse of the 100 m high cliff St. Taler and an avalanche carried debris more than 300 m out into the sea (Nadim et al. 2008, Pedersen & Gravesen 2009). Moreover the rockfalls at Stevns Klint are solely related to the erosion of the soft chalk situated below the hard bryozoan limestone with its increased strength due to the strong flint beds (Fig. 2, 3).

The largest type of landslides at Stevns Klint may be characterized as a **cliff-slide** (Fig. 4). This type of slide includes a major part of the cliff several tens of meters along strike of the coast line, which slipped simultaneously. In general the cliff-slide takes place along a steeply dipping slip surface and the volumes involved are in the order of 5–10.000 m^3.

In relation to size the next type of large slides is the **cliff-fall** (Fig. 4). This type of rockfall involves only isolated projecting points of the cliff with a considerable overhang. The cliff-fall is a simple drop of the cliff in which the bedding of the fallen block is preserved after the displacement. It looks just like a box of rock has been dropped onto the beach. The volume involved in the cliff-fall is in the order of 500 m^3 to 1500 m^3.

The third type of slides is classified as a **rockfall** (Fig. 4), and varies in size from 500 m^3 to 1 m^3. In areas where a lot of till is involved a mixed type of landslide occurs, which may be characterized as a block-slide, in which bigger blocks were displaced together with more fine-grained material. Meanwhile, the resulting aggradation of material on the beach after a rockfall is a chaotic breccia with a cataclastic mixture of the entire range of grain-sizes.

On the scale of 1 m^3 a significant type of rockfall appears at Stevns Klint, which is here referred to as **rock-bedding exfoliation** (Fig. 4). This type of platy rockfall appears in caves eroded out by the storm waves. From the roofs of the caves layers are peeled off due to exfoliation and dish shaped pieces of rock drops to the floor.

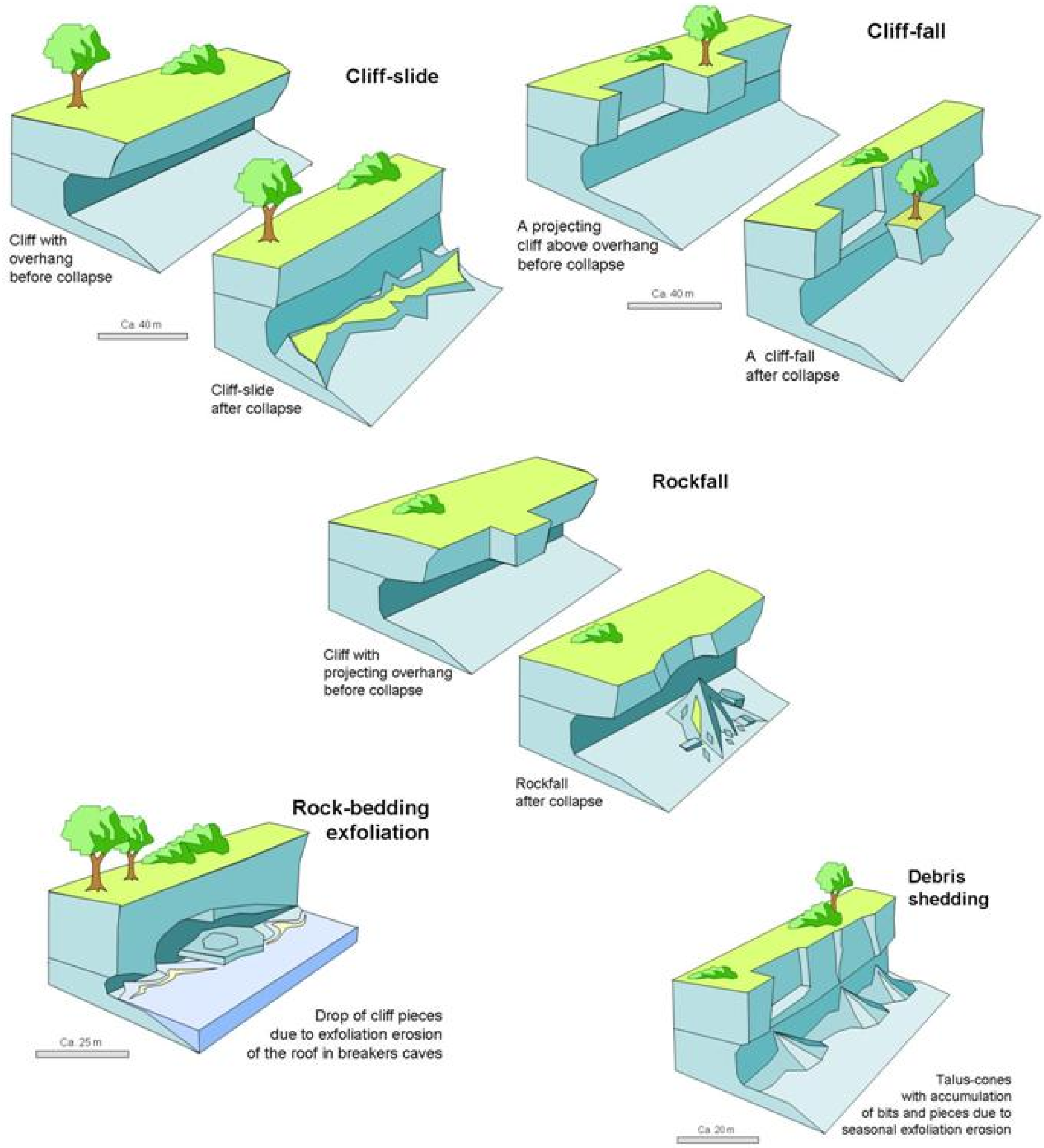

Figure 4. *Characterisation of the rockfall types occurring at the chalk and limestone cliff along Stevns Klint. The most hazardous type is the cliff-slide involving volumes in the order of 5000 m^3. The cliff-fall only includes volume in 500 m^3 size, but it gives an impressive prospect with the bedding 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 m^3, 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.*

Finally pieces of rock may fall from the cliff due to the general **debris shedding** (Fig. 4). In general the grain sizes of debris shedding are pebbles and cobbles and only occasionally clasts of stone-size are loosened from the cliff surface. The result of the debris shedding is seen as an apron of talus along the toe of the cliff, typically with irregular cone shape. The cause of the debris shedding is the seasonal contraction and expansion due to seasonal variation of frost and thaw in the winter time and desiccation during the summer.

The best known rockfalls in Denmark are the collapse of Stevns Klint below the Højerup old church (Rasmussen 1967) and the rockfall at Møns Klint that killed a French tourist in the summer 1994 (Pedersen 1994). The landslide at Højerup old church may be characterized as a cliff-slide in the classification illustrated in Fig. 4. The slide was a typical early spring event (March 1928) were the frost and thaw and general expansion and contraction due to temperature variations triggered the slide. The disastrous rockfall at Møns Klint was just a peak of rock that toppled due to its loss of cohesion due to desiccation by the July sun.

The cliff-slides at Stevns Klint

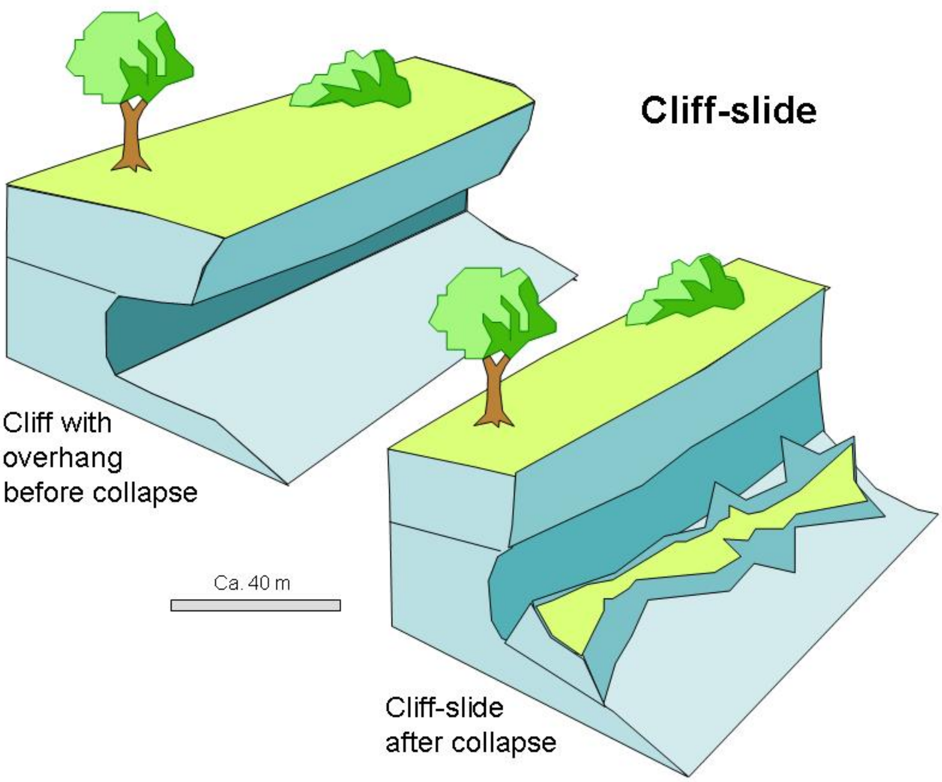

Figure 5. *The cliff-slide is characterised by the drop and slide of an overhang, which extend for about 100 m along the coastal cliff. The cliff-slide takes places where a long section of the chalk cliff is exposed to erosion from the sea for a long period (50-100 years).*

The rockfall type at Stevns Klint which involves the largest volumes is classified as cliff-slide (Fig. 5). Prior to a cliff-slide a whole section of the chalk was eroded away to create an undercutting below the limestone resulting in a considerable overhang. The size of the overhang is about 10–12 m and the thickness of the limestone and till in the overhang is about 15–18 m. The landslide at Højerup old church is regarded as representing such a slide (Figs 6, 7). The map in Fig. 7 shows the extent of this landslide, which prograded several tens of meters out into the sea. Today a coast protection with erratic blocks secures the survival of the remaining part of church for more than hundred years (Fig. 6).

Two other significant examples of cliff-slide are found north of Stevns Fyr at the locality indicated as Tommestrup (no. 13 in Fig. 1) (Fig. 8) and in the inner part of Harvig (no. 7 in Fig. 1) (Fig. 9). At both sites these landslides will serve as coastal protection for about half a century.

Figure 6. *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.*

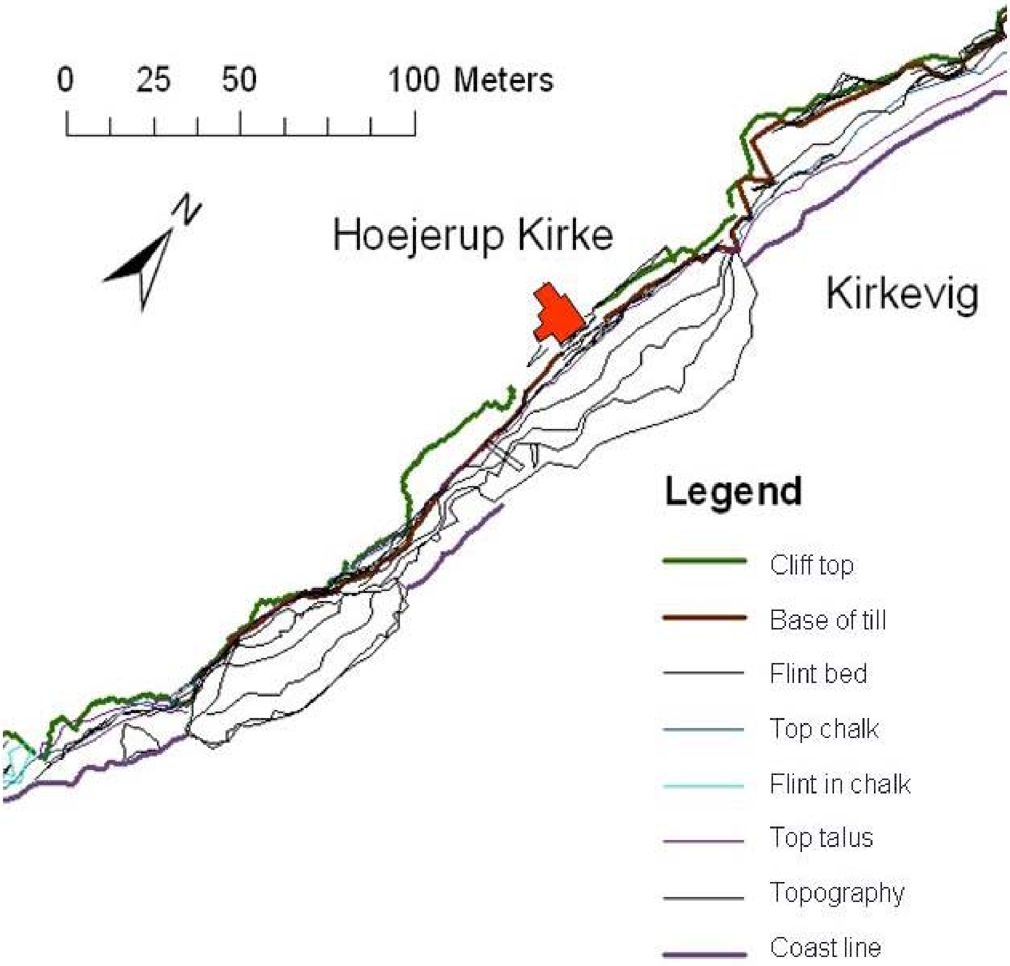

Figure 7. *Photogrammetric traced contours which document the conditions at the coastal cliff along Stevns Klint. The cliff top is defined as the point of inflection from the more or less horizontal ground above the cliff and the steeply incline surface of the cliff. The base of the till outlines the boundary between the till and the Danian limestone. Flint bed represents the tracing of representative flint layers on the cliff surface. In a vertical display of data these tracings outline very clearly the geometry of the bryozoan mounds as also demonstrated by Surlyk et al. (2006). In the horizontal display here and in the following maps of the photogrammetric tracings the lines represent an "average" position of the surface of the limestone cliff overhang. 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 8. *An example of a cliff-slide with preserved vegetation on top of the landslide. In the left side of the air-photo a recent rockfall is recognisable. Locality Tommestrup no. 13 in Fig. 1.*

Figure 9. *The cliff-slide in the inner part of Harvig (Loc. 7 in Fig. 1). The measured length of the slide along the coast is 90 m and the thickness of the displaced stratigraphy is 12 m which corresponds well with the thickness of the limestone and till in the cliff. The width of the surface in the slide is 7-10 m which consequently corresponds to the depth of undercutting below the overhang.*

The cliff-falls at Stevns Klint

The cliff-fall is a term here used for indicating a specific part of the cliff that has dropped to the toe of the cliff (Fig. 10). In the displaced cliff the bedding is still preserved and it has not been subjected to noticeably rotation. The size of the blocks have been measured to be about 1200–1500 m^3, and the surface area measures 100 m^2 indicating an overhang of about 10 m for a limestone cliff thickness of about 12–15 m.

One of the best examples of a cliff-fall is seen below the Stevns Fyr lighthouse (Loc. 12 in fig. 1). Here a rectangular part of the cliff has dropped directly to the beach (Fig. 11, 12). The thickness of the bryozoan limestone in the cliff section is about 22 m, whereas the thickness of the displaced block is only 12–14 m. This discrepancy is explained by former excavation in an old limestone quarry, which has removed c. 10 m of the limestone. The relation between limestone thickness and overhang is thus in the order of 3 to 2, which corresponds to the average measurements of rockfalls along the cliff.

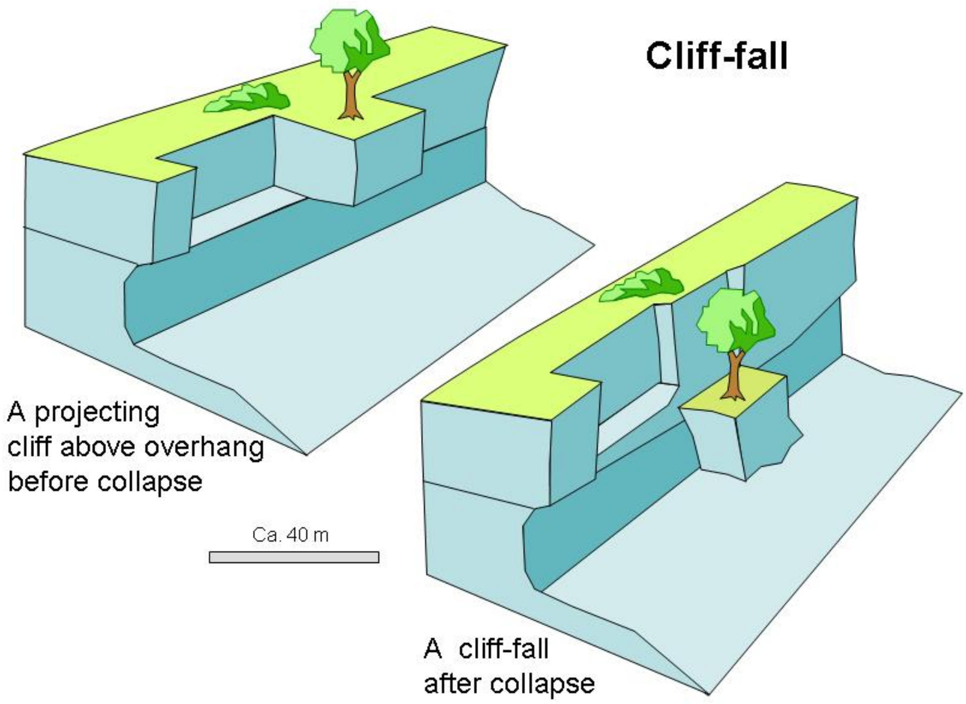

Figure 10. *Principal sketch of a cliff-fall. Note that this type of rockfall typically affects a protruding point of the cliff due to former limestone quarrying along the coastal cliff.*

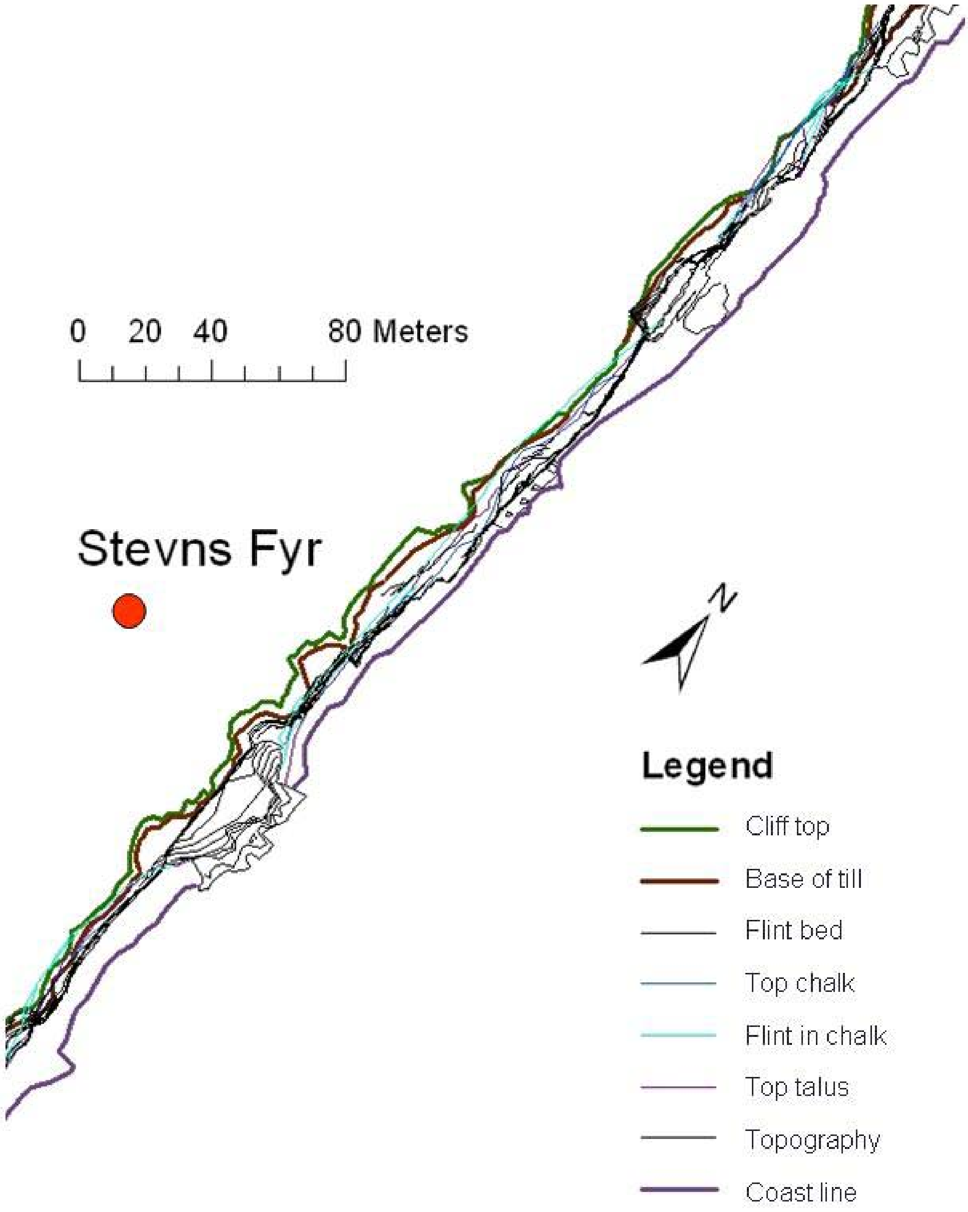

Figure 11. *Photogrammetric contour map of the area at Stevns Fyr (lighthouse). The cliff-fall is located immediately southeast of the lighthouse. The topographic contours outlining the cliff-fall have intervals of 2.5 m. The steep and squared walls of the cliff-fall can easily been seen as well as the flat top at a height of 12.5 m. Note the rectangular outline of the old limestone quarries on top of the cliff. Note also the size of the overhang north of the cliff-fall, which is given by the distance between the thin blue lines (top chalk and flint in chalk) and the black lines (traces of flint bands in limestone). The overhang amounts to 8–9 m, which is close to the maximum value of overhangs along the cliff. Explanations to the contour lines are given in Fig. 7.*

Figure 12. *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 13. *An additional example of cliff-fall from the inner part of Lille Hedding Vig (Loc. 4 in fig. 1). The cliff-fall is seen just below the yellow house, and its dimension of 1200 m^3 corresponds well with the general magnitude of cliff-falls.*

The ordinary type of rockfalls at Stevns Klint

A number of ordinary rockfalls are present along Stevns Klint (Fig. 14). Their sizes vary between100 m^3 and 1 m^3, but may occasionally be up to 1000 m^3. The largest blocks involved in the rockfalls are up to 50 m^3. Frequently the rockfalls includes thicker beds of till displaced from the top of the cliff into mixed cataclastic breccias. The exact mechanism of these slides is not fully understood, but it seems as if sequential steps of sliding may facilitate block-sliding.

In the present analysis three modern rockfalls are recognized. These represent collapses of the limestone cliff within the last 20 years, determined from the comparison of the present and the earlier photogrammetric photo series. The dimension of the rockfall amounted to 1000 m^3, and none of them was in the category of cliff-slides. One of these has already been mentioned and is shown in Fig. 8. In the southern part of the cliff section a reactivation of an older rockfall is recognized at Korsnæb (Loc. 1 in Fig. 1). This slide is estimated to amount 1000 m^3. However, it probably represents a mixed landslide, which includes a considerable amount of till as well as glacially broken chalk from the top part of the limestone in Korsbnæb Member. With a cliff height of 16 m the slide cannot be regarded as dramatic, although the overhang is situated 6.5 m a.s.l.

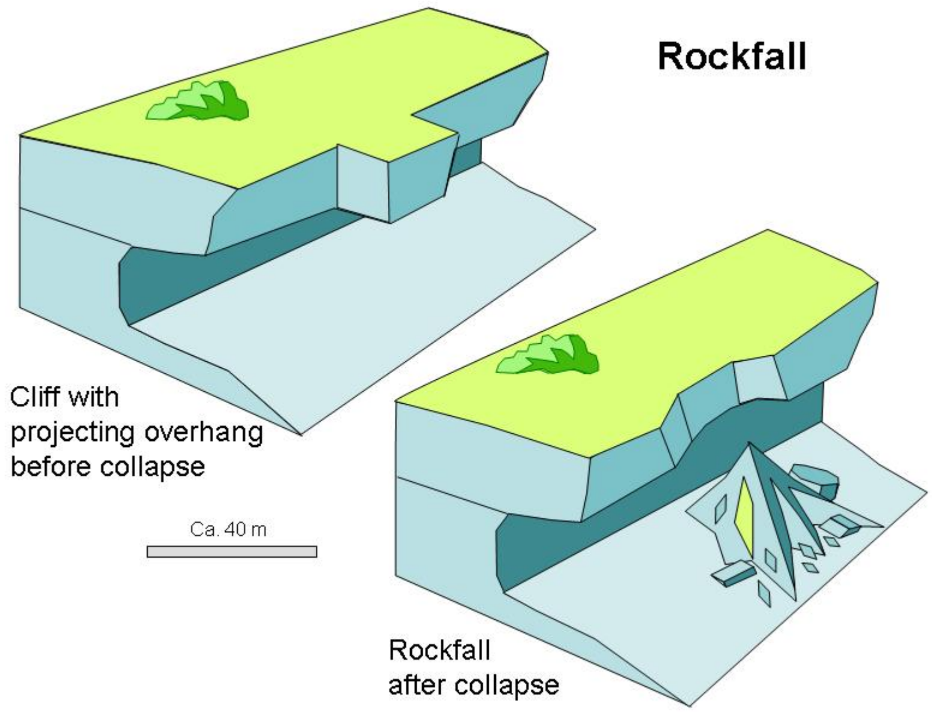

Figure 14. *The block diagrams illustrate the ordinary type of rockfalls occurring at Stevns Klint. The rockfall accumulates a cone shaped pile of debris at the foreshore, and a concave escarpment is created in the cliff.*

In general the rockfalls leaves a concave escarpment in the cliff and the aggradation of debris results in a cone expanding out into the sea. In Fig. 15 an example of one of the larger rockfall is shown. This rockfall is situated c. 200 m south of Stevns Fyr. The top of the cliff is here 38 m a.s.l., and the uppermost 4 m comprises at till bed. The base of the overhang is situated in 13,5 m a.s.l., and the extension of the debris reached 60 m from the cliff surface.

The relation between the height of the cliff and the translation of rockfall material is estimated to be one to two. In a cliff-fall this ratio is one to one (or less), wherefore it is speculated that a stepwise dynamic of the rockfall is involved, which add clayey material to the debris pile on which the concluding rockfall is sliding. A support to this speculation is the nature of the present overhang located north of the slide. Here the horizontal base of the overhang is 4 m deep. However, the tip of cliff top is projecting 8 m out over the foreshore. The reason for this inclined limestone cliff surface is the former excavation which gradually over steepened the excavation wall. Therefore a rockfall initiated by dropping the outermost part of the cliff will bring the till down to the ground, and the subsequent rockfall of the main part of the limestone will slip on the initially dropped clayey material.

Figure 15. *The large rockfall c. 200 km south of Stevns Fyr. Note the 3–4 m thick till unit at the top of the cliff. The clay content in the till contributed to a mixed rockfall development.*

The rock-bedding exfoliation at Stevns Klint

The rock-bedding exfoliation is a significant erosion mechanism at Stevns Klint. It is typically related to cave eroded by breaking waves, which wash directly against the toe of the cliff (Fig. 16). This type of erosion is enhanced by the structure of the bryozoan limestone, because the roof of the caves coincides with the bedding of the bryozoan mounds as seen in the overhang shown at Stevns Fyr (Fig. 12). From the roofs of the caves layers are loosened due to exfoliation and slaps with thicknesses of c. 0.3 m and diameters of up to 3 m have fallen from the roofs to the floor.

Caves are especially developed along stretches of the coast where shore-parallel transport is strong enough to remove the well-rounded pebbles and cobbles of flint, which form the typical foreshore along Stevns Klint (Fig. 20, 21). Caves are prominent at Boesdal (Loc. 2, in Fig. 1), north of Stevnsfortet (transition from Loc. 3 to 4), south of Storedal and at Holtug (Loc. 16 and 21). At Boesdal (Fig. 17) the C/T boundary, and thus the base of the bryozoan limestone is located close to sea level. Here the caves are undercutting the limestone and stretch up to 9 m into the cliff (Figs 16, 17).

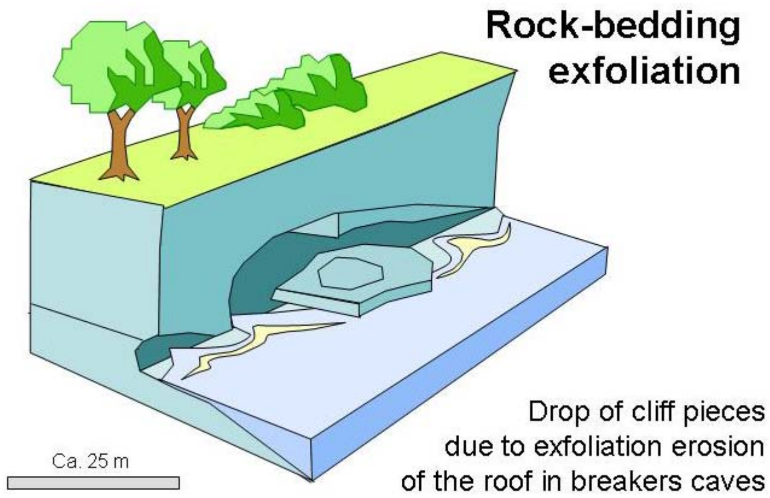

Figure 16. *The block diagram illustrates the erosion of breakers, which creates arc-formed caves at the base of the cliff. The layers in the antiformal shaped mounds are peeled off and platy bedding-blocks are successively dropped to the shore.*

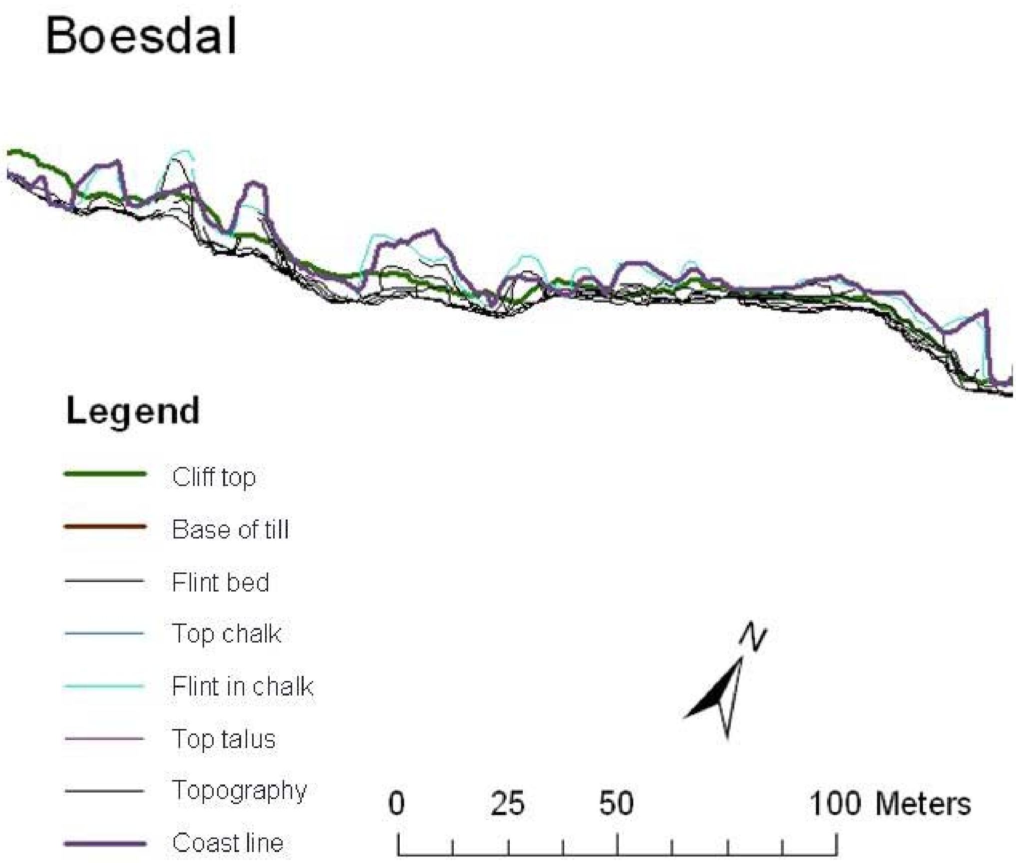

Figure 17. *Photogrammetric contour map of the coastline east of Boesdal. The extension of the wave eroded caves is indicated by the tracing of the Rødvig Formation and underlying chalk marked by blue lines on the map. Note the group of thin black lines are tracings of flint bands in the limestone which represent the surface of overhanging cliff.*

Figure 18. *The coastline east of Boesdal is characterised by breakers erosion of caves. Note the rock-bedding exfoliation blocks present at the shoreline.*

The debris shedding at Stevns Klint

The debris shedding from the cliff (Fig. 19) is just on the border of being regarded in the context of rockfall. However, the registration of the debris shedding has contributed with an important part of outlining the coastal cliff profile and it is an important part of understanding the dynamics of the background erosion. The average grain sizes of debris shedding are pebbles and cobbles and only occasionally clasts of stone-size are loosened from the cliff surface. The debris shedding is accumulated as an apron of talus along the toe of the cliff, which often is arranged as irregular cones (Fig. 20). The main cause of the debris shedding is the seasonal variation in frost and thaw during the winter time and desiccation in the dry part of the summer time, which results in the contraction and expansion that loosens pieces from the cliff. The order of erosion by debris shedding is regarded to be equal to the rate of average erosion, namely 15 cm/year.

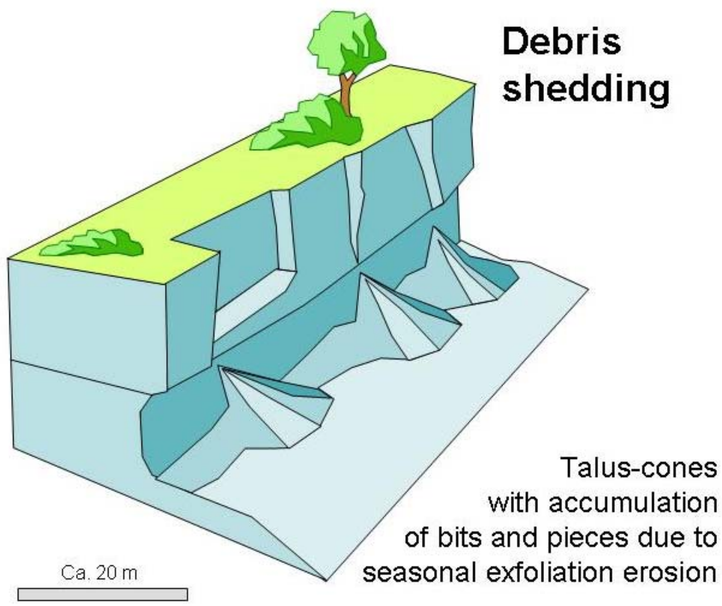

Figure 19. *The general debris shedding is regarded to represent the main coarse of erosion along the coastal cliff of Stevns Klint. Compared to the rate of erosion this shedding is in the order of 15 cm/year.*

Figure 20. *The general debris shedding generates small talus cones along the toe of the cliff at Stevns Klint. The photo shows the cliff section north of Holtug (Loc. 21 in Fig. 1). Note the characteristic composition of flint cobbles and stones on the foreshore.*

Figure 21. *The promontory Korsnæb is the location of the largest progradation of the coast line due to the accumulation of beach ridges along the foreshore.*

No	Locality	Overhang	Thickness	Degree of exposure	Access	Risk
1	**Korsnæb**	x	xx	x	xxx	xx
2	**Boesdal**	xxx	xx	xxx	–	–
3	**Stevnsfort S**	xxx	xx	xxx	–	–
4	**Stevnsfort N**	xxx	xxx	xxx	–	–
5	**Lille Heddinge Vig**	xxx	xx	xx	x	x
6	**Harvig S**	xx	xx	x	x	x
7	**Harvig C**	xxx	xxx	xxx	xx	xxx
8	**Harvig N**	xx	xx	xxx	xx	xx
9	**Knøsen**	xx	xxx	xxx	xxx	xxx
10	**Kirkevig**	xx	x	xx	xxx	xx
11	**Vindehuse**	x	x	x	x	x
12	**Stevns Fyr**	xxx	xx	xxx	x	xxx
13	**Tommestrup**	xx	xx	x	x	x
14	**Telemasten**	x	x	x	x	x
15	**Barmhjertigheden**	xx	xxx	xxx	x	xx
16	**Storedal**	x	x	xx	x	x
17	**Sigerslev**	–	–	xx	xx	–
18	**Flagbanken**	xxx	xxx	xx	xxx	xxx
19	**Mandehoved**	xx	xx	x	xxx	xx
20	**Køge Bugt**	xx	xx	xx	xx	xx
21	**Holtug**	x	x	x	xx	x
22	**Holtug-Bøgeskov Havn**	–	x	x	xx	–

Table 1. *Schematic assessment of the risk evaluated for each of the segments along Stevns Klint. The numbers of the segments are identical to the numbers located in Fig. 1.*

In the assessment analysis four important elements are considered. Most important is the size of the overhang. However, the likelihood of a collapse depends additionally on the thickness of the overhang. The shear strength and thus the point of failure for a rock is a function of the normal pressure, which corresponds to the thickness of the rock (Hobbs, Means & Williams 1976, Mandl 1988). Therefore an overhang with a thickness of 20 m is more stable than one with a thickness of only 10 m. This consideration is included in the second column in Table 1. Thirdly the degree of exposures is also evaluated. Primarily because the exposed part of the cliff will be affected by wave erosion, and secondly because the softness of the chalk is increased by salt water spray (Mortimore et al. 2004). Finally risk will be proportional to the frequency of visitors. A detailed background for the assessment is given in the more substantial report from the Geological Survey of Denmark and Greenland written in Danish (Pedersen & Strunck 2011).

The evaluation of landslide hazard risk at Stevns Klint is based on the analysis of the rockfall processes and the magnitudes of the overhang and undercutting. The rockfalls at Stevns Klint are divided into five types according to their size and the mechanisms of transport of material from the face of the cliff to its toe. The various types of rockfalls do also occur at very different frequencies. The cliff-slides and cliff-falls are both dependant on the development of an overhang. The collapse may occur at overhang depths of 4–5 m if the bryozoan limestone is less than 3 m thick, whereas overhangs with undercutting depths up to 10–12 m may be stable if the limestone is in the order of 20 m thick. However, large overhangs suggest that future cliff-slides or cliff-falls are to be expected. The data from Højerup (Fig. 22) show that most of the recession of the cliff during the last 300 years occurred during two large cliff-slides (Rasmussen 1967). This suggests that the cliff-slides are rare events, which agrees well with the average erosion rate of 15 cm/year. At this rate it would require at least 60 years to create an overhang of 10 m (Fig. 23, 24).

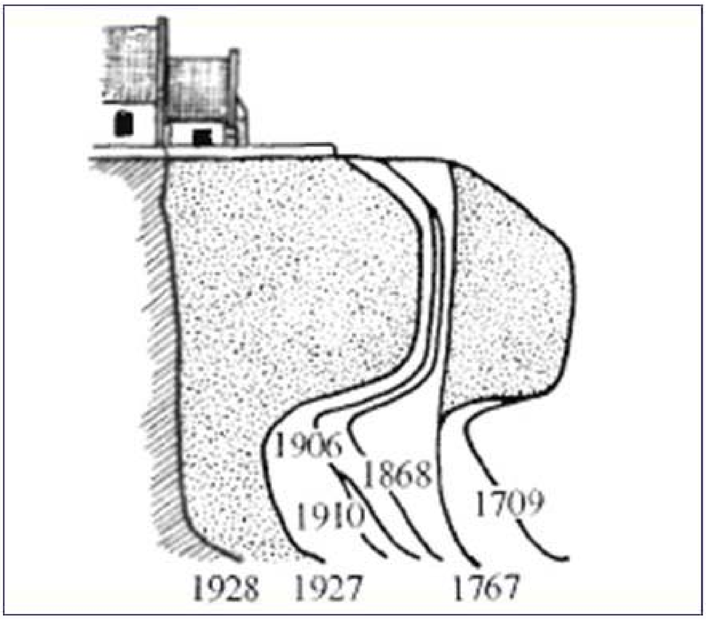

Figure 22. *The recession of the cliff below Højerup old church from Rasmussen (1967). Note that the two large rockfalls occurred in 1767 and 1928. Since then the cliff below the church has been saved by coastal protection.*

The parts of Stevns Klint where cliff-slides and cliff-falls may be expected are thus fairly easy to identify, although it is impossible to predict when the collapse is going to occur. In contrast, the average rockfalls and the debris shedding are more continuous processes involving significantly smaller volumes of limestone in each event. They are therefore unpredictable.

The large collapses are dangerous, but quite rare, with a likely frequency in order of one per 100 years. The more frequent rockfalls and debris shedding may theoretically pose a risk, although no recordings of injuries are known to the author. Comparison between the recent photo series and those taken 20 years ago document three rockfall along the entire cliff. This indicates that even smaller rockfalls occur with a low frequency and can not be rated as high risk hazards. The highest risk of rockfall is related to the locations of old limestone quarries along the edge of the cliff. The small thickness of the limestone between the floor of the pits and the undercutting of exposed parts of chalk cliff will promote collapses. However, some of these may be released in continuous debris shedding.

In the assessment of the risk of cliff collapse it should also be noted that certain parts of the cliff are inaccessible due to promontories and lack of foreshore. These segments of the cliff therefore pose no risk to public despite the magnitude of undercutting.

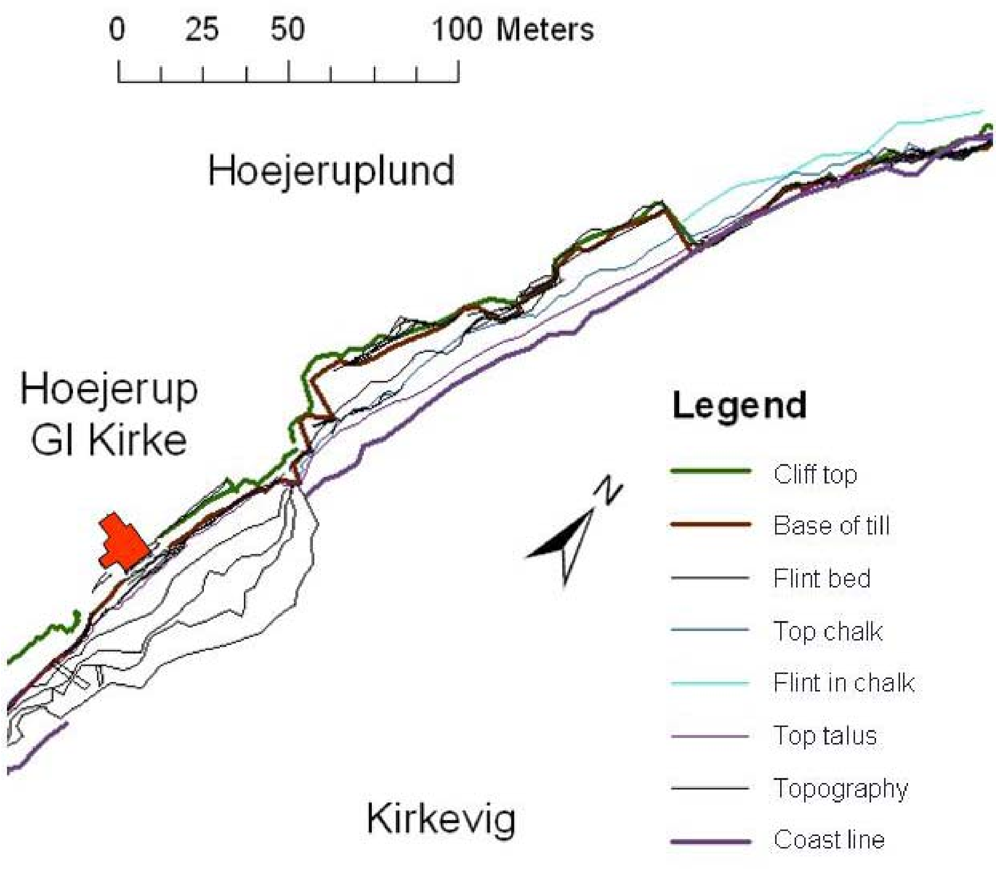

Figure 23. *Photogrammetric contour map of the coastline north of Højerup old church. The overhang north of the Højeruplund limestone quarry amounts to 7–8 m. Here an overhang prone to collapse will be created within the next 25–50 years.*

Conclusions

The landslide hazard assessment of Stevns Klint has been based on the investigation of rockfalls along the cliff. Five types of rockfalls are recognized ranging form cliff-slides to debris shedding. The cliff-slides have large volumes and occur at low frequencies (1/100 years). Debris shedding involves very low volumes and occurs at high frequencies (seasonal). The resulting average rate of erosion is 15 cm/year. The rockfalls involving meter-sized blocks, which include cliff-slide, cliff-fall and average rockfall, occur at frequencies of one per 10–100 years. Rockfalls may be initiated by frost and thaw, rainwater saturation or desiccation, but prediction of actual cliff collapses is at present not possible.

Figure 24. *The coastline north of Højerup old church. In the left side of the picture the traces of the limestone quarry at Højeruplund can bee seen. The cliff is exposed to erosion and a hazardous overhang will probably be created within the next 50 years. Photo M. Binderup 2010.*

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