Fluviokarst in the top of the Maastrichtian chalk at Rørdal, Northern Jutland, Denmark

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Construction work and planning operations in the second half of the 20th century in northern Jut-land supplied important detail to the geological background for the topographic development of the Rørdal area, eastern Aalborg. The inversion and uplift of the Sorgenfrei-Tornquist Zone in end-Cretaceous – Paleocene time initiated some 60 million years of erosion that removed the uppermost Cretaceous and Cenozoic deposits. Detailed mapping of the pre-Pleistocene chalk surface supple-mented with aerial photographs, quarry sections and excavated sections document the existence of karst phenomena and demonstrate that fluviokarst processes played an important role in formation of the topography. Live and palaeokarst features are supposed to be widespread in Danish lime-stone areas and the possible existence in a given area may be important in relation to areal planning, including raw materials extraction and water supply and protection.

Key words: Fluviokarst, sinkhole, doline, buried valley, crop mark, pre-Pleistocene surface, ground water pollution, Maastrichtian chalk.

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The pre-Pleistocene surface of the Maastrichtian chalk in the greater Aalborg area in northern Jutland forms a hilly landscape with a considerable relief that to a great extent is concealed by Quaternary deposits. Only some chalk hilltops are visible as 'islands' surrounded by broad valleys with Quaternary sediments. In some places the Quaternary sediments are hardly distinguishable from the white chalk from which they are eroded and reworked (Stenestad 1968).

The Upper Maastrichtian white chalk was deposited in a deep shelf some distance from the coast, and the amount of clay and silt brought to the depositional area was very low. However, in mid late Maastrichtian time the quiet sedimentation of biogene components (coccoliths, foraminifers) was disturbed as indicated by the occurrence of marly beds and rhythmic marl-chalk bedding in the chalk of the *Pyramidina cimbrica* foraminifer Biozone (Fig. 1) (Stenestad 1971, 2005). The reason for these changes in sedimentation is not known but the chalk at Rørdal quarry is not a lithologically homogeneous succession. In addition, laboratory tests document varying physical and chemical properties of the chalk.

The structural conditions of the Aalborg area reflect Late Cretaceous – Paleogene inversion of the Sorgenfrei-Tornquist Zone and uplift, followed by Cenozoic erosion and deposition. The age of the pre-Pleistocene surface becomes progressively younger from north-east to south-west in the greater Aalborg area. At Rørdal the surface of the chalk represents the lowermost part of the upper upper Maastrichtian (*P. cimbrica* Zone) whereas at Vokslev towards the west the chalk belongs to the uppermost upper Maastrichtian (*Pseudotextularia elegans* Zone) overlain by Danian limestones.

In the Rørdal quarry abundant joints and faults indicate that the chalk is heavily fractured. This is also seen in drilled cores such as the Rørdal-1 core where many slickensided fault planes and crushed sections are noted (Stenestad 2005). The fracturing of the chalk has facilitated erosion and development of karstic features. Sinkholes, dolines (major funnel-shaped sinkholes) and lakes with subsurface outlets are well known from many places in northern Jutland, and dramatic events such as sudden sink-in of the surface because of the collapse of a subsurface cavity have occasionally caused some publicity. A

comprehensive account on karst phenomena in northern Jutland, or elsewhere in Denmark, has not yet been published, but a number of geological descriptions relate to karstic topography (Jessen 1899, 1905, 1936; Milthers 1908; Mathiasen 1920; Hintze 1937; Corbel 1947; Troels-Smith 1964; Stenestad 1968, 1976, 1977, 1982; Ambo 1974). Construction work in the 1960ies and raw materials and water supply planning operations in the 1970ies supplied new data on karstic development in the region. Some of these data are presented here.

Pre-Pleistocene limestone is a major aquifer in many countries. Subsurface channels in karst areas together with the permeability provided by fractures and joints improve the yield. At Rørdal, the permeability is about 20 times higher in the north-eastern part of the upland than in the southern part. According to pump tests this variation in permeability reflects the amount of fractures (Ambo 1974). Assuming that the crushing of the upper part of the chalk in this area is due to the movement of glaciers it can be presumed that the north-eastern part of the chalk 'island' was the push side for ice lobe movements from the north-east. The presence of live karst or palaeokarst in a given area may be of major impor-

Fig. 1. Rhythmic sedimentation of upper Maastrichtian chalk at Rørdal.

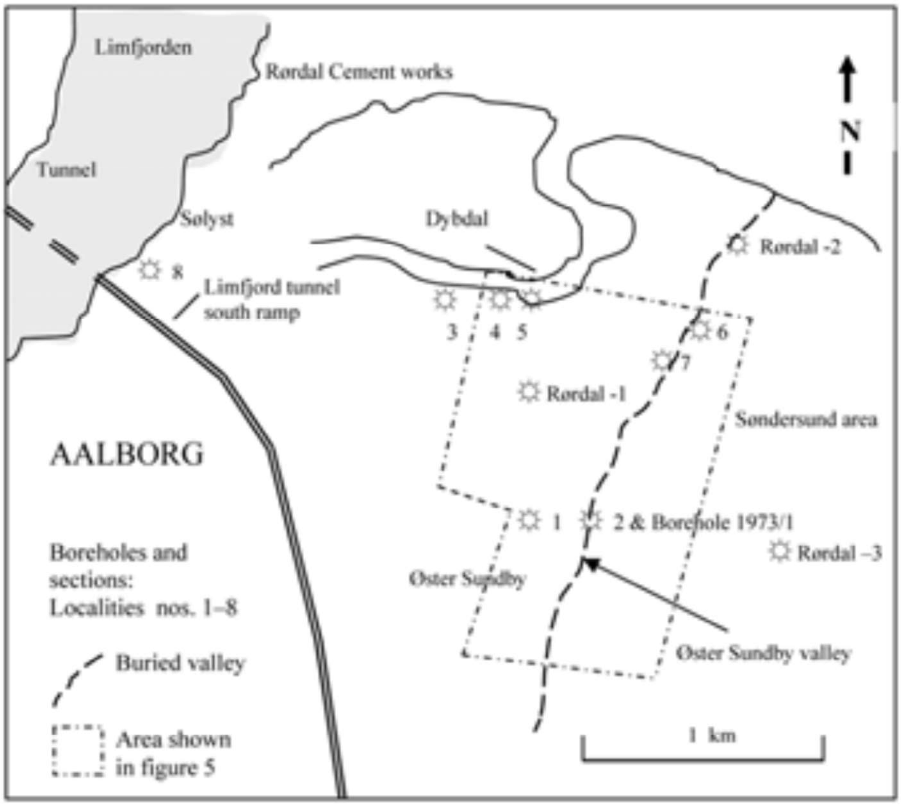


Fig. 2. Rørdal area. Locality map.

Fig. 3. Rørdal quarry, Dybdal and the Søndersund area. The crop marks from figure 4 are shaded on the contour map of the pre-Pleistocene surface. The equidistance of contours is 1 m. The boreholes in Dybdal are shown without the DGU file numbers used in figure 17.

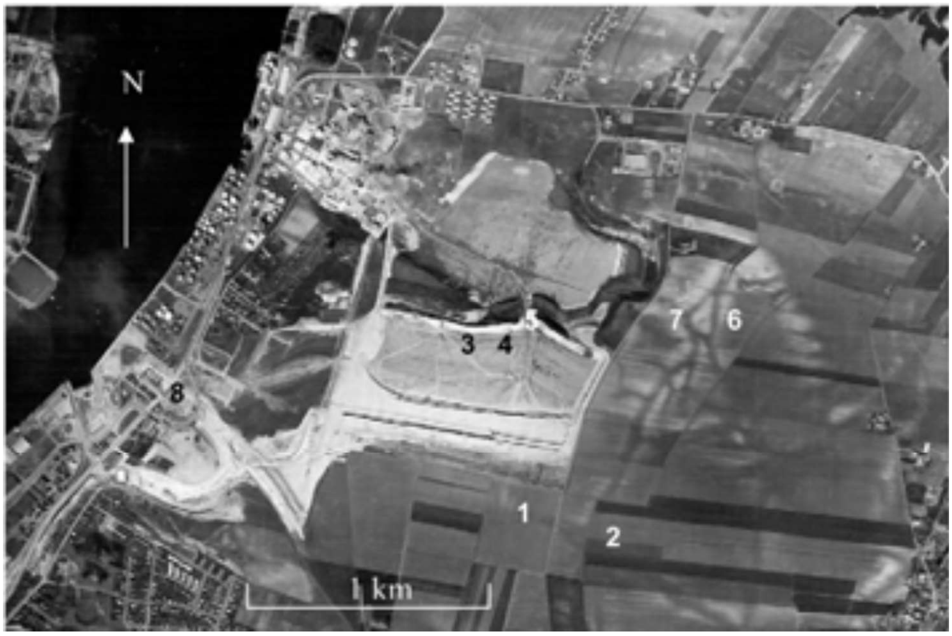


Fig. 4. Aerial photograph of the Rørdal area showing the same area as figure 2. Note crop marks. Localities nos. 1–8 are indicated. Based on an excerpt of Danish Geodetic Institute aerial photograph route 349 nr. 245. (Reproduced according to authorization A.63/75).

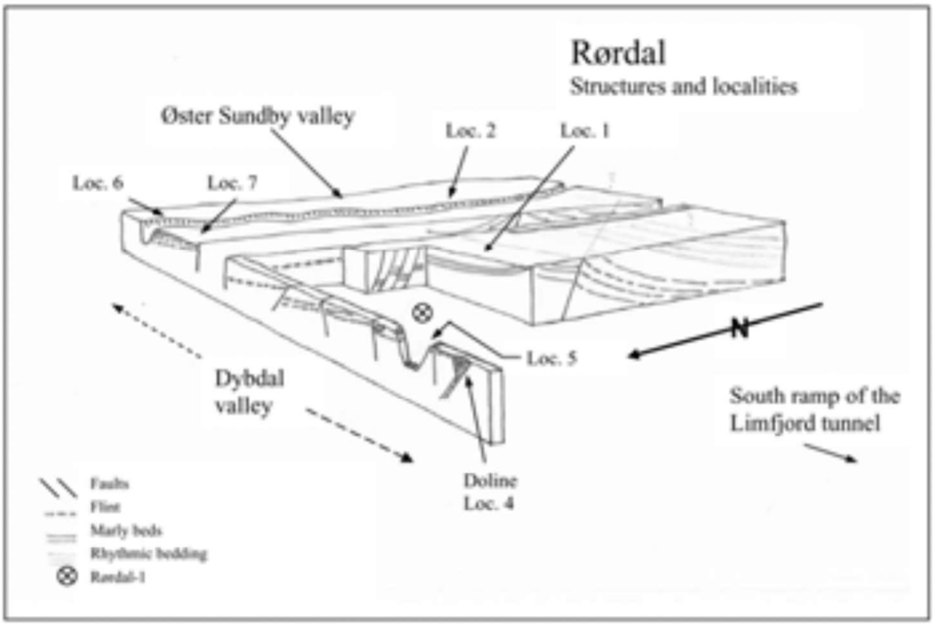


Fig. 5. Rørdal quarry. Structures and localities. The represented area is c. 1 × 1 km. (Cfr. Fig. 2).

tance for ground stability, water supply and groundwater protection (Stenestad & Sustrac 1992). Published and unpublished field observations and aerial photographs from other Danish limestone regions indicate that live karst and palaeokarst is widespread.

Fig. 6. Joints diagram based on 80 measurements. Lambert equal-area projection on lower hemisphere.

Data and methods

The description is based on observations in quarry profiles, excavations and cores from boreholes. A dense grid of drill holes was used to establish the relief of the pre-Pleistocene surface in the Søndersund area (Figs 2,3). Aerial photographs showing crop patterns helped to track the buried Øster Sundby valley (Fig. 4).

Rørdal quarry

The chalk that is exposed in the sections is white to greyish white with 90–95% carbonate and less than 0.5% Fe_2O_3 and MnO, while the remaining impurities mainly comprise clay, and a few angular silt-size quartz grains. Flint nodules are generally scarce and are found only at a few levels (Fig. 5). The chalk is thoroughly bioturbated.

Marly beds and rhythmic bedding is found only in the southern part of the area (Fig. 5). This area is also characterised by many flint nodule beds. Minor faults were found in all parts of the chalk in the Rørdal quarry. Joints striking N–S, E–W, NE–SW and NW–SE are widespread in the chalk, and these directions coincide with the direction of the valleys eroded in the chalk (Fig. 6).

Fig. 7. Locality 1. The partly excavated doline viewed from top of the chalk. The dark section next to the spade represents layers (2) to (6) in fig. 8. The bottom layer (7) is not visible.

Description of karst features

When the Quaternary deposits in the area adjacent to the southern ramp of the Limfjord tunnel was removed it was revealed that the surface of the chalk was densely scattered with sandy spots with a diameter of 0.5–1 m representing a large number of sinkholes. Such 1–2 m deep sinkholes were also observed in the quarried profiles.

A major circular, funnel shaped hollow in the surface of the chalk was studied in the southern part of the quarry (locality 1, Figs 2, 4, 5). The overburden and most of the pebbly sand in the upper part of the hollow had been removed (Fig. 7). The top diameter of the excavation was c. 5 m and the depth c. 6 m (Fig. 8). The hollow is filled with greyish-brown or ochre-coloured sandy deposits, including fine to medium-grained coarse sand with pebbles and up to 15 cm large blocks of white chalk alternating with clayey and silty layers. Spots of soil rich in organic matter, crumbling pebbles and ochre-covered flint nodules in undisturbed sand layers near the bottom of the hollow indicated the former presence of a connection to a weathered land surface. In the bottom of the hollow two undisturbed planar flint nodule beds and soft, wet, white chalk indicated *in situ* dissolution of the chalk.

The smooth and corroded walls of the hollow in the soft crumbling chalk also indicated dissolution of the chalk (Fig. 9). The contact sediment of clayey and silty sand may have been formed as layers of silt and clay on the surface of the chalk gradually

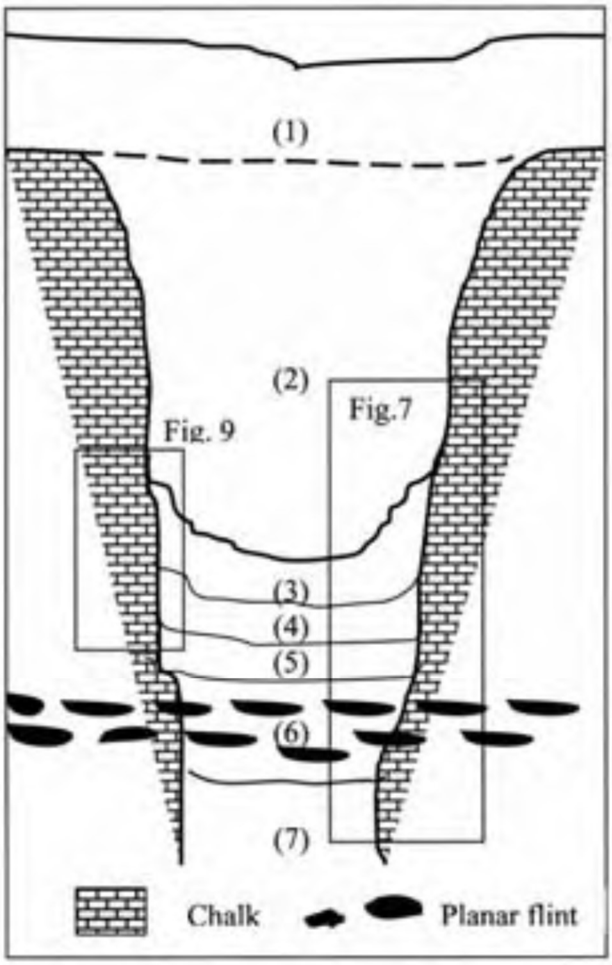


Fig. 8. Locality no.1. Doline. Diagram not to scale. Top diameter of the hollow is c. 5 m and the depth is c. 6 m. (1) Overburden; (2) Pebbly sand (partly removed), fine, greyish brown; (3) Sand, fine to medium-grained with pebbles, light greyish brown or ochre-coloured, with up to 15 cm large blocks of white chalk; (4) Sand, fine to medium-grained, greyish brown, with few pebbles, alternating with clayey and silty layers; (5) Sand, fine to medium-grained, greyish brown, with spots of soil rich in organic matter, with crumbling pebbles and ochre-covered flint nodules; (6) Sand as (5) with two undisturbed horizontal planar flint beds; (7) Chalk, white, soft, wet.

Fig. 9. Locality 1. Close up of contact to chalk *in situ.* (Cfr. Fig. 8)

sunk into the hollow during its formation as also described from the Lägerdorf chalk quarry in Holstein, northern Germany (Todtmann 1951). However, the gradual change at locality 1 of light sand in the centre of the hollow to brown silty and clayey sand at the contact to the chalk indicates that some transport of clay and silt particles from the centre of the hollow to the chalk wall have taken place. The clayey lining of the walls also indicates that the main drainage of water through the hollow took place at a deeper level, i.e. from the bottom of the funnel.

Vertical and extensive horizontal subsurface channels in the chalk were exposed in the walls of the quarry quite near locality 1. The horizontal originally open subsurface channels are 5–10 cm deep and are infilled with cross-bedded sand and gravel by eastbound streams as is indicated by the east dipping foresets (Fig. 10). The subsurface channels are interpreted as fluviokarst channels developed by running water in combination with dissolution processes.

The funnel shaped hollow at locality 1 is interpreted as a doline on the basis of the form and size of the hollow, the sediments, the character of the walls, the contact sediment, and the nearby presence of a karst type drainage system.

A funnel-shaped structure and an irregular horizontal channel with a sand-filled cavity was noted in the chalk in the quarry wall next to the Dybdal valley (locality 4, Figs 2, 4, 5). The funnel was c. 6–7 m in diameter and c. 4–5 m deep (Figs 11,12). Parallel faults (170°/68°E) formed the shaft and one side of the funnel. Fine-grained partly stratified sand and cobbles with a diameter of 15–20 cm were deposited

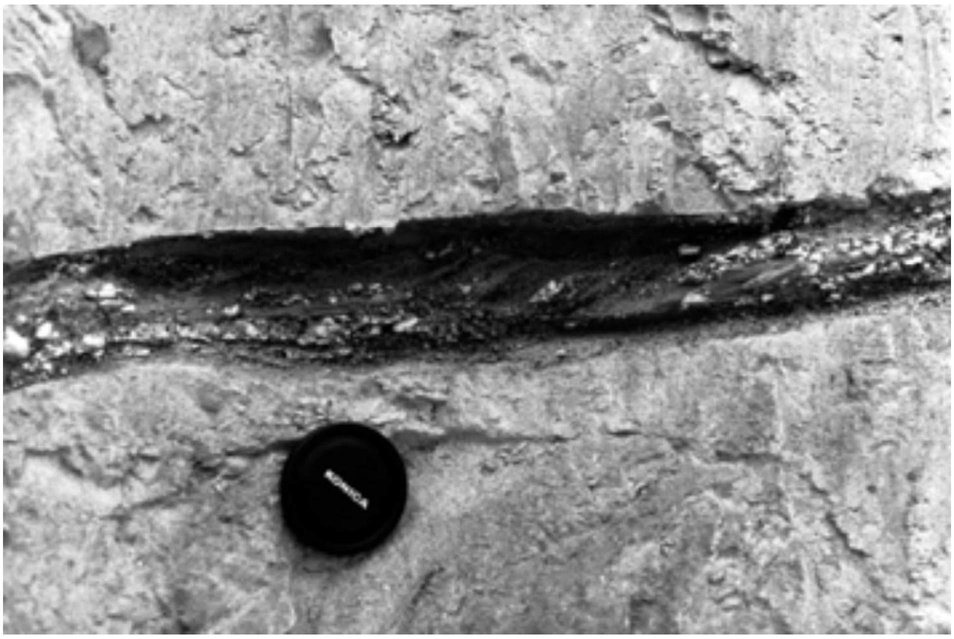


Fig. 10. Close-up of quarried wall near locality 1. Open channel in the chalk infilled with cross-stratified fluvial sediment.

Fig. 11. Locality 4. General view of the doline next to Dybdal.

in the bottom of the funnel shaft and in the channel (Fig. 13). The funnel was filled with fallen chalk fragments covered by stratified fine-grained sand and silty fine sand.

Locality 4 is interpreted as a doline formed in connection with a subsurface channel that drained away percolating water. Most likely a sinkhole was first developed in a water-eroded system of parallel faults. The funnel was connected to horizontal fractures in the chalk that eventually developed into an open channel where river sediments were deposited. A minor surface stream that eroded the upper part of the doline achieved the further development. It produced the plug of fallen chalk fragments in the fun-

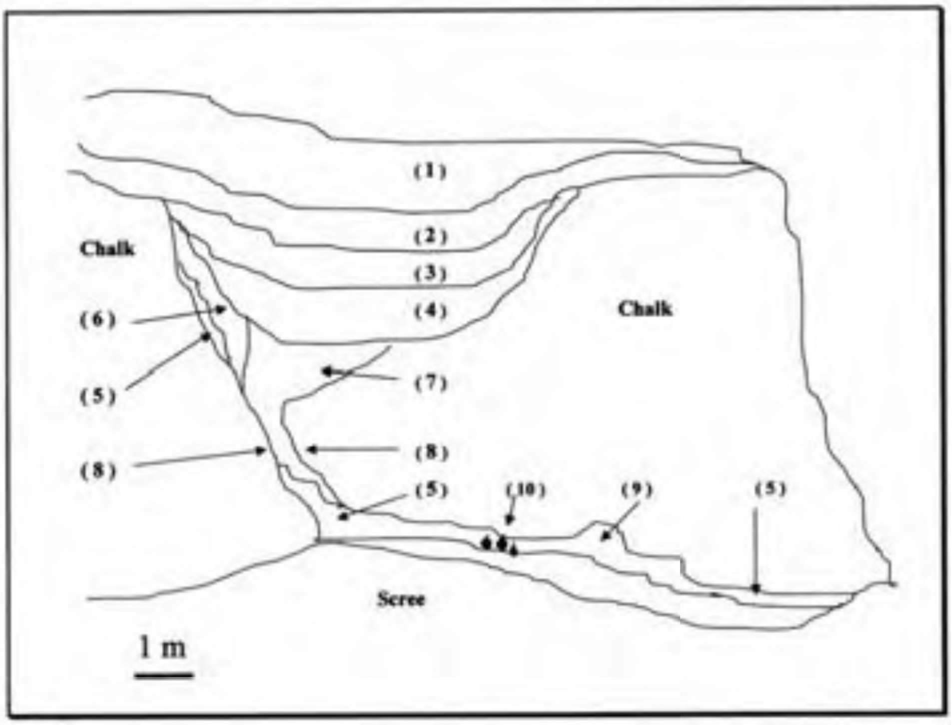


Fig. 12. Locality 4. Explanatory sketch to figure 11. (1) Landfill; (2) Soil; (3) Silty fine sand; (4) Stratified fine sand; (5) Sand, fine, partly stratified; (6) Block of solid chalk; (7) Fallen chalk fragments; (8) Faults; (9) Sand-filled cavity; (10) Cobbles with a diameter of 15–20 cm.

Fig. 13. Locality 4. Channel in the chalk filled with sand and cobbles. Cfr. fig. 12, item (10).

nel shaft and triggered the sliding down of a block of solid chalk (Fig. 12). A fining-upwards succession of bedded fine sand and silt eventually filled the channel.

At the time when the doline was developed the area was presumably a karstic plain scattered with sinkholes as it was seen in the area near the south ramp of the Limfjord tunnel. The precipitation was drained away by sinkholes and by minor surface and subsurface streams leading to major valleys like Dybdal.

Boreholes Rørdal-1, -2, -3

The Rørdal-1 core from the bottom of the quarry (Figs 2, 5) illustrates an important feature that controlled the karstic development of the area namely the deep fracturing and crushing of the chalk. The upper c. 15 m of the core is strongly fractured and crushed by Quaternary glaciers like the chalk in the quarry, but at deeper levels the core is still highly fractured with many slickensides on subvertical sliding planes, indicating fault movements in the hardened chalk. This

Fig. 14. Dybdal. Viewed from the East.

Fig. 15. Locality 5. Section of the south side of the Dybdal valley.

is also the case in the boreholes Rørdal-2 and Rørdal-3. The deep faulting and fracturing is ascribed to the structural inversion of the Sorgenfrei-Tornquist Zone in late Maastrictian – Paleogene times (Stenestad 2005).

Dybdal valley

The c. 100 m wide Dybdal valley was left behind during quarrying as a 10–20 m high 'wall' between the quarried areas (Fig. 14). The profile (locality 5, Fig. 15) represents the south side of the valley. The side of the valley is here a steep or overhanging wall of chalk in contact with fine-grained sand that is very well sorted, finely laminated or cross-bedded. The same type of contact is seen at the nearby locality 3 (Fig. 2) between graded silt without chalk and an overhanging chalk wall (Fig. 16). The chalk wall at locality 5 is oriented NE–SW, almost perpendicular to the main direction of the valley at this point but it coincides with the direction of the joints. In the valley Late Glacial fine-grained sand and silt is interbedded with coarse-grained sand, pebbly sand and sand with cobbles up to 20–30 cm diameter. Some of the drilled sections have indications of cyclic sedimentation that may reflect climatically controlled changes in the Late Glacial flow of melt water (Fig. 17). The fining-upward cycles have coarse pebbly sand at the base overlain by progressively finer-grained, well-sorted sands. The content of chalk mud and silt is low at the base of each cycle and increases

Fig. 16. Locality 3. Contact between the chalk wall and the valley-fill sediments of Dybdal.

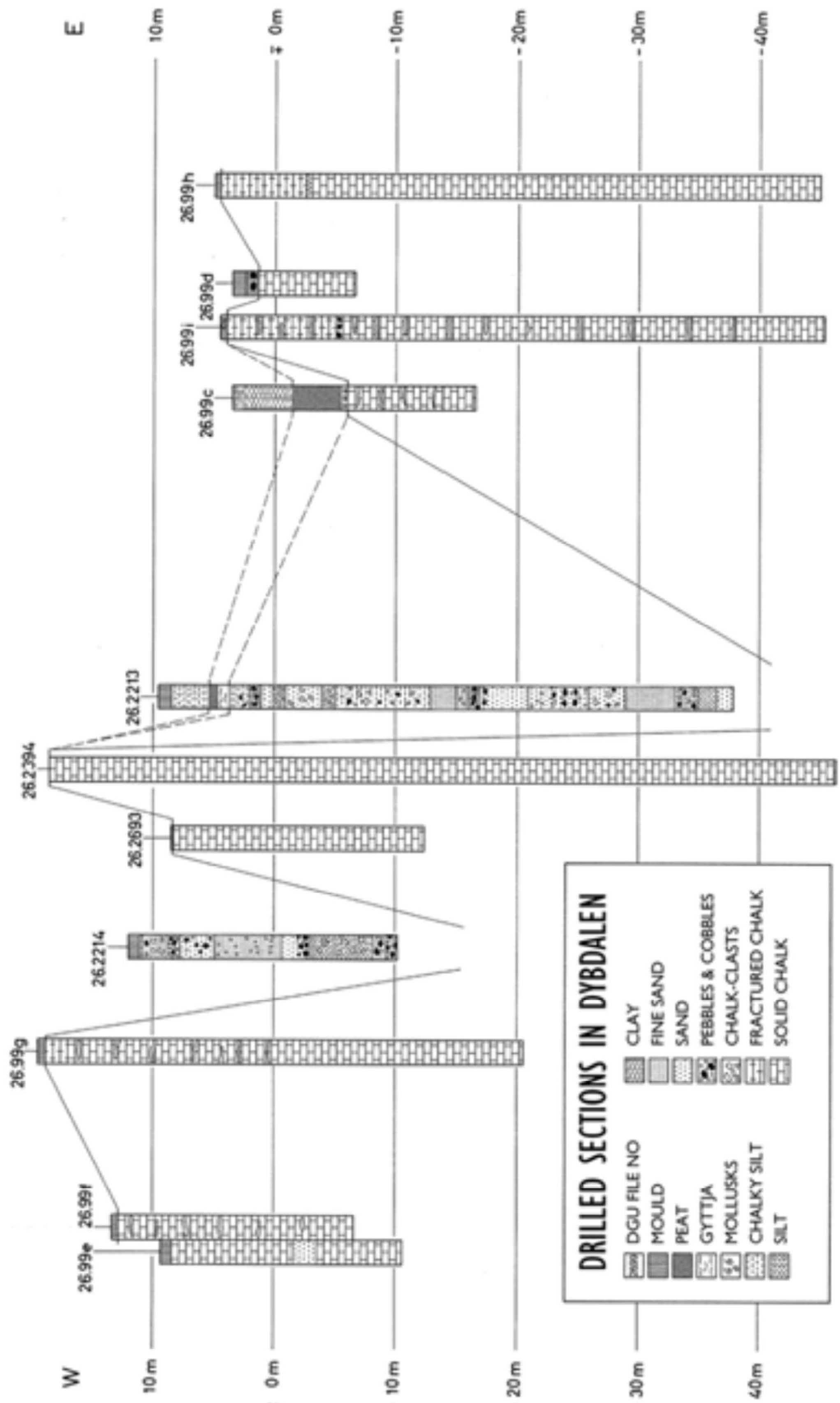


Fig. 17. Drilled sections in Dybdalen. The location of the boreholes is shown in fig. 3. The length of the composed cross-section is about 1½ km.

Fig. 18. Locality 2. The excavated cross-section of the uppermost part of the Øster Sundby valley viewed from the south. The buried valley is hardly visible in the terrain. The 10 m bar refers to the section in the centre of the picture. Barely visible spades right and left in the picture and a ranging pole in the centre for verification of the scale.

upwards. Beds of chalk fragments occur. Some poorly sorted beds were probably deposited by debris flows. Higher up in the succession lake sediments of Postglacial, Atlantic age has been found (Fig. 17, Geological Survey of Denmark File no. 26.2213. Gyttja at + 5 m dated by Bent Aaby 10/10–1974). The low lying most distal part of the valley is believed to contain a small Postglacial marine section (Cfr. map in Berthelsen 1987) and foraminifer dating of reworked sediments at nearby Limfjord tunnel south ramp (Stenestad 1968, plate 1).

The valley is narrow and deep and the bottom topography is very uneven as indicated by the boreholes in the valley (Figs 3, 17). Geoelectric measurements in the valley failed because of interference from the narrow walls of chalk. However, one of the boreholes in the valley centre (Geological Survey of Denmark File no. 26.2213) did not reach the chalk at the final depth at level –38 m some 50 m below the surface of the chalk adjacent to the valley.

The steep and in places overhanging chalk walls together with the cross-bedded fluvial sediments

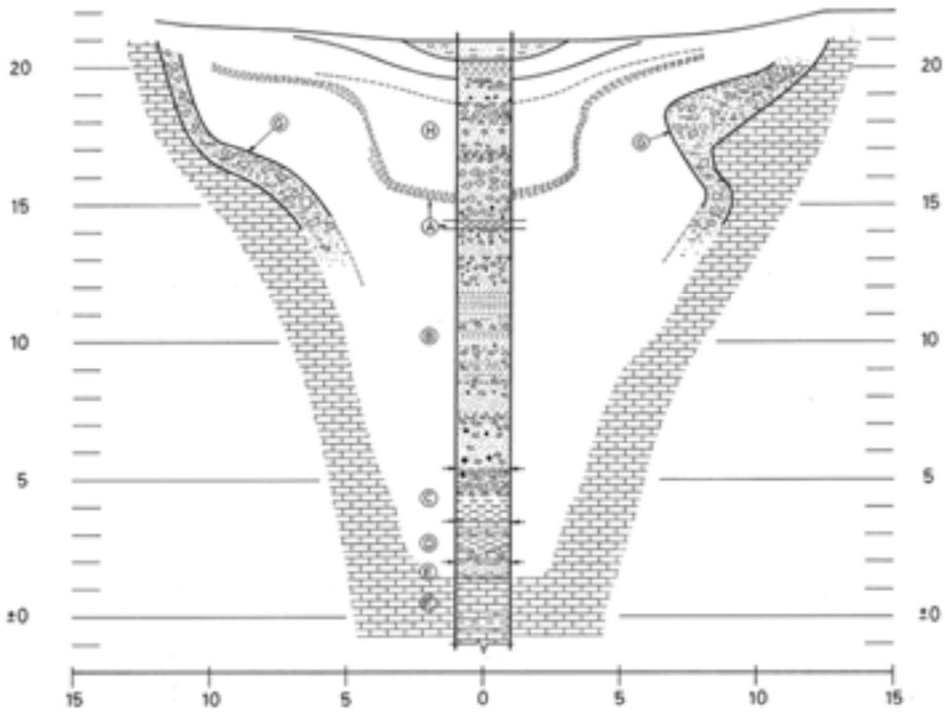


Fig. 19. Locality 2. Composite section based on the excavated cross-section (Fig. 18), and borehole 1973/1 (Figs 2, 4). Key as in Fig.17.

Fig. 20. Locality 2. Stratified contact sediments c. 5,5 – 6,3 m below the top of the excavated cross-section (Figs 18, 19).

with pebbles and cobbles up to 20–30 cm diameter suggest the former existence of a deep and narrow valley with a small but vigorous stream that eroded the bottom and sides of the valley. Later it was filled up with Late Glacial and Postglacial sediments.

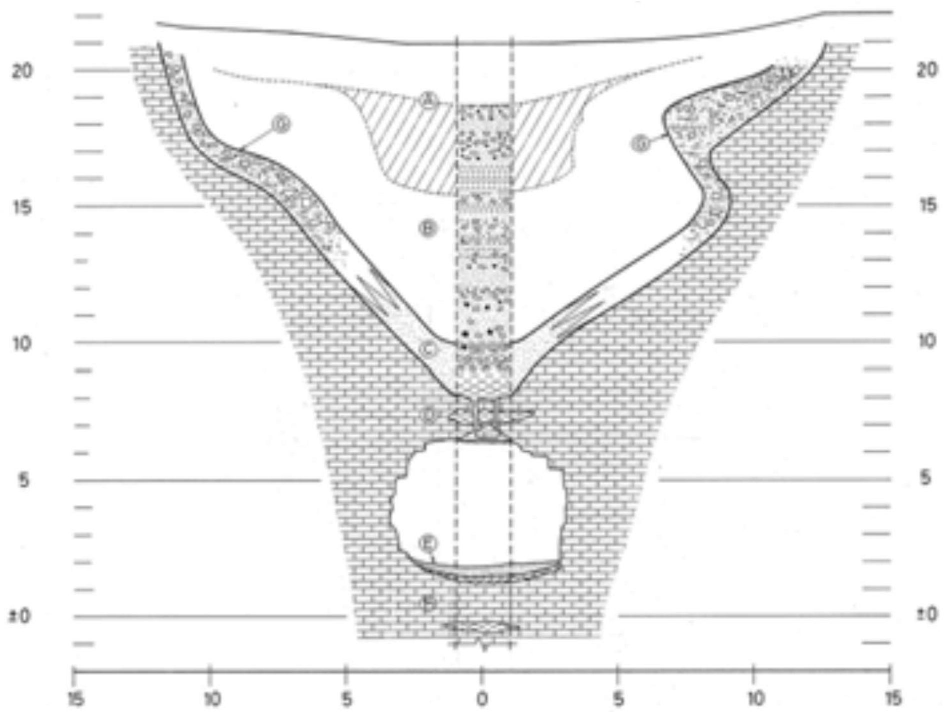
It is suggested that a river that followed the joints in a former karren surface excavated the valley. The term karren surface is used here to describe an almost barren limestone surface intersected by deep, narrow furrows representing joints that are eroded by flowing surface water and opened up for percolating acid water. Old topographic maps and aerial photographs demonstrate that the valley is characterized by having linear sections that cut each other in sharp angles and follow the direction of joints (Figs 4, 6). This is typical for a river developed on a karren surface. Sections and boreholes support the interpretation of the valley as having a karstic aspect.

The development of the Dybdal valley is suggested to have happened as a series of events. It started with uplift and erosion of the chalk in the Paleogene followed by the development of a karren plain with sinkholes and dolines in the Neogene (?) and Quaternary. It is further assumed that the bottom of the valley is constituted by a row of dolines interconnected by karstic channels forming an old subsurface drainage system that has included other dolines in the area such as the above mentioned doline at locality 4.

Subsequently, the area underwent erosion by Quaternary glaciers and Late Glacial streams and finally the valley was filled by Late Glacial – Postglacial stream or lake deposits.

Fig. 21. Locality 2. Sediments from the axis of the Øster Sundby valley c. 6,3 – 7,4 m below the top of the excavated cross-section (Figs 18, 19).

Fig. 22. Locality 2. Tentative section of the Øster Sundby valley before collapse of an assumed cavity. Key as in Fig.17.



Søndersund area

The Søndersund area is especially interesting because of the buried Øster Sundby valley. When the area was first surveyed it was hardly visible in the terrain (Fig.18). The recent valley was dry as it was drained through the bottom and not by surface streams. Crop marks (Figs 3, 4) were only visible in the spring as the humid depressions dried out in the summer.

A number of shallow boreholes and excavations were made in order to map the surface of the chalk. The resulting contour map of the pre-Pleistocene surface demonstrates that the crop marks are clearly related to the relief of the top of the chalk (Fig. 3). The Øster Sundby valley follows the orientation of

Fig. 23. Locality 6. Øster Sundby valley cross-section. Note spade for scale.

Fig. 24. Locality 6. Close up of the sidewall of the easternmost branch of the Øster Sundby valley. The chalk (at top of the photograph) is covered by greyish brown slightly argillaceous pebbly sand, and towards the axis of the valley by sands with chalk fragments (bottom of photograph). In the axis of the valley are alternating beds of fine sand and chalk fragments.

joints and faults in the chalk just like the Dybdal valley. A cross section (Fig. 18) was excavated in one of the deeper parts of the valley (Fig. 2, locality no. 2). This section did not reach the bottom of the valley and so a borehole was made at the profile (Fig. 2, borehole 1973/1). The composite profile is based on data from the excavation and the borehole (Fig. 19). The cross section of the excavated part of the valley is almost funnel-shaped. The section is c. 25 m wide at the top and c. 15 m wide at the bottom of the excavation at level +14 m. The upper 5 m of the western chalk wall of the valley is almost vertical. Below this level the wall dips towards the axis of the valley. The eastern chalk wall is overhanging to vertical. The chalk is somewhat disintegrated and clayey at the contact to the sandy valley fill, and this together with the steep and overhanging walls and the irregular funnel shaped cross-section seem to indicate that karstic processes have been active. The chalk-walls of the upper part of the valley are covered by 0.5–1 m silty and clayey sand sediment with abundant chalk clasts (Fig. 19, bed G). The sediment shows some similarity to boulder-clay (till) but it is slightly stratified and is supposed to have flowed into the valley as a debris flow.

The sediments of the valley fill are mainly fine to medium-grained sand with beds of clayey silt and chalk pebbles. The valley sediments show a common change between well sorted and poorly sorted beds of fine and medium-grained sand and pebbly sand with cobbles, including abundant chalk clasts. Fine-grained graded beds may have up to 15–20% silt. The succession from c. 4.6 m to 7 m from the top of the excavation consists of 10–20 cm thick graded beds separated by beds of chalk clasts (Figs 20, 21). Some grain-size distributions may be strongly affected by the content of chalk clasts, but the curves reveal a quite normal distribution if the chalk is removed, as was noted also for Dybdal. Because of the high porosity the chalk clasts are light for their size compared to less porous particles such as quartz sand.

The valley fill at locality 2 can be subdivided into three units: The basal unit is the *in situ* chalk that is consolidated or slightly hardened and without flint nodules. It is covered by c. 3 m of chalk-mud with chalk clasts deposited by viscous debris flows. The upper unit is a fining-upwards succession with beds of fine to medium-grained sand, silty sand, lime-mud and chalk clasts. It was laid down by a slow stream or in a lake as indicated by cross-stratification, small irregular silt patches and the small grain size. The cyclicity of the succession may reflect diurnal or seasonal changes in water flow. Organic components

Fig. 25. Locality 7. Close-up photograph of valley-fill sediment and contact to the chalk wall in the westernmost branch of the Øster Sundby valley (Figs 2, 4).

were not found in these sediments and it is assumed that organic production in the area was very low or absent at this stage. Pollen analysis of sediments from level +3.5 m (Fig. 19, bed C) failed to identify primary pollen and the precise age of the upper valley sediments is thus not known.

The bedding and sedimentary structures across the profile indicate that the valley sediments subsided at a late stage of Quaternary sedimentation (Fig. 18). The bed named A in figure 19 was followed across the profile. It was evenly bedded in the middle of the valley. Near the sides of the valley, however, it was broken up into short subvertical flakes that could be followed c. 4 m upwards to a level, where the bed was again almost horizontal but was dissected by antithetic micro-faults. The subsidence of the central sediment package could be traced into the lower part of the sediment package above bed A, but it could not be established whether the subsidence was diminishing upwards which would indicate that the subsidence took place over a period of some length, possibly to the end of the sedimentation.

Possible explanations of the subsidence might include 1) compaction of underlying soft sediments such as peat or clay rich in organic matter, 2) melting of remains of glacier ice in the deeper parts of the valley, or 3) collapse of a cavity in the chalk. Options 1) and 2) are not supported by sedimentary evidence as there was no trace of organic sediments or genuine till deposits. This leaves option 3) as the most likely explanation. For instance, the bed marked D in figure 19 may represent the roof of a collapsed cave. A tentative profile of the valley before the collapse of an assumed cavity is shown in figure 22.

Abrupt collapse of a single cave roof would not comply with the assumed gradual and rather undisturbed subsidence of the above sediments. However, changing groundwater levels may have resulted in more levels of cavities that collapsed successively as the dissolution of the chalk progressed and the weight of the overlying Quaternary sediments increased. The stability of cavities in the soft and very fractured chalk was probably low. The presence and gradual caving of a number of minor cavities is presumably more likely than one big cave that collapsed abruptly.

If the valley has a karstic history, and at this point was located on top of a subsurface cavity, it can be assumed that other deep depressions beneath the valley may have a similar origin, and that the valley was at first developed as a subsurface channel linking a row of sinkholes and dolines. This was tested by examining sections at locality 6 and 7 (Fig. 2) in the northern part of the Øster Sundby valley.

At locality 6 the chalk wall of the valley was vertical or slightly overhanging (Fig. 23). The valley fill comprises greyish brown slightly argillaceous pebbly sand (Fig. 24). Towards the axis of the valley sand with chalk fragments occurs and in the axis alternating beds of fine sand and chalk fragments having much the same appearance as the sand at locality 2.

Fig. 26. Locality 7. Photograph of section in the westernmost branch of the Øster Sundby valley showing minor faults and subsidence structures.

Locality 7 is a cross section of the westernmost branch of the Øster Sundby valley (Figs 2, 4). The chalk wall is almost vertical. The valley fill sediment is much the same till-like clayey and pebbly sand as in the Dybdal valley, the Øster Sundby valley, and the Limfjord tunnel area. It is known from other investigations in the area that the pre-Pleistocene chalk surface is in many places overlain by less than 1 m of sandy and clayey Quaternary deposits (Stenestad 1976). The till-like sandy and clayey sediment at this locality may have derived from such deposits of ablation moraine character. In cases where the sediment package is clearly stratified the individual beds

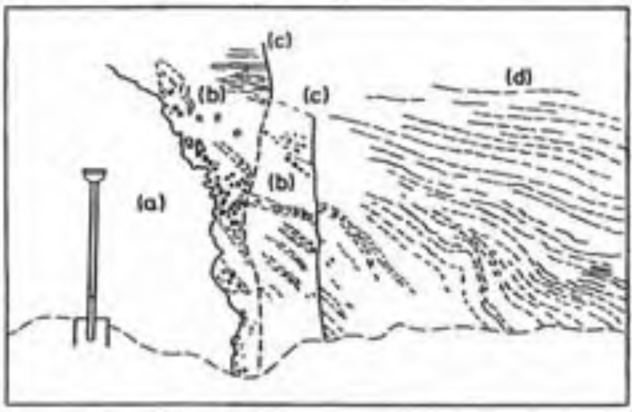


Fig. 27. Locality 7. Explanatory sketch to the photograph figure 26. (a) Chalk; (b) Stratified sand and silt with chalk fragments – possibly a debris flow deposit; (c) Faults; (d) Stratified sand and gravel. Note the subsidence structures.

Fig. 28. Locality 7. Photograph of the westernmost branch of Øster Sundby valley showing sediment structures across the section.

were laid down by series of small debris flows (Fig. 25). Angular chalk fragments that are imbedded in the sand outline the structural details and the assumed development of the sediment package. The succession seems to have been deposited in an open valley incised into the chalk. Clayey and silty sand was deposited in the valley by debris flows alternating with beds formed by fall of chalk pebbles from the fractured walls. Also at this locality a subsidence of the sediments in the valley has occurred. This happened mainly but not exclusively by small scale faulting c. 0.5 m from the chalk wall (Figs 26, 27). The distribution of the chalk fragments indicates drag, draw-out and vertical displacement of the beds along the faults. In the axis of the valley Late Glacial streams deposited horizontally bedded sand with chalk pebbles (Fig. 28). The data from locality 6 and 7 on the uppermost part of the valley support the observations from locality 2, including the subsidence of Late Glacial sediments, but they yield no details of the subsurface drainage system.

Limfjord tunnel area

Geological data obtained during the construction of the Limfjord tunnel south ramp show the presence of a 45–50 m wide and 30–32 m deep valley incised into the chalk and filled by Quaternary deposits (locality 8, Fig. 2) (Stenestad 1968, Stockholm 1968). It is believed that this valley was separated from the present Limfjord and was connected with the higher situated Dybdal. The sedimentary succession illustrates the progressive erosion of the source area. In the lowest part of the section Late Glacial fine-grained sand with gyttja containing beds from the warm Late Glacial Allerød period is overlain by chalk-ooze and chalk-silt (Stockholm 1968). Upwards, the sand and clay content decreases and the stratification become less prominent. Above these beds follows a stratified succession of chalk-ooze, chalk-silt, clay, silt and fine-grained sand. Part of this succession superficially appeared as solid chalk *in situ*, which might be misleading. According to the succession of sediments, however, this was clearly not the case. The succession is believed to be have been deposited by streams that eventually eroded pure chalk and thus re-deposited pure chalk silt that may look like solid chalk. The topmost sediment under the soil is rather fine-grained till-like clayey sand, rich in chalk fragments, obviously deposited by solifluction and derived from the thin till cover of the chalk surface. The Dybdal and Øster Sundby valley fills both comprises essentially the same types of sediment and the various sections seem to represent only variations of a common geological development history.

Discussion and conclusions

Sinkholes, dolines and subsurface channels incised into the solid chalk together with the fill by stratified and cross-stratified fluvial deposits demonstrate that fluviokarst processes were active in the Rørdal area, Aalborg, northern Jutland. The development started with Late Upper Cretaceous – Paleogene inversion and uplift of the Sorgenfrei-Tornquist Zone. This was succeeded by Cenozoic sub-aerial erosion by weathering, stream erosion, sliding, and rock fall. Eocene tropical and humid conditions may have been strongly corrosive to the chalk (Radwanski 1975). The fracturing of the chalk, that facilitated mechanical erosion, also furthered the development of karstic features such as sinkholes and underground cavities, and the still ongoing development of karstification in the area probably started early in Cenozoic times.

Even if there existed a drainage system in the solid chalk surface already in the Cenozoic it is evident that the alternating physical conditions during the Quaternary glaciations and cold and warm stages were major agents in the development of the topography. Quaternary erosion by glacier and meltwater together with karst processes completed the present-day topography. Only a melting icecap would supply the water flow necessary to transport the large amount of sand, pebbles and cobbles found in the sections. When the glaciers melted away the surface of the chalk was left behind as an undulating surface with a thin cover of sandy till (presumably an ablation moraine) and till-like sediments (solifluction earth). The surface of the chalk was characterized by scattered sinkholes and dolines. Sub-surface channels and cavities were developed as part of the drainage system. Late Glacial sediments were accumulated in lakes and streams and found their way into the karstic subsurface channels. Eventually, Postglacial clay, silt and sand were deposited in minor lakes and depressions. Today, karst processes are still active in chalk and limestone areas with a thin cover of permeable sediments though which acid surface water can percolate to the ground water. In the palaeokarst areas, where karst processes have ceased, most if not all of the old subsurface channels and cavities are now infilled with sediments or are collapsed.

Dansk sammendrag

Jordfaldshuller, skorstene, og søer med underjordiske udløb er velkendt fra mange områder i Danmark, hvor højtliggende kalksten er dækket af jordlag, som tillader nedsivning af surt overfladevand og nedbør til grundvandet. Det har været diskuteret om jordfaldshuller kan være dannet ved bortsmeltning af dødis, men der har næppe hersket tvivl om at de øvrige fænomener skyldes karstprocesser. Råstofindvinding, anlægsarbejder og planlægningsopgaver i Aalborg-området i sidste halvdel af 1900tallet gav nye oplysninger om den topografiske udvikling af Rørdal-området og om de processer, der har været aktive. Efter inversionen af Sorgenfrei-Tornquist Zonen blev det hævede Aalborgområde udsat for omkring 60 millioner års mekanisk og kemisk erosion, som kulminerede i Kvartærtiden med erosion af gletsjere og smeltevand og udvikling af karstfænomener.

Rørdal-området blev et sprækket og brokket bjerg af kridt med skorstene, doliner og sandfyldte kanaler, og med nedskårne dale i kridtoverfladen. De kvartære lag oven på kridtet er generelt tynde og sammenhængen mellem den aktuelle topografi og kridtoverfladens relief er tydelig. Dybdalens forløb ligner en meandrerende flods, men den er styret af et sprækkesystem i kridtet. Den var først en snæver og dyb dal med stejle eller overhængende kridtvægge, hvis bund nåede mere end 50 m ned under den tilgrænsende kridtoverflade. En hurtigt strømmende flod eroderede bund og sider og aflejrede groft grus og store sten. Den overliggende opad finende sandserie indeholder lag af kalk-mudder og kridtbrokker, som antyder klimabetinget cyklicitet. Sen- og postglaciale flod- og søsedimenter afslutter lagserien. Den begravede Øster Sundby dal følger ligeledes et sprækkesystem i kridtet og er dannet ved en kombination af karstprocesser og floderosion. Kalkmudder med kridtklumper skred ned i den åbne dal i kridtet, som senere blev fyldt op med sand, der blev aflejret i en langsomt flydende flod eller en sø.

Karstdannelse foregår til stadighed, hvor betingelserne er til stede. Neokarst og palæokarst kan forekomme hvor som helst i de nordjyske kalkstensområder og kan efter omstændighederne have betydning ved anlægsarbejder og ved planlægning af grundvandsudnyttelse og -beskyttelse.

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