The Periglacial Subsurface Topography of the West Coast of Jutland, Denmark

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ABSTRACT


This article concentrates on the formation and nature of the former periglacial topography of the subsurface of the continental shelf of the coastal zone of west Jutland, with particular reference to examples on the island of Rømø.

The North European Wadden Sea area, one of the largest expanses of tidal flats in the world, is geomorphologically dynamic and the relationship between erosion and deposition is rather simple to explain. For example, the formation of barrier islands is due to the gently sloping offshore shelf upon which tidal surges create beach ridges which are then sculptured by storms, wind, longshore currents and tides. Behind the barrier islands, lagoons form. Tidal waters enter the lagoons through inlets. This special seascape modifies the way in which storm waves affect the coastline. The tides here create both flood and ebb deltas. Nevertheless, to understand the origin and geomorphogenesis of the current landscape of west Rømø, it is necessary to consider the following points: (1) The size and speed of sea-level fluctuations in the southern North Sea since the last glaciation (Weichselian). (2) The tidal conditions of the different post-glacial phases. (3) Former and existing climatic fluctuations. This also includes the consideration of the frequency of storms severe enough to produce temporary sea-level depths in excess of 1.5m in a region where the sea is normally very shallow. (4) The nature of the materials that are eroded and deposited; type, size, origin, quantity. and (5) The former channel networks: The variety of channel-forming processes is highlighted because of the occurrence of channels on both glaciated and non-glaciated continental shelves. A detailed understanding of channel stratigraphy, morphology and infill processes is therefore necessary and has to be related to the broader regional palaeo-environmental setting.

ADDITIONAL KEYWORDS: The Danish Wadden Sea, Rømø, River Vidda, Younger Dryas, Pingo, periglacial geomorphology.

INTRODUCTION

In the southern North Sea, the transition zone between the land and the sea has undergone many rapid changes. Many former landscapes might have been either totally destroyed or otherwise integrated into the existing landscape as relic landforms or relic landscapes in the present coastal scenery. This indicates that there have been important changes throughout recent geological time in the Wadden Sea boundary zone, and for this reason an investigation of the area is necessary (Figure 1). Geological borings may be able to throw light on the special history of sediment dynamics that belongs to this coastal region; either through revealing the sediment stratigraphy or allowing observations to be made on the alternation of facies. It may be possible to distinguish former reliefs of earlier, sub-surface Wadden seascapes by analyzing the different patterns of sand flats and tidal channels. Not least, relics of these former landscapes may be identified and mapped. Slowly the investigation will produce a picture of how this region evolved.

During the last glaciation, especially during the Late Glacial phase, the Wadden Sea area experienced at least 4 different types of coastal channel networks. The different types relate to the river systems that were operative at specific stages of the chronological sequence (Table 1). The 4 channel stages are based on research by Fisk (1944). Parameters are related to those of today. Mean annual temperature is given in degrees celsius (Woldstedt, 1954). Assumed former prevailing conditions are bracketed.

The different channel-forming processes relate directly to the different prevailing climates, whereas the formation of glaciated and non-glaciated continental shelves relates to different base-levels determined by different sea-levels (Table 1). The amount and nature of precipitation of the different climatic periods is a critical factor.

The analysis of glacial till and glaciofluvial deposits in the southern North Sea shelf sediments bears evidence of Quaternary climatic changes; when the Saale and Weichselian ice-sheets covered parts of the area. Changes in baseline (sea-level) are a natural consequence of significant climatic change. Cold climatic phases are characterized by marine regressions and a low mean sea-level, whereas warmer phases, such as those of the Eem and Holocene, are characterized by marine transgressions and a high mean sea-level.

During the Weichselian glaciation, the River Elbe discharged into the central North Sea (Jansen, Elbe Urstromtal 1976). During the Late Glacial period, the North Sea was a shallow, brackish sea covered by sea-ice. It was surrounded
by a flat, periglacial tundra dissected by the braided lower reaches of rivers that lay beyond the mouths of current central and northern European river systems.

As mean temperature and sea-level rose, the deposition of well-stratified sediments followed. During the Belling interstadial, there was some influence by the encroaching warmer seawater of the North Atlantic Ocean (LONG et al., 1988). During the Younger Dryas, the connection with the North Atlantic Ocean remained open and pack-ice was limited in extent.

PERIGLACIAL PROCESSES SINCE THE LAST GLACIATION

Under periglacial conditions, the constant temperature fluctuation around freezing point, when combined with a reasonable amount of precipitation throughout the year, is the principle cause of the important landscape-forming processes of permafrost and solifluction. Another important process is aeolian activity, in particular the transport and deposition of sand.

The action of both permafrost and solifluction was commonplace during the Pleniglacial A and the Younger Dryas when the temperature was low and precipitation high. During Pleniglacial B, the Oldest Dryas, and the Belling and Older Dryas, weak solifluction occurred, and although permafrost almost certainly occurred too, precipitation was nevertheless low, apart from during the Belling interstadial. By contrast, permafrost and solifluction were definitely absent during the Allerød and all subsequent post-glacial periods.

These different sets of physical conditions have been decisive in determining the predominant channel-forming processes. This is illustrated in Table 1 where the physical conditions determine the presence, nature and power of the main channel erosion processes; vertical erosion (VE) and lateral erosion (LE). They also determine the nature of sedimenta-
tion in the valleys and along coasts. During Pleniglacial A, vertical erosion by meltwater streams predominated in the main channels because the amount of precipitation was high. River loads were high, which is why both gravel and niveo-fluvial sediments were found in large quantities. A minor vertical erosion of channels occurred during the Belling, but it was not until the milder climates of the Allerød and Boreal that vertical erosion became predominant due to the absence of permafrost and the occurrence of higher precipitation amounts. The sediments tended to be fine-grained.

**PERMAFROST FEATURES—PATTERNED-GROUND LANDSCAPES**

Patterned-ground landscapes composed of polygonal fissures are to be found in places on the west coast of the island of Rømø, Jutland (Figure 3). The polygonal pattern is the result of tensile stress caused by frost that may have occurred sporadically during extremely cold climatic phases such as Pleniglacial B and during the Weichselian Glaciation when the North Sea was about 100m lower than at present. Table I presents the dominant periglacial activities of the different climatic periods, while Figure 2 presents geological facts on the bed of the River Vida, which is the main water course draining the coastal saltmarsh area and whose estuary opens into the main tidal inlet of Lister Dyb immediately south of Rømø. Figure 2 also presents hypothetical river profiles at different base levels for the High Glacial, Allerød and Boreal climatic periods.

Figure 1 presents important facts from the GRIP/PAGES that prove the occurrence of rapid climatic changes during the last interstadial. The analysis of oxygen isotopes and dust from the recently extracted Greenland Ice Core (15.07.93) has proved that temperature changes were dramatic, with regional changes of > 10°C within the space of 10-20 years (IGBP Newsletter, September 1993).

**RECENT LANDSCAPE OBSERVATIONS OF INTEREST**

Evidence of former permafrost conditions were observed during an analysis of Spot Satellite Images from June 1986. The satellite images were shot during a remote-sensing and geo-ecological study of the Danish part of the Wadden Sea coastal zone. The relic landscape features appeared to be ice
wedge polygons and pingos. This discovery adds to the information on both the interacting sedimentary processes in the tidal zone and the palaeo-geographic development of the local area which responded to climatic changes.

**RELIC PERIGLACIAL LANDSCAPES AND THERMOKARST ACTION**

As stated above, the terrestrial parts of the region experienced periglacial conditions during the Weichselian period and evidence is in the form of segregated ground-ice fabrics, ice-wedge structures (STREIF, 1985), and asymmetric valley slumps.

A relic ice wedge polygon network is exposed in places within the western coastal zone of Rømø. It is imprinted in the vast area of loose sand deposits that constitutes the outwash plains that formed west of the Main Stationary Line, central Jutland, during the Weichselian Glaciation maximum (Figure 3). As Table I shows, the mean temperature at that time was very low; estimated between −6°C and −8°C (PÆWE, 1966, p. 71). As the climate grew milder, marine transgressions occurred. Eventually, warmer Atlantic seawater reached the Danish Wadden Sea area; but tidal regimes are unknown.

The permafrost structures that formed were the result of thermokarst processes, which are dependent on rock type and thermal degradation. For the purpose of this explanation, the frozen ground of the colder climatic periods may be considered as hard as a solid rock surface, and the ice frozen within it as the dominant mineral. Should the temperature rise and remain above freezing-point for a long period, the erosion of the surface material will be similar to that which creates karst landscapes. This type of morphological development is described by Solovev (SVENSSON, 1970). In permafrost landscapes characterized by repetitive or continuous melting of ice wedges and ice polygons, it is first and foremost thermal attack on the surface that causes geomorphogenesis; through the sinking or collapse of surface material and structures to produce a rounded topography of gently undulating hillocks with hollows containing shallow pools of meltwater.

When permafrost persists for long periods, the sediment, if fine-grained, will form a furrowed landscape constituting a geometric network that will be submerged by any subsequent marine transgression. Besides this widespread relief formation, micro-terrain features occur; such as thermokarst niches with distinct inner walls reaching downwards as far as 8–10 m. As the steep walls consist mainly of saturated material, they are subjected to various kinds of mass movement (SVENSSON, 1970). One of the largest thermokarst landforms is the classic Pingo Valley in East Greenland (MÜLLER, 1959).

Pingos are produced by the contraction and expansion of water crystals trapped within permafrost. Pingos are ice-cov-ered during their formation, and the ice body contained within them, the hydrolaccolite, is formed from the water that has accumulated in a permafrost depression. Once filled with sediment, the lake and its surrounding surface may be subjected to freezing and a large volume of water will be trapped within the permafrost. Pingos may result from the pressure caused by the expansion of trapped groundwater when it freezes inside such a “closed system” (MÜLLER, 1959).

The development of a pingo valley will quicken when the mean temperature rises because warmer conditions accelerate thermokarst erosion and the weathering of the melting surface layer. The constant melting and erosion of ice wedges will produce a rounded undulating landscape in which meltwater and precipitation will collect in hollows. This continuous collection of surface water will also help to accelerate the thermokarst processes, especially where large pools or lakes have formed.

When the melting of the permafrost has been completed, the pingo will collapse to form a ring, inside of which a lake will form (Figures 4 and 6). This might be the geomorphological explanation for the existence of the circular Lake Lakolk, Rømø, whose banks are particularly stable . . . so much so, that the western rim has been used for several decades as an ideal site for the construction of summer houses at the coastal resort of Lakolk.

**SUMMARY AND POSTSCRIPT**

As indicated on SPOT Satellite images from June 1986, relic landform features appeared to be ice wedge polygons (Figure 3) giving further information on the interacting sedimentary processes in the tidal zone and the palaeo-geographic development of the local area as a response to climatic changes. When permafrost persists for long periods, the fine-grained material and outwash sands are re-worked by wind erosion and deposition under periglacial conditions to form a furrowed landscape constituting a geometric network which will be submerged by any subsequent marine transgression. The permafrost structures are a result of thermokarst processes including the formation of the largest landform type; the pingo (Figure 4).

Fritz Müller (1959) informs about the morphogenesis of pingos within the Mackenzie River delta in the Beaufort Sea. The climate has an annual mean temperature of minus 10.8°C, (January—30.6°C, August +14°C). He estimates the depth of the permafrost zone to reach between 110m–125m, in contrast to the 100m estimated by Brown (1956). The conditions could be very similar to those which have existed along the southern North Sea during the Late Glacial period. The permafrost zone is the permanently frozen zone as opposed to the active zone of non-frozen material; “the talik”, which is defined as either the zone of unfrozen soil between the active zone and the permafrost, or the unfrozen soil within the permafrost. The talik is of special interest when it exists as a network, woven through the permafrost zone. This type of talik is caused by a high hydrostatic potential which in this case could be due to the processes of mineral salts from the marine environment.

The geomorphological term “pingo” was first used by Por-
SILD (1928). According to MULLER (1959), the term derives from the eskimo “pingo sariņk”, which the indigenous people use to describe the characteristic conical landforms that rise to heights of up to 50m above the coastal plain; pingo means “up” and sariņk means “to push out from the ground”. The classic pingo (Figure 4) is often 50m in height, round to oval in shape, with a base circumference of 400–500m. The upper circumference is about 200m with a diameter of 100m.

How is it possible that such a formation as we see it at Lakolk, Rømø (Figure 6) can persist to the present day, taking into account the subsequent rise in sea-level and wave erosion of storm floods through time? The landform has been reasonably determined as dating from the Younger Dryas, about 10,000 years ago, when sea-level was 20m lower than today according to the sea-depth diagram (Figure 8) in Tøndermarsken, JACOBSEN (1993). The transgressions in the Early Atlantic, later in the Sub-Boreal, Sub-Atlantic and the present, have naturally attacked the pingo formation. However, the influx of sand through the priel system of Klibjerg Lå may have strengthened the formation to withstand erosion. Future studies will prove whether or not this is the case.

Attempts have been made to determine the age of Lake Lakolk (Lakolk Sø). As is detectable from the map (Figure 3), an exchange of water takes place with the North Sea through the priel system of Klibjerg Lå. Samples taken at a depth of 4.25m in the lake sediment underwent pollen analysis at the Danish Geological Survey (DGU). (Dr. Bent Odberg is thanked for undertaking this work). The datings point to the Sub-Boreal/Sub-Atlantic; the period when the Wadden Sea was created according to datings based on the peat layer below the Wadden Sea west of Ballum-Hjerpsted.

In order to make a precise assessment of the Lakolk Basin and the pingo, 8 borings were made in the autumn of 1994 along the road, Skinnevejen, near Hotel Lakolk. The borings were arranged along a north-south axis through the lake about 400m from the hotel. They had to be made with a machine bore, as the ground consists of a very compact layer of medium-sized sand grains mixed with Cardium shell fragments. Each borings was made to a depth of 4–5m. The ground level is 2.65-3.6m DNN, while the ramp to the west is situated at 3m DNN. The borings reached a saturated, fine-grained, blackish sand, from which samples were sent to the Nordisk Laboratorium, Røø Research Centre, for lumi-
The pingo ice-core is in direct contact with the underlying unfrozen sediment. Pinguos can also contain dilation ice and ice-wedge ice.

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