Chalk-glacitectonite, an important lithology in former glaciated terrains covering chalk and limestone bedrock

Stig A. Schack Pedersen, Peter Gravesen and Klaus Hinsby

A glacitectonite is defined as a brecciated sediment or a cataclastic sedimentary rock formed by glaciotectonic deformation (Pedersen 1988). The term tectonite was initially introduced by Sander (1912), mainly for tectonically brecciated metamorphic rocks in the Alps. In the classic work on cataclastic rocks, Higgins (1971) stated that the term covered all rocks with fabric displaying coordinated geometric features related to continuous flow during deformation.Therefore brecciated lithologies formed by glaciotectonic deformations can be termed tectonites. Banham (1977) suggested the prefix glaci- to clarify the relation to glacial dynamics. Furthermore, Pedersen (1988) suggested the application of the bedrock prefix. Thus, a chalk-glacitectonite is a brecciated chalk formed by shear deformation during a glacial advance over an exposed bedrock surface of chalk (Fig. 1). Hence the term describes a sedimentary rock in which the primary structures are so disturbed that they cannot be continuously traced, and a glacitectonic fabric developed as joint fractures or shear surfaces superimposed on the lithology.

The significance of recognising chalk-glacitectonite from chalk and limestone bedrock is the difference in textural properties, which is fundamental in geological modelling. In areas dominated by glaciotectonic complexes, which include thrust sheets of pre-glacial sedimentary rocks, the sheets are subject to shearing and dragged along the sole of the ice during its movement over the glaciotectonic complex. Due to truncation and shear-drag, the glacitectonite forms at the base of the deformational layer in a lodgement till. From the source area, which typically is a detachment anticline, the

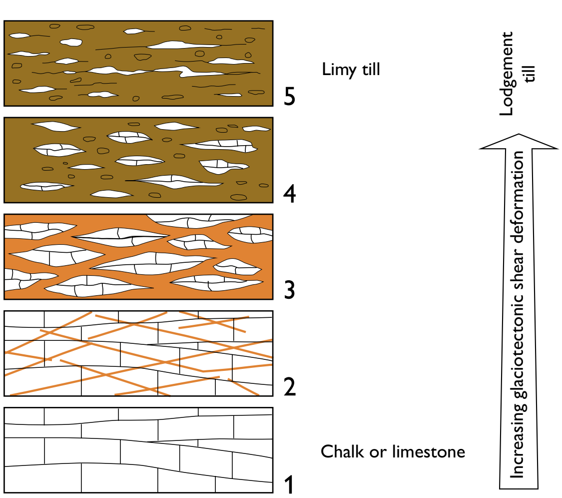

Fig. 1. Five steps in the progressive formation of chalk glacitectonite and limy till developed from bedrock of Danian limestone. The example illustrates the variation of deposits differentiated in the geological mapping of north-earstern Djursland, central Denmark (from Pedersen & Petersen 1997). **1**: Undisturbed Danian limestone occurring in the lower part of the coastal cliff at Sangstrup Klint. **2**: Anastomosing jointing is found in the limestone in the upper part of the cliff exposure. Note that the smallest angle between joints is located with a half-angle divide in the horizontal plan. This corresponds to a lateral stress in the foreland to an advancing ice margin. **3**: Clasts of chalk have been broken off and displaced in a fine-grained matrix; a chalk-glacitectonite is formed. **4**: During increased shearing the chalk clasts become more and more crushed with chalk pieces floating in a chalk-clay matrix. In-basinal erratics comprise clasts of Danian limestone and flint, ex-basinal erratics include basement stones (gneiss and granite), which start to appear in the glacitectonite derived from the overlying lodgement till. **5**: During the continuous translocation away from the source area the chalk-glacitectonite is transformed into limy till (chalk moraine), which may also be classified as a local till dominated by in-basinal clasts of chalk and flint.

Fig. 2. A one-metre thick chalk-glacitectonite exposed in a cliff section in the northern part of Stevns Klint displays shear banding of clayey till material with cataclasts of chalk and flint. The source area for the chalk is Danian limestone which occurs more than 500 m from the exposure.

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Fig. 3. The initial glaciotectonic deformation is a low-angle, anastomosing jointing, which is illustrated by an example of fractured Cretaceous chalk exposed in the northern part of the Stevns Klint cliff section.

Fig. 4. A chalk-glacitectonite developed with a limy matrix and rotated chalk clasts. Thin dark clayey shear bands illustrate the substantial amount of displacement within the rock type. Detail from the cliff section at Hvide Klint, south coast of Møn.

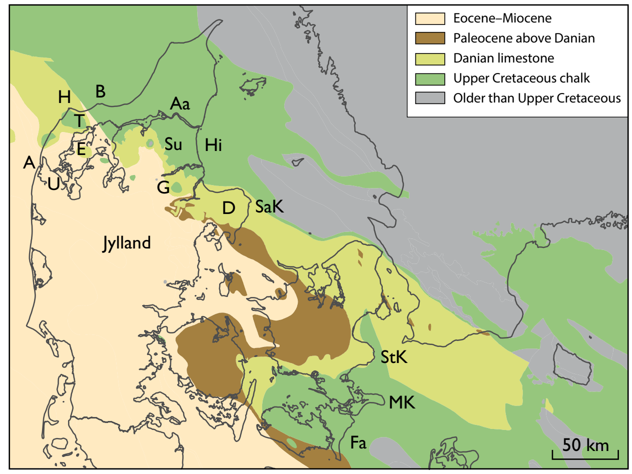


Fig. 5. Geological map showing the distribution of chalk and limestone in the bedrock of Denmark. Modified from Håkansson & Pedersen (1992). **H**: Hanstholm. **B**: Bulbjerg. **T**: Thisted. **A**: Agger. **E**: Erslev. **U**: Uglev. **Aa**: Aalborg. **Su**: Suldrup. **Hi**: Himmerland. **G**: Gassum. **D**: Djursland. **SaK**: Sangstrup Klint. **StK**: Stevns Klint. **MK**: Møns Klint. **Fa**: Falster.

glacitectonite thins out in the direction of transport from 1–2 m (Fig. 2) to a thin shear zone only a few centimetres thick over a distance of one to a few kilometres (Pedersen 1996). Moreover, brecciation of thrust sheets displaced by glacial thrusting occurs within glaciotectonic complexes. The deformation ranges from initially anastomosing jointing (Figs 1, 3) to brecciation with bedrock clasts in crushed bedrock matrix (Fig. 4). The tectonic breccia distributed from the décollement zone at the base to the truncating glacial unconformity at the top may additionally be termed glacitectonites. Here we describe the occurrence and identification of chalk-tectonites.

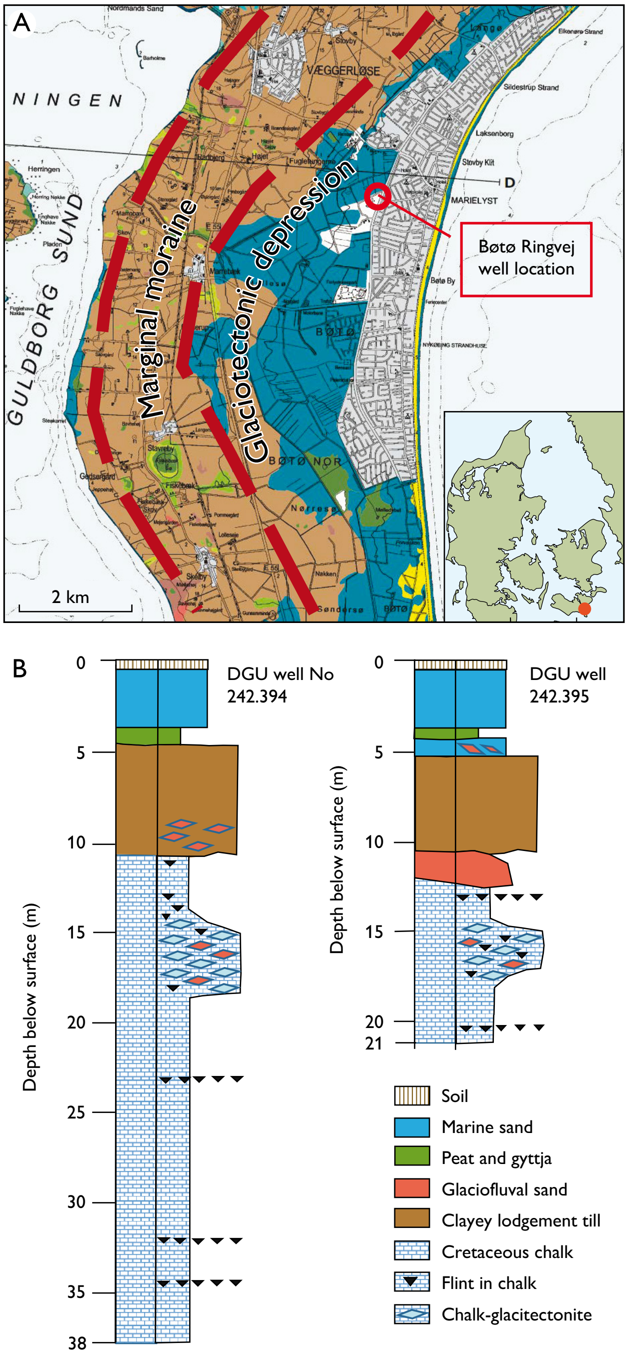
Occurrences of chalk-glacitectonites

The occurrences of chalk-glacitectonites are naturally related to the areas dominated by bedrock of chalk and limestone which in Denmark includes the eastern, north-eastern and northern regions (Fig. 5). Bedrock exposures are found at Møns Klint and Stevns Klint in eastern Denmark, Sangstrup Klint (NE Djursland) in central Denmark, in the chalk pits in Aalborg and in limestone pits in adjacent areas in NE Himmerland. Chalk-glacitectonites occur at these outcrops. Furthermore, the cliffs at Agger, Bulbjerg and Hanstholm in NW Jylland show outcrops of chalk and limestone. In addition, chalk that appears in the aureole of salt structures at, for example, Gassum, Suldrup, Batum, Erslev, Uglev and Thisted represent potential areas of glacitectonite occurrences.

The relation between the overburden of Quaternary deposits and the formation of glacitectonites is independent of the depth of the deposits. Thus a glacitectonite should always be expected between the top of the chalk and an overlying till. However, the till and glacitectonite may have been removed by erosion.

Identification of chalk-glacitectonites

There is a general understanding of the complexity of hydraulic properties related to areas with limestone and chalk located at shallow depths below Quaternary overburden (Downing *et al.* 1993). This is e.g. recognised in the greater Copenhagen area where groundwater flow paths are difficult to predict and the permeability in the glacially disturbed chalk layers of the København Kalk Formation and the underlying Danian bryozoan limestone are notably higher than in the underlying undisturbed limestones (Klitten *et al.* 2006; Bonnesen *et al.* 2009; Galsgaard *et al.* 2014). Research into the difficulty in predicting groundwater flow paths in shallow chalk aquifers is conduceted in an on-going EU project investigating



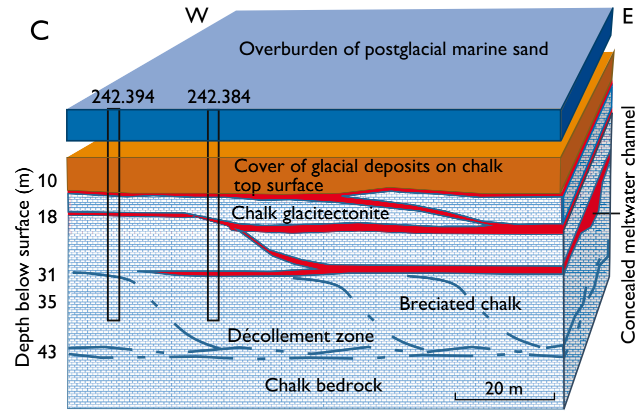


Fig. 6. The hydrogeological investigation site on Falster (the Bøtø case): **A**: geological map of the area demonstrating the glacial geological setting. **B**: two borehole logs demonstrating the lithological settings. **C**: block diagram illustrating the features and glacitectonites in the Upper Cretaceous beds.

subsurface water technologies to control saltwater intrusion (Zuurbier *et al.* 2016) on southern Falster, SE Denmark. The project focuses on the impact of climate change on the salinity of the groundwater resources (Rasmussen *et al.* 2013). At the study site the top surface of the Upper Cretaceous chalk is situated at about 10 m below the surface; it is overlain by a 5 m thick unit of glacial sediments and 5 m marine sand (Fig. 6). However, at a depth of 15 to 18 m there is a layer of chalk with gravel and pebbles of basement rocks. Based on an evaluation of data from other wells in the area, it became evident that another zone with basement gravel and pebbles existed even deeper at a level from 30 to 40 m below the surface. These findings have implications for the understanding of groundwater flow around the wells as the complexity of the hydraulic characteristics markedly changes the aquifer's behaviour. A model of the glacitectonite occurrence was established based on a glaciodynamic concept of the area (Fig. 6). A resistivity log from a nearby well supported the model predictions with a glacitectonite on top of the undisturbed chalk (Pedersen & Hinsby 2017). On-going studies indicate that in some parts of the chalk reservoir the transmissivity behaves as single porosity aquifers, while other parts behave like fractured dual porosity aquifers.

Fig. 7. An about one-metre thick bed of chalk-glacitectonite separates two till beds exposed at the north coast of Stevns, SE Denmark.

The position of glacitectonites in the glaciodynamic development of the Quaternary successions

The chalk-glacitectonites occur basically at two different positions in the glaciodynamic sequence: either as tectonic breccias on top of chalk bedrock, or as shear translocated chalk debris at the sole of a basal till. In the first position the chalk-glacitectonite may be difficult to distinguish from undeformed bedrock. This is especially the case with identification of lithologies from drill-hole samples. Identification requires that small impurities, basement pebbles etc., displaced into the fractures, are recognised and documented.

The second position of chalk-glacitectonites is easy to recognise due to the unmistakable variation in lithology (Pedersen & Gravesen 2016; Fig. 7). The bedrock material appears in a succession of glacial deposits. The typical glaciodynamic sequence contains a meltwater unit of clay/silt grading up into sand coarsening up into glaciofluvial gravel, eventually with a stone-bed of ice-contact deposits mirroring the proglacial environment. On top of the glaciofluvial sediments the basal till demonstrates the ice advance over the foreland. The till is divided into a basal deformational layer and an upper lodgement layer. Thus the chalk-glacitectonite, representing the deformational layer, documents the transition from the foreland setting to the subglacial setting.

Final remarks

Chalk-glacitectonites are an important lithology to be identified in glacial terrains with bedrock comprising chalk and limestone, i.e. where the pre-Quaternary surface consists of limestones and related carbonate rocks. Chalk-glacitectonites are divided into two main types based on the structural setting in a glaciotectonic complex: (1) brecciated sedimentary rocks deformed within the stratigraphic succession of the deformed bedrock, and (2) brecciated rock deformed below a basal till and shear-mixed into the lodgment till. The recognition of chalk-glacitectonites is important for geological and groundwater-flow modelling addressing hydrogeological and geotechnical problems. Due to the glacial deformation these sedimentary rocks are expected to show higher permeability than undeformed bedrock.

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen, Denmark. E-mail: *sasp@geus.dk*.