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GIS based map of glaciotectonic phenomena in Denmark

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An ArcView-based map of glaciotectonic phenomena in Denmark has facilitated correlation of glaciotectonic features with particular ice advances and enabled creation of an event-stratigraphic map. Well log data was used to map the intensity of glaciotectonic deformation on a large scale. The highest intensities of glaciotectonic deformation is seen in the regions underlain by pre-Quaternary marine clays and chalk or interglacial marine clays.

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INTRODUCTION

The work on the Glaciotectonic Map of Denmark started in 1992 when the Geological Survey of Denmark (from 1996 the Geological Survey of Denmark and Greenland — GEUS) initiated a project to collect data on glaciotectonic features. A number of publications ensued (Jakobsen and Pedersen, 1993; Pedersen, 1993, 1996, 2000; Pedersen and Jakobsen, 1993; Jakobsen *et al*., 1994; Klint and Pedersen, 1995; Jakobsen, 1996; Overgaard and Jakobsen, 2001; Jakobsen and Overgaard, 2002). Along side this national project, GEUS currently participates in the Central European Glaciotectonic Database and Map Project, which is a Geospatial Analysis of Glaciated Environments (GAGE) work group under the INQUA Commission on glaciation, with A. Ber as coordinator. The Glaciotectonic Map of Denmark uses slightly different categories to the Central European Glaciotectonic Map, as it was established before GEUS joined the Central European Glaciotectonic Database and Map Project.

Mapping of glaciotectonic features in Denmark has primarily been conducted as mapping of landforms based on morphological studies. A genetic classification and description of the morphology of the glacial landscape in Denmark was first undertaken by Milthers (1948). Later Smed (1962, 1982) published regional morphogenetic maps of Denmark. The objective of the Glaciotectonic Map of Denmark presented here is to compile current knowledge of the types and distribution of glaciotectonic landforms and complexes within one classification system. As it is a GIS-based map it will evolve as new insight and knowledge emerge, and it should be regarded as the "version 2002". Furthermore the distribution and intensity of glaciotectonism in Denmark correlates, on a large scale, to the lithology of the deposits which make up the pre-Quaternary surface.

GEOLOGICAL SETTING

The distribution of glaciotectonic features associated with the Scandinavian ice sheets shows a tripertite pattern (Aber and Lundqvist, 1988; Aber *et al*., 1989). An inner zone is characterised by erosion of the Fennoscandian basement shield. An intermediate zone is characterised by scattered, though widespread, glaciotectonic deformations. In an outer zone glaciotectonic phenomena are abundantly present in glacial deposits and in soft sedimentary bedrock. Denmark is mainly situated in the outer zone. The island of Bornholm, however, has characteristics of the intermediate zone. A large part of Bornholm has only a thin cover of glacial drift resting on crystalline basement and only minor glaciotectonic features may be observed.

During the Quaternary the Elsterian and Saalian glaciations covered the whole of Denmark. The maximum limit of the Weichselian Glaciation, passed through Jutland (Fig. 1b). The Weichselian landscape mainly displays relatively fresh glacial morphological features, whereas the land-

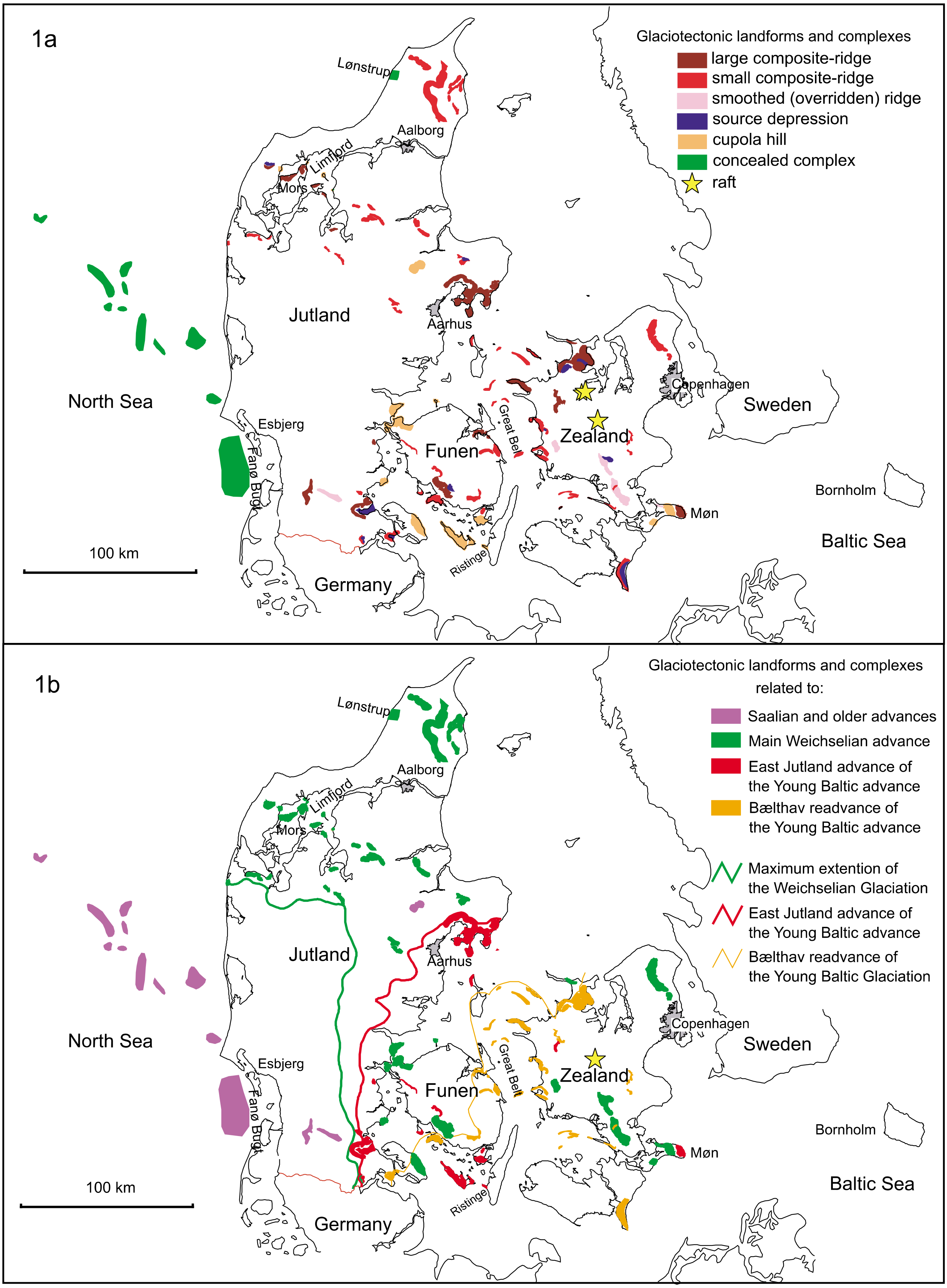

Fig. 1. **a** — Glaciotectonic Map of Denmark, showing the distribution of glaciotectonic landforms and features, locations mentioned in the text are indicated on the figure; **b** — event stratigraphic map of Denmark showing the distribution of glaciotectonic features belonging to ice advances of Saalian or older glaciations, the Main Weichselian advance, the East Jylland advance, and the Bælthav readvance

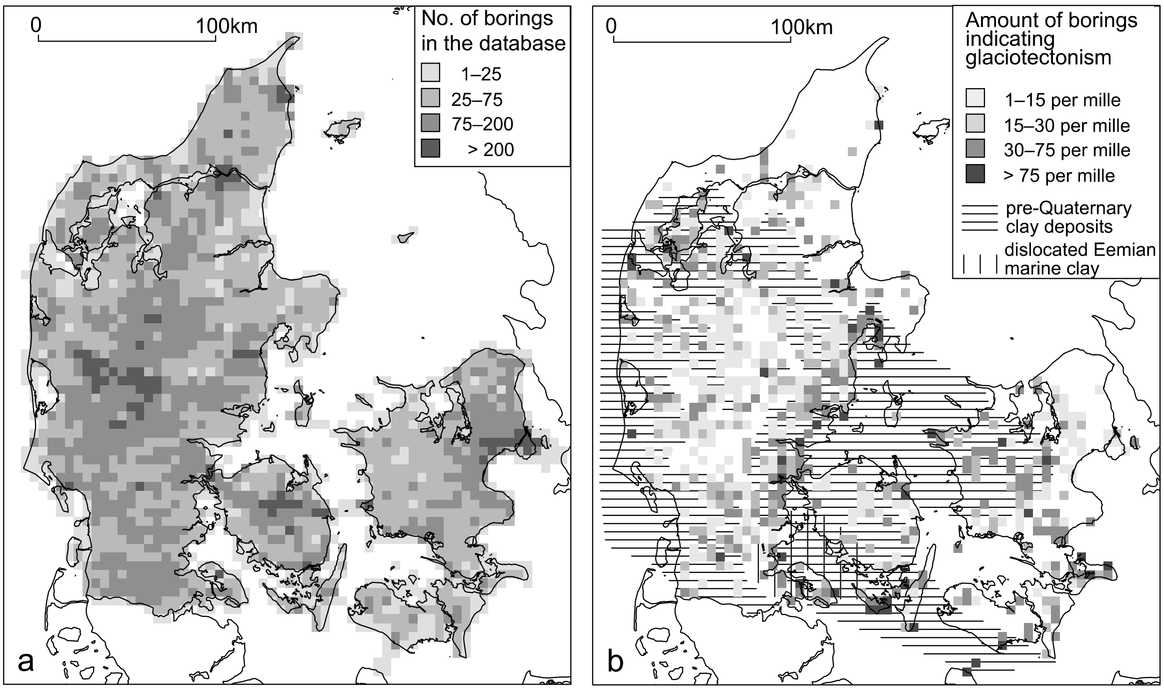

Fig. 2. a — distribution of wells in Denmark registered in the JUPITER well database; b — distribution and intensity of well records with indication of glaciotectonic deformation

Each grid cell (5 × 5 km) indicates the amount of wells with records of glaciotectonic deformation as ‰ of all wells within the grid cell (slightly revised from Jakobsen, 1996); the distribution of marine clayey deposits at the pre-Quaternary surface is depicted; the region where Eemian marine clayey deposits are known to be extensively dislocated is outlined

scape outside this has been modified by subaerial denudation over the last 125 000 years and deposition of Weichselian proglacial outwash deposits.

Many morphological features can be related to the Main Weichselian Glaciation, the Young Baltic Glaciation and readvances of the Young Baltic Glaciation. The Main Weichselian Glaciation advanced initially from the north and then turned clockwise to advance from the north-east (Houmark-Nielsen, 1987; Pedersen *et al*., 1988) and it is often referred to as the north-east advance. Recessional stages of this advance indicate readvances from the north-east. The Main Weichselian Glaciation is equivalent to the Frankfurt advance in northern Germany. The Young Baltic Glaciation advanced through the Baltic depression and reached the easternmost part of Jutland (Harder, 1908), hence the Danish name East Jylland advance (Houmark-Nielsen, 1987) (Fig. 1b). The East Jylland advance is equivalent to the Pomeranian advance in north Germany. During the deglaciation of the Young Baltic advance several readvances occurred, of which the Bælthav readvance is the most prominent (Fig. 1b). The Bælthav readvance is equivalent to the Fehmarn advance in north Germany (Stephan *et al*., 1983; Houmark-Nielsen, 1987).

DATA AND METHOD

A database was constructed in ArcView. The glaciotectonic features were digitised from 1:200 000 base maps. Data on glaciotectonic features are compiled in the database from published reports of glaciotectonic features observed in exposures, seismic surveys and as morphological interpretations. When the glaciotectonic complexes are described in exposures, the landscape behind the exposure has been interpreted according to the classification given below. The morphological interpretations from the literature have also been adjusted to the classification used for the glaciotectonic map. The submarine ridges in the Great Belt region were interpreted from topographic maps. The data compiled include the name of the complex, the type of complex, the age of deformation, and references.

Records from well logs often show evidence of glaciotectonic deformation. They might be recognised when pre-Quaternary bedrock overlies Quaternary drift or when stratigraphically well-defined units like interglacial deposits are repeated in a well log. The well log database Jupiter at the Geological Survey of Denmark and Greenland was used to extract information of glaciotectonic disturbances. The JUPITER database presently contains well log information from about 163 000 wells and 8‰ of the well records indicate glaciotectonic disturbance. In order to get a general view of the density of wells revealing glaciotectonic deformation a 5 × 5 km grid was used. For each grid cell the number of well records revealing glaciotectonic deformation are given in per mille of the total number of wells per grid cell (Fig. 2).

CLASSIFICATION OF GLACIOTECTONIC FEATURES

The classification scheme chosen for the Glaciotectonic Map of Denmark (Fig. 1a) is based on Aber (1988) and Aber *et al*. (1989) with some modifications.

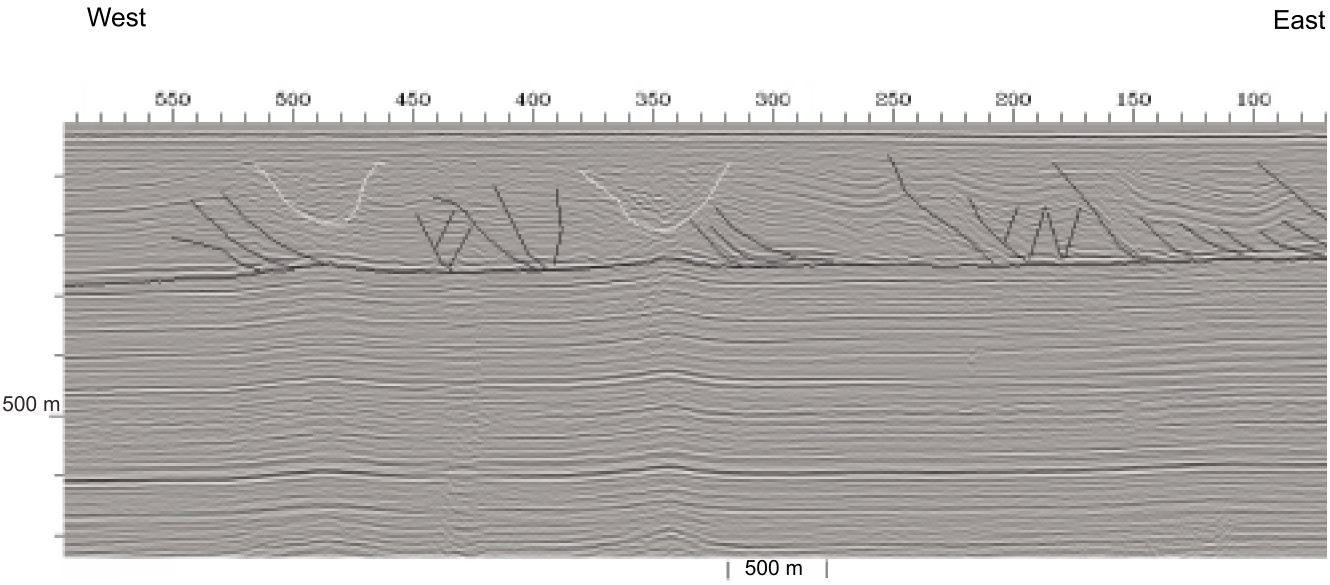

Fig. 3. Concealed glaciotectonic thrust complex in the southwestern North Sea, revealed in a seismic section

The reflector outlining the basal decollement surface is situated at a depth of about 350 m. Above the decollement surface Miocene deposits are thrusted in a extensive and in places complex thrust system. The thrust complex covers an area of at least 20 × 40 km. The thrust complex is concealed by glacial and post-glacial deposits and Quaternary valleys cut into the dislocated Miocene deposits (modified from Andersen *et al*., in prep.)

1. Large composite-ridges (up to 100–200 m in height) are a system of sub-parallel ridges, often arcuate in plan. They often include a substantial volume of contorted pre-Quaternary bedrock.

2. Small composite-ridges are also a system of subparallel ridges, often arcuate in plan. They are smaller (< 100 m in height) than the large composite-ridges and they are usually composed largely of unconsolidated Quaternary deposits.

3. A smoothed ridge is a composite-ridge, subsequently overridden and subglacially modified during glacier advance.

4. Source depressions are depressions related to composite ridges. The depressions represent the source area, from which deposits were pushed into the ridges. The depressions are often partly filled with younger glacial or post-glacial deposits.

5. Cupola-hills are smoothed domes to elongated drumlin-shape features (Smed, 1962). They have an internal structural composition similar to composite ridges, but they lack the transverse ridge morphology of ice-shoved hills. They generally have a till cover as they are substantially modified by overriding ice.

6. A concealed glaciotectonic complex is covered by younger sediments and does not express any glaciotectonic morphology. However, the structures may be very spectacular and result in highly deformed bedding and disturbed stratigraphy. Concealed glaciotectonic complexes may be recognised in cliff exposures, seismic records and in well logs.

7. Rafts (also called megablocks, floes or scales) are large allochthonous masses of dislocated bedrock. The rafts are more or less horizontal, slightly deformed, and often buried under or within thick masses of drift. There is usually no or only little morphological evidence of their presence. Hence they are very difficult to distinguish in the absence of well logs or exposures.

EVENT STRATIGRAPHY

The interplay between deformation and deposition plays an important role in kineto-stratigraphy (Berthelsen, 1978) and the concept of a glaciodynamic event and glaciodynamic sequence (Pedersen, 1993). As these concepts are generally used in modern Quaternary scientific work, the deformations observed are always related to glacial events (glaciations, ice advances or re-advances). When working with GIS tools several thematic maps might be created from the same base material. A map showing the stratigraphic framework of the glaciotectonic events is one of such thematic maps. The glaciotectonic features of Denmark have been stratigraphically related to glaciations and ice advances and they are outlined in four scenarios: Saalian or older ice advances, the Main Weichselian Glaciation, the Weichselian Young Baltic Glaciation and the Bælthav readvance of the Young Baltic Glaciation (Fig. 1b).

GLACIOTECTONIC DEFORMATIONS RECORDED IN WELLS

Well log information showing evidence of glaciotectonic deformation is widespread throughout Denmark and the distribution and regional intensity of glaciotectonic deformation recorded in wells has been presented previously (Jakobsen, 1996). The significance of the well records in terms of degree of deformation varies greatly, as such deformation might range from minor local rafts to large glaciotectonic complexes. The intensity of the recorded indications of glaciotectonism is, however, higher in certain areas (Fig. 2). In some of the high intensity areas thorough glaciotectonism is corroborated by records from outcrops and morphological evidences. Further discussion of this issue is given below.

DISTRIBUTION OF GLACIOTECTONICS

Outside the maximum extent of the Weichselian Glaciation only a few glaciotectonic features are seen in the landscape. In south-west Jutland a north-south trending ridge is interpreted as a large composite-ridge (Fig. 1a). Within the ridge system, dislocated Miocene clay has been reported (Rasmussen, 1966) as well as well log records of dislocated Holsteinian marine deposits (Andersen, 1963; Knudsen and Penny, 1987). Furthermore a less pronounced ridge trending east-west is interpreted as a smoothed ridge, based on well records. Apart from these glaciotectonic landforms there are several regions outside the Weichselian maximum extension with many well log records indicating glaciotectonic deformation and many exposures of Upper Miocene deposits have been recorded from clay pits, most of them being glaciotectonically deformed (Rasmussen, 1966). Furthermore, deformation of marine Holsteinian deposits is reported from the western part of Jutland near Esbjerg (Rasmussen, 1966; Andersen, 1967). Shallow seismic records from the North Sea show the presence of concealed large glaciotectonic thrust complexes (Huuse and Lykke-Andersen, 2000), which in some cases have dislocated Miocene deposits to a depth of 350 m (Fig. 3) (Andersen *et al*., in prep.).

In the northernmost part of Jutland, north of Aalborg, the pre-Quaternary deposits lie more than 100 m below the surface, and no glaciotectonic deformation of the pre-Quaternary deposits is seen in exposures or in well log records. Nevertheless, distinct composite ridges may be seen in the region (Jessen, 1936), originating from the Main Weichselian advance and readvances (Fredericia, 1988) (Fig. 1a, b). A large concealed glaciotectonic complex is exposed along the northwestern coastline at Lønstrup (Fig. 1a) (Jessen, 1931, 1936; Pedersen, 1987; Sadolin *et al*., 1997).

In the western part of the Limfjord, the intensity of glaciotectonic deformation recorded in well logs is very high (Fig. 2). This is in good agreement with the numerous glaciotectonic landforms (Fig. 1a) and coastal cliff exposures of glaciotectonic complexes (Fig. 4) described in this area (Gry, 1940, 1979; Håkansson and Sjørring, 1982; Pedersen and Petersen, 1988; Pedersen, 1993, 1996; Jakobsen *et al*., 1994; Klint and Pedersen, 1995). The deformation complexes in this region usually involve pre-Quaternary bedrock, deformed during Weichselian ice advances (Fig. 1b) and in many cases multiple deformation phases are recognised (Pedersen, 2000).

In the region between the Limfjord and Aarhus the overall morphological trend is north-west to south-east with several composite-ridges (Milthers, 1948; Smed, 1982) (Fig. 1a) belonging to a readvance of the main Weichselian advance (Houmark-Nielsen, 1987) (Fig. 1b). North-west of Aarhus a deformation complex of Saalian age has been described (Larsen *et al*., 1977; Kronborg *et al*., 1990) (Fig. 1b), which has a cupola hill morphology (Fig. 1a).

Fig. 4. Large composite-ridges in the Limfjord area, along the coast of the island Mors, where Eocene diatomite with ash layers are thrusted along with drift in thin-skinned thrust complexes. The cliff section in the far background is Hanklit cliff which rises 60 m above the sea, with the decollement surface situated 50 m below sea level (Klint and Pedersen, 1995)

Fig. 5. Aerial photo of the Ristinge peninsula looking east. The Ristinge peninsula is a classic example of a cupola hill (Smed, 1962), with a smooth, domed surface and a strongly tectonised interior. Close to 40 thrust sheets are exposed along the cliff section. The inclined thrust sheets are outlined by the shadows on the coastal cliff

Fig. 6. Coastal cliff in the central part of the Great Belt on Zealand, cutting through a small composite-ridge. The ridge belongs to one of the recessional stages of the Bælthav readvance (Fig. 1b)

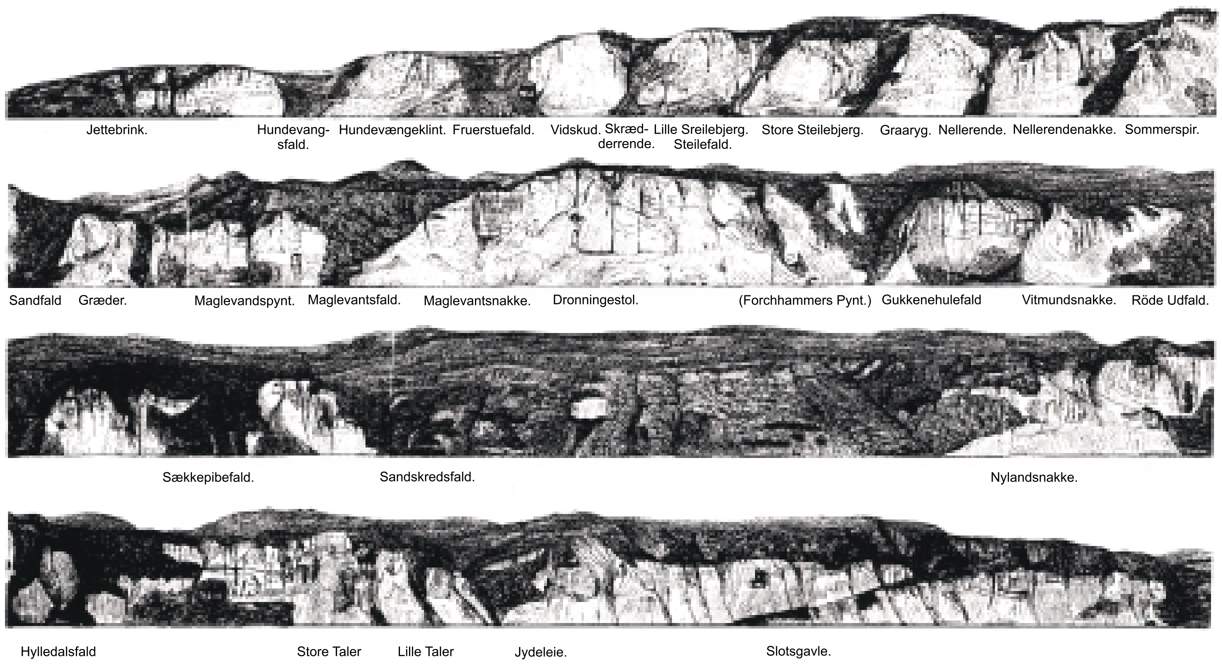

Fig. 7. The Møns Klint large composite-ridge seen from the east (reproduction of copper engraving by Puggaard, 1851)

The black lines within the chalk are flint layers outlining the deformations in the section. The section from Jettebrink to Maglevandsfald consists of imbricated thrust sheets, the section at the Dronningestol consists of an antiformal stack and at Jydeleje imbricate thrusts are seen. At Jydeleje thrusting from the east-north-east is superimposed upon the earlier imbricate thrusts (Pedersen, 2000)

Along the east coast of Jutland, from Aarhus to Germany, there is a very high intensity of glaciotectonic deformation recorded in well logs (Fig. 2), with the highest intensities east of the maximum extent of the Young Baltic Glaciation. Coastal cliff exposures in this region display extensive glaciotectonic deformation, in which Paleogene deposits, and in the southern part also Eemian marine deposits, are dislocated along with Quaternary drift (Jessen, 1930, 1935, 1945; Nordmann, 1958; Konradi, 1976; Rasmussen, 1977; Houmark-Nielsen, 1987; Pedersen and Petersen, 1997).

On the island of Funen a large variety of glaciotectonic landforms has been described (Smed, 1962) (Fig. 1). Well records of glaciotectonic deformation are more widespread on Funen, except in the north-east where several wells are situated within a composite ridge, with an associated source depression, and show glaciotectonically dislocated Palaeocene Kerteminde Marl (Jakobsen, 1993).

In the region south of Funen several glaciotectonic landforms dominate the region and the intensity of glaciotectonic deformations recorded in well logs is very high. In this region much of the recorded deformation involves dislocated Eemian marine deposits (Madsen, 1916; Konradi, 1976). The exposures in this region show that the interglacial marine deposits were deformed during several deformation phases during the Weichselian, and that the deformation is extensive (Berthelsen, 1979; Hansen, 1987, 1994). Subglacial processes are responsible for the predominantly cupola hill type of glaciotectonic landform in the region, with the peninsula Ristinge being a classic example of a cupola hill (Smed, 1962) (Fig. 5).

In the northwestern part of Zealand several large composite-ridges occur (Milthers, 1900, 1943; Petersen, 1973; Petersen and Buch, 1974), which are related to readvances of the Young Baltic Glaciation (Houmark-Nielsen, 1987) (Fig. 1a, b). In the Great Belt region several composite-ridges are seen along the Funen and Zealand coastal areas (Fig. 6) and several submarine ridges are seen within the Great Belt which can be correlated with the glaciotectonic landforms on land (Fig. 1b). The composite-ridge systems in the Great Belt region are related to minor readvances of the main Bælthav readvance (Houmark-Nielsen, 1987).

In the central part of Zealand occurrences of allochthonous rafts of Cretaceous chalk and Palaeocene Kerteminde Marl have been recorded (Hansen, 1930; Milthers, 1943) (Fig. 1a). Chalk rafts are also seen in the well log records of this region and they have presumably been transported at least 50 km from the south-east.

In the southern part of Zealand, there are elongated smooth ridges trending north-west to south-east (Fig. 1a). In this region an ice-push ridge system, partially developed with an associated source depression, is recorded (Jacobsen, 1981). Stratigraphically it is associated with a readvance from the north-east during the Main Weichselian Glaciation (Fig. 1b) and it was subsequently overridden by later ice advances.

The Copenhagen area shows a high intensity of glaciotectonism as recorded in well logs (Fig. 2). A closer inspection of the well logs reveal, however, that the majority of the pre-Quaternary units are locally derived limestone rafts, usually with a thickness of less than one metre. In temporary exposures due to construction work it was seen that the uppermost part of the Danian limestone is subglacially fractured and brecciated (Knudsen *et al*., 1995; Jakobsen and Klitten, 1999), limestone rafts being detached from the pre-Quaternary surface and incorporated in the glacial deposits.

On the eastern part of the island of Møn, south-east of Zealand, Møns Klint is the most impressive feature with chalk masses rising up to 130 m above the sea (Puggaard, 1851) (Fig. 7). Here, one of the largest glaciotectonic thrust complexes, with two deformation phases (Pedersen, 2000), is exposed in the cliff section where chalk and drift are dislocated and form a large composite ridge system inland from the cliff (Aber *et al*., 1989) (Fig. 1a). Further to the west on Møn cupola hills are seen in the glacial landscape, with glaciotectonic deformations exposed in the coastal cliffs (Berthelsen *et al*., 1977; Aber, 1979; Berthelsen, 1979; Houmark-Nielsen, 1994). Furthermore there is a very high intensity of glaciotectonic deformation recorded in wells (Fig. 2).

On a more general and large scale there seems to be a positive correlation between high intensity of glaciotectonism and the occurrence of pre-Quaternary marine clayey deposits at the pre-Quaternary surface (Fig. 2). The largest structural complexes, with well defined thrust systems, occur in these areas and include clayey pre-Quaternary deposits e.g. the Hanklit thrust complex (Klint and Pedersen, 1995) (Fig. 4), the concealed Fanø Bugt thrust complex (Andersen *et al*., in prep.) (Fig. 3). Furthermore, high intensities occur in regions with marine Eemian clay deposits in the southern part and south of Funen where all known Eemian marine deposits are dislocated (Konradi, 1976), some of them with multible deformation phases (Berthelsen, 1979; Hansen, 1987, 1994). This is in good agreement with the fact that clayey deposits are impermeable, which can facilitate elevated ground-water pressure imposed by a glacier, which again might facilitate the initiation of thrusting.

Areas where the Quaternary subsurface consist of chalk also show indications of a high intensity of glaciotectonism. Well log data show high intensities on Møn and south-west of Aalborg, where the pre-Quaternary deposits are chalk. On the island of Møn, one of the largest glaciotectonic thrust complexes is exposed at Møns Klint where chalk and drift are dislocated (Fig. 7) and form a large composite ridge system inland from the cliff. The chalk has a relatively small permeability (~ 8mD; Frykman, 2001) and might, as the clayey deposits, build up a high hydrostatic pressure which facilitates the initiation of thrusting. Within the chalk there are small clay layers which also might act as weakness planes and decollement surfaces.

CONCLUSIONS

The Glaciotectonic Map of Denmark summarises the present knowledge concerning types and locations of glaciotectonic complexes and landforms in Denmark.

The event stratigraphy of the glaciotectonic complexes is depicted, outlining the distribution of glaciotectonic complexes belonging to: Saalian or older ice advances, the Main Weichselian advance (the Frankfurt advance), the East Jylland advance (the Pomeranian advance), and the Bælthav advance (the Fehmarn advance).

There seems to be a positive correlation between high intensities of glaciotectonism and the distribution of lithologies in the Quaternary subsurface capable of building up high hydrostatic pressures and thus facilitating thrusting, such as pre-Quaternary marine clays and chalk, and interglacial marine clays.

The widespread occurrence of well log records indicating glaciotectonic deformation show that glaciotectonism occurs frequently and may be present in areas with no morphological indication of glaciotectonism; such concealed complexes may be very large. Thus, it is most likely that more glaciotectonic complexes are present in Denmark than are shown on the glaciotectonic map.

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