Fracture valleys in central Jylland – a neotectonic feature

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Geomorphological indications of tectonic activity in the Danish glacial landscape were pointed out already by Milthers (1916, 1948). He described a conspicuous system of N–S-trending, narrow valleys in central Jylland and interpreted them as fault-generated features (fracture valleys). The valleys occur in the area between Ulstrup and Hammel and in a smaller area near Skjød (Fig. 1). The most significant valley system is found near Hvorslev, and it is here referred to as the Hvorslev lineaments (Fig. 1).

An alternative interpretation of the genesis of the Hvorslev lineaments was presented by Hansen (1970). He argued that the N–S-trending valleys were formed by backward erosion from E–W-orientated erosional valleys in a former drainage system related to former higher groundwater table. However, Milther's interpretation that the valleys have a tectonic origin was later supported by Larsen & Kronborg (1994) and Torp (2001).

Former interpretations of the lineaments were primarily based on morphological studies and arguments. Recently the area with the Hvorslev lineaments was mapped as part of the systematical geological mapping of Denmark by the Geological Survey of Denmark and Greenland. The mapping of the surface lithology has added new information, and along with available seismic data it provides a framework for a well-founded interpretation of the elongated valleys, which is presented in this paper. We conclude that the fracture valleys are tectonic features, based on their morphology and because they are situated above a fault zone.

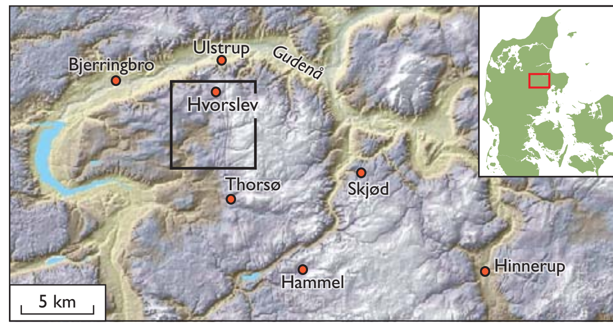

Fig. 1. Digital elevation model of the Hvorslev region with place names mentioned in the text. The focus area is the northern part of the valley system between Ulstrup and Hammel near Hvorslev. The difference in elevation from the valleys to the highest areas is around 90 m. The rectangle shows the location of Fig. 3, and the inset map of Denmark shows the location of the model.

Geological setting

The highest levels in the region are covered by a till unit, mainly a clayey till, but with patches of sandy till (Fig. 2). On

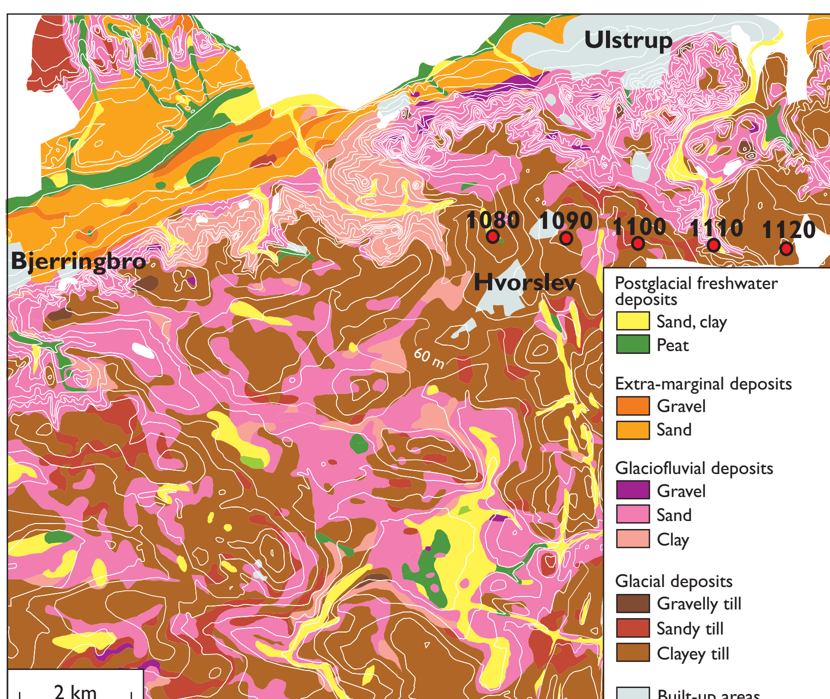

Fig. 2. Geological map of the Hvorslev area (extract from the digital map, see Jakobsen & Hermansen (2007). Contour interval 5 m. The location of the seismic line 73203 is shown with dots, which indicate the position of every 10th geophone.

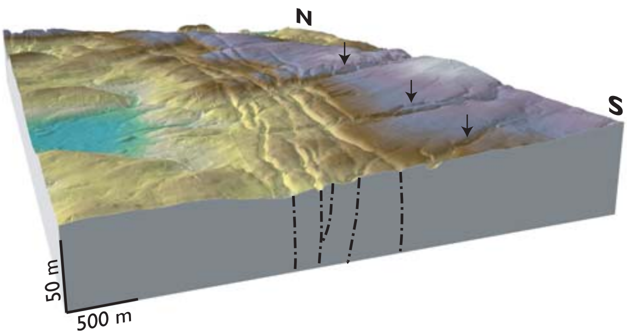

Fig. 3. Block diagram of the Hvorslev lineaments. The inferred faults are drawn on the frontal south-facing side of the block diagram. The arrows mark some of the erosional valleys.

the steep slopes of the Gudenå valley, glaciofluvial deposits are found below the till unit. Smaller outcrops of glaciofluvial sand appear in the till unit representing erosional windows in the till surface. Thus the uppermost lithostratigraphy in the region comprises a glaciofluvial unit overlain by a till. This succession is also recorded in boreholes in the region (Gravesen 1991). In most wells a clayey till is present at the top below which the glaciofluvial sand has a thickness of up to 20 m. The sand rests mainly on Oligocene mica clay and in a few places on Oligocene quartz sand.

The glaciofluvial unit is correlated with the Teppestrup Formation (Larsen *et al.* 1977; Pedersen & Petersen 1997), which was deposited on an outwash plain in front of the ice advancing from the north-east. The clayey till is interpreted as deposited by the ice advance from the north-east that reached the Main Stationary Line in Jylland. The till is correlated with the Mid Danish Till of Houmark-Nielsen (1987) and its correlative the Fårup Till of Kronborg *et al.* (1990), which date to around 23 000–21 000 years before present in this part of Denmark (Houmark-Nielsen & Kjær 2003).

Morphology

The parallel alignment of valleys in the Ulstrup–Hammel area suggests that they can be characterised as fracture valleys (Fig. 1). The length of the valley system between Ulstrup and Hammel is about 17 km. The most prominent part of the system is located at Hvorslev, where the valleys trend N–S with a spacing of 125 m to 250 m. The individual valleys are up to about 9 km long and 6 m deep. The width of the zone with fracture valleys is 800–1100 m wide (Figs 1, 3). The valleys cut hills and erosional valleys without any change of direction and are therefore not controlled by the general landscape morphology. Even one of the highest hills in the area is cut at the top by one of the valleys.

The individual valleys show an undulating floor in the longitudinal direction, occasionally with small depressions containing bogs and lakes. Most cross-sections of the individual valleys display a U-shaped morphology; in some places an asymmetrical shape is seen with a steep eastern slope and a gently dipping western slope.

The trends of the westernmost valleys south of Hvorslev are concave towards the west, curving around a depression which is filled with postglacial freshwater deposits. Downhill towards this depression, and almost perpendicular to the Hvorslev lineaments, a system of erosional valleys cuts into the surface with a gentle fall towards the west. The most prominent erosional valley system is first order valleys with branching second order valleys. The major first order valley cuts through the Hvorslev lineaments and a stream starts in its lower part where one of the N–S-trending valleys intersects the erosional valley. The second order valleys are not as deep as the first order valleys, and are cut by the Hvorslev lineaments. Some of them are hanging valleys on the sides of the N–S-trending valleys.

The E–W-trending erosional valleys were generated shortly before the Hvorslev lineaments. Most of them are dry valleys that formed at a time when surface drainage was greater than now, most likely shortly after deglaciation. Erosion within the first order valleys was so strong that it sustained the effect of the formation of the Hvorslev lineaments, which were apparently almost penecontemporaneous with the erosional valleys.

Seismic records

The seismic section 73203 shows an E–W cross-section across the Hvorslev lineaments south-east of Bjerringbro (Fig. 4). The features between geophone positions 1090 and 1112 are inter-

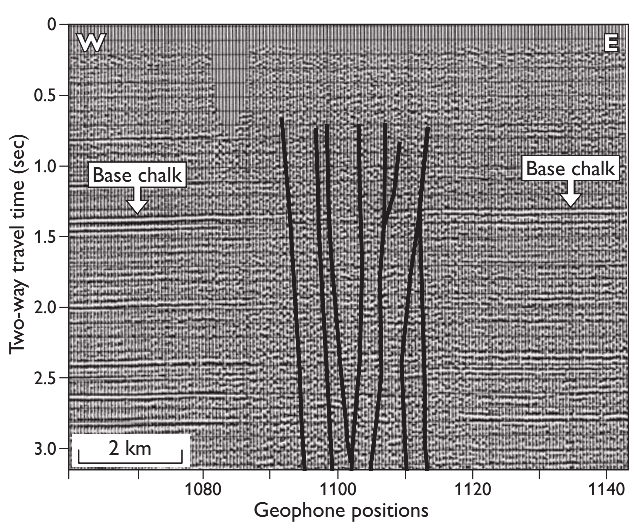

Fig. 4. Part of the seismic section 73203 in the Hvorslev region (for location see Fig. 2). The fault zone is situated between geophone positions 1090 and 1112, and the faults are marked with black lines. The height of the section corresponds to *c.* 3000 m.

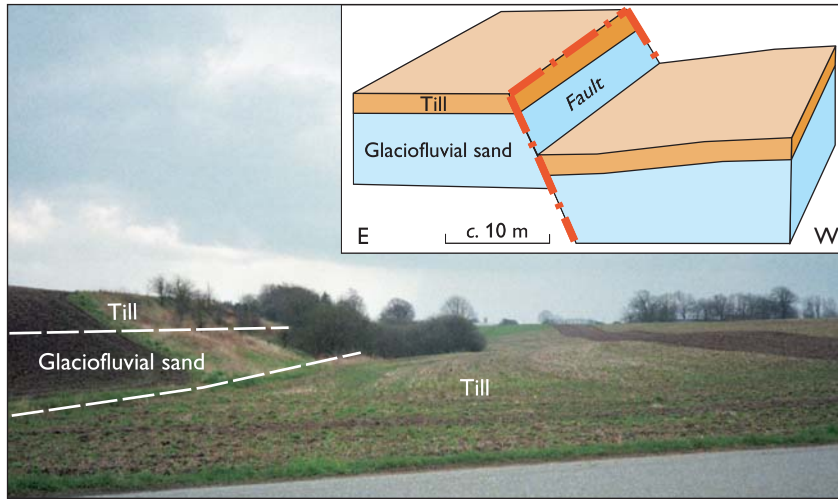

Fig 5. Photograph of one of the asymmetric valleys (viewed southwards). In the west-facing, steep slope, glaciofluvial sand is present below a clayey till. The height of the steep slope is 6 m. On the gently dipping slope clayey till drapes the surface down to the bottom of the valley. The inserted block diagram illustrates the interpretation of the valley as generated by faulting.

preted as faults. They occur over a zone *c.* 2.5 km wide situated directly below the Hvorslev lineaments. The overall structure is interpreted as a negative flower structure, where extension caused downfaulting of segments into a minor graben bounded by marginal faults. Across the inferred fault zone downfaulting towards W predominates. The largest normal fault displacement is 0.05 second at 1.4 second two-way travel time measured on the reflector of the Base chalk, which corresponds to a downthrow of *c.* 50 m at 1400 m depth. East of the fault zone the reflector is horizontal, and to the west it dips weakly towards W.

Indications of faulting at the surface

Most of the area around the Hvorslev lineaments is covered by till. Along the steepest slopes of the asymmetrical valleys, glaciofluvial sand is recorded below clayey till and on the gently dipping slopes clayey till drapes the surface all the way to the bottom of the valley (Fig. 5). Our interpretation of this distribution of the lithological units is that the upper till unit has been displaced by a normal fault down to the floor of the valley, whereby the glaciofluvial sand is exposed in the footwall (Fig. 5). The fault planes dip steeply W with a vertical displacement of *c.* 6 m.

Discussion

The correlation between the Hvorslev lineaments and the faults inferred from the seismic section indicates that the lineaments are surface traces of deep-seated faults. The Hvorslev lineaments strike N–S, which most likely corresponds to the orientation of the faults.

The Himmerland Graben is located to the north of the Hvorslev lineaments (Fig. 6; Vejbæk 1990). It is a deep-seated structure outlined by two major N–S-trending basement-attached faults, which is associated with the Sorgenfrei–Tornquist Zone (Fig. 6). Dextral strike-slip faulting in the Sorgenfrei–Tornquist Zone has resulted in E–W extension across the Himmerland Graben and led to normal faulting. The major tectonic events which caused syn-rift subsidence within the Himmerland Graben occurred during the Triassic and in the late Cretaceous.

The Hvorslev lineaments are situated south of the eastern fault of the Himmerland Graben and probably form a southern continuation of this fault. The indication of downthrow towards W within the Hvorslev lineaments corroborates this assumption. This implies that the fault activity in the Himmerland Graben continues to the south into the central part of Jylland.

The fault-related valleys formed after deposition of the youngest till in the area, because the till is cut by faults (Fig. 5). The youngest glaciation of the area was during the main Weichselian ice advance, during which the Mid Danish Till was deposited. Because the fracture valleys and the erosional valleys were formed at the same time, the faulting probably occurred shortly after the recession following the main Weichselian ice advance. The deglaciation of the region occurred around 21 000 years ago, which gives a maximum age for the formation of the fracture-valley system in central Jylland.

Two different causes can be suggested for the generation of the faults. Either the fault activity was a response to the glaciostatic rebound after the last deglaciation, or the faulting is related to the neotectonic extension responsible for the general graben subsidence in the Danish Basin. This question cannot be answered unambiguously on the basis of the available data, but the trend of the lineaments and graben faults are oblique to the general trend of the postglacial marine limit in the region (Mertz 1924) and hence are probably not linked to postglacial isostatic movements. The fact that the asymmetrical valleys show a downthrow towards W indicates that the valleys were formed in connection with tectonic activities in the Himmerland Graben. Moreover, the long length of the fault-related valleys also supports a tectonic origin.

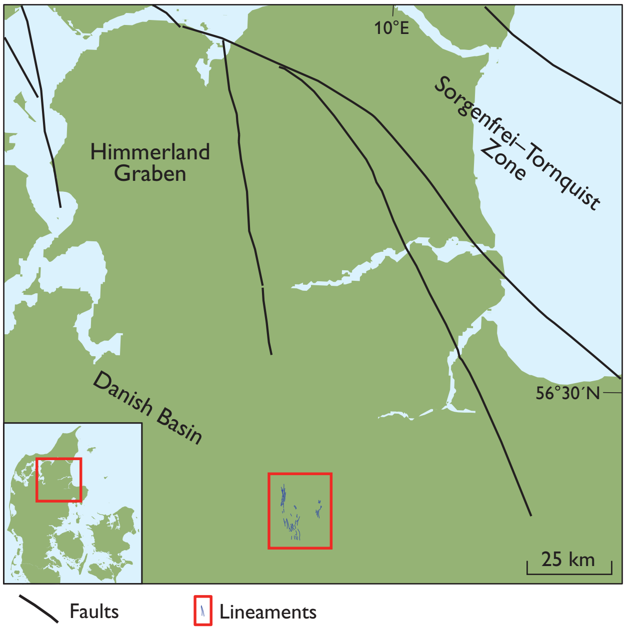

Fig. 6. Map of central Jylland showing the tectonic outline of the region. Fault-related valleys (red box) after Milthers (1916) are located in the continuation of the eastern boundary fault of the Himmerland Graben. Faults after Vejbæk (1990) and Sigmond (2002).

In addition to the fracture-valley system between Ulstrup and Hammel, another system of similar valleys occurs near Skjød, as pointed out by Milthers (1916, 1948). Fracture valleys are also found farther to the east near Hinnerup (Fig. 1; Czakó 1994). Morphologically they are similar to the Hvorslev lineaments, although they are more curved. Nevertheless, we suggest that they are fault-controlled.

Conclusions

We suggest that the system of long, straight and narrow valleys in central Jylland is related to a fault zone recognised on a seismic section across the valley system. Hence the valleys are regarded as surface traces of a deep-seated fault zone.

The faulting resulted in downfaulting of the surface-forming till along normal faults with downthrow mainly to W. The faulting occurred at a time when surface drainage was greater than at present, shortly after the last deglaciation that occurred around 21 000 years ago. The deformation is consequently a neotectonic activity. The fracture valleys indicate that the Himmerland Graben continues farther to the south than previously outlined, and that crustal deformation related to this tectonic feature took place during the late Quaternary. Fault-related valleys as described in this paper are geomorphological elements that characterise some parts of the Danish landscape. It is important to consider their potential implications for geological and hydrological models developed for the Quaternary deposits.

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