Miocene deposits at Silkeborg, Jylland, and their influence on hydrology

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A motorway was constructed in 2010–2016 through the suburbs of the city of Silkeborg (Fig. 1). The Danish Road Directorate wished to climate-proof the motorway against adverse future climate changes. The directorate collaborated with the Geological Survey of Denmark and Greenland (GEUS) to study the hydrological conditions. Studies of historical and projected climate-change-driven variations in groundwater levels in relation to urbanised hydrological fluxes were conducted by Kidmose *et al.* (2013, 2015). During the construction of the motorway, Miocene and Quaternary deposits were exposed in the slopes of the Gudenå valley and late-glacial glaciofluvial deposits were found in the valley floor. This paper focuses on the Miocene sediments and their influence on the local hydrological conditions.

At Silkeborg the Gudenå valley is *c.* 35 m deep (Fig. 1). The surrounding terrain is a till plain. In the slope of the valley, glaciofluvial sand is found below the till. Miocene deposits are found below the glaciofluvial sand. The floor of the Gudenå valley is covered by *c.* 15 m thick glaciofluvial deposits, which rest on Miocene deposits. In borehole no. DGU 87.907 49 m of Miocene deposits belonging to the Vejle Fjord Formation are recorded, consisting primarily of marine clay with minor occurrences of sandy deposits.

About 12 km south of Silkeborg lower Miocene deposits are seen in outcrops and boreholes (Fig. 2). Here the fluvial Addit Member of the Billund Formation (Rasmussen *at al.* 2010) is separated from the underlying marine Vejle Fjord Formation by a sharp erosional contact (Rasmussen 2014).
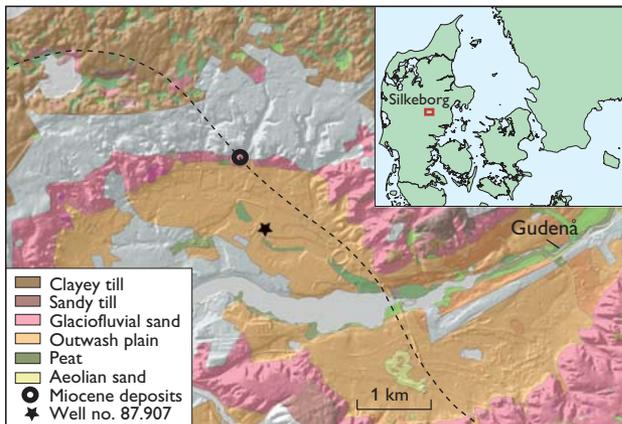
Fig. 1. Geological map of the Silkeborg area. Dashed line: motorway.
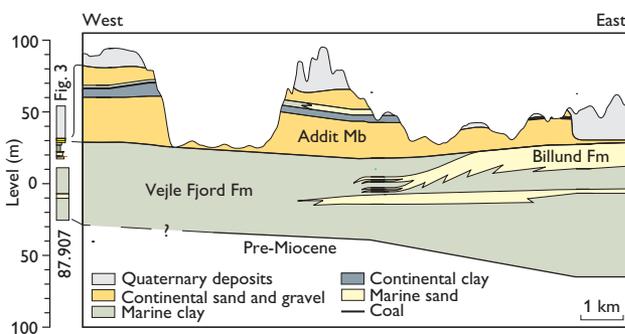
Fig. 2. East–west profile about 12 km south of Silkeborg (from Rasmussen 2014). A composite log from Silkeborg (Fig. 3) and data from well no. DGU 87.907 are shown to the left.
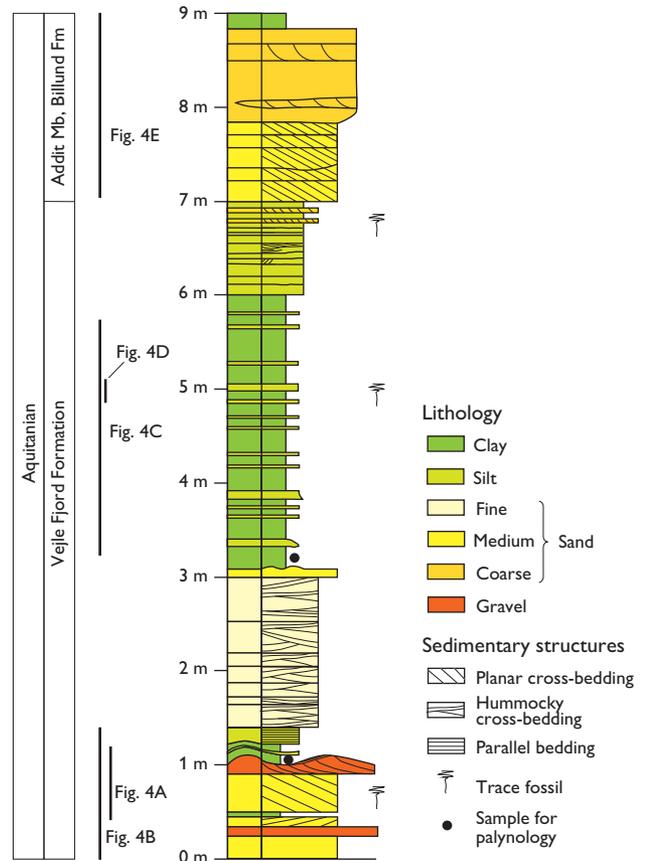
Fig. 3. Composite sedimentological log of the temporarily exposed Miocene deposits.
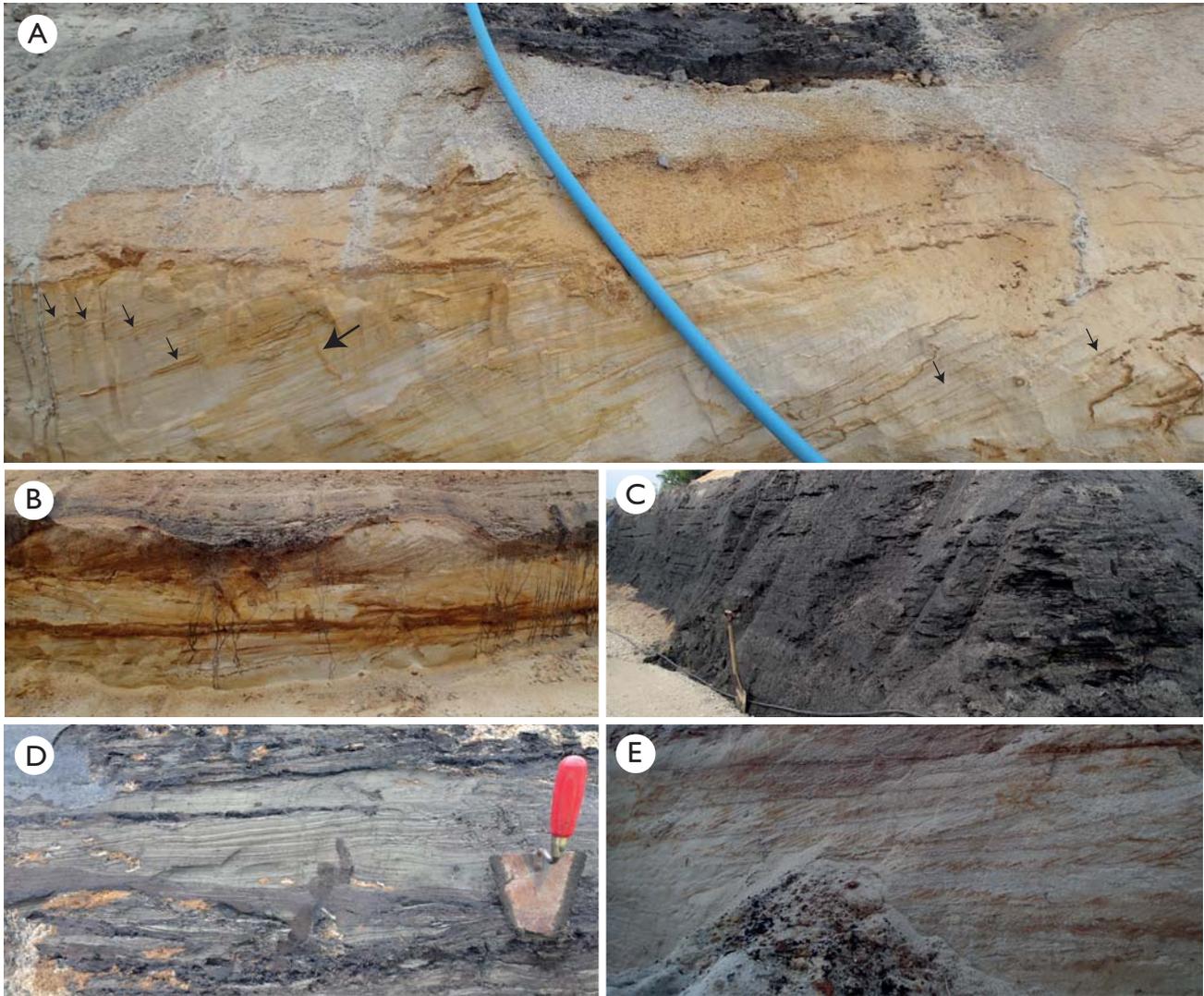
Fig. 4. Details of the Miocene deposits. The stratigraphic positions of the photos are indicated on Fig. 3. **A:** Cross-stratified medium grained sand. Double clay layers are indicated with small arrows. Trace fossil is indicated with larger arrow. **B**: Wave-formed, coarse grained ripples. **C**: Thick dark mud succession. **D**: Hummocky cross-stratification (HCS). **E**: Tabular co-sets of cross-stratified beds.

Sedimentology

The section along the motorway comprised 9 m of Miocene deposits (Fig. 3). The lower part is characterised by cross-stratified medium-grained sand, dipping *c.* 30° towards the north (Fig. 4A). A few trace fossils (*Skolithos*?) are seen. The cross-stratified sand is sharply overlain by wave-formed, coarse-grained ripples. The crests of the ripples strike SE–NW, and crest-to-crest spacing is in the range of 250 cm with amplitudes up to 35 cm (Fig. 4B). The ripples show tangential cross-bedding towards the SW. In a nearby exposure, tidal bundles form the base of the section. The presence of clay layers varies systematically and is commonly characterised by double clay layers (Fig. 4A). Dips of cross-bedding are both SW and NE. The coarse-grained ripples are in turn overlain by a dark brown mud. The mud is succeeded by silt and fine-grained sand, *c.* 1.5 m thick. Hummocky cross-stratifications (HCS) are common, especially in the upper part of the section. These are superimposed by 3 m of dark brown mud (Fig. 4C) showing a slight increase in grain size upwards where hummocky cross-stratified sands are common (Fig. 4D). A sharp boundary separates the mud from an overlying 2 m thick section of medium- to coarse-grained sand and gravel. This coarse-grained section is composed of tabular co-sets of cross-stratified beds dipping towards the south (Fig. 4E).
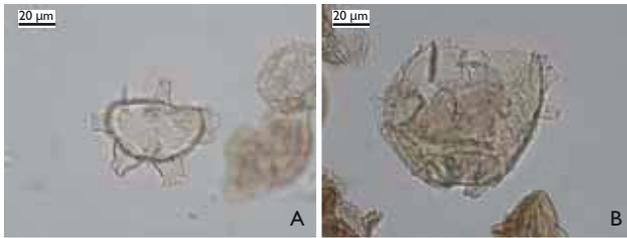
Fig. 5. **A**: *Homotryblium*? *additense*. **B**: *Chiropteridium galea*.

Bio- and chronostratigraphy and depositional environment

In order to confirm the Miocene age of the described succession and to achieve a more precise dating, two sediment samples were selected for palynological analysis. The stratigraphic positions of the samples are shown in Fig. 3.

One of the samples was almost barren, while the other contained a rich assemblage of organic particles dominated by bisaccate and non-saccate pollen. In addition, the sample contained a moderately rich and diverse dinoflagellate cyst (dinocyst) assemblage together with a few wood particles, cuticle, acritarchs and freshwater algae. This assemblage indicates a marine, inner neritic depositional environment with a high influx of freshwater (Tyson 1995).

The dinocyst assemblage is dominated by two species of the genus *Homotryblium*: *H.*? *additense* (Fig. 5A) and *H. plectilum*. Among several other dinocyst taxa, a single specimen of the stratigraphically important species *Chiropteridium galea* was found (Fig. 5B). The dinocyst assemblage refers the sample to the *Chiropteridium galea* Zone (Dybkjær & Piasecki 2010). This dinocyst zone is dated to the early Aquitanian (earliest Miocene) and the age of the sample is 23.03–22.36 Ma.

Palaeogeography

The sand and gravel in the lower part of the section were deposited during an overall regression of the Billund Formation in the early Miocene (Rasmussen *et al.* 2010). The gravel was probably originally deposited in a fluvial environment during the most extended regression. The cross-stratified sand in the lower part was formed in a marine bar that migrated landwards. The tidal bundles were formed by both ebb and flood currents, as indicated by the bipolar dips of cross-bedding, in an adjacent tidal inlet. The overlaying wave-formed, coarse-grained ripples were formed by marine reworking (Leckie 1988) of the coarse-grained fluvial sediments laid down during maximum regression and now forms a transgressive lag (Plint 1988). The depositional water depth of the coarse-grained ripples may lie in the range of 15 to 60 m (Leckie 1988) – most likely in the lower end as the sea-level changes during this part of the Miocene was *c.* 25 m (Miller *et al.* 2005). The strike of the crests of the coarse-grained rippels, SE–NW, indicates the trend of the palaeo-shoreline (Leckie 1988). The succeeding mud and HCS-dominated silt and fine-grained sand were deposited in slightly deeper water, in the offshore transition zone. The mud-dominated part with few intercalations of HCS's was deposited offshore near the storm wave base.

The assemblage of organic particles indicates that the sediment was deposited in a marine depositional setting near the coast. The two *Homotryblium* species further indicate that the palaeoenvironment was marine but probably with lowered salinity (Dybkjær 2004). These interpretations support the sedimentological interpretations and palaeogeographic maps for the earliest Miocene of Jylland, indicating that large river and delta systems existed, which transported large amounts of freshwater and sediment from the north to the middle part of Jylland (Rasmussen *et al.* 2010).
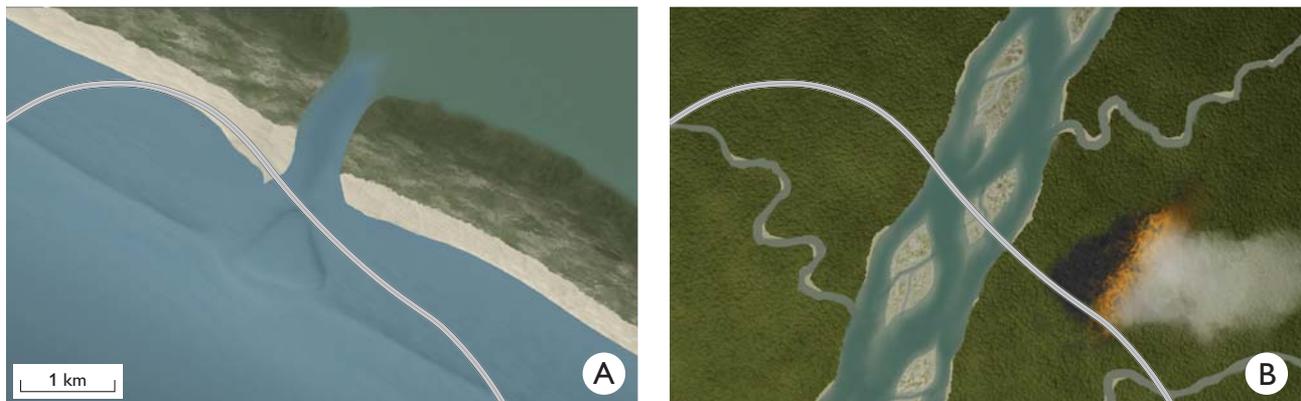
Fig. 6. Palaeogeographical reconstructions of the Silkeborg area. **A**: Early Aquitanian (earliest Miocene, Vejle Fjord Formation) tidal-dominated marine-barrier system. **B**: Late Aquitanian (Addit member, Billund Formation) fluvial environment. Grey line: motorway.
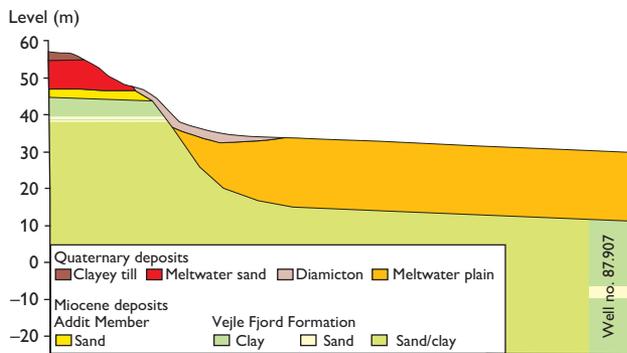
Fig. 7. Conceptual geological model along the motorway alignment.

The coarse-grained sand and gravel at the top of the studied succession, that sharply overlie the marine deposits, were deposited in a fluvial environment, the Addit Member of the Billund Formation (Rasmussen *et al.* 2010; Fig. 6). The dramatic change in the depositional environment was partly a result of an eustatic sea-level fall and partly a result of inversion of the Norwegian–Danish Basin (Rasmussen 2014). The latter resulted in marked incision in the middle and northern part of Jylland during the late Aquitanian. The Miocene succession in Silkeborg shows a strong resemblance to successions in boreholes and exposures about 12 km south of Silkeborg (Fig. 2).

Hydrology

On the floor of the Gudenå valley, wells with screens in the Miocene deposits have artesian hydraulic heads, whereas the hydraulic head in the overlying glaciofluvial sediments is in hydraulic contact with the Gudenå. This shows that the alternating Miocene layers of the Vejle Fjord Formation form a hydraulic barrier between deeper groundwater and the surficial glaciofluvial aquifer that is in contact with the motorway (Fig. 7).

In the higher terrain the measured hydraulic head in the Quaternary glaciofluvial sand is very different from the hydraulic head measured in the underlying Miocene deposits. This is because the 3 m thick Miocene mud unit (Fig. 4C) acts as a barrier. The Addit Member, however, is in hydraulic contact with the glaciofluvial sand (Fig. 7).

The hydraulic connection between the glaciofluvial sand found in the slopes of the valley and the glaciofluvial deposits in the valley floor is also affected by the Miocene deposits as the 3 m thick mud unit separates them.

The hydrogeological relations between the Miocene deposits and the Quaternary deposits illustrate the importance of applying detailed field-site geological evidence to get an impression of the local groundwater flow.

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