Buried tunnel valleys in Denmark and their impact on the geological architecture of the subsurface

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Buried valleys are elongate erosional structures in the Danish subsurface now partly or completely filled and covered with younger sediments. The majority was formed by meltwater underneath ice sheets. The number of buried-valley structures in Denmark is large, and because the valley-infill in many areas hosts significant groundwater resources, knowledge of them and their formation is important. This was the starting point of the buried-valley mapping project, which was initiated in the late 1990s and continued until the end of 2015 (Sandersen & Jørgensen 2016). This project became part of the National Groundwater Mapping Programme which was set up with the purpose of mapping the groundwater resources within areas of specific groundwater interest (Thomsen *et al.* 2004). The areas of specific groundwater interest encompass existing catchment areas and cover around 40% of the country. Within these areas, high-density electromagnetic surveys have typically been performed together with exploration drilling and supplementary geophysical measurements. The mapping of the buried valleys has been based on these newly collected data as well as existing data in the national databases. In some instances, it has also been possible to map buried valleys in less data-dense areas outside the surveyed areas, mainly on the basis of borehole data.

The groundwater resource and its vulnerability have been important in the mapping of the buried valleys. The valleys also constitute an important part of the subsurface geological architecture, and it is obvious that a thorough knowledge of them is critical for the general understand-

Fig. 1. Mapped buried valleys in Denmark as of end 2015. The mapped valleys are shown as dark grey polygons and the TEM-surveyed areas are shown in light grey. The Haderslev area covered by Fig. 2 is highlighted with a red rectangle.

ing of the geology of the uppermost 100–400 m of the Danish subsurface. In this paper we present an overview of the buried-valley mapping project and an updated buried-valley map (Fig. 1).

Mapping of the buried-valley structures

All relevant geophysical and lithological data from primarily onshore areas have been used to map and describe the buried valleys. The transient electromagnetic method (TEM; Sørensen & Auken 2004) has proven especially valuable because such surveys usually provide a spatially dense data grid that can be combined with borehole data and other geophysical data (Jørgensen & Sandersen 2009). The valleys have been delineated from an integrated interpretation of the data, and their outlines and extensions within the mapped areas were drawn as polygons using simple signatures (Fig. 2). In order to obtain a high degree of certainty and objectivity in the delineation of the valleys, the lateral extent and orientation of the valleys were to be unambiguously expressed in the data. Therefore, no interpolations outside and between the local mapped areas have been made, and accordingly the map in Fig. 1 represents the minimum occurrence of buried valleys in Denmark rather than their true distribution and density. The advantage of this approach is an un-biased picture of the valleys based on the data available and not on secondary data and assumptions. In addition to this, the approach gives an opportunity to get a valuable insight into the formation history and age of the valleys.

The highest valley densities are found in areas where TEM data have been collected and the conditions for the chosen methods were ideal. The map in Fig. 1 only shows the location of the valley structures where they can be outlined by interpretation of the data. The grey areas indicate the areas where TEM data are available and many additional buried valleys must be expected outside these areas.

Although many buried valleys have been mapped, even more are expected to exist, because not all valleys can be identified with the used methods. For instance, very narrow valleys or channels can be difficult to resolve, and valleys with low lithological and/or electrical resistivity contrast compared to the surroundings can be difficult to outline.

Occurrence and subsurface architecture

The depth of the mapped buried valleys is variable, with the deepest structures sometimes exceeding 400 m. Their width is generally between 0.5 and 1.5 km, but widths of more than 3.5 km occur. Their lengths are difficult to assess because many of the surveyed areas are small, but some exceed 25–30 km. They commonly terminate abruptly and are highly irregular, with depressions and thresholds along the valley floors. Buried valleys appear both as single valleys and in dense cross-cutting networks. Their internal structure is typically complex due to repeated erosional and depositional events.

The majority of the buried valleys were formed during the Pleistocene as tunnel valleys eroded by high-pressure meltwater underneath the ice sheets (Jørgensen & Sandersen 2006). With respect to morphology and dimensions,

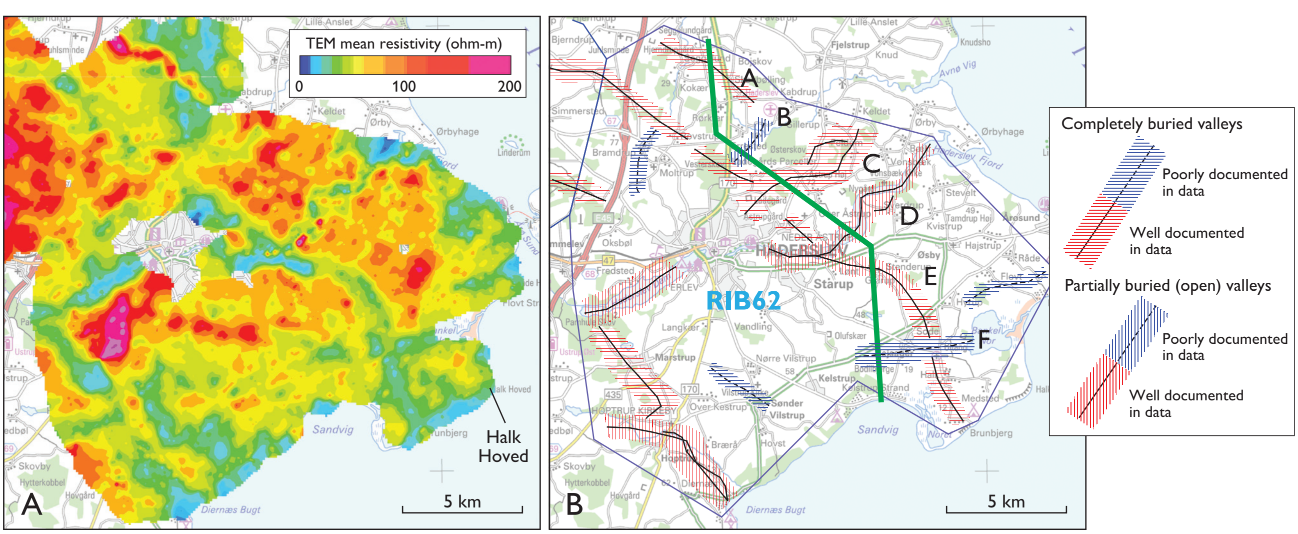

Fig. 2. Survey area RIB62 Haderslev, south-western Denmark (outlined by blue polygon). **A:** Airborne TEM resistivity data (30–35 m b.s.l.). **B**: Same map window without TEM data but with interpreted buried valleys shown as hatched polygons. Green line shows location of cross-section in Fig. 3. Tunnel valleys marked A to F corresponds to valleys shown in Fig. 3.

the mapped buried valleys are comparable with open tunnel valleys found in the present-day Danish landscape. The water seemed to flow in relatively small channels on the floors of the tunnel valleys, which gradually became ice-filled. Tunnel valleys were often re-used during repeated cycles of glaciations, producing separate valley generations and multiple internal cut-and-fill structures. The ages of individual valleys are usually difficult to assess because of the repeated erosion and the general lack of precise age determinations, but it is assumed that tunnel-valley formation has been a common phenomenon throughout the Quaternary. Relative dating of the individual generations can commonly be performed, based on the lithology of the infill and on cross-cutting relationships in the subsurface. In rare cases mapped valley generations can be related to specific ice advances (i.e. Sandersen *et al.* 2009).

Even when taking the irregular distribution of the survey areas into consideration, the mapped valleys show signs of a preferred geographical distribution (Fig. 1). For instance, the highest densities of buried tunnel valleys are typically found in areas where thick successions of Palaeogene clays occur close to the surface, and the lowest densities typically where coarse-grained sediments dominate the near-surface part of the succession. The tunnel-valley formation is thus more likely to occur in areas with impermeable substrata because the high subglacial water pressures favour channelised erosion and tunnel-valley formation. However, in areas where the permeable sediments underneath the glacier were able to drain parts of the meltwater, no or only few valleys were formed. Apparently, an important factor is whether drainage through the substrata can be sufficient to prevent tunnel-valley formation (Sandersen & Jørgensen 2012).

A map of the Pre-Quaternary surface in Denmark by Binzer & Stockmarr (1994) reveals a deep valley-network eroded into the Pre-Quaternary surface. This map was primarily based on on-shore borehole data. The interpolation of the Pre-Quaternary surface was highly interpretative and performed throughout the Danish area under the presumption that the structures were sub-aerially eroded valleys and would therefore not contain isolated depressions and blind endings. It is tempting to compare the map by Binzer & Stockmarr with the map in Fig. 1, because some of the valley structures coincide. However, the buried-valley map in Fig. 1 is made differently and is not a map of the Pre-Quaternary surface. The map shows the occurrence of buried-valley structures regardless of whether they penetrate the Pre-Quaternary surface or not and hence the map is not limited to showing valleys in the Pre-Quaternary surface, and isolated depressions and blind endings have not been avoided when making the map.

A total length of 5600 km of buried valleys has been found within the TEM-mapped areas in Denmark (*c.* 17 000 km^2) and in selected adjoining areas (*c.* 1700 km^2); in total *c.* 18 700 km^2. If the average width of the valleys is 1 km (see Jørgensen & Sandersen 2006) the valleys cover 5600 km^2.

This means that in *c.* 30 % of the mapped area, erosion of the valleys has significantly changed the lithology and architecture of the subsurface. An example where mapped buried tunnel valleys dominate *c.* one third of the area is illustrated in Fig. 2. The TEM data show that tunnel valleys in this case have been eroded through the Quaternary and Miocene deposits and in some instances deeply into the underlying Palaeogene clays (Fig. 3).

The cross-section in Fig. 3 illustrates the influence the buried tunnel valleys have on the subsurface architecture. The Pre-Quaternary succession of Miocene sands and clays have been removed and replaced with sandy and clayey infill of Quaternary age. Figure 2A shows a horizontal slice (30–35 m b.s.l.) approximately through the central part of the Miocene succession. The red to orange colours show high resistivities corresponding to predominantly sandy sediments. The buried tunnel valleys are seen as both green elongate structures where the green colours represent predominantly clayey sediments and red elongate structures consisting of predominantly sand. As seen on the cross-sec-

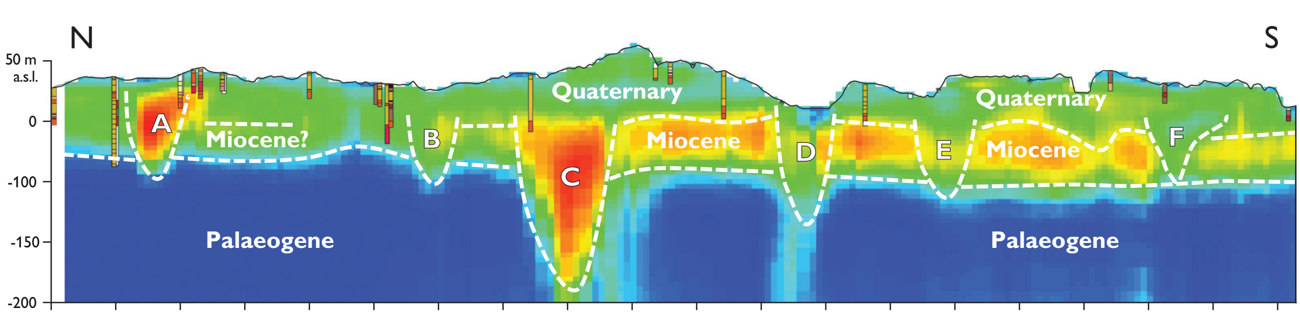

Fig. 3. Cross-section of tunnel valleys A to F in survey area RIB62 Haderslev based on 3D-gridded airborne TEM resistivity data. Vertical exaggeration 15 times. Vertical rods are boreholes included in the national Jupiter database. See Fig. 2 for resistivity legend and location.

tion (Fig. 3) valley erosions reach down to the Palaeogene clays, seen as very low resistivities in the TEM data (blue colours).

The valleys show dominant orientations of NE–SW and SE–NW, respectively (Fig. 2B). The valley infill is of Quaternary age, but the precise age of the valleys is not known. However, relative ages of the individual valley generations can be inferred from cross-cutting relationships, the terrain and the character of the overlying sediments. The buried tunnel valley D in Fig. 2B, for example, is partially buried and is expected to extend all the way to the terrain surface because it coincides with an open tunnel valley in the present-day terrain (Smed 1982). The valley obviously belongs to a young generation. The deep valley C, however, is completely buried by predominantly clay tills and apparently not reaching the surface. This valley is therefore most likely older than the adjacent valley D to the south-east. The valley E and its extension to the north-west appear to be cut by the valleys C, D and F, thus suggesting an older generation. The southern part of valley E is quite easily seen in the TEM-data from *c*. 30 to 100 m b.s.l., whereas the levels above the succession are dominated by low-resistivity clays apparently not belonging to the valley. At the nearby coastal cliff of Halk Hoved in the south-easternmost part of the area (Fig. 2), a large glaciotectonic complex formed by proglacial deformation of the NE-advance in Late Weichselian has been described by Madsen & Piotrowski (2012). This thrust-fault complex consists of stacked layers of tills and glaciofluvial sediments deposited during the Warthe glaciation in Late Saalian. According to Madsen & Piotrowski (2012), the decollement layer of the glaciotectonic complex is *c*. 20 m b.s.l. which is apparently above the level of the buried valley E farther to the south-west. The uppermost parts of the buried tunnel valley may have been deformed by the glaciotectonic event in Late Weichselian, but obviously the formation of the deep tunnel valley can be related to an earlier event.

Conclusions and perspectives

If the rough calculation above is extrapolated to cover all of the Danish onshore area, a plausible total length of buried valleys of around 13 000 km emerges. Despite the uncertainty of this calculation, the figure calls for attention when interpreting the subsurface geology of areas not at present covered by dense geophysical datasets. Mapping outside the areas with specific groundwater interests is at present sparse, but the general knowledge obtained from the mapping project can be used in areas not yet covered by dense datasets. Along with the continuously increasing knowledge of the occurrence and the origin of buried tunnel valleys in Denmark, the importance of their structures has become more and more evident. The importance for assessments of groundwater resources and their vulnerability is straightforward (i.e. Andersen *et al*. 2013; Sandersen & Jørgensen 2003), and the necessity of making the buried-valley structures play a significant role in the geological interpretations of Quaternary sedimentary sequences is unquestionable.

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