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Buried Quaternary valleys in western Denmark—occurrence and inferred implications for groundwater resources and vulnerability

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Abstract

Numerous geophysical investigations in the western part of onshore Denmark constitute the basis for a delineation of buried Quaternary valleys. The geophysical methods comprise primarily Transient ElectroMagnetic (TEM) and reflection seismic surveys, and the geophysical data have been combined with lithological data from boreholes. Buried valleys appear both as single valleys and in dense networks. The internal structure of the valleys is typically complex due to repeated erosional and depositional events. Buried valleys are common geological structures in the region and they influence the distribution of Tertiary and Quaternary sediments greatly. A large number of buried valleys in the region contain important aquifers, whose natural protection varies depending on thickness and character of overlying clay layers. Many of these aquifers are deep-seated and well protected, but because of the prevailing heterogeneity of the valley infill and the erosional incisions created by different valley generations, preferential flow paths for downward transport of contaminated water from shallow aquifers may occur.

Keywords: Buried Quaternary valleys; Geophysical surveys; TEM; Groundwater resources; Vulnerability

1. Introduction

A large part of the water supply in western Denmark (Fig. 1) is based on groundwater abstraction from sand and gravel in buried Quaternary valleys. Because the valley infill may contain groundwater resources as well as act as potential pathways for contaminants from the surface to deeper reservoirs, buried valleys have gained increased attention in recent years. As buried valleys are presumed to have a high influence on the occurrence of groundwater resources and groundwater flow paths, a thorough understanding of the occurrence and architecture of the buried valleys is necessary. Especially when attempting to describe the relations between the aquifers, the groundwater flow and the groundwater vulnerability.

During the past 10–15 years, the waterworks and the counties of Jutland and Funen have carried out numerous hydrogeological investigations. The purpose of these investigations has been to delineate the extent and quality of the groundwater resources as well as the thickness and character of covering clay layers. The investigations typically include geophys-

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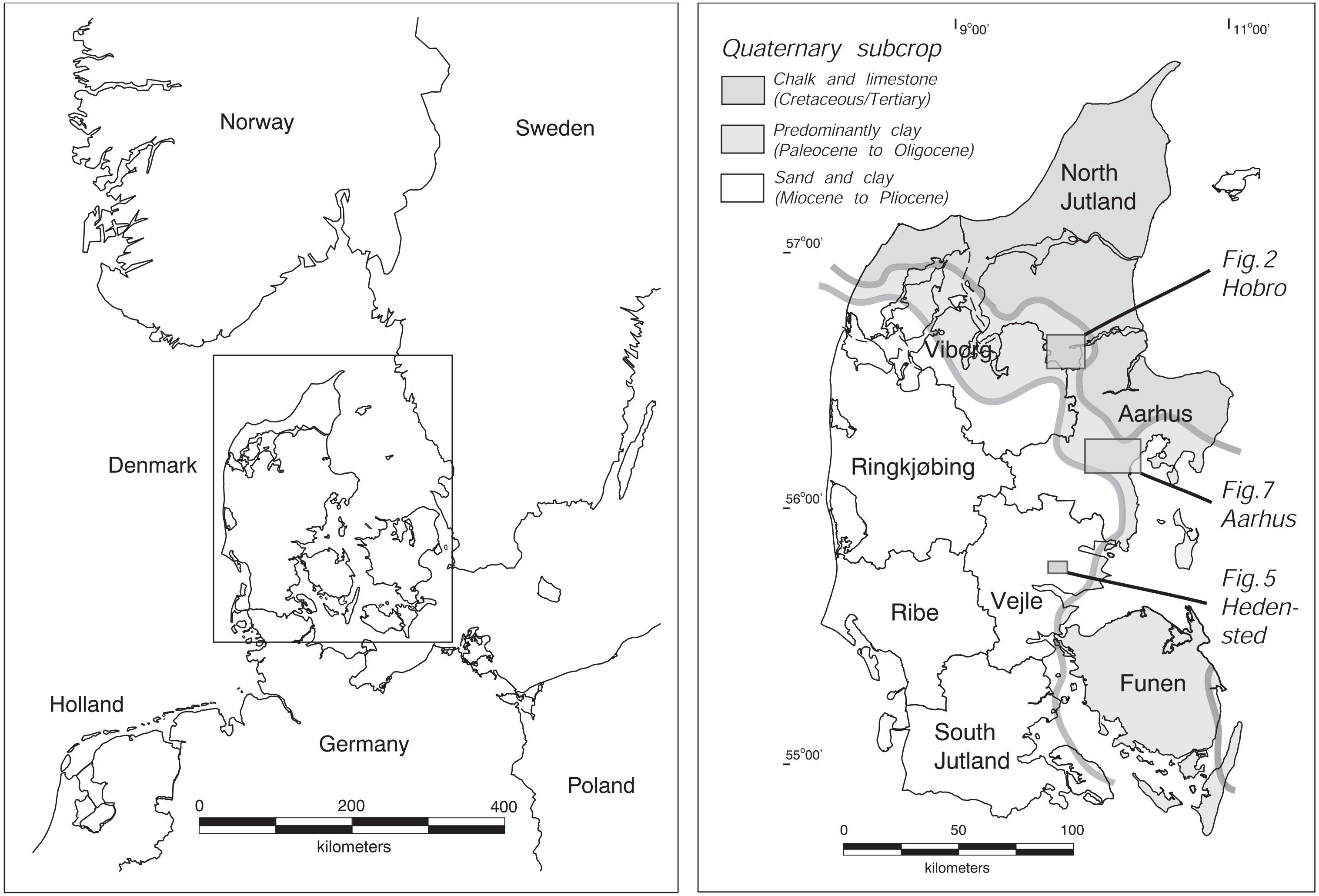

Fig. 1. Location of the study area. The map to the right shows the counties of Jutland and Funen and the Quaternary subcrop (simplified after Sorgenfrei and Buch, 1964).

ical surveys, exploratory drilling and hydrological and hydrochemical assessments. Investigations of this type are planned to continue for at least another decade and will constitute the basis for extensive groundwater protection plans for the groundwater recharge areas.

The investigations have revealed numerous buried valleys and in 1998, the counties of Jutland and Funen funded a project of piecing together the large amount of primarily geophysical data and borehole data with the purpose of creating an overview of the occurrence and characteristics of the buried valleys. This paper reviews parts of the results of the first 4 years of the project (Sandersen and Jørgensen, 2002; Jørgensen and Sandersen, 2000). We present the characteristics of the mapped buried valleys and their inferred influence on groundwater resources and groundwater vulnerability. While the purpose of this paper is to summarise and simplify the results of the large amount of data from the region, other papers in this volume describe specific buried valleys within the region in more detail (Jørgensen et al., 2003a,b).

2. Previous work on buried valleys in Denmark

The existence of buried valleys and their importance for the occurrence and extent of groundwater reservoirs in Denmark have been known for several years, but an overview of the occurrence of the valleys and a detailed description of the valley dimensions, directions and interconnections has been lacking. Without the geophysical data, the existing lithological borehole data have not been sufficient to produce detailed maps of the buried valleys. A map of the Pre-Quaternary surface in Denmark has been made primarily on the basis of lithological borehole data (Binzer and Stockmarr, 1994). The map gives an overall view of the variations in the Pre-Quaternary surface, but as the data coverage is sparse, extensive interpolations have been necessary. As many buried valleys are relatively shallow, only valleys that have been eroded into the Pre-Quaternary surface are visualised.

Individual buried valleys or small areas with buried valleys in the region have been described by several authors (e.g. Lykke-Andersen, 1973, 1986; Madirazza, 1975; Bruun-Petersen, 1987; Olsen et al., 1993; Auken et al., 1994; Gravesen, 1996; Sørensen, 1996, 1997; Poulsen and Christensen, 1999; Huuse and Lykke-Andersen, 2000a; Sørensen et al., 2004), but no overall picture of the buried valleys has been made. In the Danish offshore area, Salomonsen and Jensen (1994) and Huuse and Lykke-Andersen (2000b) have mapped deep buried valleys by means of high-resolution reflection seismic profiling. A review of the occurrence of buried valleys in North Western Europe is given by Huuse and Lykke-Andersen (2000b).

3. Geological setting

The Pre-Quaternary sediments in the region consist of Upper Cretaceous and Danian chalks and limestones overlain by unconsolidated Paleogene clays and Neogene clays, silts and sands (Sorgenfrei and Buch, 1964). The Pre-Quaternary succession dips toward SW and W and thus, the older units underlie the Quaternary to the N, NE and E while the younger units underlie the Quaternary to the S and SW (see Fig. 1). The Tertiary clays, silts and sands attain thicknesses of up to approximately 300 m. Denmark has repeatedly been covered by ice sheets during several Quaternary glaciations (Houmark-Nielsen, 1987; Kronborg et al., 1990; Larsen and Kronborg, 1994). The Quaternary sediments consist of tills, meltwater deposits, glaciolacustrine, interglacial and postglacial sediments. Their total thickness is highly variable—from 0 to more than 300 m.

4. Methods

4.1. Transient ElectroMagnetic (TEM) surveys

TEM soundings constitute the main geophysical data set used in the project. The used data are of both the conventional 40×40 TEM and the High Moment TEM (HiTEM) type as described by Danielsen et al. (2003). The conventional 40×40 TEM has a penetration depth of around 130 m, whereas the HiTEM method approximately doubles this depth. The TEM surveys are typically performed with approximately 16 soundings per square kilometre, while in a few areas, 4 to 5 TEM soundings per kilometre have been made along profiles with an individual spacing of 1–1.5 km. Recently, the Pulled Array TEM (PATEM) method has been developed allowing TEM soundings to be performed along profiles with a spatial sampling distance of 25 or 50 m (Sørensen et al., 2004).

Figs. 2 (Hobro), 3A (Todbjerg) and 3B (Kasted) show a selection of locations where TEM data in combination with borehole data have been used to delineate buried valleys. At Todbjerg, both conventional 40×40 TEM and PATEM have been performed. Detailed descriptions of other buried valleys in the region mapped by the use of TEM are presented in Jørgensen et al. (2003a). The authors also present experiences concerning the resolution capabilities of the TEM method when mapping buried valleys. The TEM method has proven to be successful when mapping buried valleys if the resistivity contrasts between the infill and the surrounding sediments are relatively high. In areas where the valley infill and the surrounding sediments show moderate or varying resistivity contrasts, parts of the valley will normally appear in the TEM survey. In areas with generally low resistivity contrasts, the appearance of buried valleys in the TEM data is weak and determination of valley outlines requires additional data. Although many buried valleys have infill sediments with resistivities higher than the surrounding sediments, some valleys show the opposite contrast. A buried valley filled with, for example, marine interglacial clay or glaciolacustrine clay, may in a TEM survey appear as a low resistivity ridge or an elongate, low resistivity formation, surrounded by sediments of higher resistivity (e.g. Jørgensen et al., 2003a; Fig. 4). In a case like this, the determination of whether the clay represents a buried valley or a clay formation of another origin requires supplementary data such as lithological data from boreholes penetrating the clay or data from seismic surveys. Many buried valleys have a complex internal structure, but TEM data alone may provide an overview of large areas and enable an interpretation of the overall geological structures in and around the buried valleys.

4.2. Seismic surveys

Despite the limitations in making reliable geological interpretations of the uppermost records of conventional exploration seismic data onshore, it has in a few cases been possible to detect deep parts of buried valleys (e.g. Friborg and Thomsen, 1999). Detailed mapping of buried valleys offshore Jutland using multi-channel reflection seismic profiling has been performed by Huuse and Lykke-Andersen (2000b). Onshore, however, the seismic surveys are generally of lower quality compared to offshore surveys, but good results have been obtained by using reflection seismic profiling with focus depths of between 50 and 500 m (Olsen et al., 1993; Jørgensen et al., 2003b). The seismic method is capable of resolving buried valley outlines and internal structures of the infill sediments and is thus gradually increasing its importance in Denmark—especially in areas with low resistivity contrasts. Seismic profiling has only been performed at a limited number of localities and is typically used to confirm the presence of buried valleys and to map the outline and internal structures of the valleys. The seismic interpretation can be significantly improved by adding data from vertical seismic profiling (Jørgensen et al., 2003b). Fig. 5 shows an example of a buried valley mapped using seismic profiling in combination with TEM soundings and borehole data.

4.3. Gravimetric surveys

Gravimetric surveys have only been used at a limited number of localities, and have been used to map density differences between valley infill and the surrounding sediments. As shown by, e.g. Wolfe and Richard (1996) and Friborg and Thomsen (1999), the potential of the method in the search for buried valleys is fairly high, as the valley fill and the surrounding sediments commonly show bulk density differences. The method is at present not commercially available in Denmark and is therefore not used in the ongoing mapping of groundwater resources.

4.4. Data interpretation

The mapped areas are water recharge areas and other areas of groundwater related interest. Therefore, the geophysical surveys are confined to separate areas of the region. Data types and data coverage vary throughout the region, because different contractors have collected data during the years.

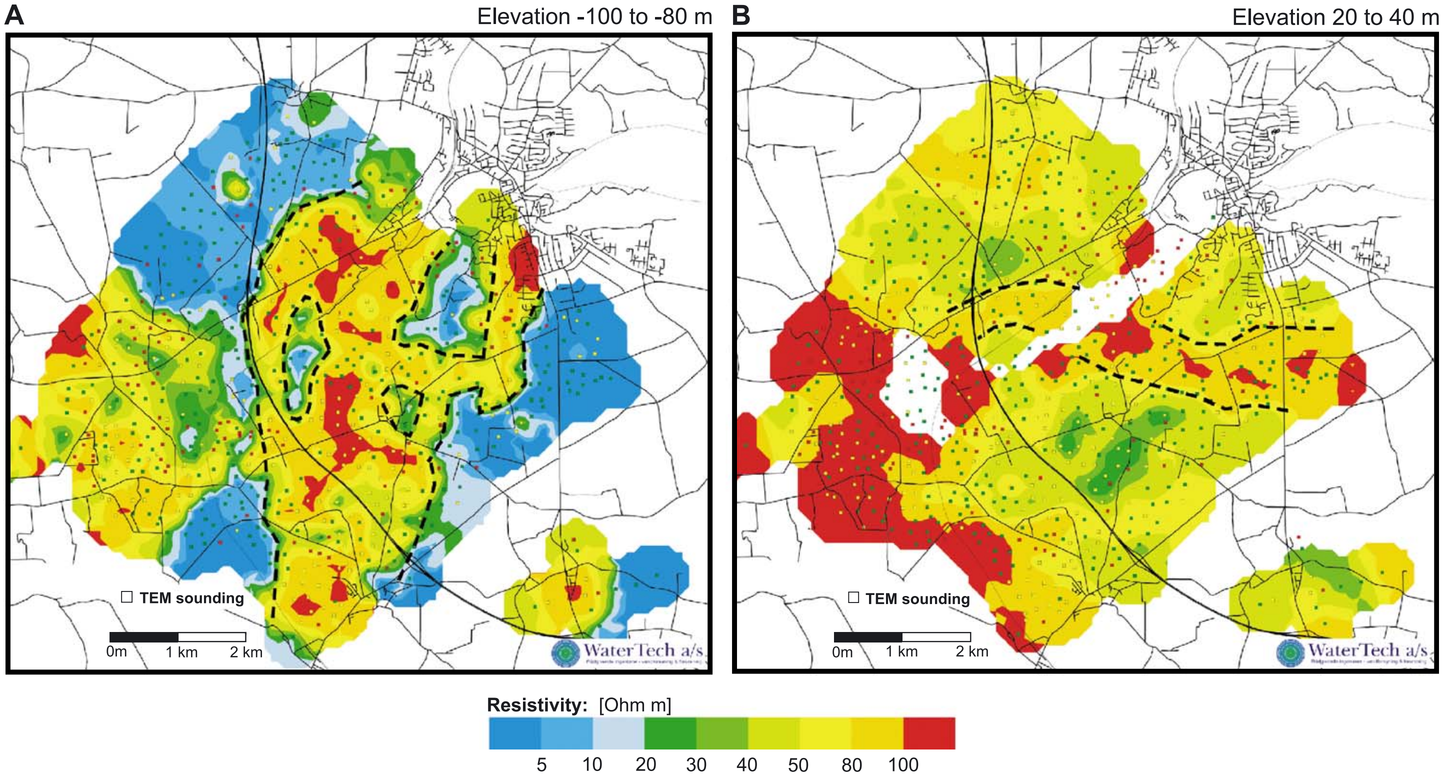

Fig. 2. TEM maps from the area south-west of Hobro. Two slices showing the mean resistivity of sediments between −100 and −80 m a.s.l. (A) and between +20 and +40 m a.s.l. (B). Valley outlines are shown as dashed lines. See Fig. 1 for location.

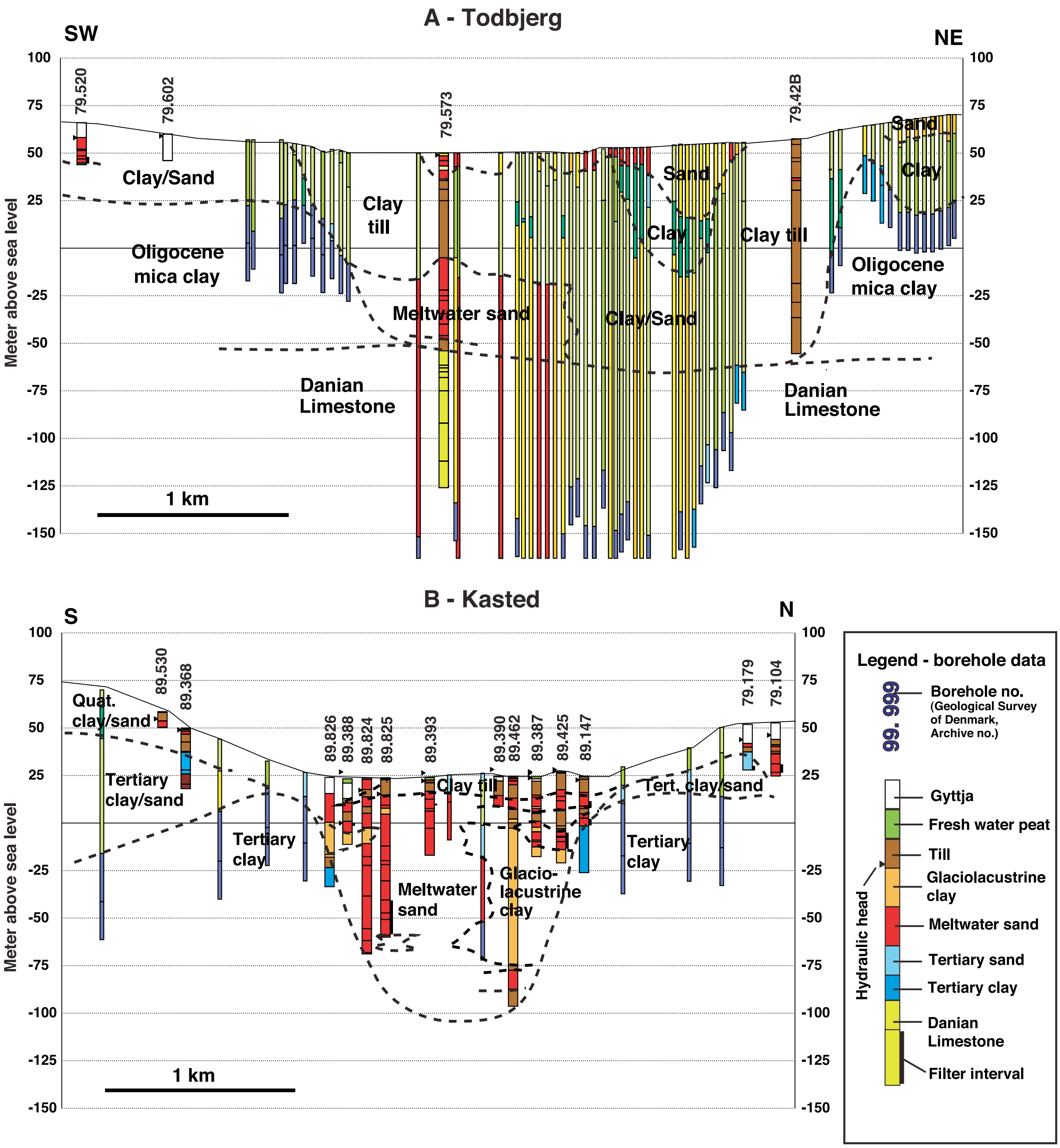

Fig. 3. Profiles across buried valleys at Todbjerg (A) and Kasted (B) mapped using data from boreholes and TEM soundings (conventional TEM and PA-TEM). TEM soundings are visualised as 1-D models in narrow coloured vertical columns (for legend, see Fig. 5). On the Todbjerg profile, the soundings are cut deeper than 150 m a.s.l. Boreholes are visualised as broader vertical columns. Geological interpretations are added. The location of the profiles is shown in Figs. 4 and 7.

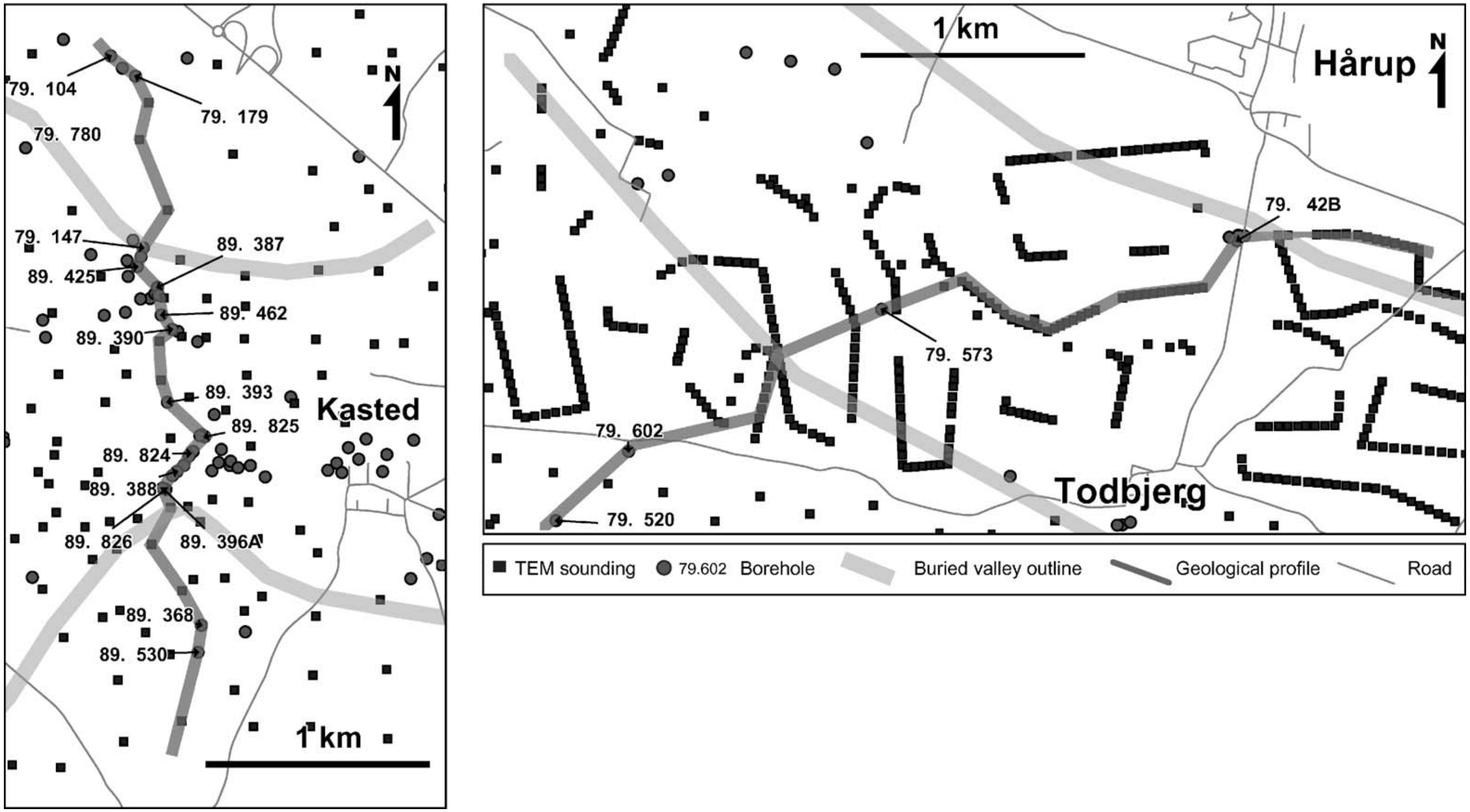

Fig. 4. Location of profiles in Fig. 3A and B across the buried valleys at Todbjerg and Kasted, respectively. The location of the examples in the Aarhus area is shown in Fig. 7.

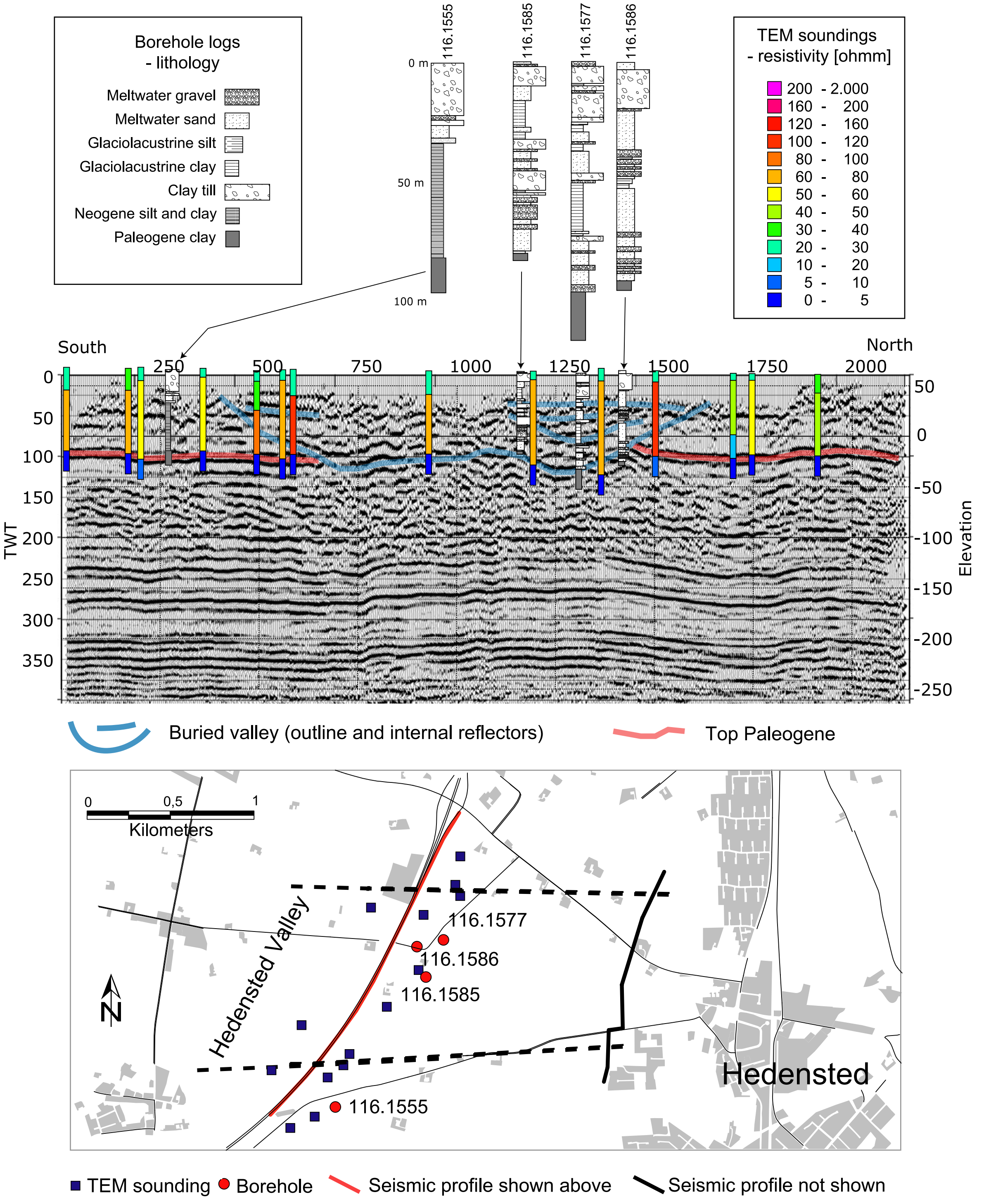

Fig. 5. Buried valley at Hedensted mapped using lithological borehole data, TEM soundings and reflection seismic profiling (unmigrated 32-fold stack). Lithological logs and 1-D models of TEM soundings (coloured vertical columns) are projected and superimposed onto a seismic section from distances of up to about 300 m. See Fig. 1 for location.

In general, the best results of mapping buried valleys have been obtained when data from TEM soundings, seismic surveys and boreholes are combined. In a large number of areas, however, only TEM data and borehole data exist, and the number of deep boreholes is often limited. In the county of Aarhus, for example, the number of boreholes per square kilometre is only around 2.5, and out of the total number of boreholes, only a quarter reach 50 m in depth and only one borehole per 15 square kilometres reaches 100 m (Sørensen et al., 1995). As many valleys are deeper than 100 m, the lithological data alone is not sufficient for a detailed delineation of the valleys. Furthermore, the quality of the lithological data varies significantly due to the different drilling methods used and the age of the boreholes. Consequently, the lithological data should be used in combination with geophysical data. However, performance of geophysical well logs may increase the value of the data from boreholes and enable detailed correlations.

When interpreting the geophysical data, the appearance of buried valleys may vary from very distinct to vaguely discernible depending on electrical contrasts and the density/porosity variations of the sediments, as well as the amount of data and the suitability of the used methods (Jørgensen et al., 2003a,b). Conditions favourable for detailed interpretations of buried valleys are present at many localities. Especially in the counties of Viborg, Aarhus, Vejle and Funen (Fig. 1) where the deep parts of buried valleys typically are eroded into low resistivity Tertiary clays and filled with high resistivity sediments. The upper parts of the valleys, however, may be difficult to discern if eroded into heterogeneous Quaternary sediments. In the western part of Jutland, many buried valleys are eroded into sand-dominated sediments and infilled with sandy sediments as well. Under such conditions, the resistivity contrasts are minimal and the electrical methods experience difficulties in resolving the outline of the valleys. In these cases, the use of seismic profiling and gravity surveys may produce better results as these methods focus on other properties than electrical resistivity (Jørgensen et al., 2003b; Thomsen et al., 2002). Thus, the selection of optimal geophysical methods to be used in specific areas is highly dependent on experience from neighbouring areas.

5. Results

5.1. Geographical occurrence

The buried valleys delineated in the study area are shown in Fig. 6. A total of 1023 km of buried valley segments has been mapped, with 70% being completely buried and 30% partly buried. Contrary to the completely buried valleys, the partly buried valleys have a modern counterpart in the present day topography. The buried valleys appear as isolated segments or groups of segments, because no interpolations between the valley segments have been made. Interpolations have been avoided in order to obtain a high degree of certainty of the valley location and the valley orientation.

Although single valleys occur, the buried valleys occur as systems of valleys, sometimes arranged in dense networks. An example of a dense valley network can be seen around Aarhus (Fig. 7), where the presence of low resistivity Tertiary clays and a high density of geophysical investigations document the valley network. A comparable geological framework can be found in large parts of the counties of Vejle, Viborg and Funen. In the northern part of Jutland, Tertiary clays are absent, but here clay tills and marine interglacial clays may constitute a low resistivity substratum. In the south-western and western part of Jutland, low resistivity Tertiary clays are typically found at great depths and in some areas deeper than the maximum penetration depth of the TEM method. Accordingly, the uneven geographical distribution of the buried valleys as it appears in Fig. 6 is not necessarily expressing a natural distribution of the valleys, but is believed to be a result of differences in mapping conditions and the density of geophysical surveys.

5.2. Dimensions

The maximum length of the individual buried valleys cannot be estimated because the geophysical surveys are confined to smaller areas. Many of the valley segments are therefore probably longer than they appear in Fig. 6. In some cases, valleys have, however, been traced for distances of 25–30 km (Fig. 6). It is presumed that the mapped valleys are parts of larger systems of valleys comparable to other buried

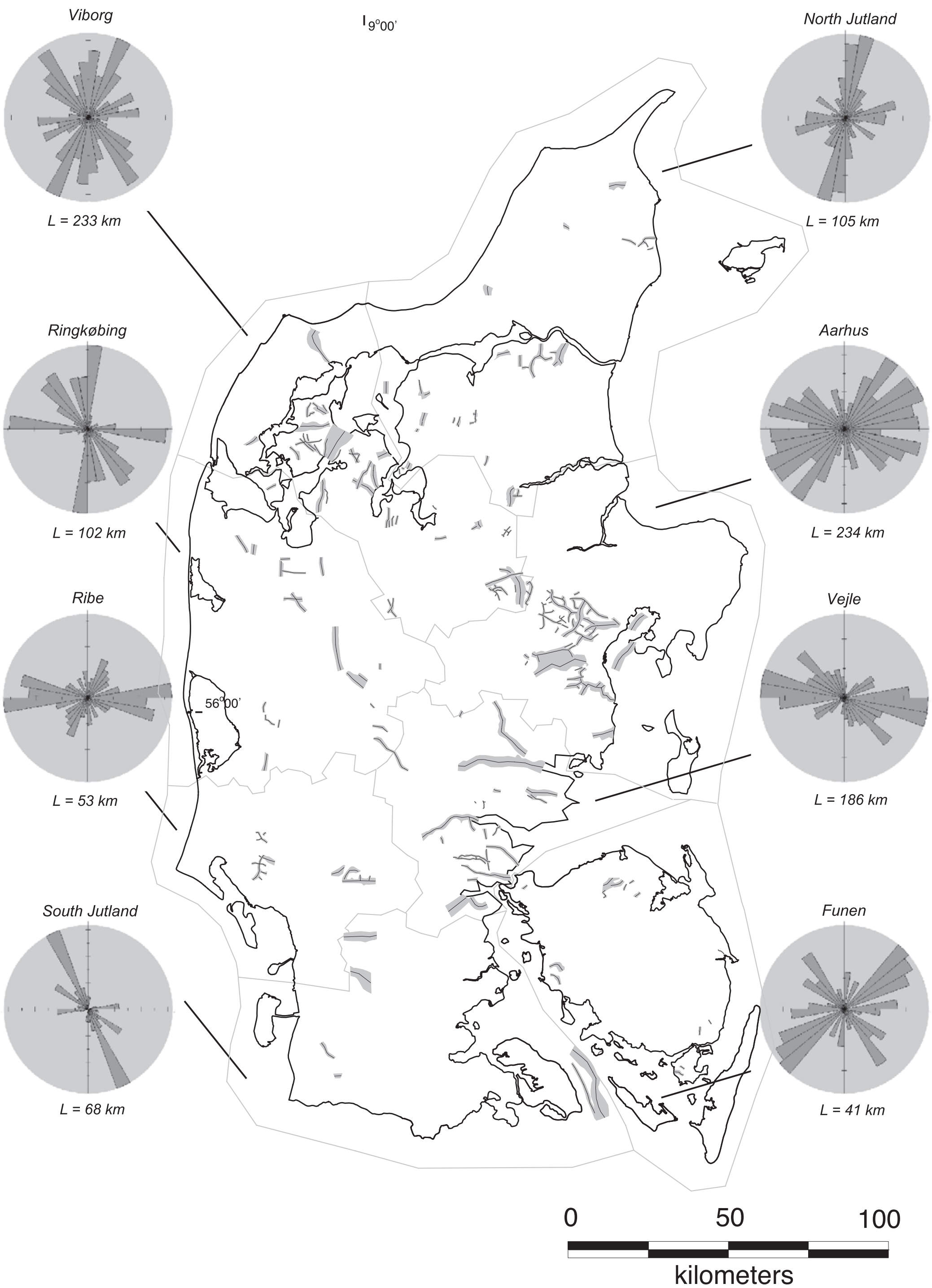

Fig. 6. Mapped buried valleys in the western part of Denmark. Outlines of mapped buried valleys are shown. Cumulated lengths of the buried valleys within each county are shown in rose diagrams (10° intervals). The axes of the rose diagrams are relative.

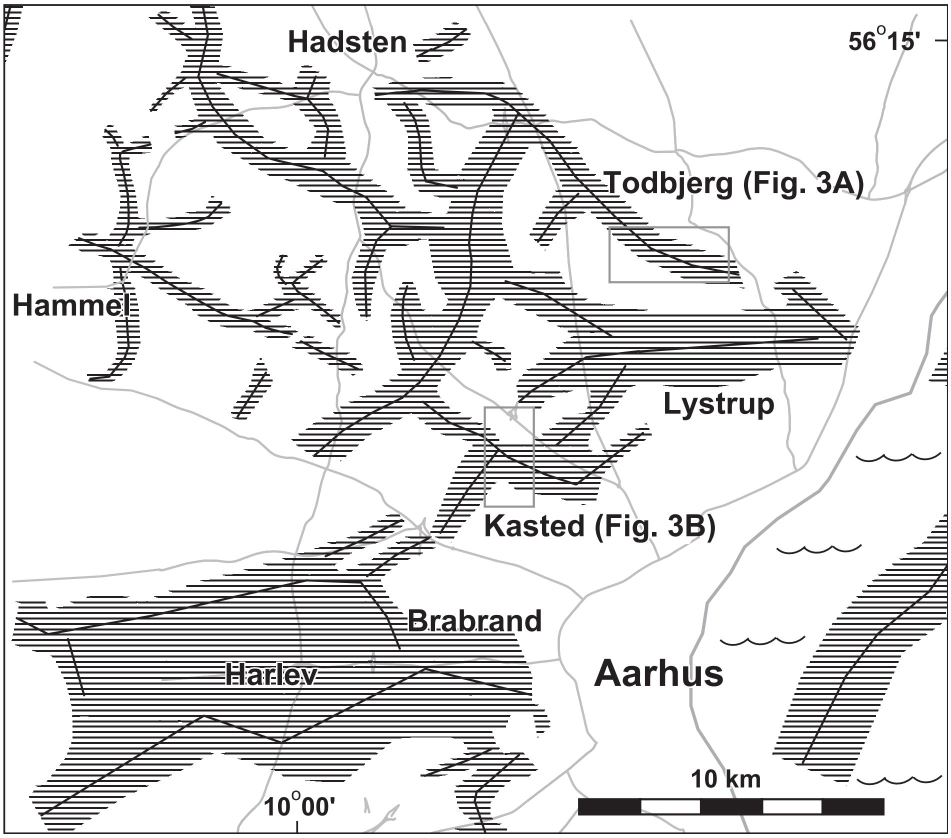

Fig. 7. Buried valley network west and northwest of Aarhus. Outlines of mapped buried valleys are shown in horizontal hatch and lines along the valley centre are shown in black. Centre lines that form junctions illustrate buried valleys with the same bottom level. Valleys with centre lines that do not intersect the centre line of a crossing valley illustrate a valley at a higher level. The locations of the Todbjerg and Kasted examples (Fig. 3A and B) are shown as grey rectangles. For location of the Aarhus area, see Fig. 1.

valley systems in Northwest Europe as described by, e.g. Huuse and Lykke-Andersen (2000b).

The depth of the buried valleys varies from less than 25 to 350 m. However, the actual depths of many valleys remain undetermined, because the valley floors are not always resolved correctly or reached by the TEM soundings. Either because the resistivity contrast to the underlying valley floor is too low, or because the valley is deeper than the maximum penetration depth of the TEM-method. In some cases, the TEM method overestimates the valley depth at localities where the low resistivity Tertiary clay is completely or partly removed by erosion, making the valley fill rest more or less directly on underlying limestone in the deepest parts of the valley. If the limestone aquifer has an upper freshwater zone and a lower saltwater zone, the TEM soundings will define the deep good conductor as the top of the saline water table below the central parts of the valley and as the top of the Tertiary clays on the valley flanks and outside the valley. An example of this is shown in Fig. 3A (Todbjerg), where a valley is eroded through low resistivity Tertiary clays, thus exposing Tertiary limestone in the valley floor as verified by borehole data (GEUS, archive no. 79.573). The upper part of the limestone contains fresh groundwater, which creates a high resistivity zone in contrast to the deeper, low resistivity saline zone. Without the borehole data, the valley would, according to the TEM soundings, appear to be more than 50 m deeper than it actually is. The opposite situation, where saltwater invade the lower part of the buried valley, the valley depth may be underestimated. A deep borehole (archive no. 88.676) situated at Harlev in the buried valley west of Aarhus (Fig. 7) reveals Tertiary limestone underneath approximately 125 m of Quaternary infill (Lykke-Andersen, 1973). As nearby waterworks experience increased chloride levels in a number of wells, it is presumed that saltwater to a certain extent has found its way into the aquifers in the lower parts of the buried valley. However, any influence on the TEM measured valley depth in this area has not been verified by lithological data.

Because of the uncertainties in the determination of the valley depth, the shapes of the longitudinal bottom profiles of the deepest valleys are therefore typically unknown. In shallower valleys, the shape of the valley floor becomes visualised in the TEM surveys. A typical example is shown in Jørgensen et al. (2003a) from Hornsyld, where the buried valley system shows an undulating bottom profile with hollows and thresholds and varying gradients. This is presumed to be the result of an irregular erosional cut, but factors such as erroneous resistivity models caused by inductive coupling to cultural structures, low resistivity Quaternary valley fill, salt water intrusion or glacial thrusting may also be responsible for irregularities of the valley floor.

The width of the mapped buried valleys is predominantly between 1 and 2 km, as for example seen at Todbjerg, Kasted and Hedensted (Figs. 3A,B and 5, respectively). Valley widths between 0.5 and 1 km and between 2 and 4 km are less frequent. In other cases, multiple episodes of erosion and subsequent sediment infill of larger valleys have created individual narrow valleys. The Hornsyld and Holstebro examples in Jørgensen et al. (2003a; Figs. 3 and 4) show narrow incisions inside larger buried valleys. In many cases, the actual width of a buried valley is difficult to determine because the upper parts of the valleys may be less discernible than the deeper parts, due to for instance limitations of the used geophysical methods and due to sparse lithological data.

5.3. Preferred orientations and valley generations

The cumulated lengths of the buried valleys within 10° intervals are shown in rose diagrams in Fig. 6. The diagrams show that in each county, one to three preferred orientations of valleys can be found, and that the preferred orientations vary from county to county. In the county of North Jutland, preferred orientations around N–S and E–W dominate, with the N–S orientation being the most prominent. In Viborg County, approximately the same preferred orientations occur, but in addition to these, a NW–SE orientation is fairly dominant. Almost the same picture can be seen in Ringkjøbing County. In the county of Aarhus, the rose diagram orientations around NE–SW and WNW–ESE dominate, and in contrast to the three first mentioned counties, orientations around N–S are infrequent. In the counties of Vejle and Ribe, orientations around E–W dominate and subordinate orientations are NW–SE and NNE–SSW, respectively. In the county of Funen, orientations around NW–SE and NE–SW dominate. The rose diagram for the county of South Jutland is dominated by the orientation of two buried valleys in the easternmost part of the area with orientations around NNW–SSE. A picture of the preferred orientations for the rest of the county cannot be determined because of the limited amount of data. A discussion of the causes of these distinct preferred valley orientations lies beyond the scope of this paper, but it is obvious that geographically based differences prevail.

Two to three different valley orientations can be found in many mapped areas. The valleys within these sets may occur at the same level below the surface, but can also be found at different levels. The different preferred orientations indicate the presence of different valley generations. Northwest of the city of Aarhus, at least three preferred orientations were found (Fig. 7). The NW–SE orientation dominates followed by NE–SW, whereof the broad valley in the upper central part of the figure is most prominent. The middle section of the NE–SW valley has a bend in a N–S direction and valley segments with N–S directions can also be seen south of Hadsten and east of Hammel. Whether the N–S direction represents a separate generation or is directly associated with the NE–SW valleys is uncertain. Under the town of Lystrup, a broad E–W buried valley represents a valley direction that seems to be related to the valleys south and west of Aarhus (Fig. 7).

In the Hobro area (Fig. 2), an up to 2.5-km-wide buried valley system with a distinct N–S direction is eroded into low resistivity Tertiary clays, as seen on the TEM mean resistivity slice A in Fig. 2 (interval − 100 to − 80 m a.s.l.). A 0.5-km-wide valley with an

E–W direction crosses the N–S valleys. In deeper intervals, this E–W valley is not present, but in higher intervals (−80 to −20 m a.s.l.), the N–S and the E–W valleys both appear in the TEM data. In the interval between −20 and +20 m a.s.l., the buried valleys are covered by a clay rich Quaternary sequence of relatively low resistivities and no valleys can be distinguished in the TEM data. In the uppermost slice representing the interval between +20 and +40 m a.s.l. (Fig. 2, slice B), a completely buried valley with an E–W direction and a width of 1 km becomes visible. The valley has a high resistivity infill and is located precisely above the E–W trending valley visible in the deep intervals. A SW–NE valley in the present landscape cuts through the buried valley, leaving isolated segments of the E–W valley on both sides of the present day valley. The valley in the landscape is seen as the elongate white area in the middle of the TEM slice. Apparently three generations of buried valleys dominate in the Hobro area: a deep N–S trending valley system, an E–W trending valley in higher intervals and a SW–NE open valley in the present day landscape. Obviously, the N–S valleys are the oldest and the valley in the present day landscape the youngest, whereas the E–W valley has an intermediate age.

Different valley generations with different orientations are also described in the Vonsild example presented in Jørgensen et al. (2003a,b). The repeated events of erosion and deposition inside buried valleys, as for example seen in the Hornsyld example of Jørgensen et al. (2003a,b) may also represent different valley generations.

Rose diagrams showing the directions of partly buried and completely buried valleys are shown in Fig. 8. The partly buried valleys have dominating directions around E–W, whereas the completely buried valleys show at least three directions: E–W, NW–SE and N–S. The most striking difference between the two diagrams is that the partly buried valleys show practically no directions around N–S. The N–S directions probably represent a generation of buried valleys with a high potential of being completely buried.

Existence of different valley generations has also been reported by, e.g. Salomonsen and Jensen (1994) from the Danish North Sea and by, e.g. Cameron et al. (1987), Wingfield (1989), Ehlers and Wingfield

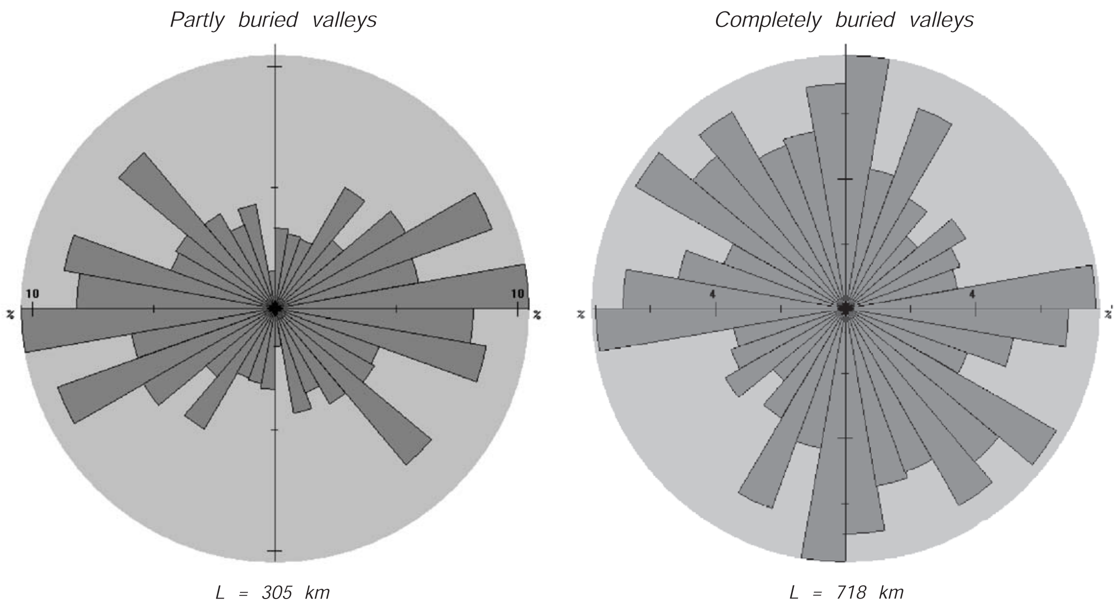

Fig. 8. Rose diagrams of orientations of partly buried and completely buried valleys. Each petal represents the summarised length of the valley centre lines within 10° intervals relative to the summarised length of all valleys. L = total length of valleys.

(1991), Piotrowski (1994) and Praeg and Long (1997) for adjoining areas.

5.4. Internal structures and infill sediments

The internal structure of the buried valleys is typically very complex and the complexity of the valleys is primarily caused by repeated erosion and deposition inside the valley tract and probably also by glacitectonic deformation. The complex internal structure can be seen in many seismic surveys and also in certain TEM surveys. Examples of this can be seen in the valleys at Hedensted (Fig. 5) and at Hornsyld, Vonsild and Viuf shown in Jørgensen et al. (2003a,b).

The mapped buried valleys typically consist of elongate incisions that have been filled with sediments prior to subsequent erosional episodes. The erosional channels inside the valley trace can be broad or narrow, have steep or gentle slopes and have sediment infill of varying character. In the Kasted valley (Fig. 3B), thick successions of coarse-grained and fine-grained sediments can be found side by side. Distinct elongate features were for instance seen in the TEM survey of the Hornsyld valley (Jørgensen et al., 2003a). Here, high resistivity feature measuring 0.5×4 km in the north-eastern part of the valley is interpreted as representing a young sand and gravel filled valley inside a broader predominantly clay-filled buried valley.

In the Hobro as well as in the Aarhus area, TEM surveys showed valleys of different orientations crossing each other at different levels below surface (Figs. 2 and 7). Although seismic surveys have not been performed in these areas, it is obvious that these crossing valley generations will add even more complexity to the architecture of the valley fill.

The infill sediments are of Quaternary age, with glacial meltwater deposits and tills dominating. Interglacial and postglacial sediments occur to a lesser extent. The sediment types vary both laterally and vertically and there are no distinct patterns in the distribution of the different sediment types inside the mapped valleys. However, as seen in Fig. 9, there is a

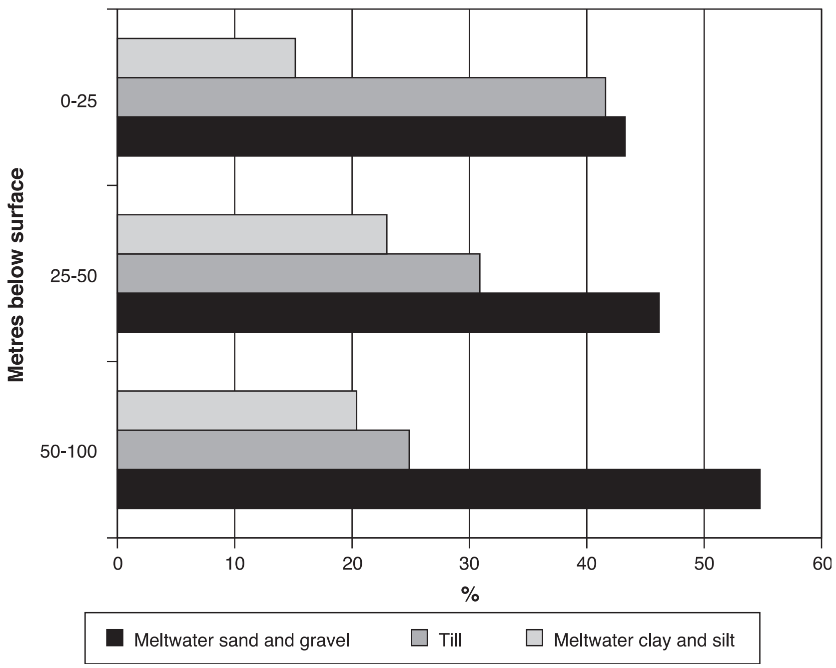

Fig. 9. Depth variations in valley fill sediments. Percentage of meltwater sand and gravel, till and meltwater clay and silt in three depth intervals. Lithological data collected from boreholes deeper than 25 m inside buried valleys (Lithological database from the Geological Survey of Denmark and Greenland).

tendency that tills are more frequently found in the upper parts of the valley infill than in the lower parts, whereas the opposite trend is seen for meltwater sand and gravel.

Regional differences in the character of the valley infill are indicated by the histogram in Fig. 10. The histogram shows the ratio between glaciolacustrine clay/silt, tills and meltwater sand/gravel found in boreholes located inside the valleys. In the western counties of Jutland (Ringkjøbing and Ribe), the ratio between tills and meltwater sand/gravel is around 1:10, in contrast to an average ratio of 1:1.5 in the remaining part of the region.

5.5. The valleys and the character of the substratum

On the basis of the differences in the character of the substratum, the mapped buried valleys can be divided into three major groups: Group 1: buried valleys eroded into clay dominated sediments, Group 2: buried valleys eroded into alternating clayey and sandy layers and Group 3: buried valleys eroded into chalk and limestone. Fig. 11 shows sketches of the three groups of valleys and illustrates the variations inside the region.

The valleys of group 1 are typically found on Funen and in East and Northwest Jutland where sandy and clayey Quaternary sediments constitute the valley infill in a generally clay dominated Tertiary substratum (Fig. 1). This group represents valleys that can be mapped in the most detailed way with the used geophysical methods in combination with borehole data. The sketch marked A shows a partly buried valley eroded deeply into a high lying substratum of tertiary clay, whereas the sketch B shows a completely buried valley eroded into a Tertiary sequence of clay in the lower part and alternating clay and sand in the upper part. The valley at Kasted (Fig. 3B), for example, is a valley of the A-type, whereas the valleys at Hedensted (Fig. 5) and Hobro (Fig. 2) represent B-type valleys. The sketch C shows a deep valley eroded

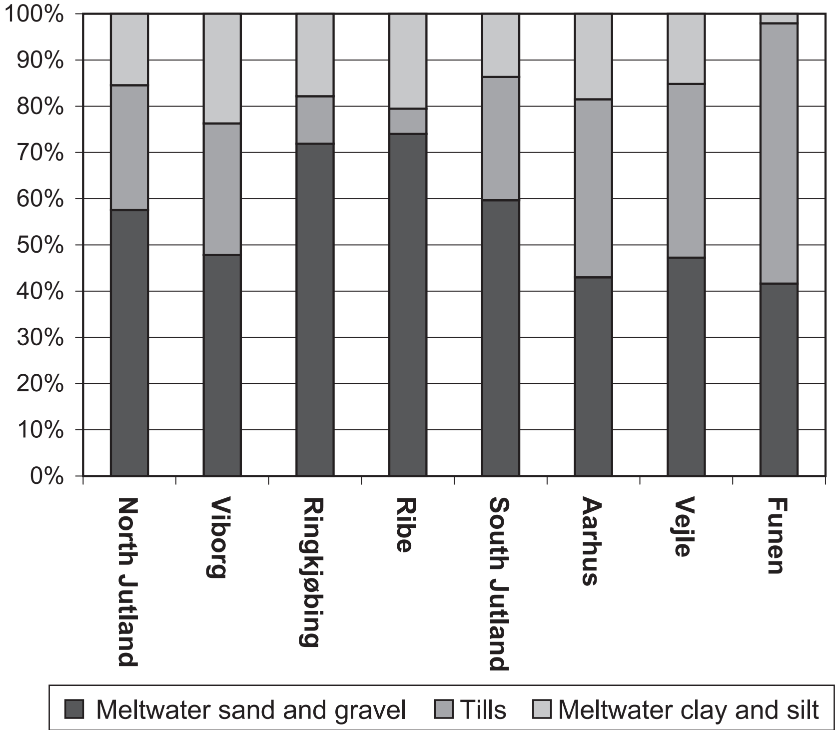

Fig. 10. Regional differences in valley fill sediments. Percentage of meltwater sand and gravel, till and meltwater clay and silt in buried valleys in the counties of the region. For location of the counties, see Fig. 1. Lithological data collected from boreholes deeper than 25 m inside buried valleys (Lithological database from the Geological Survey of Denmark and Greenland).

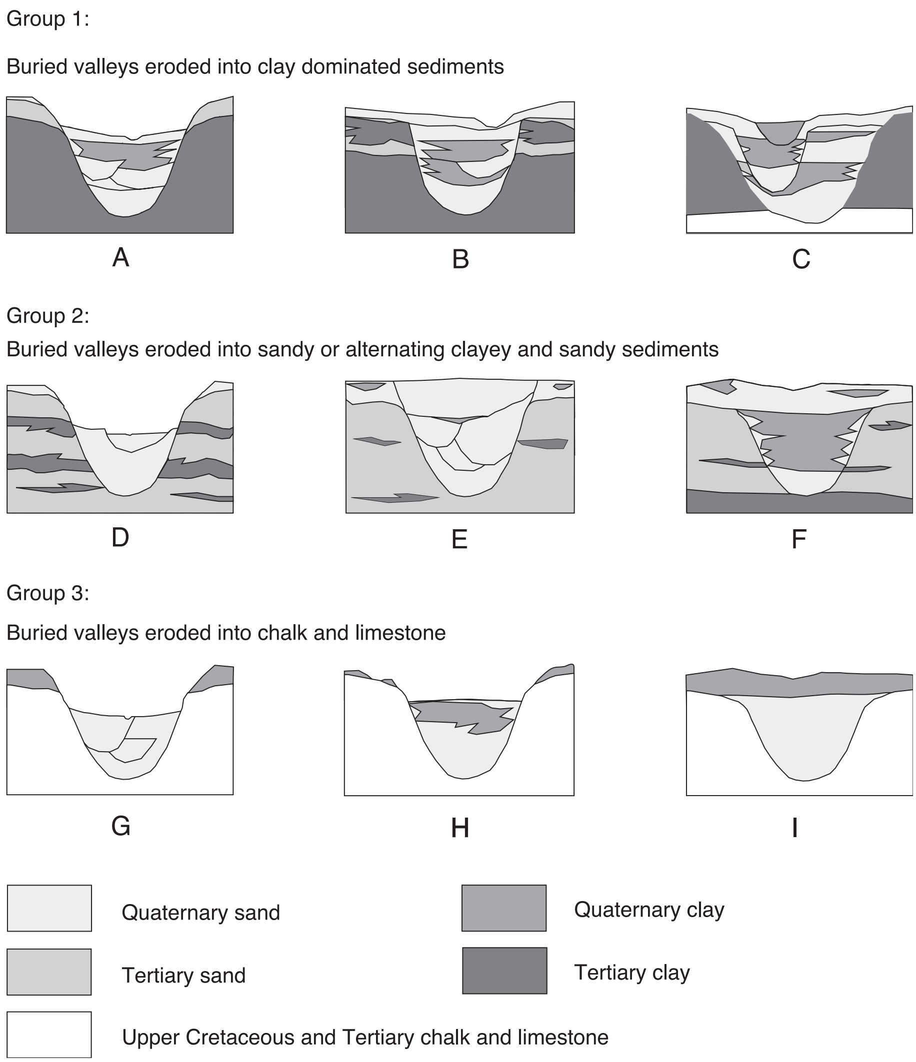

Fig. 11. Sketches of examples from the three main groups of buried valleys. See text for explanation.

into the underlying limestone. The valley at Todbjerg (Fig. 3A) is an example of a C-type valley.

The valleys of group 2 are eroded into alternating clayey and sandy layers and are typically found in West and South Jutland (Fig. 1). In these areas, predominantly sand filled valleys are eroded into mainly Tertiary sequences of alternating layers of sand, silt and clay. The valleys of group 3 are eroded into chalk and limestone and are found in the northern and easternmost parts of the region (Counties of North Jutland, Aarhus and Funen; Fig. 1).

5.6. Origin and age of the buried valleys

Regarding dimensions, sedimentary infill, preferred orientations and general architecture, the buried valleys in western Denmark show a close resemblance to the buried valleys in the Eastern North Sea as described by Huuse and Lykke-Andersen (2000b) and Salomonsen and Jensen (1994) and to the buried valleys in north-western Germany as described by, e.g. Ehlers et al. (1984) and Piotrowski (1994). Buried valleys like these are generally presumed to have been formed by subglacial meltwater erosion or probably glacial scouring during the Quaternary glaciations (see Huuse and Lykke-Andersen, 2000b for review).

It has nowhere in western Denmark been possible to attain an exact age of the valleys. Because the uppermost parts of the valleys generally dissect Quaternary sediments and because the infill sediments are of Quaternary age, it is obvious that the majority of the buried valleys have been created during the Quaternary period. The successive episodes of erosion and deposition within the valleys indicate that the valley formation in general was a repetitive process. The infill includes deposits from the Weichselian, Saalian and Elsterian glaciations and deposits from the Eemian and the Holstenian interglacials. This indicates that buried valleys have been active geologic features at least since the Elsterian glaciation, and valleys have in many cases been re-eroded during subsequent glaciations.

Determination of relative age relationships of valley generations has in some cases been possible. For instance, where crossing valleys are sand filled and clay filled, respectively, the relative age of the valleys may be obvious. In other cases, such as the Hobro valleys (Fig. 2), a relative dating of the three valley generations was possible from a combination of the TEM data and the topography.

6. Inferred implications for groundwater resources and vulnerability

6.1. Groundwater resources

The buried valleys are incised into a substratum of varying character depending on the location inside the region and the valley depth (Fig. 11). In areas where low permeable tertiary sediments lie close to the surface, the aquifers in the valleys typically constitute the only possibility for large-scale ground water abstraction. The clayey valley walls restrict the lateral extent of the aquifers and there will be only limited water exchange between the aquifers in the buried valley and the surrounding layers. The flow of deep groundwater will take place inside the valley, but the groundwater recharge to the aquifers, however, will take place both in the area occupied by the valley and in areas outside the valley via surficial sand layers. A significant part of the recharge area may therefore lie at relatively large distances from the valley itself. A situation like this can be found at Hedensted (Fig. 5), Todbjerg (Fig. 3A) and Kasted (Fig. 3B). The valley aquifer in Kasted initially had a hydrostatic pressure above ground, indicating hydraulic contact to higher lying aquifers in the surrounding hills. Extensive ground water abstraction in the area, however, has since then lowered the hydrostatic pressure below ground surface.

Internal erosional surfaces may constitute sharp contacts between individual aquifers inside the valley, and typically the individual aquifers are elongate and may only occupy parts of the valley, but follow the overall valley trend. Hydrogeological investigations in and around the Brabrand valley west of Aarhus (Fig. 7) have found restricted hydraulic contacts between close lying aquifers within the valley and between aquifers inside and outside the valley (e.g. Jørgensen, 1990).

Where buried valleys are eroded into sand-dominated sediments or alternating layers of sand, silt and clay, the water-bearing layers inside and outside the valley will constitute one large aquifer (Fig. 11; sketches D and E). This is commonly found where valleys are eroded into sandy and clayey Tertiary sediments. The hydraulic conductivity of the sandy Tertiary aquifers outside the buried valleys is generally lower than the Quaternary aquifers inside the buried valleys, and accordingly the buried valleys often constitute the highest yielding parts of the aquifer system. Clay-filled valleys, on the other hand, may restrain the groundwater flow in the aquifer system (Fig. 11; sketch F). Where sand-dominated valleys are eroded into chalk or limestone, the water-bearing sediments inside and outside the valley will constitute one aquifer system. However, differences in the hydraulic properties of the infill and the surrounding layers due to structural and textural differences are likely to affect the groundwater flow in the aquifer system.

As seen in Fig. 6, the mapped buried valleys show preferred orientations in different parts of the region. This fact is highly useful in the prediction of buried valleys in areas where investigation has not yet been performed—especially in clay dominated areas where groundwater resources outside the valleys are sparse.

6.2. Groundwater vulnerability

Determination of groundwater vulnerability to potentially harmful chemical compounds introduced at the ground surface is complicated. Chemical and biological processes may retain or degrade the chemical compounds before they reach the aquifer, or the compounds may not find its way to the aquifer due to physical conditions such as protective clay layers or an upward hydraulic gradient. In areas with buried valleys, the physical conditions may be very complex because the valleys cut through sedimentary successions and because of the complex internal architecture of the valleys. In this way, preferred flow paths for transport of contaminated water from shallow aquifers to deeper aquifers may exist.

A consequence of the generally complex internal structure of the valleys is that the potentially protective clay layers above the aquifers are discontinuous and heterogeneous. The aquifers inside the valley will thus have a varying degree of natural protection. Typically smaller sand-filled valleys eroded into alternating clay and sand layers may constitute vulnerable zones as the clay cover is penetrated. The Brabrand valley, for example, has a highly varying electrical resistivity 5–15 m below the surface inside the valley (Sørensen et al., 2004). At Kasted, the profile Fig. 3B shows the complex valley infill consisting of primarily meltwater deposits. The clay layers in the valley have a limited lateral extent, and in addition to this, the reversed hydraulic gradient due to groundwater abstraction has increased the vulnerability of the aquifer. Along the valley walls, preferential flow paths for transport from the surface to deeper levels are assumed to exist where the valley walls are glacitectonically deformed or otherwise disturbed.

In the area around Hedensted, the only way to find large groundwater resources is to find aquifers in buried valleys. As shown in Fig. 5, the hydrological investigations have located a buried valley west of the town and new water abstraction wells have been made in the central part of the valley. The complex valley infill and the fact that pesticides have been found in the groundwater underneath the town indicate that the groundwater resource in the valley may be vulnerable. This emphasises the need for a detailed groundwater protection plan for the recharge areas of the new well field.

Where multiple generations of valleys are crossing each other, potentially vulnerable zones may occur. In the Hobro area (Fig. 2), an E–W trending valley in the uppermost part of the subsurface is incised into a clay dominated Quaternary sequence and down into the underlying N–S trending valley system. The E–W trending valley is sand dominated and thus, the total thickness of potentially protective clay layers above the deep aquifers in this zone is reduced.

The aquifers in predominantly sand filled valleys are generally highly vulnerable because of the limited amount of protective clay layers. This is typically a problem in the western part of Jutland. Even when clay layers are present, their protective effect will only have local importance if the surrounding sediments are sand dominated. The valleys eroded deeply into alternating sandy and clayey Tertiary sediments may create short-circuits between the Quaternary aquifers in the valley and the surrounding Tertiary aquifers. Friborg and Thomsen (1999) describe buried valleys eroded into the elsewhere well-protected deep Tertiary aquifer, the Ribe Formation in Jutland.

Where the Tertiary clays at the bottom of the buried valleys have been removed by erosion, the deep-seated Quaternary aquifers and the underlying limestone will be in hydraulic contact. In this case, naturally occurring chloride and fluoride in the limestone aquifer may affect the groundwater quality in the Quaternary aquifer. If large amounts of groundwater are withdrawn from the valley, the intrusion of deep groundwater may be increased. In the Aarhus area, limestone is exposed in the valley floor for instance in the Todbjerg valley (Fig. 3A) and the Brabrand valley (Fig. 7). In Todbjerg, the upper part of the limestone aquifer contains fresh water, whereas a number of abstraction wells in the Brabrand valley show increased concentrations of chloride and fluoride, thus indicating a chemical influence from deeper levels.

7. Conclusion

Geophysical investigations comprising TEM and reflection seismic surveys in combination with borehole data have revealed more than 1000 km of buried Quaternary valleys in western Denmark. The buried valleys appear both as single valleys and in dense networks, and different valley generations with varying orientations are common. The internal structure of the valleys is typically complex due to repeated erosional and depositional events and due to glacitectonic disturbances. The buried Quaternary valleys are common geological structures in the region and the occurrence of the Tertiary and Quaternary sediments is highly influenced by the valleys.

Water bearing coarse-grained sediments in the buried valleys are highly appreciated as resources of drinking water throughout the region. However, as the valley infill differs from the surrounding strata and the valley infill structure commonly is complex, restrictions in aquifer thickness and lateral extent may occur. Where buried valleys are eroded into a clay-dominated substratum, the valleys may be the only possibility for large-scale groundwater abstraction. However, as the aquifers are restricted to parts of the valley infill, detailed geophysical mapping is required in order to delineate the aquifer extent and to estimate the groundwater recharge areas.

The natural protection of the aquifers in the valleys varies depending on the thickness and character of the overlying clay layers. Many aquifers in the valleys are deep-seated and well protected, but because of the prevailing heterogeneity of the valley infill and the erosional incisions, the vulnerability of the aquifers may be increased. Preferential flow paths for downward transport of contaminated water from shallow aquifers may occur. In areas where valleys have been eroded into alternating sand and clay layers, the buried valley may cause leakage between shallow and deep aquifers surrounding the valley.

Therefore, in the process of making regional-scale assessments of groundwater resources and vulnerability, it is important that the presence of buried valleys are taken into account. On a local scale, a delineation of valley extent, infill types, valley architecture and relationships between different valley generations is necessary and thus a detailed mapping of buried valleys is required. The combination of TEM soundings, borehole data and seismic surveys has proven to provide the best results.

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