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Buried valley mapping in Denmark: evaluating mapping method constraints and the importance of data density

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Abstract: A large number of hydrogeological investigations in Denmark comprising TEM (transient electromagnetic) surveys, reflection seismic surveys, drillings and other methods have been performed during the past 10 to 15 years. These data have brought new geological insight into the uppermost 200 to 300 m of the Quaternary and Tertiary sedimentary successions. Buried tunnel valleys occur in intricate cross-cutting networks within this setting and by using the collected data a map showing the occurrence of the valleys has been produced. Local case studies as well as studies of relations between regional valley distribution and data distribution are used to demonstrate the importance of dense data grids and considerable penetration depths provided by the mapping methods. Buried valleys cannot be properly resolved on the basis of scattered borehole data and seismic data and thus dense data grids with a high lateral resolution are needed to resolve the comprehensive structural variations induced by the valleys. Although TEM data do not offer vertical resolutions as detailed as borehole and seismic data, dense TEM data grids and deep penetration make the method very useful for mapping of buried valleys.

Kurzfassung: In Dänemark wurden in den letzten 10 bis 15 Jahren umfangreiche hydrogeologische Untersuchungen mit TEM, Reflexionsseismik, Bohrungen sowie anderen Methoden durchgeführt. Diese Daten haben neue Erkenntnisse für die Geologie der quartären und tertiären Sedimentabfolge der oberen 200 bis 300 m gebracht. Zusedimentierte Tunneltäler erscheinen hierin in kompliziert verflochtenen Systemen. Durch die jetzt vorliegenden Daten konnte eine Karte erstellt werden, die die Verteilung der Rinnen zeigt. Anhand lokaler Fallstudien und Untersuchungen der Beziehungen zwischen regionalem Rinnenverlauf und Datenverteilung wird die Bedeutung von Kartiermethoden, die dichte Datengitter und große Erkundungstiefen liefern, aufgezeigt. Allein auf der Basis einzelner Bohrungen und seismischer Profile können Rinnen nicht genau kartiert werden, sondern dichte Datennetze mit hoher lateraler Auflösung sind notwendig, um die komplexe strukturelle Vielfalt der Rinnen zu erfassen. TEM-Daten liefern zwar nicht eine so gute vertikale Auflösung wie Bohrungen oder seismische Daten, aber durch die hohe Datendichte und die große Eindringtiefe ist diese Methode sehr wertvoll für die Kartierung von eiszeitlichen Rinnenstrukturen.

Keywords: buried valleys, tunnel valleys, transient electromagnetic, TEM, reflection seismic, hydrogeophysics, mapping

Schlüsselwörter: Verborgene Täler, eiszeitliche Rinnen, Tunneltäler, Transientelektromagnetik, TEM, Reflexionsseismik, Hydrogeophysik, Kartierung

1. Introduction

The Danish water supply is widely based on buried valley aquifers. Most frequently valley infill sediments contain groundwater resources, but the valleys may also act as pathways for contaminants percolating from the surface to deeper aquifers (Sandersen & Jørgensen 2003). Buried valleys also have significant influence on groundwater flow paths (Jørgensen et al. 2008) and affect the practicability of proper stratigraphic correlations (Jørgensen & Sandersen 2008). Therefore, a thorough understanding of the occurrence, architecture and origin of buried valleys is important. Improved insight into the processes giving origin to the valleys will enable us to better predict their occurrence, infill distribution, morphology, dimensions, preferred orientations, substratum etc. and to appropriately model areas comprising buried valleys.

Buried valleys are frequently referred to as tunnel valleys because of the shared morphological characteristics (e.g. Woodland 1970, Huuse & Lykke-Andersen 2000, Jørgensen & Sandersen 2006). The origin of tunnel valleys has long been discussed, but agreement on their precise origin is still

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lacking. However, research into this area has been intensified due to improved investigation methods and increased scientific focus on subglacial processes.

Tunnel valleys are generally described as large, elongated depressions incised into unconsolidated sediments and bedrock beneath marginal zones of large ice sheets. The valleys contain undulating thalwegs with upwards sloping sections that often terminate at the apex of an outwash fan. There is consensus that subglacial meltwater is the primary causative factor of tunnel valley erosion (O'Cofaigh 1996, Huuse & Lykke-Andersen 2000, Jørgensen & Sandersen 2006). The valleys may have served as major subglacial drainage pathways for large volumes of meltwater escaping from the subglacial environment. They are therefore considered as important elements of the subglacial hydraulic system.

The term **tunnel valley** was proposed by Madsen (1921) to describe Danish Late Weichselian valleys, which by Ussing (1903, 1907) were interpreted as meltwater-eroded valleys. The term is not broadly acknowledged or used in all contexts, and other terms such as **incision** (e.g. Wingfield 1990, Ehlers & Wingfield 1991) and **tunnel channel** are used (Clayton et al. 1999).

Traditionally buried valleys have been identified and mapped on the basis of borehole data. As borehole data are normally poorly spaced, it was very difficult to delineate the valleys precisely, and only tentative valley maps were produced in Denmark. One existing map of the Danish Pre-Quaternary surface (Binzer & Stockmarr 1994) gives an overall view of variations in the Pre-Quaternary surface. This map is, however, mainly based on borehole data and the production of the map required extensive interpolation. Furthermore, many buried valleys are relatively shallow, and only valleys with deep erosion into the Pre-Quaternary surface are visualised on this map.

The Danish water supply is based on pure, uncontaminated groundwater from numerous small water works and private wells. As contamination, mainly by nitrate and pesticides, threatens the groundwater quality, protection plans are currently being implemented to preserve the decentralized water supply structure. The threats against the water resources were acknowledged in the 1990s, and by 1998 the Danish Government launched a hydrogeological mapping programme embracing about one third of the Danish land area to secure the resources and thereby establish site-specific groundwater protection zones (Thomsen et al. 2004). The mapping programme comprises several geophysical methods, but the succession below depths of 20–30 m, where the main aquifers are usually situated, has primarily been mapped using the transient electromagnetic method (TEM; e.g. Fitterman & Stewart 1986, Sørensen & Auken 2004) and reflection seismic surveys with shallow focus depths (e.g. Steeples & Miller 1990).

Based on these newly collected Danish hydrogeophysical data, it is now possible to map many buried valleys in detail and it is thus possible to visualize their wide distribution in the Danish subsurface (Sandersen & Jørgensen 2003, Jørgensen et al. 2005, Jørgensen & Sandersen 2006). In the present paper, we demonstrate that dense grids of geophysical data are needed to map buried valleys and describe their dimensions, orientations and interconnections.

2. Regional setting

The Danish landscape is characterised by a variety of outwash plains and hummocky or gently undulating moraines. The highest point reaches 173 m above sea level. The Quaternary subcrop is limestone and chalk in the northern and eastern parts of Denmark, Paleogene heavy clays in a zone from northwest to southeast, and Neogene sands, silts and clays to the southwest (Fig. 1). The Quaternary cover has a thickness of 5 to 100 m, and the Pre-Quaternary surface is generally situated from 50 m below to 50 m above sea level. However, considerable deviation from this general pattern is frequent (Binzer & Stockmarr 1994).

Glacial and glaciofluvial sediments are the most common components of the Quaternary setting, but interglacial deposits also frequently occur. Pre-Elsterian deposits have been described at some localities (Andersen 1965, 1967, Kronborg et al. 1990, Larsen & Kronborg 1994), but deposits from the Elsterian and Saalian glaciations are more widespread. These deposits document at least three ice advances in each glaciation (Houmark-Nielsen 1987, Larsen & Kronborg 1994). Glaciolacustrine and glaciomarine clays from the Late Elsterian are widespread and typically followed by marine sediments from the Holsteinian in Northwest and Southwest Jutland (Jensen 1985, Bruun-Petersen 1987, Knudsen 1987a, 1987b, Ditlefsen 1991). Freshwater deposits from the Holsteinian and Eemian and marine deposits from the Eemian are also found at many locations (Andersen 1965, Houmark-Nielsen 1987, Knudsen 1994, Larsen & Kronborg 1994).

During the Pleistocene Denmark was repeatedly covered by glaciers, either partly or totally. Some glaciers entered the Danish area from the southeast via the Baltic Depression, while other glaciers advanced from the east, north or northeast (Houmark-Nielsen 1987, Larsen & Kronborg 1994). At the Late Glacial Maximum, the northern and eastern parts of Denmark were covered by an ice sheet advancing from the northeast, and the ice margin resided along the Main Stationary Line (Larsen & Kronborg 1994, Houmark-Nielsen & Kjær 2003, Kjær et al. 2003). At that time, large outwash plains were formed in Southwest Jutland and tunnel valleys were eroded in the subglacial environment close to the ice margin (Ussing 1903, 1907, Smed 1998).

3. Methods

3.1 Transient electromagnetics

Originally, during the 1960s and 1970s the transient electromagnetic (TEM) method was developed to explore mineral deposits (Spies & Frischknecht 1991, Fountain 1998). Subsequently, the method has proven to be useful within hydrogeology. TEM surveys performed in connection with hydro-

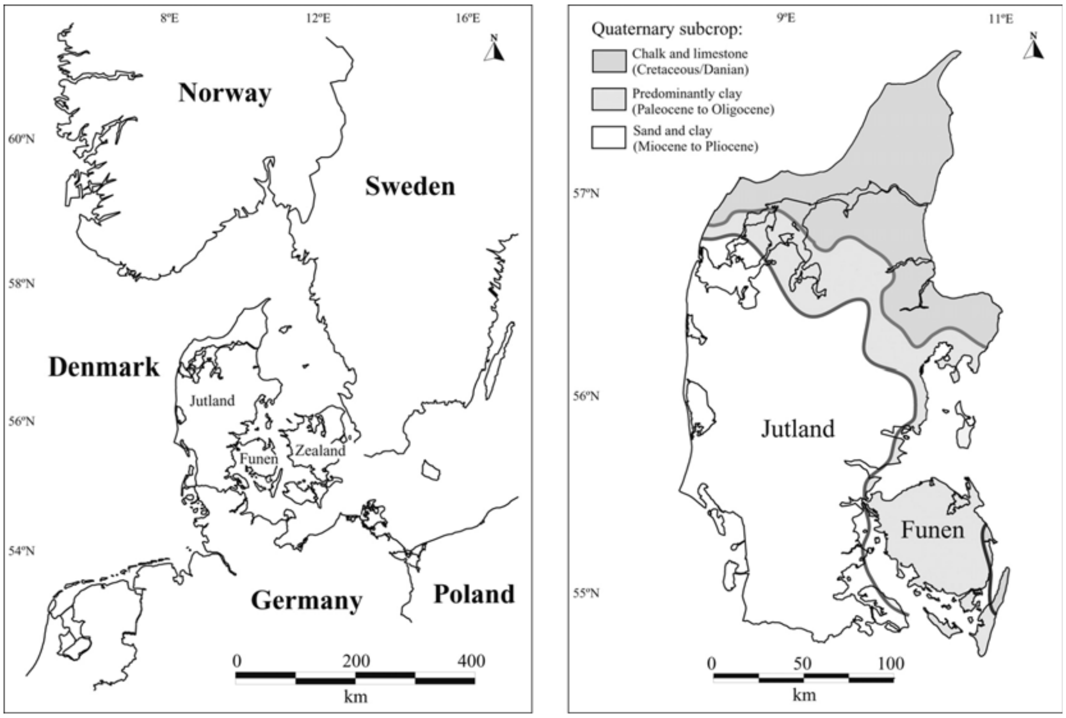


Fig. 1: Location map and map of the Quaternary subcrop (after Sorgenfrei & Berthelsen 1954).

geological investigations were first reported in the 1980s by e.g. Fitterman & Stewart (1986) and McNeill (1990). In Denmark, the first such studies were performed in the early 1990s (Christensen & Sørensen 1998, Poulsen & Christensen 1999, Sørensen et al. 2001), and during the 1990s the TEM method became widely used for hydrogeological mapping.

The TEM method is an electromagnetic method in which a primary current is set up in a large transmitter loop while a responding signal is recorded in a small receiver loop. When the current is turned off abruptly, secondary currents are induced in the subsurface. The secondary currents diffuse downwards and outwards through the subsurface and, as time passes, their magnitude decreases. A secondary magnetic field is produced by the decaying secondary currents and this is measured by the receiver coil as the responding signal from the subsurface.

Traditionally the TEM data have been one-dimensionally inverted, with the measured volume divided into 3–5 layers. Detailed descriptions of inversion procedures are available in Effersø et al. (1999), Danielsen et al. (2003) and Auken & Christensen (2004).

In recent years TEM instrumentation for hydrogeophysical surveys has been developed intensively. A configuration with a 40 × 40 m^2 single-turn transmitter loop employing the Geonics PROTEM 47 receiver was previously widely used in Denmark. The penetration depth of this method is approx. 120–150 m, but it is largely dependent on subsurface resistivity and background noise level (Spies 1989). A standard coverage of 16 soundings per km^2 using the above configuration is a typical solution to the trade-off between sufficient resolution capability, data quality and acceptable survey costs. The 40 × 40 m^2 TEM configuration remains in use for small surveys, but new TEM systems have gradually taken over allowing for deeper penetration and improved spatial coverage. One of the new systems is the HiTEM system (Danielsen et al. 2003) with penetration depths reaching 250–300 m. While the HiTEM system is a single-site system, the helicopter-borne SkyTEM system (Sørensen & Auken 2004) measures continuously along flight lines. This system reaches penetration depths similar to those of the HiTEM system, but continuously obtained data significantly increase data quality. The development of interpretation algorithms follows the development of instrumentation, and the continuously measured data are inverted by laterally constrained inversion (LCI; Auken & Christiansen 2004). In this approach, layer resistivities and boundaries are coupled using a variance reflecting the expected lateral resistivity variations. Resistivity equivalence and layer suppression problems are significantly reduced with the use of LCI.

3.2 Reflection seismic data

Reflection seismic data originate from multi-channel seismic reflection surveys, generally carried out with two separate field applications; either by a source of small dynamite charges and grounded geophones or by a vibrator source and towed land-streamer geophones (Doll et al. 1998, Veen & Green 1998, Vangkilde-Pedersen et al. 2003). A typical field layout counts 48–96 geophones with spacings of 1.25–5 m and shot/vibration point spacings of 5 or 10 m. All data are acquired using the common mid-point (CMP) technique.

The shallowest reflectors resolved are typically found at depths of 30 to 50 m, and penetration depth is at least 500 m. The data quality depends heavily on the character of near-surface sediments. Optimal quality is obtained in areas with clayey soils and without shallow unsaturated sand layers.

3.3 Borehole data

All borehole data are stored in the national database, Jupiter, hosted and maintained by the Geological Survey of Denmark and Greenland (GEUS). This database comprises well construction logs, lithological logs, hydraulic data, etc.

The vast majority of borehole data originate from water well drillings, but a limited number of exploratory drillings performed for hydrogeological purposes are also available. The boreholes are generally performed using the air-lift technique in which case high quality sediment samples are typically collected for every drilled meter, or as rotary drillings generally yielding sediment samples of poor quality. Due to the different drilling methods used and the age of the boreholes, a large part of the borehole data is of poor quality, making geological interpretations difficult. On average, less than one borehole per km^2 reaches 50 m in depth and only one borehole per 15 km^2 reaches 100 m (Sørensen et al. 1995).

3.4 Other data types

Another method used for mapping of buried valleys is gravimetry (e.g. Wolfe & Richard 1996, Thomsen 1997, Gabriel 2006). This method requires that the valley fill generates bulk density variations relative to the surrounding sediments. Furthermore, the geoelectrical methods, Continuous Vertical Electrical Sounding (CVES; e.g. Bernstone & Dahlin 1999) and Pulled Array Continuous Electrical Sounding (PACES; Sørensen 1996), may be used for buried valley mapping. However, their penetration depths are limited and only the upper part of shallow valleys can be detected with these methods.

4. Mapping of buried valleys

4.1 Mapping concept and current map

All available and relevant geophysical and lithological data from the Danish onshore area are continuously evaluated and examined to map and describe buried valleys (e.g. Sandersen & Jørgensen 2006). A set of criteria has been developed to obtain a high degree of certainty and objectivity in the process of valley mapping. The most important criterion is that the lateral extent and the orientation of the valleys must be unambiguously expressed in the data. Therefore, no interpolations between the surveyed areas are made, and the map should therefore be considered a representation of the minimum occurrence of buried valleys. Using the criteria, more than 2500 km of buried valleys have presently been mapped (Fig. 2).

4.2 Interpretation of borehole data

Mapping of buried valleys on the basis of borehole data is mainly performed in two ways: (1) recognition of typical valley fill sediments in boreholes and mapping of the lateral distribution of these, and (2) modelling the morphology of, or mapping discontinuities in distinct and widespread layer boundaries or horizons.

Sediments typically found in valleys are glaciolacustrine clay and various types of interglacial deposits. If sediments of these types are found in a group of boreholes they may mark the outline of a buried valley, particularly if they are found close to or just below sea level (Sandersen & Jørgensen 2006). Within the Danish geological setting, the most prominent example of a distinct and widespread layer boundary which frequently reveals buried valleys is the Pre-Quaternary surface. The Pre-Quaternary surface varies in composition from mica sand, silt and clay to heavy impermeable Paleogene clay and various kinds of limestone and chalk deposits. Provided the lateral borehole data density and quality are high, a representative morphology of the surface may be constructed and may reveal valley structures. Typically the valleys are not penetrated entirely by the boreholes, but if boreholes indicate Quaternary deposits below the general level of the Pre-Quaternary surface, this may indicate the presence of buried valleys. An example of a Quaternary deposit which is widespread and easy to recognize in borehole samples is clayey till. Clayey till is also easily distinguished from tertiary deposits, and if found at deep levels it can be an indicator for buried valleys.

The poor coverage combined with a generally shallow borehole depth makes boreholes difficult to use for mapping of buried valleys, which are frequently deeper than 100 m. Additionally the data are frequently encumbered with a high degree of uncertainty arising from the different and sometimes unauthorised drilling methods used, casual sampling and handling of sediment samples, poor sample quality, poor sample description and interpretation, etc.

4.3 Interpretation of TEM

Typical resistivity values for various freshwater-saturated sediments related to the buried valleys estimated from comparisons between TEM data and borehole logs in Denmark are listed in table 1 (Jørgensen et al. 2003b).

As an electromagnetic diffusion method, the resolution capability of the TEM method decreases with depth. The general experience is that shallow 15–20 m thick layers can be resolved, while layers at 100 m depth must be more than 20–50 m thick to be resolved (e.g. Jørgensen et al. 2003a, b, 2005).

Also, the lateral resolution capability of 3D structures decreases with depth (e.g. West & MacNae 1991). Therefore

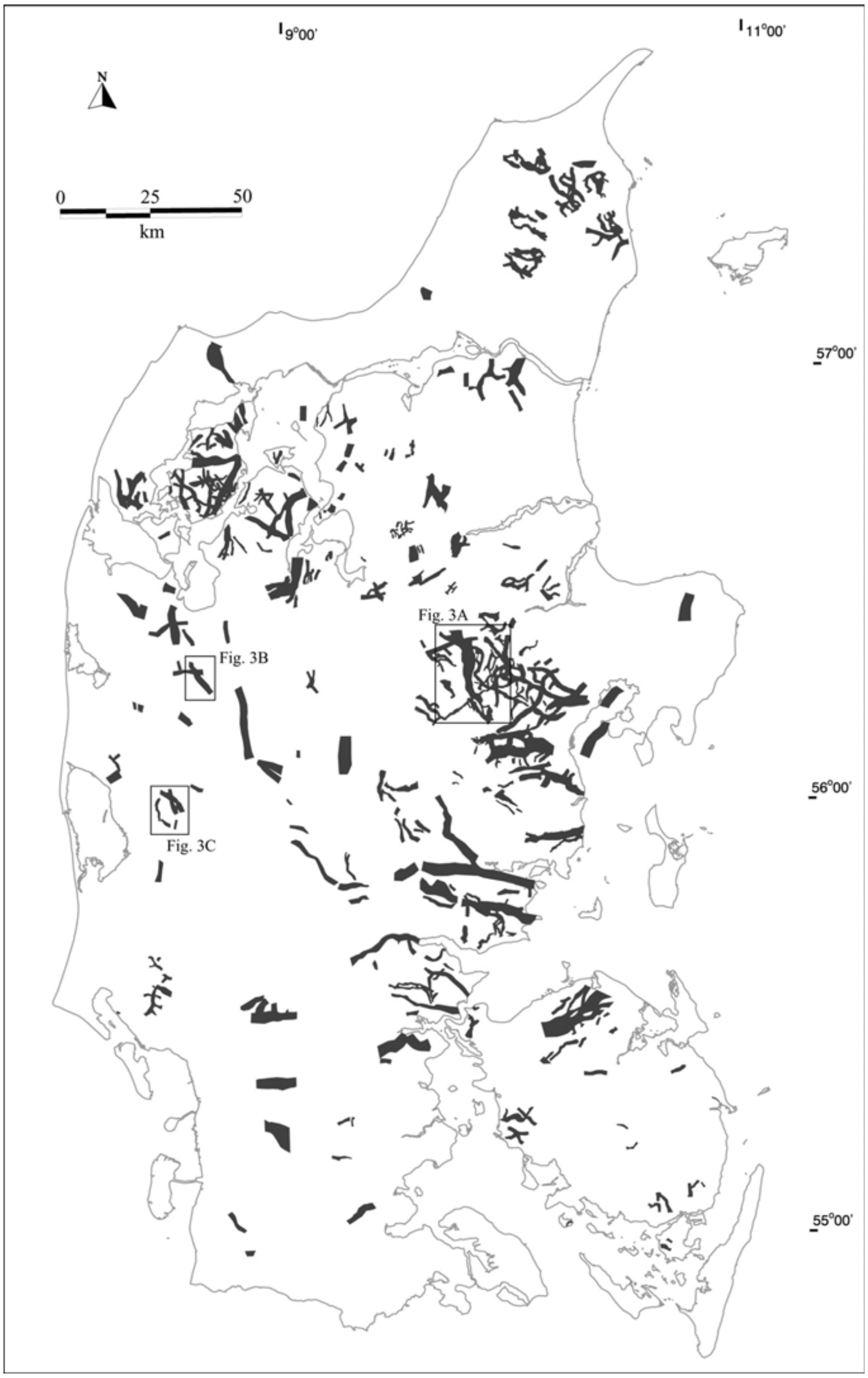


Fig. 2: Mapped buried valleys in Jutland and Funen. Locations of valleys shown in figure 3 are indicated.

Tab. 1: Estimated resistivity values for sediments related to buried valleys in Denmark (modified from Jørgensen et al. 2003b).

Sediments	Resistivity [ohmm]
Meltwater sand and gravel	> 60
Clayey till	25–50
Glaciolacustrine clay	10–40
Neogene mica silt/sand	> 40
Neogene mica clay	10–40
Paleogene clay	1–12
Danian limestone	> 80

3D structures are less resolvable and become more diffuse with depth. Consequently, and of special importance for the mapping of buried valleys, are the effects arising in connection with valley walls. Steep slopes will not be correctly imaged in TEM data and will normally appear with less steep slopes (Danielsen et al. 2003).

The inverted TEM models are typically presented in interval resistivity maps, in elevation maps of low resistivity layers (Fig. 3) and in cross-sections to facilitate the geological interpretation (e.g. Jørgensen et al. 2005). The interval resistivity maps are normally produced in 10 m intervals, where resistivity values from each TEM sounding model layer are averaged within each interval. Interval resistivity maps are useful for the visualisation of TEM survey results, as the complete succession can be embraced by intervals from surface to the maximum penetration depth. Elevation maps of deep-seated low-resistive layers are calculated from selections of the deepest model layer with resistivities below a given threshold in the inverted models.

Cross-sectional presentations of TEM data are frequently used for comparison with other data or if TEM models need to be studied in detail. The TEM models are often shown on the sections as narrow vertical bars. The results of TEM surveys can also be visualised on cross-sections by means of a dissected succession of interval resistivity grids (Jørgensen et al. 2005, Jørgensen & Sandersen 2006).

The challenge associated with geological interpretation of TEM data lies in the conversion from model resistivity to lithology and from lateral model layer geometry to structural reality. When making this conversion, several factors must be considered: (1) identification and exclusion of coupled and otherwise noise-infected soundings, (2) vertical and horizontal resolution capability, (3) resistivity values of survey area lithologies and (4) pore water ion content (Jørgensen et al. 2005). Experience with geological interpretation of TEM data and understanding how subsurface resistivity images may be understood and interpreted in geological terms is primarily achieved through comparison with borehole data (Jørgensen et al. 2003a).

The most successful mapping of buried valleys is attained where a substratum of low-resistive Paleogene clay is located within the uppermost 150 m. Buried valleys are usually deep enough to be incised into this surface and the resistivity contrast clearly reveals both floor and walls (e.g. Fig. 3A). The resistivity contrasts between the Paleogene clays and the Quaternary sediments will nearly always be detectable. Such valley images are frequent in large parts of East Jutland. In the western part of Jutland, however, valleys are usually cut into sandy Tertiary sediments, for which reason their outline may, in many cases, only be determined on the basis of infill sediment characteristics. Valleys filled with sandy deposits with resistivities close to those of the surrounding sediments may therefore remain undetectable for the TEM method (Fig. 3B). If mapped at all, the lateral extent of buried valleys in sandy environments is often inaccurate. However, if the fill material comprises clay-rich deposits like clayey till or glaciolacustrine clay, the valleys may easily be mapped (Fig. 3B). In some parts of West Jutland, sections of the Miocene succession are composed of silty mica clay with medium resistivity levels. If such layers have been incised by a buried valley subsequently filled with sandy sediments, the valley outline will appear as a high-resistive structure (Fig. 3C).

A special feature of the valleys is that they normally contain cut-and-fill structures filled with varying types of sediment (Jørgensen et al. 2003a, b, Sandersen & Jørgensen 2003, Jørgensen et al. 2005, Jørgensen & Sandersen 2006). Such cut-and-fill structures are seen as alternating longitudinal structures indicating sequences of infill of single incisions at different levels. It is often difficult to determine whether the valley exposed in the data is only a part of a buried valley (i.e. one cut-and-fill structure) or an entire buried valley. Likewise, different valley generations can occur in very complicated crosscutting networks and are therefore occasionally impossible to delineate. If undetected valleys crosscut older valley sediments, only the missing TEM response in the crosscut area marks the existence of the younger valley; in other words, the presence of one valley reveals the presence of the other (Fig. 3B).

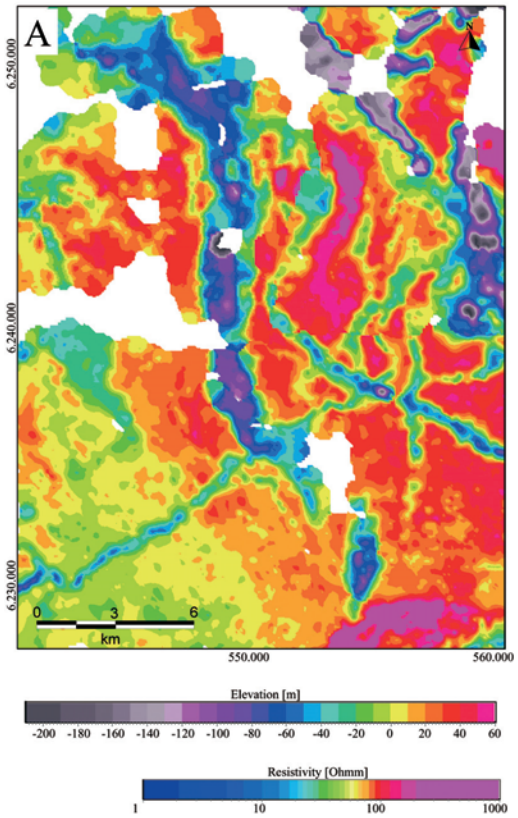
4.4 Interpretation of seismic data

With the reflection seismic method buried valley outlines and internal structures of the infill sediments can be resolved. The method is particularly important in areas where the TEM method encounters problems due to poor electrical resistivity contrasts. Seismic surveying is not performed as frequently as the TEM method, and in relation to buried valleys it is typically used to confirm their presence and to map internal valley structures (Fig. 4). If the data is of a low quality, buried valleys can occasionally be detected by occurrence of lateral shifts in the data quality along the section, or by velocity-induced structures in the underlying strata (Jørgensen et al. 2003a). Erosion surfaces within the valleys (cut-and-fill) appear as coherent high-amplitude reflections or as indistinct reflections. However, the surfaces can sometimes only be identified by reflection terminations. As the seismic data do not resolve the uppermost layers properly, the shallow part of the valleys cannot be mapped by use of seismics. Conversely no restrictions apply when mapping very deep valleys. If high-quality data are obtained, the method may be used – as the only method – to preclude the existence of the deep buried valleys by showing a lateral, uneroded sequence of layers.

5. Results and discussion

5.1 Applicability of methods in buried valley mapping

The extensive use of geophysical methods within groundwater mapping combined with the analysis of borehole data has provided valuable experience about advantages and disadvantages of the methods in connection with mapping of buried valleys. The most important factor for the mapping of buried valleys is that the area has to be densely covered by data. This need for dense data grids is exemplified by a case from Rækker Mølle (Fig. 5) located in West Jutland. In this area borehole data frequently indicate depressions in the Pre-Quaternary surface, which primarily consists of Miocene mica clay, silt and sand. The area is 113 km^2 and the national borehole database, Jupiter (GEUS 2006), contains 489 boreholes exceeding 10 m in depth. However, the boreholes must be relatively deep in order to provide useful information about the existence of buried valleys, and only 93 boreholes



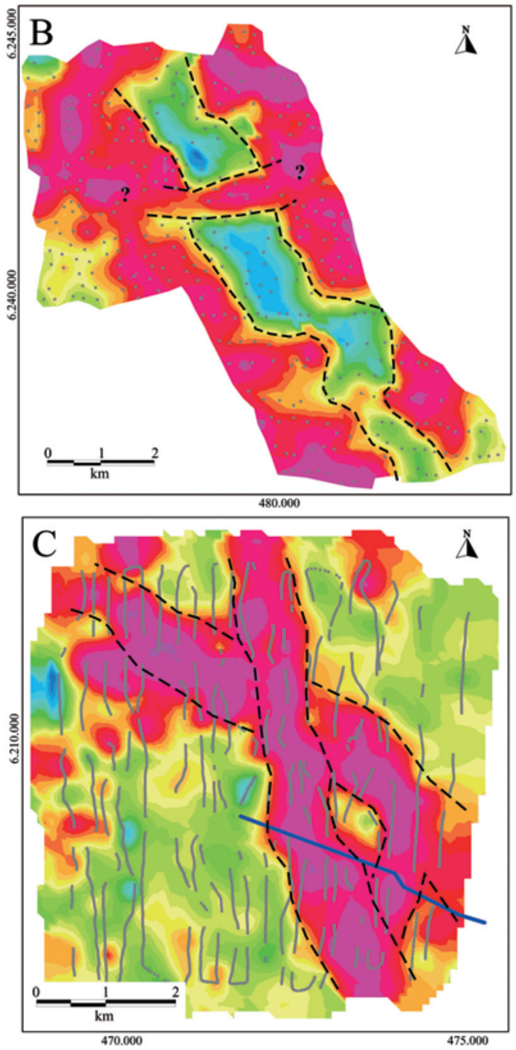


Fig. 3: Examples of buried valleys seen in TEM data. For location see figure 2. Coordinate system in metres (UTM zone 32/euref 89). A: Contoured surface of the low-resistive bottom layer (< 12 ohmm) in TEM soundings acquired in ground-based and SkyTEM surveys in an area northwest of Aarhus. The surface largely coincides with the surface of the Paleogene. B: Interval resistivity map (30–40 m below sea level) from an area southwest of Holstebro. The map shows a buried valley filled with low-resistive clay. A younger valley filled with high-resistive deposits cross-cuts the area and can only be detected where it crosses the older valley. Valley outlines are shown with dashed black lines, TEM soundings with grey dots. C: Interval resistivity map (50–60 m below sea level) from the area of Rækker Mølle. Two buried valleys filled with high-resistive deposits are incised into medium-resistive layers of the Miocene. Valley outlines are shown with dashed black lines, TEM soundings with grey dots/lines. The seismic line shown in figure 4 is indicated by a blue line.

are more than 40 m deep. Furthermore, only a limited number of the boreholes have detailed sediment sample descriptions and lithological interpretations. The borehole data were examined and divided into two groups, one group indicating Pre-Quaternary sediments within the uppermost 30–40 m, and one group with Quaternary sediments reaching depths of more than about 30–40 m. In all, only 52 boreholes yielded information that could be used for valley mapping. Although some of these boreholes indicated buried valleys, it was impossible to delineate valleys on the basis of the boreholes alone (Fig. 5). Several seismic lines have been collected in the area and most of these data are of high quality (Fig. 4). Several deep buried valleys were found on the seismic lines, but even though the lateral coverage of seismic lines was relatively dense in the area, the valleys could not be interconnected and thus could not be mapped. Even if borehole data were taken into account, the actual extent and orientations of the valleys remained obscure. Not until a dense grid of SkyTEM data were collected (Foged & Westergaard 2006; Fig. 3C) the outlines of the buried valleys appeared. This SkyTEM survey covered an area of about 35 km^2 and 125 km of data were collected along lines with a spacing of 250 m. A system of SE–NW striking, 1–2 km wide valleys with high-resistive infill could be outlined among sediments with medium resistivitiy levels (Fig. 3C). The locations of the valleys as found in the SkyTEM data correspond to the buried valleys found on the seismic lines (Fig. 4). On the basis of seismic data the depth of the valleys was estimated to exceed 200 m. Based on the SkyTEM survey, a deep exploratory drilling (GEUS Jupiter, archive no. 93.1094) was performed

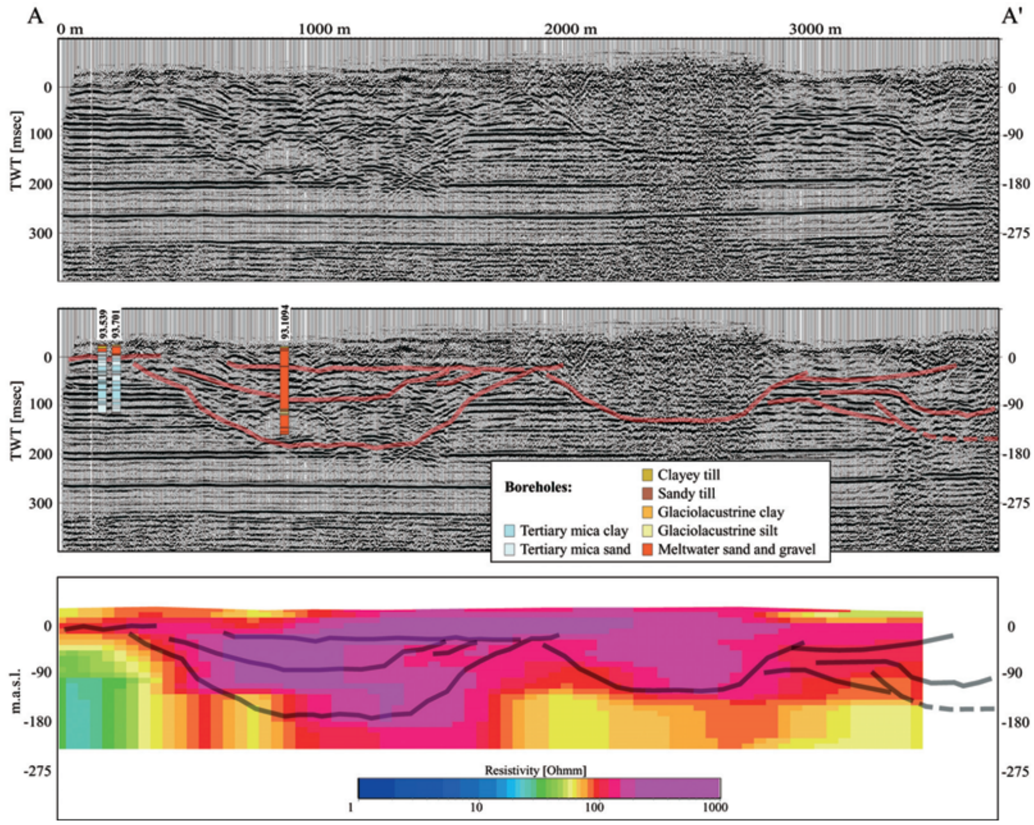


Fig. 4: Three panels showing the same cross section through the Rækker Mølle area, see fig. 3C and 5 for location. Upper panel: Seismic data. Seismic velocities of about 1800 m/s are assumed for the depth scale shown on the right side of the section. Seismic data collection and processing by COWI (www.cowi.com). Middle panel: Interpretations of major incisions and their internal structures are highlighted in red on the seismic data. Lithological borehole logs from three deep drillings are projected and superimposed onto the section from distances of up to 300 m. Lower panel: Interpolated and dissected succession of interval resistivity grids calculated from the SkyTEM data. Interpretations based on the seismic data (as seen on the middle panel) are indicated with black lines.

centrally in the SSE–NNW striking valley (Figs. 4 and 5). The drilling confirmed the existence of the valley because no Tertiary sediments were found and because it showed that the infill sediments were predominantly composed of meltwater sand. The valley floor was not reached at a depth of 193 m. The sand corresponds to the high resistivities (> 100 ohmm) found in the SkyTEM data, and the surrounding layers showed medium resistivity level (30–40 ohmm) corresponding to silty Tertiary mica clay (e.g. GEUS Jupiter, archive no. 93.539 and no. 93.701). As seen in figure 5, there are some contradictions between the borehole and SkyTEM data: Layers which were interpreted as Tertiary sediments in the boreholes were found in areas where the SkyTEM data showed the presence of valley structures. There was, however, close correspondence between the SkyTEM data and the seismic data, and a possible reason for the discrepancy may be lithological interpretation errors of borehole samples. Erroneous interpretations of borehole samples are common in areas where Tertiary sands are found below meltwater sand. The meltwater sand may be dominated by reworked Tertiary sand and therefore a distinction between the sand types can be very difficult. The Tertiary layers may also represent glaciotectonic rafts replaced and now constitute a part of the valley fill. The difficulties related to interpreting boreholes properly complicate the use of borehole data in buried valley mapping. Sometimes they even hamper correlation between data points, and if no geophysical data are available, erroneous correlations between poor quality borehole data may result in wrong outlines of the valleys. Three segments of buried valleys are also found in the southern part of the Rækker Mølle area outside the SkyTEM surveyed area (Fig. 5). These valleys were outlined by a dense grid of gravity measurements (Thomsen 1997, Thomsen et al. 1999).

5.2 Data grid density

The numerous hydrogeophysical surveys in Denmark show that buried valleys occur in complicated patterns and because the density of boreholes generally is low and borehole data are difficult to interpret and use, only rough valley outlines can be mapped from borehole data alone. Consequently, geophysical data in dense data grids are needed for valley mapping. In the case of Rækker Mølle only 52 boreholes were found suitable for buried valley mapping, and some of these even provided misleading information. The resulting density of boreholes with usable information is therefore only 0.46 boreholes per km^2. In comparison the typical density for

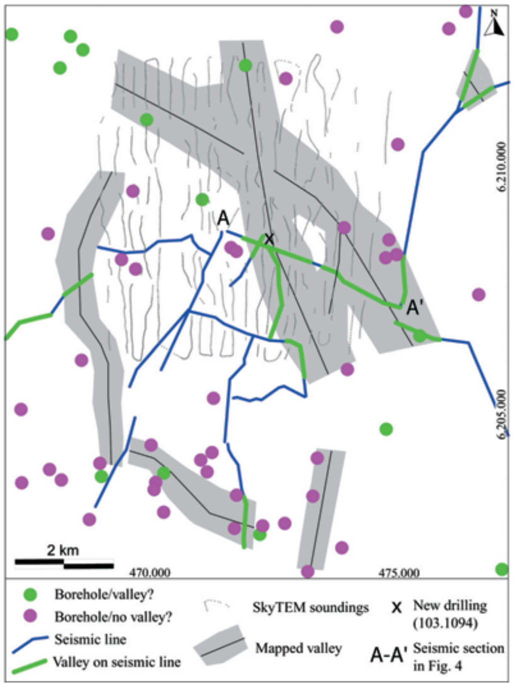


Fig. 5: A selected area with buried valleys in the western part of Jutland (Rækker Mølle area). The mapped valleys and the data used for the mapping of the valleys are shown. Coordinate system in metres (UTM zone 32/euref 89).

SkyTEM is four lines of continuously collected soundings per km^2, and the corresponding figure for ground-based TEM is 16 soundings per km^2. This means that TEM provided about 35 times as many data points as the existing borehole database. Furthermore, only 11 boreholes reached deeper than 100 m, and because some of these are clustered and some lack geological sediment sample descriptions, borehole information from depths of more than 100 m are only found at 6 sites within the Rækker Mølle area. With the setup used in the SkyTEM survey, a penetration depth of about 200 m is obtained for all TEM soundings. Compared to the boreholes, the TEM soundings offer a lower layer resolution, but this is in fact of minor importance when mapping buried valleys. The subsurface is three-dimensional, has a complex architecture and thus cannot be considered as a simple layered 2D environment in which detailed successions can be correlated over long distances.

5.3 Regional valley distribution

The need for dense data grids can also be discussed on a regional scale. Together with all mapped buried valleys, all TEM surveyed areas and high-resolution seismic lines are specified on the map in figure 6. A close inspection of the correlation between the mapped valleys and the two types of surveys indicates a clear relationship between the TEM surveyed areas and a high density of mapped valleys. Conversely, there is no clear correlation between areas with seismic surveys and valley occurrence. Most seismic surveys are performed in the middle and southwestern parts of Jutland, where relatively few buried valleys are mapped, whereas most TEM surveys are performed in the eastern, northwestern and northern parts of Jutland, where the highest density of buried valleys is mapped. These relations could imply that buried valleys are more efficiently mapped with the dense data grids of the TEM method in comparison to the seismic method, which only produces data along a few lines. However, this conclusion presupposes an even distribution of the buried valleys within the entire mapped area. The apparent distribution of the mapped buried valleys as seen on the map may also reflect a true distribution which could be dependent on other factors such as the character of the subsurface. A comparison with the Quaternary subcrop (Fig. 1) reveals that most mapped buried valleys are found within the area with clayey Tertiary subcrop. If the distribution seen on the map is a true distribution and not caused by the irregular regional data coverage, the ability of the valleys to be formed in the area with a clayey Tertiary subcrop may have been greater than in neighbouring areas with more permeable substrates. The reason for this might be that subglacial meltwater could not escape through the impermeable clayey substrate and hence was forced to follow the ice/bed interface. There may also have been a relationship between the extent of ice margins and the subcrop. The transition from a clayey subcrop to a sandy subcrop in south- and westward directions may have caused some of the glacier ice margins to reside here, allowing valleys to erode within the clay dominated zone and not farther south and west.

However, as seen in figure 7, many valleys do exist in the western part of Jutland, regardless that only few valleys have been mapped here. In the seismic sections, many buried valleys are seen to crosscut this area, but they cannot be mapped without dense data grids – as seen for the Rækker Mølle area (Fig. 5). Hence, the map in figure 6 does not give a complete picture of the actual valley distribution. Future investigations providing a more even data coverage of Denmark will show to which degree factors such as subcrop permeability may have affected the distribution of buried valleys.

5.4 Other methods

On a small as well as on a larger scale it is evident that dense data grids are needed to outline buried valleys in Denmark. As demonstrated above, the need for dense data grids has become apparent as huge amounts of TEM data corresponding to large areas of Denmark have been collected and examined. Other geophysical methods enabling the collection of dense data grids may also provide the spatial information needed for mapping. The PACES method (Sørensen 1996) is typically not penetrating sufficiently deep to be able to map the valleys, but the Helicopter-borne ElectroMagnetic (HEM) method may prove useful in certain areas where valleys are situated at intermediate depths (Siemon et al. 2004). The gravity method is another area-covering method which has proved successful for buried valley mapping. This method is, however, relatively expensive to perform and will primarily

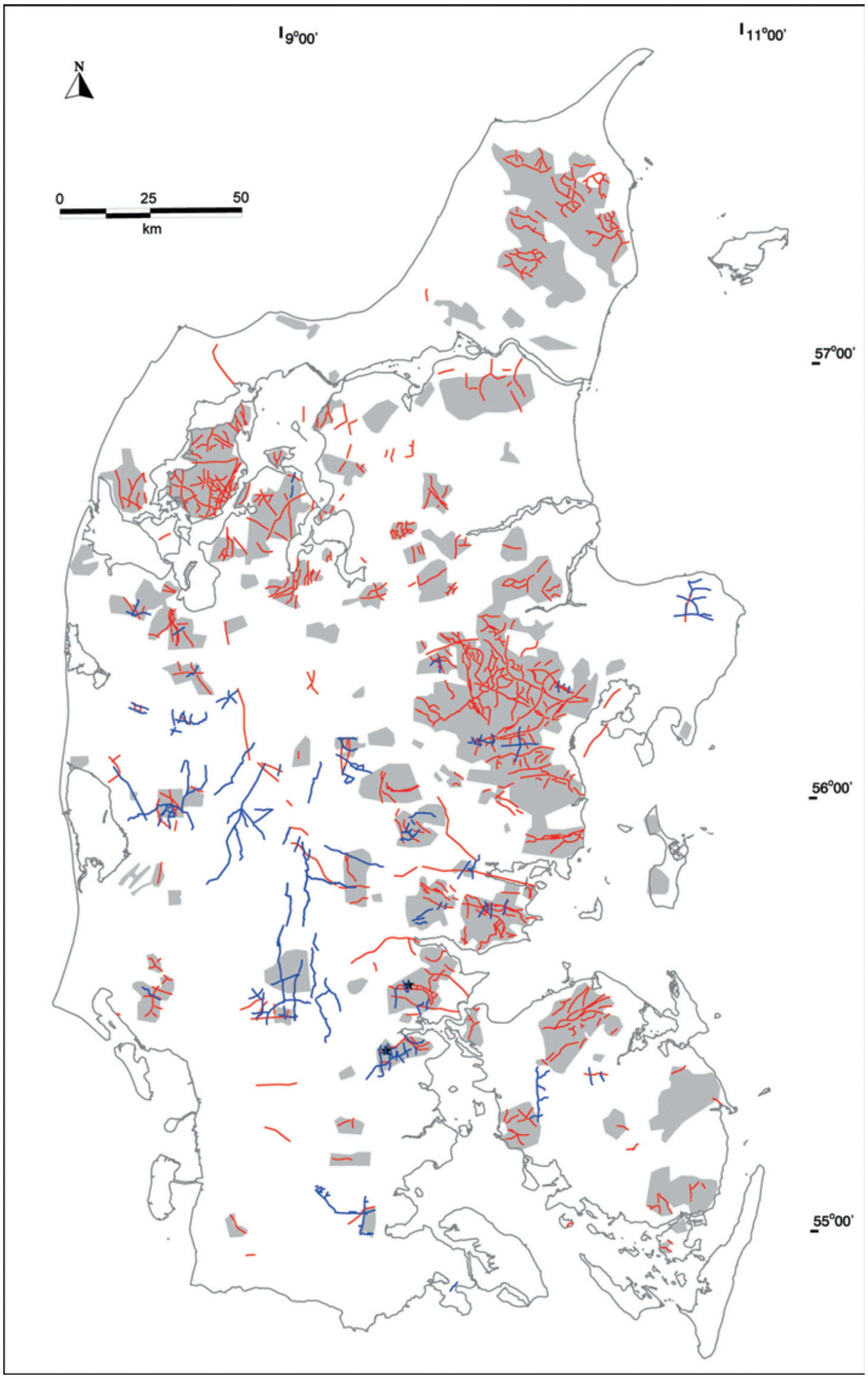


Fig. 6: Mapped buried valleys, TEM surveyed areas and high-resolution seismic sections in Jutland and Funen. Mapped buried valleys shown with red lines, seismic sections with blue lines and TEM surveyed areas in grey.

be useful in areas where electromagnetic methods cannot be applied.

Recent near-surface interpretation of 3D seismic data from the North Sea has reached the same conclusions concerning dense and complex networks of buried valleys as seen onshore in Denmark (Praeg 2003, Lonergan et al. 2006, Kristensen et al. 2007). 2D seismic grids with line spacings of down to a few km was found insufficient for the mapping of buried valleys, but by using the 3D seismic technology, the spatial resolution improved dramatically and features like tunnel valleys could easily be outlined (Praeg 2003). It was also established that mapping of buried valleys is better supported by dense grids of seismic lines (< 1 km) with a low vertical resolution than by poorly spaced seismic lines (5–15 km) with a high vertical resolution (Praeg 2003). This can be compared with the situation onshore where dense grids of TEM data provide a better mapping result than the widely spaced borehole data with a higher vertical resolution.

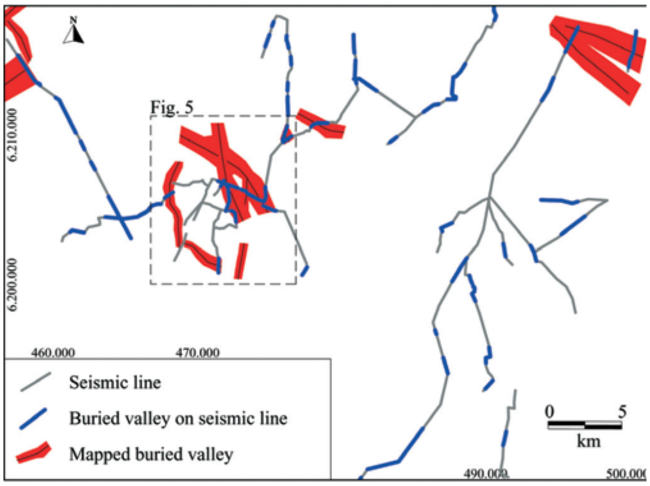


Fig. 7: A selected area in the western part of Jutland showing the high frequency of buried valleys found in seismic data. Correlations between the seismic lines require dense geophysical data grids. The Rækker Mølle area (Fig. 5) is marked. Coordinate system in metres (UTM zone 32/euref 89).

Even though many buried valleys are revealed by the TEM method in Denmark, it is important to stress that this one method does not fulfil all the requirements of buried valley mapping. In some cases valleys are clearly imaged by the data, but it is generally necessary to verify valleys indicated by the TEM data by comparing such data with data obtained by other types of geophysical surveys or by borehole data. If the objective is not just to outline the buried valleys but to model or investigate buried valleys in detail, the need for other data increases further. In such cases a combination of TEM, seismic data, pre-existing borehole data and exploratory drilling data seems to comprise the most optimal investigation strategy (Jørgensen et al. 2003a).

5.5 Perspectives

The chosen mapping concept including collection of dense geophysical data grids has brought a new overview of the frequently occurring buried valleys in Denmark. This has provided us with a new map, which is very different from other types of maps with buried valleys, such as the Pre-Quaternary surface map (Binzer & Stockmarr 1994) or other buried valley maps based on low density data grids. Maps based on low density data grids may therefore be highly inaccurate in areas with intricate buried valley systems like in Denmark. If used, uncertainties induced by correlation between widely spaced boreholes or seismic sections have to be considered carefully. Valleys and valley systems may be incorrectly imaged or even overlooked and these uncertainties have to be considered, for instance when the maps are used for further investigation of buried valleys. Especially if valley distribution patterns are to be studied, the most credible maps will be those based on dense data grids and with a high degree of objectivity in the data correlations.

6. Conclusions

Buried valleys occur in extensive and complicated patterns in the Danish subsurface and can only be properly mapped where dense data grids are available. Such data grids must be composed of data with a penetration depth covering the level where the valleys occur and an ability to resolve the valley structures. The TEM method which provides dense data grids has proven to fulfil these demands and to correctly map the valleys, but in areas where the resistivity contrasts are low the TEM method may be less useful. In such cases the seismic method may be used, although it is very costly when applying closely spaced lines. Borehole data can be difficult to use for buried valley mapping but are, nevertheless, important for the validation of buried valleys exposed in geophysical data. Boreholes are often too widely spaced for valid correlation and rarely constitute a sufficient data basis for the mapping of buried valleys.

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