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Geophysical investigations of buried Quaternary valleys in Denmark: an integrated application of transient electromagnetic soundings, reflection seismic surveys and exploratory drillings

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Abstract

Buried Quaternary valleys are important hydrological structures in Denmark. Geophysical and geological investigations were performed to develop an integrated interpretational methodology for a quantitative description of their structure and lithology. Three buried valleys in central eastern Jutland, Denmark were investigated using the transient electromagnetic (TEM) sounding method, two-dimensional reflection seismic profiling, vertical seismic profiling (VSP) and analyses of data and samples from exploratory drillings. The most advantageous approach for fieldwork is the sequence of (1) resistivity mapping with TEM to identify the buried valleys, (2) reflection seismic profiling across the valleys, (3) location and drilling of exploratory drillings, and (4) vertical seismic profiling. The accuracy of the geological interpretation is improved substantially by combining the structural information from the seismic profiling with the predominantly lithological information derived from the TEM soundings. Sequential interpretation of the data sets is optimal when variations in geology are low to moderate. Strong variations may, however, lead to breakdown of the interpretation models. Buried valleys occur primarily as cut-and-fill structures filled with Quaternary deposits consisting of till, glacio-lacustrine clay/silt and meltwater sand and gravel. The seismic velocity of the tills is considerably higher (2150 m/s) than it is for the other valley-fill sediments (1750 m/s). Resistivities of the clays are distinctly less than those of sands and gravels. Hence, classification of these parameters gives indirect information about the lithology of the valley fill as well as the structure.

Keywords: Buried valleys; Reflection seismic; Vertical seismic profiling; Transient electromagnetics; TEM; Hydrology

1. Introduction

Buried valleys have been utilised for water supply in Denmark for about a century, and their onshore existence is well documented by water supply wells. Only recently, a thorough account on the buried valleys based on all available geological and geophys-

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ical data has been worked out for the western part of onshore Denmark (Jørgensen and Sandersen, 2000; Sandersen and Jørgensen, 2002, 2003). In the last few years, the county administrations in Denmark have conducted systematic investigations of buried valleys as part of a targeted effort to locate and characterize well-protected aquifers. Buried valleys as studied by reflection seismic surveys in the North Sea region have been reviewed by Huuse and Lykke-Andersen (2000b).

Buried valleys, characterized as overdeepened with irregular longitudinal bottom profiles as well as irregular cross-sections, are thought to be products of subglacial meltwater erosion and, in some cases, probably in combination with glacial scouring (Huuse and Lykke-Andersen, 2000b). The dimensions of the buried valleys in Denmark vary between 0.5 and 4 km in width, 25 to 350 m in depth, and they have lengths of up to roughly 30 km for onshore structures and 100 km offshore (Huuse and Lykke-Andersen, 2000b; Jørgensen and Sandersen, 2000; Sandersen and Jørgensen, 2002, 2003). In the most intensively studied areas in Denmark, valleys belonging to more than one generation form intricate braided patterns dissimilar to subaerially formed dendritic drainage patterns. The primary factors controlling location, size and shape of the valleys appear to be gross structure of the ice sheet in combination with lithology and structure of the substratum of the ice.

Increased knowledge of the structure and lithology of buried valleys and how they appear in geophysical data makes it possible to construct geo logical models without extensive drilling. To attain this knowledge, it is necessary to investigate buried valleys thoroughly including exploratory drillings to get exact lithological information. An integrated approach for this is necessary for efficient and accurate investigations. We present results and experiences from investigations of three buried valleys from Vejle County in central eastern Jutland: Hornsyld, Vonsild and Viuf, shown in Fig. 1. The studies include an integrated interpretation of TEM soundings, reflection seismic and VSP data, and analyses of exploratory drillings.

2. Geological setting

The pre-Quaternary succession in Jutland consists of Upper Cretaceous and Danian limestones overlain by Paleogene marls and heavy clays followed by Neogene clays, silts and sands (Sorgenfrei, 1954). Dipping SW and W, towards the North Sea Basin, the succession of older units subcrop the Quaternary

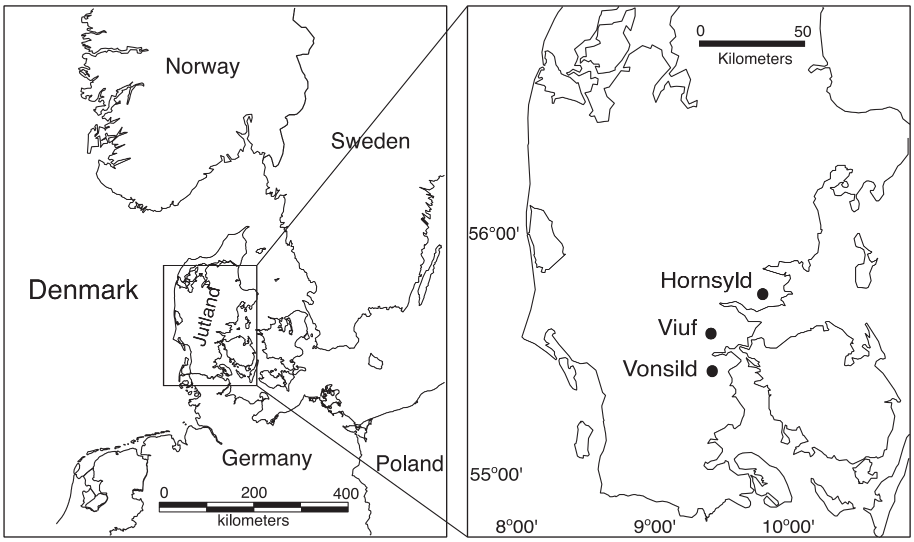

Fig. 1. Location maps showing the Hornsyld, Viuf and Vonsild study areas.

to the N and NE; the younger to the S and SE. In the study area, upper Cretaceous and Danian limestones are generally found at depths of 200–300 m. Paleogene marls and clays and Neogene clays, silts and sands attains a thickness of about 200 m.

Denmark has repeatedly been covered by ice sheets during several glaciations (Houmark-Nielsen, 1987; Kronborg et al., 1990; Larsen and Kronborg, 1994), and it is believed that the buried valleys may have formed during these (Sandersen and Jørgensen, 2002, 2003). The fill sediments in the valleys consist mainly of glaciofluvial sediments, glacio-lacustrine and marine clays, and glaciogenic (till) materials with local intercalations of interglacial lacustrine and marine deposits. Holsteinian interglacial deposits and Elsterian glacial deposits are identified in a number of buried valleys. Thus, it is likely that at least some of the Danish buried valleys were formed during the extensive Elsterian glaciation (Sandersen and Jørgensen, 2002, 2003). This is in good accordance with some of the German buried valleys, which also are suggested to be of Elsterian age (e.g. Ehlers et al., 1984).

Some subglacially formed valleys are also exposed at the surface. Exposed valleys, frequently seen in the present-day landscape in Jutland, gave rise to the theory of subglacially formed tunnel valleys created during the Weichselian glaciation (Ussing, 1903, 1907). Later discoveries of buried valleys that underlie exposed valleys suggest that the formation of valleys is a multiphase erosional process.

3. Field methodology

3.1. Transient electromagnetics (TEM)

The TEM method is an induction method with which the magnetic field due to a pulse of current in a transmitter loop is measured in the time domain (Nabighian and Macnae, 1991). We refer to measurements from about 10 μs to 5 ms using a 40×40 m^2 transmitter loop carrying a steady current of about 3 A as a “conventional” sounding. The penetration depth for a conventional TEM sounding is normally not greater than about 130 m depending on the average resistivity of the subsurface and on the level of the natural background noise (Spies, 1989). Under ideal circumstances, depth of the penetration can reach 150 m.

Recently, a high moment TEM (HiTEM) system was developed for greater depth of penetration (Danielsen et al., 2002; Sørensen et al., 2003). A HiTEM sounding is acquired in about the same time as a conventional sounding, but the magnetic moment is almost 20 times larger resulting in a penetration depth of 250 to 300 m—ideal for sequential interpretation with seismic data. Typical formation resistivities for different freshwater saturated sediments related to buried valleys can be found in Jørgensen et al. (2003) and more thorough discussions of the TEM method as used in the Danish environment can be found in Danielsen et al. (2003), Jørgensen et al. (2003) and Sørensen et al. (2003).

3.2. Reflection seismics

Multi-channel seismic reflection surveys were carried out with two different field systems: a source of small (25–50 g) dynamite charges with grounded geophones, and a small vibrator (MiniVib™) source with towed land-streamer geophones (Doll et al., 1998; Van der Veen and Green, 1998; Jensen et al., 2002). A typical field layout comprised 48 geophones with a spacing of 5 m and near-offsets of 20 m to shot/vibration points, spaced at 5 or 10 m. Data were acquired using the common mid-point (CMP) technique with a coverage of at least 12.

The shallowest reflectors imaged were typically at depths of 30 to 50 m, and the depth of penetration was at least 500 m. Data quality is strongly dependent on the characteristics of the near-surface sediments; the highest quality data were obtained in areas with clay soils and no unsaturated shallow sand layers in the sequence.

3.3. Air-lift drilling

Drilling was carried out with the air-lift technique. Cuttings and suspended sediments are lifted to the surface inside the drill pipe. Reverse mud circulation is achieved by compressed air released in the drill pipe just above the drill bit. Both roller bits and drag bits were applied. Drill holes were made with diameters of 400 to 450 mm, and 2 to 6 kg of sediment samples were collected per meter drilled. Sandy sediments are disintegrated with this technique, but it was possible to obtain tens of cm-sized, undisturbed samples of coherent materials such as till, glacio-lacustrine clay, Neogene and Paleogene clays.

Logging with gamma and resistivity tools, carried out in all exploratory drillings, are in good agreement with the lithological samples. Hence, the air-lift technique is a dependable drilling method that provides reliable lithological data and depth information.

3.4. Vertical seismic profiling (VSP)

After completion of the holes, VSP data were recorded with the recording tool inside the installed PVC tube using a borehole streamer with 12 hydrophones at 2 m intervals. Cap detonators fired in 1 m deep mud-filled holes at 10–20 m from the wellhead were used as energy source. The interval below the ground water table was covered by shifting the streamer downwards with an overlap of one hydrophone position between two consecutive shots. Seismic velocities were calculated from first arrivals for layers >4 m thick.

4. Investigation strategy

A three-step strategy was developed for the study of the buried valleys:

(1) Regional resistivity mapping with the TEM technique was carried out. An average spacing of 250 m between soundings yielded a density of about 16 soundings per km^2. Maps constructed from one-dimensional resistivity–depth inverse models provide a relatively inexpensive and effective means for identification and location of the buried valleys. Many buried valleys in the region are partly incised into the Paleogene clays, and a distinct contrast in resistivity between the Paleogene clays and the sediments in the valley-fill exist. Hence, the horizontal as well as the vertical extent of the valleys are mapable with resistivity techniques. It is possible too, to determine the overall fill properties of the valleys (Jørgensen et al., 2003).

(2) A detailed investigation of the structure of the buried valley and its vicinity is attained with reflection seismic data along carefully selected transects. By combining the stratigraphic and structural information contained in the seismic data with the predominantly lithological information in the resistivity models, a preliminary geological model is built.

(3) This model forms the basis of the third step—exploratory drilling. Given the lithological and stratigraphical information from sample analyses and data on the seismic velocities from VSP data, the interpretation of the TEM data and the reflection seismic data is adjusted and a final geological model is produced.

5. The Hornsyld valley

The buried valley near the village of Hornsyld, located in Fig. 1, was identified and mapped by means of a dense grid of 734 TEM soundings. Conditions for detailed mapping of the subsurface morphology with the TEM technique were very favourable. The surface of the low-resistivity Paleogene clay, which hosts most of the valley, is at a relatively shallow depth of 25–50 m. The buried valley is recognised as a prominent depression in the surface of the good conductor as seen in the three-dimensional (3-D) topographic display in Fig. 2, which is constructed from one-dimensional (1-D) inversion of the TEM sounding data. Images of different valley features as seen in maps of mean resistivity and the surface of the good conductor are presented and discussed in Jørgensen et al. (2003). The overall trend of the buried valley is E–W. The main 2 km wide branch has a relief exceeding 150 m, and narrower side branches show relief of 50 to 100 m. Based on this resistivity image, seismic reflection data were acquired on four transects. The seismic sections are displayed as vertical panels in Fig. 2, where the interpreted floor of the buried valley is outlined in blue on the panel and black in the surface of the good conductor.

The Hornsyld 2 seismic section is shown in detail in Fig. 3. Using an average seismic velocity of 1800 m/s resistivity models derived from the TEM and exploratory drilling data are superimposed onto the seismic section. The TEM models are projected from distances up to about 150 m from the profile line.

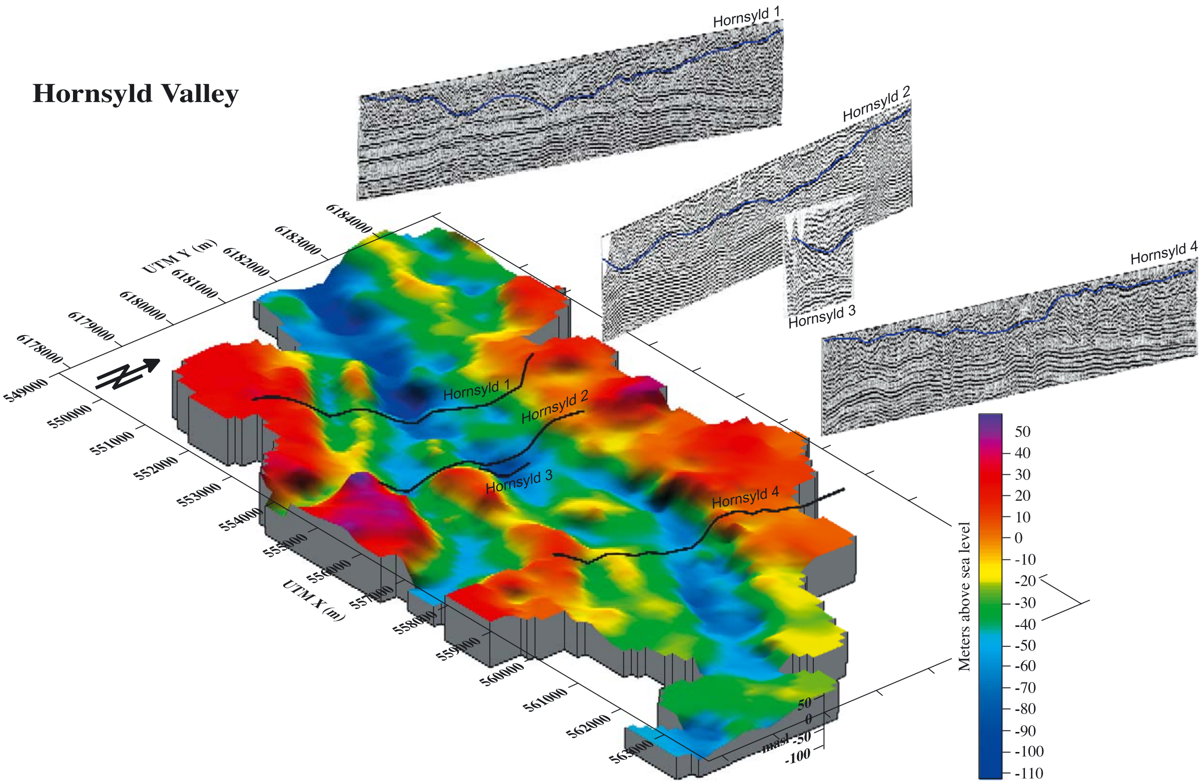

Fig. 2. The buried valley at Hornsyld displayed as a 3-D topographic representation of the surface of the conducting Paleogene clay, determined from 1-D inversion of 734 TEM soundings. Depth units are meters above sea level (masl). The four seismic reflection profiles cross the buried valley perpendicular to strike. The base of the buried valley, as obtained by joint interpretation of TEM and seismic data, is depicted as blue lines on the four seismic sections and black lines on the 3-D TEM display.

Values less than 10 Ω m in the deepest parts of the resistivity models are interpreted as Paleogene clay. This is in good agreement with observations in the exploratory drilling, which is located in the central part of the buried valley. The lithological log, as obtained from sample descriptions, is projected onto the section and shown in detail along with velocities derived from a VSP. The base of the valley was found through joint interpretation of TEM and seismic data. Based on this the average seismic velocity of the valley fill can be calculated to about 1800 m/s. Major erosion surfaces are denoted by solid red and blue lines and bedding planes by dashed red lines.

A high amplitude reflection of two-way times varying between 50 and 125 ms and denoted by a blue line is interpreted as the base of the buried valley. When viewed exclusively on the seismic section the validity of this interpretation is not at all obvious. The expectation was to find the base of the buried valley as an erosional unconformity truncating regular and almost horizontal reflections, representing the hemipelagic Paleogene clay. What is seen is a reflection separating an upper storey with complex and spatially variable reflection patterns from a region below with a similarly complex architecture.

When the seismic section is compared with the TEM models, it is clear that the deepest portion of the highlighted erosion surface is coincident with the top of the low-resistivity layer. The low resistivity is a lithological indicator for the heavy Paleogene clay confirming the location of the base of the buried valley in the seismic section. Minor deviations between the reflection and the resistivity models are attributed to (1) the assumption of constant velocity in

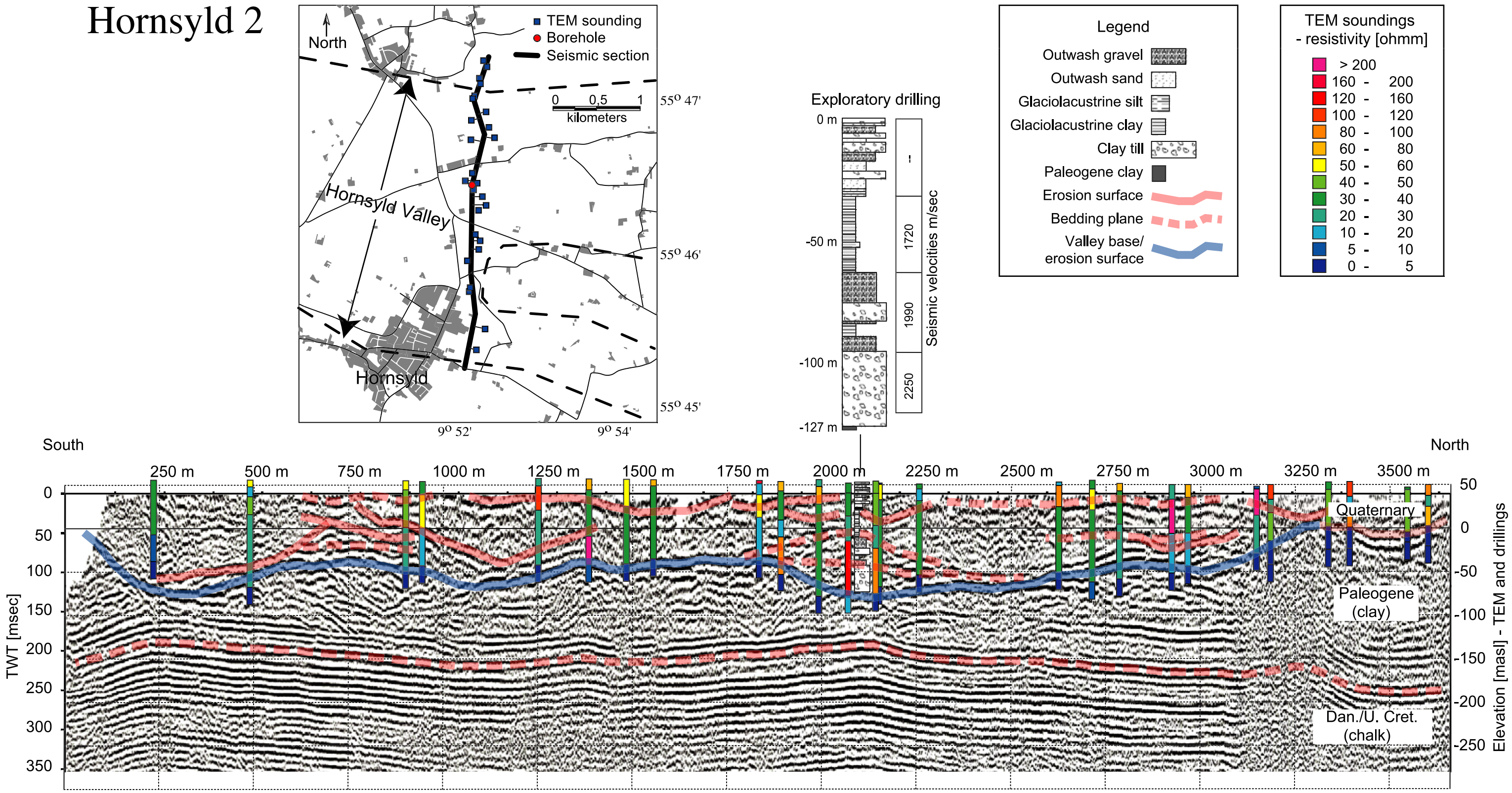

Fig. 3. Seismic section Hornsyld 2 (unmigrated 12-fold stack) with 1-D TEM resistivity models and a lithological log, at the centre of the section, superimposed assuming a seismic velocity of 1800 m/s. Major reflections are highlighted: Dashed lines denote bedding planes and solid lines erosion surfaces. The base of the valley obtained by interpretation of TEM and seismic data is noted by the solid blue line between the Quaternary sediments and Paleogene clay. Location of the seismic profile line, the borehole, and TEM sites are shown on the inserted map.

the valley fill, (2) errors originating from depth variations in the seismic section that are transferred by the projection of TEM models onto the seismic section, and (3) presence of locally reworked Paleogene clay or rafts of Paleogene clay among the fill sediments. The major discrepancy in the southernmost TEM sounding could, however, be a result of inductive coupling to cultural structures (e.g. cables) leading to distorted TEM data.

Despite these discrepancies, the integration of the resistivity model supplying primarily lithological information, and the seismic data providing mainly structural information leads to a significant improvement in reliability of the geological interpretation. In addition, we believe that the observed discrepancies may contain useful information about variations in velocity.

The irregular reflection patterns observed below the base of the buried valley are unusual for Paleogene hemipelagic clays. With the base of the valley determined, we could evaluate the irregular image in geological terms. The criss-cross reflection patterns probably indicate glaciotectonic thrust structures that are outside the plane of the seismic section (e.g. between 500 and 1000 m in Fig. 3). Based on the present data it is impossible to evaluate whether the reflections originate from structures within the valley fill sediments or, from disturbed Paleogene strata below the interpreted valley base.

Internal reflection patterns in the valley indicate a cut-and-fill architecture. According to the TEM models, the major part of the valley fill has moderate resistivities of 30 to 50 Ω m. Judging from the lithological log from the exploratory drilling located on the seismic profile and logs from exploratory drillings and water wells situated elsewhere in the valley, clay tills and glacio-lacustrine clay with varying amounts of sand intercalations prevail in the valley fill. The somewhat higher resistivities of 50 to 80 Ω m occurring in the valley fill reflect sequences containing meltwater sand and gravel.

In the deepest central part of the valley, a resistivity high of 80 to 120 Ω m is observed in three of five TEM soundings. The upper part of this high-resistivity interval corresponds to gravel and sand dominated sequence, as documented in the lithological log. The lower part of the high-resistivity interval encompasses a till, which is not resolved in the models. The seismic section reveals a mounded feature with its apex at the drilling site and its base on a gently northward dipping reflection shown in Fig. 3. The mound is about 25–30 m high at the apex and its width is estimated at 250 m at the base. The dimensions and the dominant lithology suggest that the mound may represent the cross-section of a buried esker. The common occurrence of eskers in relation to open tunnel valleys (Wright, 1973; Moors, 1989; Patterson, 1994; Smed, 1998) supports this interpretation. However, this interpretation remains tentative due to the fact that the TEM-models do not unambiguously support the lithological aspect of the interpretation, and the fact that the elongated appearance peculiar for eskers has not so far been unambiguously documented by neighbouring seismic sections and TEM soundings. The relatively thin sequence of high-resistivity deposits compared to the depth makes it difficult for the TEM method to resolve.

6. The Vonsild valley

South of the town of Kolding near its suburb Vonsild, TEM data provide evidence of a NE–SW striking buried valley about 4 km wide (Jørgensen et al., 2003). According to TEM-soundings, the examined part of the valley is cut into Paleogene clay at depths varying between 150 and ca. 300 m as seen in Fig. 4 and in Jørgensen et al. (2003, Fig. 6). A 2.4-km-long seismic section covers the northern half of the buried valley. The transect is perpendicular to the strike of the valley, except for a portion between 850 and 1250 m that is almost parallel to the valley. The section was depth converted with velocities obtained from a VSP acquired in the exploratory drilling located at the middle of the seismic section. The depth conversion was carried out by assuming layers with constant velocity and adopting a simplistic geological interpretation of the seismic section.

In contrast to most of the Hornsyld valley the base of the Vonsild valley is not imaged as a reflecting surface, but is identified in the seismic section of Fig. 4 by truncation of the approximately horizontal reflections in the Paleogene clays. This interpretation is regarded as reliable due to the good data quality and to the continuity of the Paleogene reflections. The seismic interpretation is in reasonably good agreement

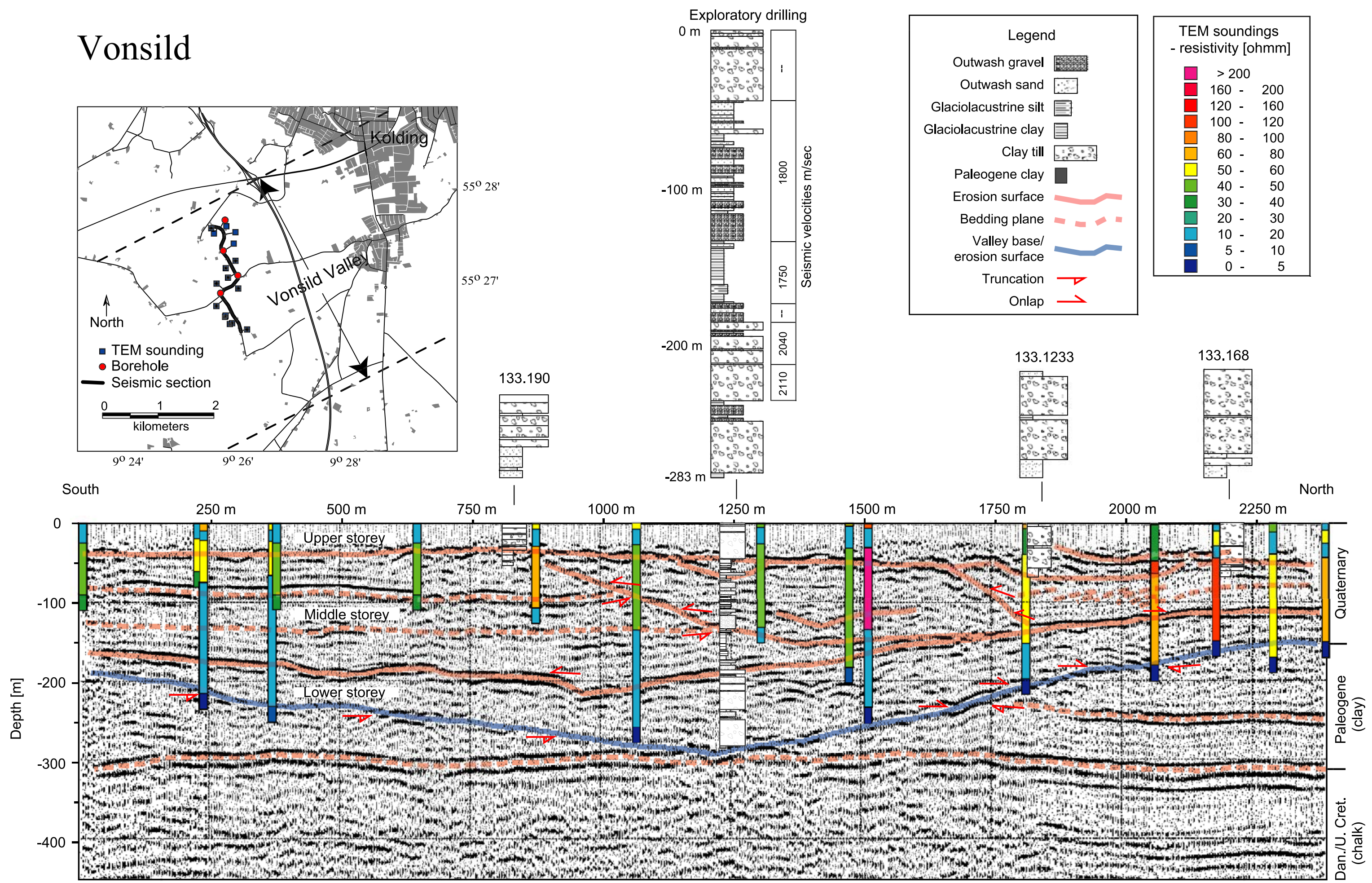

Fig. 4. The three storeys of the buried valley at Vonsild are bounded by solid red lines on the seismic depth section (unmigrated 32-fold stack). The base of the valley is denoted by a solid blue line. Location of the seismic profile line, boreholes, and TEM sites are shown on the inserted map. Resistivity models derived from both conventional and HiTEM sounding data are superimposed along with the lithology in the exploratory drilling and three water supply wells. VSP velocities and lithological data are shown above the section.

with depths to the low-resistivity Paleogene clays as derived from the TEM soundings.

The structure of the valley fill is clearly imaged in the seismic section. Three storeys with different architecture are recognized. The lower storey is characterized by one coherent unit extending through the whole section. The middle storey has a more complex cut-and-fill structure composed of a number of units with limited extent. The boundary between these two storeys is marked by an almost continuous high amplitude reflection that to some extent mimics the shape of the base of the valley. In the upper storey the fold coverage and the data quality are reduced.

6.1. Lower storey

The lower storey is about 100 m thick in the central parts and thins gradually towards the flanks. Internal reflections are relatively well defined and onlap the Paleogene clays, as clearly displayed along the northern flank of the valley.

The lithological data from the exploratory drilling show that the lower unit is composed of clay till with thin beds of meltwater gravel. The resistivity models indicate resistivities of 10 to 20 Ω m near the drilling and in the southern part of the valley. Such resistivities are exceptionally low for clay tills, but there are several possible explanations for this: (1) a high percentage of reworked low-resistivity Paleogene clays may be present in the tills, (2) groundwater samples from the thin beds of meltwater gravel show high ion content, (3) the till layer is too thin to be resolved with the TEM method, so the mean resistivity of the till and the covering layers of glacio-lacustrine clay is determined. The latter could also be the reason why the TEM soundings situated on the northern flank of the valley indicate high resistivities for the till layer.

6.2. Middle storey

The oldest unit in the middle storey appears in the south side of the valley as a stack of approximately horizontal layers imaged by coherent reflections with low amplitude. Layers onlap the dipping surface of the tills in the lower storey. The maximum recorded thickness of the unit amounts to about 170 m. The exploratory drilling penetrates the lower part of the unit, and the sediment is classified as glacio-lacustrine clay. This observation is in good agreement with the character of the internal reflection pattern, which is taken to express a low energy depositional environment. The resistivity models with resistivities of 10 to 20 Ω m are also in good agreement. An erosional unconformity cuts through the unit in the central part of the section.

The space created by this renewed erosional feature reaches a depth of about 100 m in the central part of the section. The deposits that first filled this new valley, about 30 m in the lowest part, are imaged as wavy reflections with varying amplitudes. This interval may correspond with the sediments classified as meltwater gravel in the lithological log. The uppermost 50 to 60 m show relatively well ordered internal layering imaged by coherent, low amplitude reflections showing onlaps onto the erosional unconformity. Lithological descriptions classify the sediments as dominantly meltwater sand and silt. The TEM models indicate resistivity levels mainly in the range of 30 to 50 Ω m, which is quite low for such a sedimentary sequence. The resistivity of sandy sediments, however, is inverse proportional to the ion content of the pore water, and the presence of high ion content, as proposed for the lower storey, could therefore be the explanation of this.

Another erosional unconformity is seen to truncate these deposits in the northern part of the section. The seismic image changes markedly northwards across this unconformity. The almost transparent picture is taken to indicate sediments with a high degree of homogeneity. The coherency of the low amplitude reflections points to an environment of relatively low energy, and a southwards progradational pattern shows that currents must have been active during sedimentation. Resistivities in this progradational unit are in the range of 50 to 120 Ω m, thus indicating sandy sediments.

The two sand-filled erosional unconformities are seen as one single incision in the resistivity maps of Jørgensen et al. (2003, Fig. 6).

The uppermost layers in the middle storey in the southern part of the section are characterized by horizontal, primarily coherent, high amplitude reflections. According to a lithological construction report from a water well (Danish Geol. Surv. file no. 133.190) this succession is composed of meltwater sand, which is in agreement with resistivity values between 40 and 80 Ω m.

6.3. Upper storey

High amplitude and wavy or almost horizontal reflections dominate this storey in the northernmost half of the section. As shown in Fig. 4, the exploratory drilling and lithological logs from water wells along the section show that the sediments of the Upper Storey consist of clay till. This is in good agreement with the TEM models, which find a low-resistivity, clay rich layer in the top.

7. The Viuf valley

The buried valley at Viuf shown in Fig. 5 was discovered and mapped through a grid of TEM soundings. A seismic reflection profile was acquired perpendicular to the E–W trending valley, and subsequently an exploratory drilling was made in the central part of the buried valley. The surface of the low-resistivity Paleogene clay is identified in the TEM models at depths of approximately 120 m outside the buried valley. By assuming an average velocity of 2000 m/s the same surface is inferred in the seismic section by a wavy and more or less coherent reflection at about 120 ms, two-way travel time. The reflection is well defined north of the buried valley, but less so south of the valley due to deterioration of the data quality.

The base of the buried valley is difficult to identify. The truncation of reflectors in the southern flank is clear, contrary to the northern flank. The base of the valley on the northern flank was chosen primarily from observations of changes in the reflection pattern and the 1-D TEM models. Interpretation of the deep parts of the buried valley is problematic. The TEM models show a clear depression in the surface of the low-resistivity formation, but the level is about 30 m deeper than that in which Paleogene clay is recorded in the exploratory drilling.

Although somewhat obscure, the seismic data can provide some insight. A high amplitude, south dipping reflection at about 1200 m in Fig. 5, coinciding with the low resistivity level in a TEM model, may be the expression of a steeply inclined raft of Paleogene clay. The presence of steeply inclined rafts in the area is plausible due to the discrepancy between the levels of the Paleogene clay observed in the drilling and in the neighbouring TEM soundings. It might be speculated that the generation of rafts is related to glaciotectonism. Precise imaging of supposed complex glacial structures like these is not possible with the methods employed here. Large-scale thrust structures have, however, been imaged in seismic surveys offshore (Huuse and Lykke-Andersen, 2000a).

The exploratory drilling shows thick sequences of clay till in the uppermost 60 m, meltwater sand and silt from 60 to 85 m, clay till again between 85 and 101 m, and glacio-lacustrine clay to the apparent base of the valley at 137 m. This sequence corresponds well to the resistivity structure derived from the TEM models. The deeply buried lacustrine clay is defined by resistivity values of 10 to 20 Ω m, while the upper sequence of till is determined by the medium values of 40 to 60 Ω m.

Reflection patterns internally in the buried valley indicate cut-and-fill structures from multiple erosion events, filled with various sediments as seen in the exploratory drilling. Lateral variations in seismic velocity are not known in detail, and abrupt changes occurring in the valley fill may produce pull-up and pull-down structures in the underlying seismic section. Presently it is not known whether the folds and faults seen in the high amplitude reflection at two-way times of about 250 ms are real or an effect of velocity anomalies in the valley fill.

8. Velocity effects

The problem of variable seismic velocities is approached by compilation and analysis of velocities measured by VSP in five exploratory boreholes from buried valleys in Vejle County. Data from three of the five drillings are presented as part of the examples from Hornsyld, Vonsild and Viuf.

The distribution of velocities as a function of sediment type is straightforward. Velocities for intervals of homogeneous lithological sequences greater than about 16 m thick are presented in Fig. 6. Classification of the drilled sediments falls in two distinctly different velocity groups each with a low scatter. The first group encompasses meltwater sand

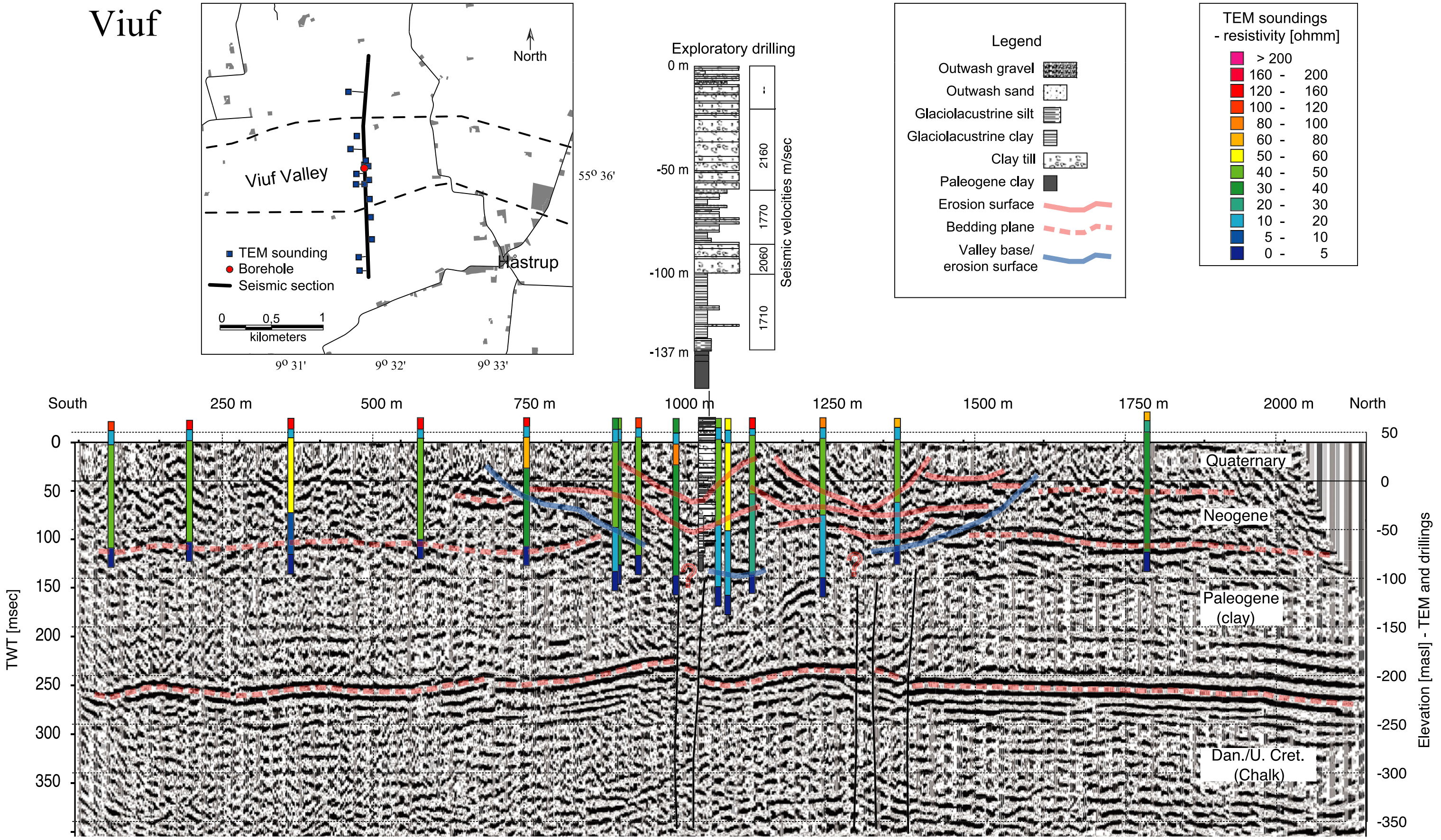

Fig. 5. The buried valley at Viuf is depicted by solid blue lines on the reflection seismic section (migrated 12-fold stack). 1-D resistivity models computed from the TEM sounding data and lithology from an exploratory drilling in the centre of the valley are inserted in the seismic section assuming a velocity of 2000 m/s. Dashed red lines denote bedding planes, the solid red lines denote erosion surfaces and the solid blue lines denote the valley base. Location of the seismic profile line, the borehole, and TEM sites are shown on the inserted map.

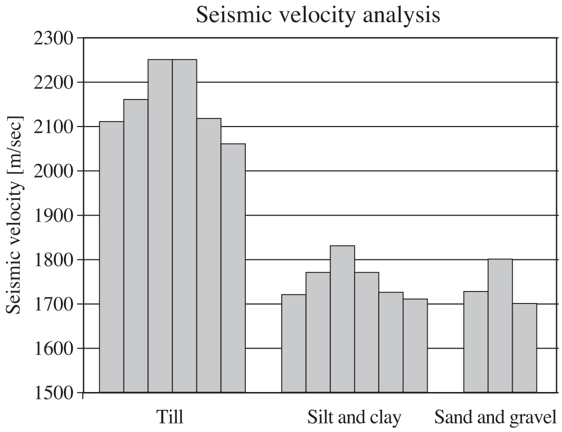

Fig. 6. Velocities calculated from VSP in five exploratory drillings penetrating the sediment fill in buried valleys of Vejle County. Two distinct velocity groups appear: Clay/silt and sand/gravel at 1750 ± 100 m/s, and till at 2150 ± 100 m/s.

and gravel and glacio-lacustrine silt and clay with velocities of 1750 ± 100 m/s, and the second group contains the clay tills with velocities of 2150 ± 100 m/s. Higher velocities in tills relative to other glacial sediments have also been reported by e.g. Hunter et al. (1998), Wiederhold et al. (2002). The velocities of the Neogene and Paleogene deposits at shallow depth have not been investigated in detail, but velocities around 1750–1800 m/s seem likely (Lykke-Andersen and Tychsen, 1977; Nielsen and Japsen, 1991). Japsen and Langtofte (1991) reported velocities between 2400 and 4000 m/s for the Danian limestone and the Upper Cretaceous white chalk. Any depth dependence on the seismic velocities is not seen in the relatively sparse data material.

As the sediments filling the buried valleys consist of various proportions of sediments from the two groups, it follows that significant variations in average velocities may occur depending on the vertical and horizontal distribution of the lithological components. This distribution is dependent on the internal structures of the valleys, such as the commonly found cut-and-fill structures, and results in various degrees of pull-up and pull-down structures. A total of approximately 70 m of till were found in the exploratory drilling within the buried valley at Viuf. Water well construction reports from outside the valley indicate the amount of till in the relatively thin sequence of Quaternary deposits to be normally less than 70 m. Thus, the hypothesis of pull-up structures in the strata underneath the valley in the Viuf case history is supported.

Pull-up structures can probably also be identified in the strata below the Hornsyld valley in Fig. 3. Underneath the exploratory drilling, between 1750 and 2250 m, a significant local high is seen in the strata of limestones and chalk. The high is situated under a local depression in the valley base and under the mounded esker-like feature too. According to the lithological log, the depression is filled with clay till, and the mound consists of meltwater gravel intercalated with clay till and glacio-lacustrine clay. The seismic velocities of the two units are recorded to be 2250 and 1990 m/s, respectively. The total thickness of the till/gravel complex is about 65 m, and the average seismic velocity is 2110 m/s—significantly higher than expected for other valley fill sediments. Assuming that the valley fill sediments on each side of the till/gravel complex consist of meltwater clay with the same seismic velocity as the meltwater clay in the middle of the borehole (1720 m/s), a pull up structure reaching a height of about 14 ms TWT in the underlying sequence can be calculated using the following formula:

$$\Delta TWT = 2d\left(\frac{1}{V_1} - \frac{1}{V_2}\right)$$

where $d = 65$ m, $V_1 = 1720$ m/s, and $V_2 = 2110$ m/s.

Actually, the height of the structure can be measured to be between 12 and 20 ms, and therefore, it is plausible that the structure is a pull-up effect generated by the high velocity sediments concentrated in this part of the valley.

Because of high contents of till materials, buried valleys can in some cases be recognised and identified by the presence of pull-up effects in underlying strata. Furthermore, it is possible to draw lithological information from the seismic records on this basis. In cases where poor data hide buried valleys in the uppermost parts of seismic sections, pull-up and pull-down structures may help reveal the presence of buried valleys in the subsurface. Pull-down structures under buried valleys are not traced in this study, but nevertheless they are common in places where valley-fill deposits have significantly lower velocities than discovered here (e.g. Jürgens, 1999) or where valleys are cut into, for example, limestones.

9. Conclusions

Geological interpretations of buried Quaternary valleys in Jutland, Denmark, are substantially improved by integrated use of TEM and seismic data. The TEM sounding data provide information about depth and to some extent of the subsurface lithology, while seismic profiling data provide information about the structure of the valley fill and the substratum.

The lower parts of the buried valleys presented in this study cut into low-resistivity Paleogene clay, and the depth to this surface is well determined using the TEM method. The HiTEM method is especially useful to extend the depth of investigation of TEM soundings and thus integrate with seismic data. The TEM models also support the seismic interpretation of the internal layering of the valleys, particularly if they are partially filled with relatively thick and widespread sequences of glacio-lacustrine clay. VSP measurements show that tills have significantly higher seismic velocities than those of other sediments occurring in the valleys. Accumulations of tills in erosional structures generate pull-up effects in the substratum, because of a localized increase in seismic velocity. Dimensions of pull-up structures can be used to determine the relative amount of till occurring in lithological successions in the valley above the pull-up structure.

The three valleys investigated differ with respect to dimension, structure and general distribution of the fill sediments. Nevertheless, thick sequences of till, glacio-lacustrine clay and silt, meltwater sand and gravel are delineated in large and small cut-and-fill structures. Glacio-lacustrine clays and silts, and meltwater sands in thick sequences appear in the seismic data as coherent low-amplitude reflections. Gravel and tills are seen as more complex or wavy patterns in the seismic sections. Erosion surfaces appear as high-amplitude coherent reflections, as indistinct reflections, or are sometimes only identified by reflection terminations. In two cases, there are indications for glacial thrusting at the bases or inside the valleys because the otherwise horizontal layered and well-stratified Paleogene clay is imaged as an irregular reflection pattern. The complexity of these structures cannot be resolved satisfactorily by the methods used, however the investigation strategy can indicate their occurrence through significant discrepancies between the various data sets. If the complexity of these relatively small-scale glacial thrusting structures has to be correctly imaged, 3-D techniques are required.

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