

Reservoir Characterization Applying High-Resolution Seismic Profiling, Rabis Creek, Denmark

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Abstract

Onshore reflection seismics have been used to characterize the geometry and lithology of ground-water reservoirs. The study was carried out as a seismic sequence and facies analysis along Rabis Creek in western Denmark. A 1350 m long seismic section was produced on a presumed homogeneous outwash sand plain. High resolution data to a depth of 160 m (200 msec two-way time) were obtained along most of this section, and reflections from more than 400 m in depth were obtained locally. The seismic data have been correlated with electrical resistivity logs. The reservoir is, in contrast to the expectations, highly heterogeneous, composed of three distinguishable seismic sequences of unconsolidated sediments. Layers down to 1.5 m thick were recognized in the seismic data. The study shows that onshore reflection seismics provide a unique possibility of 2-D reservoir scale characterization of geological structures. Combined with seismic facies and sequence analysis, seismic profiling forms a strong hydrogeological tool that may supplement traditional boring and logging methods.

Introduction

The geological structure, i.e. basin geometry and sediment properties, is of vital importance in modeling ground-water flow in aquifers. Recent applications of hydrological models to pollution plume modeling have made this problem more apparent (e.g. Anderson, 1989; Poeter and Gaylord, 1990). In the last few years onshore reflection seismics have been successfully introduced in the exploration of the shallow geological structure (Doornenbal and Helbig, 1983; Hunter and others, 1984; Knapp and Steeples, 1986a, b; Jongerius and Helbig, 1988). In Denmark the reflection seismic method has been developed and used in relation to hydrogeological investigations as a supplement to the mapping method by borings (Ploug, 1990, 1991; Ploug and Olsen, 1991).

Throughout the implementation of the method, our aim has been to develop a technique that is economical compared to other geophysical and geological mapping techniques. Therefore, the equipment for data acquisition is lightweight and can be handled by two persons, whereas the data processing system runs on a personal computer. The total (commercial) price per kilometer seismic section,

including acquisition and processing, is approximately \$7,000-\$8,000 (U.S.).

Setting

There is direct evidence of four glaciations in Denmark during the Quaternary (e.g. Sjørring, 1983). Glaciers originated in the highlands of Scandinavia and invaded Denmark from northerly to southeasterly directions resulting in an almost complete cover of tills and outwash deposits. During the latest glaciation in Weichselian, only parts of Denmark were ice-covered. The Main Weichselian Advance transgressed the country from NE and terminated along the so-called Main Stationary Line in mid Jylland. Consequently, large parts of western Jylland were covered by outwash plains (Figure 1A). Therefore, western Jylland is now covered mainly by a thick sequence of sandy outwash deposits. The exact thickness of outwash deposits is, however, unknown in most places due to poor quality or lack of drilling information (mainly water-supply drillings) and difficulties in distinguishing the sandy outwash from underlying sandy fluvial deposits of Miocene age.

The present study was carried out along the Rabis Creek in central Jylland west of the Main Stationary Line (Figure 1). The survey consists of a 2 km continuous seismic line. The base of the outwash sequence at this locality was unknown, although preliminary investigations seemed to indicate that the base was situated at a depth of approximately 30 m below sea level, giving a total of 80 m of outwash deposits (Kristiansen and others, 1990). The ground-water table is situated about 35 m above sea level, approximately 10 m below the terrain. In the meadow area along Rabis Creek the ground-water table occurs immediately below the surface.

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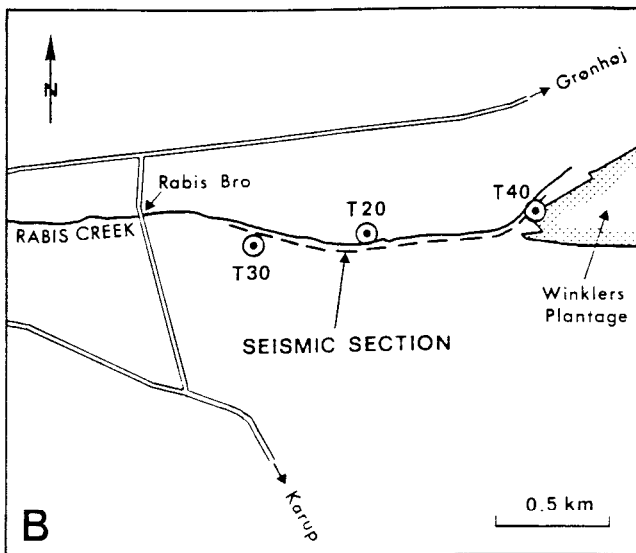
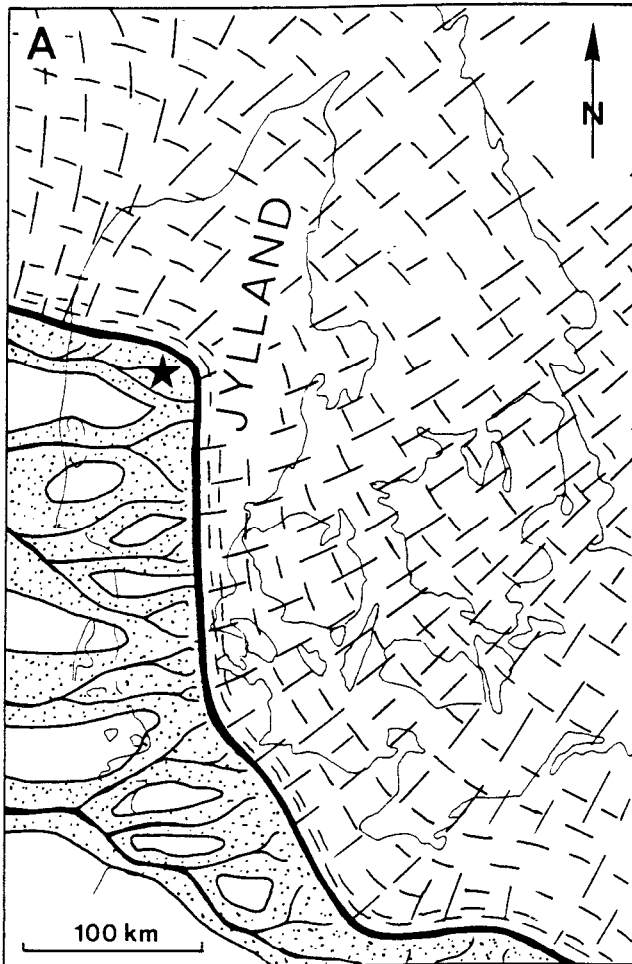


Fig. 1. A: Generalized palaeogeography during the Main Weichselian Advance in Denmark. Ice cover is shown by hachured line signature. The Main Stationary Line (ice margin position), located in the Jylland peninsula, is shown by thick line. Large parts of western Jylland are covered by outwash plains indicated by dotted signatures with channel patterns. In the northeasternmost outwash plain, the study area along the Rabis Creek is indicated by a star. The present day shorelines are indicated by thin lines. Based on Hurtig (1969) and Smed (1982). B: Location map, indicating the position of the seismic line and the borings (T20, T30, T40).

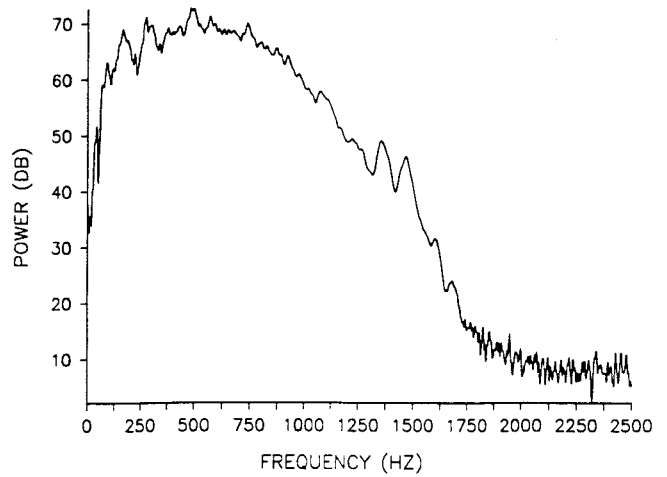


Fig. 2. Power spectrum of one shut. Notice the high energy of frequencies as high as 1700 Hz.

Acquisition and Processing

The seismic instrument used in this study was a Geometrics ES-2401 with instantaneous floating point amplifiers and 15 bit A-D converters. The seismic source was a shotgun with special strong charge, and the receivers were single 100 Hz geophones (Geospace GS100). The power spectrum indicated energy in excess of 20 db for frequencies as high as 1700 Hz (Figure 2). The dominating frequency was 500 Hz. Using $\frac{1}{8}$ wavelength as the maximum vertical resolution (Widess, 1973), a mean seismic velocity of 1600 m/s and a frequency of 500 Hz, a theoretical resolution of 0.4 m should be achieved for the uppermost sedimentary layers. However, in practice, a resolution on the order of $\frac{1}{4}$ wavelength is more appropriate, i.e. 0.8 m. At the present locality, beds as thin as 1.5 m were distinguished.

The main constraints for high-resolution shallow reflection seismics in Denmark are unsaturated conditions in the uppermost layer and bogs. Such surface conditions generate scattering and reverberation. This problem was, however, reduced by placing the geophones with marsh case in 1 m deep drilled holes.

An E-W seismic line was shot partly along the stream and partly upstream of the stream head. The geophone spacing was 3 m, and the distance from source to the first geophone was 9 m. Data acquisition made it possible to construct a 12-fold Common Depth Point (CDP) section along a more than 2 km segment of the creek. The data quality of the upstream 400 m and the downstream 400 m was, however, poor due to an unsaturated top layer and the presence of peat, respectively, in these areas exceeding the depth of drilled holes. Accordingly, only 1350 m of high resolution seismic profile was gathered (Figures 1B and 3).

The processing procedure comprised mainly standard exploration methods, modified to run on a personal computer. The processing included static correction, frequency filtering, f-k filtering, deconvolution, spiking, and stacking.

In addition to the stacked CDP section, 24 Common Offset sections (COF) were constructed. In COF sections only recordings sharing a common distance between source and geophone are shown. Accordingly, no stacking is performed.

The advantage of CDP profiles is that strong reflec-

tions are amplified and noise is reduced. Thus the general geological structure is very well displayed. However, a number of weak reflections may be lost. The advantage of COF profiles is the high resolution of the data and capability of portraying even very weak reflections. However, such data are very vulnerable to noise, and usually several sections need to be investigated to confirm the existence of weak reflections.

Seismic Stratigraphy and Facies Analysis

The concepts of seismic stratigraphy and facies analysis (Vail and others, 1977) have been applied to the present study in order to characterize the internal geometry of the reservoirs and interpret the various facies in terms of depositional environment and lithology. The first step is the definition of seismic sequences separated by major surfaces of discontinuity (i.e. reflection terminations) and correlative continuity surfaces. These surfaces are interpreted as unconformities. In the stacked CDP profile, three distinct seismic sequences, and their constituent facies, with the following characteristics are recognized (Figure 3):

Sequence I (A-C): Many parallel reflections with good continuity and variable amplitude.

Sequence II (A-E): Dominance of subparallel and undulating, discontinuous reflections with variable amplitude.

Sequence III: Parallel reflections with low continuity and amplitude.

Detailed Seismic Analysis

The detailed seismic facies and sequence analysis was performed by standard methods (cf. Vail and others, 1977) although the change of scale compared to petroleum exploration seismics makes it possible to subdivide individual sequences into smaller facies units. The lack of three-dimensional control makes it impossible, however, to outline the 3-D external form of seismic facies. It should be noted that the tops of the seismic profiles approximate the level of the ground-water table. Because the ground-water table dips about 0.3 degrees towards the west, true horizontal bedding apparently dips 0.3 degrees towards the east in the seismic sections.

In the following, seismic facies are defined on the basis of reflection configuration, continuity, frequency, and amplitude. The amplitude is indicated relatively, as a \pm percent of the distance between geophone traces, i.e. +100% indicates an amplitude reaching the 0 amplitude line of the geophone immediately to the right. The facies descriptions below are supplemented with brief environmental and lithologic interpretations.

Sequence I

The base of sequence I is not observed in the seismic section. Sequence I is bounded at the top from 0-450 m along the section by a continuous positive reflection (amplitude +110%). Reflections below the surface clearly dip towards the west at an apparent angle of 0.3 degrees, whereas the top surface itself apparently dips 0.3 degrees in the opposite direction (Figure 3D). Accordingly, the top of the sequence is either truncated at the positive reflection at a

very low angle, or the top of the sequence is a toplap. The first alternative is preferred because bedding in the entire sequence I dips at the same angle, probably due to subsidence or tectonism. From 450 m to 820 m, sequence I is bounded by a truncation surface dipping steeply towards the east, apparently 13 degrees. On the 60 m COF profile (Figure 3C, D) the eastward continuation of this truncation surface (800 m-1350 m) is seen to dip in the opposite direction, however, at a lower apparent angle (3 degrees).

The sequence is subdivided into three facies units, A-C. IA and IC are high-continuity and high-amplitude facies with parallel reflections of high frequency (Figure 3A). The amplitude is commonly in the range of ± 75 -110%, and the dominating period is typically 5 msec. This facies pattern suggests continuous strata deposited in a relatively widespread and uniform environment with interbedding of high- and low-energy deposits, typically a shallow marine environment (cf. Vail and others, 1977). The high frequency and high amplitude indicate thin beds of varying lithology. In the 60 m COF profile, several concave-up reflections are observed immediately below the topmost continuous reflection in IA (Figure 3C, D). The reflections are in the range of 60-120 m in apparent width and approximately 5-10 m in relief. They probably indicate channel fill deposits (cf. Jongerius and Helbig, 1988) either of tidal or fluvial origin.

Facies unit IB is a low-amplitude facies with reflection amplitudes typically in the range of -50% - $+25\%$. The geometry is apparently sheet-like (Figure 3). The facies is indicative of either very thin beds or uniform deposits (Vail and others, 1977). The high resolution of the present data makes the latter alternative more likely. The facies may be either sand-prone or clay-prone.

Sequence II

Sequence II is bounded below by a truncation surface, previously described as the top truncation surface for sequence I. The surface is flat in the western part of the profile and concave-up in the eastern part (Figure 3). The top surface is an almost continuous positive reflection with an amplitude of about +90% (Figure 3). The sequence is composed of 5 facies units, A-E.

Facies IIA is composed of subparallel to wavy reflections with variable continuity, draping the underlying truncation surface (Figure 3C, D). From 450 m to 820 m the reflections exhibit amplitudes of $\pm 75\%$. Further east the amplitudes are weaker, typically less than $\pm 50\%$. The draping pattern may suggest deposition from suspension. However, the reflectors are neither perfectly parallel nor perfectly continuous, as would be expected from suspension fallout deposits. An interpretation as mass-transport creep deposits may be suggested due to the local wavy or contorted appearance and the position along the sides of a previous topographic low.

The overlying unit IIB is bounded below by an undulating concave-up discontinuous positive reflection with an amplitude of +50-75%. The main lower part of this facies is characterized by very low amplitudes, and no reflectors can be distinguished (Figure 3C). In the upper part, two concave-up subunits are recognized (Figure 3C, D). These subunits are characterized by positive and negative high-

frequency reflections indicating prograding fill in the western subunit and divergent fill in the eastern subunit. The reflections are high amplitude in the range of $\pm 100\%$. The top of the unit is locally difficult to pick out precisely. The

facies indicates an upward transition from deposits of one predominant lithology to deposits of alternating lithologies, apparently forming channel fills. The facies is interpreted in terms of upward-falling energy conditions in a fluvial, prob-

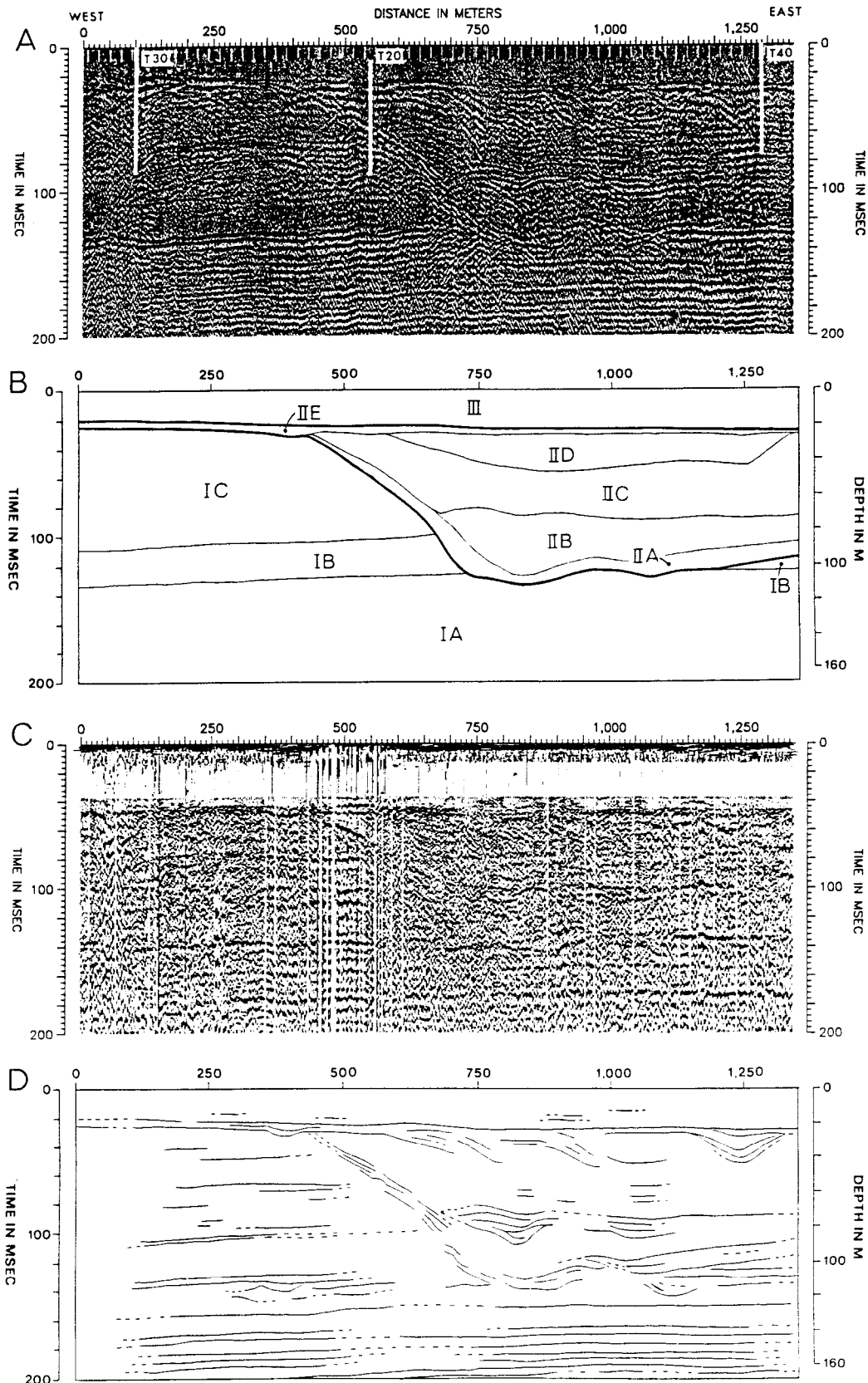


Fig. 3. The seismic survey. A: Stacked CDP section with indication of borings in which electrical resistivity logging was carried out. B: Subdivision of the seismic profile into seismic sequences and facies based on COF sections and the CDP section. C: An example of a COF section (nonstacked data) with 60 m offset between the source and geophones. D: Reflections observed in CDP and COF sections.

ably braided river environment. The main lower part is probably composed of rather massive sand and gravel with low acoustic impedance contrasts, whereas the upper subunits indicate thin interbedding of beds with high acoustic impedance contrasts, probably sand and clay.

Unit IIC is a low-continuity and variable-amplitude facies ($\pm 50\text{--}75\%$). Some relatively high-continuity and high-amplitude ($\pm 75\text{--}100\%$) reflections are, however, observed within this unit (Figure 3C, D). The facies is typical of alluvial deposits with rare continuous beds of contrasting acoustic impedance (cf. Vail and others, 1977).

Unit IID is channel or trough shaped and composed of two subunits (Figure 3D). The base and top of the unit are not developed as continuous reflections but are clearly visible due to the termination of internal reflections. The western subunit is characterized by inclined (apparently 7–9 degrees) variable-frequency and high-amplitude (-110% – $+110\%$) reflections exhibiting a downlapping relationship. The eastern subunit shows a divergent fill of a symmetrical channel or trough form. Reflections in this subunit are also high frequency and high amplitude (-110% – $+110\%$). The facies is interpreted as a lateral accretion (point bar) and channel plug unit with alternating sand and clay beds. The unit may be either fluvial or tidal.

Facies IIE is bounded by a distinct top positive continuous reflection ($+90\%$) (Figure 3C, D). The base is defined by a continuous reflection from 0–550 m in the profile. East of 500 m, the base is not developed as a reflection. Instead, it is defined by the toplap of the underlying facies IID (Figure 3D). Locally internal reflections are observed (Figure 3D, 280 m–460 m). The base and top of facies IIE are subparallel and apparently dip 0.2–0.3 degrees towards the east, i.e., horizontal when compensating for the dip of the groundwater table. The unit is interpreted to be composed of a thin sheet with a high acoustic impedance, possibly a clay/silt layer as interpreted later. The high continuity and evenness of the top reflection suggest a marine or lacustrine origin.

Sequence II, accordingly, is dominated by a valley fill composed of mass-transport and flood basin deposits (facies IIA and IIC, respectively) and channel deposits (facies IIB and IID). The general depositional environment is probably an alluvial valley which may be of subglacial origin. Braided rivers were active in the initial phase (facies IIB); they were later replaced by a meandering river (IID) and the associated flood basin (IIC). The sequence is topped by a sheet-like unit (IIE) which probably indicates the development of a wide lake after the valley was filled with deposits.

Sequence III

Sequence III is bounded below by a flat continuous positive reflection (see previous sections). The top is not observed because the top of the profiles is the groundwater table. The sequence is composed of only one facies.

The unit is a low-continuity and variable-amplitude facies (Figure 3). In concurrence with facies IIA and IIC, this facies is interpreted as an alluvial deposit with low lateral continuity of beds. Locally poorly developed sub-horizontal to broadly concave-up reflections are observed (Figure 3A) interpreted as wide channel forms.

The internal reflections apparently indicate that the

sequence conformably overlies sequence II. A seismic log carried out in borehole T40 (Figure 3A) indicates, however, that the seismic velocity abruptly changes from c. 1750 m/s in sequence II to c. 1600 m/s in sequence III. This is interpreted as a major change in consolidation associated with a major time lag. The boundary is interpreted as a parallel unconformity.

Electrical Resistivity Logs

Three electrical resistivity logs were obtained along the seismic line to provide better lithological information (Figures 3A and 4). The high resolution electrical resistivity measurements were carried out while drilling with four electrodes mounted in a Wenner configuration on an auger (Sorensen, 1989a, b). Sands and gravels are characterized by high resistivities (70–500 ohmm) whereas clays possess low resistivities (10–40 ohmm).

Sequence I

Log T30 indicates that the upper two-thirds of facies C in sequence I is composed of sand with only one minor clay layer. The sand exhibits a regular bedding in beds approximately 5 m thick. Log T20 indicates that facies IC coarsens up from a clay unit. The base of facies IC is thus probably transitional to the uniform facies IB which most likely is composed of clay.

Sequence II

T20 penetrates both facies IIA, IIC, and IIE, whereas T40 penetrates facies IIC, IID, and IIE. T20 indicates that IIA is composed of sand, probably reworked sediments (mass-transport creep) from IC. T20 and T40 indicate that sequence II is composed of alternating clay and sand beds with low lateral continuity except for the topmost clay layer (facies IIE, see below). In the western part of the palaeovalley in sequence II, a dominance of meter scale thick clay beds is observed in facies IIC. In T40 facies IID is clay-prone in the lower part and sand-prone in the upper part. The channel plug in facies IID is seen to be composed of silty clay, at least in the lateral part of the plug penetrated by T40. Facies IIE is a continuous clay bed with thin silt layers, corresponding to the positive continuous reflection in the seismic study. At T40 facies IIE is difficult to differentiate from the clay plug of facies IID.

Sequence III

All three logs indicate that sequence III is composed of clay-free sand. Samples collected from this sequence are similar to the outwash deposits exposed at the surface, and sequence III is interpreted as the subsurface part of the outwash system.

Sedimentary Architecture and Hydraulic Properties

The hydraulic properties of the sediments may be approximated using the combined geometric and lithologic data from the seismics and logs and data from wells in the area. Grain-size data are available from a number of water-supply and research borings near Rabis Creek. The majority of borings, however, do not penetrate below sequence III.

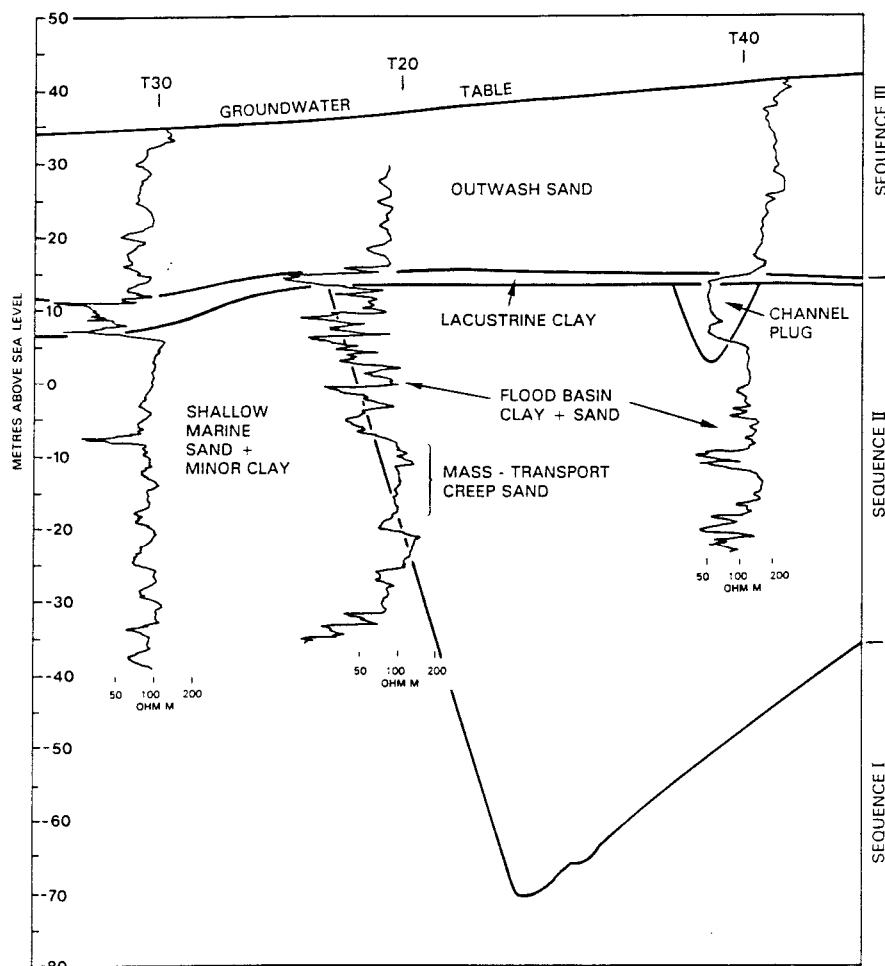


Fig. 4. Electrical resistivity logs along the seismic survey. Lithological units interpreted from logs and seismics are indicated. For position of borings see Figure 3A.

Moreover, information concerning the hydraulic conductivities of the aquifer system is sparse.

The uppermost aquifer, sequence III, is the best known with reliable grain-size and field test data. The sediments are composed of medium-grained sand (0.2-0.6 mm) with thin layers of granules and pebbles. A pumping test from Rabis Dal, immediately north of Rabis Creek, indicates a transmissivity of $5.8 \times 10^{-3} \text{ m}^2/\text{s}$, estimated to correspond to a hydraulic conductivity of approximately $2 \times 10^{-4} \text{ m/s}$ (Miljostyrelsen, 1983). This figure has been confirmed by pumping tests, tracer tests, and other methods in two borings carried out at the Rabis Creek site (Hansen, 1991). The sequence III aquifer is about 20 m thick at this locality, thickening to the east and thinning to the west of the locality. It has a large lateral extent, on the order of 500 km^2 (Miljostyrelsen, 1983).

Sequence III is underlain by an aquitard of clay and silt, unit IIE. No field test data or experimental data exist from this unit. An empirical estimate of the hydraulic conductivity is on the order of 10^{-10} - 10^{-7} m/s (e.g. Freeze and Cherry, 1979; Carlsson and Gustafsson, 1984). The thickness of IIE at the site of the seismic survey is 1-6 m. Resistivity measurements indicate that the clay layer wedges out 0.5-1 km east of the limit of the seismic section. Laterally in other directions the clay layer is locally present as judged from water-supply well data. The variable data qualities prohibit, however, a detailed mapping of this unit.

No direct grain-size data or hydraulic tests exist from the palaeovalley of sequence II. Both the seismic data and the resistivity measurements indicate a very heterogeneous composition with alternating layers of gravel/sand, silt, and clay with limited lateral continuity. Accordingly, the hydraulic conductivity probably ranges from 10^{-9} - 10^{-4} m/s (op. cit.) within very short distances both vertically and laterally. Channel deposits such as units IIB and IID are probably close to the upper value of this range whereas the flood basin unit (IIC) is close to the lower value. Facies IIA is composed of clean sand in the westernmost part, where it rests on the sandy facies IC. If the interpretation of this facies as creep deposits is correct, the central and eastern part IIA may be composed of material similar in composition to facies IB, with which it is closely associated (i.e. clay deposits). The main part of facies IIA may thus possess hydraulic conductivities on the order of 10^{-11} - 10^{-9} m/s (op. cit.).

A bulk conductivity value is difficult to estimate for the paleovalley, but it probably lies around 10^{-6} - 10^{-5} m/s . The paleovalley possesses a maximum thickness of 80 m. To the west it wedges out within the seismic profile. To the east, the paleovalley wedges out approximately 1 km east of the profile as judged from the inclination of the lower sequence boundary. A seismic survey carried out 3 km north of Rabis Creek (Ploug, 1991) indicates that the paleovalley trends NNV-SSE.

The uppermost part of sequence I is composed of a sand-prone aquifer, unit IC. Only limited grain-size data from water-supply wells exist, indicating a dominance of medium-grained sand. Resistivity data indicate the presence of only one minor clay layer in the upper c. 40 m. Below this sandy part a 20 m thick portion with gradually increasing clay content is present, interpreted from the T20 log. Accordingly, 40 m of high permeability aquifer is underlain by 20 m of lower permeability aquifer grading downwards to aquitard properties (unit IB). No hydraulic well tests or laboratory tests have been carried out to outline the properties of unit IC. However, flow and transport modeling using a hydraulic conductivity of $1-2 \times 10^{-4}$ m/s for the upper sandy part of IC provided very satisfactory results (Hansen, 1991), and this figure seems realistic. The lower clay-rich portion is probably characterized by hydraulic conductivities of 10^{-9} - 10^{-5} m/s. The bedding in unit IC is tabular, and individual portions may be laterally extensive. The unit is, however, bounded to the east by sequence II.

No direct data of grain-size and hydraulic properties are available for units IB and IA. The investigations indicate that IB is clay-prone, whereas IA, in a seismic sense, is similar to IC and probably dominated by well-bedded sand. Hydraulic conductivities, accordingly, are estimated at 10^{-11} - 10^{-9} and approximately 10^{-4} m/s for units IB and IA, respectively. The thickness of unit IB is 20 m, whereas unit IA is +70 m. Both units are tabular and apparently have a large lateral extent. However, unit IB is truncated by sequence II and thus separated into two subunits. At present no data exist to constrain the regional lateral extent.

The different facies are connected at or near the location of the present seismic survey as evidenced in the discussion above giving rise to the following hydraulic reservoirs. Aquifer unit IA is separated from the other aquifers partly by IB and partly by the aquitard part of IIA (Figure 3B), and in practice IA may be considered a separate reservoir unit. IC seems to be connected hydraulically with IIA (western part), IIB, IIC, and IID. This composite and heterogeneous hydraulic reservoir is separated from the aquifer sequence III by the aquitard IIE in the study area (Figure 3B). In contrast, facies IC and sequence III will probably act as one hydraulic reservoir east of the profile because both the aquitard IIE and the underlying paleovalley wedge out within 1 km, resulting in superposition of sequence III on facies IC.

Conclusions

Seismic profiling associated with seismic facies analysis provides a unique possibility of reservoir scale 2-D geometrical and lithological interpretation of geological structures in ground-water reservoirs. When supplemented with well data and geophysical logs, the seismic method provides highly valuable data from both the shallow and deeper lying parts of the reservoirs.

Acknowledgment

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