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Unraveling the shallow geology of the western Wadden Sea using high resolution seismics

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Abstract

Modelling of the shallow subsurface of the Dutch Wadden Sea is merely based on lithological information extracted from a limited amount of core samples. In order to improve the subsurface model and to provide a better basis for engineering purposes, seismic data have recently been acquired, processed and interpreted. This study focuses on the interpretation of seismic data in a pilot area in the southwestern part of the Dutch Wadden Sea near the Afsluitdijk. In order to acquire a maximum detail of subsurface information in a time-efficient way, multiple types of seismic systems were deployed simultaneously in a 'one-sweep-survey', providing information over depth ranges up to 60 m subsurface depth. Data from three seismic systems are presented; a chirp system, a boomer and sparker source in combination with hydrophone streamers. Geological interpretation of the seismic data was made by identifying seismic facies units and subsequently correlating them to geological cross-sections, running parallel to the Afsluitdijk. Geological cross-sections were derived from the existing geological and hydrogeological model and from relatively densely spaced borehole information. Six key reflectors were identified on the seismic data along the Dutch Afsluitdijk that make up four seismic facies units. Results of seismic profiles show good recognition of internal structures in especially Holocene sediments. A clay plug and a shallowing of a channel at the eastern side of the pilot area were interpreted as channel infills resulting from the rather sudden dominance by newer tidal channels to the west, probably coinciding with the opening of the Marsdiep channel. The channel wall deposits observed were interpreted as a turning of the drainage channel after closure of the IJsselmeer. Strong reflections of deeper levels (>15 m below Dutch vertical datum, i.e. N.A.P.) were interpreted as clay/sand interfaces in the Middle-Pleistocene Urk Formation and were more continuous than previously thought. It is concluded that high resolution seismics add valuable information yielding improved understanding of the sedimentary structure of the shallow subsurface, which in turn can be useful for near future engineering works along the Afsluitdijk.

Keywords: Wadden Sea, shallow geology, seismics, tidal area

Introduction

Coastal areas are among the most dynamic sedimentary environments in the world leading to highly variable and non-uniform deposits. Also, due to the current highstand of the world oceans, a series of heterogeneous sedimentary deposits, which developed on the flooding surface, is often present beneath the more recent deposits. This is especially true for the North Sea Basin coasts where several highstands (present, Eemian) more or less reached the same position on top of earlier Pleistocene landscapes (Zagwijn, 1983; Westerhoff et al., 2003).

In the western part of the Dutch Wadden Sea (indicated in Fig. 1) a better understanding of the shallow geology is required in order to assess possible consequences of human intervention. Amongst these interventions is the planned reconstruction of the Afsluitdijk, an enclosure dam built in 1932 with a length of 30 km. The Afsluitdijk bounds the southern part of the westernmost Wadden Sea and closes off the large inland sea, which is nowadays called IJsselmeer. Widening of the Afsluitdijk requires knowledge of the geology of the shallow subsurface underneath the dam. For example, knowledge on the composition, thickness and depth of the youngest strata is needed to assess the amount of material to be removed by dredgers and to determine the depth of the subsurface layers suited for founding the possible extensions of the dam. Furthermore, the reconstruction of the dam could affect existing water flow directions and strengths, in turn resulting in changes in erosional and depositional patterns at the sea bottom, depending on the types of sediment present in the shallow subsurface (Oost & de Boer, 1994). Moreover, additional sluice capacity has to be realised in the Afsluitdijk to enable water management of the large inland lake, the IJsselmeer, situated south of the enclosure dam. There are several important management issues that are linked to the sub-surface geology – issues that hitherto have received little attention. For instance, as Pleistocene glacial tills are much more resistant to erosion by high current velocities, removal of the till during channel deepening or construction of pipelines, may potentially lead to a concentration of flow in that particular area. This can lead to unwanted effects, such as the washing out of sands put in place to cover the pipelines.

Here, the results of a study are presented focusing on a pilot area near the Afsluitdijk in which various high resolution seismic datasets were acquired simultaneously in a 'one-sweep-survey' (Dubelaar et al., 2010; Paap et al., 2010). Existing studies related to geological characterisation of the shallow subsurface of the Wadden Sea were performed at the German and Danish parts (Zeiler et al., 2000; Boldreel et al., 2010). This study concentrates on the southwestern part of the Dutch Wadden Sea, situated near the Afsluitdijk, as is shown in Fig. 1. The acquired seismic data, providing geological information on the upper 60 m of the subsurface, were to be interpreted using existing information from boreholes and extractions from the Digital Geological Model (DGM) and Hydrogeological Model (REGIS II) of the Netherlands.

Site characteristics and depositional environment

The Wadden Sea area is situated in the German Bight of the North Sea. It is the largest temperate zone tidal flat area with little river influence in the world and stretches over 400 km from Denmark, via Germany to Holland. The system is characterised by relatively small (10 km to 30 km in length) mainly drumstick-shaped, barrier islands. It is a shallow water environment characterised by intertidal and subtidal flats (5 m below N.A.P.) and dissected by tidal channels. The back-barrier tidal basins have a considerable size and the mixed micro- to macro-tidal, semidiurnal regime is characterised by a large and

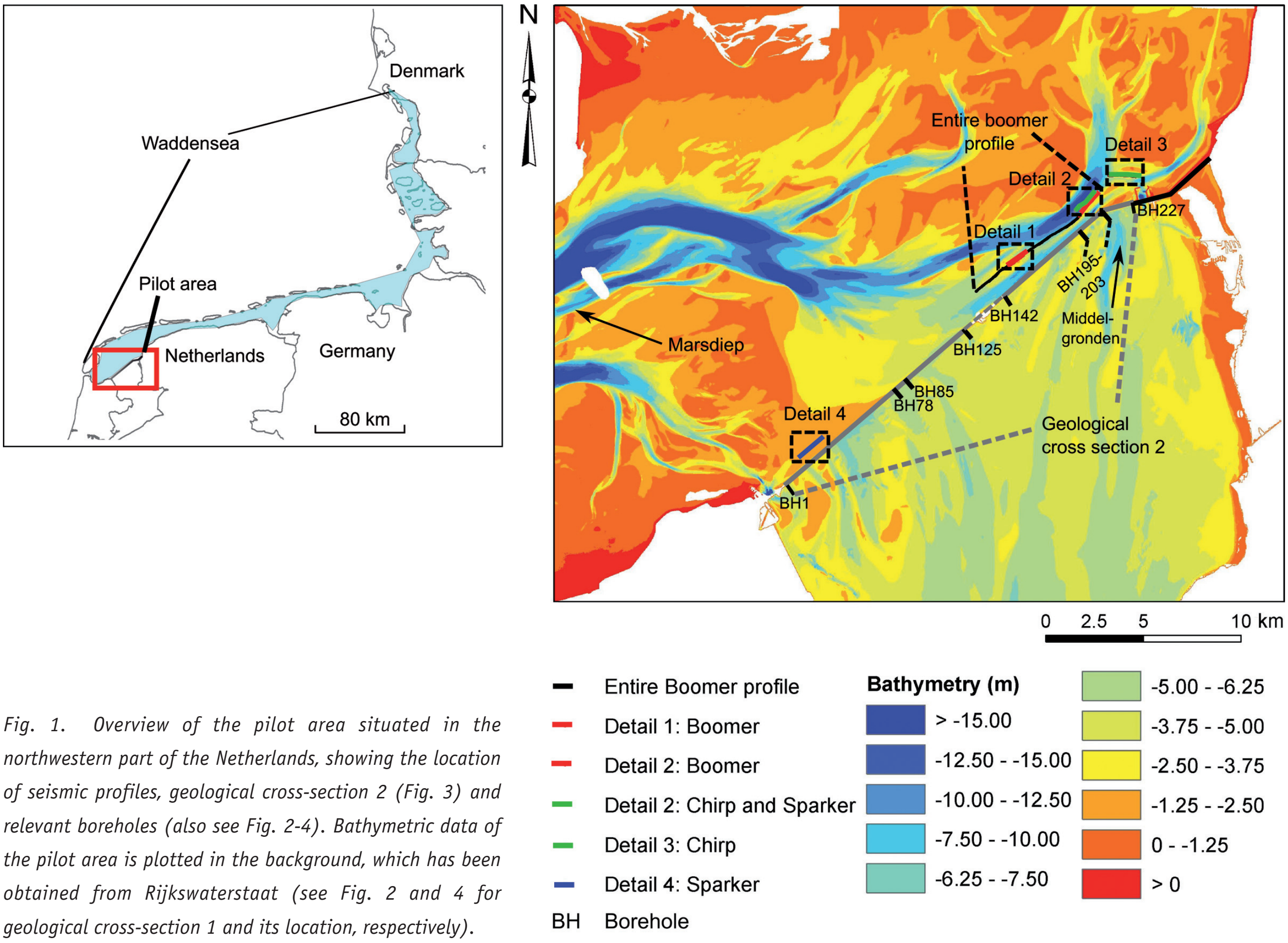

Fig. 1. Overview of the pilot area situated in the northwestern part of the Netherlands, showing the location of seismic profiles, geological cross-section 2 (Fig. 3) and relevant boreholes (also see Fig. 2-4). Bathymetric data of the pilot area is plotted in the background, which has been obtained from Rijkswaterstaat (see Fig. 2 and 4 for geological cross-section 1 and its location, respectively).

geographically varying tidal range: from 1.4 m at Den Helder (western Wadden Sea, the Netherlands), to 3.5 m in Bremerhaven (central part Wadden Sea in the German Bight, Germany) to 1.5 m at Skallingen (northern Wadden Sea, Denmark; Wiersma et al., 2009). Mean annual significant (offshore) wave height varies from 1.1 m to 1.3 m. During storm surges, the maximum recorded set-up in water level can be 3.25 m to 3.75 m, in the western part of the Dutch Wadden Sea (Rijkswaterstaat, 2009).

Geology of the western Wadden Sea

Existing knowledge of the shallow geology is sparse in the Dutch Wadden Sea, especially the shallow part of the subsurface under consideration in this study (0-60 m below N.A.P.). Only a limited number of studies have been performed in this area (Koerselman et al., 2002; Van Staalduinen, 1977; Ter Wee, 1976; Zagwijn & Van Staalduinen, 1975). Additional use of seismic data is considered to be very useful, but the required data acquisition is severely hampered by the shallow water depths observed in this tidal basin. The general description of the geological setting of the western part of the Wadden Sea near the Afsluitdijk is based on drillings, the Digital Geological Model (DGM V1.3, Gunnink et al., in press) and REGIS II.1 (Vernes & Van Doorn, 2005, 2008). Both DGM and REGIS II cover the entire Netherlands and are based on a set of 16,500 drillings, selected from the Geological database of the Netherlands (TNO, 2012).

Based on existing geological information, Table 1 presents an overview of the lithostratigraphic units known to be present in this study area. Main characteristics of the lithology, the interpreted depositional environment and an indication of the chronostratigraphic position of the lithostratigraphic units are listed in this table. These units range in age from Middle-Pleistocene to Holocene (Westerhoff et al., 2003).

Two geological cross-sections (Figs 2 and 3) were constructed for the study area, both extending along the Afsluitdijk from SW-NE (see Figs 1 and 4 for location). Geological cross-section 1 is extracted from the REGIS II model (Fig. 2). Although this cross-section is based on a relatively small amount of deep boreholes it does give an indication of the distribution and the lithology of the Holocene and Pleistocene formations. In Fig. 4 the distribution and depth of the boreholes is given, indicating that the deeper part of the geological sequence is not well represented in the boreholes.

Geological cross-section 2 was constructed to provide more detail in the shallow part of the subsurface up to 15 m below N.A.P. (Fig. 3). This cross-section is derived from approximately 250 boreholes up to 15 m below N.A.P. collected 50 m south of the Afsluitdijk in the period 1974-1976. The boreholes are situated parallel to the Afsluitdijk and have an average spacing of 100 m. Geological cross-section 2 clearly shows the distribution and thickness of the lithostratigraphic units. There is a gap at the center of this cross-section of approximately 2200 m where borehole information is absent (Figs 1 and 3). Geological cross-section 2 shows the presence of the Naaldwijk Formation at the top (Holocene marine, tidal basin deposits), which in general increases in thickness towards the northeast, due to the occurrence of the main tidal channels. The underlying Boxtel Formation (Late-Pleistocene, Weichselian, mainly eolian sands, loam and occasional peat, deposited in small rivers and lakes) has a wide distribution, which is thinning out to the southwest. The top of the underlying glacial till (Gieten Member of the Middle-Pleistocene Drente Formation) is gently dipping towards the northeast. On the former island Wieringen situated more to the southwest just outside of the study area, the glacial till is exposed at the surface. The glacial till is present along the main part of the cross-section. Due to erosion it is absent

Table 1. Main characteristics of the lithostratigraphical units in the western Wadden Sea (Westerhoff et al., 2003). N.A.P. stands for Dutch vertical datum used as reference level.

Lithostratigraphic unit	**Top and Base**	**Lithology and depositional environment**	**Age**
Naaldwijk Formation	Sea bottom ca 7-15 m –N.A.P.	Pre-dominantly moderately coarse to fine shelly sand	Holocene
Nieuwkoop Formation	-	Small erosional remnants of thin basal peat layer	Holocene
Boxtel Formation	5 m –N.A.P. 15 m –N.A.P.	Fine sand and silt with intercalations of thin peat layers	Weichselian (Late-Pleistocene)
Eem Formation	10 m –N.A.P. 25 m –N.A.P.	Channel fill with fine to coarse marine sand and clay	Eemian (Late-Pleistocene)
Drente Formation	10 m –N.A.P. 15 m -N.A.P.	Till (Boulder Clay), sand and silt with erratics	Saalian (Middle-Pleistocene)
Drachten Formation	15 m –N.A.P. 20 m –N.A.P.	Fine to moderately coarse sand	Saalian (Middle-Pleistocene)
Urk Formation	20 m –N.A.P. >60 m –N.A.P.	Fine to coarse fluvial sand with clay layers (1-5 m thick)	Middle-Pleistocene
Peelo Formation	40 m –N.A.P. >100 m –N.A.P.	Very fine to very coarse sand, very thick clay deposits. Fluvioglacial deposits	Elsterian (Middle-Pleistocene)

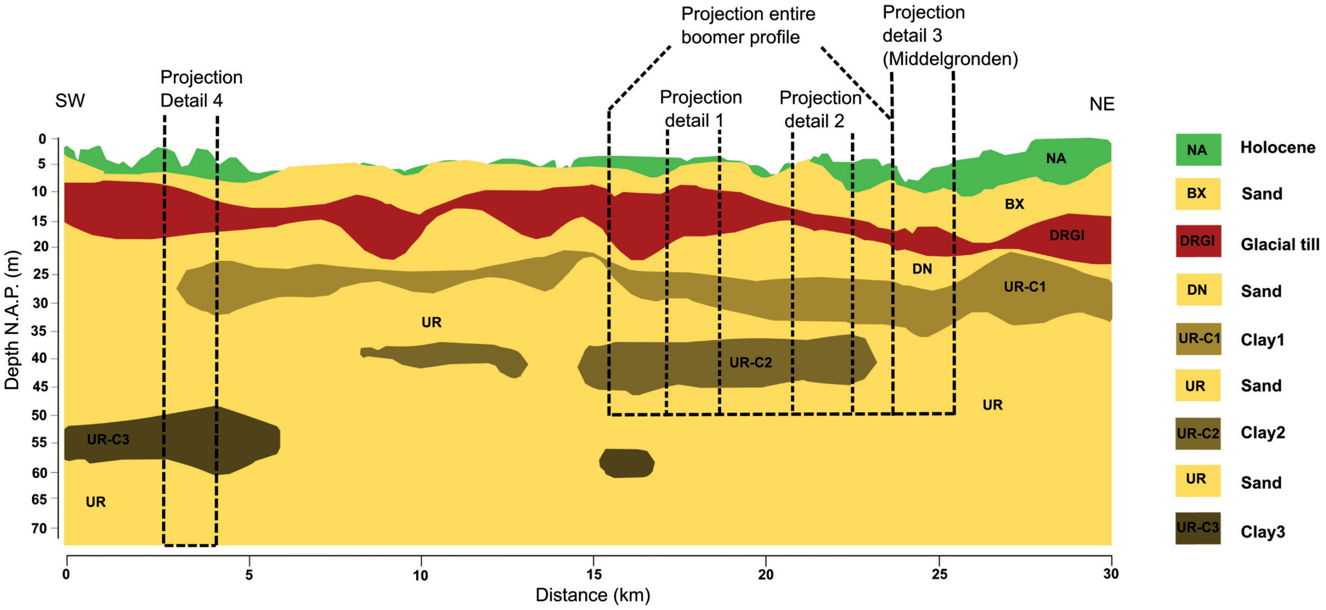

Fig. 2. Geological cross-section 1 is situated in the south western part of the Wadden Sea, extending along the Dutch Afsluitdijk up to 75 m depth. This cross-section was extracted from the Dutch hydrogeological model REGIS II (Vernes & Van Doorn, 2005, 2008). The location of this cross-section is indicated in Fig. 4. This cross-section is based on the lithostratigraphical classification of Westerhoff et al. (2003). NA: Naaldwijk Formation, BX: Boxtel Formation, DRGI: Drente Formation, Gieten Member, DN: Drachten Formation. UR: Urk Formation. See table 1 for description of lithostratigraphic units (presented information is obtained from TNO (2012)). See Fig. 4 for location of cross-section 1.

at a few places, notably near boreholes 78 and 85 (indicated in Figs. 1 and 3), pointing to the presence of deep channels of Late-Pleistocene age, which contain marine deposits from the Eemian (Ter Wee, 1976; Van Staalduinen, 1977).

Seismic systems, data acquisition and processing

The acquisition of seismic data in the Wadden Sea area is complicated by the limited accessibility due to shallow water depths. Therefore a vessel with a small draft of 0.7 m was used. To obtain subsurface information over a depth range of approximately 60 m below N.A.P., three different seismic systems were used. Sailing time was reduced by deploying two seismic systems simultaneously in a 'one-sweep-survey'. The seismic systems used consisted of a chirp system in combination with a boomer or sparker source. Table 2 shows an overview of source, receiver and data characteristics for each seismic system, including the vertical resolution and maximum depth up to which geological information is provided (i.e. penetration depth). The vertical resolution is determined by the dominant frequency of the

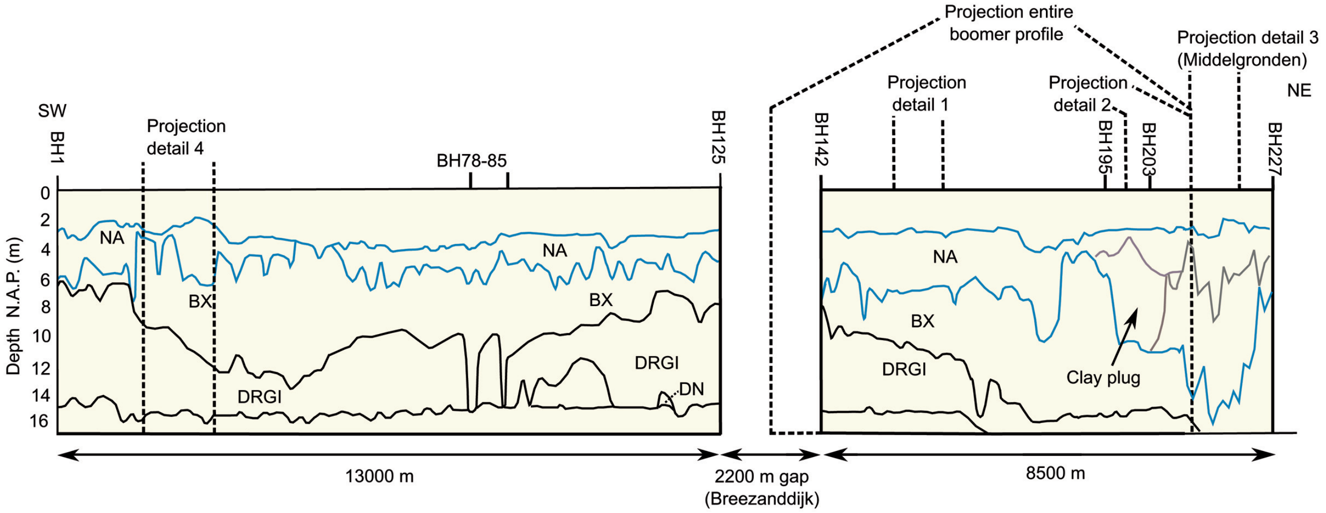

Fig. 3. Geological cross-section 2 along the Afsluitdijk derived from borehole information up to 15 m depth. The location of this cross-section is indicated on the right side of Fig. 1. NA: Naaldwijk Formation, BX: Boxtel Formation, DRGI: Drente Formation (Gieten Member), DN: Drachten Formation. See Table 1 for description of lithostratigraphic units (presented information is obtained from TNO (2012)). See Fig. 1 for location of cross-section 2

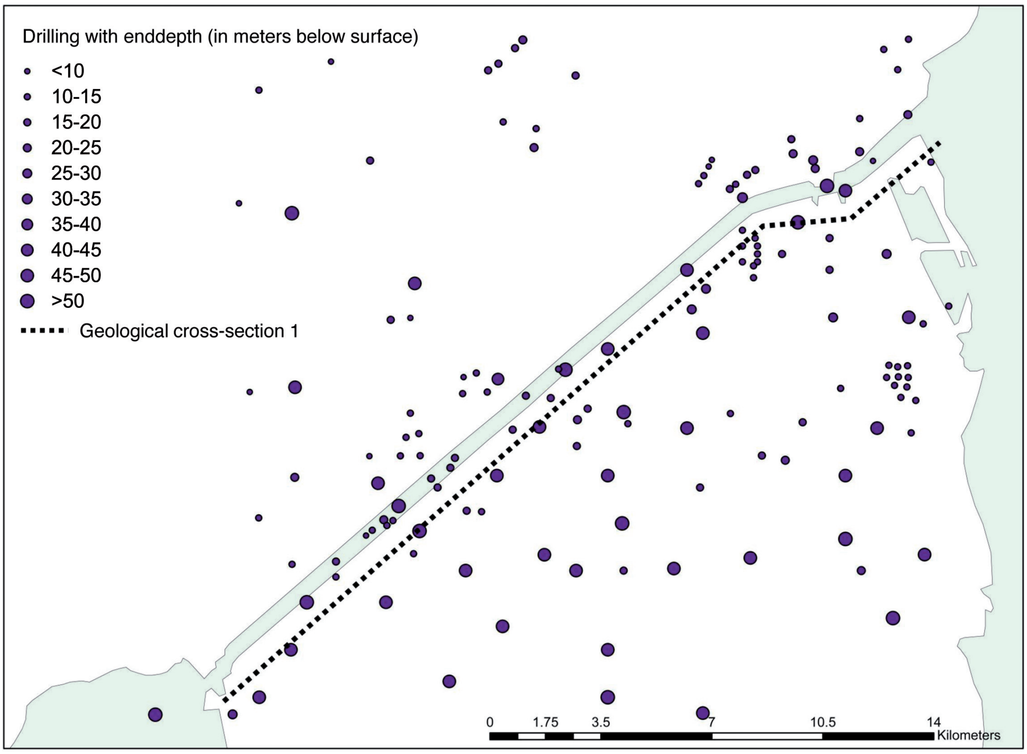

Fig. 4. Distribution and depths of deeper boreholes present in the survey area used to construct geological profile 1 (Fig. 2), indicating that the deeper part of the geological sequence is not well represented in the boreholes. The shallow boreholes situated just south of the Afsluitdijk that are used to construct geological profile 2 (Fig. 3) are not indicated on this map.

seismic signal. Increasing penetration depths are obtained respectively by the chirp, boomer and sparker sources (Telford et al., 2004).

Data were continuously recorded with the chirp sub-bottom profiler system, providing information approximately up to 15 m below seabed (Table 2). Boomer measurements were performed in combination with a single channel streamer, providing shallow subsurface information up to 60 m depth. In order to obtain deeper subsurface data, a 24-channel streamer was used to record the sparker data. To minimise interference of seismic source signals during data acquisition, the distance between the chirp and either the boomer or sparker was approximately 20 m, which proved to be sufficient for an acceptable data quality.

The collected seismic data were processed in dedicated seismic data processing software (Promax©) and consisted of standard processing steps (Telford et al., 2004; Yilmaz, 1987).

Data processing of single-channel chirp and boomer data consisted of:

- Trace editing;
- Bandpass filter;
    - Chirp: Lowcut: 2000-2500 Hz, highcut: 5000-5500 Hz;
    - Boomer: Lowcut: 650-700 Hz, highcut: 1800-1900 Hz;
- Application of automatic gain control and
- Time to depth conversion, with an estimated average acoustic sediment velocity of 1600 m/s.

Table 2. Overview of the specifications of the seismic systems used for the shallow seismic reflection survey and seismic data characteristics.

		Seismic system		
		Chirp	**Boomer**	**Sparker**
Source characteristics	***Brand***	Edgetech	Geo-resources	Geo-resources
	Type	SB-512i	Geo-Boomer 300 - 500	Geo-Source 200
	Transmit power	2000 W	500 J (supplied by Geo-Spark 1000)	1000 J (supplied by Geo-Spark 1000)
	Shot interval	0.5 s	1.0 s	1.0 s
	Towing depth	0.5-1.0 m below water surface	At water surface	At water surface
Receiver characteristics	***Number of receiver groups***	1	1	24
	Near source-receiver offset	~0.5 m	~1.5-3.5 m (affected by currents)	~4.0 m
	Receiver group spacing	Not applicable	Not applicable	3 m
Data characteristics	***Maximum penetration depth***	15 m	50 m	100 m
	Dominant frequency	2500-4000 Hz	1300 Hz	750 Hz
	Vertical resolution	~0.2-0.3 m	~0.3-0.5 m	~0.4-0.6 m

Processing of multichannel data acquired with the sparker source and 24-channel streamer consisted of:

- Trace editing;
- Bandpass filter: lowcut 150-200 Hz, highcut: 1200-1300 Hz;
- Velocity analysis, see explanation in next paragraph;
- Spiking deconvolution;
- Normal moveout correction;
- CDP ensemble stack and automatic gain control; and
- Time to depth conversion, with an estimated average acoustic sediment velocity of 1600 m/s.

Preferably a velocity model of the study area would have been obtained from velocity analysis of the multichannel sparker data, to be subsequently used for time depth conversion of chirp, boomer and sparker data. However, obtaining an accurate velocity model from velocity analysis of multichannel sparker data was complicated by restricted sparker data quality and the observed heterogeneity of the shallow geology. Only part of the sparker data was of sufficient quality to yield a consistent velocity model from velocity analysis.

In addition, attributing representative vertical velocity profiles to the observed shallow Holocene and Late-Pleistocene structures was found to be complicated, due to the finite spatial extent that these structures have, with dimensions typically smaller than a few hundred meters in the upper 20-30 ms. In general more constant velocity values were found below 30 ms, of 1650 m/s to 1680 m/s. A sparker track of 1300 m length was used where sparker data was of sufficient quality, to define vertical velocity profiles during velocity analysis (see Fig. 1 at location of detail 4). This resulted in a three layer velocity model that was used to perform an NMO correction of this sparker track:

- Layer 1: 1480 m/s, 0-5 ms;
- Layer 2: 1550 m/s, 5-30 ms;
- Layer 3: 1650 m/s, 30-100 ms.

Considering the high lateral heterogeneity of the subsurface observed on the acquired seismic data, this velocity model was assumed to be representative only for the location of this specific sparker track. Based on the three-layer velocity model, an average acoustic p-wave velocity of 1600 m/s was assumed to be an acceptable estimate and used for final time-depth conversion of chirp, boomer and sparker data. This is supported by Bachman (1985) and Hamilton & Bachman (1982), presenting values of 1480 m/s for high porosity marine clays to 1650 m/s for dense sand. Additionally, Boldreel et al. (2010) also estimated a p-wave velocity of 1600 m/s for time-depth conversion of seismic sparker data collected in the Danish part of the Wadden Sea.

Accuracies in depth values of seismic data are affected by the following uncertainties:

- The assumed seismic velocity model of 1600 m/s introduces an uncertainty in depth positioning of approximately ±3-8%, when considering acoustic velocities might range from 1480 m/s to 1650 m/s (Bachman, 1985; Hamilton & Bachman, 1982).
- Strong currents resulted in motion of the light-weight single channel streamer with respect to the boomer source, resulting in source-receiver offset varying between 1.5 m and 3.5 m. This effect is considered to result in a maximum uncertainty in depth of 0.3 m for boomer data, based on an acoustic velocity of 1600 m/s and waterdepths varying from 3 m to 10 m.
- The effect of tidal influence. The tidal range is known to be approximately 2 m, resulting in uncertainties of seismic depth values of approximately ±1 m. Seismic profiles are given in depth relative to water level as present during the survey.

Geological interpretation of seismic data

A geological interpretation of seismic data was performed by analyzing seismic facies units observed on the seismic data and subsequently integrating this with the geological information provided by the geological cross-sections (Fig. 2 and 3) and DGM/REGIS II models. Representative seismic profiles are presented in this section, i.e. one long boomer profile situated at the northeastern part of the Afsluitdijk and three additional seismic profiles collected with the three seismic systems (Figs 5-9). The locations of these seismic profiles are indicated in Fig. 1.

Each seismic profile is shown twice; one showing indication of seismic facies units and one showing the geological interpretation (Figs 5-9). The seismic profiles are vertically exaggerated to improve visualisation of the information content.

In general the seismic data acquired in the northeastern part of the Afsluitdijk are of better quality than those from the southwestern part of the Afsluitdijk. Therefore we mainly focus on the northeastern part of the Afsluitdijk, with one additional example of a seismic profile in the southwestern part of the Afsluitdijk.

Seismic facies analyis

The boomer profile shown in Fig. 5 has a total length of 7500 m. This profile was used as basis to analyze seismic facies for the study area, since it is a long track of good data quality showing seismic reflections at various depths that can be followed along the major part of the profile. Key reflections were identified and interpreted into seismic reflectors. Table 3 shows an overview of the classification of seismic facies units and the top and bottom reflectors defined for each seismic facies unit. Six well-pronounced reflectors, indicated by R1-R6, are interpreted on this profile and used to distinguish seismic facies units (Fig. 5).

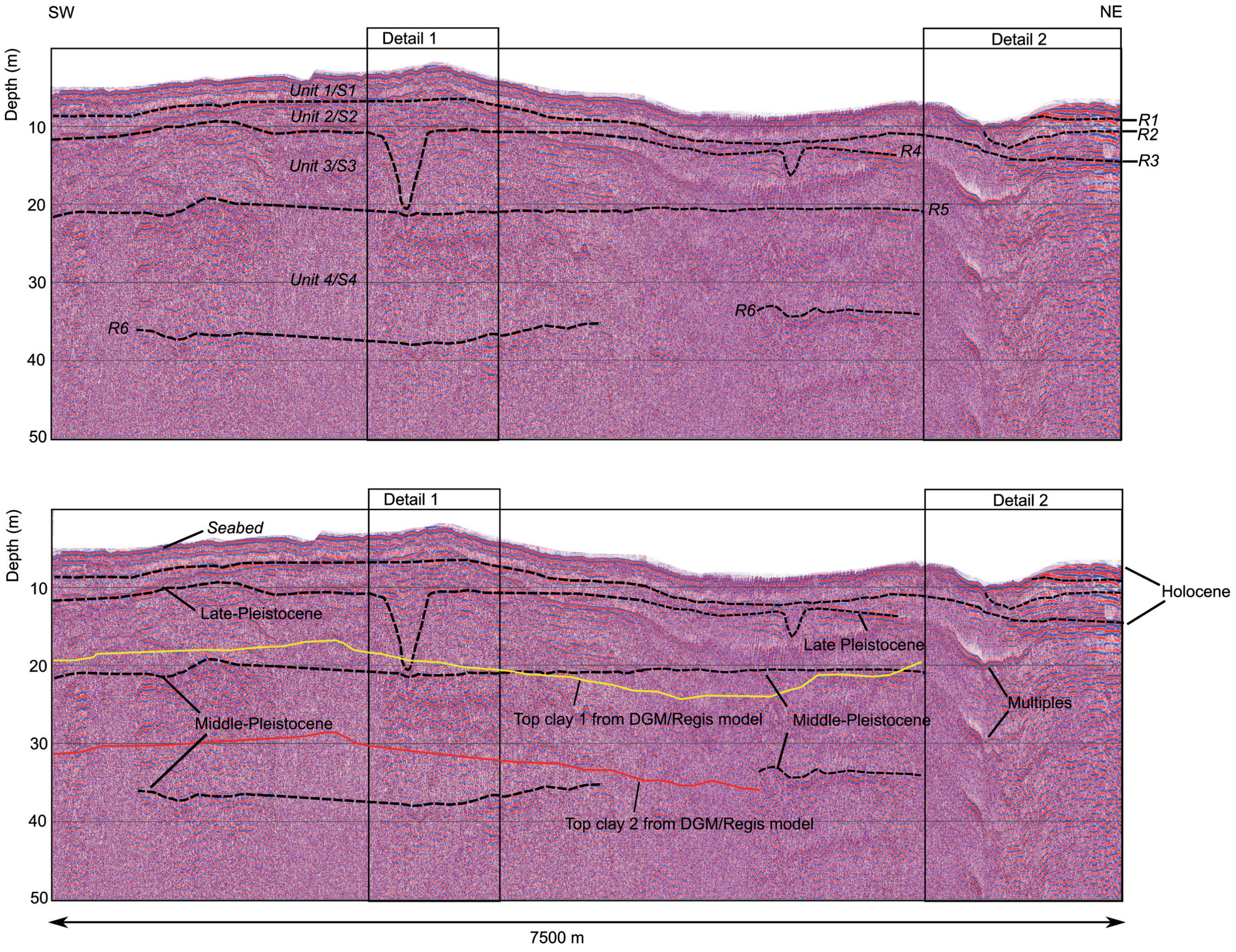

Fig.5. Boomer profile within northeastern part of pilot area. Top: Seismic interpretation. Bottom: Geological interpretation. The bottom profile also shows depth position of two Middle-Pleistocene sand-clay interfaces extracted from REGIS II model that are compared to reflectors R5 and R6. See Fig. 1 for location of this profile. Detail 1 and 2 are given respectively in Figs 6 and 7.

Table 3. Overview of interpreted seismic reflectors and seismic facies units.

Seismic facies unit	Top and bottom reflector
S1	Seabed-R1
	R1-R2
	R2-R3
S2	R3-R4
S3	R4-R5
S4	R5-R6

Reflectors R1 and R2 are high amplitude events locally observed in the northeastern part of the seismic profile, respectively present at approximately 2 and 3.5 m below seabed (total depth on seismic data is 9 m to 12 m). Reflector R3 is a continuous event with a medium to high amplitude that is observed along the entire profile at approximately 4 m to 6 m below seabed (total depth on seismic data is 6 m to 15 m). Reflector R4 is a high amplitude event present at approximately 9 m to 17 m below seabed (total depth on seismic data is 10 m to 21 m). R4 locally has a dipping orientation that suggests the presence of channel structures (see Fig. 5 at location of detail 1). R5 is a high amplitude, continuous and near horizontal event observed at approximately 15 m to 20 m below seabed (total depth on seismic data is 19 m to 21 m). R4 and R5 are not observed at the northeastern part of the profile. R6 is a low amplitude event that is partially observed at a depth of approximately 26 m to 35 m below seabed (total depth on seismic data is 33 m to 38 m).

Based on the identified seismic reflectors, the following four seismic facies units (i.e. S1-S4) were identified (also see Table 3):

- Seismic facies unit 1 (i.e. S1) is the top unit and observed along the entire profile, with a thickness varying from 2 to 7 m, being bounded by R3 at its base. Maximum thickness is attained in the northeast where reflectors R1 and R2 are observed being part of S1 for a stretch of about 1100 m.
- Seismic facies unit 2 (i.e. S2) is present below unit 1. Its base corresponds to reflector R4 that is not observed in the

northeastern part of the profile (Fig. 5). The thickness of unit 2 varies from a rather thin 2 m up to a 15 m thickness at detail 1 in Fig. 5, where it resembles a channel infill.

- Seismic facies unit 3 (i.e. S3) is slightly thinning towards the northeast with thickness decreasing from 10 m to 7 m. Its top and bottom reflectors – R4 and R5 – are absent in the northeastern part where this unit has undefined depth and thickness.
- Seismic facies unit 4 (i.e. S4) underlies unit 3 and has a rather constant thickness of approximately 13 m to 16 m that is observed along the same part of the profile as seismic facies unit 4.

The defined seismic facies units were used for seismic interpretation of the seismic profiles presented in Figs 5-9.

Figure 6 shows detail 1 of the boomer profile of Fig. 5, where reflector R4 and underlying reflectors locally reveal channel shaped structures.

The seismic interpretation of the upper 30 m of detail 2 of the boomer profile from Fig. 5 is shown in Fig. 7a (top). The middle and lower profiles of Fig. 7a respectively show chirp and sparker profiles acquired relatively close to each other and stretching close parallel to the boomer profile. Lateral offset with respect to the boomer profile varies between 350 m at the southwest side and 150 m at the northeast side of the profiles. The chirp and sparker profiles were recorded simultaneously and have a negligible lateral offset of approximately 20 m. The boomer section in Fig. 7a (top) shows dipping reflections that are locally present in between R1 and R2. R3 corresponds to the deepest reflection visible on the boomer section. Compared to the boomer section, the chirp and sparker sections show a deeper seabed (10 m to 15 m compared to 8 m to 10 m) and a different position of observed seismic reflections. Reflectors R1 and R2 are expected at a depth smaller than 10 m, but not identified as such on the chirp and sparker profile, where the seabed already is situated at a larger depth of 10 m to 15 m.

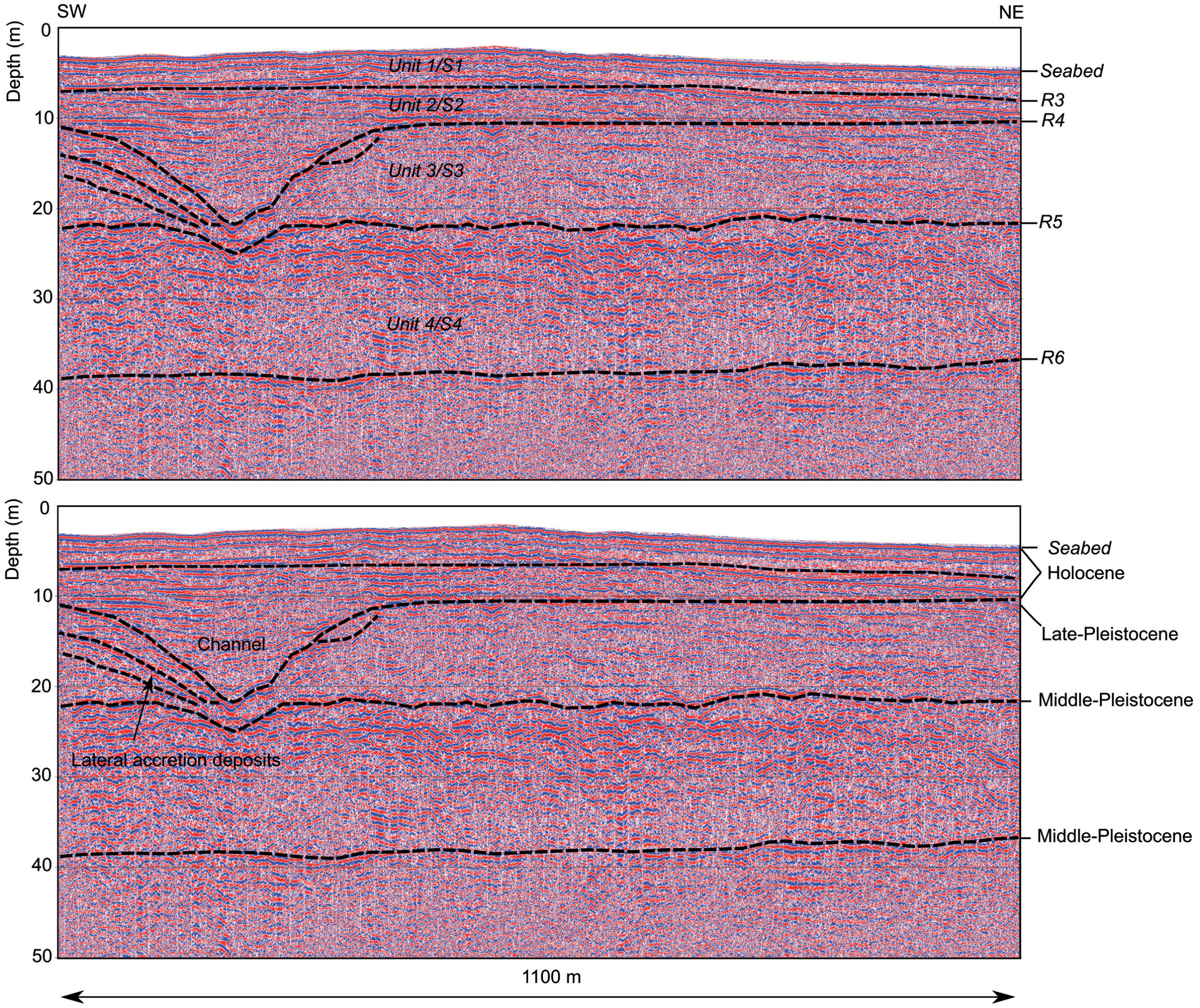

Fig. 6. Detail 1 showing a boomer profile, which is a close up of part of the boomer profile shown in Fig. 5. Top: Seismic interpretation. Bottom: Geological interpretation. See Fig. 1 for location of this profile.

Reflector R3 is observed between 12 m and 17 m depth on the chirp and sparker profiles. The deeper reflection visible on the chirp and sparker sections at 18 m to 25 m depth, is thought to represent reflector R4 observed on boomer profile (Fig. 5), since it has a similar depth range and as delineates the base of a channel structure, similar to the R4 reflector observed in Fig. 5. The sparker profile provides deeper subsurface information complimentary to the chirp profile, and reveals the entire buried channel structure that has a lateral extent of approximately 1000 m.

Figure 8 shows a chirp section situated approximately 1500 m north of the Afsluitdijk (location of detail 3 in Fig. 1). This section shows various shallow reflections at 4 m to 10 m depth below water level that are dipping in western direction. The deepest reflection present at 5 m to 10 m depth could represent reflector R2 as they are observed at similar depths. This is not certain as it could also represent another reflection that is only present locally.

The seismic profile collected with the sparker system in the southwestern part of the study area (location indicated as detail

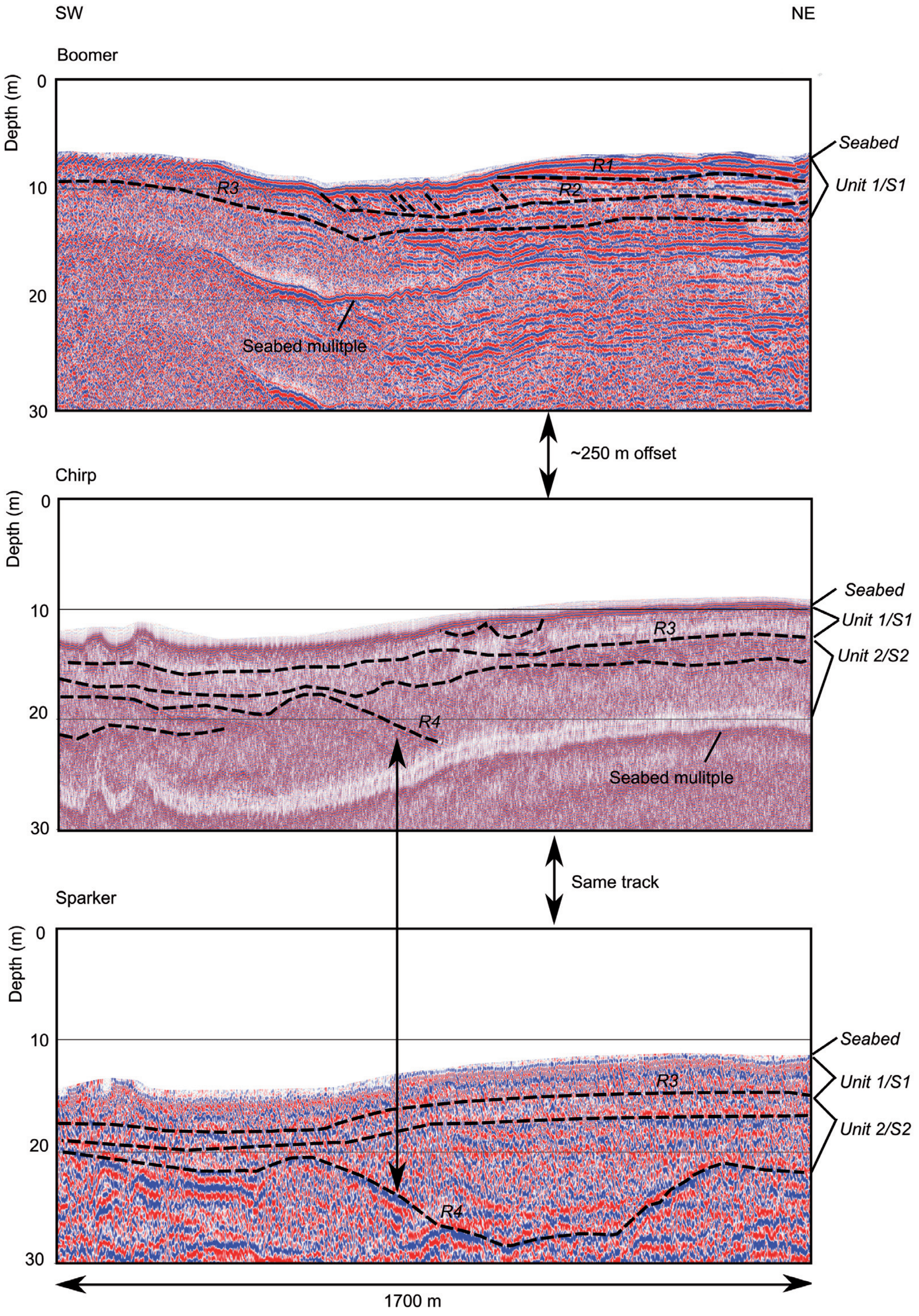

Fig. 7a. Seismic interpretation of detail 2 on boomer (top), chirp (middle) and sparker (bottom) profiles. See Fig. 1 for location of these profiles.

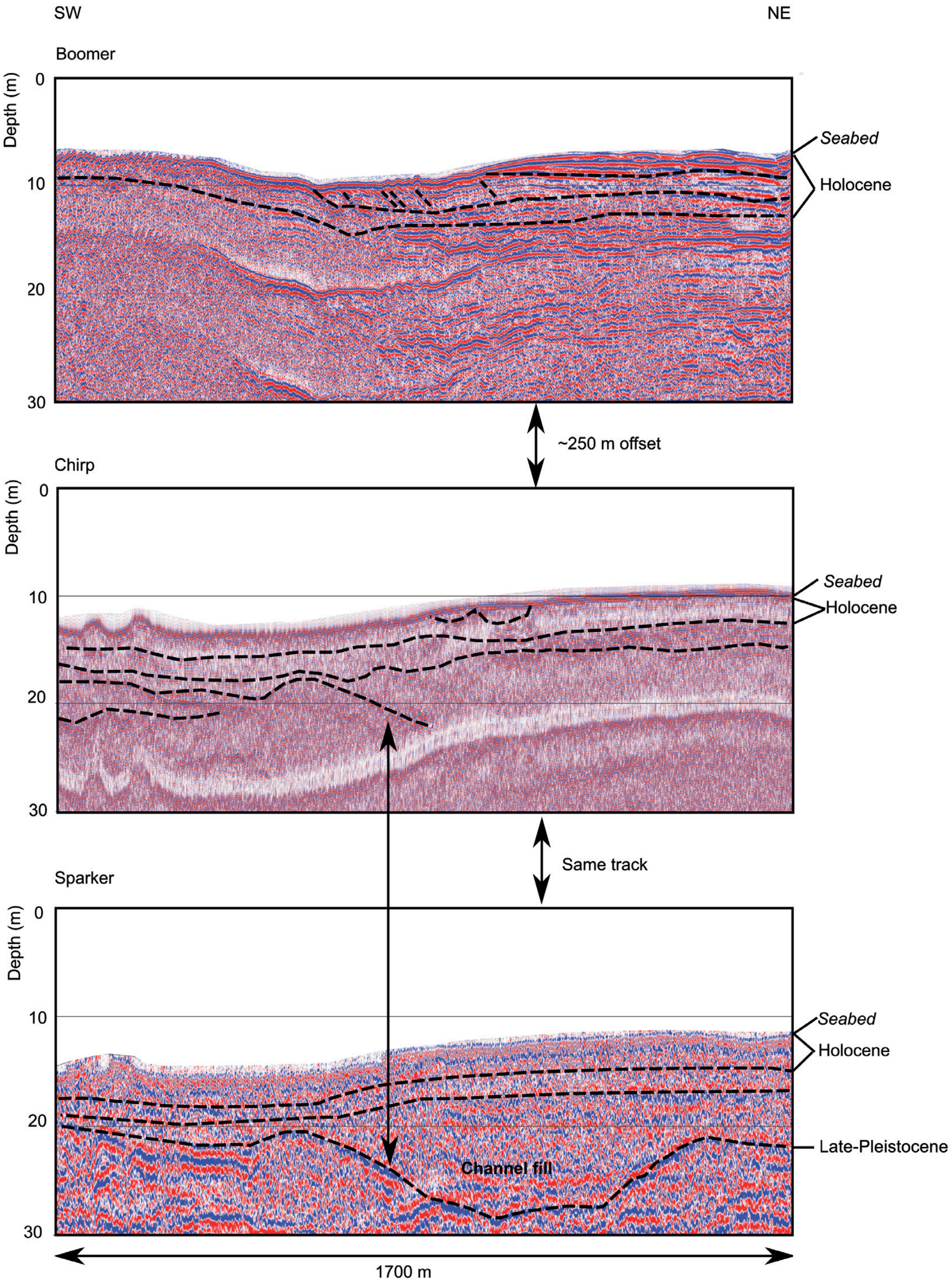

Fig. 7b. Geological interpretation of detail 2 on boomer (top), chirp (middle) and sparker (bottom) profiles. See Fig. 1 for location of these profiles.

4 on Fig. 1), clearly shows the presence of seismic reflections starting from a depth of approximately 20 m until a depth of 90 m below water level (Fig. 9). The marked seismic events show a general dip towards the northeast. The slope with which the reflections are dipping appears to increase below a depth of about 45 m, with a significant increase in depth of 20 m along a lateral distance of 1000 m. The reflection at 20 m depth agrees with the depth of reflector R5 observed on the boomer profile in Fig. 5 and is therefore thought to correspond to the boundary between seismic facies units 3 and 4. Similarly the reflection at 35 m to 40 m depth is considered to correspond to reflector R6, defining the base of seismic facies unit 4. However, the 10 km offset between the sparker profile and the boomer profile restricts a justification of this correlation (Fig. 1). Below R6, several deeper reflectors are observed up to approximately 80 m depth that were not observed on other seismic profiles, and are not considered to belong to S4.

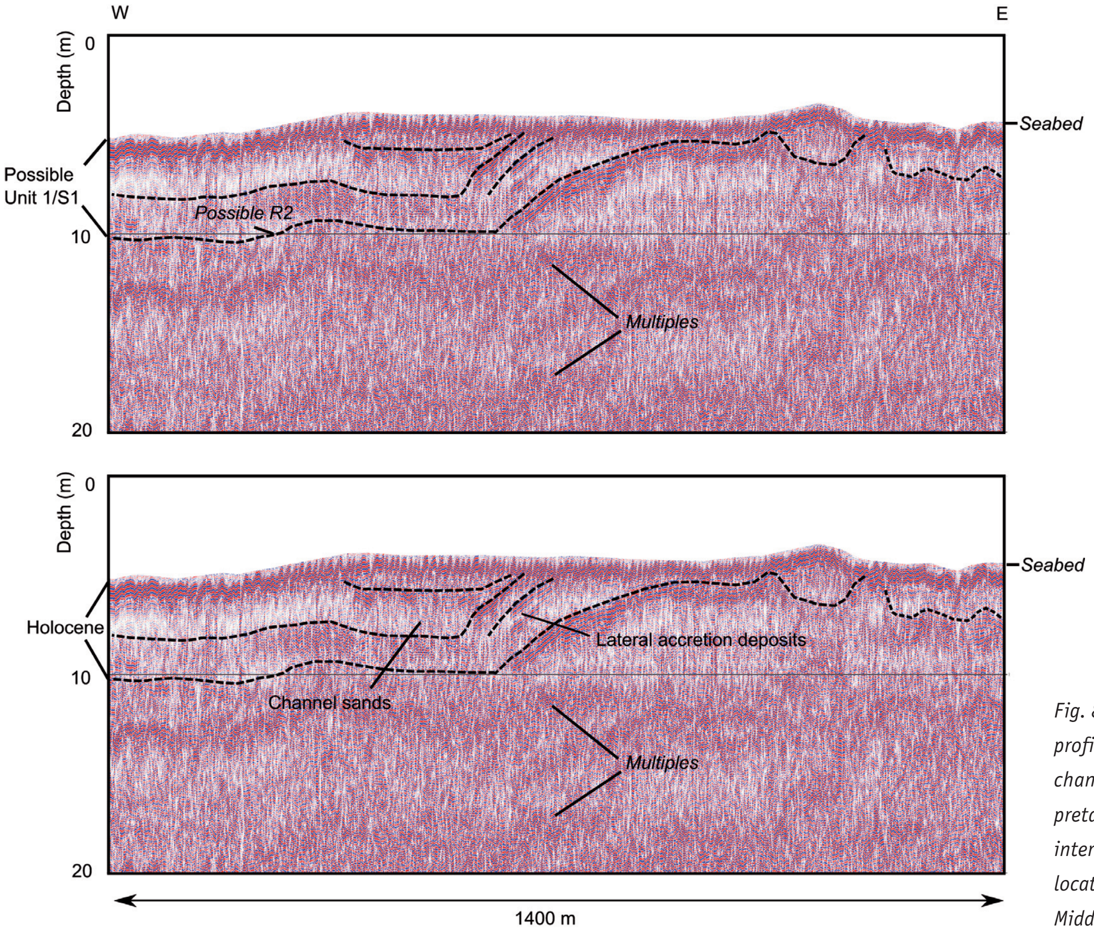

Fig. 8. Detail 3 showing a chirp profile near the Middelgronden channel. Top: Seismic interpretation. Bottom: Geological interpretation. See Fig. 1 for location of this profile and the Middelgronden channel.

There are some parts of especially the boomer and sparker data in which the seismic data of the deeper parts are of poorer quality. This might result from the occurrence of gas in the shallow subsurface, resulting in blanking of the seismic data. Another explanation might be absorption of the acoustic signal by coarse sandy material. Also, strong multiples can cause data distortions, as is indicated at the right side of Fig. 5.

Geological interpretation of seismic facies

The offset between geological cross-sections 1 and 2 situated along the Afsluitdijk and the seismic data to the north is approximately 500 m. Comparison between the geological and seismic datasets, requires a correlation of lithofacies observed on the geological cross-sections with seismic facies units observed on the seismic data. Correlation of both datasets relies on depth positioning for a considerable part. Since there is no data available along the projected 500 m distance, an uncertainty is introduced. Based on observed variation in depth of seismic reflectors (Fig. 5), vertical variations of approximately ±1 m to 2 m meters can be expected when correlating both datasets over such a distance. Including the uncertainties of seismic data depths mentioned previously, a total uncertainty in depth positioning of ±2 to 4 m is considered realistically, when correlating the two datatypes.

Pleistocene

Considering the boomer profile of Fig. 5, the base of seismic facies unit 1 is defined by R3 (observed at 6 m to 15 m), and is thought to correlate to the interface between the Holocene deposits (Naaldwijk Formation) and underlying Weichselian deposits (Boxtel Formation). Based on geological information (see Table 1, Fig. 2 and Fig. 3) this interface is estimated at a similar depth of 7 to 15 m below N.A.P. Seismic reflector R3 is considered to represent the lithological transition from predominantly coarse/fine shelly sand (Naaldwijk Formation) towards fine sand and silt with intercalations of thin peat layers (Boxtel Formation). Seismic facies unit 2 is bounded at its bottom by R4 at 10 to 21 m depth, revealing channel shaped structures on which horizontal deposits are super positioned (see detail 1 in Figs. 4 and 5). Seismic facies unit 2 is thought to correlate with the Late-Pleistocene Eemian age during which marine sand and clays were deposited inside Middle-Pleistocene glacial valleys. Based on geological information (Table 1, Figs. 2 and 3) the top and base of the Eemian are present at 10 to 25 m below N.A.P. (Table 1) which agrees with the observed depths of top and base of seismic facies unit 2. Figure 5 shows reflections at the southwest side of the channel structures that are interpreted as lateral accretion deposits, which could indicate the migration of this channel in a north-

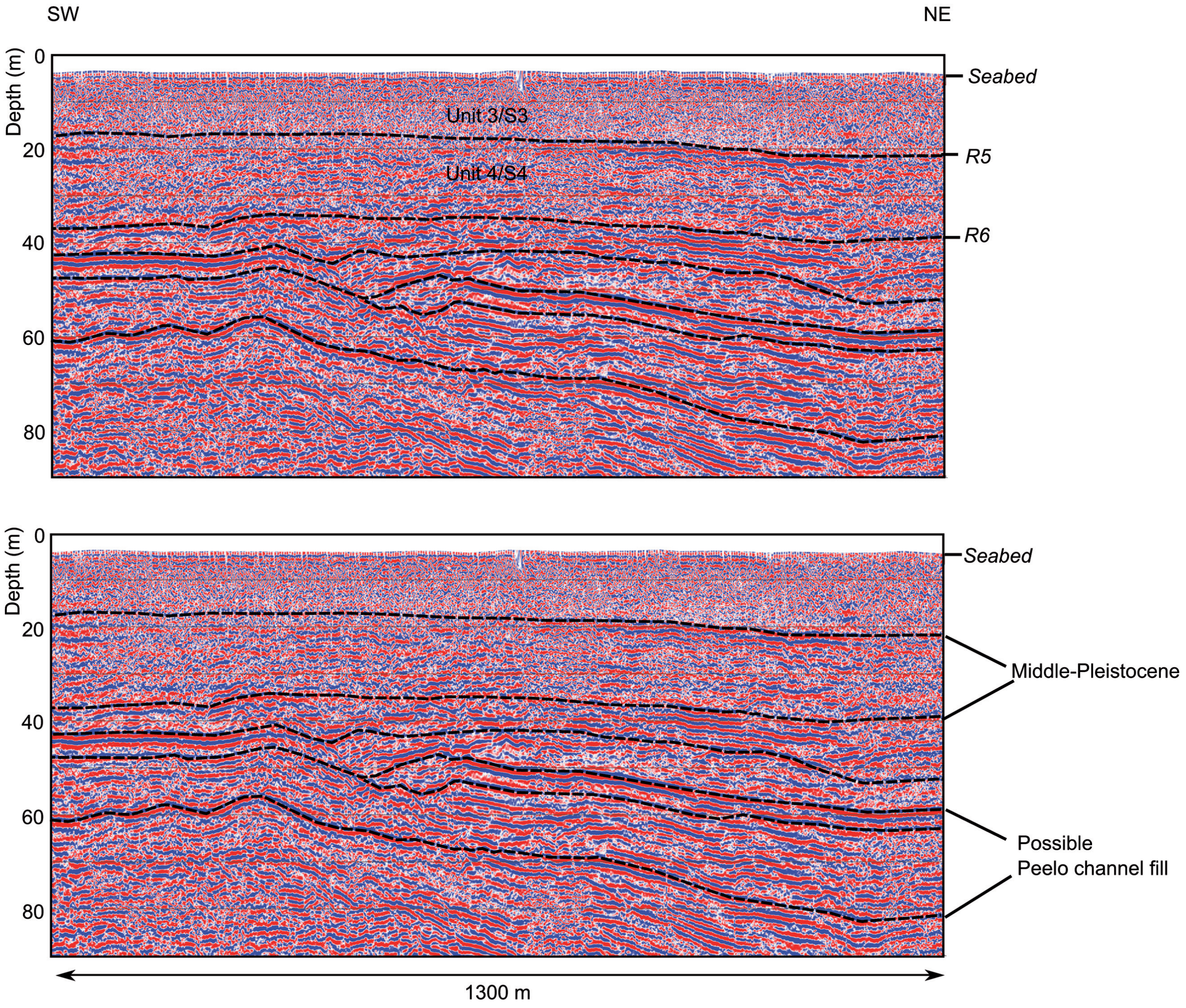

Fig. 9. Detail 4 showing a sparker profile in the southwestern part of the pilot area. Top: Seismic interpretation. Bottom: Geological interpretation. See Fig. 1 for location of this profile.

east direction during the Late-Pleistocene. The two prominent reflectors R5 and R6 are considered to correspond with two sand-clay interfaces present in the Middle-Pleistocene Urk Formation, based on their depth positions. R5 and R6 respectively have depth positions of 19 m to 21 m and 33 m to 38 m (Figs. 4 and 5) similar to the Middle-Pleistocene interfaces – sand-clay1 and sand-clay2 – are respectively present at 20 m to 25 m and 35 m to 40 m below N.A.P. (see Fig. 2).

On the seismic sparker profile obtained in the southwestern part of the study area reflectors R5 and R6 are interpreted (Fig. 9) that might represent lithological sand-clay interfaces in the Middle-Pleistocene Urk Formation. Due to the lack of borehole information of the deeper units it is quite difficult to interpret the lithostratigraphy of these strata. The steeply dipping beds below ca 45 m might point to a large valley fill with glacial deposits of the Peelo Formation (see Table 1 and Fig. 9).

Holocene

The Holocene channels that cross the Afsluitdijk (indicated in Fig. 1) are the most prominent sedimentary features in the Naaldwijk Formation. The depths of the channel floors are in the western part comparable to the depths of tidal channels observed on older maps (Oost & Kleine Punte, 2004). The depth of the cross-sectional area of a channel is directly determined by the tidal volume flowing through it (Oost, 1995a, b). Sand will be removed or deposited when the current velocities are too high or too low respectively, causing a channel to widen or shrink in cross-section and depth. The fact that the observed channel dimensions are roughly not exceeding the maximal observed historical depths, indicates that the tidal volume flowing through it has never been substantially larger.

However, there are two indications for a decrease in tidal volume: the infill of part of the Middelgronden channel and the clay plug in a channel deposit directly west of it indicated on the geological cross-section 2 (Fig. 3) between boreholes 195 and 203. The exact timing of both developments is not known, but it is clear that the clay plug was deposited as a later part of the infill of part of the Middelgronden channel. From geological cross-section 2 it can be deduced that there has been a phase during which the Middelgronden channel had a depth of about 13 m to 15 m. This is deeper than can observed on available historical maps (the map of Waghenaer, 1584, for instance gives approximately 10 m) and based on soundings collected in 1850 and 1928 (Oost & Kleine Punte, 2004). The clay plug west of it is situated approximately 600 m south of the seismic profiles from detail 2 (Fig. 1 and Fig. 7). It may have been formed by an initial shift of the channels to the east as proposed by Schoorl (1999), before partial abandonment of the Middelgronden channel. Such clay fills may deposit rather fast, once a channel is abandoned. A comparable example of such massive clay deposition over some 8 m height and 1 km cross-section in 11 years in a tidal channel has been observed after the drastic reduction of tidal volume from about 300 to 200 million m^3 following the closure of the Lauwerszee area at the Frisian Inlet (Oost, 1995a; Oost, 1995b).

The shallow reflectors R1 and R2 present within seismic facies unit 1 (observed above R3 in the northeast part of Fig. 5), are considered to express lithological transitions in recent Holocene deposits present within the Naaldwijk Formation, based on their depths corresponding to those found from cross-sections 1 and 2 (Figs 2 and 3).

The profiles given in Fig. 7 show a high degree of lateral variation in shallow seismic reflectors, as can be expected in a highly dynamic subtidal environment. The shallow reflectors R1 and R2 present at the northeastern side of the boomer profile in the upper 8 m to 12 m in detail 2 (Fig. 7a, top), and the small disc-shaped reflectors just below the seabed on the chirp profile (Fig. 7a, center) might represent the base of the clay plug and the filling of the Middelgronden channel that is observed at approximately 10 m depth at the geological cross-section in Fig. 3. Unfortunately this correlation is complicated by the difference in water depths observed at the location of the bore holes situated south of the Afsluitdijk and the seismic profiles situated north of the Afsluitdijk. Larger water depths at the location of the seismic profiles, compared to shallower water depths south of the Afsluitdijk, make it probable that a major part of the clay plug/channel fill has been eroded at the locations of the seismic profiles.

Channel structures observed on the chirp profile at detail 3 (Fig. 8) might represent the northern extension of one of the Middelgronden channels. It shows shallow channel structures which are expected to be formed very recently, based on the fact that these reflections are observed at less than 10 m depth. The channel structures show lateral accretion deposits at the eastern side indicative of channel migration towards the west. The channel structures observed on the chirp profile could very well be related to the shallowing of the northern extension of the Middelgronden channel and the reorientation of the channel after the closure of the Zuiderzee by the building of the Afsluitdijk in 1932 (see below).

Development of Holocene channel systems

From the geological profiles, but especially from the core hole information obtained along the Afsluitdijk and available historical maps prior to the closure of the Zuiderzee in 1932, it has been observed that a series of channels has been present. The most important being Javaruggen, Vlieter, Zwin, Wierbalg and Amsteldiep, all connected to the Marsdiep Inlet. From maps it is observed that these channels never increased or decreased in depth from the 16th century until 1932 (Oost & Kleine Punte, 2004). On geological profiles there are no indications for channel fills. As indicated by the infill of the Middelgronden channels and the clay plug, the easternmost channels in the entrance of the Zuiderzee (now: IJsselmeer) became shallower in the course of time, hence a reduction in tidal volume occurred. The question rises how this (partial) abandonment took place. The following hypothesis seems to be the most plausible one. The channels which took over drainage were most likely situated to the west of the Middelgronden channel and the channel was filled by the clay plug. This happened before 1600 since historical maps do not indicate any shallowing or deepening since then. The genesis of the westernmost channels must have occurred after the formation of the Zuiderzee between 100 BC and 400 AD. It coincides well with the ideas on the genesis of the Zuiderzee and with the opening of the Marsdiep tidal inlet south of Texel. Between 800 and 1300 AD, most likely in the 12th century, the Marsdiep Inlet is reconstructed to have opened (Ente, 1986; Schoorl 1999; Oost et al., 2004; Van Heteren et al., 2008) and new channels were formed from this inlet stretching to the southeast. Such new tidal channels into the Zuiderzee will have taken over part of the drainage of the older channels at the eastern part of the entrance of the Zuiderzee area, which were connected with the Vlie tidal inlet (Oost & Kleine Punte, 2004).

Discussion

Comparing interpreted seismic facies to hydrogeological model (REGIS II)

Finalised geological interpretations of the seismic data were compared to the existing hydrogeological model, to provide opportunities for model modifications and improvements. This was done by vertically referencing REGIS II data with respect to the seismic data by leveling the seabed reflector with the bathymetric data obtained in this area. The interpreted seismic reflectors were subsequently compared to the spatial occurrence of lithostratigraphic formations from the REGIS II model in order to assess the degree of similarity between the two data sets, and to assess the possibility for updating the existing REGIS II model. Fig. 5 additionally shows the occurrence of the Middle-Pleistocene top clay layers 1 and 2 from REGIS II (yellow and red, respectively), allowing a comparison with interpreted depths of reflectors R5 and R6 of the boomer profile. R5 and R6 are very pronounced on the boomer profile, indicating a strong lithological contrast and are therefore likely to represent the top of the Middle-Pleistocene clay layers 1 and 2 from REGIS II (UR-C1 and UR-C2 in Fig. 2).

The comparison in Fig. 5 shows that the interpreted reflectors have a smaller variation in depth compared to the surfaces extracted from REGIS II. Reflector R5 shows a near horizontal surface, while the top of clay-layer 1 from the REGIS model (yellow line in Fig. 5) shows more variation in depth. R6 has a vertical shift up to 8 m in the southeast compared to the top clay 2 layer from REGIS II. Also R6 is still present at the northeastern part, where top clay 2 layer from REGIS II is absent. Therefore, the seismic data show that the clay layer 2 most likely extends further to northeast, than is suggested by the existing REGIS II model. This example shows that in this area the acquired seismic data provide valuable information with a spatial resolution of approximately 1 m to 2 m, which is much higher compared to the spatial resolution of lithostratigraphic information present in REGIS II.

Implications for future human interventions

Plans are currently developed to heighten the Afsluitdijk to guarantee the needed safety level. Also, to be able to bring the fresh water from the lake to the sea during peak discharges either a new sluice complex or pumping installations will have to be built. Particularly the drainage of fresh water will require massive works at and around the eastern side of the Afsluitdijk. The high heterogeneity of especially the Holocene deposits as observed on the seismics will have to be taken into account during the building and development process. Especially the clayey abandoned channel deposits may compact when loaded. It is therefore recommended to determine the geophysical engineering characteristics of the sediments before building.

Conclusions

The outcomes of this study showed that seismic data provide valuable information in addition to existing geological knowledge based on borehole data, for a better understanding of the shallow geology of the western Wadden Sea. In a pilot area north of the Afsluitdijk, seismic data provide detailed information allowing interpretation of the upper 60 m of the subsurface. The methodology of using various seismic source and receiver systems simultaneously was performed successfully.

Six key reflectors were identified on the seismic data along the Dutch Afsluitdijk that make up four seismic facies units. On a local scale, channel structures, interpreted as being Holocene in age, were observed on the seismic data, with a lateral extent up to a few hundred meters and a depth up to 15 m. The history of the lateral displacement, and eventually the abandonment of part of the Holocene Middelgronden channel and the total abandonment of an adjacent channel directly west of it indicates a takeover of tidal volume. It is concluded that takeover was established by tidal channels more to the west, which have been connected to the Marsdiep Inlet system. The latter channels have never decreased in depth or cross-sectional area, judging from the geological observations and the available historical maps. The change is explained by the formation of the Marsdiep Inlet system.

The depths of interpreted seismic reflectors of the boomer profile and the lithostratigraphical interfaces of Middle-Pleistocene Urk Formation extracted from REGIS II, in general show similarity. The interpreted seismic reflectors indicate a larger lateral variation in depth compared to the REGIS II lithostratigraphical interfaces that show rather smooth interfaces. The comparison demonstrates that the seismic data provide more detailed spatial information, which is useful information of the dimensions and lateral continuity of these low permeability zones in the subsurface of the Wadden Sea.

The observed variation in seismic data quality between the northeastern and southwestern part of the Afsluitdijk could result from the smaller water depths observed in the south-western part, resulting in more and stronger multiples. However, in the northeastern part, some areas with shallow water were encountered where seismic data of good quality was acquired. Furthermore shallow gas might be present more abundantly in the southwestern part resulting in blanking of the seismic signal and additionally coarse sand could result in increased damping of the acoustic signal. The acquired seismic data allow improvement of the existing shallow geological model.

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References

Bachman, R.T., 1985. Acoustic and physical property relationships in marine sediment. Journal of the Acoustical Society of America 78: 616-621.

Boldreel, L.O., Kuijpers, A., Madsen, E.B., Hass, C., Lindhorst, S., Rasmussen, R., Nielsen, M.G., Bartholdy, J. & Pedersen, J.B.T., 2010. Postglacial sedimentary regime around northern Sylt, South-eastern North Sea, based on shallow seismic profiles. Bulletin of the Geological Society of Denmark 58: 15-27.

Dubelaar, C.W., Paap, B.F. & Gunnink, J.L., 2010. Kartering van de westelijke Waddenzee met behulp van ondiepe seismiek. TNO report 034-UT-2010-00938, 31 pp.

Ente, P.J., 1986. Het ontstaan van het Marsdiep en de Zuiderzee. Rijksdienst voor de IJsselmeerpolders (Lelystad), Werkdocument 1986-102, 34 pp.

Gunnink, J.L., Maljers, D., Van Gessel, S.F., Menkovic, A., & Hummelman, J.H., In press. A 3D geological raster model of the Netherlands. Accepted by Netherlands Journal of Geosciences.

Hamilton, E.L. & Bachman, R.T., 1982. Sound velocity and related properties of marine sediments. Journal of the Acoustical Society of America 72: 1891-1904.

Koerselman, S., Oost, A.P. & Van den Brenk, S., 2002. Aanvullend historisch onderzoek Afsluitdijk – Inventarisatie van de ligging en geologie van Pleistocene lagen, oude stroomgeulen, sluitgaten en scheepswrakken. RDIJ report 2002-14.

Oost, A.P., 1995a. Sedimentological implications of morphodynamic changes in the ebb-tidal delta, the inlet, and the drainage basin of the Zoutkamperlaag tidal inlet (Dutch Wadden Sea), induced by a sudden decrease in the tidal prism. *In:* Flemming, B.W. & Bartholomä, A. (eds): Tidal signatures in modern and ancient sediments. International Association of Sedimentologists, Special Issue 24: 101-119.

Oost, A.P., 1995b. Dynamics and sedimentary development of the Dutch Wadden Sea with emphasis on the Frisian Inlet; a study of the barrier islands, ebb-tidal deltas and drainage basins. Geologica Ultraiectina 126, 518 pp.

Oost, A.P., & De Boer, P.L., 1994. Sedimentology and development of barrier islands, ebb-tidal deltas, inlets and backbarrier areas of the Dutch Wadden Sea. Senckenbergiana 24: 65-115.

Oost, A.P. & Kleine Punte, P.A.H., 2004. Autonome morfologische ontwikkeling westelijke Waddenzee. Report RIKZ/2004.021, 88 pp.

Oost, A.P., Van Heteren, S., Wallinga, J., Ballarini, M. & Elias, E., 2004. The history of northern Holland and the Marsdiep, compiled from luminescence ages and historical records. SWPLA 2004 Field trip guide.

Paap, B.F., Dubelaar, C.W. & Gunnink, J.L., 2010. Geological characterization of the Dutch Wadden Sea using shallow reflection seismics. Proceedings of the 16th European Meeting of Environmental and Engineering Geophysics. European Association of Geoscientists & Engineers (Houten).

Rijkswaterstaat, 2009. Getijtafels voor Nederland, 2010. Sdu (Den Haag), 159 pp.

Schoorl, H., 1999. De Convexe kustboog, Deel 1. Het westelijk Waddengebied en het eiland Texel tot circa 1550. Pirola (Schoorl), 187 pp.

Telford, W.M., Geldart, L.P. & Sheriff, R.E., 2004. Applied Geophysics (2nd ed.), Cambridge University Press, 792 pp.

Ter Wee, M.W., 1976. Toelichtingen bij de Geologische kaart van Nederland 1 : 50.000. Blad Sneek (10W, 10 O). Rijks Geologische Dienst (Haarlem), 131 pp.

TNO, 2012. *www.dinoloket.nl*. Accessed at June 7, 2012.

Van Heteren, S., Oost, A.P., Van der Spek, A.J.F. & Elias, E.P.L., 2008. Island-terminus evolution related to changing ebb-tidal-delta configuration: Texel, the Netherlands, Marine Geology, 235: 19-33.

Van Staalduinen, C.J. (red.), 1977. Geologisch Onderzoek van het Nederlandse Waddengebied. Rijks Geologische Dienst (Haarlem): 77 p.

Vernes, R.W. & Van Doorn, Th.H.M., 2005, 2008. Van Gidslaag naar Hydrogeologische eenheid. Toelichting tot de totstandkoming van de dataset REGIS II. TNO report NITG05-038-B, incl. addendum 2008.

Waghenaer, L.J., 1584. Spieghel der Zeevaerdt. Plantijn (Leyden), 256 pp.

Westerhoff, W.E., Wong, Th.E. & De Mulder, E.F.J., 2003. Opbouw van de ondergrond. *In:* De ondergrond van Nederland. Geologie van Nederland 7. Nederlands Instituut voor Toegepaste Geowetenschappen TNO (Utrecht): 247-352.

Wiersma, A.P., Oost, A.P. Van der Berg, M.W., Vos, P.C., Marges, V. & De Vries, S., 2009. Thematic Report No. 9: Geomorphology. *In:* Wadden Sea Ecosystem No. 25. Common Wadden Sea Secretariat (Wilhelmshaven), 22 pp.

Yilmaz, O., 1987. Seismic data processing, Society of Exploration Geophysicists. Tulsa (Oklahoma), 526 pp.

Zagwijn, W.H., 1983. Sea-level changes during the Eemian in The Netherlands, Geologie en Mijnbouw 62: 437-450.

Zagwijn, W.H. & Van Staalduinen, C.J., 1975. Toelichting bij Geologische Overzichtskaarten van Nederland. Rijksgeologische Dienst (Haarlem), 134 pp.

Zeiler, M, Schulz-Ohlberg, J. & Figge, K., 2000. Mobile sand deposits and shoreface sediment dynamics in the inner German Bight (North Sea). Marine Geology 170: 363-380.