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Continental Shelf Research 22 (2002) 2291–2301

CONTINENTAL SHELF RESEARCH

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Very high-resolution seismic mapping of shallow gas in the Belgian coastal zone

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Received 1 December 1998; received in revised form 1 November 1999; accepted 1 April 2000

Abstract

Very high-resolution reflection seismic investigations off the Belgian coast have revealed an extensive area marked by poor seismic penetration that is probably caused by the presence of shallow gas. The gas is believed to be of biogenic origin, and its geographical distribution is bound to a wide band oriented more or less parallel to the coast. The main origin of the gas could to some extent be linked to the presence of a shallow, thin peat-rich layer of Late Pleistocene/Early Holocene age. Local high sedimentation rates furthermore favoured gas formation in the shallow fine-grained Holocene sediments.

The gas-related features observed on the seismic profiles include acoustic turbidity and blanking, strong multiple reflections, and to a lesser extent bright spots and phase reversal. The sea-floor morphology does not reveal any clear gas escape from the sea bed, although there are some indications of local seepage of small bubbles or dissolved gas into the water column. The top of the acoustically turbid layer is located between 0 and 7 m below the sea-bed surface. It generally forms a sharp boundary, often marked by a varying offset probably due to different levels of gas penetration which could be related to the lithology of the overlying sediments. Seismic characteristics and velocity data seem to suggest a low concentration of gas, most likely less than 1%.

Keywords: Shallow gas; Seismic mapping; Coastal zone; Belgium

1. Introduction

Over the past 20 years a large number of reflection seismic surveys have been carried out on the Belgian Continental Shelf. These surveys have formed the basis of detailed studies of the stratigraphy and structure of the Tertiary and Quaternary sediments (e.g. Mostaert et al., 1989; De Batist, 1989; Liu, 1990). The seismic records from the nearshore area are marked by large zones lacking seismic penetration, which have been attributed to the presence of shallow gas and which were long regarded as a nuisance because of the extreme low seismic resolution and penetration (e.g. Henriet et al., 1978; De Batist, 1989). Up to now no serious attempt has been made to quantify and describe these (presumed) shallow gas zones.

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PII: S0278-4343(02)00056-0

The growing concern about their potential impact on the marine environment and man's activities, especially in the viewpoint of the industrial and economical importance of the study area, demands a better knowledge of these sediments.

Shallow gas can significantly alter the geotechnical properties and behaviour of sea-floor sediments (e.g. Wheeler, 1990; Sills et al., 1991). This can be of crucial importance for geoacoustical modelling studies and engineering applications, such as foundation design for offshore structures. In recent years shallow gas has become the subject of various studies, mostly focused on a more qualitative description of the acoustic characteristics (e.g. Anderson and Bryant, 1990; Hart and Hamilton, 1993; Figueiredo et al., 1996). Detailed studies of the behaviour of fine-grained soils containing gas have been carried out in laboratories (e.g. Wheeler, 1990; Sills et al., 1991). However, more quantitative studies of the in situ acoustic characteristics of shallow gas-bearing sediments based on seismic investigations are rare (e.g. Fu et al., 1996).

This paper presents a study of the shallow sediments offshore the Belgian coast based on very high-resolution reflection seismic data. The study area largely focuses on the eastern part of the coastal zone, roughly between Oostende and the Schelde estuary, where most of the acoustic turbidity is observed. The main topics include the various seismic evidence of the (presumed) shallow gas, the origin of the gas, its occurrence and distribution, and quantification of the gas. The knowledge of shallow gas-bearing sediments is still limited and this paper by no means pretends to be complete. In order to tackle this phenomenon in depth a multi-disciplinary approach is necessary in which geophysical, geotechnical, geochemical and biological techniques are combined.

2. The study area

The study area is located in the southern part of the Southern Bight of the North Sea (Fig. 1). The Palaeogene substratum consists of sandy and clayey sediments of marine origin, occasionally marked by limestone and sandstone beds (De Batist, 1989). They are overlain by a complex sequence of Quaternary deposits characterized by strong lateral variations in lithology and stratigraphical build-up reflecting the rapid succession of glacial and interglacial phases, and with an overall thickness ranging from a few metres to locally up to 30 m (Liu, 1990). The Pleistocene deposits mainly consist of reworked Tertiary clays and sands. On land they are marked by an increasing content of aeolean and fluviatile deposits towards the top, most likely related to the Weichselian glacial (Libbrecht, 1980). The rapid rise of sea level at the end of the Pleistocene induced strong tidal currents which caused serious reworking of the outcropping Pleistocene and Tertiary deposits. During the Holocene the sea-level rise slowed down and sedimentation started in the nearshore areas, influenced by periodic phases of transgressive and regressive tendencies (Köhn, 1988). Repeated reworking and removing of the fine-grained material took place which led to the deposition of the present sea-bed sediments (Liu, 1990).

The surficial sediments in the nearshore area (water depths <12 m MLLWL—mean lowest low water level) mainly consist of fine to very fine grained sands ($d_{50}<250\,\mu$m), locally with a high content of mud (70% silt, 30% clay) taking the form of a large, elongated 'mud field' oriented roughly parallel to the coast; further offshore the sediments become coarser and more sandy (d_{50} 250–500 μm) (MOW, 1993). Shallow cores near the harbour of Zeebrugge revealed a typical tidal/storm sequence of thin, alternating sand and mud layers for the upper few metres of sediment (MOW, 1993). The present sediment transport is marked by a convergence zone near Zeebrugge, suggesting a "hydrodynamical trap" for the suspended muddy sediments. The extension of the harbour and recent dredging and dumping activities, however, have largely influenced this local transport pattern, causing sediment displacements that are far more significant than those due to natural processes. The mud-rich sediments in the Zeebrugge area are highly anoxic, and marked by a high amount of organic matter (2–8%) and carbonates (20%) (Malherbe, 1989).

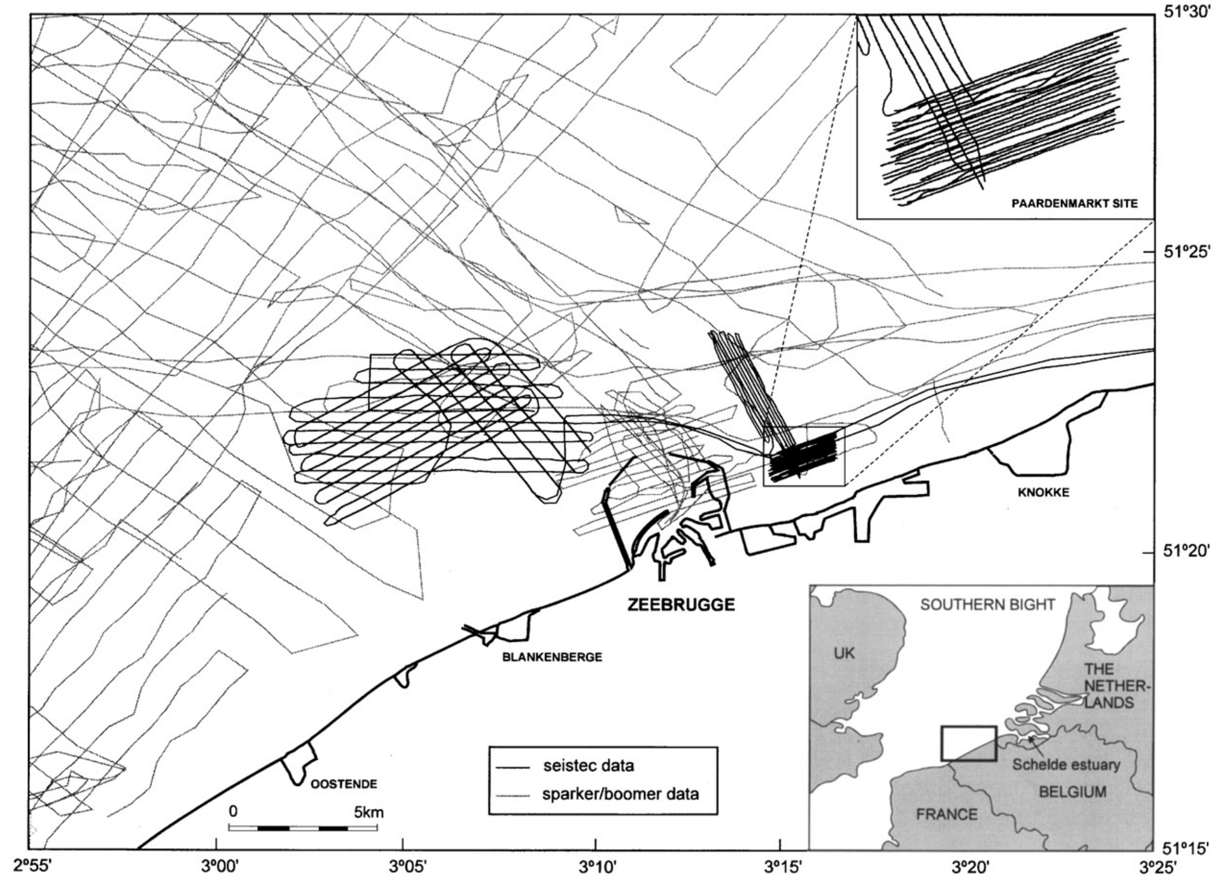

Fig. 1. Location of the study area and overview of the seismic network.

3. Data acquisition

The seismic network covering the Belgian Continental Shelf includes over 25,000 km of very high-resolution reflection seismic profiles. The database for this study involved two main data sets (Fig. 1):

1. A set of older, mainly analogue sparker and Uniboom profiles (main frequency $\sim$1 kHz, penetration 100–200 m). Parts of these data were acquired in the framework of a site study for the expansion of the Zeebrugge harbour, which not only covered the harbour area but reached as far as 30 km offshore (Henriet et al., 1978). Although these sparker and boomer records were quite ‘‘dated’’ their quality was often remarkably good.
2. A set of digital Seistec boomer records (main frequency $\sim$4 kHz, penetration 10–20 m) acquired in the framework of a detailed site study for the so-called ‘‘Paardenmarkt’’ area east of Zeebrugge, an ancient military dumping site (Henriet and Winthagen, 1996). During this study additional data were also acquired west of Zeebrugge. The Seistec data were subjected to some further processing (including a.o. band-pass filtering, age scaling, deconvolution and swell filtering).

The Seistec data enabled a detailed study of the shallow subsurface features, thus forming a complementary database to the older records that focused on the deeper reflectors and gas zones. Some additional side-scan sonar records and seismic multi-channel data (using a 16-channel bottom streamer and small sparker) were also available from the Paardenmarkt area. During the sonar survey a limited number of shallow grab samples were taken from the surrounding area (sampling was not allowed on the actual dumping site). The samples, which all contained fine sandy and muddy sediments, did not reveal any presence of gas.

4. Seismic evidence of shallow gas

The most evident gas-related feature observed on the seismic profiles is acoustic turbidity, which appears as a diffuse and chaotic seismic facies masking nearly all other reflections. It most likely results from scattering of the acoustic energy by interstitial gas bubbles in the sediment (Schubel, 1974)—although other possible causes, such as reflection from gravel beds or sand beds, must also be considered. The acoustic turbidity is observed in the upper sequence, often sharply cutting across the stratification (thus indicating that it is probably not lithology-related) (Fig. 2) and occasionally reaching up to the sea floor (Fig. 3). However, no clear velocity effects (e.g. pull-down) can be observed at the edge of the turbidity zones. The top of the acoustically turbid layer cannot always be clearly resolved, which is possibly due to minor gas seepage.

The gassy areas are occasionally marked by reflection-free patches. The latter is most likely due to acoustic blanking caused by absorption of the seismic signal in the gas-charged sediments. However, it could also be caused by acoustic transparency related to the absence of sediment layering (possibly due to the migration of gas), as suggested by the deep reflector observed in Fig. 4 (left arrow). The presence of a hard sediment layer may also produce a similar effect, as is the case for some buried shell-rich sand layers observed in the nearby Schelde estuary. Although the existence of such layers has not been reported from the study area, their presence cannot be completely ruled out.

The acoustic turbidity often starts at a few metres below sea bed. The overlying sediment is locally marked by a large number of (sub-)parallel reflectors (Fig. 5) suggesting different phases of deposition and erosion related to tidal and storm

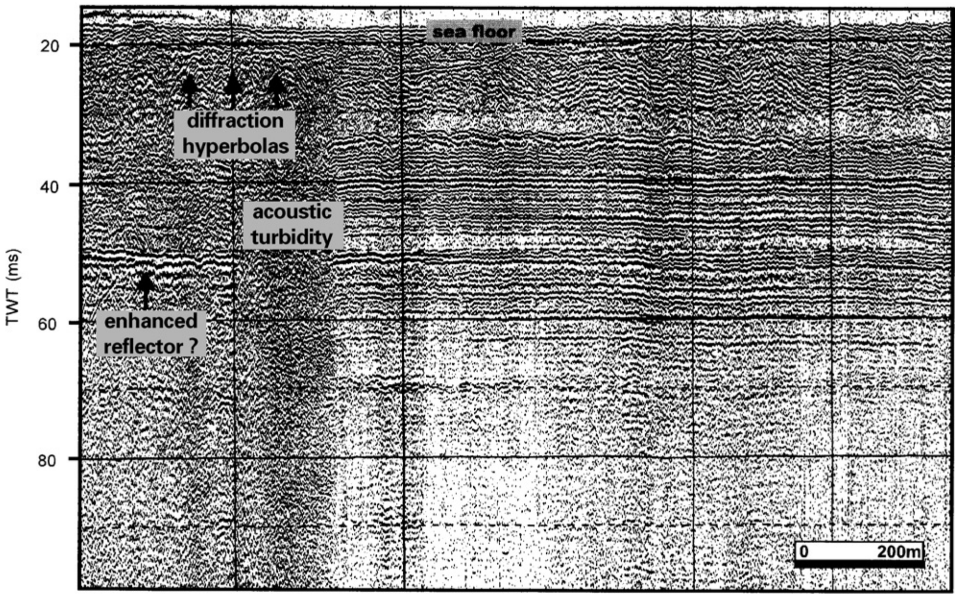

Fig. 2. Analogue boomer profile showing zones of acoustic turbidity sharply cutting across the stratification. Note that the turbidity does not fully reach the sea floor. The high-amplitude reflector on the left is possibly gas-related.

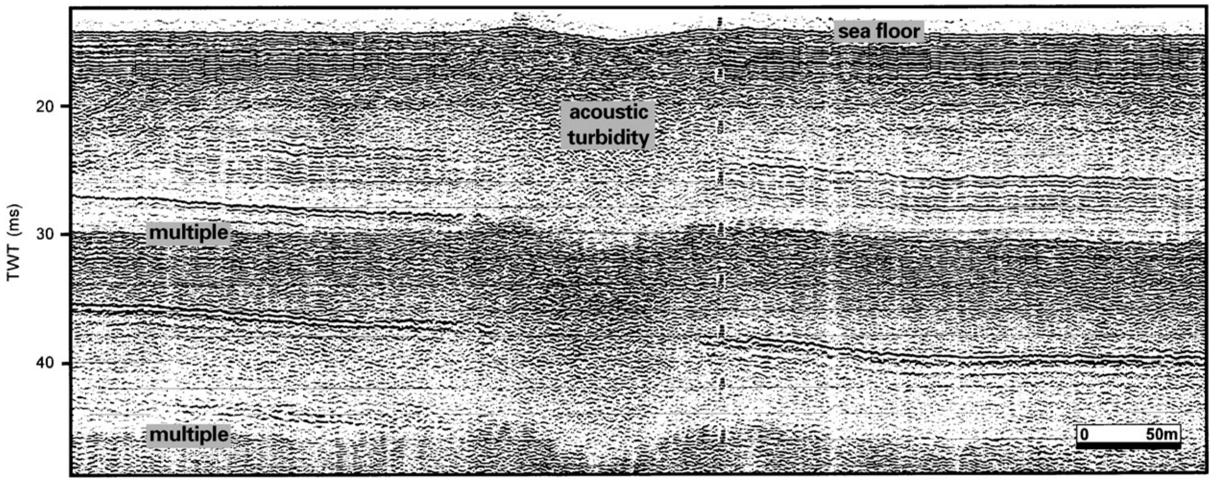

Fig. 3. Seistec profile showing acoustic turbidity reaching up to the sea floor. It is uncertain whether the shallow depression is due to the presence of gas or related to human interference. The vertical disturbances observed in the water column left of the depression are most likely due to acoustic noise related to the seismic equipment and/or the vessel.

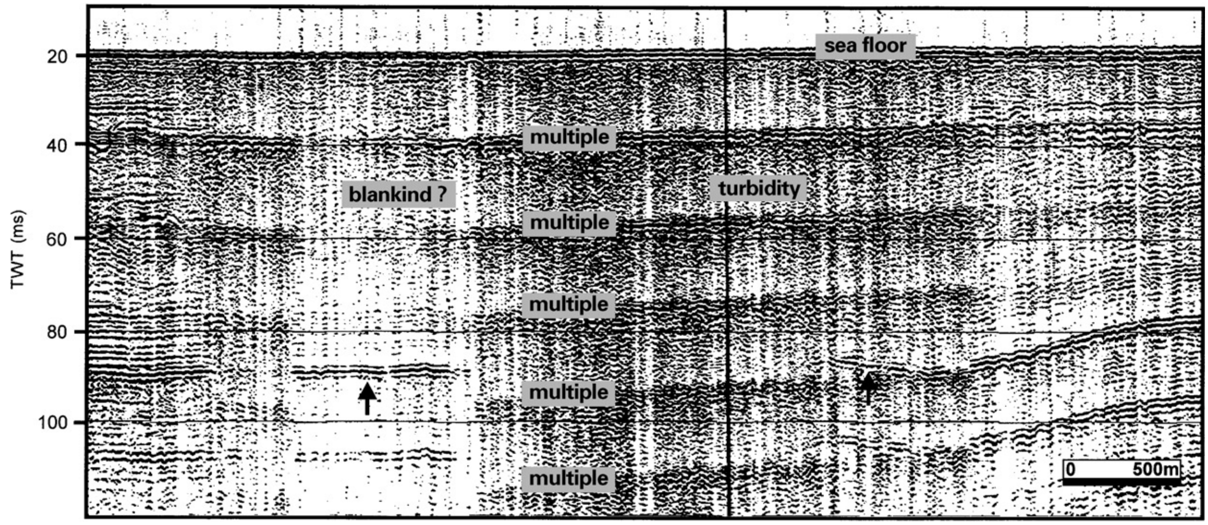

Fig. 4. Analogue sparker profile showing acoustic turbidity and blanking presumably due to the presence of shallow gas. The vertical disturbances observed in the water column are most likely due to acoustic noise related to the seismic equipment and/or the vessel.

sequences, as indicated by the alternating thin sand and mud layers in shallow cores near Zeebrugge (MOW, 1993). Similar thin layering has also been reported along the Dutch coast, where temporary mud deposits were deposited during slack tide or during prolonged periods of calm weather and eroded again with increasing wave action, some mud being buried under sand (Eisma, 1981). Some of the thin mud beds may have acted as traps for the upward migrating gas, giving rise to different levels of acoustic turbidity (Figs. 5 and 6).

Enhanced reflections are locally observed, generally at the top of the turbid layer but sometimes

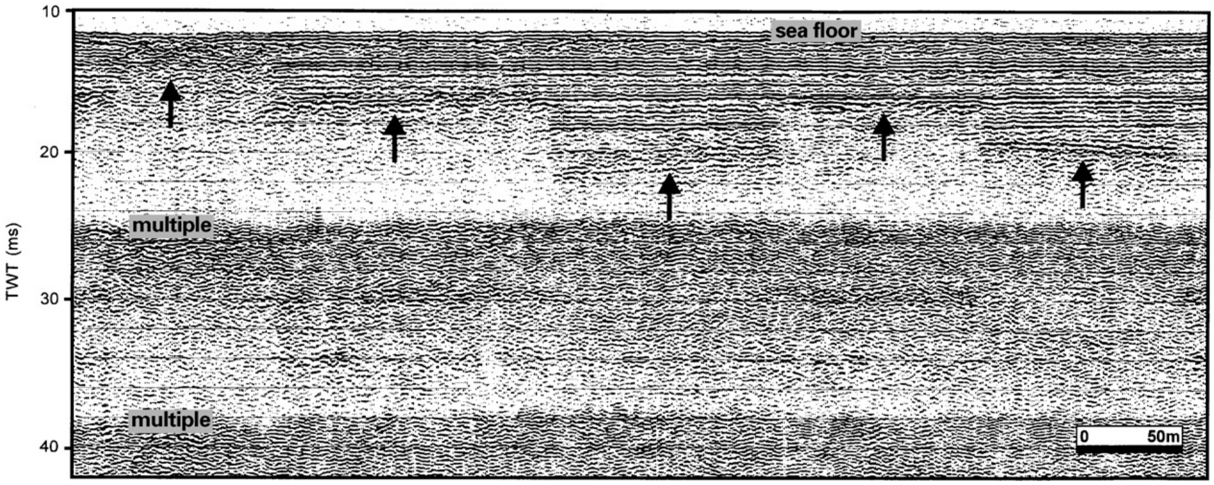

Fig. 5. Seistec profile showing different levels of acoustic turbidity (marked by arrows) attributed to upward gas migration.

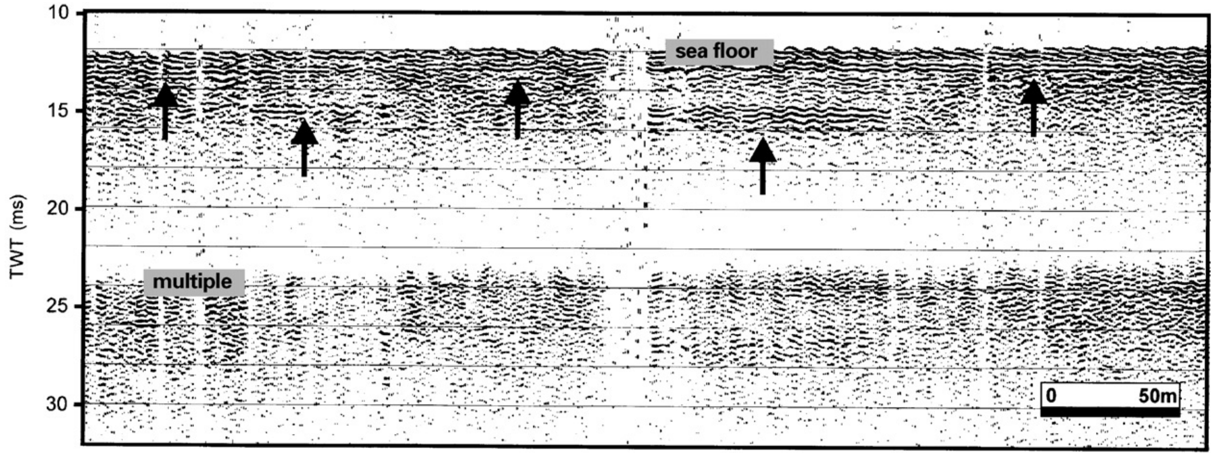

Fig. 6. Seistec profile from the Paardenmarkt area showing different levels of acoustic turbidity attributed to gas penetration. Note the regular sand ripples at the top. The vertical disturbances observed in the water column and the underlying sediments are most likely due to acoustic noise related to the seismic equipment and/or the vessel.

well below this, and most likely indicate a local increase in gas concentration (Fig. 7). Occasionally the reflections are seen to extend laterally from the zone of acoustic turbidity, a phenomenon also described by Judd and Hovland (1992). The latter also seems to be the case for the high-amplitude reflector observed in Fig. 2, although its depth (roughly 25 m below sea bed) possibly suggests some origin other than gas-related. On certain profiles a polarity inversion (‘‘bright spot’’) can be observed at the sea bed, indicating a large mismatch in acoustic impedance (Fig. 8). This effect of phase inversion is more clearly observed on the sparker records. The latter may possibly be related to the effect of a lower sound speed (associated with lower source frequencies), which will increase the impedance anomaly and the chance to generate a negative reflection coefficient.

The acoustically turbid sediments are often marked by strong series of multiple reflections

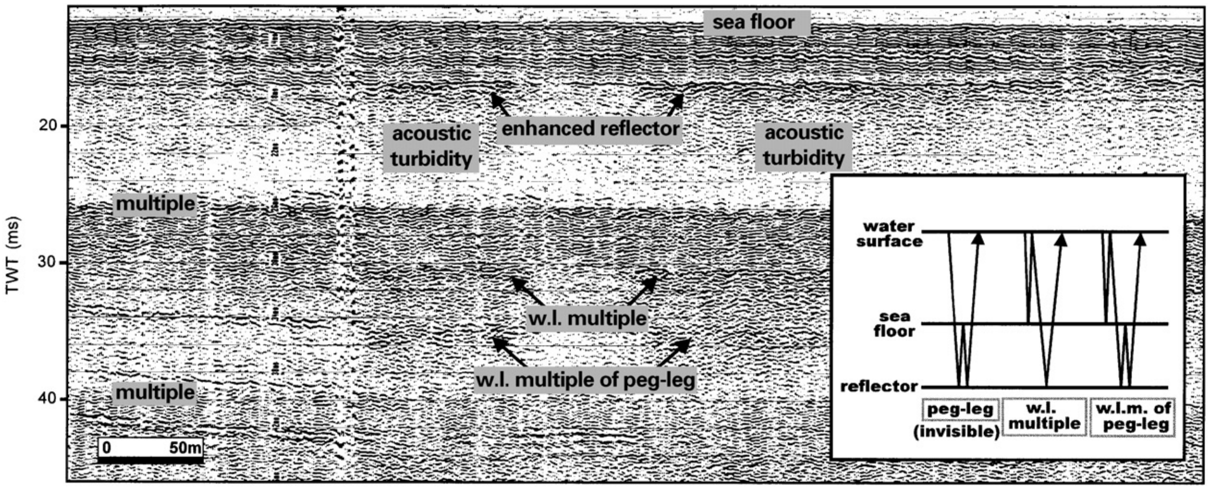

Fig. 7. Seistec profile showing different types of multiples related to a gas horizon (w.l. = water layer). The vertical disturbances observed in the sediments on the left are most likely due to acoustic noise.

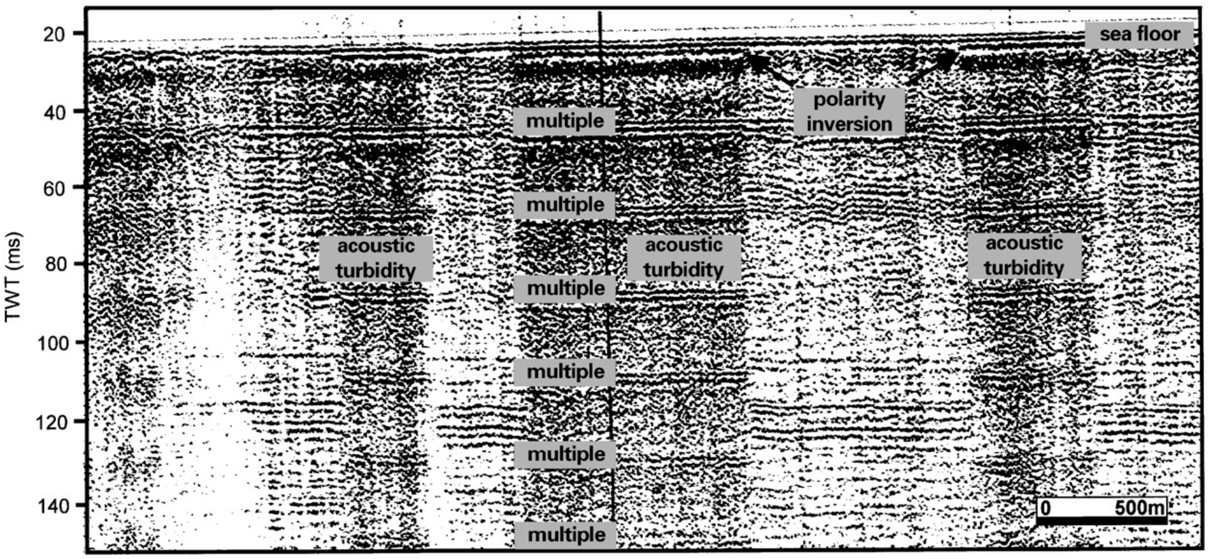

Fig. 8. Analogue sparker profile showing acoustic turbidity and strong multiple sequence marked by phase reversal at the sea floor. The vertical disturbances observed in the water column are most likely due to acoustic noise related to the seismic equipment and/or the vessel.

(Fig. 4). This is due to the fact that most of the energy of the downgoing wave will be reflected by the gassy surface and re-reflected at the sea surface, resulting in many repetitions of these low-loss reflections. In the case of a negative sea-bed reflection this results in multiples of common polarity (Fig. 8). Strong sea-floor multiples may, however, also be related to effluent or an influence of waste material, a phenomenon often observed in industrial areas subject to human activity. Due to the proximity of the Schelde estuary and the Zeebrugge harbour this effect cannot be ruled out completely.

In the case of buried gassy sediments the water-layer multiples are not so evident (Fig. 7). Internal multiples between the sea floor and the top of the gas (so-called "peg-legs") are sporadically observed, although often very weak and barely distinguishable. The water-layer multiple is, however, generally more visible. This effect could be due to the constructive interference of equivalent paths of propagation that are spatially different but equivalent in travel time (McGee, 1991).

Although the acoustic turbidity locally reaches the surface, the sea-floor morphology does not reveal any clear gas-related features. A small depression (roughly 50–60 m wide, 2–3 m deep) is observed NW of Zeebrugge (Fig. 3). The acoustic turbidity observed beneath the depression seems to suggest that it could well be related to the presence of gas. Close inspection of the seismic data, however, reveals less distinct but roughly similar features on a few adjacent profiles, indicating some lateral extension (perhaps a shallow gully or channel?) rather than an isolated collapse depression. The proximity of the Zeebrugge harbour possibly suggests a relation to disturbed soil caused by dredging. Although maintenance operations are common in the area, the location of the (presumed) gully—due west of the harbour entrance (Fig. 9)—and its limited depth make this somewhat unlikely. Still the (apparent) continuity of the gully in areas of complete masking, and the raised sides of the depression, do not rule out some human interference (e.g. cable or pipeline trench).

No clear evidence is found of actual gas escape from the sea bed, such as pockmarks or gas plumes in the water column. The vertical disturbances occasionally observed on the profiles may seem to suggest the presence of small gas seeps (Figs. 3, 4, 6 and 8). However, these features are also observed in gas-free areas, indicating that they are most likely due to acoustic noise related to the seismic equipment and/or the vessel itself, or possibly fish shoals. Nevertheless, some local seepage of small bubbles or dissolved gas through the sea bed cannot be excluded. The latter could possibly explain the unusually low sound velocities recorded in the water column during refraction experiments in the Paardenmarkt area (Henriet and Winthagen, 1996). Using a bottom streamer and seismic source located on the sea floor, direct wave velocities as low as 1350 m/s were observed in areas of poor seismic penetration. (In some cases the seismic equipment may have sunk slightly into the (locally soft) sea bed, thus yielding a direct wave path through the surficial sediments—however, this was unlikely in more sandy sea-floor areas.) The occurrence of dark, acoustically reflective sea-bed patches on the side-scan sonar records could furthermore possibly confirm a minor form of diffused fluid seepage from the sea bed. Still, similar features may also be produced by a change in sediment type or local hardening of the sea bed (Judd and Hovland, 1992).

Large parts of the study area are marked by diffraction hyperbolas, mainly concentrated in the uppermost part of the sediment column or at the sea floor (Fig. 2). The diffractions are often related to gas horizons, and possibly caused by an irregular morphology due to the presence of gassy sediments. Still some relation to local gravel or shell layers, boulders, shallow pits or small sand waves cannot be ruled out.

5. Origin and distribution of the shallow gas

Gas in shallow marine sediments has two main potential sources: (1) biogenic gas produced by bacterial degradation of organic matter at low temperatures, and (2) thermogenic gas produced by high-temperature degradation and cracking of organic compounds at considerable burial depths. The geology of the study area does not suggest any possible deep thermogenic sources, and it seems more likely that the gas has accumulated in situ in the shallow organic-rich sediments. Geological studies, both offshore and onshore Zeebrugge, have revealed the presence of a thin (1–2 m) peat-rich layer containing methane gas that can most likely be linked to the Late Pleistocene/Early Holocene formation of Wenduine (MOW, 1978; Libbrecht, 1980). The layer is located at a depth between 6 and 9 m below sea bed in the coastal area, dipping deeper further offshore. It most likely represents the widespread "basal peat" which developed on the Pleistocene surface due to the rise in ground water level caused by the

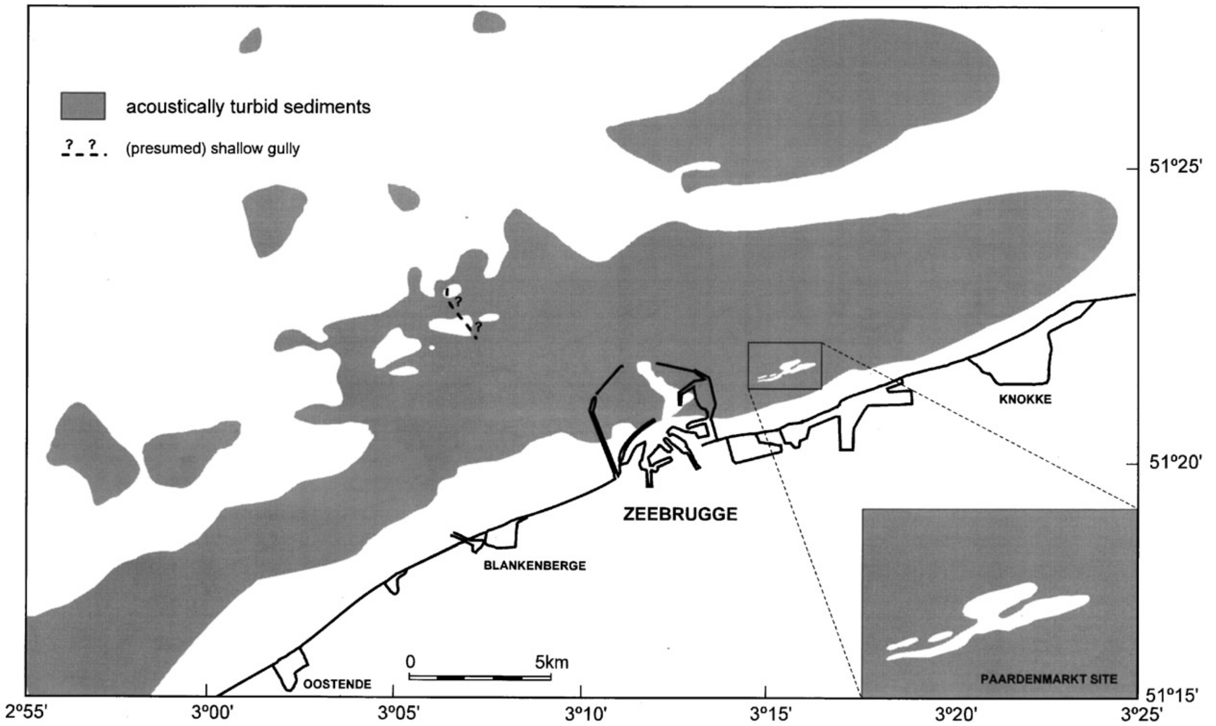

Fig. 9. Geographical distribution of the acoustically turbid sediments in the study area. The (presumed) location of the shallow gully in Fig. 2 is indicated by the dashed line.

postglacial sea-level rise (Köhn, 1988). This peaty layer, perhaps in combination with remnants from other peat-rich layers related to regressive phases, could well be the main cause for the acoustic turbidity observed in the study area. In addition, the abundant presence of fine-grained, muddy sediments and the high sedimentation rates (resulting in fast burial of the organic matter) also formed an ideal basis for the generation of biogenic gas. The extensive human activity in the Zeebrugge area furthermore possibly caused some minor organic contamination that may have induced a limited degree of gas formation in the uppermost (10–20 cm) sediments.

The geographical extent of the acoustically turbid sediments is shown in Fig. 9. The gassy area is bound to a wide band oriented more or less parallel to the coast, which may well to some extent reflect the boundary of the area where peat growth was induced. The top of the turbid zone is generally less than 10 ms ($\sim$7.5 m) below sea bed. The depth may to some extent be controlled by the lithology of the overlying sediments (a higher permeability may allow the gas to migrate upward more freely) and the amount of gas trapped in the sediments (a higher concentration may favour gas escape). Still it is difficult to determine the exact thickness of the gassy layer from the seismic profiles due to the masking effect. Indeed complete masking may already result from a gassy layer as thin as 1–2 m (Schubel, 1974). This seems to be supported by the results from NMO analyses on the multi-channel data from the Paardenmarkt area, which suggest the presence of thin low-velocity layers (max. thickness $\sim$2 m) down to a depth of 6–8 m below sea bed.

6. Quantification of the shallow gas

A quantification of the shallow gas based on seismic data is difficult since a small amount of gas as well as high gas saturation both may produce a similar response (Judd and Hovland, 1992). In general, however, the masking effect observed in the study area seems to be more complete on the Seistec data as compared to the sparker or boomer records, where reflectors are occasionally observed in acoustically turbid zones (Fig. 4 right). The latter seems to suggest a potential frequency effect—indeed the attenuation in fine-grained sediments is known to increase with frequency (Anderson et al., 1998). Nevertheless, a possible relation to a local increase or decrease in gas content cannot be excluded.

It is generally believed that gas in shallow fine-grained sediments normally occurs in relatively low concentrations of discrete gas voids that are characterized by zones of acoustic turbidity, whereas interconnected gas-filled pore spaces may lead to much higher concentrations in coarse-grained sediments, giving rise to enhanced reflections and bright spots (Hovland and Judd, 1988). The scarce presence of the latter therefore seems to confirm a low gas concentration, allowing the attenuation and diffusion of the seismic energy but generally insufficient to form strong, enhanced reflections. Studies of shallow gas-rich muddy sediments in the Western Baltic have shown that acoustic turbidity may already occur with less than 0.5% gas present (Abegg and Anderson, 1997). Analogy with the mud-rich deposits observed in our study area may therefore suggest equally low values.

The sound velocity may give an indication of the overall gas volume of the sediment. Because the bulk modulus of a gassy soil is much lower than that of a saturated soil, the velocity will rapidly decrease with increasing gas content (this is true for frequencies below the bubble resonance frequency—as is the case here) (Anderson and Hampton, 1980). Refraction and borehole measurements on land in the Zeebrugge area revealed P-wave velocities as low as 1050 m/s, locally even down to 700 m/s, for the methane-containing peaty sediments (Cherlet, 1978; Libbrecht, 1980). Seismic multi-channel measurements offshore Zeebrugge yielded velocity estimates as low as 850 m/s (Henriet and Winthagen, 1996). It is known that the presence of peat-rich sediments, even without gas, can in itself lower the acoustic velocity due to the increased compressibility (organic matter absorbs water and causes clay particles to aggregate, creating an open structure that is weak and easy to deform) (Silva et al., 1998). Still the extreme low velocities encountered here, together with the evidence displayed in the seismic data, strongly support the presence of gas. The velocity values are well in agreement with the theoretical and experimental curves presented by Anderson and Hampton (1980) and Sills et al. (1991), and suggest a gas concentration of less than 1%.

7. Conclusions

Acoustic turbidity is a widely spread phenomenon in the nearshore Belgian coastal zone. The turbidity is likely due to the presence of shallow gas. The gas is most likely of biogenic origin and can possibly be linked to the presence of a thin peat-rich layer. Additional gas-related features observed on the very high-resolution seismic records include strong multiple reflections, and occasional bright spots, enhanced reflections and blanking. No clear gas escape from the sea bed is observed, but some minor seepage cannot be ruled out. The depth of the acoustically turbid layer is generally less than 8 m below sea bed, and often marked by step-like offsets indicating different levels of gas penetration possibly due to interbedded deposits of fine sand and mud. The seismic characteristics and velocity data suggest a low concentration of gas, most likely less than 1%.

Acknowledgements

The acquisition of data reported in this study has been carried out in the framework of contracts from the Ministries of Environment, Public Works and Economic Affairs, and the Belgian Science Policy Office. The Seistec unit has been acquired through a grant of the Fund for Scientific Research (FWO). The Management Unit of the Mathematical Model of the North Sea and Schelde Estuary and the officers and crew of the Belgica are gratefully acknowledged.

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