A new 3D seismic acquisition system for very high and ultra high resolution shallow water studies

T. Missiaen[1], W. Versteeg[1] & J.-P. Henriet[1]

Introduction

The adaptation of 3D techniques to very high and ultra high (multi-kHz) frequency marine seismic investigations is progressing steadily. In recent years, the Renard Centre of Marine Geology (University of Gent) has scaled down the shallow marine 3D method to very high resolutions, thereby entering the world of small-scale geological structures (Henriet *et al*. 1992). VHR 3D seismic data were acquired in a modest and cost-effective way, using a compact field system with close streamer and channel spacing.

Despite good results, the data were not of optimum quality due to a number of technical shortcomings (low sampling rate, positioning restrictions, coverage difficulties). In order to further increase the resolution, adaptation and optimization of the 3D acquisition method were required, taking into account recent developments in positioning and data sampling techniques. In doing so, the seismic strategy must be chosen as a function of the geological target, sampling laws, the desired resolution and the acquisition and processing costs.

Based on past 3D experience, a new compact 3D acquisition system was developed in the framework of the EC MAST3 Project 'Very high resolution marine 3D seismic method for detailed site investigation – VHR3D'. The acquisition array is flexible, which allows it to be tailored to specific site characteristics. The system is designed for studies in shallow water (< 30 m), providing limited penetration (< 50 m bsf) and is aimed at target sites of limited areal extent (approximately $100 \times 100\ m^2$). The desired resolution (both horizontal and vertical) is in the decimetre range.

The acquisition system

The 'Opus3D' acquisition system consists of a central 6 m long rigid inflatable boat (RIB), flanked by two inflated modular wings, each consisting of three slim catamaran-shaped frames (Fig. 1). The frames, 2 m wide and 4 m long, give the system a full wingspan of 14 m and provide spatial control for the spread of eight dual-channel streamers. The streamers are 7.5 m long, with a channel spacing of 2 m and two hydrophones per channel (hydrophone spacing of 0.25 m). The streamers are towed a few metres behind the modules, the distance depending on the desired offset.

The surface-towed frames are kept under air pressure (± 0.5 bar), which allows convenient deployment and recovery by inflation and deflation. The inflatable frames are made of flexible hose of 10 cm diameter. Each frame consists of two length-wise floats connected by three cross-wise floats, the latter curving upwards in order to reduce contact with the water (Fig. 1). Their form has been 'pre-shaped' to increase the rigidity of the frames. The use of a modular system allows the dimensions of the acquisition system to be varied, by simply increasing or decreasing the number of modules and streamers.

The central RIB has a catamaran structure to ensure optimum stability at sea, and it is wide enough to allow ample storage of the modular frames. Furthermore, the positioning antenna can be placed on it. The antenna is normally installed on the rear of the boat, near the source and streamers, in order to reduce relative positioning errors to a minimum. The source (IKB SEISTEC, a wide-band electrodynamic boomer with a dominant frequency of 2–3 kHz) is towed closely behind the RIB.

The system is typically deployed from small- to medium-sized vessels, preferably with an A-frame or small crane. All components are folded within the RIB, and once deployed at the correct distance behind the vessel the modules are inflated. A central rope fixed to the RIB is used for towing with additional lines attached to the module tips, ensuring a good array layout. After the survey, the modules are deflated and rolled (with the streamers) inside the RIB, which is placed on the deck of the vessel.

In protected waters (harbour areas, rivers, canals and lakes) and in the absence of strong currents, the system can also be used autonomously. To this end the central RIB is converted into a survey vessel unit with twin engines and a

[1]*Renard Centre of Marine Geology, Geological Institute, University of Gent, Krijgslaan 281-S8, B-9000 Gent, Belgium.*

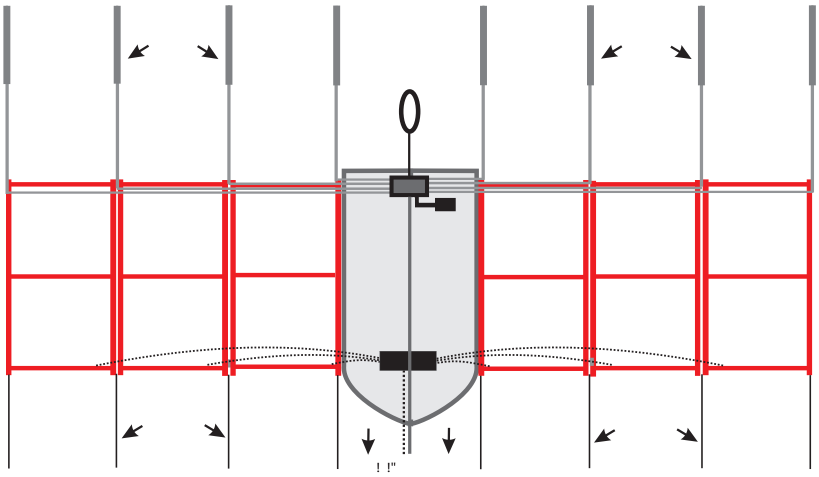

Figure 1 Schematic overview of the new 3D acquisition array (top) and deployment during the Schelde 1999 survey (bottom). Note the well-aligned streamers behind the floating frames.

rail-mounted console containing the seismic, navigation and positioning equipment. The 3D system can thus easily be transported on a trailer to any site, offering a unique flexibility and allowing optimal use of good weather windows for performing high-quality 3D data acquisition without the high standby costs of survey vessels.

Target test site

A first test survey was carried out with the flexible 3D acquisition system on board the *RV Belgica* in September 1999 on the River Schelde. The target consisted of a small diapir near Antwerp, which has been the subject of previous geotechnical surveys and 3D seismic investigations in the framework of a former European project (Schittekat *et al.* 1983; Henriet *et al.* 1992). These studies have made the diapir site a well-documented test ground and therefore a perfect site for optimal validation of the new 3D methodology for geotechnical applications.

The diapir in the Rupelian clay has an apparent diameter of 60 m and a vertical amplitude increasing from a few decimetres at a depth of 50 m to a few metres at about 25 m depth (Fig. 2). The origin of the diapir is most probably related to decompaction, the sediment load being reduced by erosion of the river-bed (Verschuren 1992). Concretions in the clay beds (so-called septaria), which have a diameter of 0.5–1 m and a thickness of 0.2–0.3 m, stand out locally as diffraction clusters on analogue boomer profiles recorded during former seismic surveys (Hemerijckx *et al.* 1983) (Fig. 2).

Geotechnical measurements have identified at least 15 different septaria horizons in the clay diapir area (Heldens 1983). Each individual horizon has its own characteristics – shape, size, fill material – and also the number of septaria in a horizon is typical (Vandenberghe & Laga 1986). In general the distribution of septaria in each horizon is quite regular, the average distance ranging from a few metres up to approximately 10 m.

The challenge was to assess this new acquisition method for estimation of the 3D spatial distribution of the concretion beds. Whereas the clay diapir itself is not expected to form a major hazard (the geotechnical properties inside the diapir are not significantly different from those of undisturbed clay), this may no longer be true for the concretions, which may also have been displaced by the formation of the diapir.

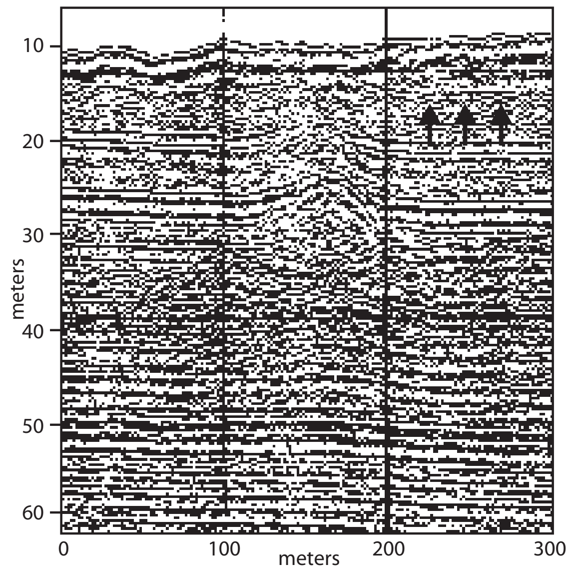

Figure 2 Analogue Uniboom profile across the clay diapir. Diffraction hyperbolae on concretions (marked by arrows) can be observed along the reflectors.

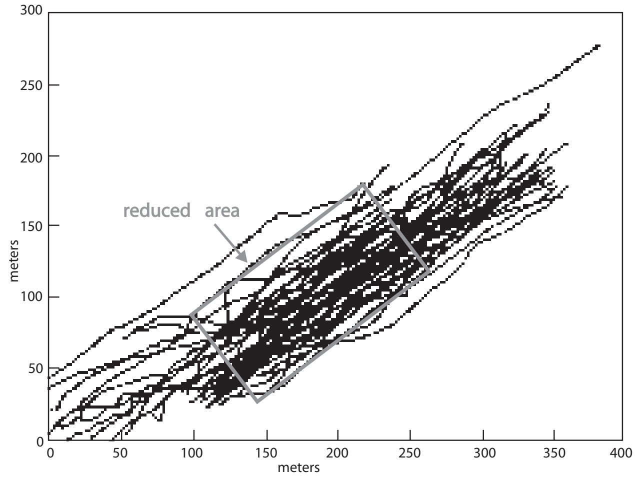

Figure 3 3D seismic network over the clay diapir.

Data acquisition

In 2 days a dense network of 48 seismic profiles was recorded over the diapir site, with an average profile length of 300 m (Fig. 3). The modules were towed some 15 m behind the vessel (Fig. 1); the offset between the source and the nearest receivers was ± 7 m. Each shot generated 16 subsurface reflection points in a swath 7 m wide, corresponding to a receiver array width of 14 m. Theoretical line spacing was defined at 6 m in order to ensure a full subsurface spatial coverage.

The streamer and channel spacing was set at 2 m (8 streamers – 16 channels). In order to reduce the noise level, the vessel was driven by electrical propulsion. Recording of the seismic data was done using the Elics Delph24 multichannel seismograph, using a shot interval of 0.5 s. The sampling rate was 16 kHz, in order to avoid any possible aliasing effects. The total recorded data volume amounted to approximately 3.5 Gbytes.

Positioning was carried out using a short-range DGPS system based on real-time kinematic positioning with a dual-frequency receiver and UHF data link. The reference antenna was located on a high building near the survey area. Thanks to the extremely fast update rate, real-time (x, y, z) positions could be acquired for each shot with a centimetre accuracy. Because the source frame proved very stable in the river environment, the positioning antenna was installed on the SEISTEC source, which further minimized the relative positioning errors.

The Schelde is noted for its strong tidal currents. In order to keep the array stable and well stretched behind the vessel, the seismic tracks were sailed against the current, alternately forwards and backwards, the latter simply by decreasing the speed. This resulted in a highly variable vessel speed of between 0.5 and 3.5 knots. Due to the low vessel speed and the sometimes busy shipping traffic, accurate steering was not always possible, and therefore regular profile spacing could not always be achieved.

Geometry processing

Shot and receiver coverage was calculated from the antenna positions taking into account the ship's movement. Small high-frequency variations in the antenna positions (both horizontal and vertical), caused by wave movement due to passing ships, were filtered. Profiles of inferior data quality were left out. The network was finally reduced to a 150×80 m^2 area covering the clay diapir, resulting in a total 3D data volume of approximately 1.5 Gbytes.

The (theoretical) source and receiver positions were calculated assuming a rigid and well-aligned array, parallel to the heading. Indeed, observations during the survey indicated that the streamers remained well stretched (Fig. 1). This was not only due to the protected river environment (causing relatively little wave motion) but also to the fact that all profiles were acquired parallel to the (often strong) current, thus keeping the streamers aligned.

Close inspection of the first-break arrivals showed that this theoretical approach did not always match reality. Occasional changes in the shot-gather pattern could be observed (especially at low vessel speed), indicating a slow swaying movement of the streamer array. However, the effect of the latter was relatively small (< 0.5 m) and therefore it was decided not to apply any geometrical corrections.

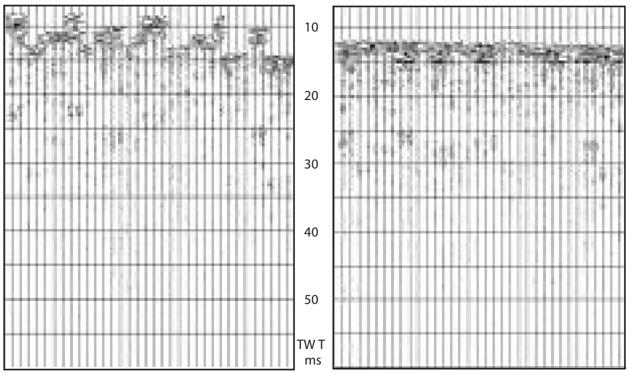

Figure 4 Stack bin traces before (left) and after (right) NMO and tidal correction.

Seismic data processing

Since the tidal action on the Schelde is quite large, with amplitudes up to 6 m, tidal correction was essential. This was done by adding a time-shift, based on the vertical coordinates of the antenna. The tidal shifts were carried out on the zero-offset data, after NMO correction (velocities ranging from 1500 to 1650 m/s). The different tidal corrections also resulted in suppression of the sea-bed multiple in the process of stacking. Additional processing included band-pass filtering, AGC and deconvolution.

Since the target was at a shallow depth, a stack grid of 1×1 m^2 bins was set out. This adequately oversampled the first Fresnel zone. Trace midpoint positions were determined from the source and receiver positions, and the resulting fold coverage was calculated. Due to the difficult navigation on the Schelde, the fold coverage was variable. However it was generally good over the area of interest (average of 20–30 traces per bin), reaching peak values of 100 in areas of very low vessel speed. The actual stacking process was carried out per bin, resulting in a total of over 16 000 stacks. The good line-up of traces in the stack bins justified the geometrical correction approach discussed above (Fig. 4).

Imaging results

The quality of the stacked 3D data is very good. Time sections are marked by a large number of continuous and highly energetic reflectors, which appeared weaker and less coherent on the 1990 data. Although the upper part of the diapir remains quite disturbed, some internal reflectors are now clearly observed (Fig. 5). Time slices reveal a sharply defined concentric reflector pattern increasing towards the base of the diapir (Fig. 6). Time slices from the upper part of the diapir are less coherent, although the concentric pattern can still be clearly observed (Fig. 7).

Different levels of diffraction hyperbolae can be observed on the 3D data. They are most probably related to the presence of concretions (or clusters of septaria) in the clay layers. Up to now, these concretions were only observed on analogue recordings. The limitation of the sampled frequency band in 1990 probably largely explains their absence on these data, whereas the broader frequency range and improved acquisition in 1999 produced a higher imaging resolution. However, not all identified horizons could be observed on the 3D data – indeed some septaria may have been too small or there may have been too few of them.

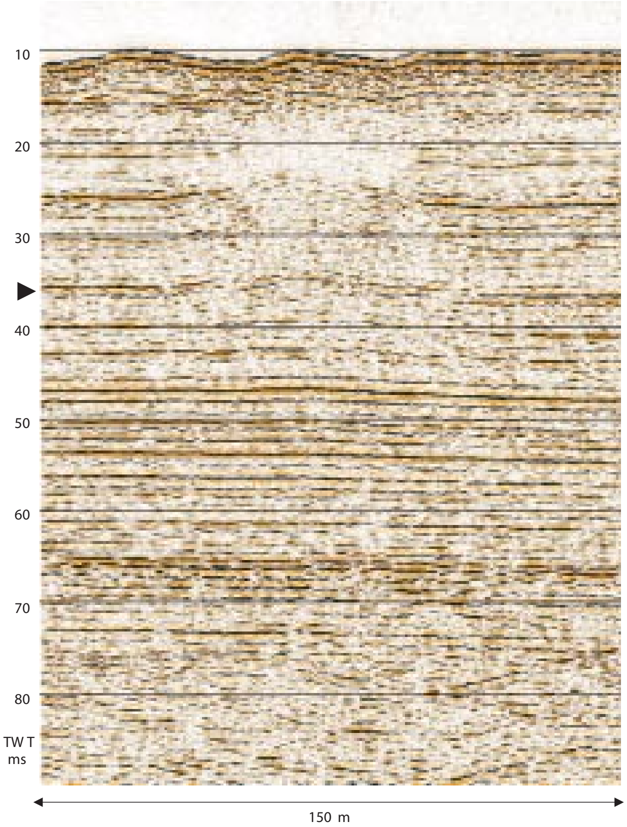

Figure 5 In-line stack section across the central part of the diapir; the arrow indicates the location of the time slices shown in Fig. 6.

In order to resolve the spatial distribution of the septaria beds, various reflectors – identified by horizons marked by large concretions – were carefully picked. Figure 8 shows septaria horizon S4. A number of horizon slices were made at very small intervals (4–5 cm). The consecutive slices are marked by a gradually appearing and disappearing blotchy pattern. The location, size and regularity of the pattern seem to suggest that we might be dealing either with single concretions or with small clusters of concretions.

Future work and perspectives

With the bin size used, of dimensions 1×1 m^2, it is not possible to draw any definite conclusions on the septaria distribu-

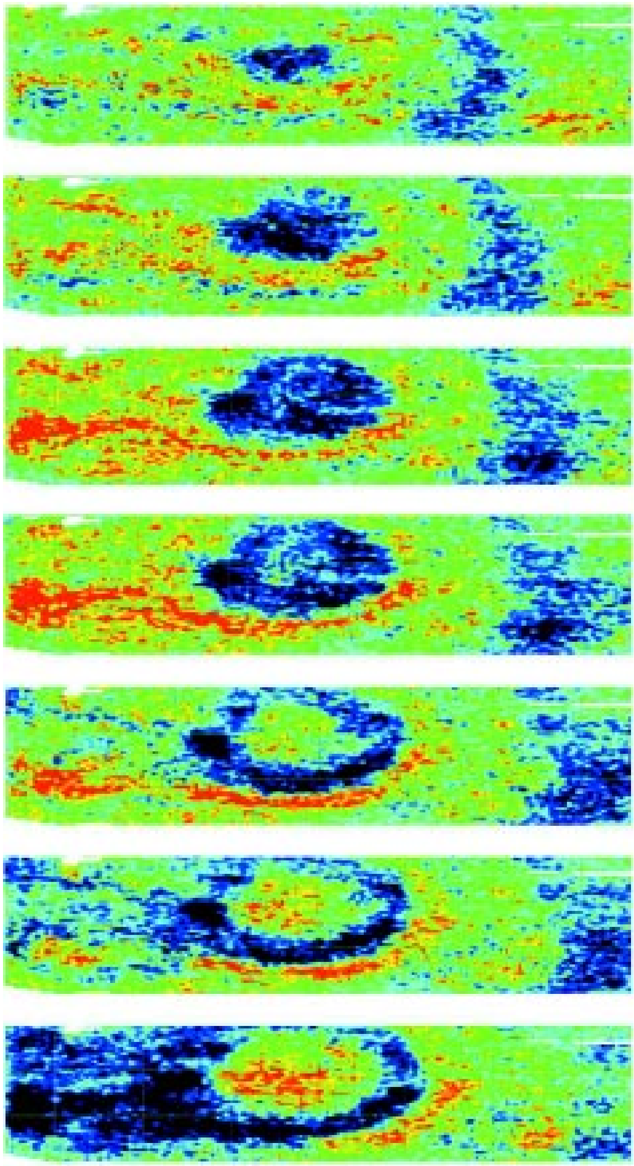

Figure 6 Time slices at ± 10 cm interval (≈0.07 ms) showing concentric reflector patterns over the clay diapir and a slight dip to the NE. Area dimensions 140×60 m^2.

tion. Any subsequent verification will therefore have to be done by further decreasing the bin size. Additional 3D migration processing is also expected to improve the seismic image. Experience from the 1990 data has proved that migration tends to reduce the background noise (the effect of repositioning being negligible due to the lack of velocity stratification), but it also results in a certain amount of smoothing (Marsset *et al*. 1998). This will have to be tested on the new 3D data set.

The resulting 3D data set – based on very stringent parameters – will allow further investigation into the effect of simplification of acquisition, processing and modelling parameters. This will allow a definition of the simplest 'set-up', depending on the desired resolution-to-cost ratio, and may eventually result in a practical guide of specifications for economic use of this shallow marine VHR 3D seismic method.

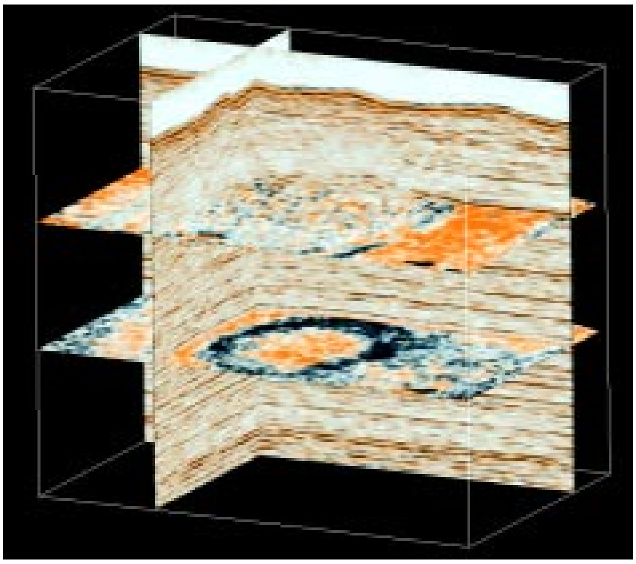

Figure 7 Panel section combining time slices and vertical sections. Although less clear, the concentric reflector pattern can still be observed in the upper part of the diapir.

Conclusions

In recent years the RCMG has demonstrated that the acquisition of high-quality VHR shallow 3D data is feasible in a modest and cost-effective way, without requiring complex field procedures. The development of a new, flexible 3D acquisition system has enabled the imaging resolution to be improved, even when based on relatively simple processing, and thus the shallow 3D method can be further scaled down, leading to ultra-high resolution and a decimetre scale.

The new acquisition system is aimed at studies in shallow water (< 30 m water depth) providing limited penetration (< 50 m bsf). Potential areas for investigation include geotechnical and environmental sites of limited lateral extent (typically 100×100 m^2). Acquisition and positioning constraints (array deployment, source–receiver positioning accuracy and UHF range limitations) limit the system to nearshore studies. In protected areas and on rivers, canals and lakes, the system may also be used autonomously.

Acknowledgements

This study was carried out in the framework of the EEC MAST-III Project 'VHR3D' (Project MAS3-CT97-0121). We

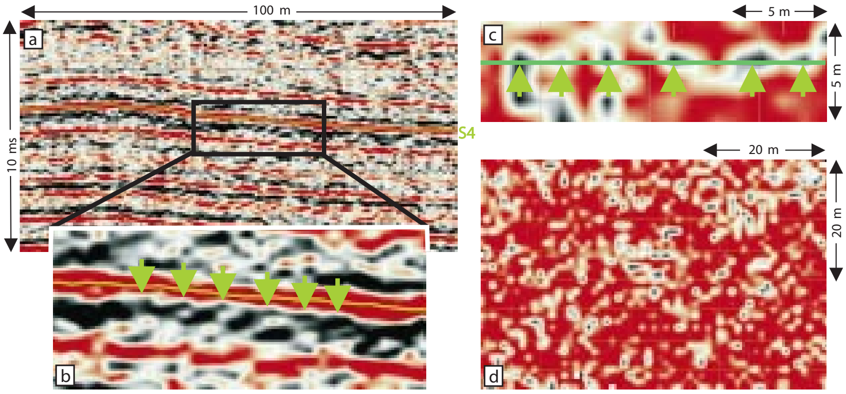

Figure 8 (a) In-line section showing septaria level S4. (b) Detailed close-up with individual diffraction hyperbolae. (c) Horizon slice at 0.2 ms below level S4 – the green arrows refer to hyperbolae identified in (b). (d) Enlarged section showing typical blotchy pattern possibly suggesting concretion distribution.

thank the officers and crew of the RV Belgica. We are very grateful to Paolo Diviacco and Nigel Wardell from OGS who helped in sorting the 3D data.

References

Heldens, P. [1983] *Een seismische studie van de klei van Boom en de klei van Ieper*. PhD Thesis, University of Gent, Belgium.

Hemerijckx, E., Carpentier, R., De Schrijver, P., Henriet, J.P. and Heldens, P. [1983] Preliminary investigations of concretion horizons in a Tertiary clay layer in view of the construction of a pre-metro tunnel under the river Scheldt at Antwerp (Belgium). *Symposium on Engineering Geology and Underground Construction, Lisbon, Proceedings* **1**, 53–73.

Henriet, J.P., Verschuren, M. and Versteeg, W. [1992] Very high resolution 3D seismic reflection imaging of small-scale structural deformation. *First Break* **10**, 81–88.

Marsset, B., Missiaen, T., Noble, M., Versteeg, W. and Henriet, J.P. [1998] Very high resolution 3D marine seismic data processing for geotechnical applications. *Geophysical Prospecting* **46**, 105–120.

Schittekat, J., Henriet, J.P. and Vandenberghe, N. [1983] Geology and geotechnique of the Scheldt surge barrier – characteristics of an overconsolidated clay. *Proceedings of the 8th International Harbour Congress, Antwerpen* **1**, 121–134.

Vandenberghe, N. and Laga, P. [1986] The septaria of the Boom Clay (Rupelian) and its type area in Belgium. *Aardkundige Mededelingen* **3**, 229–238.

Verschuren, M. [1992] *An integrated approach to clay tectonic deformation*. PhD Thesis, University of Gent, Belgium.