Pseudo-3D seismic imaging of shallow structural deformations for the development of new windfarms offshore Belgium

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Introduction

Assessing subsurface conditions and identifying potential obstacles or hazards within the upper ~100 m of sediments below the seafloor are critical for the installation of offshore wind turbines. To do this, the acquisition of 2D high-resolution (HR) seismic data has been the traditional first step. This was also the case in the Princess Elisabeth Zone (PEZ) in the Belgian part of the North Sea, where new offshore windfarms will be developed in the coming years, in shallow water depths between ~10 and 45 m. The subsurface of the PEZ is characterized by a thin and irregular Quaternary cover overlying Early Eocene (Ypresian) clays that are part of the Kortrijk Formation. Previous studies (Henriet et al., 1988; De Batist, 1989), based on 2D seismic datasets acquired in the early 1980s, have identified intense, mainly intra-formational deformations in these clays, which in the PEZ manifest as faults and folds.

While newly acquired 2D-HR seismic datasets provide a good general view on the stratigraphy and geomorphology in the PEZ, further analysis is required to evaluate the spatial organisation of the deformations. Hence, within the dedicated *Clay Tectonics* research project, this study outlines the application of innovative processing techniques to create (pseudo-)3D cubes from densely spaced 2D-HR sparker seismic datasets, to enable a detailed visualisation and structural interpretation of the deformations in 3D. Specifically, this study explores and compares two distinct strategies; in the first approach, a 3D subsurface model (Cube-1) is generated through geospatial interpolation of horizons picked in the 2D-HR sections using dedicated software, whereas in the second approach, a 3D seismic volume (Cube-2) is created through CDP reflection point allocation, 3D binning and interpolation using the 2D-HR seismic sections as input (Figure 1). As such, the study aims to specify requirements and optimize the methodology for creating 3D subsurface models from dense 2D-HR seismic grids.

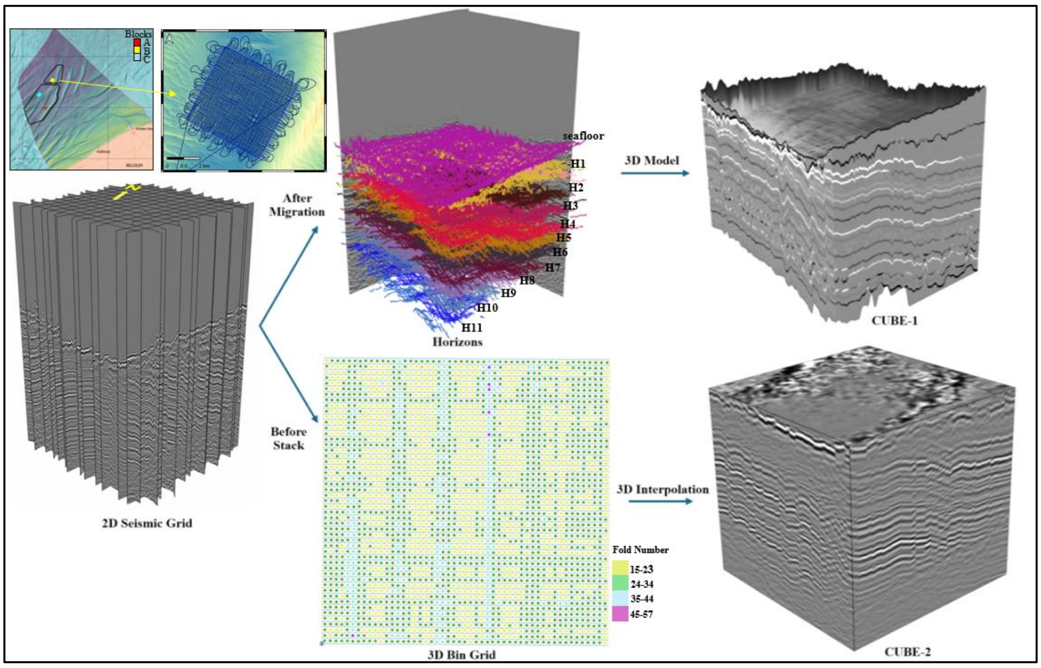

Figure 1 *The creation of Cube-1 and Cube-2 involves distinct methodologies. Cube-1 is generated through geospatial interpolation of 12 interpreted horizons, including the seafloor, derived from the 2D seismic data. In contrast, Cube-2 is constructed via bin allocation and subsequent interpolation, resulting in the generation of a 3D seismic volume with in- and crossline seismic sections.*

Materials and Methods

Within the framework of the *Clay Tectonics* project, four dense seismic grids were collected in the PEZ. This study uses the data from Block-B, which comprises a 2.5 x 2.5 km network with 39 SW-NE and 38 NW-SE 2D profiles, intersecting at approximately 50 m intervals. The 2D seismic system consisted of a 24-channel streamer with a 2 m channel spacing and an 800 J multi-tip Sparker source with a ~150-3000 Hz frequency content. The shot interval and sample rate were set to ~1 m and 8 kHz, respectively. The reflection point coordinates were calculated based on the ship's GNSS-determined position, along with the relative distances of the receiver and source to the GNSS antenna. The following sections outline the key steps in the creation of the pseudo-3D cubes for the two distinct approaches tested in this study.

Cube-1: 3D model generated from 2D horizon picks

In the first approach to generate a 3D cube, the 2D-HR seismic data were first processed following a conventional workflow, yet with a particular focus on clearly imaging the clay tectonic deformations. This included the following steps: 1) geometry definition, 2) denoise (burst noise removal, time-frequency denoise, bandpass filter, F-K filter), 3) surface-related multiple elimination, 4) velocity analysis (for all 2D lines individually), 5) NMO correction, 6) stacking, 7) deghosting (predictive deconvolution), 8) 2D Kirchhoff time migration.

The processed 2D sections were then imported into the software *PaleoScan* (Eliis) to create a 3D geological model (in the time domain). The primary steps in this process are: 1) the creation of a 2D data model grid, 2) semi-automated horizon picking, 3) generating a 2D Relative Geological Time (RGT) Model, 4) horizon stack generation, 5) the calculation of the 3D RGT Model. The result is a full 3D subsurface model (Cube-1), which enables a detailed stratigraphic and structural analysis of the area based on vertical, time and horizon slices and derived attribute maps (e.g. azimuth, dip) (Figure 2).

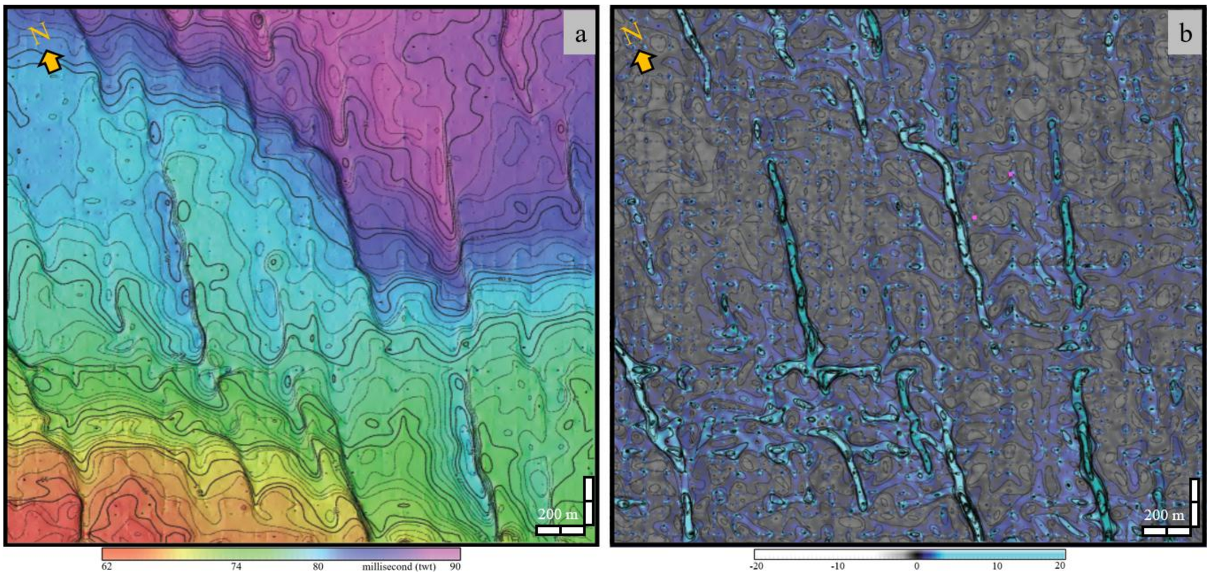

***Figure 2** Attribute analysis of Cube-1 horizon stack 10 of 20 in a) Relative time slice map, and b) Dip attribute map (representing the relative inclination of the horizons). These maps can be used for an overall understanding of the study area and allow to readily identify structural features such as faults.*

Cube-2: 3D volume generated through conventional bin gridding

In the second approach, the pre-stack processing of the 2D seismic sections was the same as for Cube-1, but subsequently 3D binning and stacking were applied. An appropriate 3D bin grid size was determined by considering the seismic line spacing and streamer feathering angles caused by waves and currents. Bin sizes of 25x25 m, 50x50 m, and 75x75 m were tested. A 50x50 m bin size, leading to 51 inlines and 51 crosslines, provided optimal results in terms of both vertical and horizontal detectability of strata and structures.

After 3D binning and stacking, 3D interpolation was applied, followed by denoising and trace amplitude equalization to get a more consistent representation of the reflection amplitudes. Finally, 3D Stolt migration was applied to the data using a constant velocity. The resulting seismic cube (Cube-2) can be loaded as a 3D volume in any seismic interpretation software for further analysis, using the regularly spaced in- and crossline sections and amplitude variations on time slices (Figure 3).

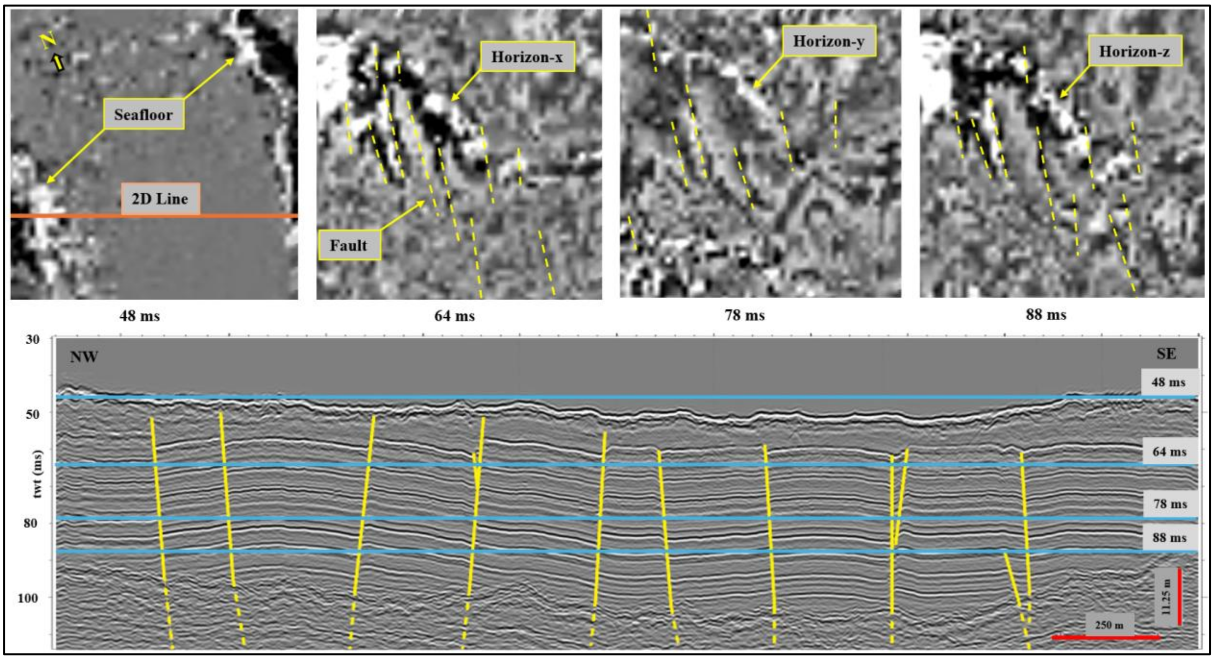

Figure 3 *NW-SE-oriented 2D-HR seismic profile at the bottom, with yellow lines marking faults and blue lines indicating the Cube-2 time slice locations shown at the top. Amplitude variations in time slices are presented at 48, 64, 78, and 88 ms, respectively. The orange line corresponds to the location of the 2D section shown at the top. Dashed yellow lines highlight potential N-S-oriented fault lines.*

Results and discussion

Cube-1 offers a very detailed visualisation of the stratigraphic organisation and structural features in the time domain (Figure 2). Horizon time maps, in combination with structural attribute maps, allow to precisely infer the 3D fault plane orientations and distribution, most clearly between the seafloor and first multiple reflection of the seafloor (around 100 ms).

In Cube-2, the amplitude variations of seismic reflections observed in time slices offer a general indication of the depositional trends and stratal geometry (Figure 3). However, the spatial resolution of Cube-2 is lower than in Cube-1 due to the limited number of CDP reflection points within the grid and turns out to be insufficient to clearly resolve all fault planes. It can be concluded that the input 2D-HR dataset (with a 50 m line spacing) was too sparse to generate an accurate 3D seismic volume, and a more densely spaced (regular) grid of 2D-HR lines would be required to make this second approach more successful.

Given the above analysis, it is clear that the generation of 3D models following the approach adopted for Cube-1 is essential to enable an accurate 3D analysis of the structural complexity in the PEZ. Yet, the approach adopted for creating Cube-2 still has a value, as it offers a fast way to generate a 3D impression of the general geological trends in the study area without having to perform (time-consuming) 2D horizon picking. In addition, amplitude information is preserved in Cube-2 (in contrast to Cube-1). In this respect, both approaches can be used in a complementary way to establish a comprehensive stratigraphic and structural interpretation.

It is finally recommended to visualise the resulting 3D cubes in combination with the original 2D-HR seismic data, to allow an integrated 2D/3D interpretation and maintain a good control on the presence of potential model artefacts (Figure 4).

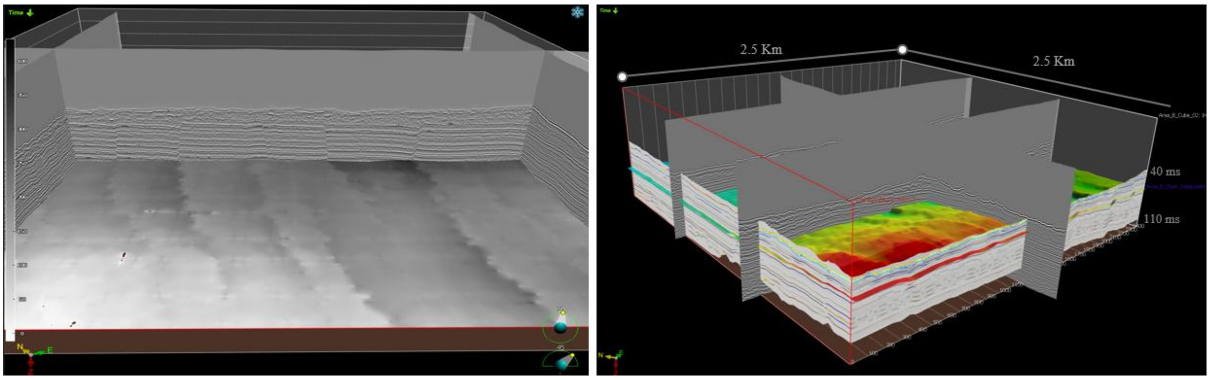

Figure 4 *Examples of the integration of 2D-HR sections and maps derived from the 3D RGT model in PaleoScan.*

Conclusions

This study demonstrates that creating adequate (pseudo-)3D models from 2D-HR seismic data for the spatial evaluation of structural deformations is feasible, posing a viable, cost-effective alternative to (expensive and logistically complex) 3D seismic surveys *sensu stricto*. For a grid of 2D-HR seismic profiles collected at ~50 m intervals in shallow water depths, we conclude that a 3D model built from interpreted 2D horizons is preferred over 3D binning/interpolation of (sparse) 2D data for generating a detailed 3D representation of the subsurface stratigraphy and structure in the study area.

In the *Clay Tectonics* project, the resulting cubes will enable a robust stratigraphic and structural analysis, with a good control on the 3D spatial organisation of the deformations. 3D fault models in particular will serve as a critical input for the geotechnical assessment of the PEZ, with potential repercussions for the planning, foundation design and longer-term stability of the new wind turbines. Beyond this specific project and context of the PEZ, the here presented case study contributes to optimizing the methodology for the 3D visualisation of geomorphological and structural features in the shallow subsurface, which is critical for making informed decisions in the development of offshore infrastructure in shallow marine environments worldwide.

Acknowledgements

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