CLAY TECTONICS PROJECT – DELIVERABLES

D1.1 REPORT ON THE SELECTION OF STUDY AREAS BASED ON AVAILABLE GEOPHYSICAL DATASETS AND LITERATURE

Thomas Mestdagh[1], Ruth Plets[1], Tine Missiaen[1], Hans Pirlet[1]

[1] Flanders Marine Institute (VLIZ), Jacobsenstraat 1, 8400 Oostende, Belgium

1. Introduction

The Clay Tectonics project (2023-2025) is a cSBO-project funded by Flanders Innovation and Entrepreneurship (VLAIO) through the Blue Cluster (DBC). The project aims to investigate the influence of clay tectonic features (CTFs) within the Kortrijk Formation on offshore wind foundation design and installation in the Belgian Part of the North Sea (BPNS). The project partners (VLIZ, UGent, VUB - OWI-Lab) will apply a multidisciplinary strategy, combining geophysical, geological and geotechnical methods.

The scope of the first work package in this project (WP1) is to develop an innovative field measurement and processing strategy to generate ultra-high-resolution, pseudo-3D seismic data volumes, using parametric echosounders, single- and multi-channel sparker systems and a chirp sub-bottom profiler mounted on an Autonomous Underwater Vehicle (AUV). The goal is to adequately visualize the different types of CTFs occurring in the Kortrijk Formation. After all, it is described that the nature and intensity of the CTFs exhibit geographical variations (De Batist, 1989). Based on a first reconnaissance of the northwestern part of the BPNS, a few small study areas will be selected that can be considered representative for the entire Princess Elisabeth Zone (i.e. the designated zone for new offshore wind developments). In this respect, a first, essential consideration is to carefully select the appropriate study areas for the envisaged detailed acoustic measurements.

The goal of this deliverable (D1.1) is to document the selection of the study areas that will be targeted during the Clay Tectonics project, as well as the substantiation and approach that were used for this selection. In a first step, the selection procedure consisted of an evaluation of existing information on CTFs in the BPNS (with a particular focus on the Princess Elisabeth Zone), including literature and previously collected geophysical datasets (section 2). Secondly, based on this information coupled to a list of practical and methodological constraints, different study areas for performing the acoustic measurements are selected and substantiated (section 3).

2. Information available prior to the project

2.1. Literature

The presence of CTFs in the BPNS was discovered in the 1980s, based on high-resolution seismic (mainly sparker) profiling (Henriet et al. 1983; Henriet et al. 1988). It was reported that the deformations predominantly affect the Lower-Eocene (Ypresian) Kortrijk Formation (see Palaeogene subcrop map in Fig. 1), which was corroborated by evidence from onshore outcrops (De Batist, 1989; Henriet et al. 1991; Verschuren, 1992; Verschuren, 2019). In the BPNS, the CTFs appear as imbricated fault systems with tilted blocks and inclined fault planes, collapse structures and festoon-like sequences of cuspate anticlines, often developing into diapir-like escape pipes which locally pierce into the Quaternary cover (Henriet et al. 1983).

A detailed analysis by De Batist (1989) revealed geographic variations in deformation style or intensity. As shown in Figure 2, two deformation types have been discerned within the Princess Elisabeth Zone (PEZ): (i) irregular, intense or dense deformations (example in Fig. 3a), dominantly in the central part of the PEZ; and (ii) relatively widely spaced, regular block faulting (example in Fig. 3b), mainly in the NE part of the PEZ. In the SW part of the PEZ, the deformation type could not be defined based on the then available data.

Since the original work of the abovementioned authors in the 1980s and early 1990s, no new case studies or systematic analyses focusing on CTFs in the BPNS have been conducted.

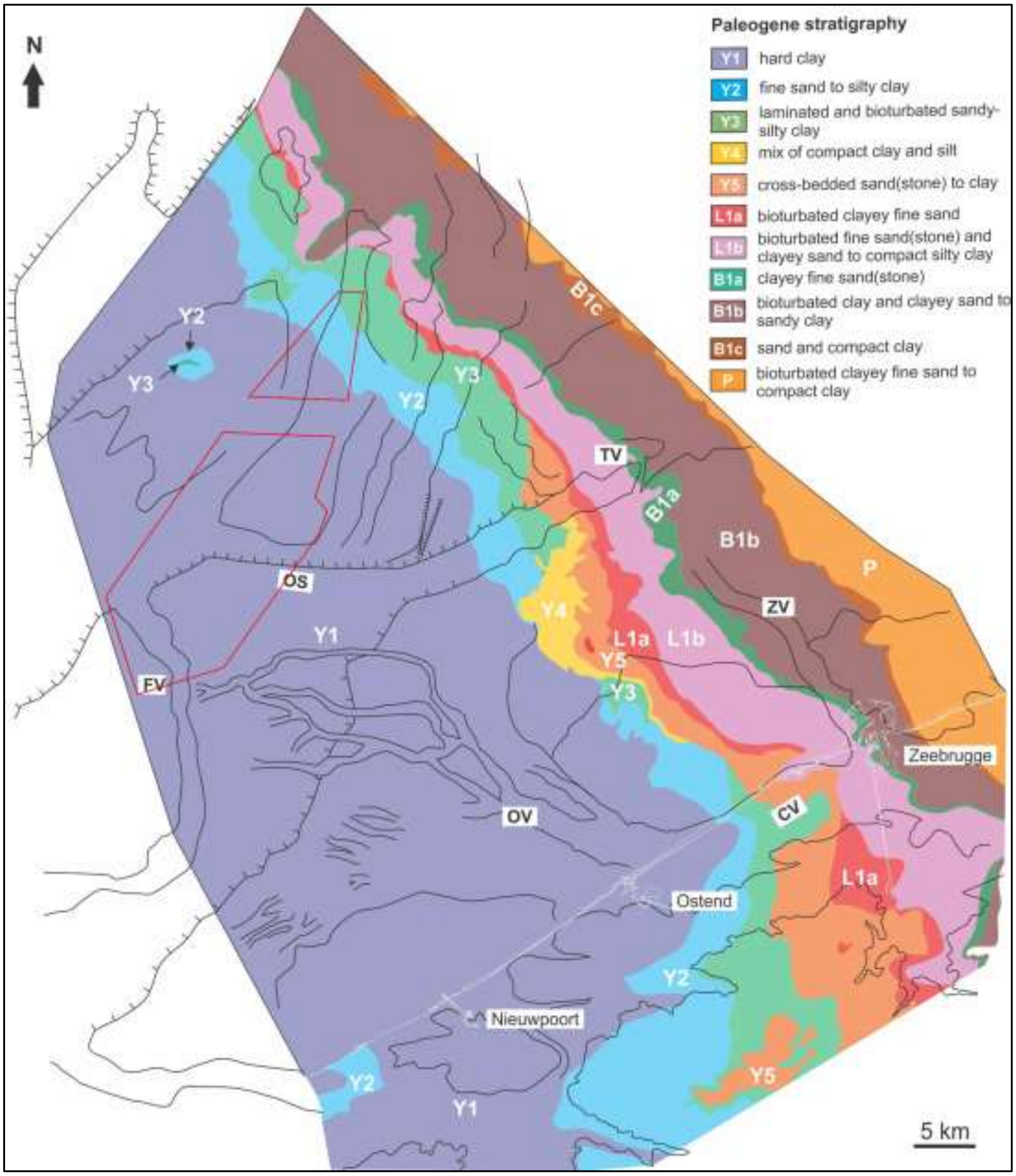

__Figure 1.__ Subcrop map of Palaeogene seismo-stratigraphic units underlying the Quaternary cover on the BPNS. The Princess Elisabeth Zone (red polygon) is mostly underlain by Ypresian (Lower Eocene) unit Y1, corresponding to the Kortrijk Formation. Figure from De Clercq (2018), based on a synthesis by Le Bot et al. (2003).

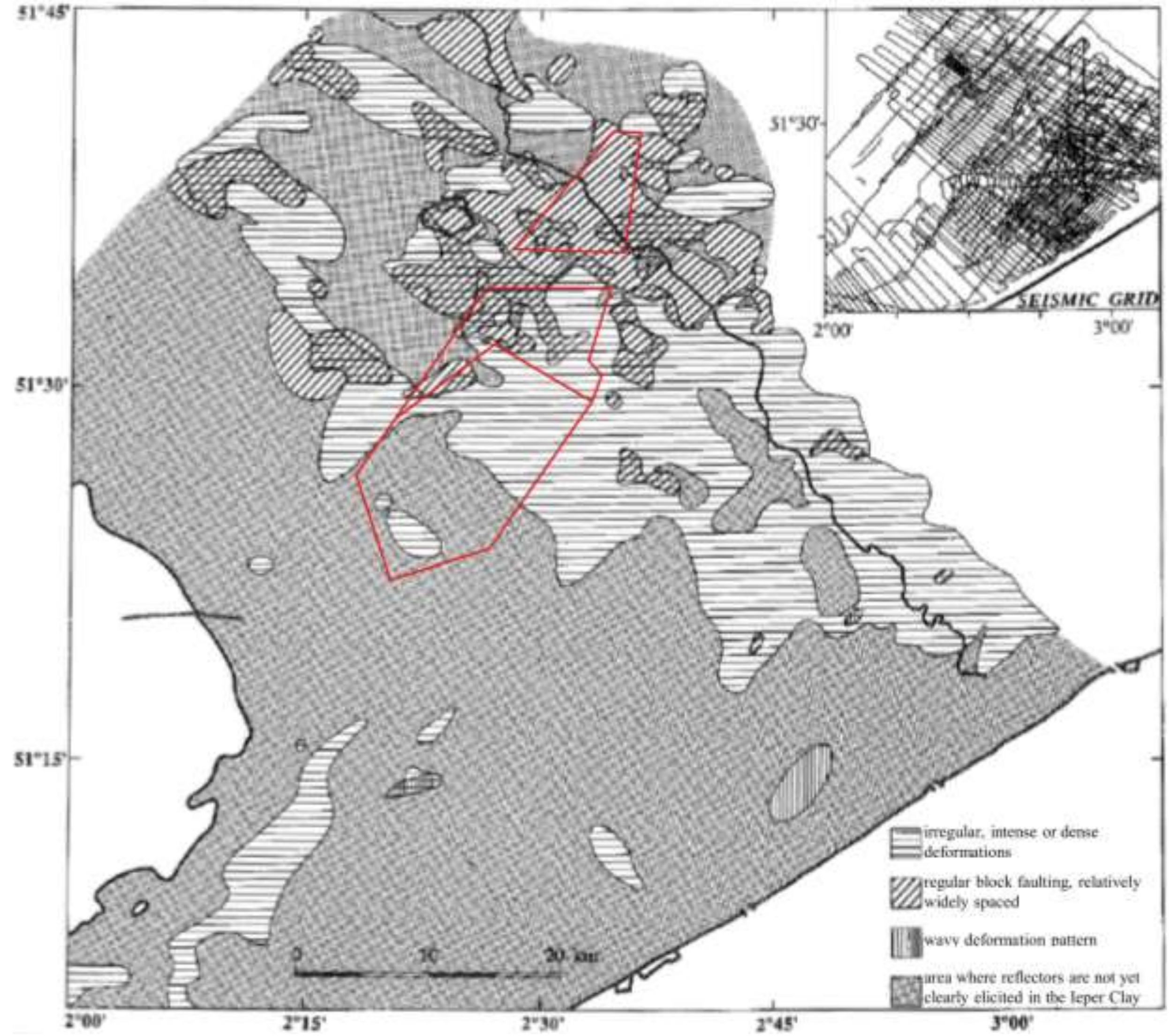

Figure 2. *Geographic variation in clay tectonic deformation types in the (wider) BPNS. The Princess Elisabeth Zone (red polygon) is marked by the occurrence of both irregular, intense deformations and regular, more widely spaced block faulting. Figure from Henriet et al. (1991), based on an analysis by De Batist (1989).*

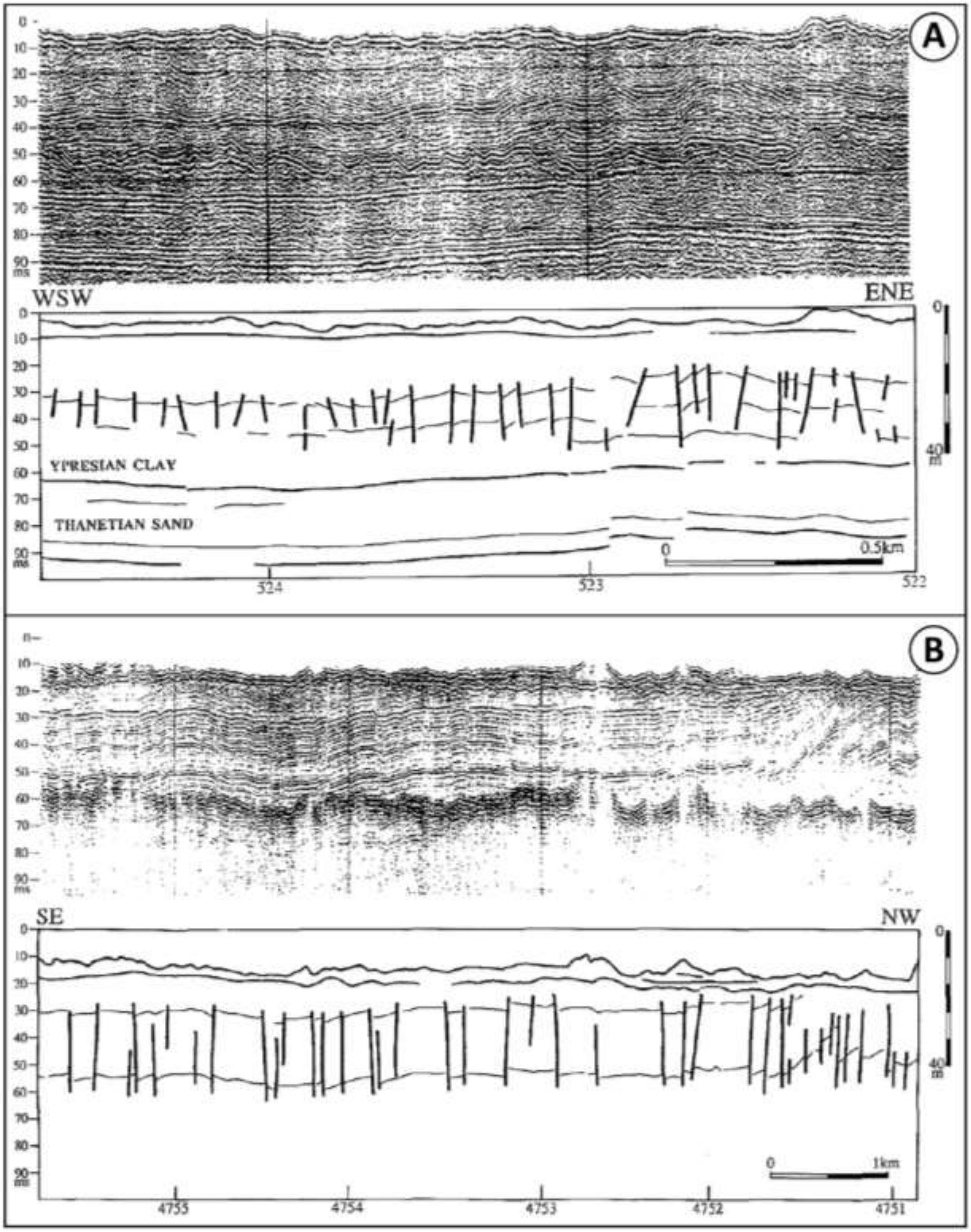

Figure 3. *Sparker profiles from the BPNS from Henriet et al. (1991), showing examples of the clay tectonic deformation styles that have been reported to occur in the PEZ:* ***(A)*** *more irregular, dense or intense deformation;* ***(B)*** *more regular and widely spaced block faulting. Note the difference in the horizontal scale between (A) and (B).*

2.2. Geophysical data

Besides the published research presented in the above section (2.1), additional geophysical (seismic) data were gathered to make an informed selection of study areas for the Clay Tectonics project. These data comprise (i) sparker profiles collected prior to 2022 by partners within the consortium, and (ii) sparker and parametric echosounder profiles collected in 2022 during the preparatory phase of the Clay Tectonics project.

2.2.1. Sparker data collected prior to 2022

Over the past decades, partners within the consortium (UGent-RCMG and VLIZ) have collected a large amount of seismic data in the BPNS, for various projects and purposes (a.o. for the research already presented above, in section 2.1). These data were mainly acquired using sparker sources and single-channel streamers, and have a vertical resolution of ~1-2 m. Three of these datasets cover the Princess Elisabeth Zone, and are thus relevant to the Clay Tectonics project (Fig. 4). The following paragraphs provide some examples and background on these datasets.

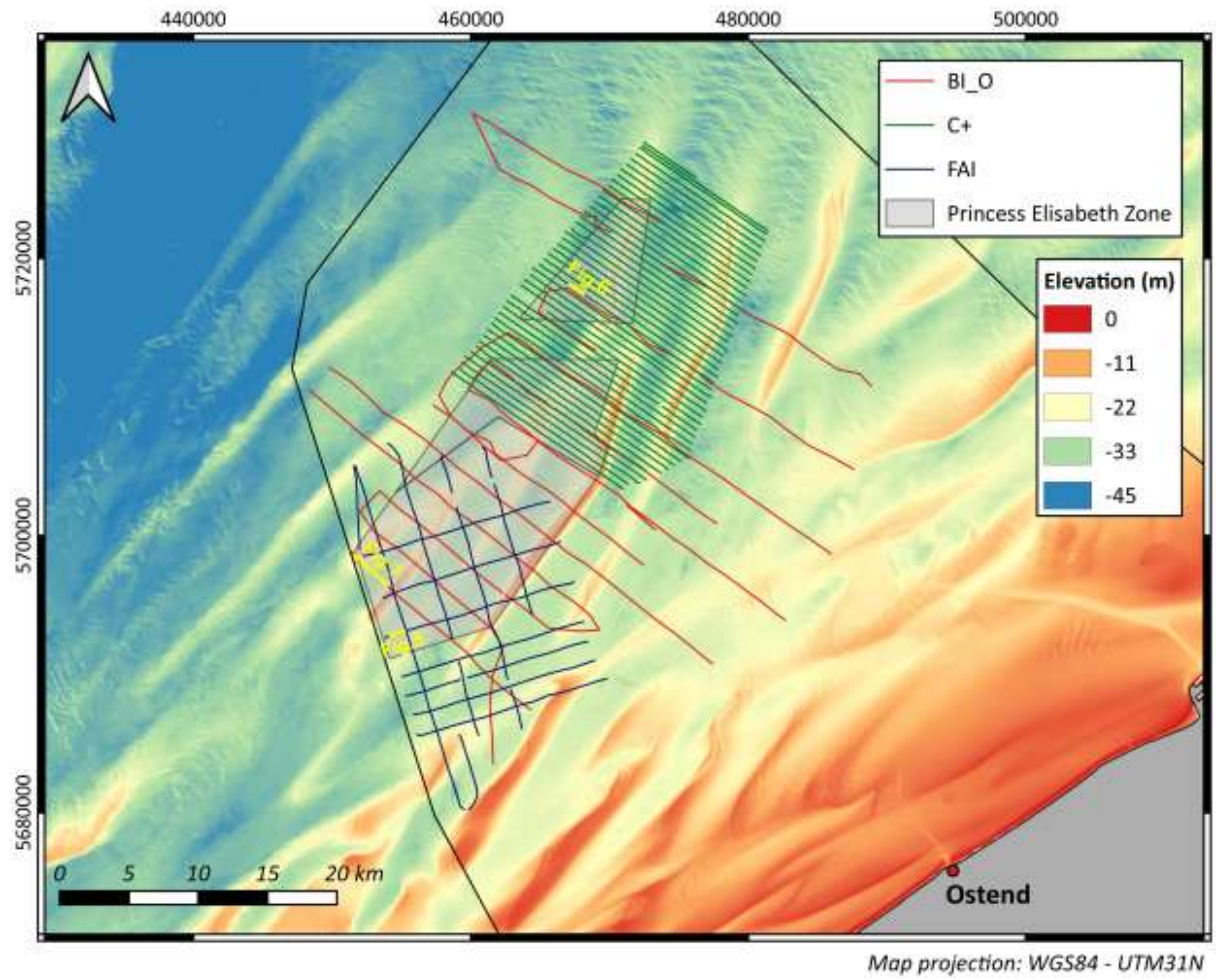

***Figure 4.** Map of the BPNS, indicating the seismic datasets (collected by consortium partners prior to 2022) that cover the Princess Elisabeth Zone. Bathymetry from the Flemish Hydrography Bathymetric database (2022).*

(i) Dataset “FAI”: These data were collected over and south of the Fairy Bank, as such covering the SW part of the Princess Elisabeth Zone (Fig. 4). The survey was conducted in April 2015 onboard RV Simon Stevin, using a GSO360 sparker source, in the context of the IWT SBO project “SeArch” (more context, acquisition and processing details in Zurita Hurtado and Missiaen, 2016). An example is shown in Fig. 5, illustrating that CTFs (in this case, faults) can be observed in the data, albeit rather vaguely.

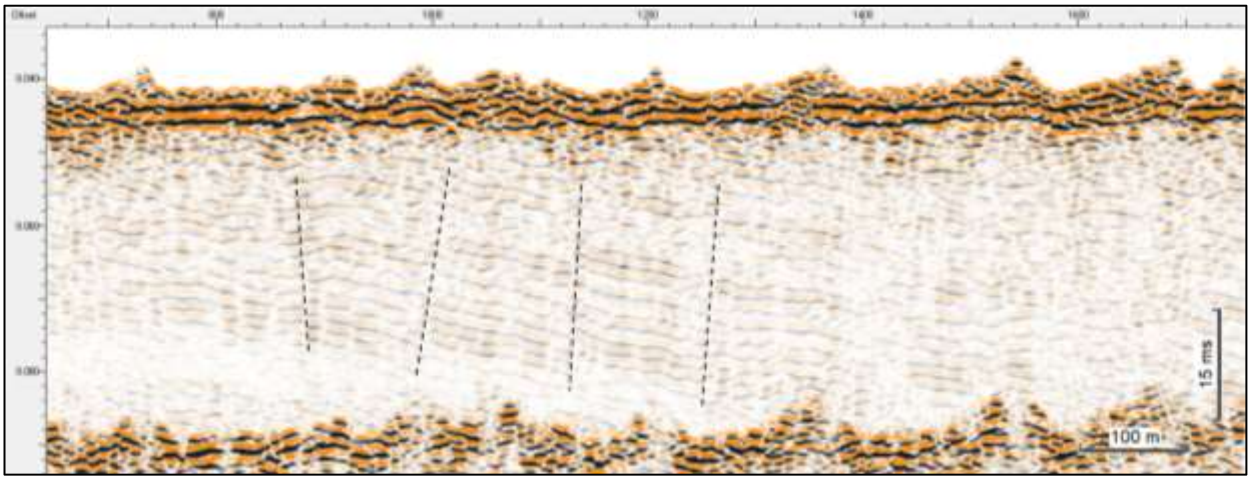

Figure 5. *Example of a sparker profile from dataset “FAI” within the Princess Elisabeth Zone (location indicated in Figure 4), vaguely suggesting the presence of faults (black dashed lines). The vertical scale is in seconds two-way travel time (10 ms twtt corresponds to ~8 m assuming a sound propagation velocity of 1600 m/s).*

(ii) Dataset “C+”: This dataset was collected over the northern half of the Westhinder, Oosthinder and Noordhinder tidal sandbanks, covering the NW part of the Princess Elisabeth Zone (Fig. 4). The data were commisioned by the Flemish government (Agentschap voor Maritieme Dienstverlening en Kust; MDK) and collected by G-Tec in 2009 (acquisition and processing details in Depret, 2009), in the context of an evaluation of sand resources in this area executed by UGent-RCMG (Mathys et al., 2009). The data clearly reveal the presence of CTFs (faults) in this area (Fig. 6).

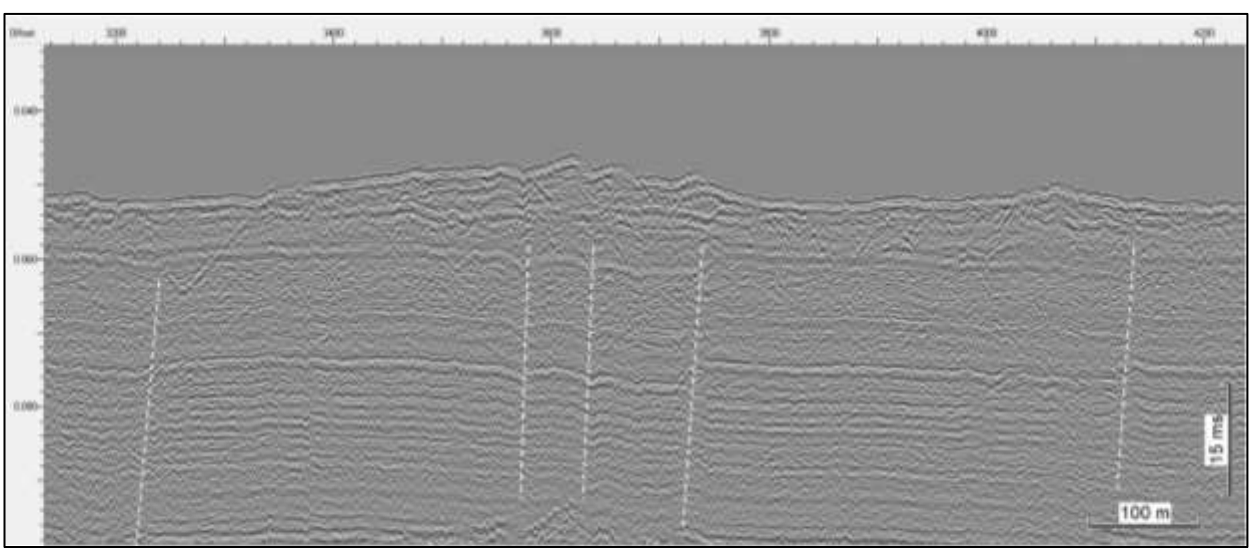

Figure 6. *Example of a sparker profile from dataset “C+” within the Princess Elisabeth Zone (location indicated in Figure 4), indicating the presence of faults (white dashed lines). The vertical scale is in seconds two-way travel time (10 ms twtt corresponds to ~8 m assuming a sound propagation velocity of 1600 m/s).*

(iii) Dataset “BI_O”: These data are part of large regional surveys covering most of the BPNS (including the Princess Elisabeth Zone; Fig. 4), performed by UGent-RCMG in the 1980’s in the framework of the marine geological exploration of the Belgian Continental Shelf. They are mostly analogue recordings of sparker, boomer and water gun seismic profiles (e.g. De Batist, 1989). The data show variable quality, with some of the profiles vaguely suggesting the presence of CTFs in the PEZ (Fig. 7).

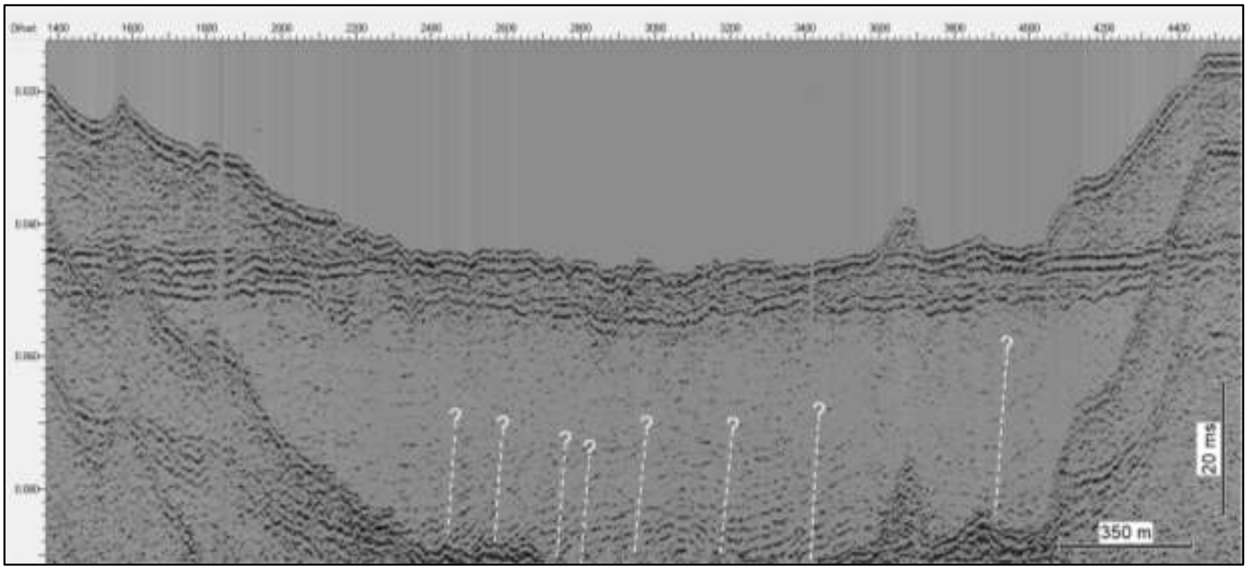

Figure 7. *Example of a sparker profile from dataset “BI_O” within the Princess Elisabeth Zone (location indicated in Figure 4), vaguely suggesting the presence of faults (white dashed lines). The vertical scale is in seconds two-way travel time (10 ms twtt corresponds to ~8 m assuming a sound propagation velocity of 1600 m/s).*

2.2.2. Sparker and parametric echosounder data collected in 2022

In the course of 2022, a number of preliminary, exploratory surveys were performed by VLIZ during the preparation of the Clay Tectonics project proposal (Fig. 8). These surveys deployed state-of-the-art ultra-high-resolution parametric echosounders (PES) and/or sparker systems, allowing for very detailed sub-bottom imaging (down to centimetric vertical resolution). Some background and examples of these datasets are briefly presented in the following paragraphs.

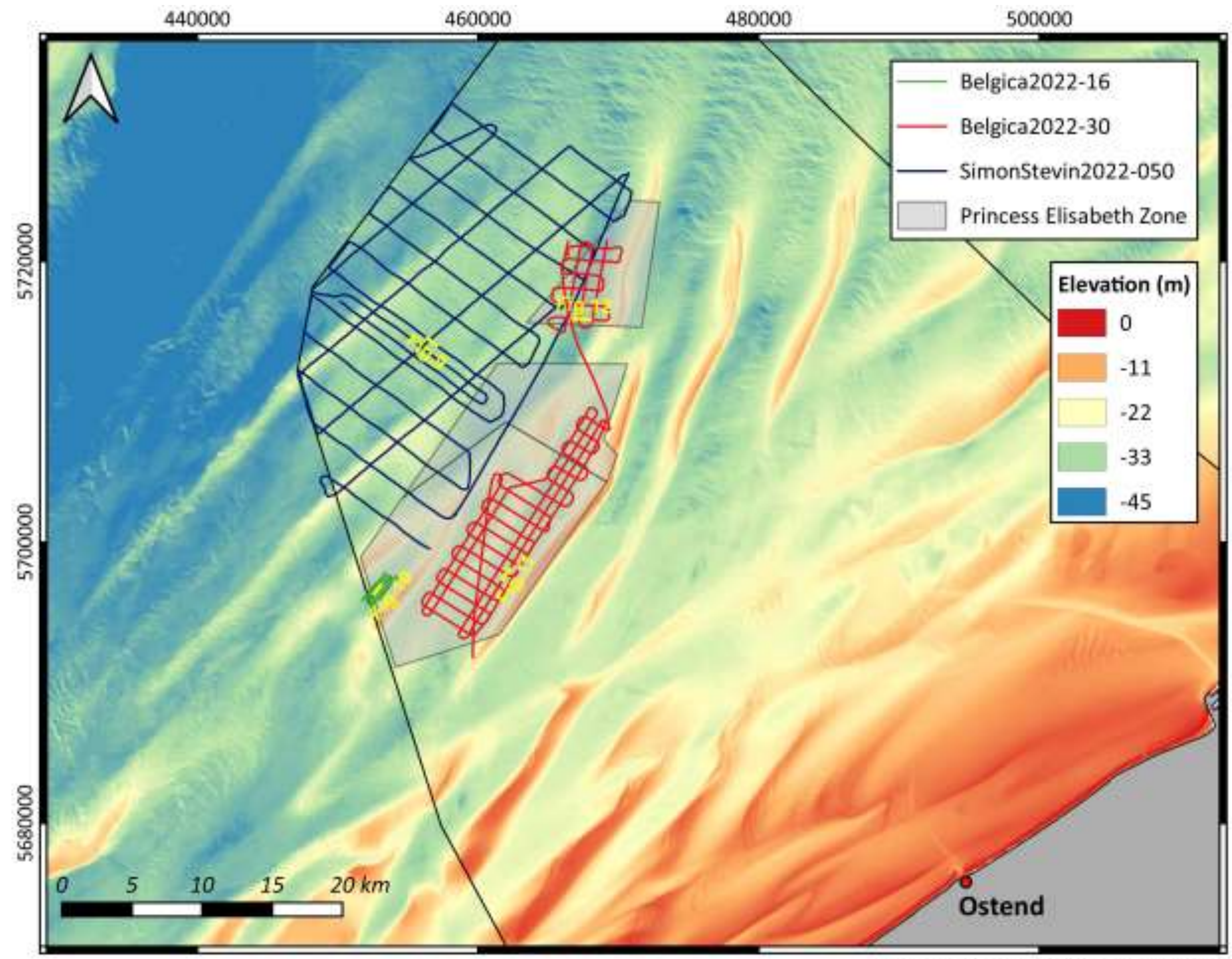

Figure 8. *Map of the BPNS, indicating the seismic datasets collected by VLIZ in (and around) the Princess Elisabeth Zone in 2022. Bathymetry from the Flemish Hydrography Bathymetric database (2022).*

(i) Sparker and PES SimonStevin2022-050: During this survey (January 2022, RV Simon Stevin), an Innomar quattro PES (frequency 8 kHz) and GSO360 sparker (in combination with a 24-channel streamer) were deployed on a large grid on the outer, NW part of the BPNS (Fig. 8). This survey framed in a preliminary reconnaissance of the so-called Exploration Zone, to evaluate the available sand resource in this area (as part of a collaboration between VLIZ and FPS Economy – Continental Shelf Service). Although imaging clay tectonic deformations was not the aim of this survey, CTFs (faults) could clearly be observed in the acquired data, both NW of and within the Princess Elisabeth Zone (e.g. PES profile in Fig. 9). It was this observation that eventually instigated the cSBO Clay Tectonics project.

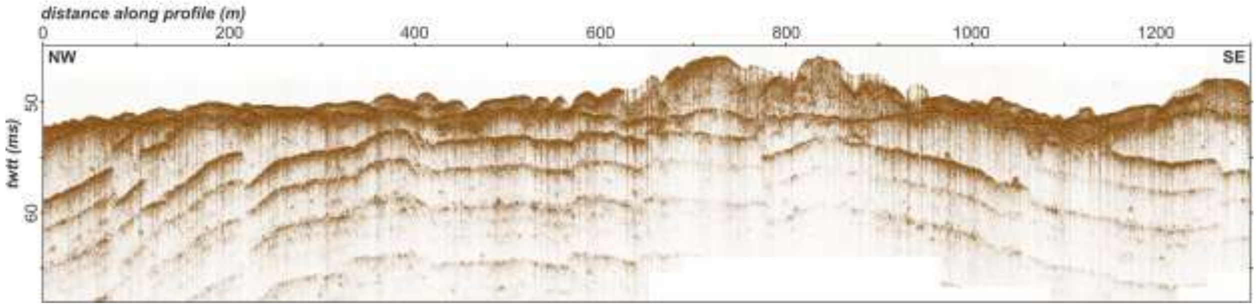

Figure 9. *Example of an Innomar quattro PES profile acquired during survey SimonStevin2022-050 northwest of the Princess Elisabeth Zone (location indicated in Figure 8). On the vertical scale, 10 ms twtt corresponds to ~8 m (assuming a sound propagation velocity of 1600 m/s).*

(ii) TOPAS Belgica2022-16: These profiles were acquired using the (hull-mounted) TOPAS PS18 (Kongsberg) PES onboard RV Belgica in July 2022. The measurements were performed by VLIZ to test the capabilities of this instrument (which was at that moment new and still largely unused), during simultaneous multibeam echosounder measurements in the framework of the *SD-Monitoring of natural hard substrates* program of the Royal Belgian Institute of Natural Sciences (RBINS) (Van Lancker et al., 2022). Figure 10 shows one of these TOPAS profiles (frequency 6 kHz), demonstrating the presence of (intense) faulting in the Palaeogene strata.

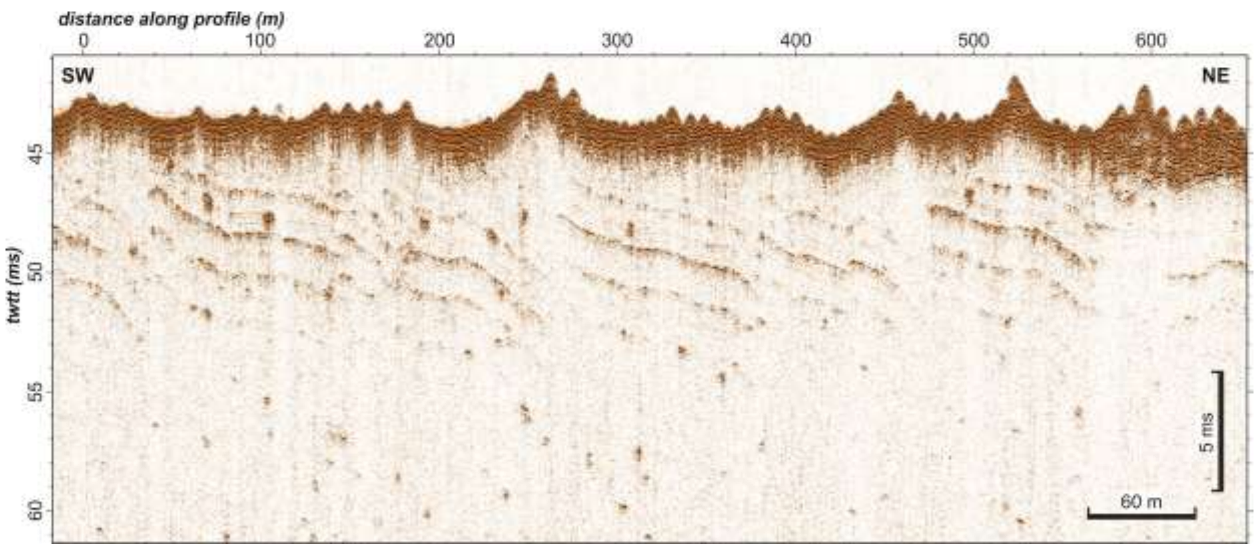

Figure 10. *Example of a Kongsberg TOPAS PS18 PES profile acquired during survey Belgica2022-16 within the Princess Elisabeth Zone (location indicated in Figure 8). On the vertical scale, 10 ms twtt corresponds to ~8 m (assuming a sound propagation velocity of 1600 m/s).*

(iii) TOPAS Belgica2022-30: Another TOPAS PS18 dataset was collected onboard RV Belgica in November 2022 by VLIZ. These data were collected to explore the presence of and variation in CTFs in the Princess Elisabeth Zone, as a preliminary evaluation prior to the start of the Clay Tectonics project (Fig. 8). Different deformation types could indeed be identified, with the southern part of the survey grid displaying more intense, irregular faulting (Fig. 11; frequency 4 kHz), and the northern part of the survey grid showing more regular and widely spaced fault blocks (Fig. 12; frequency 2 kHz), in line with the earlier findings of De Batist (1989) (see Fig. 2 and 3).

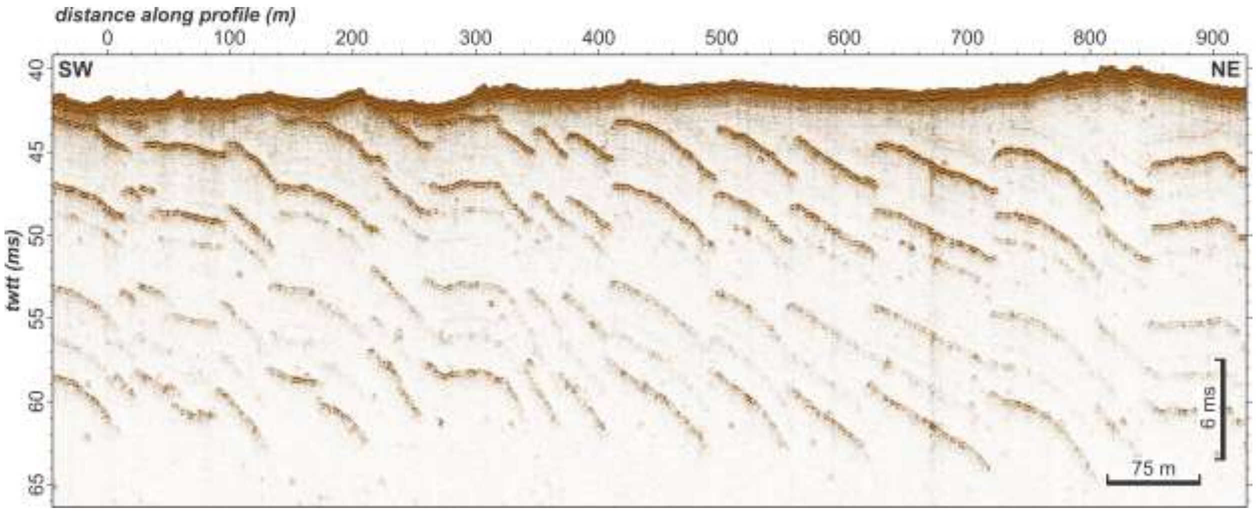

Figure 11. *Example of a Kongsberg TOPAS PS18 PES profile acquired during survey Belgica2022-30 in the central part of the Princess Elisabeth Zone (location indicated in Figure 8). On the vertical scale, 10 ms twtt corresponds to ~8 m (assuming a sound propagation velocity of 1600 m/s).*

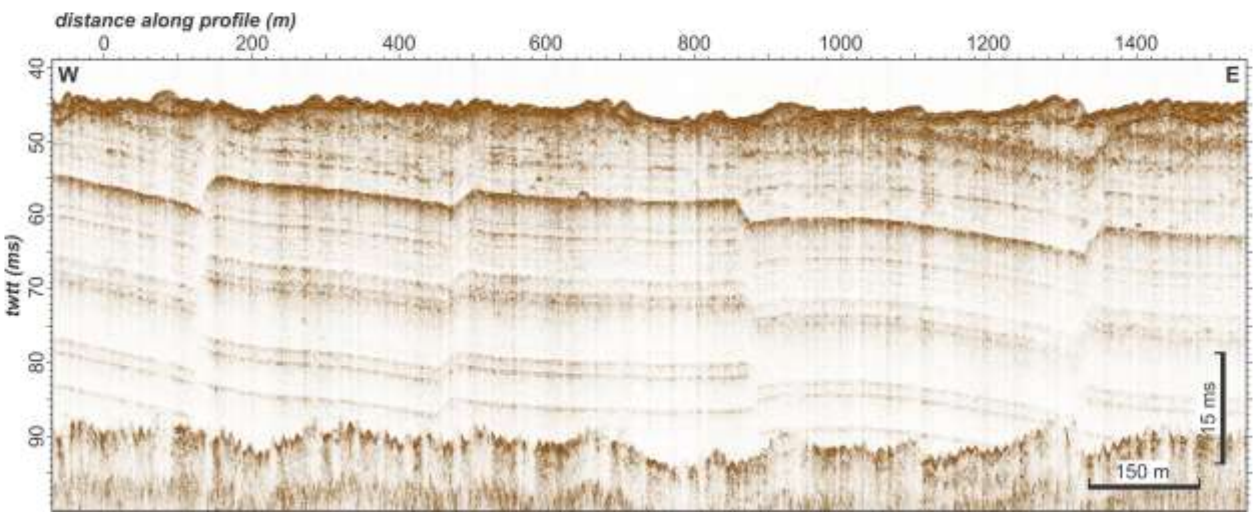

Figure 12. *Example of a Kongsberg TOPAS PS18 PES profile acquired during survey Belgica2022-30 in the northern part of the Princess Elisabeth Zone (location indicated in Figure 8). On the vertical scale, 10 ms twtt corresponds to ~8 m (assuming a sound propagation velocity of 1600 m/s).*

3. Selection of new study areas

3.1. Criteria

The selection of study areas for detailed pseudo-3D acoustic profiling within the Princess Elisabeth Zone is bound by a number of methodological and practical constraints, in order to fit the scope of the Clay Tectonics project. These criteria are outlined in Table 1, together with a description of the desired conditions.

Table 1. *Description of criteria for the selection of suitable study areas for pseudo-3D acoustic profiling.*

Constraint	Description
Bottom penetration	An essential requirement for the CTFs to be adequately imaged, is that there is sufficient acoustic penetration in the selected study areas. This is especially critical for the highest-resolution instruments that will be used during the project (Innomar PES and AUV-mounted chirp), as these inherently have the lowest penetration. Therefore, locations with a thick Quaternary cover (with dominantly sandy sediments impeding penetration), overlying the Palaeogene strata containing the CTFs, have to be avoided to the extent possible. This implies that study areas have to be selected in the swales in between the major sandbanks in the PEZ (Fairy Bank, Westhinder and Noordhinder), where the Quaternary cover is absent, thin (max. a few meters) or more patchy.
Presence of identifiable reflectors	Lithological contrasts within the (dominantly clayey) Kortrijk Formation may be rather subtle, potentially resulting in the absence of clearly identifiable reflectors in the collected seismic data, which in turn would impede the identification and characterization of CTFs (Henriet et al. 1988). This risk can on the one hand be mitigated by carefully selecting the appropriate seismic equipment and finetuning the acquisition settings, but also by selecting study areas where previously acquired data demonstrate the suitability of the selected methods in that specific place. New study sites will therefore be selected where previous data (as presented in section 2.2) have indicated the presence of clearly identifiable reflectors.
Deformation style variability	As described in section 2.1, different deformation styles occur within the PEZ (Fig. 2), which was corroborated by the new parametric echosounder data acquired in 2022 (section 2.2.2; Fig. 11 and 12). Since the aim of the Clay Tectonics project is to provide a representative image of CTFs in the PEZ, the number and location of new study areas have to be chosen as a function of the (currently known) geographical distribution of the deformation styles.
Kortrijk Formation subcrop	The research on CTFs in the BPNS has so far predominantly focused on the Kortrijk Formation (section 2.1), which consequently also is the main formation of interest in the Clay Tectonics project. Onshore outcrop samples will furthermore be collected in quarries within the Kortrijk Formation (during the geotechnical part of the project), which forms another argument to ensure that the new offshore sites also address this formation. As shown in Fig. 1, the PEZ is nearly entirely underlain by the Kortrijk Formation, except in its NE corner; this corner will hence not be considered for detailed acoustic imaging.

Size of the study areas and line spacing	The size of the new survey grids for pseudo-3D acoustic profiling should be large enough to provide an adequate image to enable the characterization of larger-scale CTF attributes (e.g. the dimension and orientation of fault planes, fault patterns in plan view, …). On the other hand, the spacing between the survey tracks within the grids should be small enough to capture sufficient detail to also characterize the smaller-scale CTF attributes (e.g. fault bifurcations or smaller-scale secondary faulting, the width of the zone affected by an individual fault, …). Both factors have to be chosen based on the already available information (section 2) and balanced as a function of the available shiptime (three continuous surveys of ~85 h are foreseen in the first months of the project).
Administrative division of PEZ	The Belgian federal government has subdivided the PEZ into three parcels, for which separate tendering procedures and development phases for new offshore windfarms are foreseen. Although of secondary importance, this administrative division may be taken into account in the selection of survey sites, as a (more or less) even distribution of data/information over the parcels might be of interest to the members of the project's Industrial Advisory Board (IAB) who intend to play a role in the development of the new windfarms.

3.2. Site selection

Based on the above analysis, three sites (named "Block A", "Block B" and "Block C") for detailed acoustic profiling have been selected (Table 2). Their locations and line planning are shown in Figures 13 and 14.

Table 2. *Overview of the survey grids selected for pseudo-3D acoustic profiling, as shown in Fig. 13 and 14. See Figure 14 for the definition of the grid corners for which coordinates are given in this table (in WGS84).*

Name	Location			Dimensions	Line spacing	Priority
Block A	SE side of central PEZ			1.6 x 1.6 km	40 m (in- and crosslines)	1
	1	51° 26.67702' N	2° 27.39218' E			
	2	51° 26.18736' N	2° 28.52902' E			
	3	51° 26.89773' N	2° 29.31281' E			
	4	51° 27.38752' N	2° 28.17581' E			
Block B	S side of northern PEZ			2.5 x 2.5 km	50 m (in- and crosslines)	1
	1	51° 35.38599' N	2° 30.30605' E			
	2	51° 34.75705' N	2° 32.22025' E			
	3	51° 35.94934' N	2° 33.23057' E			
	4	51° 36.57856' N	2° 31.31576' E			
Block C	NW side of central PEZ			2.4 x 3 km	60 m (in- and crosslines)	2
	1	51° 30.92075' N	2° 23.47615' E			
	2	51° 32.06041' N	2° 25.31683' E			
	3	51° 31.14153' N	2° 26.77820' E			
	4	51° 30.00213' N	2° 24.93755' E			

This selection of survey sites fulfills the constraints presented in Table 1 as follows:

- All three blocks avoid the major tidal sandbanks within the PEZ (Fig. 13A), in order to get an optimal acoustic penetration in the Palaeogene strata. The sites are furthermore located where recent parametric echosounder (either Innomar quattro or TOPAS) data are already available (see section 2.2.2), which further ensures the presence of sufficient acoustic penetration and identifiable reflectors within the targeted Palaeogene Kortrijk Formation. At the same time, the sites have been selected in areas where a thin Quaternary cover is occasionally present, which allows to verify potential reactivation of CTFs during the Quaternary.

- Two sites (Block A and Block B) have been given first priority, as they capture the two distinct deformation styles recognized by De Batist (1989) within the PEZ (Fig. 13B), corroborated by the preliminary data acquired in 2022 (Fig. 11 and 12). Block A is selected to study the more intense, irregular deformations, whereas Block B should image the more regular and widely spaced block faulting. The suggested line spacing is adapted to the deformation style, with more closely spaced tracks in Block A where more dense deformations are expected (Fig. 14). The line spacing is furthermore adapted to the observed dimensions of CTFs (e.g. fault spacing) in the already available data (section 2.2). An additional site with second priority (Block C; Table 2) has been defined in a transition zone between the abovementioned deformation styles (Fig. 13B), which could help to further elucidate the control on and stratigraphic relation between the deformation types.

- Given the shiptime available (~250 h) and taking into account a ~100h bad weather buffer, the study sites have been defined to comprise in total ~150h of effective survey time. As the number of sites (3) and line spacing within the grids (respectively 40, 50 and 60 m for Block A, B and C) are already dictated by the geology (see above section), only the grid sizes remain to be chosen. These have been maximized such that all data can be acquired within ~50 h per grid, resulting in the dimensions defined in Table 2.

- Finally, the sites for pseudo-3D seismic profiling are all located within the Kortrijk Formation (Fig. 13C) and in different parcels (PEZ I – III; Fig. 13D), to optimally comply with the scope of the Clay Tectonics project and interests of the project's IAB members.

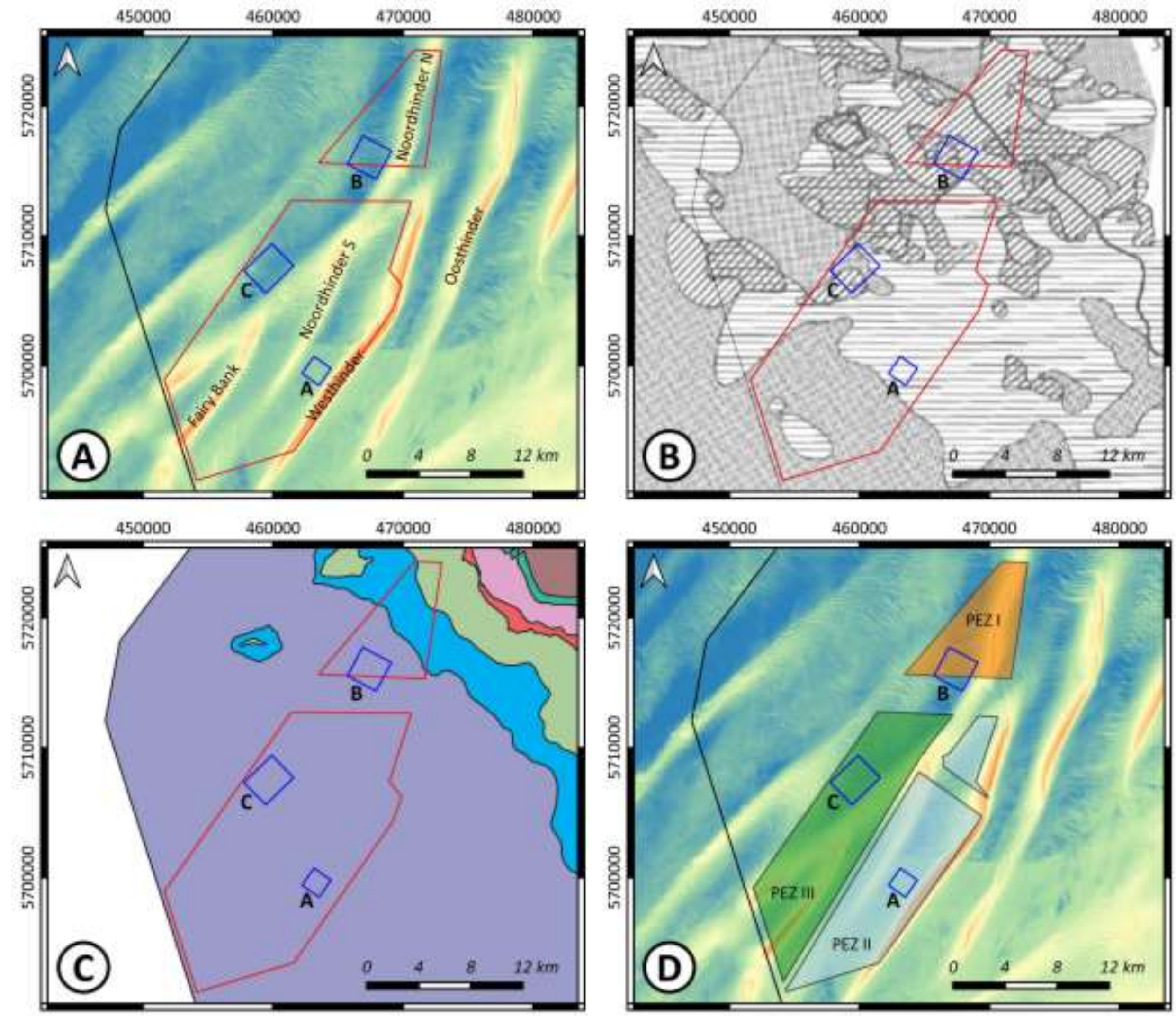

Figure 13. *Location of the sites selected for detailed (pseudo-3D) acoustic profiling (Block A, B and C) within the PEZ, relative to:* ***(A)*** *the major sandbanks in the study area (bathymetry from the Flemish Hydrography Bathymetric database, 2022);* ***(B)*** *the geographic variation in deformation style (figure from Henriet et al.,1991 - legend in Fig. 2);* ***(C)*** *the Palaeogene subcrop (figure from De Clercq, 2018 – legend in Fig. 1);* ***(D)*** *the administrative division of the PEZ into parcels PEZ I – III. Map projection is WGS84 – UTM31N.*

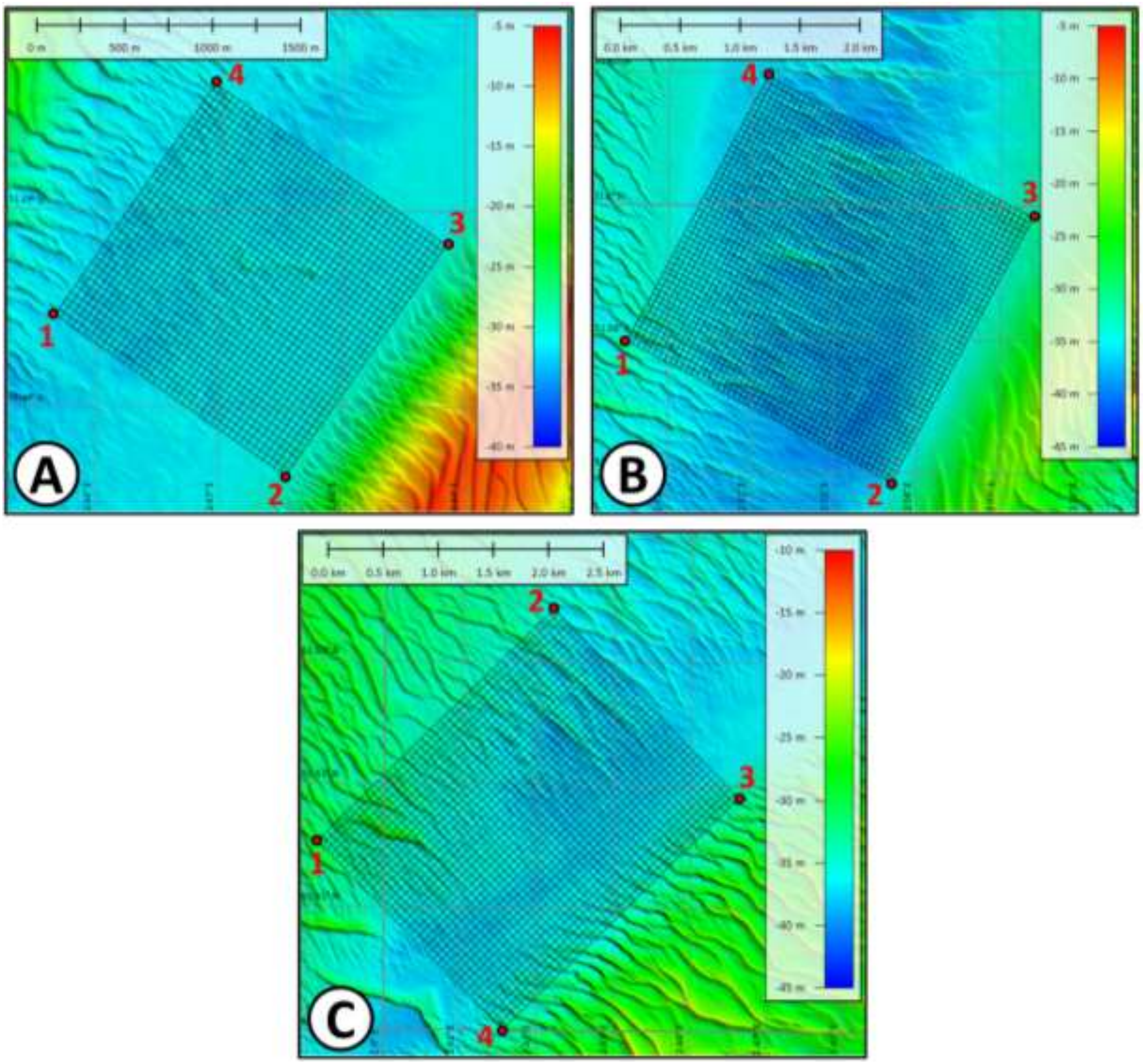

Figure 14. *Detail of the line planning in the blocks selected for pseudo-3D acoustic profiling.* ***(A)*** *Block A (40 m line spacing).* ***(B)*** *Block B (50 m line spacing).* ***(C)*** *Block C (60 m line spacing). Coordinates of the grid corners are given in Table 2. See Figure 13 for the location of the blocks within the PEZ. Bathymetry from the Flemish Hydrography Bathymetric database (2022).*

4. Conclusions

In this deliverable of the Clay Tectonics project, the selection of new study sites for detailed, pseudo-3D acoustic imaging within the Princess Elisabeth Zone has been substantiated. Based on an analysis of existing literature and previously acquired geophysical data, three blocks have been selected. The location, size and line spacing of these blocks have been defined by carefully considering geological/geophysical factors (variations in clay tectonic deformation style, Quaternary cover thickness, bottom penetration, presence of identifiable reflectors, Palaeogene subcrop stratigraphy) and practical constraints (shiptime available, parcel division of the PEZ). As such, this deliverable will support/enhance the feasibility of the planned surveys, the quality of the resulting data and their suitability for tackling the research questions addressed in the Clay Tectonics project.

References

De Batist, M. (1989). Seismostratigrafie en struktuur van het paleogeen in de Zuidelijke Noordzee – Volume 1: tekst. PhD Thesis. Rijksuniversiteit Gent, Faculteit der Wetenschappen: Gent. 107 pp.

De Clercq, M. (2018). Drowned landscapes of the Belgian Continental Shelf: implications for northwest European landscape evolution and preservation potential for submerged heritage. Unpublished PhD thesis, Ghent University, Belgium, 353 pp.

Depret-G-tec (2009). Seismisch onderzoek in Exploratiezone 4 op het Belgisch Continentaal Plat. 08D-005-Depret-SeisVibro/MA/GP/RE001, 236 pp.

Henriet, J.-P., D'Olier, B., Auffret, J.P. and Andersen, H.L. (1983). Seismic tracking of geological hazards related to clay tectonics in the Southern Bight of the North Sea, in: Symposium Engineering in Marine Environment. pp. 1.5-1.15.

Henriet, J.P., De Batist, M., Van Vaerenbergh, W. and Verschuren, M. (1988). Seismic facies and clay tectonic features of the Ypresian clay in the southern North Sea. Bull. Belg. Ver. Geologie = Bull. Soc. Belg. Geol. 97(3-4): 457-472.

Henriet, J.-P., De Batist, M. and Verschuren, M. (1991). Early fracturing of Palaeogene clays, southernmost North Sea: relevance to mechanisms of primary hydrocarbon migration, in: Spencer, A.M. (Ed.) Generation, accumulation, and production of Europe's hydrocarbons. Special publication of the European Association of Petroleum Geoscientists, 1: pp. 217-227.

Le Bot, S., Van Lancker, V., Deleu, S., De Batist, M. and Henriet, J-P. (2003). Tertiary and Quaternary Geology of the Belgian Continental Shelf. Science Policy Office, Brussels, Belgium, 76 pp.

Mathys, M., Van Lancker, V., Versteeg, W. and De Batist, M. (2009). Wetenschappelijke begeleiding en geïntegreerde interpretatie van seismisch onderzoek en trilboringen in Exploratiezone 4 op het Belgisch Continentaal Plat. Agentschap voor Maritieme Dienstverlening en Kust, afdeling Kust, 148 pp.

Van Lancker, V., Kapasakali, D., Mestdagh, T., Montereale Gavazzi, G. and the Shipboard Scientific Party (2022). RV Belgica Cruise report ST2216, period 4-8/7/2022. Belspo and Royal Belgian Institute of Natural Sciences, OD Nature, 33 pp.

Verschuren, M. (1992). Een integrale 3D benadering van kleitektonische vervormingen en de ontwikkeling van een nieuwe 3D oppervlaktemodelleringsmethode = An integrated 3D approach to clay tectonic deformation and the development of a new 3D surface modelling method. PhD Thesis. Universiteit Gent: Gent. 359 pp.

Verschuren, M. (2019). Outcrop evidence of polygonal faulting in Ypresian marine clays (Southern North Sea Basin) leads to a new synthesis. Mar. Geol. 413: 85-98.

Zurita Hurtado, O. and Missiaen, T. (2016). IWT SBO PROJECT 120003 “SEARCH”: Archaeological heritage in the North Sea. Scientific results on (sub-)seafloor offshore imaging (WP 1.3.4). 57 pp. + Annexes.