



HAL
open science

Contribution of high-resolution 3D seismic near-seafloor imaging to reservoir-scale studies: application to the active North Anatolian Fault, Sea of Marmara

Y. Thomas, B. Marsset, G.K. K Westbrook, Céline Grall, L. Géli, P Henry, G. Çifçi, A. Rochat, H. Saritas

► To cite this version:

Y. Thomas, B. Marsset, G.K. K Westbrook, Céline Grall, L. Géli, et al.. Contribution of high-resolution 3D seismic near-seafloor imaging to reservoir-scale studies: application to the active North Anatolian Fault, Sea of Marmara. *Near Surface Geophysics*, 2012, 10 (4), pp.291 - 301. 10.3997/1873-0604.2012019 . hal-03455599

HAL Id: hal-03455599

<https://hal.science/hal-03455599v1>

Submitted on 1 Dec 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**Contribution of high-resolution 3D seismic imaging to fine-scale studies:
application to the active North Anatolian Fault, Sea of Marmara**

Y. Thomas^{1,*}, B. Marsset¹, G.K. Westbrook¹, C. Grall^{1,2}, L. Géli¹, P. Henry², G. Cifçi³, A.
Rochat¹, H. Saritas³

¹ *Ifremer - French Research Institute for Exploration of the Sea, Marine Geosciences, Plouzané, France*

² *Aix-Marseille Univ., CEREGE, CNRS, Marseille, France*

³ *Institute of Marine Sciences and Technology, Marine Geophysics, Izmir, Turkey*

* thomasy@ifremer.fr

LIST OF KEYWORDS

3D seismic imaging, High Resolution, Sea of Marmara.

ABSTRACT

High Resolution (HR) marine seismic acquisition contributes to numerous researchfields. The vertical resolution is of metric to sub-metric scale in order to study geological processes at a short time scale or to characterise small objects. 3D seismic imaging allows optimal resolution to be reached whereas 2D images are blurred mainly by side effects. Developed for the oil industry decades ago and tailored to the exploration for hydrocarbon reservoirs, 3D seismic, as applied to higher resolution targets, is more recent. Available technological advances in acquisition have allowed research institutes to develop innovative high-resolution 3D marine seismic systems tailored to these targets.

The seismic survey carried out in 2009 on the Western High, Sea of Marmara, illustrates the value of 3DHR imaging. Since the destructive İzmit earthquake in 1999, an intensive international research effort has demonstrated that the Western High is one of the key structures for assessing the processes of deformation related to the North Anatolian Fault (NAF). The 30-km² 3DHR survey centred on the main NAF was acquired using a dual streamers - dual source-array configuration. In spite of the minimal 3D processing sequence that was applied to the data, the fine imaging of the seabed and of the sedimentary stratigraphy and structure is incomparably better than 2D HR seismic. Comparison with an AUV multi-beam bathymetric survey carried out at the same location enables the limits of the vertical resolution of the seismic data to be assessed. The lateral resolution is better than 25 metres at the seabed. The 3D HR seismic data highlight the interplay between tectonic processes and stratigraphy. In particular, differential uplift leads to syntectonic deposition and submarine slides. The widespread occurrence of gas in the sedimentary sequence is clearly shown by anomalously high seismic amplitude. 3D imaging of these high amplitudes enables the identification of the pathways through faults and permeable units that gas takes as it migrates to the seabed.

INTRODUCTION

Major marine research fields in the environment, palaeoclimatology, geological hazard or mineral resources need High Resolution (HR) data to observe short time-period phenomena (e.g. Mahieux *et al.*, 1998; Berné *et al.*, 2004) or small objects (Vardy *et al.*, 2008) and to understand and quantify sedimentary processes at the metric scale. Conventional seismic surveys carried out for oil exploration purposes may reach 25 m lateral resolution and 6 m vertical resolution. Using a tailored seismic acquisition configuration and appropriate processing, lateral resolution from HR seismic surveys ranges from 4 to 20 m and vertical resolution from 1 to 5 m, whereas Very High Resolution (VHR) surveys aim at decimetre resolution (table 1).

The optimal lateral resolution for a given seismic layout may only be reached using a 3D seismic survey (Cartwright and Huuse, 2005). Reflections from out-of-the-plane, which are considered to be noise in 2D processing, become signal in 3D processing (French, 1974). 3D migration processing will then ensure optimal resolution by collapsing the radius of the first Fresnel zone (Sheriff, 1980). The limit of the resulting horizontal resolution is a function of the dominant wavelength, the depth of the reflection point and the survey aperture width (Chen and Schuster, 1999).

3D imaging has brought unmatched definition of geological structures, thus increasing the quantitative characterisation of sediment properties with the combination of seismic data and *in situ* measurements. Initiated several decades ago by the oil industry, marine 3D seismic acquisition has today become an acquisition standard. Following the current trend to achieve higher resolution, the oil industry still makes substantial investments in 3D marine seismic research and development (Long and Buchan, 2004; Carlson *et al.*, 2007; Soubaras and Dowle, 2010). 3D HR acquisition follows the same rules as 3D exploration seismic; however improving the final resolution requires higher resolution sources and more closely spaced receivers. The price for higher resolution is therefore lower penetration and smaller surveyed areas limited to several tens km².

The objective of this contribution is to highlight the recent effort made by the scientific community to develop 3D HR and VHR facilities tailored to their research fields. The first part recalls the fundamentals of the 3D technique as applied to a HR seismic survey and recently developed academic 3D seismic acquisition systems for high-resolution imaging are examined. The second part illustrates the benefits of 3D versus 2D through a HR seismic data set acquired on the Western High in the Marmara Sea as part of an international research effort to assess the seismic hazard in the area. This illustration focuses on structures and stratigraphic features related to the activity of the North Anatolian Fault.

3D HIGH AND VERY HIGH RESOLUTION SEISMIC ACQUISITION

The aim of a 3D acquisition system is to obtain a volume of amplitude response, free from artefacts, with the optimal lateral resolution allowed by the frequency content of the seismic source and by the seismic layout. Valid considerations for any 3D survey should therefore include:

- 1) adequate spatial sampling to prevent spatial aliasing (Sheriff, 1991),
- 2) adequate accuracy of the source and receiver positioning consistent with the expected lateral resolution (Archer *et al.*, 1999),
- 3) ability to obtain a uniform fold to avoid artefacts generated by an uneven survey footprint (Gesbert, 2002),
- 4) adequate length of the streamers which should be long enough to enable the determination of seismic velocities (Dix, 1955),
- 5) homogeneity of the seismic data throughout the survey in terms of signal to noise ratio and frequency content.

Most of these considerations bring critical constraints to HR and VHR 3D surveys. Spatial sampling to prevent aliasing requires close streamer spacing, which in turn makes it difficult to deploy long streamers (Fig. 1). Positioning accuracy becomes paramount in the dynamic marine environment to attain the desired high resolution.

Tidal variations have to be corrected for in HR surveys, while centimetre motion of source and receivers have to be compensated for in VHR applications (Wardell *et al.*, 2002; Vardy *et al.*, 2008). Changes over time of the water column velocity have also to be monitored (MacKay *et al.*, 2003). Source and receivers have to be towed at a shallow water depth to preserve the high frequency content of seismic signal, making HR and VHR 3D surveys highly sensitive to the sea conditions.

3D academic seismic layouts (table 2) range from almost industrial multi-streamer configuration (Mutter *et al.*, 2009) down to VHR systems of decimetre resolution (Gutowski *et al.*, 2008; Vardy *et al.*, 2008). The scope of scientific applications is broad: imaging of the crustal mid-ocean ridge (Mutter *et al.*, 2009), fluid flow through sub-seabed sediments and gas hydrates (Plaza-Faverola *et al.*, 2011; Perez-Garcia *et al.*, 2011), active deformation zones (Scheidhauer *et al.*, 2005; Crutchley *et al.*, 2011), shallow-water engineering (Vardy *et al.*, 2008, 2011), and archaeological studies (Plets *et al.*, 2009; Müller *et al.*, 2009). Whereas most of these systems were developed in the framework of research programs, the P-cable project (University of Tromsø, National Oceanography Centre and IFM GEOMAR; Planke *et al.*, 2004) has reached an almost industrial level, with numerous significant HR applications (Petersen *et al.*, 2010; Bangs *et al.*, 2011; Crutchley *et al.*, 2011; Perez-Garcia *et al.*, 2011; Plaza-Faverola *et al.*, 2011).

Since 1997, the French Marine Research Institute (Ifremer) has been involved in marine 3D VHR seismic imaging to study the fine-scale geometry of recent deposits (Marsset, 2001; Marsset *et al.*, 2002; Marsset *et al.*, 2004). A 3D HR system was later developed to carry out larger scale surveys (Thomas *et al.*, 2004; Meunier *et al.*, 2004). Recent applications have included environmental studies, geological hazards (Nouzé *et al.*, 2004), sedimentary processes and fluid flows (Hustoft *et al.*, 2007). Target sizes are several tens of km² with theoretical resolution limits of 12 m horizontally and 3.5 m vertically (table 2).

The following 3DHR seismic example, acquired in the Sea of Marmara, is presented to illustrate and to evaluate the advantages of 3D HR versus 2D HR seismic to study tectonic features and fluid flow in the vicinity of the active North Anatolian Fault.

3D HR MARMARA SURVEY

Geological Context

The North Anatolian Fault (NAF) is the major plate boundary between Anatolia and Eurasia (Şengör *et al.*, 1985; Armijo *et al.*, 1999; Le Pichon *et al.*, 2001). The northernmost branch of the NAF runs through the Sea of Marmara (Parke *et al.*, 1999; Grall *et al.*, 2012) where basins and highs are associated with the present-day fault network (Fig. 2). The Mw 7.4 İzmit earthquake devastated part of north-western Turkey in 1999 (Barka, 1999), and raised great concern about the probability of another earthquake in the Istanbul region populated by more than 12 million inhabitants. As a result, extensive research efforts have been made to improve the understanding of the seismo-tectonics in this region, including several scientific cruises since 2000 (Henry *et al.*, 2007; Laigle *et al.*, 2008; Shillington *et al.*, 2009).

The occurrence of gas hydrates and the composition of the fluids actively being emitted on the Western High, (Fig. 2) opened new perspectives on the processes that are active close to the NAF (Géli *et al.*, 2008; Bourry *et al.*, 2009; Zitter *et al.*, 2008; Tryon *et al.*, 2010). This feature was therefore selected for the deployment of a 3D high-resolution seismic survey to investigate the sub-seabed distribution of fluid conduits and the stratigraphic / structural framework. The location of the 3D survey was defined according to the results of the previous 2D HR survey carried out in this area as part of the Turkish-American Marmara Multichannel research project (Shillington *et al.*, 2009).

Methodology

The 3DHR seismic source consists of small volume air guns (mini-GI gun, 110 Hz dominant frequency) able to produce a repetitive signal but with the reduction of the bubble oscillations common in traditional air guns. Two source arrays, 12.5 m apart, are fired alternately in order to halve the cross-line sampling interval for a given number of streamers (Fig. 3; table 2, HR3D system). Two streamers are deployed 25 m apart using two eight-meter long rigid bars fixed to the vessel's frame. Each streamer hosts 48 channels, with a 6.25 m group interval. This seismic layout prevents spatial aliasing of dipping events up to 40° in the in-line direction and 20° in the cross-line direction (Fig. 1).

Positioning of sources and receivers is determined using the DGPS position and gyrocompass of the vessel, and magnetic compasses from 3 depth controllers along each streamer. Given the accuracy of these sensors and the short length of the streamers (400 meters), receiver positions are calculated within an accuracy of 2 m at the head of the streamers, to 4 m at the tail. Source positions are measured to an accuracy of 1 metre. This precision in positioning is consistent with the expected resolution; positioning accuracy falls between $\lambda/4$ and $\lambda/3$ (where λ is the dominant wavelength) which is acceptable to preserve the main frequency content of the seismic data. A major drawback is that this approach does not allow operating longer streamers, as accuracy will become poorer.

To obtain a uniform fold (around 20) using a bin size of 6.25 x 6.25 m, acquisition lines are sailed 25 m apart (Fig. 3). Data editing and updating of the fold map are performed at the end of each line to assess the homogeneity of the data and to adjust the acquisition program to acquire additional in-fill lines to cover gaps in the fold map.

Data set and processing

The 3D HR survey of the MARMESONET cruise covered an area of 3 x 11 km² and was centred on and parallel to the main North Anatolian Fault where it cuts the Western High (Fig. 2). The water depth ranges from 500 m near the top of the Western High to 800 m in the NAF axial valley (Fig. 2). The east-west orientation of seismic lines was dictated by the presence of the maritime corridor linking the Dardanelle to the Bosphorus straits. The 3D HR survey was completed in 9 days of acquisition. It is worth noting that a surface current led to a slight drift of the streamers relative to the track (< 5°) and thus to an overlap of the CMP lines for track lines 25 m apart. As a result of this streamer drift, very few in-fill lines were required to fill fold gaps. A total of 135 lines were recorded (20 million traces), including 5 re-shoot lines, and 7 in-fill lines.

Prior to processing, the seismic data were edited for frequency content and signal-to-noise ratio. The immersion of the streamers was monitored using the data from the depth controllers but also from the position of the notch frequency in the seismic signal. This screening identified faulty seismic traces, and 1.6 % of the total number of traces were thus rejected for various reasons, such as: out-of-range streamer immersion, electronic failure, high noise from nearby ships, bad sea conditions, or source breakdown.

The shot gathers were then processed, including corrections for source delay variations and band-pass filtering (20-250 Hz). After positioning processing and binning using the real positions of sources and receivers, constant water velocity Normal Move Out was applied followed by 3D stacking and a two-pass constant velocity Stolt migration (Fig. 4).

The imaging processing requires the knowledge of the velocity distribution within the sediments to better focus the seismic data. As source-receiver offsets of the 3D seismic layout are too short with respect to the water depth, attempts to constrain the velocity field using 2D long offset HR seismic data were carried out. This was achieved by acquiring 2D HR seismic data during the PirMarmara cruise of the Turkish

R/V K. Piri Reis (DEU, Izmir, 2010) using a 1500 m long streamer and a 6.25 metres receiver group interval. This 2D data set allowed the velocity of the upper sedimentary cover to be assessed with a relatively low mean interval velocity of 1650 m/s. A three-layer velocity model, 1515 m/s for the water column, 1650 m/s for the upper sedimentary cover, and a constant gradient of 500 m/s increasing for the underlying sediments was then employed to perform 3D stacking prior to constant velocity two-pass Stolt migration (Fig. 4).

Results and discussion

Resolution

The sea-bottom 3D seismic amplitude map demonstrates the ability of 3D data to properly focus the seismic signals both in shape and in amplitude. The chaotic stack amplitude data (Fig. 5A), related to diffractions, are not properly focused in 2D (2D in-line migration, Fig. 5B). Two-pass 2D migration collapses properly the diffractions on the sea-bottom, as emphasised by the seismic amplitude map (Fig. 5C) and the seismic bathymetry (Fig. 5D).

Comparisons between micro-bathymetry acquired with an AUV and the seismic bathymetry provided the opportunity to evaluate the resolution of the seismic data. The AUV was operated at an altitude over the seafloor of 70 meters; its 200 kHz multibeam provides a lateral resolution of 2 meters and a depth resolution of one centimeter:

- The first area of comparison presents small circular depressions from the AUV map (Fig. 6A; see Fig. 5D for location) that are not visible on the seismic bathymetry (Fig. 6B). These structures have a diameter of around 25 meters; their maximal depressions range between 25 to 50 centimeters. The depth sampling of the seismic survey around 0.4 m (for time sampling of 0.5 ms and velocity of 1515 m/s) does not allow these depressions to be imaged.

- The second area of comparison was selected on the mounds closed to the NAF (see Fig. 5D for location). Most of the structures shown by the AUV bathymetry (Fig. 6C) are well imaged by the 3D seismic HR data (Fig. 6D). Structures on the crest of the mounds, as close as 25 meters and with only 1 meter of local variation in depth, are distinguished well in both data sets. Consequently, the lateral resolution of the 3D HR seismic is shown to be between the 12 m theoretical resolution limit and the 25 m resolution obtained for these features.

Seismic sections

The results of 2D migration of a stacked section shows that 2D seismic data do not allow proper imaging in comparison with the results of 3D migration (Stolt two-pass 2D migration) of the same section (Fig. 7). Out-of-plane reflections that cannot be focused are obvious after 2D processing, whereas the 3D migration shows faults, amplitude anomalies, and stratigraphy in great detail.

The depth penetration of the HR seismic data from the Western High is limited by strong impedance contrasts, strong deformation and steeply dipping horizons. The resulting penetration is strongly variable: from no penetration on the NW outcrop down to 600 ms TWT in the SW corner of the survey, and primarily depends on the thickness of the gently deformed upper sedimentary cover and on the degree of deformation of the deeper sediments (Fig. 8).

The imaging of the deeper structures with relatively high dips could be improved by using more advanced imaging methods such as 3D DMO correction, 3D finite difference migration or 3D Kirchhoff pre-stack migration. However, this requires a well-constrained 3D velocity model, and despite the good quality of the 2D long offset data set, reliable seismic velocities in the deeper structures could not be obtained, due to strong out-of-plane reflected and diffracted acoustic energy. This limitation in imaging

complex 3D structures with velocity variation is common to any 3D seismic layout operating with too short an offset with respect to the target depth.

The illustrations from the Marmara data set are, therefore, limited to the upper sedimentary sequence where 3D HR imaging is of excellent quality.

Geological insights

The sea-bottom amplitude is relatively uniform except on the northern side of the NAF where two localised areas of high amplitude are associated with the outcrops of consolidated material, which are also well expressed as positive features in the seismic bathymetry (Fig. 5C-5D). The structure on the NW border of the survey is related to folds that bring to the surface consolidated sedimentary sequences older than those covering most of surveyed area. The second high amplitude area is located close to the NAF (Fig. 5C, in the middle of the survey). It is related to the presence of authigenic carbonate deposits and gas hydrates reported at this site by Tryon *et al.* (2010). The seismic bathymetry also highlights the different networks of faults on the Western High along the NAF (Fig. 5D).

Most of the upper coherent sedimentary sequence north of the NAF, which reaches up to 400 ms TWT thickness shows thinning, on-lapping and, locally, erosive unconformities (Figs. 7B and 8). South of the NAF, the coherent sequence of sedimentary layers is less than 150 ms TWT thick, where it lies above the crest of an anticline that runs parallel to the NAF (Fig. 5D), but thickens southwards (Fig. 8). This, together with the onlapping nature of many of the layers, indicates syntectonic deposition on the flanks of this growing anticline.

Evidence of submarine slides is widespread, with numerous episodes of slide occurrence. The broken strata at the top of a submarine slide are depicted clearly in the 3D processed image of Figure 7B. The anticline south of the NAF, also exhibits abundant evidence of sliding from both its flanks, some recent and some buried under a thin cover of sediment.

The strong shallow reflector H1, which is prominent across nearly all of the 3D survey, has a high amplitude and negative polarity (opposite to that of the seabed), which varies little in relation to the reflector's position or dip (Figs. 7B and 8). This is likely due to a layer of a different lithology and high porosity resulting in lower acoustic impedance than the overlying sedimentary strata. Although this negative polarity may also be locally enhanced by the presence of gas, the uniformity of the phase and of the amplitude of the reflector, and its correlation with the detachment surfaces of the slides (Fig. 7B) support an interpretation of a layer of high porosity supported by over-pressure as the cause of the negative polarity reflector.

Normal faults with a NW-SE strike pervade the eastern part of the 3D box (Fig. 5D). Examples of these normal faults are presented in Figures 8 and 9. Many of the faults outcrop at the seabed, where they can be followed in the bathymetry (Fig. 5D). More than half of the faults have their upper termination at or beneath reflector H1. The faults sole out in horizons between 150 and 200 ms beneath the seabed (Fig. 8).

It has been established from previous observations and measurements at the seabed that water and gas are being expelled into the Sea along the main Marmara fault zone (Zitter *et al.*, 2008). The 3D HR seismic volume provides evidence of past fluid movement and present occurrence of gas beneath the seabed. Gas is widespread in the area and can be recognised from its effect on reflectors, locally increasing amplitude of negative polarity where the gas occupies traps, typically in small anticlines (Fig. 8). Although the observation is not obvious on seismic sections, local reflection brightening caused by gas can be seen on seismic amplitude maps along horizons extracted from the 3D volume. Horizon H2 (75 to 100 ms bsf, Fig. 8), which otherwise has a relatively weak amplitude, displays strong brightening caused by gas distributed along the NW-SE trends of the faults, as well as by gas occupying the crests of anticlines (Figs. 8 and 10).

CONCLUSIONS

Technological advances over recent years have allowed the development of efficient 3D marine seismic systems dedicated to High and Very High Resolution seismic surveys. The quality of the achieved 3D seismic imaging allows fine-scale stratigraphic and tectonic features to be recognised and analysed. This is crucial to assess complex interplaying of geological processes at high temporal resolution.

The seismic survey carried out in the Marmara Sea in 2009 illustrates the benefit of 3DHR seismic imaging of a complex geological structures, such as the Western High, cut by the North Anatolian Fault. One of the topics arising from more than ten years of intensive surveys in the area has been the temporal and spatial connection between fluid and seismic activity, especially in terms of earthquake monitoring. The preliminary analysis of the 3DHR data set has showed that understanding of the area derived from 2D seismic sections was badly constrained and often misleading, because of the poor imaging of three dimensional structures. The 3DHR survey, however, allowed the following features to be identified in the upper sedimentary sequence:

- the interplay between tectonic processes and stratigraphy, such as syntectonic deposition of sedimentary units and widespread submarine sliding caused by differential tectonic uplift of the seabed;

- the widespread occurrence of gas, trapped in the crests of anticlines and adjacent to faults through which gas is migrating and following pathways to the seabed through permeable strata and faults.

Further interpretation of this data set, in progress, will provide keys to unravel the sequence of tectonic events that brought about the existence of the NAF in its present situation and to understand the processes involved in the deformation associated with the activity of the NAF. Understanding observations of fluid expulsion from the seabed in relation to the deformational processes will be used to evaluate the

potential of monitoring fluid movement in the assessment of seismic hazard in the Sea of Marmara.

ACKNOWLEDGEMENTS

We wish to acknowledge Captain and crew of the R/V *Le Suroît*, and Genavir seismic team for their support in achieving 3D survey through the Marmara maritime traffic. The support of the Turkish coast guards of the Sea of Marmara was also very valuable. This support at sea and the setting of the final location of the 3D survey using previous Turkish seismic data were achieved thanks to the Seislab team of the Dokuz Eylül University (Izmir). The Marmara-DM cruise was supported by ESONET NoE, Network of Excellence, coordinated by IFREMER and co funded by EU as part of FP6 (2009). We also thank the reviewers for their comments, which have helped to improve the manuscript.

TABLES

Table 1. Seismic resolution

Resolution	Dominant frequency range	Lateral resolution	Vertical resolution
"Exploration"	30–75 Hz	> 20 m	> 5 m
High Resolution	80–375 Hz	19 - 4 m	4.5 - 1 m
Very High Resolution	> 375 Hz	< 4 m	< 1 m

Definition of the seismic resolution ranges as stated in the article; theoretical lateral resolution limit is given as the main wavelength of the seismic signal (λ) and theoretical vertical resolution limit as the quarter of λ .

Table 2. 3D academic marine acquisition devices and their main characteristics

Device	Source	Receiver	Resolution	Target
3D CHIRP (NOC)	Frequency modulated f = [1.5 -13 kHz]	12 streamers @ 25 cm 5 traces @ 25 cm	< 10 cm	100 x 300 m ² z < 30 m
SEAMAP 3D (CAU)	Boomer f = 4.5 kHz	8 streamers @ 50 cm 4 traces @ 50 cm	10 cm	100 x 300 m ² z < 50 m
OPUS3D (RCMG)	Boomer f = 2 kHz	8 streamers @ 2 m 2 traces @ 2 m	20 cm	100 x 300 m ² z < 70 m
VHR3D (IFREMER)	Sparker 250 J f = 500 Hz	4 streamers @ 4 m 6 traces @ 2 m	75 cm	1 x 2 km ² z <100 m
3D (UNIL)	Single mini air gun f = 300 Hz	3 streamers @ 7.5 m 24 traces @ 2.5 m	1.2 m	1 x 2 km ² z <300 m
HR3D (IFREMER)	2 mini air gun arrays f = 110 Hz	2 streamers @ 25 m 24 traces @ 6 m	3.5 m	4 x 6 km ² z <1000 m
P-Cable (NOC-UiT)	2 air guns f = 90 Hz	12 streamers @ 12.5 m 8-16 traces @ 6.25 m	4 m	4 x 10 km ² z <1000 m
R/V Langseth (LDEO)	2 large air gun arrays f = 50 Hz	4 streamers @ 150 m 468 traces @ 12.5 m	7.5 m	12 x 50 km ² z >1000 m

The name of the system is followed by the research institute: NOC (The National Oceanography Centre, Southampton), CAU (Christian-Albrechts-University, Kiel), RCMG (Renard Centre of Marine Geology, Gent), IFREMER (French Research Institute for Exploration of the Sea), UNIL (University of Lausanne), UiT (University of Tromsø), LDEO (Lamont-Doherty Earth Observatory, Columbia University); source: type of source and dominant frequency ("2 air gun arrays" means shooting alternately); receiver: number and spacing of streamers, number and spacing of seismic groups; resolution stands for vertical resolution limit; target: example of typical survey size and penetration (rough estimation as it is also function of the geology and of the water depth).

REFERENCES

- Archer S., Gikas V., Pinel C., Ridyard D. and Cross P. 1999. Spatially and temporally correlated navigation errors: how do they manifest themselves in seismic data? *First Break* **17**, 355–362.
- Armijo R., Meyer B., Hubert A. and Barka A. 1999. Westward propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics. *Geology* **27**, 267–270.
- Bangs N.L.B., Hornbach M.J. and Berndt C. 2011. The mechanics of intermittent methane venting at South Hydrate Ridge inferred from 4D seismic surveying. *Earth Planetary Science Letters* **310**, 105–112.
- Barka A. 1999. The 17 August 1999 İzmit earthquake. *Science* **285**, 1858–1859.
- Berné S., Rabineau M., Flores J.A. and Sierro F.J. 2004. The Impact of Quaternary Global Changes on Strata Formation: Exploration of the Shelf Edge in the Northwest Mediterranean Sea. *Oceanography* **17**, vol. 4, 92–103.
- Bourry C., Chazallon B., Charlou J.L., Donval J.P., Ruffine L., Henry P., Géli L., Çağatay M.N., İnan S. and Moreau M. 2009. Free gas and gas hydrates from the Sea of Marmara, Turkey: Chemical and structural characterization. *Chemical Geology* **264**, 197–206.
- Carlson D., Long A., Söllner W., Tabti H., Tenhamn R. and Lunde N. 2007. Increased resolution and penetration from a towed dual-sensor streamer. *First Break* **25**.
- Cartwright J. and Huuse M. 2005. 3D seismic technology: the geological 'Hubble'. *Basin Research* **17**, 1–20.
- Chen J. and Schuster G.T. 1999. Resolution limits of migrated images. *Geophysics* **64**, 1046–1053.
- Crutchley G. J., Berndt C., Klaeschen D. and Masson D. G. 2011. Insights into active deformation in the Gulf of Cadiz from new 3D seismic and high-resolution bathymetry data. *Geochemistry Geophysics Geosystems* **12**.

- Dix C.H. 1995. Seismic velocities from surface measurements. *Geophysics* **20**, 68–86.
- French W.S. 1974. Two-dimensional and three-dimensional migration of model-experiment reflection profiles. *Geophysics* **39**, 265–277.
- Géli L., Henry P., Zitter T., Dupré S., Tryon M., Çağatay M.N., Mercier De Lepinay B., Le Pichon X., Şengör A.M.C., Görür N., Natalin B., Uçarkuş G., Özeren S., Volker D., Gasperini L., Burnard P., Bourlange S. and the Marnaut Scientific Party. 2008. Gas emissions and active tectonics within the submerged section of the North Anatolian Fault zone in the Sea of Marmara. *Earth and Planetary Science Letters* **274**, 34–39.
- Gesbert S. 2002. From acquisition footprints to true amplitude. *Geophysics* **67**, 830–839.
- Grall C., Henry P., Tezcan D., Mercier de Lepinay B., Bécel A., Géli L., Rudkiewicz J.L., Zitter T. and Harnegnies F. 2012. Heat flow in the sea of Marmara Central Basin: Possible implications for the tectonic evolution of the North Anatolian fault. *Geology* **40**, 3–6.
- Gutowski M., Bull J.M., Dix J.K., Henstock T.J., Hogarth P., Hiller T., Leighton T.G. and White P.R. 2008. Three-dimensional high-resolution acoustic imaging of the sub-seabed. *Applied Acoustics* **69**, 412–421.
- Henry P. and the Marnaut Scientific Party. 2007. Cruise Report, Marnaut Expedition, 85 pp.
- Hustoft S., Mienert J., Bünz S. and Nouzé H. 2007. High-resolution 3D-seismic data indicate focused fluid migration pathways above polygonal fault systems of the mid-Norwegian margin. *Marine Geology* **245**, 89–106.
- Laigle M., Bécel A., de Voogd B., Hirn A., Taymaz T., Özalaybey S. and members of the SEISMARMARA Leg1 Team. 2008. A First deep seismic survey in the Sea of Marmara: Deep basins and whole crust architecture and evolution. *Earth and Planetary Science Letters* **270**, 168–179.

- Le Pichon X., Şengör A.M.C., Demirbağ E., Rangin C., İmren C., Armijo R., Görür N., Çağatay N., Mercier de Lépinay B., Meyer B., Saatçılar R. and Tok B. 2001. The active Main Marmara Fault. *Earth and Planetary Science Letters* **192**, 595–616.
- Long A. and Buchan I. 2004. Seismic frequency bandwidth constraints in deepwater survey locations. *First Break* **22**.
- MacKay S., Fried J. and Carvill C. 2003. Water-column changes pose seismic challenges. *Offshore* **63**, 114–116.
- Mahieux G., Proust J.N., Tessier B. and DeBatist M. 1998. Comparison between high-resolution seismic and sequence stratigraphic approaches applied to the upper Jurassic deposits of the Dover Strait area (Northern France). *Marine and Petroleum Geology* **15**, 329–342.
- Marsset B. 2001. Very High Resolution marine 3D seismic method for detailed site investigation. Final report, Contract MAST3 MAS3-CT97-0121.
- Marsset T., Marsset B., Thomas Y. and Didailier S. 2002. Very High Resolution 3D seismic: a new imaging tool for sub-bottom profiling. *Comptes Rendus Geosciences* **334**, 403–408.
- Marsset T., Marsset B., Thomas Y., Cattaneo A., Thereau E., Trincardi F. and Cochonat P. 2004. Analysis of Holocene sedimentary features on the Adriatic shelf from 3D very high-resolution seismic data (Triad survey). *Marine Geology* **213**, 73–89.
- Meunier J., Thomas Y. and Marsset B. 2004. New tools for Ocean Survey: The Challenge of High Resolution. *Sea Technology*, April 2004.
- Mutter J.C., Carbotte S., Nedimovic M., Canales J.P. and Carton H. 2009. Seismic Imaging in Three Dimensions on the East Pacific Rise. *Eos Trans. AGU* **90**, p. 374.
- Müller C., Woelz S., Ersoy Y., Boyce J., Jokisch T., Wendt G. and Rabbel W. 2009. Ultra-high-resolution marine 2D-3D seismic investigation of the Liman

- Tepe/Karantina Island archaeological site (Urla/Turkey). *Journal of Applied Geophysics* **68**, 124–134.
- Nouzé H., Contrucci I., Foucher J.P., Marsset B., Thomas Y., Thereau E., Normand A., Le Drezen E., Didailier S., Regnault J.P., Le Conte S., Guidart S., Lekens W., Dean S. and Throo A. 2004. First results of a geophysical survey on the northern flank of the Storegga slides (Norway). *Comptes Rendus Geoscience* **336**, 1181–1189.
- Parke J.R., Minshull T.A., Anderson G., White R.S., McKenzie D., Kuscu I., Bull J.M., Görür N. and Şengör A.M.C. 1999. Active faults in the Sea of Marmara, western Turkey, imaged by seismic reflection profiles. *Terra Nova* **11**, 223–227.
- Perez-Garcia C., Berndt C., Klaeschen D., Mienert J., Haffert L., Depreiter D. and Haeckel M. 2011. Linked halokinesis and mud volcanism at the Mercator mud volcano, Gulf of Cadiz. *Journal of Geophysical Research* **116**.
- Petersen C.J., Bünz S., Hustoft S., Mienert J. and Klaeschen D. 2010. High-resolution P-Cable 3D seismic imaging of gas chimney structures in gas hydrated sediments of an Arctic sediment drift. *Marine and Petroleum Geology* **27**, 1981–1994.
- Planke S., Mienert J., Berndt C. and Åsheim S., 2004. "Ny metode for innsamling av høyoppløselig 3D seismikk", *Geo*, September 2004.
- Plaza-Faverola A., Bünz S. and Mienert J. 2011. Repeated fluid expulsion through sub-seabed chimneys offshore Norway in response to glacial cycles. *Earth and Planetary Science Letters* **305**, 297–308.
- Plets R.M.K., Dix J.K., Adams J.R., Bull J.M., Henstock T.J., Gutowski M. and Best A.I. 2009. The use of a high-resolution 3D Chirp sub-bottom profiler for the reconstruction of the shallow water archaeological site of the Grace Dieu (1439), River Hamble, UK. *Journal of Archaeological Science* **36**, 408–418.

- Scheidhauer M., Marillier F. and Dupuy D. 2005. Development of a system for 3D high-resolution seismic reflection profiling on lakes. *Marine Geophysical Researches* **26**,183–195.
- Şengör A.M.C., Görür N. and Şaroğlu F. 1985. Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: *Strike-slip deformation, basin formation, and sedimentation* (eds Biddle K.D. and Christie-Blick N.), pp. 227–264. Spec. Publ. SEPM **27**.
- Sheriff R.E. 1980. Nomogram for Fresnel-zone calculation. *Geophysics* **45**, 968–972.
- Sheriff R.E. 1991. Encyclopedic dictionary of applied geophysics: *Society of Exploration Geophysicists*, 3rd edition.
- Shillington D.J., Dondurur D., Seeber L., Steckler M.S., Sorlien C.C., Diebold J.B., Çifçi G., Gurcay S., Okay S., İmren C., Kurt H., Timur D. and Demirbağ E. 2009. Gas slumps and faulting in the Marmara Sea: new results from TAMAM high-resolution seismic reflection data. *American Geophysical Union*, Fall Meeting.
- Soubaras R. and Dowle R. 2010. Variable-depth streamer - a broadband marine solution. *First Break* **28**.
- Thomas Y., Marsset B., Didailier S., Regnault J.P., Le Conte S., Le Roux D., Farcy P., Magueur M., Viollette P., Herveou J., Guedes J.C., Jegot B., Gascon G., Prud'homme C., Nouzé H., Thereau E., Contrucci I. and Foucher J.P. 2004. High Resolution marine 3D seismic: A new surveying tool for the Scientific Community. *Comptes Rendus Géoscience* **336**, 579–585.
- Tryon M.D., Henry P., Çağatay M.N., Zitter T.A.C., Géli L., Gasperini L., Burnard P., Bourlange S. and Grall C. 2010. Pore fluid chemistry of the North Anatolian Fault Zone in the Sea of Marmara: A diversity of sources and processes. *Geochemistry Geophysics Geosystems* **11**.
- Vardy M.E., Dix J.K., Henstock T.J., Bull J.M. and Gutowski M. 2008. Decimetre-resolution 3D seismic volume in shallow water: A case study in small-object detection. *Geophysics* **73**, B33–B40.

Vardy M.E., Bull J.M., Dix J.K., Henstock T.J., Plets R.M.K., Gutowski M. and Hogarth

P. 2011. The geological 'Hubble': A reappraisal for shallow water. *The Leading Edge*, February 2011, 154–159.

Wardell N., Diviacco P. and Sinceri R. 2002. 3D Pre-processing techniques for marine VHR seismic data. *First Break* **20**, 457–466.

Zitter T.A.C., Henry P., Aloisi G., Delaygue G., Çağatay M.N., Mercier de Lepinay B., Al-Samir M., Fornacciari F., Tesmer M., Pekdeger A., Wallmann K. and Lericolais G. 2008. Cold seeps along the main Marmara Fault in the Sea of Marmara (Turkey). *Deep Sea Research Part I* **55**, 552–570.

LIST OF CAPTIONS

FIGURE 1. Maximum incidence angle without spatial aliasing function of frequency for a homogenous medium; curves are computed for various spatial samplings from 12.5 cm to 25 m. Seismic resolution ranges are given at the bottom of the graph (see table 1). Typical spatial sampling to avoid aliasing for dips in the 20-45° range are 12.5 to 25 m for “exploration” seismic, 3.1 to 6.25 m for High Resolution and 1 to 0.125 m for Very High Resolution. Application to the IFREMER 3DHR device (spatial samplings: 3.1 m in-line and 6.25 m cross-line; maximum seismic dominant frequency: 175 Hz): in-line dip higher than 43° are aliased (respectively cross-line dip higher than 20°).

FIGURE 2. Top Inset: map of the Sea of Marmara and the main fault segments of the NAF. In white, the Main Marmara Fault (Le Pichon *et al.*, 2001) and in black other segments of the NAF (Parke *et al.*, 1999; Grall *et al.*, 2012). TB: Tekirdağ Basin, WH: Western High, CeB: Central Basin, CH: Central High, CiB: Çınarcık Basin. Bathymetry on the Western High: location of the 3D survey (blue box 3x11 km²); white dashed line: the main dextral Marmara Fault track on the seabed; red star: site location where gas hydrates were found (Bourry *et al.*, 2009).

FIGURE 3. 3D High Resolution seismic layout (IFREMER); dual streamers 25 m apart (48 traces each, 6.25 m group interval); dual sources, 12.5 m apart, shooting alternately; track lines are 25 m apart to achieve a uniform fold of cover; spatial samplings are 6.25 m cross-line and 3.1 m in-line.

FIGURE 4. Processing sequence applied to the 3D HR Marmara seismic data set; the first step consists in constant velocity stacking and migration; 2D long offset HR seismic data (PirMarmara cruise, DEU) are used to constrain layer consistent velocities within the upper sedimentary sequence. The second step used the derived velocity model for stacking.

FIGURE 5. A) Seabed amplitude maps from 3DHR seismic, from A) stacking, B) 2D in-line migration and C) two-pass migration (in-line and cross-line). D) 3DHR seismic bathymetry from the two-pass migrated data set (illuminated from the North). Boxes

and lines show the locations of figures; white dashed line: the main Marmara Fault track on the seabed.

FIGURE 6. Seabed dip along the north-south direction (positive toward the North) of the AUV 200 kHz multibeam (A & C, bin size 2 m) and of the 3DHR seismic (B & D, bin size 6.25 m). See Fig. 5D for location of the two areas. Track-parallel artefacts are noted on the AUV map. The AA' and BB' sections compare AUV (black curve) and 3DHR (red curve) bathymetry. AA': this section crosses small-scale depressions (25 m diameter, 25-50 cm vertical depression), which are beyond the vertical resolution of the 3DHR tool. BB': this section crosses the crest of one of the seamounts with two small structures 25 m apart. Small-scale faults (vertical offset of 1 m or less) are noticed on both maps C & D.

FIGURE 7. Comparison between 2D and 3D imaging of a seismic section (for location see Fig. 5); A) 2D migration (Stolt) of the cross-line stack section. B) 2 x 2D migration (Stolt) of the 3D stack cube. The same velocity model was used for both the 2D and 3D migrations. Both north and south of the NAF, the 3D migration has clarified the stratigraphy and structural features that were not properly focused using 2D. Horizon H1 and H2 are located within the upper sedimentary cover.

FIGURE 8. Arbitrary section (top figure: location of the time slice at 880 ms, Fig. 9, and of the amplitude map, Fig. 10; bottom figure with interpretation) through the 3D seismic volume perpendicular to the NW-SE strike of the normal faults that pervade this part of the Western High (for location see Fig. 5D). The reflectors H1 and H2 occupy the top 100 ms of section on both sides of the NAF. Locally bright reflectors (indicated by asterisks) mark the occurrence of gas. Upper sediments (<200 m) are gently deformed: lower sediments show steep dips and scattering.

FIGURE 9. Time slice at 880 ms from the 3D volume of post-stack 2x2D migrated data (see location in Figure 5D). The left-hand image is uninterpreted. The right-hand image shows the line of the section shown in Figure 8, the trace of the NAF (bold dashed line)

and the NW-SE strike of the normal faults that pervade this part of the Western High. The high amplitude black horizon is the H1 horizon (negative polarity).

FIGURE 10. Seismic amplitude along the horizon H2 south of the NAF (for location see Fig. 5D). The amplitude varies greatly in response to the presence or absence of gas, showing brightening of 15 dB or more where gas is present: in the crests of anticlines and where H2 is cut by faults (Fig. 8); black dashed line: the main Marmara Fault track on the seabed.