DOI 10.4330/bgta0082

Cold seeps, active faults and the earthquake cycle along the North Anatolian Fault system in the Sea of Marmara (NW Turkey)

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(Received: July 20, 2011; accepted: November 15, 2012)

ABSTRACT After the 1999 İzmit earthquake (M_w7.4), along the North-Anatolian Fault (NAF), an increase in gas emissions from the seafloor of the Sea of Marmara was observed. Using a multidisciplinary approach, that includes a combined analysis of high-resolution marine geophysical and gas-geochemical data, we determined the character of gas/fluid emissions and their spatial relationship with tectonic structures in the Darıca Basin (Gulf of İzmit), close to the western termination of the 1999 earthquake surface rupture. Data collected during several oceanographic expeditions allowed us to investigate the fine structure of active fault branches, as well as the geochemical signature of the cold seeps. We observed that gas emissions at the seafloor of the Darıca Basin are mostly constituted by biogenic CH_4, and are aligned along strike-slip and transtensional fault segments. Although maximum CH_4 concentrations were measured in correspondence of transtensional strands, we suggest that the biogenic CH_4 emissions found along strike-slip segments, showing a relatively low gas background noise and a potential to increase during seismic events, are more suitable to study relationships between gas expulsion and the earthquake cycle.

Key words: cold seeps, earthquake cycle, İzmit earthquake, Gulf of İzmit, North Anatolian Fault (NAF), Sea of Marmara, seafloor observatories.

1. Introduction

Cold seeps are manifestations at the seafloor of endogenic gas expulsion in the form of pockmarks, mud volcanoes, carbonate crusts or patches of reduced material or brine pools (Hovland and Judd, 1988). Unlike hydrothermal vents, which are associated to volcanism, cold seeps can be found in a number of geodynamic setting, including convergent and transform margins. Another important difference between cold seeps and hydrothermal vents is that gas expulsion at cold seeps may be slow, intermittent and episodic, generally sensible to tectonic stress and seismic activity; this makes cold seeps privileged sites for monitoring seismogenic fault activity.

Increased gas emissions were actually observed along seismogenic faults, either at sea or on land, before and during earthquakes (e.g., Brown *et al*., 2005; Mazzini *et al*., 2007). One point not completely understood and still debated concerns coupling between seismic stress release and pore pressure changes during large earthquakes (e.g., Manga *et al*., 2009). Interactions between

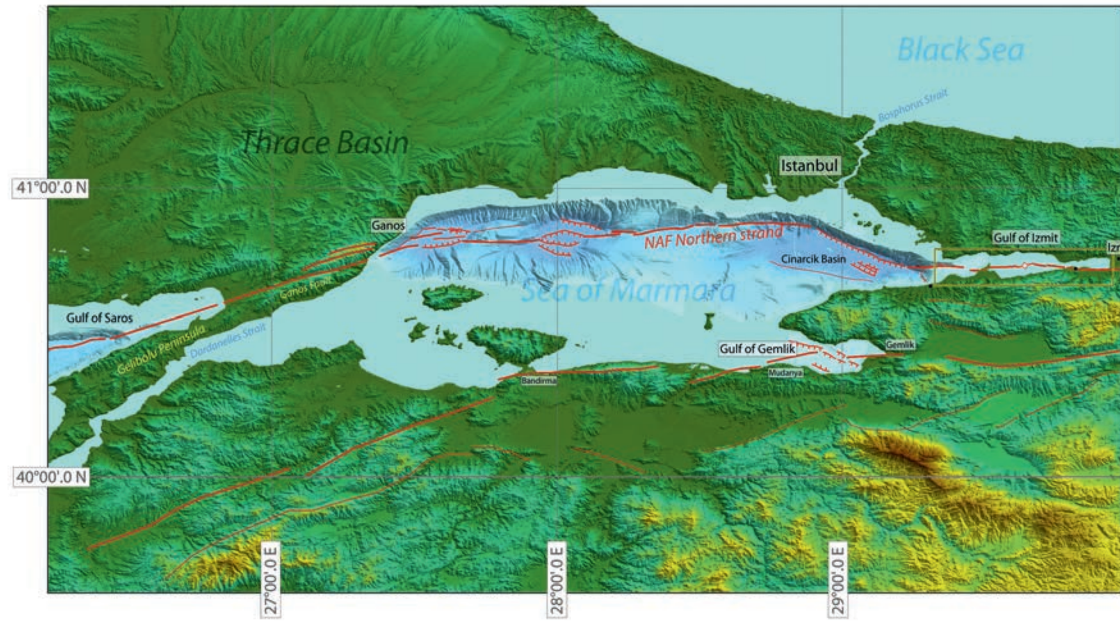

Fig. 1 - Tectonic map of the NAF in the Marmara region. The Gulf of Izmit is indicated (box). Topography is from SRTM database. Bathymetric data are from different sources, including: Le Pichon *et al*. (2001), Polonia *et al*. (2004), Gasperini *et al*. (2009). Red thick solid lines mark the NAF trace, both in the north and south strands. Position of faults in areas not included in this study is from: Sengör *et al*. (1985), Şaroglu *et al*. (1992), Le Pichon *et al*. (2001), Armijo *et al*. (2002), Gasperini *et al*. (2011b).

fluids and crustal strain (seismic and aseismic) have been widely studied on land (Muir-Wood and King, 1993; Trique *et al*., 1999), while the importance of fluids in the dynamics of submarine faults has been recognized in relatively recent times, with the progress of deep seafloor exploration (e.g., Moore *et al*., 1990; Le Pichon *et al*., 1992; Henry *et al*., 2002).

Fluid outflows associated to active faults have been observed in the Sea of Marmara along the submerged portion of the North-Anatolian Fault (NAF) northern strand (Fig. 1), where it is marked by carbonate crusts, black patches, and bacterial mats (Armijo *et al*., 2005; Geli *et al.*, 2008; Zitter *et al*., 2008). In the Marmara basins, free gas emissions are common, and appear to be influenced by the occurrence of earthquakes (Tary *et al*., 2011). Moreover, based on the analysis of high-resolution seismic reflection profiles acquired before and after the 1999 İzmit earthquake, Kusçu *et al*. (2005) reported increased post-event hydroacoustic flares likely related to gas emissions.

Due to these observations and to the high seismogenic and tsunamigenic hazard facing the highly populated coasts of the Sea of Marmara, the submerged portion of the NAF system has been identified as a natural laboratory to study relationships between fluids and seismicity, and the Sea of Marmara selected within the EC funded ESONET-NoE (European Seas Observatory NETwork - Network of Excellence) as a key area for a demonstration mission. Part of this project is focused on the study of the western end of the Gulf of İzmit, not far from the epicentre of the 1999 destructive earthquake of İzmit (M_w 7.4) that caused damages and a large number of

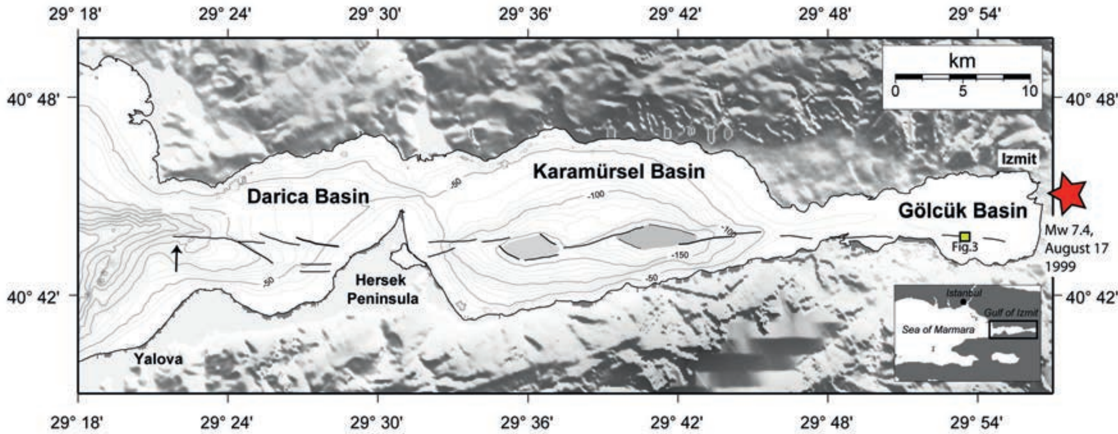

Fig. 2 - Tectonic map of the Gulf of Izmit derived from high-resolution multibeam bathymetry and chirp-sonar profiles (modified from Polonia *et. al.*, 2004). We note how deformation is focused at the basin edges and more diffused close to the basin depocenters. Epicentre of the 1999 M_w 7.4 İzmit earthquake (red star) and Fig. 3 locations (yellow box) are indicated.

casualties (Fig. 1). The main reason for focusing our studies along this segment of the NAF is that it has been suggested that the İzmit earthquake caused an increase in tectonic loading in this area, that will be probably dissipated close to Istanbul through a large earthquake during the next decades (Hubert-Ferrari *et al*., 2000).

We used a multidisciplinary approach, that included a combined analysis of high-resolution marine geophysical and gas-geochemical data, to study cold seeps that have been found in association with active faults in the Darıca Basin (İzmit Gulf), close to the surface rupture termination of the 1999 İzmit earthquake (Fig. 2). After a preliminary study, more focused on the geochemical nature of the seeps (Gasperini *et al*., 2012), we discuss here their potential as monitoring sites for combined seismological/gas-geochemical long-term experiments.

2. The North Anatolian Fault below the Gulf of İzmit

The NAF is a major continental transform system that extends E-W across the northern Turkey for over 1600 km, separating the Anatolian and Eurasian plates. Close to the Sea of Marmara region, it splays into three major branches, the northern, the middle and the southern strands (Barka, 1992): the Sea of Marmara is bounded by two of these branches, the northern and the middle, about 50 km apart (Fig. 1). Several kinematic models were proposed to describe the present-day tectonic setting of the Marmara region. One of these models (Armijo *et al*., 2002) integrates several levels of complexities both in time and space, and describes the Marmara depression as a sequence of relatively stable pull-apart basins, controlled since their earliest formation by major oversteps along the main NAF. On the other hand, the model proposed by Le Pichon *et al*. (2001) suggests the recent formation of a single throughgoing fault, overprinting the pre-existing pull-apart tectonic regime. Both alternative models are based on the same data set, and this witnesses the geological complexity of strike-slip deformation zones in general, and of the Marmara region, in particular.

The northern branch of the NAF enters the Gulf of İzmit at its eastern end, forming a sequence of ridges and depressions at various scales, from a few hundred meters to several kilometers throughout the gulf (Fig. 1). The NAF crosses the entire Sea of Marmara where it forms deep (up to 1200 m) basins separated by structural highs and finally emerges onshore along the so called Ganos Fault in the southern Thrace (Fig. 1). Geodetic measurements (McClusky *et al.*, 2000) suggest a 24 mm/yr right lateral plate motion in this region, with more than 80% of the total motion (i.e. > 20 mm/y) accommodated along the northern branch (Armijo *et al.*, 2002; Meade *et al.*, 2002). However, GPS geodetic measurements cover a period of two decades, a short time interval if compared to recurrence period of major earthquakes in the region (Ambraseys and Finkel, 1991). On the other hand, slip rate estimates over longer time intervals have been carried out through the analysis of displaced geomorphic features in the Ganos region (Armijo *et al.*, 1999; Gasperini *et al.*, 2011b) and in the Gulf of İzmit (Polonia *et al.*, 2004), and they suggest lower slip rates relative to geodetic estimates. The 10 mm/yr Holocene deformation rate, reported by Polonia *et al.* (2004) and Gasperini *et al.* (2011b), is high compared with sedimentation rate (Çağatay *et al.*, 2003), and this allows for detailed reconstruction of fault location and kinematics, because active fault traces have a morphological expression at the seafloor.

The northern branch of the NAF disappears below the Sea of Marmara immediately west of the 1999 İzmit epicentre, and cannot be traced using field and remote sensing observations. Prior to the 1999 Düzce and İzmit earthquakes, marine geological data in this area were scant. Geophysical data, including high-resolution bathymetric maps and seismic reflection profiles, have been extensively collected in the Gulf of İzmit and the deep Marmara basins as a consequence of the international effort that followed the 1999 disaster. The morphobathymetric map of the Gulf of İzmit, compiled using high-resolution mutibeam echo-sounder data collected during different cruises (Polonia *et al.*, 2002-2004; Cormier *et al.*, 2006; Gasperini *et al.*, 2009) is one of the major results. It shows a complex pattern of releasing and restraining bends along the submerged trace of the NAF, causing the subsidence of three main basins separated by sills (Fig. 2). While the easternmost Gölcük Basin is a shallow embayment with maximum depths < 30 m, the Darıca and Karamürsel depressions accommodate significant extension. These two basins, however, show different morphologies. The Darıca Basin in the western end of the Gulf of İzmit (Fig. 2) is shallower than Karamürsel, and does not show a well-defined depocenter; the narrow principal displacement zone of the NAF emerges from a generally flat topography and converges into a narrow E-W aligned furrow at the western end of the Gulf of İzmit (Fig. 3).

A common pattern observed in the three basins is that deformation zones widen at the basin centres and become narrow, and comparatively more focused, at their edges. This imply that pure or almost pure strike-slip deformation could be found in very few places that can be considered key regions where measure the Anatolia-Eurasia plate motion.

3. Seismicity and cold seeps

The İzmit earthquake shows some correlation between seismicity and gas emission at the seabed. In fact, besides eyewitness who reported gas bubbling in the waters of the Gulf of İzmit,

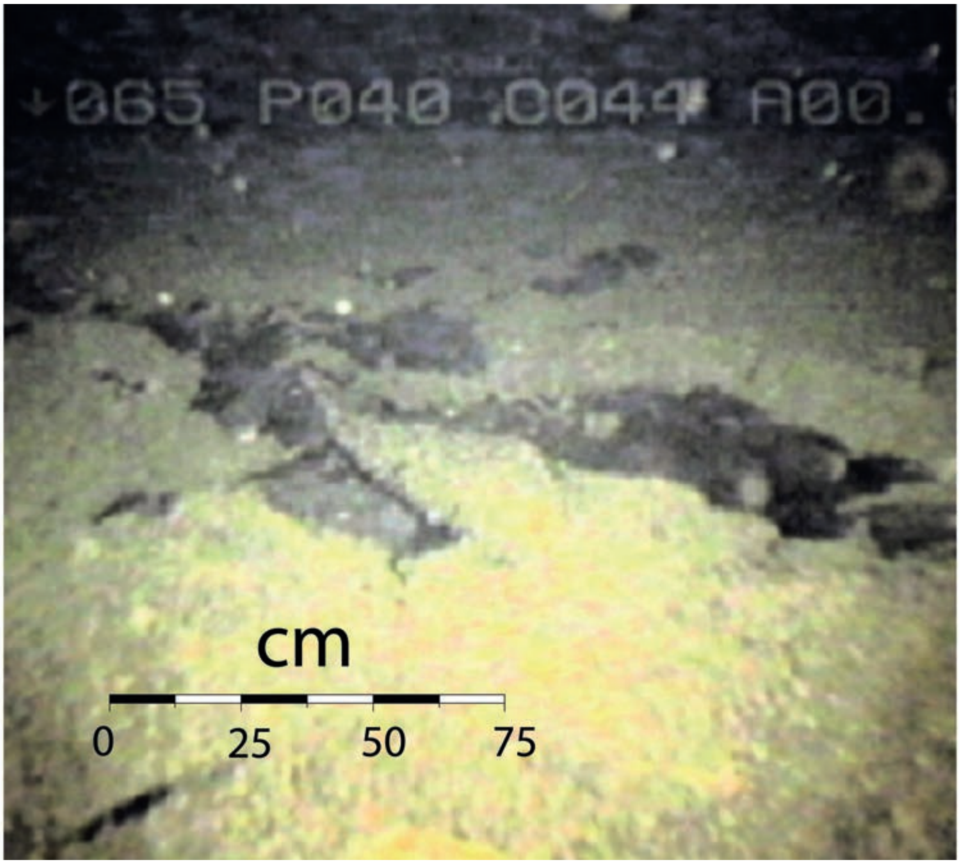

Fig. 3 - Underwater photo of the Marmara seafloor close to the epicentre of the 1999 Izmit earthquake collected using a ROV on board of R/V Urania during Marmara 2001 expedition. The surface rupture is visible, as well as the effects of fluid seepage that produced black-coloured sediments along the fracture.

a study based on analysis of repeated geophysical surveys before and after the earthquake suggested that the intensity of gas emissions from the seafloor increased immediately after the event (Kusçu *et al*., 2005). Fluid emissions from the seafloor where observed analyzing acoustic backscatter from different sources, including echo-sounder and chirp-sonar profiles as well as side-scan sonar images in a number of works, including Geli *et al*. (2008). The acoustic waves used to insonify the seafloor with frequencies ranging from few kHz to hundreds of kHz, are scattered by gas bubbles in the water column, showing a typical diffraction pattern in the records. Because these data are collected to imaging the seafloor (multi- or single beam echo-sounder, side-scan sonar system) or the shallow sub-seafloor (chirp-sonar or subbottom profiling systems) it becomes possible correlating gas emissions with tectonic structures, either marked by morphological features or acoustic discontinuities and diffraction patterns at depth.

The occurrence of gas emission and the availability of accurate morphotectonic maps of the NAF below the Marmara Sea, acquired by the strong international effort that followed the 1999 earthquakes, give us the opportunity of quantitatively study the relationship between cold seep, active faults and the earthquake cycle, within well constrained tectonic models. This was carried out by repeated surveys, from 2000 to 2010 (see cruise reports in http://www.ismar.cnr.it/prodotti/reports-campagne) and, more effectively, by using seafloor observatories to continuously monitor different parameters at the seafloor (Marinaro *et al*., 2008), including seismic activity (seismometers) and changes in the rate of emission of gas from the subsurface (methane sniffers and other geochemical sensors) during relatively long periods (years).

Typical expressions of gas emission at the seafloor of the Sea of Marmara are the so called black patches, that mark unevenly the NAF track (Armijo *et al*., 2005; Geli *et al*., 2008; Gasperini *et al*., 2011a). Such features are indicators of relatively continuous emission of dissolved methane at the seafloor. The anaerobic oxidation of methane, in fact, triggers a suite of geochemical reactions that ultimately result in the production of black Fe and Mn sulfide mineral assemblages. Methane originates from microbial degradation of organic matter or from deeper thermogenic hydrocarbon generation and passes upwards as a dissolved component in pore fluid advection or as a buoyant gas phase. The sulfate source is the overlying water column, with sulfate diffusing across the sediment-water boundary. Secondary reactions include precipitation of authigenic calcium carbonate, precipitation of Mn sulfides, and production of a variety of Fe. The latter dominates the sulfidic sediment of methane seeps and produces the typical black color. Fe oxyhydroxides often make up a significant percentage of ocean margin seafloor sediment, and these are prone to biogeochemical reduction often through a microbial intermediary. Black sediment patches are indicators of rapid, prolonged and current methane emissions. The emissions must be rapid and intense enough to keep the bottom boundary layer completely anoxic. Flow measurements made in such environments have indicated outflow rates of centimeters to meters per day (Tryon *et al*., 2002). Sulfide oxidation is rapid (Wang and Chapman, 1999) and in the absence of outflow, oxygenated bottom water will interact with the sediment, which will quickly (days) lose its black colour. One control on how long the site has been active is the presence or absence of carbonates. The anaerobic oxidation of methane reaction leads to the production of authigenic calcium carbonate at and just below the seafloor. While there are many factors affecting the accumulation rate, as a general rule the lack of significant carbonate structures relates to a relatively short lifetime of venting activity on the order of some tens of years or less. Black patches of reduced sediments were observed in the Gulf of İzmit close to the 1999 epicentre (Polonia *et al*., 2002) in the Gölcük Basin (Fig. 3), and the Darıca Basin, during a Nautile dive (Gasperini *et al*., 2011a).

4. Methods

A high-resolution morphotectonic map of the study areas was compiled using multibeam swath bathymetry data and shallow penetration seismic reflection profiles collected in the Marmara Sea during MARMARA-2009 cruise (Gasperini *et al*., 2009) onboard of R/V Urania (see cruise report for more details at http://www.ismar.cnr.it/products/). Multibeam data were collected using a Kongsberg 710 system, while chirp profiles using a 15 transducer Benthos Chirp II. Processing and interpretation of seismic reflection data, including reflectivity analysis and reflector picking was carried out using the open-source software package SeisPrho (Gasperini and Stanghellini, 2009).

Areal surveys with visual and instrumental inspection were performed by a deep-sea probe called MEDUSA (Module for Environmental Deep UnderSea Applications).

Technical details of the survey carried out with MEDUSA in the Sea of Marmara are reported in Gasperini *et al*. (2012).

Seawater samples were collected by a Tedlar® pipe whose sampling inlet was fixed close to the methane sensors and the video camera. In correspondence of high CH_4 concentration sites, as indicated by the methane sensors, the bottom seawater was pumped onboard, for the time interval necessary to drain the pipe (knowing water flow and depth of the sample).

C_1-C_6 hydrocarbons, hydrogen (H_2) and stable carbon and hydrogen isotopic composition of CH_4 ($\delta^{13}C_{CH4}$ and δD_{CH4}) were analysed by Isotech Labs Inc. Illinois, USA (Carle AGC 100-400 TCD-FID GC; accuracy 2%; 10% at the detection limit; Finnigan Delta Plus XL mass spectrometer, accuracy ± 0.1‰).

5. Character of cold seeps in the Gulf of İzmit

In the Darıca Basin, along the NAF principal deformation zone, we selected two sites characterised by different strain regimes, to carry out a detailed geophysical/gas-geochemical study: 1) an E-W oriented, strike-slip segment, close to the western termination of the Gulf of İzmit (Fig. 5), where the surface rupture of the 1999 earthquake was reported (Gasperini *et al*., 2011a); 2) a series of en-echelon transtensional strands, where a group of mounds (Fig. 6), surrounded by a peripheral depression possibly related to mud volcanism and fluid emission have been found (Gasperini *et al*., 2012). Analysis carried out on samples from different areas shows that the gas seeping from the seafloor is mostly CH_4 with a clear microbial origin, similar to that reported for the nearby Çınarcık Basin (Bourry *et al*., 2009). The isotopic ratio of hydrogen (δD_{CH4}) is relatively high, up to -109‰ VSMOW, in comparison with that typically reported for microbial gas. This could be due to methane oxidation, to be verified by further analyses (Gasperini *et al*., 2012).

5.1 Strike-slip segments

Close to the western end of the Darıca Basin, the principal deformation zone appears as an E-W trending asymmetric v-shaped valley, following the small-circle of the Anatolia-Eurasia plate motion (Fig. 4). Here, geological slip-rates of 10 mm/y have been estimated, on the basis of displaced geomorphic features (Polonia *et al*., 2004). Chirp-sonar profile B2_32 (Fig. 5) clearly shows the sub-vertical trace of the NAF in this area, as well as the uppermost displaced sedimentary sequence which consists of an upper transparent marine unit deposited during the Holocene, and a lower lacustrine unit, separated by a high-amplitude unconformity (Polonia *et al*., 2004). Seismic section shown in Fig. 5 also highlights the presence of gas in the sediments, producing the typical blind windows. Approaching the fault, the fading due to the presence of the gas in the sediments disappears, and the signal is able to penetrate to deeper levels. Although we do not observe any gas plumes in the water column, sediments close to the fault appear free of gas, and this could indicate that it is drained through the fault conduit. A CH_4 profile collected across the fault (Fig. 5) shows a peak in concentration that coincide with the fault trace position. Gas concentrations detected in the bottom water, few meters above the seafloor, reach maximum values of 0.023 μM/l (Fig. 5). Black patches of reduced sediments at the seafloor were observed

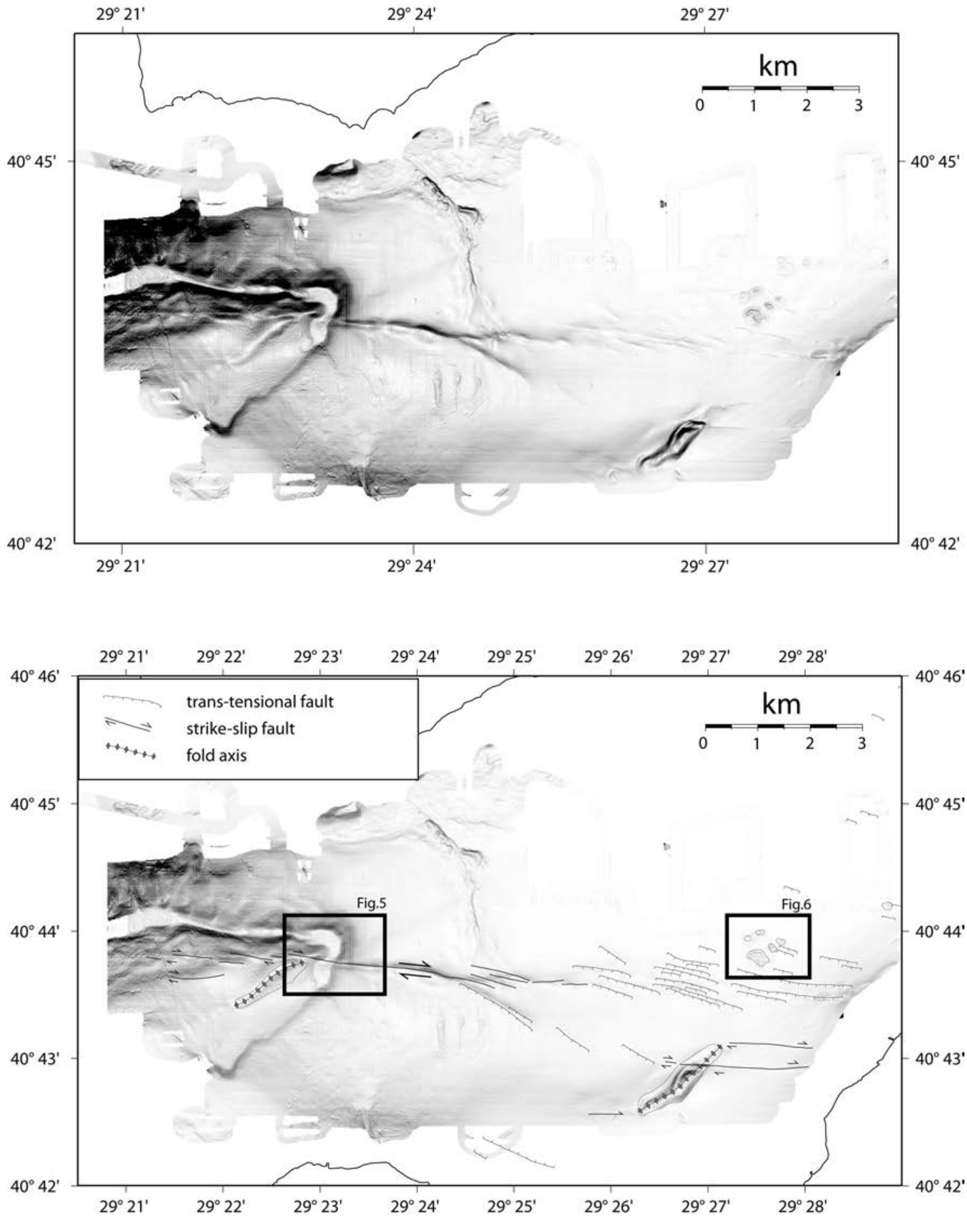

Fig. 4 - Morphotectonic map of the Darıca Basin. Main structural and morphological features are indicated, as well as the two areas characterized by different deformation patterns analyzed in this work (Figs. 5 and 6).

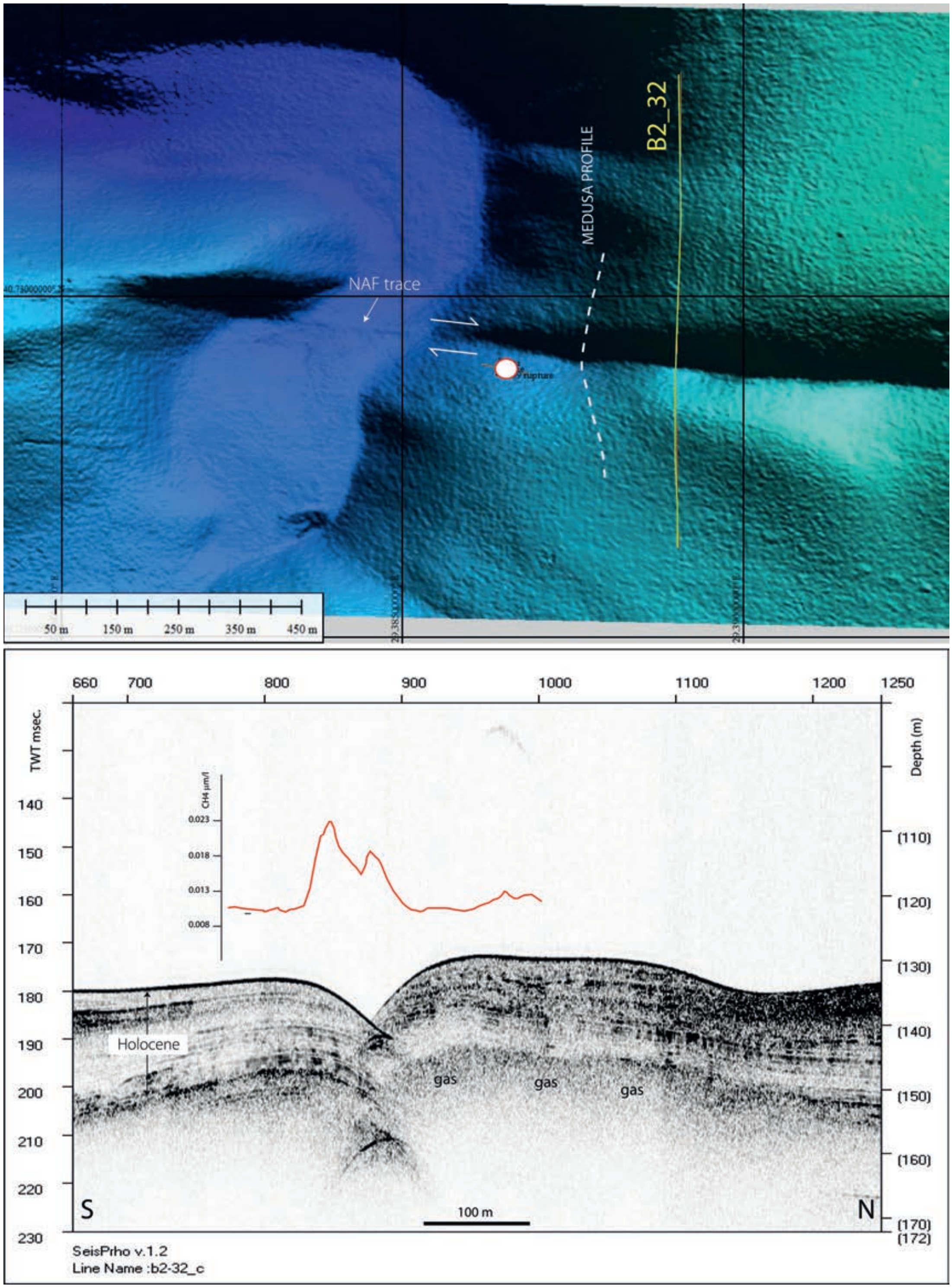

Fig. 5 - Top: high-resolution morphobatimetric map of the western end of the Darıca Basin. NAF deformation zone is marked by a v-shaped valley reaching a depth 180 m and is in this area very focused; location of Medusa profile (white dotted line) and chirp-sonar profile B2_32 (yellow line) are indicated, as well as position of black patches (white circle). Bottom: chirp-sonar profile B2_32 across the NAF valley; a CH_4 profile collected using Medusa across the fault is also indicated, showing a maximum peak of 0.023 μM/l centered on the NAF principal displacement zone.

in this area during a Nautile submersible dive (Gasperini *et al*., 2011a), and this might indicate a persistent emission from below.

5.2 Transtensional strands

Moving to the eastern side of the Darıca Basin, the almost pure strike-slip deformation pattern is replaced by the presence of a number of short, NE-SW trending en-echelon transtensional fault strands (Fig. 4). At the NE tips of the transtensional en-echelon segments, a cluster of mounds elevating few meters from the seafloor are observed (Fig. 6). Chirp-sonar profiles collected across these fault segments (Fig. 6) show that: i) they are active, since the uppermost part of the sedimentary sequence is displaced along the fault trace; ii) they accommodate significant extension, together with dextral strike-slip deformation; iii) they form a diffuse deformation zone along the NAF (several hundreds of meters wide), wider than in the western Darıca Basin.

Gas measurements carried out along these mounds indicate high CH_4 concentrations, higher than in the strike-slip segment, but more diffuse in several spots along a widespread zone (Fig. 6). Notwithstanding the relatively high values of CH_4 concentration (up to > 0.15 μM/l, Fig. 6), gas bubbles in the water column were not observed.

6. Discussion

Observations carried out before, during and after the 1999 İzmit earthquake suggest that combining observations of cold-seep emission intensity (and possibly nature in the near future) with seismicity along the submerged portion of the NAF could give important insights on transients signals related to stress load and large magnitude earthquakes. However, because deformation patterns are complex along the NAF we need to accurately constrain geological variables in selected sites in the Sea of Marmara suitable for a meaningful monitoring.

The two study areas we observed along the principal displacement zone of the NAF in the Darıca Basin (Gulf of İzmit) showed different characters. The maximum CH_4 emissions were observed in correspondence of the en-echelon transtensional segments, on top of the mounds in the NE sector of the basin. However, in this area emissions appear diffused, i.e., not focused in narrow deformation zones, and this could complicate monitoring strategies, because it would be difficult to select a single strand more significant than the others. Moreover, high concentration in CH_4 emissions, possibly not stable in time, could saturate the sensors and decrease their ability to detect transients. Conversely, measurements performed over the narrow deformation zone of the strike-slip fault segments, as in case of the western end of the Gulf of İzmit, showed weaker but relatively steady-state emissions, that could be eventually enhanced during (or hopefully before) a large earthquake, as observed in 1999.

Although no direct measures of gas emissions were collected in the Gulf of İzmit after the 1999 event, we note that the gas flares observed by Kusçu *et al*. (2005) were mostly located in the transtensional strands of the NAF. However, we observe gas emissions and black patches over a strike-slip segment several years after 1999, and this might indicate relatively stable and long-lived processes. Furthermore, we could speculate that they were enhanced by the stress drop that took place during (or before) the seismic event, but this should be verified by further observations.

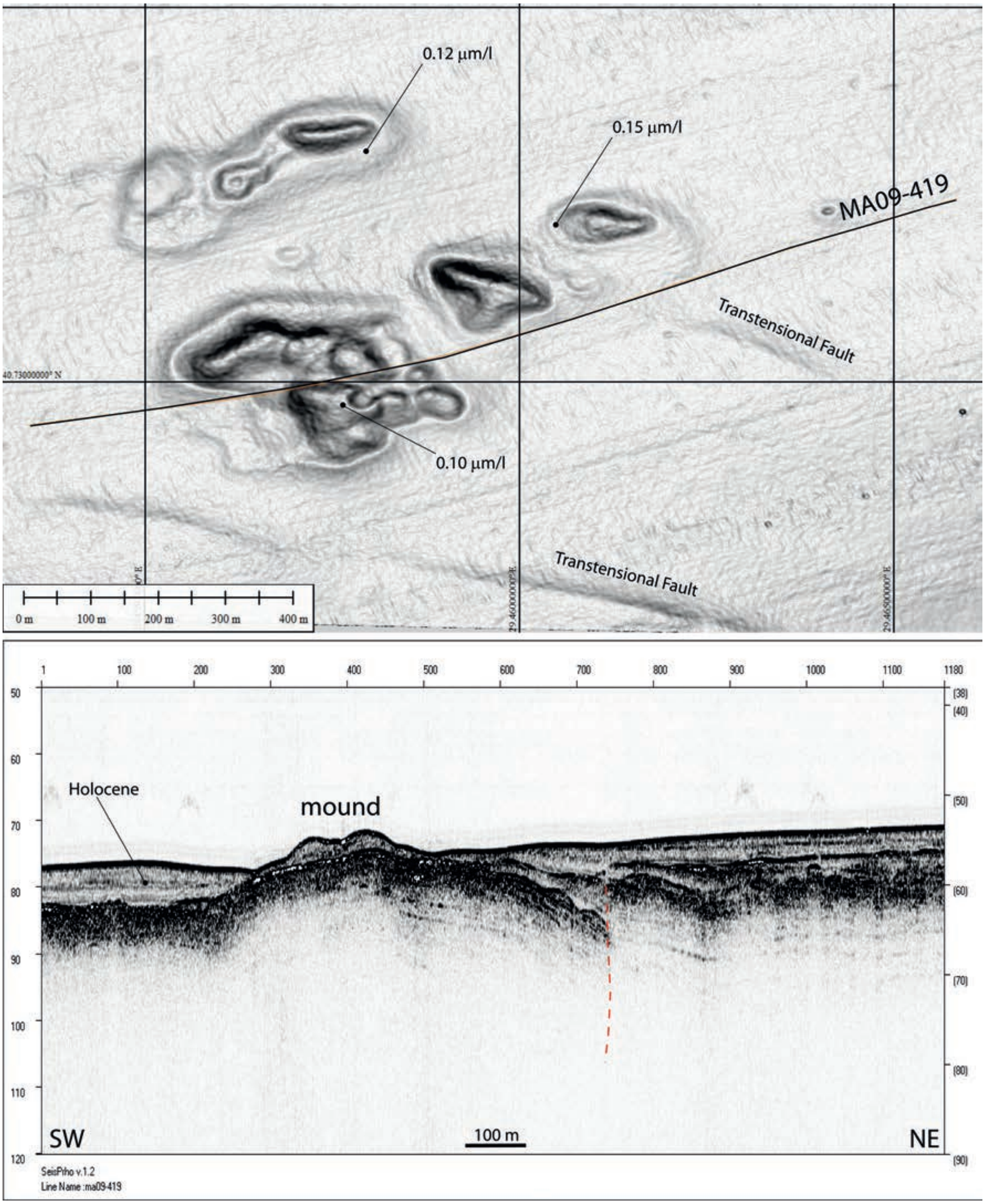

Fig. 6 - Top: high-resolution morphobatimetric map of the “mounds area”, where transtensional deformation occurs along en-echelon fault segments. CH_4 measures (indicated by numbers in µM/l) reach a maximum of 0.15 µM/l in the eastern sector; track of chirp-sonar profile MA09-419 is indicated (black solid line). Bottom: chirp-sonar profile MA09-419 across the transtensional deformation zone and the “mound area”. We note the thin marine Holocene transparent layer and the transtensional fault displacing the erosional base.

To summarize, the focused strike-slip fault segment connecting the shallow Gulf of İzmit to the deeper Çınarcık Basin and the main Marmara depressions, represents an interesting key area to study relationships between seismicity and gas emissions from the seafloor. In fact: 1) it is close to the western end of the surface rupture associated with the 1999 İzmit earthquake, representing the most probable area where the next earthquake affecting the fault strand towards Istanbul will nucleate; 2) it is where gas emission related to the fault activity was documented by our geophysical/gas-geochemical detailed survey and other studies; 3) it is an area characterized by a "focusing" of the principal deformation zone, thus representative of the overall motion along the NAF and reconstruct the average strike-slip rate during the Holocene; 4) it is a relatively accessible area, due to the moderate water depth (200 m) and the vicinity to the coastline.

Thanks to these observations, the Darıca Basin has been selected as a test site for a long term monitoring experiment: a SN-4, GEOSTAr class seafloor observatories (Favali *et al*., 2006), equipped with a broad-band seismometer, methane and oceanographic sensors, was deployed in the Darıca Basin from October 2009 to March 2010. We consider this experiment a first step towards the study of relationships between fluid/gas outflow and seismicity, with the final ourpose to detect transient signals immediately before and during large magnitude earthquake.

7. Conclusion

Multidisciplinary geophysical/gas-geochemical survey of the Darıca Basin, in the İzmit Gulf, close to the western termination of the 1999 İzmit earthquake surface rupture, allowed to determine a spatial correlation between tectonic structure and gas-seepages at the seafloor. High-resolution multibeam morphobathymetric map and seismic reflection data were used to reconstruct the fine structure of the NAF in this key region; gas-geochemical observations have shown that cold seeps are aligned along the principal deformation zone of the NAF system. Tectonic structures control the distribution of gas in the sedimentary sequence by confining gas pockets in delimited sectors, or by creating conduits for gas-escape. For this reason, the seepage of gas from the subsurface is almost invariably connected to the presence of tectonic structures. Our observations indicate that, combining geological and geochemical studies, our knowledge on the tectonic activity of the NAF may improve, and this approach may be applied to other seismogenic features in different geodynamic settings. Moreover, we suggest that the Darıca Basin, in the Gulf of İzmit is an ideal site to carry out combining seismological/gas-geochemical long-term monitoring experiments.

Acknowledgments. We thank captain and crew of R/V Urania that helped us in many ways during the cruise MARMARA-2009 and many other cruises carried out in the Sea of Marmara. This work is part of the EC funded ESONET-NoE (European Seas Observatory NETwork - Network of Excellence) project Marmara Demo-Mission, coordinated by Louis Geli. Suggestions and comments from Dario Slejko (editor), M. Pipan (reviewer) and A. Del Ben (reviewer.) greatly improved the quality of the paper.

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