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
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# A review of 20 years (1999–2019) of Turkish–French collaboration in marine geoscience research in the Sea of Marmara

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## Abstract

This paper retraces the history and main achievements of the ongoing Turkish–French collaboration in marine geoscience research in the Sea of Marmara, which was initiated in the aftermath of the 1999, Izmit and Duzce earthquakes. The collaboration resulted in nine large oceanographic cruises along with six recovery operations involving diverse vessels, and in the participation in two major EU-funded programmes (ESONET-NoE and MARSITE) and to one bilateral project, e.g. the MAREGAMI Project, co-funded by TUBITAK and ANR (the Turkish and French national funding agencies for research, respectively). In this paper, we review the major scientific contributions on the tectonic evolution of the North-Anatolian Fault in the Marmara Region; on the relationships between faulting, seismicity, fluids and ecosystems; and on paleo-seismology and paleo-oceanography in the Sea of Marmara.

## 1 Introduction: the situation before the 1999 earthquakes

During the second half of the XXth century, after Ketin (1968) first established the relations between the general tectonic features and earthquake activity in Turkey, the North Anatolian Fault Zone received considerable attention (e.g. Şengör 1979; Barka 1981). The westward migration of earthquake ruptures (starting from the 1939 Erzincan earthquake in the easternmost end of the NAF) had already been established in the late 1970's (e.g. Töksöz et al. 1979) and in 1997, when Stein, Barka and Dieterich estimated “a 12% probability for a large event ( $M > 6.7$ ) to occur south of the major western port city of Izmit in the next 30 years” (Stein et al. 1997), it was nothing but a premonition. What a posteriori became an astonishingly successful prediction when the earthquake struck in Izmit 2 years later, Barka (1999) was based on the detailed mapping of surface slip and fault geometry of the North Anatolian Fault, that resulted from

3 decades of continuous geophysical and geological onshore investigations (e.g. Şengör et al. 1985; Barka 1992, 1996; Barka and Kadinsky-Cade 1988, and references therein). On-land studies also benefited from spectacular advances in space geodesy that revolutionized earth sciences in the 1990's (e.g. Le Pichon et al. 1995; Reilinger et al. 1997). In contrast, by the end of the century, there was a tremendous gap in knowledge between the onshore and offshore domains in the Marmara Region. Consequently, the question of the westward propagation of the North-Anatolian Fault into the Sea of Marmara was entirely open.

Indeed, prior to 1995, the knowledge of the Marmara sea-floor was essentially based on: hydrographic maps from the Office of Navigation, Hydrography and Oceanography of Turkey (SHOD); sparse borehole data from the oil industry; and a few, widely spaced seismic reflection lines, acquired by the Turkish Petroleum Corporation (TPAO), by Marathon Oil, and by the Institute of Marine Sciences and Technology (IMST) of Dokuz Eylül University (DEU) in İzmir (e.g. Smith et al. 1995; Ergün and Özel 1995; Özel 1992; Wong et al. 1995; see also review in Palabiyik et al. 2020; Görür et al. (1997) and references therein). In 1995, the research vessel (R/V) *Piri Reis* of IMST acquired 3300 km of single channel, seismic profiles and 1000 km of deep-towed boomer profiles. These data were used to draw-up a bathymetric map revealing three deep (> 1000 m) basins “bounded by and internally cut by numerous steeply, dipping faults” (Aksu et al. 1999). In 1997, (the Scientific and

Technical Research Council of Turkey (TUBİTAK) initiated the Turkish Marine Programme, coordinated by Naci Görür and funded by the State Planning Organization of Turkey (DPT). The programme had access to the research vessels of Mineral Research and Exploration Directorate of Turkey (MTA) and Turkish Naval Forces—Office of Navigation, Hydrography and Oceanography (SHOD). The programme acquired 2200 km of multi-channel seismic reflection lines, with MTA's *R/V Sismik-1* (see review in Imren et al. 2001, p. 145). Two different groups, from Istanbul Technical University (ITU) and from the University of Cambridge, respectively, proposed two different tectonic interpretations, reflecting the contrasting views that prevailed at that time, based on land observations. Okay et al. (1999) supported Pinar's (1943) early idea of a single through-going fault, later called the "Main Marmara Fault" (MMF; Le Pichon et al. 2001), bisecting the Gulf of Izmit and the three Marmara deeps, in agreement with the view of Şengör (1979) and Şengör et al. (1985). In contrast, Parke et al. (1999) supported the view depicting the Sea of Marmara as a rift basin with *en echelon* faulting and little or no strike-slip fault in the central Marmara Sea (e.g. Armijo et al. 1999). In February 1999, multibeam bathymetric data were collected and sediment pore fluids were sampled from the deep Marmara basins during R/V Meteor cruise 44 (Halbach et al. 2000), identifying methane anomalies, suggesting the existence of an active hydrological system associated with the submarine fault system.

## 2 In the aftermath of the 1999 earthquakes: the NATO conference on May 14–17th, 2000

The catastrophic death toll (> 20,000 victims) of the Izmit and Düzce earthquakes in August and November 1999 created an immense worldwide shock and emotion. Meanwhile, an earthquake hit Athens on September 7th, 1999, causing 143 deaths. These three events compelled international collaboration for future earthquake risk assessment in the region. A first conference was held at ITU in 1999, during which different strategies were presented to fill the knowledge gap in the Sea of Marmara (e.g. Le Pichon et al. 1999). A second conference was held in Istanbul on 14–17 May 2000 as a NATO international Advanced Research Seminar with the primary objective of providing a platform for open discussions and for fostering international collaborative studies. Coordinated by TUBİTAK, the NATO seminar was attended by 83 scientists from Turkey, France, Italy, USA, UK, Japan, Germany and Greece (Görür et al. 2002).

Earthquakes were known to have occurred in the Sea of Marmara near Istanbul in the past (e.g. Ambraseys and Finkel 1995). The question that was on everyone's mind

was: when and where will the next earthquake strike? As a corollary: how will the stress be transferred in the submarine domain, between the 1999 rupture in Izmit and the 1912 rupture in Saros? More generally, from a geodynamic point of view, the major scientific issue was to understand how the North-Anatolian Fault, a major strike-slip plate boundary, propagates into the Aegean extensional system. Different views—or different groups of ideas—having different implications for earthquake hazard assessment were discussed during the NATO seminar. The first group considered the prevailing role of extension (Parke et al. 1999) and viewed the Marmara Trough as a pull-apart basin with oblique extension (e.g. Barka and Kadinsky-Cadé 1988; Armijo et al. 1999; Hubert-Ferrari et al. 2000). The second considered the prevailing role of strain localization along a transform, through-going, strike-slip fault following a small circle corresponding to the relative motion between the Eurasian and Anatolian plates (e.g. Le Pichon et al. 2001). And the third group considered the Marmara Area as "a negative flower structure controlled by a single master fault", identified as the northern branch of the North Anatolian Fault Zone (e.g. Okay et al. 1999; Alpar and Yaltırak 2000).

After the NATO seminar, a number of research programmes in marine geoscience research were set up, through bi-lateral and tri-lateral collaborations between Turkey and a large number of foreign countries, including the United States, Italy, Germany, Japan and France. The Turkish–French cooperation programme, initiated by Xavier Le Pichon and Çelal Şengör, was coordinated by INSU and TUBİTAK. It started 3 months later, once Xavier Le Pichon had obtained the funds for the mapping cruise of R/V Le Suroit (12 September–3 October 2000) from the ECHO division of the European Community.

## 3 Actions under the Turkish–French collaboration in marine research since 1999

The collaboration resulted in nine large oceanographic cruises and six recovery operations involving diverse vessels since 1999. All cruises included scientists from other countries (e.g. Germany, Italy, USA, Spain, China, etc.). The collaboration largely benefited from the assistance of the Turkish Coast-Guard Command (Sahil Güvenlik) and was supported by EU-funded programmes, which in turn allowed for access to marine facilities at different institutions in Europe. Most particularly, the research vessel *Urania*, from the Italian National Research Council, was used on many occasions within the framework of EU supported projects, e.g. ESONET-NoE and MARSITE (see Gasperini et al. 2018 and cruise reports in <http://www.ismar.cnr.it/prodotti/reports-campagne>). The collaboration also benefited from the

knowledge gained through other bi-lateral programmes, such as between Turkey and the USA. For instance, the TAMAM cruise on *R/V Piri Reis* in 2010 (co-P.I.s Çifci from Dokuz Eylül University and Steckler, from Lamont Doherty Earth Observatory) offered unique opportunities for scientific exchanges within the marine geoscience community.

The cruises that were conducted on French vessels were given a DOI (Digital Object Identifier), providing immediate access to the associated publications. The full list is detailed in Table 1. A brief, chronological summary is provided here below:

- 2000: The MARMARA cruise (Chief scientists: Le Pichon, Şengör, Demirbağ) on *R/V Le Suroît* provided the first, detailed integral mapping coverage of the Marmara seafloor. In addition to high-resolution, multibeam bathymetry and imagery data (grid-mesh size of 38 m), deep-towed side scan sonar data were collected along with shallow seismic data using a surface sparker source and a deep-towed seismic source (e.g. Rangin et al. 2001; Le Pichon et al. 2001; Imren et al. 2001; Demirbağ et al. 2003). See more and publication list on: <https://doi.org/10.17600/20100>.
- 2001: The SEISMARMARA cruise on *R/V Nadir* (Chief Scientists Hirn, Singh & Taymaz), was conducted with the support of *R/V Simik-1* of MTA and divided into two legs. Leg I (P.I. Hirn & Taymaz) resulted in the acquisition of 4000 km of large penetration, reflection seismic data along with refraction seismic data (OBS and on-shore stations), to determine the deep (> 10 km) structure below the Sea of Marmara (e.g. Laigle et al. 2008; Bécel et al. 2009, 2010; Bayrakci et al. 2013). Leg II (P. I. Singh & Taymaz) provided high-resolution seismic imaging of the Eastern Sea of Marmara (Çınarcık Basin and its margins) along 80, densely spaced (0.5–0.9 km) lines (e.g. Carton et al. 2007). See more and publication list on: <https://doi.org/10.17600/1080050>.
- 2001: The MD 123–MARMACORE cruise on *R/V Marion Dufresne* within the GEOSCIENCE 1 project (coordinated by Turon), provided a large variety of long, sediment cores, establishing the base for all future paleo- seismological and paleoceanographic studies in the Sea of Marmara (Chief Scientists: Mercier de Lépinay, Labeyrie, Çağatay). See publication list on: <https://doi.org/10.17600/1200050>.
- 2002: The MARMARASCARPS (P.I.s Armijo, Mala- vieille & Çağatay) on *R/V L'Atalante* with ROV Victor provided fine-scale mapping of active fault scarps along with 3.5 kHz sediment profiling and long cores for paleo- seismological studies (e.g. Armijo et al. 2005). ROV dives also provided the first visual observations of cold seeps along the fault (e.g. Zitter et al. 2008). See publication list and more on: <https://doi.org/10.17600/2010140>.
- 2004: The MARMARA VT 67 & MARMARA VT68 cruises on *R/V Marion-Dufresne* (Chief Scientists: Henry, Delaygue & Çağatay for VT67 and Lericolais for VT68), provided very long cores for advanced studies in paleo- seismology paleoceanography. See publication list on <https://doi.org/10.17600/4200080> (VT-67) and (VT68) 10.17600/4200120.
- 2007: The MARNAUT Cruise conducted on *R/V L'Atalante* with the *Nautille* submersible (Chief Scientists: Henry; Şengör; Çağatay), provided the first visual observations of gas seeps and in situ gas samples, leading to the characterization of fluid emissions (e.g. Tryon et al. 2010) and to the evidence that the North Anatolian Fault was cutting through a gas and oil system related to the Thrace Basin oil field (Bourry et al. 2009). See more in § V.2 and publication list on: <https://doi.org/10.17600/7010070>.
- 2009: The MARMESONET Cruises on *R/V Le Suroît* (chief scientists: Géli; Henry; Çağatay) represented the Demonstration Mission aiming at preparing future deployments of multi-parameter, permanent seafloor observatories on the Marmara seafloor within the European Seafloor Observatory Network of Excellence (ESONET-NoE). It was one of the first worldwide acoustic surveys of the water column, using multibeam echosounder. See more in § V.3 and publication list on: <https://doi.org/10.17600/9020040>.
- 2010: The PIRMARMARA Cruise (P. I.s Çifci and Marsset) on *R/V Piri Reis*, provided long-offset, 2D seismic data from the deep Marmara Trough that successfully completed the coverage obtained during the Marmesonet cruise (e.g. Şaritaş 2018). Additional profiles from the southern shelf were also acquired for further investigations on the Messinian event in the Sea of Marmara.
- 2014: The MARSITECRUISE on *R/V Pourquoi pas?* with the ROV Victor-6000 (P. I.s Géli, Ruffine, Henry and Çağatay) was part of the marine operations conducted within the MARSITE Project (P.I. Nurçan Özel). During leg 1, seafloor instruments were deployed. During leg 2, sediment, water and gas samples were taken using ROV Victor-6000 (e.g. Ruffine et al. 2018a, b, c). During leg 3, additional 3.5 kHz and sediment cores were acquired at key sites for paleo-seismological studies. See more in § IV.2 and in § V.4, and publications list on: <https://doi.org/10.17600/14000500>.

**Table 1** List of cruises conducted in the Sea of Marmara within the Turkish–French collaboration in marine geoscience since

1999 Cruise		Summary of measurements
Name	Marmara	Bathymetry and reflectivity with EM300 echosounder
Year	2000	Single-channel seismics using surface source (sparker)
Vessel	R/V Le Suroit (Ifremer)	Deep-tow sidescan sonar (SAR)
Chief scientists	Le Pichon, Şengör Demirbağ	Deep-tow High resolution seismics (PASISAR)
Doi	10.17600/20100	
Programme	Cnrs/Tubitak Coll.	
Funding Source	EU (ECHO Programme)	
Name	SEISMARMARA	4000 km of MCS profiles
Year	2001	Coordination with on-land seismological networks (permanent complemented by 30 temporary stations to record off-shore seismic shots)
Vessel	R/V Nadir (Ifremer) +support of MTA Sismik-1	Leg 1 (Hirn)
Chief scientists	Hirn, Singh, Taymaz	Deep-penetration, low-frequency source for deep seismic soundings: 8100 cu-inch; 12 air-gun array on single bubble mode
Doi	10.17600/1080050	4 E–W lines and 30 cross-lines in the whole Marmara Trough
Programme	Cnrs/Tubitak collab.	Deployment of 37 OBSs with MTA Sismik-1 for refraction seismics and seismic tomography (OBSs from IRD, INSU, University of Hokkaido).
Funding Source		Leg 2 (Singh)
		2900 cu-inch source allowing denser shot spacing
		80 dip-lines at 0.6–0.9 km spacing (0.6–0.9 km) in the Cinarcik basin and its margins
Support vessels	MTA Sismik-1	OBS recovery
	Turkish coast guard	Permanent operational assistance
Name	MD-123 MARMARACORE-1	Piston-corer (of the giant CALYPSO-type) core samples
Year	2001	Gravity core samples
Vessel	Marion Dufresne (IPEV)	Deep-water coral zoobenthos sampling
Chief scientists	Mercier de Lépinay, Labeyrie, Çagatay	
Doi	10.17600/1200050	
Programme	GEOSCIENCE 1 Project (coord JL Turon) and European projects POP and GEOMOUND	
Funding Source	EU	
Name	MARMARASCARPS	Micro-bathymetric surveys with Victor and Seabat
Year	2002	8101. 6 dives, 300 km surveyed
Vessel	Pourquoi pas ? / ROV VICTOR 2000 (Ifremer)	Visual exploration of faults, core samples by Victor and rock samples
Chief scientists	Armijo, Malavieille, Çagatay	6 dives, 80 km of exploration (231 SVHS tapes; 45 Betacam), 94 Victor cores and 13 rock samples taken
Doi	10.17600/2,010,140	Transit xwith 3.5 kHz profile acquisition, 10 trips, 600 km of 3.5 kHz at 6 knots
Programme	Cnrs/Tubitak collab	Kullenberg core samples - 8 cores taken
Funding Source		
Support vessels	Turkish coast guard	Permanent operational assistance
Name	MARMARA-VT 67	MARMARA-VT67 (Henry, Delaygue) – 03/05 to 07/05/2004
	MARMARA-VT 68	Sediment sampling
–	2004	13 long Calypso cores
Vessel	Marion Dufresne (IPEV)	3 Gravity cores
Chief scientists	Lericolais, Henry, Delaygue	2 Interface core samples
Doi	10.17600/4200080 and 10.17600/4200120	3.5 kHz (sediment penetrator) profiles
Programme	ACI-FNS hazards and global change project/ ASSEMBLAGE Project	Hydrological stations with water bottle sampling
Funding Source	EU	MARMARA-VT 68 (Lericolais)
		Sediment sampling from long sediment cores
		Extraction of interstitial fluids for geochemical and isotopic analysis (e.g. dO <sup>18</sup> )

**Table 1** (continued)

Cruise		Summary of measurements
Name	MARNAUT	<p>30 dives by Nautille: video recordings, still photos, temperature and salinity measurements (Microcat), samples of water, dissolved gases and gases under pressure (Pegaz), samples of sediment (tube and box corers), rocks and authigenic carbonates</p> <p>44 heat flow measurements on 3 transects</p> <p>12 yo-yo piezometer stations on 6 sites</p> <p>35 Kullenberg core samples, 13 interface core samples, 3 multitube core samples</p> <p>Extraction of interstitial fluids from the cores (Kullenberg and Nautille tube core samples) using rhizons or centrifugation. Chlorinity and sulphate analyses done on board</p> <p>13 CTD stations with sampling rosette</p> <p>406.14 km of EK60 profiles (detecting methane emissions in the water column)</p> <p>127 Chirp profiles</p> <p>8 OBS set up for the duration of the cruise and then recovered (SUBTECH trial)</p> <p>Long-term installation of 1 piezometer and 4 OBS for 3 months and 7 osmotic flow-meters and samplers for 1 year (recovery with</p>
Year	2007	
Vessel	L'Atalante/Nautille sub	
Chief scientist	Henry	
Doi	10.17600/7010070	
Programme	Cnrs/Tubitak collab	
Funding Source	EU / Ifremer/CNRS	
Support vessels	Turkish coast guard R/V Yunus (ITU)	<p>Permanent operational assistance during Nautille dives</p> <p>September 2007: Recovery of 4 OBSs (1 lost) and 1 piezometer during MARNAUT Cruise</p>
Name	MARMESONET	Leg 1
Year	2009	Micro-bathymetric mapping using AUV AsterX (16 dives)
Vessel	Le Suroit (Ifremer)	High-resolution seismic sediment profiling using AUV AsterX (2 dives)
Chief scientist	Géli, Henry, Çağatay	Water column imagery using Simrad-EM302 multi-beam echosounder
Doi	10.17600/9,020,040	Bathymetry using Simrad-EM302 multibeam echosounder
Programme	ESONET-Noe / MARMARA-DM (FP7)	Chirp profiles underway (8 knots)
Funding Source	EU/Ifremer	<p>24 heat flow measurements in the Marmara Sea</p> <p>23 core samples: 3 Kullenberg, 7 Ronanberg and 13 gravity core samples. Interstitial fluid samples taken on some cores</p> <p>2 "Deployment and recovery" operations for BOB (Bubble Observatory) in the Cinarcik Basin and Central High, respectively</p>
Support vessel	Turkish coast guard	Leg 2
Support Vessels within ESONET-NoE	R/V Urania (CNR, Italy) MARM-2009 Cruise Chief Scientist: Gasperini	<p>HR-3D seismics on the Western High zone where gas hydrates have been recovered.</p> <p>Operational assistance during AUV dives</p> <p>Deployment of Ifremer equipment: 10 OBSs and 5 piezometers in Eastern Marmara</p>
	R/V Yunus (ITU)	Recovery of Ifremer equipment: 8 OBSs (2 lost) and 5 piezometers in Eastern Marmara
	R/V Urania (CNR, Italy) MARM-2010 Cruise Chief Scientist: Gasperini	Sediment coring and pore water sampling from Western High

**Table 1** (continued)

Cruise		Summary of measurements
Name	PIRMARMARA	Acquisition of high-resolution, 2D, seismic data using a 1500 m long streamer (240 traces) 31 profiles (total length 350 km) 3 deep areas : Central High, Central Basin and Çınarcık Basin 1 shallow area on the Marmara southern shelf (for investigation of the Messinian unconformity)
Year	2010	
Vessel	R/V Piri Reis (DEU, Izmir)	
Chief scientist	Çifçı	
Doi	?	
Programme	ESONET-Noe / MARMARA-DM (FP7)	
Funding Source	EU-FP7/DEU	
Support vessel	Turkish coast guard	Operational assistance
Name	MARSITECRUISE	Leg 1 (Géli)
Year	2014	Deployment of
Vessel	R/V Pourquoi pas + ROV Victor 6000 (Ifremer)	10 stations (4 LDO, 6 from GEOMAR) for acoustic geodesy
Chief scientist	Géli, Ruffine, Henry, Çagatay	8 OBS (6 GEOMAR, 2 Ifremer).
Doi	10.17600/14000500	1 Bubble recorder (BOB) and ANITRA/ADCP mooring
Programme	MARSITE (FP7)	Leg 2 (Ruffine)
Funding Source	EU/Ifremer	5 ROV dives for in situ observations and sampling 35 interface corers 2 blade corers 7 titanium bottle 18 gas samples taken with PEGAZ/ROV 41 direct in-situ measurements (with ROV) of gas flow Sampling with ROV of 28 RAMAN measurements taken in situ (with ROV) for gas compositions 8 CTD casts and water sampling using rosette fitted with methane sensors (Franatech and MESSEA) Leg 3 (Henry, Çagatay) Calypso cores Sediment penetrator (3.5 kHz) profiling Recovery of 1 piezometer (deployed with Urania in october 2013) Recovery of the 10 OBSs
Support vessel	Turkish coast guard	Operational assistance during ROV dives
Support Vessels within MARSITE	Urania (CNR, Italy)	Deployment of 2 piezometers on Western High on September 2013 (recovered in nov 2004 with R/V Pourquoi pas?)
	MARM-2013 Cruise Chief Scientist: Gasperini	
	R/V Yunus (ITU)	Deployment of 10 OBS on Western in April 2014 (recovered in nov 2004 with R/V Pourquoi pas?)
	R/V Yunus (ITU)	Recovery and deployments of Geomar and LDO geodetic stations in April 2015
	R/V Yunus (ITU)	Recovery and deployments of Geomar and LDO geodetic stations in April 2015

## 4 Contribution to studies on the tectonic evolution of the NAF in the Marmara Region

### 4.1 Seafloor mapping and basins structure

The bathymetric map after the Marmara cruise on R/V Le Suroit in 2000 (Rangin et al. 2001) revealed the main physiographic and structural features of the Marmara seafloor.

It replaced previous maps based on single-beam data (e.g. Aksu et al. 2000) and was used as a common reference for all subsequent studies in marine geosciences. In the absence of information on the deep crustal structure, this map gave rise to contrasting interpretations, emphasizing model elements as diverse as the importance of extension (e.g. Parke et al. 2002, 2003); the presence of negative flower structure related to a deeply rooted, single master fault (e.g. Aksu et al. 2000; Yaltirak 2002); block or plate-like junctions or



geometry (Okay et al. 2000); pull-apart or transtensional jog activity at diverse scales (Armijo et al. 2002); evolution to strike-slip localization (Le Pichon et al. 2001).

Shortly afterwards, based on the modelling of the geotectonically observed secular velocity field in northwestern Turkey, Meade et al. (2002) suggested that strain accumulation was highly localized in the Marmara region, confirming “the existence of a Marmara block delimited to the north by the northern branch of the North Anatolian fault (with the Marmara branch close to pure dextral strike slip over its whole length) and to the south by the southern branch” (quote from Le Pichon et al. 2003). Based on a complementary data set, including sparker and deep-towed high-definition seismics (Demirbağ et al. 2003) and additional multichannel seismic lines from TPAO, Rangin et al. (2004) further proposed that most of the N 120° trending normal faults framing the deep basins are now inactive, discarding the hypothesis that strain was distributed along presently active, extensional blocks. These findings eventually lead Şengör et al. (2005) to propose “a new look” of the North Anatolian Fault, including its westward continuation into the Sea of Marmara.

The interpretation of the deep reflection and wide-angle seismic data collected in 2001 during the SEISMARMARA cruise provided information that lead to embed all the different models into a broader and deeper context, discarding hypotheses involving crustal faults only with predominance given to extension, while supporting large, through-going strike-slip faults, cutting the whole crust down to the Moho, as quoted from Laigle et al. (2008): “Sections across the eastern half of the North Marmara Trough (NMT), crossing the Çınarcık and Imralı basins, revealed several faults having varying strike and varying proportions of normal and strike-slip displacement, that might be viewed as petals of a large scale negative flower-structure that spreads over a width of 30 km at surface and is rooted deeper in the lithosphere. Under the Central Basin a very thick sediment infill is revealed and its extensional bounding faults are active and imaged as much as 8 km apart down to 6 km depth. We interpret them as two deep-rooted faults encompassing a foundering basement block, rather than being merely pulled-apart from a jog in a strike-slip above a décollement”.

Further analysis of the dense grid of multichannel seismic profiles along the southwestern margin of the North Marmara Trough reveals a dipping reflector through the upper crust with tilted basement blocks on top, while wide-angle reflection and refraction seismics using OBS reveal a significant and sharp reduction in Moho depth, in the order of 5 km beneath both the eastern and western rims of the North Marmara Trough, with a more progressive crustal thinning from the south (Bécel et al. 2009). More generally, the crystalline basement exhibits sharp topography across the Central High, the Kumburgaz Basin and the eastern tip of the

Çınarcık—North Imralı Basin in an unexpected way with respect to the sea-bottom depressions (Bécel et al. 2010). Several large, tilted, basement blocks separate the deep basins as between the Çınarcık and Imralı basins, suggesting that the process of deformation partitioning may have taken place over one or even two faults across the North Marmara Trough, which may have changed activity in time and space (Bécel et al. 2010).

These findings were further detailed by the 3-D tomographic inversion of first arrival times of seismic shots recorded by the OBS and land-stations network (Bayrakci et al. 2013). Similar sedimentary thickness (> 6 km) is observed below the North Imralı Basin (located on the southern continental shelf) than below its northern neighbours. The Tekirdağ and Central basins form a 60-km-long basement depression, as no basement high is found below the Western High (Note: this general picture was recently updated by Tarancioğlu et al. (2020), using additional OBS data collected by TÜBITAK collected in 2006, and enriched by a discussion on the significance of the results for identifying locked and creeping sections along the Main Marmara Fault). Last but not least, gravity data collected during the MARSITECRUISE were merged with a global gravity model derived from satellite altimetry and were inverted, taking into account constraints from seismic refraction and receiver function studies, to quantify the amount of crustal extension and determine the geometry of the Moho over the whole Marmara area (Kendé et al. 2017).

#### 4.2 Re-evaluation of the seismo-tectonics of the Sea of Marmara within the Marsite Project

The EU-funded Marsite Project (P. I. Nurcan Meral Özel, [www.marsite.eu](http://www.marsite.eu)) provided the unique opportunity to re-evaluate the seismo-tectonics of the Sea of Marmara, using all available marine data, including those collected during the Turkish–French collaboration programme: seismic lines, Görür and Elbek (2013) high-resolution bathymetry, chirp profiles, stratigraphic data from sediment cores, drill wells, etc.). The GIS fault map provided as Marsite deliverable D7.2 is based primarily on multichannel data and thus represents the fault geometry at a few kilometres depth within the syntectonic basins (Şengör et al. 2014). Faults are categorized as deep-rooted faults that also cut through the seafloor, blind faults, and shallow syn-sedimentary faults. For the purpose of hazard assessment, information from sediment sounder profiles and high-resolution bathymetry is essential to assess fault activity and deformation style, but the geometry to be preferentially considered for the construction of earthquake scenarios is that of the faults at crustal level. Where crustal structure is poorly imaged below the Sea of Marmara Basin, the three-dimensional fault geometry at



depths (Hergert et al. 2010, 2011) was largely inferred from seismic imaging in the syntectonic basins (Bécel et al. 2010; Carton et al. 2007). Fault models were further constrained, by taking relocated seismicity into consideration (Bulut et al. 2009; Karabulut et al. 2011; Schmittbuhl et al. 2015).

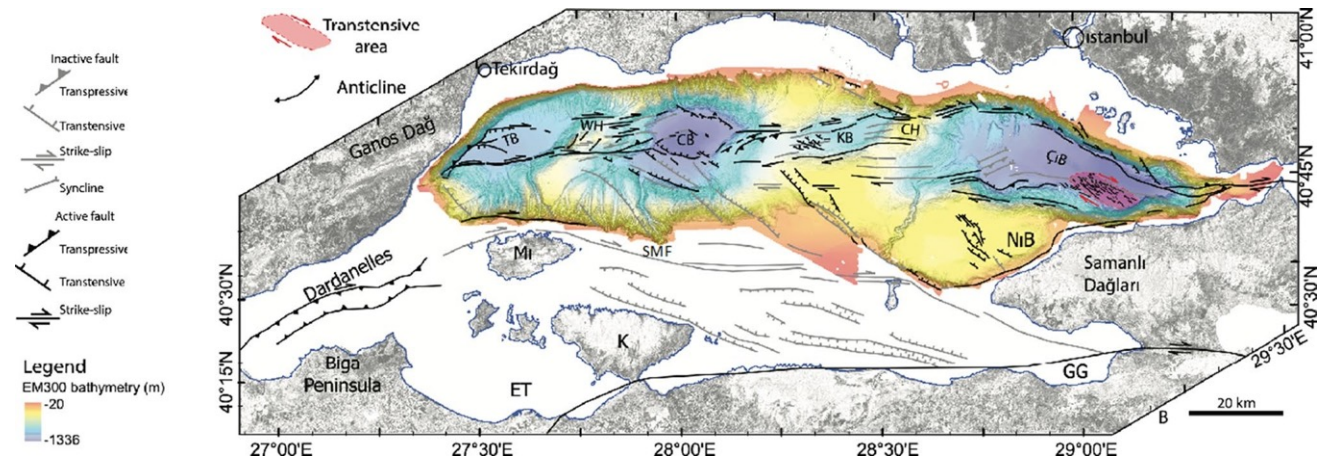
The work conducted within Marsite (e.g. Özel et al. 2017) resulted in the identification of which faults are cutting the seafloor (and thus currently active) and which ones do not (see deliverable D7.1 report in Henry et al. 2007). Several now inactive (or marginally active) fault systems appear to have played a role in the structuring of the basins. This is for example the case for the system of extensional detachments and tilted blocs between the southern shelf and the deep basins (Bécel et al. 2009) for the South Marmara Fault, connecting the Gemlik Bay to the Dardanelles (Le Pichon et al. 2003) and for an *en-écheleon* system lying in prolongation of the Izmit fault (Grall et al. 2012). On the other hand, several arrays of normal faults observed at a shallow level in the sediment are not deeply rooted, and could result from the interaction of slope instability with underlying crustal deformation (Zitter et al. 2012).

#### 4.3 Current knowledge on the tectonic history of the NAF System in the Marmara Region

After 20 years of continuous marine investigations, the Marmara Sea floor has become one of the most well-known submarine domains on Earth. The currently active fault system only comprises a fraction of the faults that have been active since the initiation of the North Anatolian Fault, and this situation may account for the initial diversity of tectonic

interpretations in the Sea of Marmara. Interpretations of deep seismic and bathymetric data have now largely converged to a scheme with a master fault—the Main Marmara Fault, or MMF, connecting the Izmit segment that ruptured in 1999 with the Ganos segment that ruptured in 1912—and subsidiary fault branches (e.g. Le Pichon et al. 2001; Armijo et al. 2002, 2005; Demirbağ et al. 2003; Rangin et al. 2004; Seeber et al. 2004, 2006; Meghraoui et al. 2012), a view further supported by studies of seismicity (e.g. Sato et al. 2014; Örgülü 2011). Remaining differences arise partly from the characteristics of the data sets used, and notably the resolution and depth of investigation of seismic data.

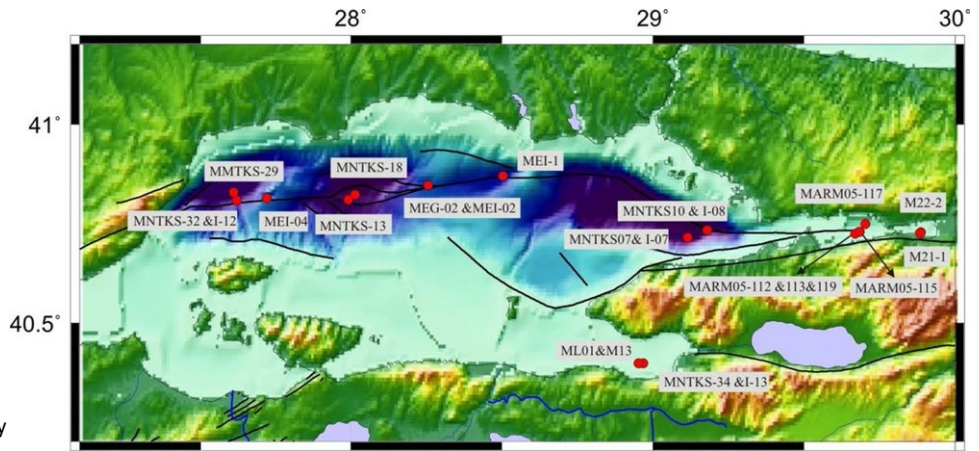
The present-day knowledge on the tectonic evolution of the Marmara Region is summarized in the three following papers, that use all available data listed in § IV.2: Şengör et al. (2014) -see Fig. 1; Le Pichon et al. (2014); Le Pichon et al. (2016). Using mainly the data from the deep basins, Şengör et al. (2014) establish a sequence of faulting events in the northern Marmara shear zone from the Miocene to present, confirming that the shear zone has been evolving and becoming narrower since its inception. While a tendency is observed towards strain localization in a 7-to-10 km swath along the Main Marmara Fault, some deformation is still accommodated over a broader area, and subsidiary faults display a complex history of fault activation/deactivation (Şengör et al. 2014). Using a comparable approach, based on a dataset enriched with seismic lines from the Marmara southern shelf, Le Pichon et al. (2014) completed the picture by mapping the evolution of the recently documented “South-Marmara Fault” (SMF) since the late Pliocene (Fig. 2).



**Fig. 1** After Şengör et al. (2014). Synthetic fault map summarizing the current knowledge on the tectonics of the Sea Marmara, super-posed on seafloor bathymetry map for depths > 100 m (Rangin et al. 2001). The black segments are active faults and the grey segments are presumably inactive. The tectonic interpretation is based not only on the data listed in the text, but also on seismic lines indicated in Panel A of Fig. 4 in Şengör et al. (2014), e.g.: MTA lines, Maden Tetkik

ve Arama Genel Müdürlüğü (General Directorate of Mineral Exploration and Research in Turkey) lines and TPAO lines, Türkiye petroleri Anonim Ortaklığı (Turkish Petroleum Company). CB Central Basin, CH Central High, ÇİB çınarcık Basın, ET Erdek Tombolo, GG Gulf of Gemlik, K Kapıdağ Peninsula, KB Kumburgaz Basin, MI Marmara Island, NİB North İmralı Basin, TB Tekirdağ Basin, WH Western High, SMF South Marmara Fault (e.g. Le Pichon et al. 2014)

**Fig. 2** Cores from Marnaut (MNTKS) and MarmEsonet cruises (MEI) listed in the text (and used for paleoseismological studies in the Sea of Marmara (see coordinates in Table 2)



**Table 2** List of Cores used by Çağatay

Location	Core No.	Core type	Water depth (m)	Length (cm)	Long	Lat	Cruise
İzmit Körfezi Gölcük Basın	M22-2	W/S interface	38		29.88588	40.72890	Urania 2010
	M21-1	W/S interface	38	106	29.88459	40.72574	
İzmit Körfezi Karamürsel Basın	MARM05-112*	W/S interface	212	112.5	29.68351	40.72973	Urania 2005
	MARM05-113*	W/S interface	212		29.68326	40.72961	Urania 2005
	MARM05-115	Gravity	199	231	29.66890	40.72464	Urania 2005
	MARM05-117	Gravity	68	251	29.70303	40.74994	Urania 2005
	MARM05-119	Gravity	210		29.68314	40.72962	Urania 2005
Gemlik	M13-1	W/S interface	113	87.5	28.96716	40.39837	Urania 2010
	ML01_1	Gravity	112.9	338			
	MNTKS-34	Gravity	105	940	28.95870	40.39328	L'Atalante
	MNTKI-13	W/S interface	105	87			Marnaut
Çınarcık	MNTKS-10	Gravity	1265	905	29.17970	40.73390	L'Atalante
	MNTKI-08	W/S interface	1265	83			Marnaut
	MNTKS-07	Gravity	1265	71.7	29.11416	40.71568	
	MNTKI-07	W/S interface	1220	81			
Central high	MEI-01	W/S interface	800	130	28.50292	40.87069	Le Suroit 2009
	MEG-02	Gravity	692		28.25500	40.84667	
Central Basin	MNTKS-12	Gravity	1262	960			L'Atalante
	MNTKS-13	Gravity	1248	920	27.99152	40.81068	Marnaut
	MNTKS-18	Gravity	1260	920	28.01385	40.82330	
Western high Tekirdağ Basın	MEI-04	W/S interface	741	40.5	27.72211	40.81464	Le Suroit 2009
	MNTKS-32	Gravity	1123	945	27.61130	40.82895	L'Atalante
	MNTKI-12	W/S interface	1123	94			Marnaut
	MNTKS-29	Gravity	1117	930	27.62213	40.80853	

The initiation of the North Anatolian Fault in the Sea of Marmara was preceded by deformation affecting the Eocene–Oligocene Thrace basin, which peaked during the Late Miocene to Early Pliocene. “The beginning of the formation of a localized plate boundary occurred between 4.5 and 3.5 Ma at the location of the present Sea of Marmara by the initiation of a shear zone” (quote from Le Pichon et al. 2016). The first part of the formation of the Sea of Marmara was thus purely extensional. With crustal thinning

possibly due to ductile lower crustal flow. At the present rate of areal extension derived from GPS data, about 5 Ma would be needed to explain the observed crustal thinning, which is probably slightly older than the onset of deformation related to the North Anatolian Fault. Hence, the areal extension rate was probably not constant, but may have peaked in the early Pliocene, as suggested by Le Pichon et al. (2016). The pre- sent strike-slip system that today cuts across the whole of Sea of Marmara began to develop after 2.5 Ma and evolved

since then, more likely through a progressive reorganization related to basin growth than as a sudden event (Grall et al. 2012; Sorlien et al. 2012; Akbayram et al. 2016). No major change in tectonic regime at the scale of the Sea of Marmara is required over the last 400 ka, although local variations in the rates of subsidence/uplift and in the strain distribution around the main fault are documented (Grall et al. 2012, 2013).

## 5 Contribution to paleo-oceanography and paleo-seismology

### 5.1 Paleoceanography

The Sea of Marmara is currently connected to the Aegean Sea and Black Sea through the Dardanelles and Bosphorus straits having sill depths of 65 and 35 m, respectively. Its hydrography is characterized by a two-way water exchange between the waters of the adjacent seas, with a permanent pycnocline located at  $\sim 25$  m between the two water masses. Due to the shallowness of the sills, oceanographic and environmental conditions alternated between marine and lacustrine phases during the Quaternary glacial and interglacial glacio-eustatic sea level changes. Despite its interesting oceanographic setting, palaeoceanographic studies on the Sea of Marmara were scarce before the international collaborations, including the Turkish–French programme (e.g., Stanley and Blanpied 1980; Aksu et al. 1999).

Earlier studies hypothesized the late Quaternary palaeoceanographic history mainly on the basis of the global sea level curve rather than proper chronological dating. These studies were carried out on short gravity cores recovered mostly on board Turkish research vessels such as the MTA Sismik-1, Piri Reis and Bilim. A few of these studies, using radiocarbon datings, showed that Sea of Marmara was fresh-brackish lake during the late glacial period and that marine conditions were fully established  $\sim 12$  ka BP. It was also discovered that the marine connection was followed by deposition of two sapropel units during the Holocene (Çağatay et al. 1999, 2000; Aksu et al. 2002).

The Turkish–French collaboration, using the French research vessels, recovered giant piston cores that sampled the older strata reaching back to the marine isotope stage (MIS-6). One  $\sim 29$  m long core (MD01-2430) recovered from the Western High extended back to 70 ka, and provided important paleoceanographic, paleoclimatic and tephra records (Vidal et al. 2010; Valsecchi et al. 2012; Çağatay et al. 2015a). The records revealed that the Sea of Marmara was fresh to brackish lake during MIS-4 to MIS-2 and that a fully marine connection occurred at 12.6 ka BP. Using the robust age model for the core, the Holocene main and the upper sapropel units were dated to 12.3–5.7 ka and

5.4–2.7 ka BP, respectively (Çağatay et al. 2015a). Earlier, however, Vidal et al. (2010) documented that the initial marine connection took place at 14.7 ka BP, and that the hydrologic change from lacustrine to marine conditions was gradual. These authors also documented an increase in the salinity and sea surface temperature in the Sea of Marmara after the Younger Dryas (12.7–11.5 ka BP).

Palynological analysis of core MD01-2430 by Valsecchi et al. (2012) documented the existence of climate changes during the Last Glacial Maximum (LGM)-Holocene. Cold and dry conditions prevailed during the LGM, the late glacial until the Bølling-Allerød interstadial and during the Younger Dryas, whereas warm and moist climate conditions occurred during the early and middle Holocene. Multi-proxy analyses of the core by Çağatay et al. (2015a) showed a robust correlation with the north Greenland ice core (NGRIP) isotope (NGRIP members, 2004), Tenaghi Philippon pollen (Müller et al. 2011) and Black Sea Ca (Nowaczyk et al. 2012) records during MIS-4 to MIS-1, indicating strong teleconnections between the NW Anatolia, Eastern Europe and the North Atlantic. Core MD01-2430 also revealed some interesting tephra layers that were matched with the 3.9 ka Avelino eruption of Vesuvius-Somma, the 22 kyr BP Cape Riva eruption of Santorini, and 39.3 ka Campanian Ignimbrite eruption of Campi Flegrei (Napoli) (Çağatay et al. 2015a). Study of piston cores recovered during the 2004 MARMARA-VT 67 cruise effectively elucidated the late Quaternary evolution of the northern shelf of the Sea of Marmara, and the water-exchanges via the Bosphorus Straits during the Holocene (Eriş et al. 2007). Core MD-04-2745 on the northern shelf sampled two additional sapropel units deposited during the MIS-5. Data from this core, together with other staggered cores, allowed to date seismic stratigraphic units observed in Chirp profiles on the shelf, and determine the lake/sea level changes during the late Quaternary. Core MD04-2750 recovered a submerged channel-levee complex succession from the Marmara outlet of the Bosphorus channel. Analyses by Eriş et al. (2007) concluded that the undulating unit in the succession was formed by a Black Sea outflow during the Younger Dryas, and that the radial delta lobe was sourced by a creek east of the Bosphorus during Mid-Holocene rather than by the Black Sea outflow. However, these conclusions were later challenged by Hiscott et al. (2008), Eriş et al. (2008). Utilizing pore-water isotope and salinity data from MARMARA-VT 67 cruise cores, Aloisi et al. (2015) carried out modelling studies that showed that the Marmara “Lake” waters prior to the latest marine reconnection were brackish ( $S \sim 4\%$ ), and that following MIS-5, the freshening of the Marmara Sea by the Black Sea spill-out started at least 50 ka BP.

Up to 20 m-long piston cores were recovered from different parts the Sea of Marmara during MARSITECRUISE of R/V Pourquoi pas? in 2014. Some cores were specifically



located to date some seismic reflector surfaces and study paleoceanographic conditions during MIS-5 and 6 (Çağatay et al. 2019; Kendé 2017 PhD thesis), and for palynological analysis (S. Leroy and D. Biletekin, pers. com.). Multi-proxy analyses of two Marsite cores from the İmralı Basin produced important results on stratigraphy and environmental and hydrographic changes during MIS-5 and 6 (Çağatay et al. 2019). The chronology of cores showed that the regional “Red” seismic reflecting surface of Sorlien et al. (2012) corresponded to a hiatus at the MIS 5/MIS 4 transition (70–80 ka BP) rather than 110 ka BP, estimated by these authors. The paleontological and geochemical results indicated that fresh-brackish lacustrine conditions existed in the Sea of Marmara during MIS 6 and that the transition to marine conditions during Termination II took place at ~134 BP. Marine conditions prevailed during MIS 5, except during MIS-5b stadial and three sapropels were deposited during MIS-5 interstadials a, c, and e. The geochemical proxy records of the MARSITE cores showed good correlation with the NGRIP oxygen isotope and regional terrestrial and marine records, and the strong influence of the North Atlantic climatic events. The core data also suggested that the Dardanelles sill depth was at  $-75 \pm 5$  m during the reconnection at Termination II and at  $-55 \pm 5$  m during most of MIS 5, while the Bosphorus sill depth was more stable at -35 to -40 m, similar to that of the current day depth (Çağatay et al. 2019).

## 5.2 Paleo-seismology

Sub-aqueous paleoseismological studies are important for obtaining recurrence interval of earthquakes over several thousand years. This information is in turn important for probabilistic earthquake risk assessment. Such studies in the Sea of Marmara started after the 1999 İzmit earthquake (Polonia et al. 2002; 2004; McHugh et al. 2006), but increased considerably after Turkish–French geoscience collaboration, with the recovery of long piston cores and seafloor observations using ROV Victor and manned submersible Nautila (Armijo et al. 2005; Beck et al. 2007, 2015; Drab 2012; Çağatay et al. 2012; Eriş et al. 2012; McHugh et al. 2014). Up to 38 m-long cores allowed to obtain earthquake records extending back to several thousands of years, and to match the more recent ones with the 2500-year-long historical records of the Marmara Region (Ambraseys and Finkel 1995; Ambraseys 2002; Guidoboni et al. 1994; Guidoboni and Comastri 2005).

The sedimentological study of the 2001 MARMACORE cruise giant piston cores revealed that a considerable part of the sedimentary succession in the deep Marmara basins consists of turbidites, most of which were likely triggered by earthquakes. Radiocarbon dating of the cores indicated high sedimentation rates (1–3 m/ka) in the deep Marmara

basins, which could allow the individual seismic events to be distinguished in the sedimentary succession (e.g., Beck et al. 2007, 2015; Eriş et al. 2012). Moreover, Beck et al. (2007) also discovered a 5–8-m thick, 16-ka-old turbidite–homogenite (T–H) unit of tsunamogenic origin in cores MD01-2431 and MD01-2429 in the Central Basin. This distinct stratigraphic marker was clearly visible in the 3.5 kHz seismic profiles, and used for sedimentation, slip and subsidence rates estimations. For example, Çağatay and Uçarkuş (2018) estimated average sedimentation rates over the last 16 ka in the depocentre and basin margin of the Central Basin at 2.70 mm/year and 1.05 mm/year, respectively, and the subsidence rate in the depocentre at 6 mm/year.

The 4–5 m of piston cores and push cores, together with video recordings and micro-bathymetric mapping of fault scarps, obtained during the 2002 Marmarascars cruise on board R/V L’Atalante with the ROV Victor provided important data on the paleoseismology (e.g. Armijo et al. 2005). Considering the fresh fault scarps in the Tekirdağ Basin and the Western High, Armijo et al. (2005) concluded that the 1912 Mw=7.4 Şarköy-Mürefte earthquake rupture extended all the way to the Central Basin. Uçarkuş (2010) used micro-bathymetry data and  $^{210}\text{Pb}/^{137}\text{Cs}$  dating of the disturbances in the push cores to show that the 1912 earthquake rupture extended at least to the Central High. Drab et al. (2012) analysed the long cores of the Marmarascars cruise for turbidite paleoseismology and documented the records of the 1894, 1509, 1343 and 740 earthquakes in the Çınarcık Basin; 1912 (Şarköy-Mürefte), 1766, 1343 (or 1354), 1063 and 557 earthquakes in the Tekirdağ Basin; and evidence of the 1912 Şarköy-Mürefte earthquake in the Western High and the Central Basin (all dates are Common Era).

The Marnaut Cruise in 2007 provided 9–10 m long piston cores, ~1 m long water/sediment interface cores with undisturbed tops for paleoseismological studies as well as direct observations along the NAF. More than 20 MARNAUT piston and interface cores located in different basins and the highs were studied for turbidite paleoseismology using multi-proxy analyses and radionuclide datings by Çağatay et al. (2013) and three piston cores in the Central Basin by McHugh et al. (2014). More recently, the MARSITE-CRUISE with *R/V Pourquoi pas?* recovered ~20-m-long cores from the Kumburgaz and İmralı basins. A 21-m-long Marsite core, dating back to 6.1 ka from the Kumburgaz Basin on the Central High segment, included 28 seismo-turbidite units, providing an average recurrence interval of 220 years (Yakupoglu et al. 2019). However, the age-depth model indicated that the latest 1200-year-long record was missing, and thus, the archive for the recent major historical events such as of 1766 CE and 1509 CE could not be ascertained. Surprisingly, the MARSITE cores from the İmralı Basin contained almost no seismoturbidites, possibly

suggesting that low magnitude earthquakes in the south did not produce any mass-wasting from the basin's southern margin.

The main conclusions of all the above seismoturbidite studies can be summarized as follows: (i) turbidites triggered by  $M_w > 6.5$  earthquakes commonly consist of a coarse basal turbidite layer and an overlying homogeneous-looking mud layer (homogenite), forming together a turbidite–homogenite (TH) unit. The TH units range from a few to tens of centimetres in thickness, and usually have a sharp and erosional basal contact; (ii) the average recurrence interval over the last 5–6 ka is 200–300 years, compatible with GPS velocities and geological slip rates. However, the interval between two consecutive events can be highly variable; (iii) the records from different areas appear to be specific to the events on the nearby fault segment; (iv) basin depocentres and perched basins on highs are the best locations to obtain a complete earthquake record.

## 6 Fluid emissions, faulting and seismicity

### 6.1 Fluid emissions and their origin

Gas emissions in the water column in response to the August 17th, 1999 earthquake were observed by Alpar (1999) less than 1 month after the main shock, based on high-resolution (Sparkler) seismic data from the Gulf of İzmit and from the northern escarpment of the Çınarcık Basin. In the deeper basins of the Sea of Marmara, investigations in February 1999 with sediment sampling and a towed camera during the R/V Meteor, cruise 44 (e.g. Halbach et al. 2002; Kusçu et al. 2008) and in September 2002 with remotely operated vehicle during the MARMARASCARPS cruise on R/V Pourquoi pas? found indications of fluid expulsion along the active faults. These visual observations include: bubbles immediately beneath the seafloor at reduced sediment patches, notably on the Western High; active chimneys and carbonate crusts in the Central Basin and in the Tekirdag Basin—where fluid outflow is visible, due to a contrast in optical indices (Armijo et al. 2005). After the first findings of Halbach et al. (2004), a shallow sulfate–methane reaction zone (SMRZ) was also detected in sediment cores sampled during the MARMARA-VT cruise from the same areas at depths of 3–5 m below the seafloor. Based on these observations, the high-resolution seismic data (3.5 kHz) and deep-towed side-scan profiles collected by Le Pichon et al. (2001), were reprocessed, confirming the probable presence of trapped gases within the uppermost sedimentary sequences and gas escapes into the water column (S. Dupré, Pers. Comm.).

After numerous fluid vents and related features had been

discovered along the MMF, it became clear that the Sea of Marmara was an ideal site (possibly unique on Earth) to

study the coupling between deformation, seismic activity, fluid flow and gas expulsion within an active, submarine transform fault. As a consequence, from 2007 onwards, a massive effort was undertaken with support of the EU, to test the hypotheses that “the fluid properties within the MMF evolve with time throughout an earthquake cycle”, and that “some of these changes, or their consequences, can be recorded at the seafloor”. In total, three major expeditions were organized with French vessels to study the submarine hydrogeological system and how it was coupled to the tectonic system, through the interaction of fluid pressure and stress state. These expeditions are described here after.

- MarNaut (2007): The MARNAUT expedition of R/V L'Atlante in 2007 (Henry et al. 2007), was mainly dedicated to: (i) in situ deep-sea sampling of fluids (including gas), carbonate crusts and bacterial mats along the NAF submerged system using the *Nautilus* submersible (e.g. Bourry et al. 2009; Crémière et al. 2012; Burnard et al. 2012); (ii) gas emission mapping using single-beam 38 kHz echo-sounder (e.g. Géli et al. 2008); (iii) heat flow measurements (e.g. Grall et al. 2012); (iv) sediment coring; and (v) deployment of seafloor instrumentation (e.g. Tary et al. 2012; Tryon et al. 2012). Free gases were sampled at three sites, showing different composition and origin. Gases from the Western High—where gas hydrates were found—and from the Central High were predominantly methane gas of thermogenic origin and genetically related to the Thrace hydrocarbon Basin, whereas microbial methane gases were predominant in the easternmost Çınarcık Basin (Bourry et al. 2009; Ruffine et al. 2012). In contrast, dissolved gas extracted from water samples taken near the Tekirdag escarpment exhibit a predominance of methane, an abundance of  $\text{CO}_2$  and a mantle helium signature, suggesting a high permeability conduit from the mantle to the seafloor (Burnard et al. 2012). The diversity of pore fluids composition reflect mixing of fluids from different sources (Tryon et al. 2010; Ruffine et al. 2015) varying with time, based on long-term monitoring of fluid properties (Tryon et al. 2012). Microbial chemosynthetic communities (Ritt et al. 2010) and carbonate crusts (Crémière et al. 2012) were found to develop near venting sites, in relation to the anaerobic oxidation of methane (AOM) and other heavier hydrocarbons. Lipid biomarkers in authigenic carbonates were investigated, providing evidence that AOM mediated by methanotrophic archaea (ANME) and their bacterial partners, is the major process leading to sequestration of methane-derived carbon (Chevalier et al. 2011, 2013).
- Marmesonet (2009) and PirMarmara (2010): The Marmesonet expeditions (Leg 1 and 2) of R/V *Le Suroit* in 2009 were dedicated to: (i) the systematic mapping

of the water column using the shipborne multibeam echosounder for gas bubble detection (e.g. Dupré et al. 2015; Grall et al. 2018a); (ii) high-resolution bathymetric mapping (using an Autonomous Underwater Vehicle -AUV- allowing a resolution of 2.5 m) at three potential candidate sites for the deployment of multi-disciplinary observatories (Grall et al. 2013); (iii) the testing of seafloor instrumentation for the monitoring of fluid properties: piezometers, OBSs and acoustic bubble detector (e.g. Tary et al. 2012; Bayrakci et al. 2013; Tsang-Hin-Sun et al. 2019); (iv) high resolution, 3D seismic imaging to characterize the plumbing system below the Western High, where gas hydrates were found, in association with a mud volcano (e.g. Thomas et al. 2012;). The 3D seismic imaging was complemented by high-resolution 2D profiling using a longer streamer during the PirMarmara Cruise of R/V Piri Reis (e.g. Saritas et al. 2018). These cruises helped identify the complex connections between the fault network and the manifestations of fluid activity at the seabed (gas emissions, cold seeps, pockmarks, mud volcanoes, sediment instabilities, etc.). It seems one outcome of the Marmesonet cruise is an estimation of the MMF geological slip rate from offset geomorphological features and mass transport deposits (Grall et al. 2013).

- MarsiteCruise (2014): The MarsiteCruise expedition was divided into three legs. The first was devoted to the deployment of submarine instrumentation to collect long period series of geodetic and geophysical data (in collaboration with GEOMAR) to determine correlations between fault motion, intermittent fluid discharge and micro-seismicity (Sakic et al. 2016; Lange et al. 2019). The second leg was dedicated to ROV-Victor 6000 dives to investigate the geochemical dynamics of selected cold-seep sites (Fig. 4). During the third leg, sediment samples from long-gravity cores were collected to complete dating of seismic reflector surfaces in view of establishing chronostratigraphy for the last hundred thousand years. A Special Issue, entitled “Fluids and processes at the seismically active fault zone in the Sea of Marmara”, was published in 2018 in Deep Sea Research, Part II, providing the state of knowledge on the links between fluids, faults, seismicity and the hydrocarbon system in the Sea of Marmara (Ruffine et al. 2018a). A new strategy was deployed during the MarsiteCruise for gas-seep sampling and for developing new proxies to relate fluid properties to fluid migration history. As a result, the gas bubbles emitted at the seafloor were shown to be mixtures of primary and secondary microbial gases with thermogenic and mantle-derived gases with an asymmetric contribution of each source (Ruffine et al. 2018b). In addition, the authigenic carbonate crusts sampled at the seafloor during the cruise were dated less than 9.6 kyr BP and a majority were younger than 1000 years, suggesting

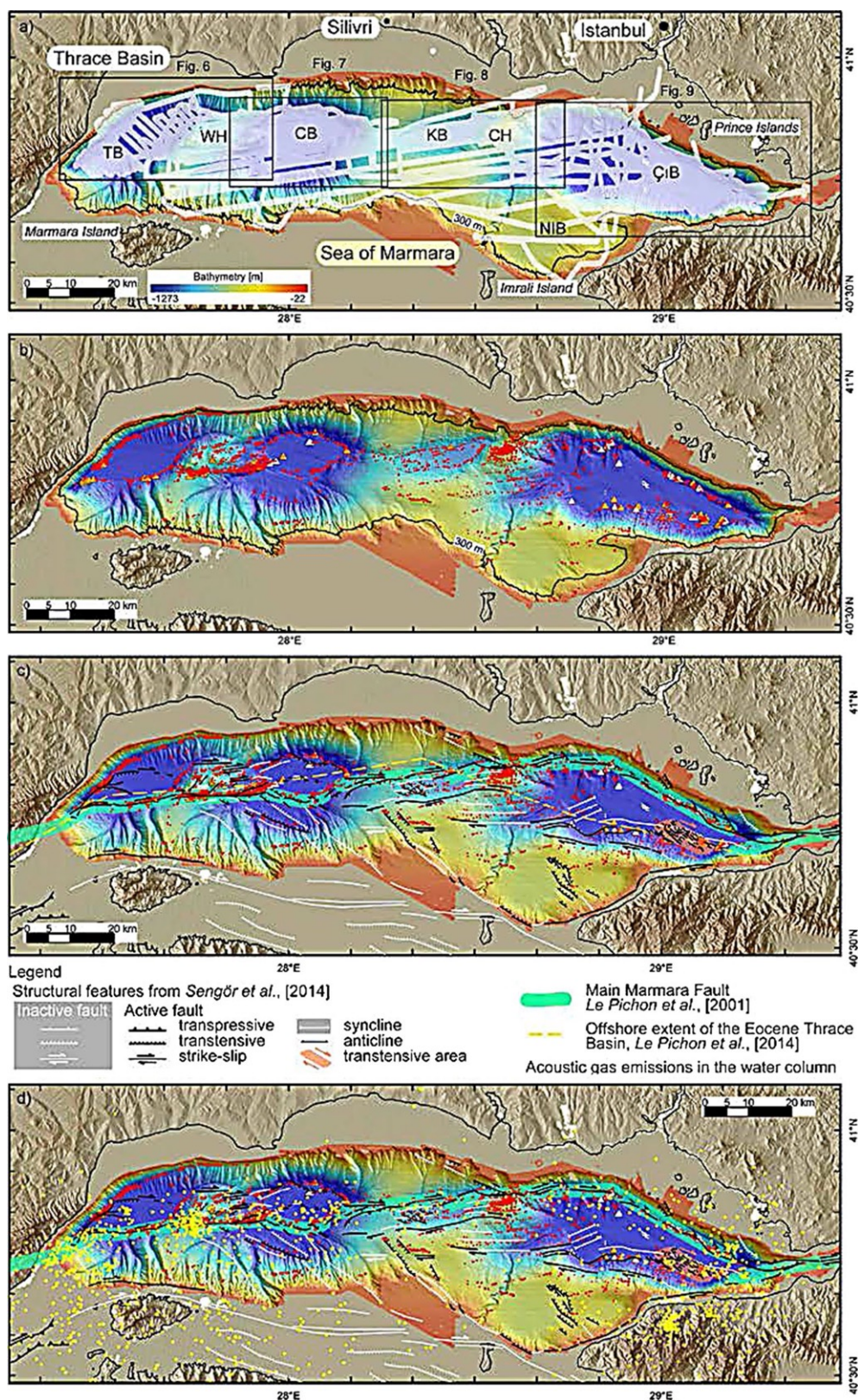
that authigenic carbonates could yield archives of fluid emission activity correlatable to historic seismic activity (Çağatay et al. 2018; Teichert et al. 2018). The geological and biological diversity of fauna was also investigated, showing that seeps sustain typical Mediterranean cold seep fauna, but also unusual communities likely related to the interaction of seeps with hypoxic conditions (Ondréas et al. 2020). These results naturally triggered renewed interest for assessing the hydrocarbon potential of the Marmara Sea basin (Palabiyik et al. 2020).

## 6.2 Relations with faulting and seismicity: summary of current knowledge

The new knowledge considerably improves our understanding of the fluid system in relation to faulting and seismicity in the Sea of Marmara and more generally in submarine environments. The EM-302 multibeam survey carried on R/V Le Suroit during the MARMESONET cruise (2009) provided a nearly continuous and uniform coverage of acoustic anomalies in the water column indicative of gas emissions at the seafloor. The superposition of the acoustic anomaly map on the active fault map (Fig. 3) indicates that (quote from Dupré et al. 2015): “gas emissions are spatially controlled by a combination of factors, including fault and fracture networks in connection to the MMF system and inherited faults, the nature and thickness of sediments (e.g., occurrence of impermeable or gas-bearing sediments and landslides), and the connectivity between the seafloor Drensen and Malin (2017) and gas sources, particularly in relation to the Eocene Thrace Basin. The relationship between seepage and fault activity is not linear, as active faults do not necessarily conduct gas, and scarps corresponding to deactivated fault strands may continue to channel fluids. Within sedimentary basins, gas is not expelled at the seafloor unless faulting, deformation, or erosional processes affect the sediments. On topographic highs, gas flares occur along the main fault scarps but are also associated with sediment deformation.”

Henry et al. (2018) later applied a statistical approach to characterize quantitatively the relationship between seeps and active fault and found that gas emissions are more abundant within a swath of 900–1000 m (half-width) from an active fault, which corresponds to the width of the deformation zone observed at the seafloor in association with major faults. To explain the remaining 20%, Grall et al. (2018b) distinguish gas migration pathways controlled by sedimentary structure from those controlled by faults. A conceptual model is further proposed, in which (quote from Henry et al. 2018) (see also Okay and Aydemir 2016): “Updip migration along permeable strata will result in gas migration toward the edges of the basins and its accumulation in anticlines and at sedimentary discontinuities (sediment-basement contact and







◀ **Fig. 3** After Dupré et al. (2015). Relations between active gas emissions and active faulting. **a** EM302 water column multibeam track lines during the 2009 Marmesonet expedition. The white buffer along the navigation stands for the insonified zone within which gas bubbles are detectable. *TB* Tekirdağ Basin, *WH* Western High, *CB* Central Basin, *CH* Central, *KB* Kumburgaz Basin, *ÇİB* Çınarcık Basin, *NİB* North İmralı Basin. **b** The 2-D Marmara shaded bathymetry map with gas flare distribution, **c** fault networks from Şengör et al. [2014] with the offshore extent of the Eocene Thrace Basin from Le Pichon et al. (2014), and **d** microearthquake epicenters (yellow dots) recorded between 2005 and 2011 [Şengör et al. 2014; H. Karabulut, personal communication, 2013]. White, orange, and red marks stand for water column acoustic anomalies recorded in 2000, 2007, and 2009, respectively. The maps illustrate the 2009 seepage activity over more than 1 month (from 4 November 2009 to 14 December 2009). Each of these acoustic anomalies is displayed as a 150 m radius red dot

intra-sediment onlaps). Gas is eventually expelled along anticlines through extensional structures or along basin edges. This pattern will be observed if faults do not have high permeability, which may be the case during the inter-seismic period if faults are locked. It can be suggested that this is the current state in the Central High zone. After an earthquake, permeability increase in the ruptured fault enables focused fluid migration through the fault zone and a transient redistribution of gas emission sites at the seafloor. If fault creep also enhances permeability, permanent fluid expulsion through creeping fault zones could occur, following a similar pattern as for post-seismic fluid flow. It can be suggested that this is the case for the Western High zone". Eventually, Henry et al. (2018) put this difference in perspective with recent work showing that "creep is occurring on the western segment of the Main Marmara Fault (this also causing micro-seismicity) while the central Istanbul-Silivri segment may have remained locked since the 1766 magnitude 7 + earthquake. This suggests that aseismic slip (and not only earthquake occurrence) effectively maintains high permeability conduits in fault zones in sediments."

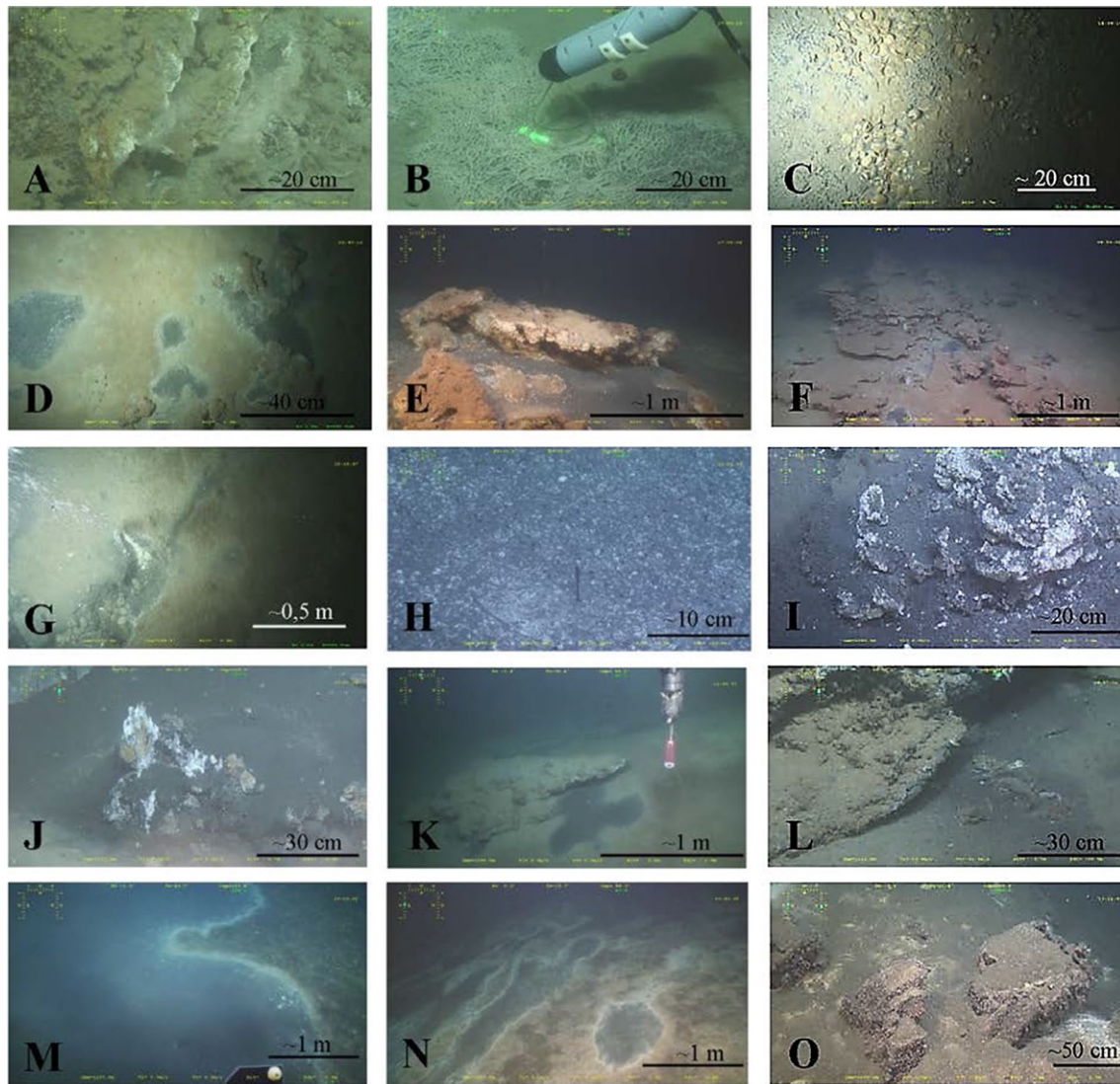
Let us now address the question of the relations between gas emissions and micro-seismicity. Géli et al. (2018) note that the occurrence of gas emissions appears to be correlated with the distribution of micro-seismicity, particularly on those segments where creeping is suspected along the MMF. Indeed, events of magnitude greater than  $\sim 4.2$  regularly occur in the Western Sea of Marmara, generating large sequences of aftershocks below sites where the density of gas emissions is at a maximum along the MMF. A large number of the aftershocks that followed the M 5.1 earthquake of 25th July 2011 occurred below the Western High, within a zone where pressurized gas is expected to migrate along the MMF, all the way up through the surface sediment layers. Hence, they concluded that gas-related processes should also be considered for a complete interpretation of the micro-seismicity ( $\sim M < 3$ ), particularly at

supposedly creeping segments, where high permeabilities within the damage zone are expected to channel gas up to the seafloor.

### 6.3 Implications for earthquake hazard assessment

The geometry of the MMF is now well established. One of the many questions facing the scientific community is how the MMF will rupture? In one single segment? Or in multiple segments? What is more, active faults causing offsets within the recent sediments have been identified, as well as buried faults which may be interpreted as blind faults with uncertain activity (Şengör et al. 2014), suggesting that ruptures may happen outside the MMF fault plane. While predicting earthquakes on out-of-plane faults (secondary or splay) is generally considered to be impossible, active research is presently ongoing to determine the seismological behavior of the different segments along the MMF, which involves 75% of the geodetic strain across the Sea of Marmara (e.g. Meade et al. 2002; Hergert and Heidbach, 2010; Reilinger et al. 2010; Le Pichon et al. 2016; Özbey et al. 2021; Zabci et al. 2019). Numerous recent papers have been dedicated to addressing which segments are creeping and which are locked along the MMF.

Land-GPS data show a lack of elastic strain accumulation along the central and western part of the MMF (Ergintav et al. 2014). Inversion of data in 3D finds heterogeneous locking on the MMF (Bulut et al. 2019; Klein et al. 2017), but today, land-GPS data alone cannot yet resolve the distribution of interseismic loading rates vs. aseismic slip rates on the central and western part of the offshore fault (Klein et al. 2017). Seismology approaches suggest that the MMF has a deep creep component in the western Sea of Marmara, but not on the Central High nor on the Prince Islands segment (Bohnhoff et al. 2013, 2016, 2017; Schmittbuhl et al. 2015; Uchida et al. 2019). The Western High and the Central Basin segments are characterized by a higher level of background seismicity that at the adjacent segments (Schmittbuhl et al. 2016) and by the common occurrence of repeating small earthquakes (Bohnhoff et al. 2017; Schmittbuhl et al. 2016). Furthermore, acoustic ranging experiments indicate an aseismic creep rate at the seafloor of 9–16 mm/year on the Western High (Yamamoto et al. 2019) and no creep at the Central High and Kumburgaz Basin, where the level of microseismicity is notably low (Sakic et al. 2016; Lange et al. 2019). Joint inversion of land GPS and marine geodesy constraints shows that there is no incompatibility between these two data sets and that the MMF has significant creep west of 28.2° E but is essentially locked eastwards (Özbey et al. 2021). These conclusions are also supported by other approaches, including the analysis of seismic velocity data (e.g. Tarancioğlu et al. 2020).



**Fig. 4** After Ruffine et al. 2018b. Seafloor observations with ROV Victor reported during the MARSITE (MRS) Cruise on *R/V Pour-quoi pas?* See also <http://dx.doi.org/10.1016/j.dsr2.2018.03.006>. **a–c** Dive MRS-DV592 starting from eastern border of the Kumburgaz Basin to the Central High. Black patches associated with bacterial mats and fauna (**a**); In-situ RAMAN spectrometer analyzing gas streams bubbling from sites covered with specific white spaghetti-like bacterial (**b**); Hemipelagic sediment covered at some seep sites by dense accumulation of bivalve shells, presumably dead (**c**). **d–f** Dive MRS-DV593 on the Western High. Areas with reduced black sediment associated with both bacterial mats (narrow or large ones) and carbonate crusts (**d**); Large areas of massive carbonate crusts, with or without bacterial mats around and discontinuous oil seeps (**e**); Brown soft sediment present with bioturbation as well as dead or alive sea urchins outside the seepage areas covering carbonate crusts. **g–i** Dive MRS-DV594 in the Tekirdag Basin. Intensive bubbling site at the foot of the Tekirdag escarpment discovered during MarNautCruise and called “Boris Bubbler” after Henry (2007) (**g**); Wide spread oil

seep emitting oil droplets, creating a cloud of beads rising into the water column (**h**); seep discharging a shimmering fluid through small carbonate chimneys along with continuously or intermittently gas and oil seeps (**i**). **j–l** Dive MRS-DV595, a 2-km length track from east to west along the SE border of Tekirdag Basin. Site named “Jack the Smoker”, a chimney covered with microbial mats and discovered during Marnaut cruise (Burnard et al. 2012; Tryon et al. 2010), revisited during MARSITE cruise (**j**); near-by, active bubbling site, located at a canyon outlet south of Tekirdag basin (**k**); bubbling site characterized by corals, anemones and mussels fixed on carbonate crusts (**l**). **m–o** Dive MRS-DV596 in the Cinarcik Basin. Large black reduced sediment patches with surface areas of ~ 100–200m<sup>2</sup>, bacterial mats (orange and white) and carbonate crusts (**m**); Seeps associated with numerous massive carbonate crusts of few meters scale in dimension and elongated black (**n**); Diversified fauna observed upon and around carbonate crusts, along the SE border at the foot of the slope: amphipods, anemones, corals and crustaceans (**o**)

If we superpose these results—on the distribution of creeping segments—and those on the distribution of the zones where the amount of gas emissions is at a maximum

(Dupré et al. 2018), we note a systematic correlation between the two (Henry et al. 2018). In summary, for the Western High, we have the following sequence: (i) relation

seismicity/creep: (Schmittbuhl et al. 2015, 2016); relation seismicity/fluids: (Géli et al. 2018); relation creep/fluids: (Henry et al. 2018); confirmation of creep using acoustic geodesy: (Yamamoto et al. 2019).

All these findings draw up new research avenues regarding the possible use of gas emissions mapping as a proxy for characterizing the behaviour (locked vs creeping) of the MMF, and more generally, the behavior of submarine transform-fault segments (e.g. Hensen et al. 2019).

## 7 Implementing seafloor observatories in the Sea of Marmara

### 7.1 Present situation

The turn of the century was also a time when major deep seafloor, multidisciplinary observatory programmes were being initiated world-wide, giving birth to today's large infrastructures such as: "Ocean Network Canada" in Canada (<https://www.oceannetworks.ca/>); Ocean Observatory Initiative in the USA (<https://oceanobservatories.org/>); DONET (<https://www.jamstec.go.jp/donet/e/>) and S-Net (<https://www.bosai.go.jp/e/>) in Japan. In Europe, the EU was promoting the European Seafloor Observatory Network (ESONET) and European Multidisciplinary Sea Observatory (EMSO), aspiring to developing multidisciplinary seafloor observatories off the coast of European and associate countries, e.g. including Turkey (Çağatay et al. 2015b). In this context, the Sea of Marmara Sea was considered as the ideal location for implementing seafloor observatories geared towards hazard assessment, due to (i) the potentially high societal impact, in a region where more than 15 millions people are under the threat of seismogenic hazard in the whole MARNAUT Area; (ii) the logistics, favored by the proximity to the coastlines (only 5–30 km), which make for cost-effective and realistic the establishment of permanent seafloor observatories; (iii) the deformation rates (20 mm/year) are very high compared to all other marine sites in Europe, resulting in active sub-marine processes that are measurable on short time scales. The route towards permanent, real-time, multi-disciplinary seafloor observatories is very long (Fig. 4). However, some progress has been made over the last decade:

- Based on the results of the MarNaut cruise, the EU successively funded the Marmara Demonstration Mission (DM) as part of ESONET-NoE (cf Ruhl et al. 2011 and <http://www.esonet.marmara-dm.itu.edu.tr/>) and the Marsite Project (P.I. Nurcan Özel; cf Özel et al. 2017 and <http://marsite.eu/>), in which one work package was dedicated to marine operations (including MARSITE-CRUISE of *R/V Pourquoi pas?*), for preparing the implementation of multidisciplinary seafloor observatories.

Four optimum sites for future deployments of multi-parameter, permanent observatories were identified at, respectively: the Western High, the central basin, the Central High and at the entrance of the Gulf of İzmit. Moreover, the deployment of autonomous, innovative instrumentation provided the expertise and know-how for monitoring pore fluid properties on the seafloor Çağatay et al. (2015a). The instrumentation included: acoustic bubble detectors (e.g. Bayrakci et al. 2014); aqueous flux meters for very low to moderate discharge rates (Tryon et al. 2012); piezometers (Henry et al. 2007); oceanographic sensors (temperature, salinity, current velocity, dissolved oxygen, turbidity) and methane sensors (e.g. Embriaco et al. 2013); and also, extensometers for acoustic ranging for seafloor geodesy (Sakic et al. 2016; Lange et al. 2019).

- At the same time, the Marmara Sea Bottom Observatory (MSBO) project of the Kandilli Observatory and Earthquake Research Institute (KOERI) was funded by Turkish Telecom, independently of ESONET. Five cables connecting land stations to seafloor observatories (including broad band seismometer, accelerometer, differential pressure meter, hydrophone, temperature meter, current meter, and tiltmeter sensor) were operated from 2009 to 2012 by KOERI as part of the Turkish national network for earthquake and tsunami hazards monitoring (e.g. Kalafat et al. 2009; Kalafat et al. 2009; Gürbüz et al. 2011; Kalafat et al. 2012; Gürbüz et al. 2009). Other international bilateral collaborations were established by KOERI in the field of marine geosciences, particularly with JAMSTEC (Japan Agency for Marine-Earth Science and Technology) for OBS deployment (e.g. Yamamoto et al. 2019) and acoustic extensometers for seafloor geodesy (e.g. Yamamoto et al. 2019).

### 7.2 Challenges in seafloor geodesy

The relative motion between Anatolia and Europe is constrained by data from space geodesy (e.g. Reilinger et al. 2006, 2010) and amounts to  $24 \pm 1$  mm/year of the geodetic slip rate on the North Anatolian Fault. The North Anatolian fault system divides westward into a northern fault branch crossing the Sea of Marmara between İzmit Gulf and Ganos and a Southern fault system, which itself comprises the Gemlik fault and its offshore prolongation (the Middle Branch) as well as the Southern Branch. The strain partitioning between the two systems is such that the northern fault branch takes up most of the strike-slip component of plate motion while the southern fault system accommodates oblique extension (e.g. Flerit et al. 2003; Reilinger et al. 2010; Le Pichon et al. 2016). Therefore, a critical issue for seismic hazard assessment is to determine the mechanical behaviour of the different segments along the MMF, and thereby identify those with the highest

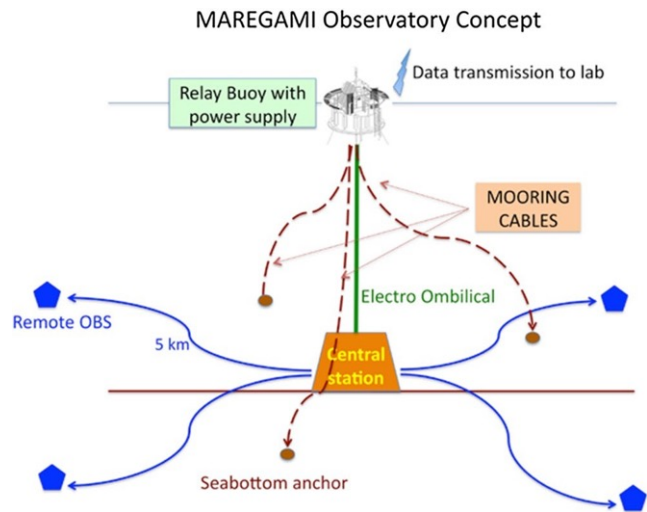


probability to rupture during the next expected Marmara earthquake. For instance, the low, or absence of, interseismic loading in the Istanbul area at about 10 km distance from the fault is puzzling (Ergintav et al. 2014; Le Pichon et al. 2003). But the presence of the water cover above the fault trace and the absence of islands to the south of the fault limits the use of land-based GPS data in estimating the strain accumulation and slip deficit along each of the segments. The efforts made so far to collect acoustic-based geodetic data are encouraging (e.g. Sakic et al. 2016; Lange et al. 2019; Yamamoto et al. 2019). However, acoustic ranging techniques are restricted to very small areas of a few kilometres in length along the fault, which limits their interest for studies at the scale of the entire submarine fault. Moreover, the integration of acoustic ranging data in GPS-based networks with the required accuracy is a challenge that appears to be unreachable today. Technical solutions, hereafter called GNSS/A do exist, combining acoustic transmission in the water column and the Global Navigation Satellite System (e.g. Chadwell 2017). In the next section, we propose to include GNSS/A geodesy in the Maregami concept described hereafter.

### 7.3 The Maregami concept including GNSS/A

Distributed Acoustic sensors -DAS- based on fiber optics, is certainly the most promising technology for future seismological monitoring in the Sea of Marmara (e.g. Sladen et al. 2020). Still, we present here the Maregami concept, which pre-dates the DAS revolution (Lindsey et al. 2017), as it allows multi-parameter seafloor monitoring and possible integration in GNSS.

In 2017, ANR and TUBITAK (respectively, the French and Turkish national funding agencies for research) decided to fund the 3-year-long MAREGAMI Project (P.I.s Louis Géli -Ifremer- and Ziyaadin Çakir—ITU). One of the objectives of the project was to design an optimized submarine monitoring observatory system, with the following attributes: (i) simple; (ii) robust; (iii) fully integratable in the local monitoring network; (iv) densely distributed (spatially) on the Marmara seafloor. To ensure the adequate spatial distribution, the “MAREGAMI observatory concept” was proposed as a versatile and multi-disciplinary alternative to cabled sea-floor observatories. It is based on three components (Fig. 5): (i) a sea-surface «buoy» or «platform» for energy production from solar panels and data transmission to land; (ii) three mooring lines and a link from surface to sea-floor, consisting of an electro-mechanical umbilical for energy transfer and data communication; (iii) a central node equipped with measuring instrumentation and connected (via electric cables) to four remote nodes, located 5 km away. Based on the results of the ESONET-NoE and MARSITE projects, three sites were selected: the Western High, the Central



**Fig. 5** In 2017, ANR and TUBITAK decided to fund the 3 years-long MAREGAMI Project, with the objective to design an optimized submarine monitoring observatory system, having the following attributes: i) simple; ii) robust; iii) fully integratable in the local monitoring network; iv) densely distributed (spatially) on the Marmara seafloor. To ensure the adequate spatial distribution, the “MAREGAMI observatory concept” was proposed as a versatile and multi-disciplinary alternative to cabled sea-floor observatories. It is based on three components (see lower panel): (i) a sea-surface «buoy» or «platform» for energy production from solar panels and data transmission to land; (ii) three mooring lines and a link from surface to sea-floor, consisting of an electro-mechanical umbilical for energy transfer and data communication; (iii) a central node equipped with multi-parameter instrumentation and connected (via electric cables) to four remote nodes, located 5 km away. Work is presently in progress for integrating the possibility of collecting GNSS/A data in the MAREGAMI concept

Basin and the Central High (for details, see technical reports: Abalain 2018; Bompais 2018; Lagadec 2018). Work is currently in progress for the possible integration of GNSS/A data acquisition in the MAREGAMI concept.

## 8 Conclusions and perspectives

Based partly on the several seismic and bathymetric surveys carried out within the framework of Turkish–French collaboration, there is no question today that the western prolongation of the NAF within the Sea of Marmara comprises a through-going dextral strike-slip fault—called the Main Marmara Fault—that enters the sea through the gulf of Izmit and joins the Ganos Fault at its western extremity. Also, the MMF holds about 75% of the geodetic slip rate (Le Pichon et al. 2016; Zabci et al. 2019), which suggests that at least 25% of the displacement is taken outside the MMF principal shear zone, on other fault branches (e.g. 3–4 mm/yr on the southern NAF branch in Gemlik Bay (Polonia et al. 2004; Gasperini et al. 2011; Vardar et al. 2016; Özbey et al. 2021)

and as distributed deformation. After 20 years of investigations, on-shore and off-shore, we still do not know where and when the next earthquake will strike. The next earthquake of  $M > 7$  may occur along the seismic gap on the MMF or along one less prominent fault of the NAF system with no, or sparse, historical seismicity.

After the success of the prediction of Stein et al. 1997, the common view was that assessing the probability of the next big one ( $M > 7.4$ ) in the Sea of Marmara, comparable to the 1766 earthquake, was a reachable objective (e.g. Parsons et al. 2000; Parsons et al. 2004; Pondard et al. 2007). In 2000, for instance, Parsons et al. found “a  $62 \pm 15\%$  probability (one standard deviation) of strong shaking during the next 30 years and  $32 \pm 12\%$  during the next decade”. Today, the probability of an earthquake of  $M > 7$  occurring along the MMF is estimated to be the highest for the central or eastern part of the Sea of Marmara (e.g. Bulut et al. 2019), and the “possibility of a western-initiated, super-shear rupture propagating eastward, the worst scenario for the Istanbul region, cannot be ruled out” (quote from Aochi and Ulrich 2015). When the September, 26th 2019, earthquake of magnitude 5.4 occurred in the MMF principal shear zone near the western end of the Istanbul-Silivri segment (Karabulut et al. 2020), 20 years after the Izmir earthquake, nobody was able to tell whether this event was the precursor of a larger earthquake of  $M > 7$ . The despair that then affected the scientific community reflects that we still have much to learn and many scientific questions to address:

- What is the role of the deep crustal structure on theseismicogenic behavior of active faults?
- What is the role of asymmetry in crustal elastic properties north and south of the fault? Does it for instance explain the low, or no, interseismic loading in the Istanbul area at about 10 km distance from the fault (Ergintav et al. 2014)?
- What is the real significance of “creeping” along active faults? (Cetin et al. 2014)
- How much stress is released or transferred to adjacent segments by earthquakes of intermediate magnitude?
- What is the contribution to creeping that can be, respectively, ascribed to the presence of: (i) serpentinite crustal bodies at depth as below the Ismiztpaşa (e.g. Cetin et al. 2020)? (ii) soft sediment cover (e.g. Yamamoto et al. 2019)? (iii) high fluid pressure (Géli et al. 2018)?
- Are there slow-slip events—yet undetected—along the MMF?

The Sea of Marmara has also been shown to be a unique, natural laboratory to improve our understanding of the relationships between fault activity, seismicity, fluid migration and ecosystems at a major, transform plate boundary (e.g. Ruffine et al. 2018a; Hensen et al. 2019):

- Are there changes in the fault-fluid properties during the earthquake cycle that could be detectable from the seafloor?
- Can fluids transformations produce archives of past seismicity along the MMF fault segments?

Continuous, long-term time series are cruelly missing to address some of the fundamental questions listed above. Implementing multi-parameter seafloor observatories (including seismology, geodesy and sensors on fluid properties) is a long-term enterprise, that demands sustained efforts, adapted facilities, dedicated manpower, which all require political and financial support. We are only in the middle of the way and we must go on. What is the most needed today, is to unite forces, to build a project supported by all institutions in Turkey and by the international scientific community.

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