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High-Resolution Seismic Characterization of Shallow Gas Accumulations in the Southern Shelf of Marmara Sea, Turkey

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Abstract

High-resolution seismic survey was conducted to investigate acoustic characteristics of gassy sediments along the southern shelf of the Sea of Marmara. The acoustic turbidity zones outlined within the study area are generally below 2-9 m (2-10 ms TWT) the seafloor whilst this vertical distance varies between 9 and 21 m (10-25 ms TWT) for acoustic blanket type reflections. The gassy sediments cover an area of sea floor of about 45, 110, and 75 km^2 in front of Gönen River, Kocasu River, and Gemlik Bay, respectively. The gassy sediments in the center of Gemlik Bay exhibited an elliptical geometry similar to its basin while the others have deltaic forms in front of the rivers. The sea bottom and near surface sedimentary units are made-up of organic-rich sediments, mostly transported by the southern rivers. The gas observed in sediments is thought to be of biogenic origin, which may be caused by degradation of organic matter in the sediment.

Key words: shallow gas, pockmarks, high-resolution seismic, southern Marmara Sea, acoustic properties.

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1. INTRODUCTION

Gas bearing sediments occur worldwide (*e.g.*, Emeis *et al.* 2004, Laier and Jensen 2007, Mazumdar *et al.* 2009, Chun *et al.* 2012), typically in shallow environments with a depth of less than 50 m (Fleischer *et al.* 2001). As derived from low-temperature chemical and biochemical processes at or near the sea-floor, methane (CH_4) is the most common and abundant hydrocarbon gas in near-surface sediments from offshore areas (Judd *et al.* 2002). If methane concentrations are high enough to exceed methane solubility, then free gas occurs and permits the formation of gas bubbles (Schubel 1974, Abegg and Anderson 1997, Whiticar 2002). Methane is a strong greenhouse gas and is believed to contribute to rapid global climate changes depending on its concentration levels in the atmosphere (Overpeck and Cole 2006). Its global warming potential is more than 20 times higher compared to CO_2 (Hovland and Judd 1988, Hovland *et al.* 1993, Judd *et al.* 2002, Lowe and Walker 1997).

Gas bearing sediments are also geologically hazardous. Any changes in pressure or temperature affect their stability. This may trigger sediment failure, especially in front of submarine deltas on continental shelves and continental slopes, and can be destructive because it breaks submarine cables, collapse marine infrastructures, and even produce tsunamis (Prior and Coleman 1982, Hovland and Judd 1988). In addition, shallow gas accumulation may also cause dangerous blowouts if they are encountered unexpectedly during drilling operations.

Considering the Turkish coastal seas, several gas bearing regions have been discovered in the Black Sea (Ergün *et al.* 2002, Çifçi *et al.* 2003, Dondurur 2005), Aegean Sea (Bange *et al.* 1996, Dondurur *et al.* 2011) as well as in the Sea of Marmara (Zitter *et al*. 2008). The gas seepage and fluid escapes in the Sea of Marmara might have resulted from a combination of various factors, mostly associated with active tectonic features (Ritt *et al.* 2010). Following the devastating earthquake of 17 August 1999, many water-column acoustic targets were recorded, representing expulsion of gas through seafloor fault ruptures in the Gulf of Izmit (Alpar 1999). Armijo *et al.* (2005) observed cold fluid and methane seepages in the deep basins of the Sea of Marmara which were in close spatial association with the active fault zones. The methane contained within gas hydrate sampled along the main fault on the Western and Central Highs was clearly thermogenic, whereas biogenic methane mixed with a trace amount of thermogenic ethane was reported in the eastern basin of the Sea of Marmara (Bourry *et al.* 2009). Local gas-bearing sediments were also observed in the late Quaternary depositional sequences in the Strait of Çanakkale (Dardanelles) (Alpar *et al.* 1996); these are basal transgressive marine sediments, basinward-prograding deltaic sediments and post-transgression marine deposit from bottom to top (Yaltırak *et al.* 2000). The gas could have been formed by fermentation reactions during the early diagenesis of the basal transgressive marine sediments.

Gas in shallow sediments has two main potential sources: (i) biogenic gas produced by bacterial degradation of organic matter at low temperatures, and (ii) thermogenic gas produced by high temperature degradation and cracking of organic compounds at considerable burial depths (Rice and Claypool 1981, Missiaen *et al.* 2002).

Thermogenic hydrocarbon gasses are produced in the sediment at depths where organic matter encounters high temperatures and pressure, *i.e.*, several hundred of meters to kilometers below the Earth's surface (Schoell 1988). Thermogenic methane, for example, represents the last stage of hydrocarbon production or upward migration of gas if identified in a hydrate. Its presence in sediment depends on a fault or a bedding plane in the vicinity that could provide the pathways for the gas (Kvenvolden *et al.* 1981).

Biogenic formation of gas, principally methane, is due to anaerobic degradation of living organisms such as planktonic matters, plants, fishes, and other organic material derived from solid wastes. Most biogenic methane is produced by the anaerobic degradation of abundant organic matter and deposited in marine subsurface where the sedimentation rate is high (Hovland and Judd 1988). The deltaic sediments constitute the major sink for organic material where higher rate of sedimentation increases the average accumulation rate, and prevents oxidation of organic matter until bacterial degradation (Baraza and Ercilla 1996). In addition to low temperature, availability of organic matter and sufficient space, methane accumulation become dominant after sulfate in sediment pore water is depleted (Rice and Claypool 1981). Therefore, biogenic (microbial) methane is usually generated hundred meters below the seabed and considered as shallow accumulations (Judd *et al.* 2002). It is typically associated with fine-grained sediment due to its characteristically higher initial organic content. Most of the shallow gas-bearing sediments, as well as gas escape features, are seen in the bays, deltaic accumulations and in the basins (Vilas *et al.* 1995, Okyar and Ediger 1999, Ivanov *et al.* 1998, Yun *et al.* 1999).

Biogenic gas may be an eco-friendly fuel for various energy needs. Many shallow biogenic gas reservoirs, associated mostly with the Late Quaternary deposits, have recently been discovered throughout the world (*e.g.*, Judd and Hovland 1992, Okyar and Ediger 1999, Fleischer *et al.* 2001, Ergün *et al.* 2002, Garcia-Gil *et al.* 2002, Gay *et al.* 2006, Dondurur *et al.* 2011) and successful efforts have been made for their exploitation. The main scope of present paper is to describe the distribution of gas bearing shelf sediments along the southern margin of the Sea of Marmara (Fig. 1). The aspects of their origin related to the seismically delineated stratigraphic structure of study area will be discussed based on the shallow Chirp seismic reflection profiles, some of which have been published previously (Vardar *et al.* 2014).

2. SEISMIC EXPRESSION OF SHALLOW GAS

Buried hydrocarbons represent an opportunity to meet natural gas needs in the future. Evidence of the buried hydrocarbons above and below the seabed may take many forms. Depending on their different velocities and frequency-dependent attenuation responses, gas-bearing sediments may have various characteristic expressions in high-resolution subbottom seismic profiles (Judd and Hovland 1992, Baraza and Ercilla 1996). The presence of free gas in the shallow sediments changes the physical properties of sediment, causing absorption and scattering of most of the seismic energy. Anomalously high-amplitude reflections related to gas bearing sediments blank out the deeper data (Field *et al.* 1980, Baltzer *et al.* 2005). The gassy sediments can be easily determined by high-resolution reflection seismic data. Depending on their seismic character, size and geometry, various descriptive expressions have been used for gas-bearing sediments, such as acoustic blanket, plumes, curtain, and acoustic turbidity (Yun *et al.* 1999, Garcia-Gil *et al.* 2002, Baltzer *et al.* 2005).

Acoustic blankets. These types of gas accumulations are identified on high-resolution seismic records by their high-amplitude and diffuse facies and often are completely masking the underlying seismic record. They are characterized by enhanced upper reflections and abrupt lateral facies changes. These zones contain higher amount of gas (Judd and Hovland 1992).

Acoustic column. These types of gas accumulations are identified by their transparent pillar shapes as vertical smearing features in seismic data. Acoustic column type seismic signatures are caused by rising up free gas through the sedimentary layers and usually located in the vicinity of blanket and curtain type signatures (Hovland and Judd 1988).

Acoustic curtains. These type of gas accumulations are characterized by high-amplitude and diffuse facies, with a sharp upper boundary. Acoustic curtains are smaller in lateral extension if compared to the acoustic blankets. If the acoustic curtain reaches the seafloor and follows the seafloor morphology then it is called “black shadow” or “white fringe”, depending on its seismic appearance.

Acoustic turbidity. Local gas bubble accumulation absorbs the acoustic energy, preventing acoustic penetration at certain depths. At these depths, seismic reflections are chaotic or disturbed and they are characterized by strong scattering of seismic energy, enhanced reflectors with inverse polarity and velocity pull-downs. The upper boundary of acoustic turbidity (gas front) may have various shapes. Under the gas front, the acoustic turbidity usually wipes out other coherent seismic signals completely or reduces their amplitudes (Judd and Sim 1998).

Natural gas and/or overpressure fluid flow in near-surface sediments causes pockmarks which are crater-like features on the seafloor (*e.g.*, Baraza and Ercilla 1996, Ergün *et al.* 2002, Çifçi *et al.* 2003, Gay *et al.* 2006, Iglesias and García-Gil 2007, Judd and Hovland 2007, Savini *et al.* 2009, Crutchley *et al.* 2010, Valle and Gamberi 2011). The main agent responsible for the formation of these remarkable geological features is either ascending gas or fluid flow (King and MacLean 1970). The fluids or gas cannot escape without percolating through fine-grained sediments (mud in our case) and such disturbances cause pockmarks. They often appear as isolated patches. The pockmarks are usually found in groups and associated with acoustic disturbances originating from layers lying beneath recent sediments, implying some active faults or vents through which gas or liquids migrate (Rollet *et al.* 2009, Canet *et al.* 2010, Dondurur *et al.* 2011). Buried pockmarks range in size and stratigraphic position and may be related with gas bubbles trapped in the substrata. In addition, active gas seepage in water column may be observed at tectonically controlled fault zones, especially after strong earthquakes (Alpar 1999).

3. TECTONIC AND SEDIMENTOLOGICAL SETTING

The recent-day tectonic activities and structural phenomena of the Marmara Region are controlled by various compressional and extensional tectonic systems along the North Anatolian Fault (NAF), a 1500-km-long intracontinental transform fault which splits into three branches to the west of the Sea of Marmara (Şengör 1979). This is caused by the transition of the pure strike-slip regime into a stress regime with additional N-S extension (Barka and Kadinsky-Cade 1988). The northern branch of NAF is the most active one with an average slip rate of ~10 mm/year for the last 10 kyr (Polonia *et al.* 2004). The middle strand of NAF cuts through our study area. It is less active and therefore it is considered less prone to rupture. It extends along the southern coast of Lake Iznik (Öztürk *et al.* 2009) and enters the sea in the Gemlik Bay which is formed as a pull-apart basin and controlled by east-trending faults (Yaltırak and Alpar 2002). The middle strand of NAF continues westward to emerge on land as the Mudanya Fault (Kuşçu *et al.* 2009) following the southern coast of the Bandırma Bay and then changes its direction southwestward at the eastern part of the Erdek Bay (Vardar *et al.* 2014). The NWW-SEE trending normal faults in the Erdek Bay are older as they have no effects on the recent seismic units (Vardar *et al*. 2014).

Late Quaternary sedimentation in the Sea of Marmara has been controlled mainly by sea or lake level changes and then by regional tectonic uplifts and increased supply of terrigenous sediments by southern rivers

(Table 1). The most important fluvial sources in the region are Kocasu, Gönen, and Biga Rivers (Fig. 1). The Kocasu and Gönen Rivers have their own underwater deltas (Kazancı *et al.* 1999).

Table 1

The drainage area, average discharge rate and suspended solid matter of the southern rivers (from Aksu *et al.* 1999)

Rivers	Drainage area [km^2]	Rate of average discharge [m^3s^{-1}]	Suspended solid matter per year [t]	Explanations
Kocasu	21 611	150.6	1 986 000	Delta
Gönen	1193	16.0	78 000	Delta
Biga	2096	18.6	97 000	No delta

The surface sediments covering the study area, which includes three small semi-isolated basins of Erdek, Bandırma, and Gemlik (Fig. 2), are composed of terrestrial silisiclastic material reflecting the effect of strong riverine inputs (Kocasu, Gönen, and Biga) and carbonate-rich biogenic sediments (Ergin *et al.* 1997, Balkıs and Çağatay 2001, Ünlü and Alpar 2006, Mülayim *et al.* 2012). The surficial sediments of Erdek Bay are dominated by mud, temporarily transforming northward to sandy silt. Sandy silt is also dominant at the western margin of the isthmus connecting the Kapıdağ Peninsula to the mainland. The inner part of the Bandırma Bay is covered with silty clay, except of the outer part where gravelly sand is dominant. Silty clay is dominant between the Bandırma and Gemlik bays but disturbed by

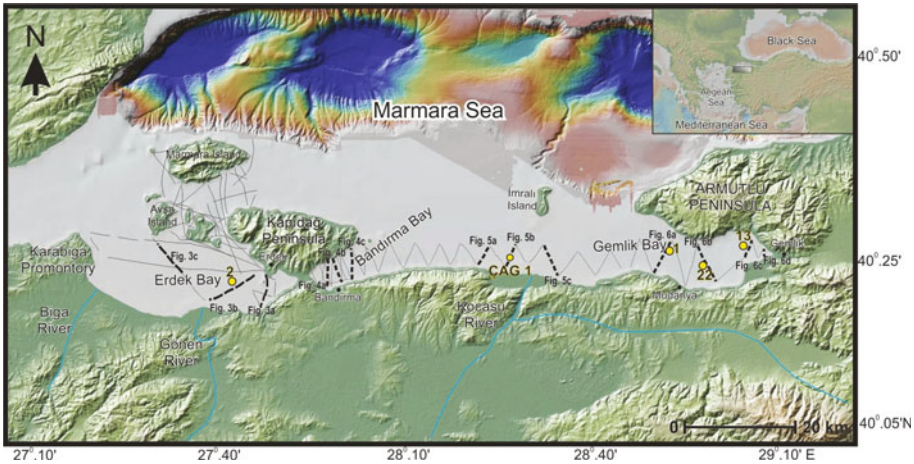

Fig. 1. Map showing the study area, the Chirp seismic lines and the locations of short gravity cores. The bathymetry is from Rangin *et al.* (2001).

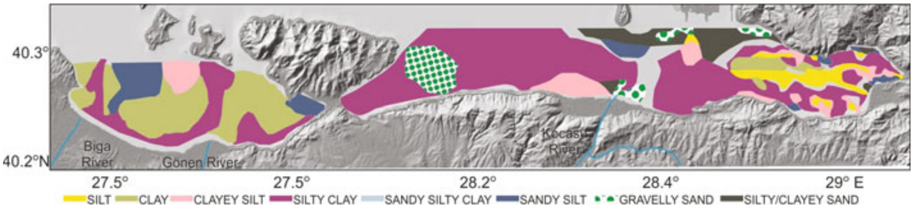

Fig. 2. Distribution of sea bottom sediment texture along the southern shelf of the Sea of Marmara. Granulometric data is from Ergin *et al.* (1997), Balkıs and Çağatay (2001), and Ünlü and Alpar (2006) for the Bandırma, Erdek, and Gemlik bays, respectively.

gravelly sand and sandy silt offshore the Kocasu River mouth. The sedimentary texture in Gemlik Bay is a composition of several steps dealing with the coarse fraction (sand and gravel) and the fine fraction (silt and clay) (Fig. 2).

4. MATERIAL AND METHOD

A total of 1000 km of new shallow seismic reflection records have been analyzed and interpreted in order to detect shallow gas signatures in the southern shelf of the Sea of Marmara (Fig. 1). The data sets were combined from two different field surveys and were collected using Chirp seismic source in 2010 (350 km) and 2011 (650 km). Chirp data were collected using Bathy 2010P™ Chirp sub-bottom profiler and bathymetric echo sounder which provides high performance sub-bottom survey capability usually for shallow inland waterways. The system uses 4 transducers, each producing 2-8 kHz Chirp signals. The power level, sweep bandwidth and detection threshold were adjusted automatically during the survey. The transmit pulse repetition rate was 1 Hz dependent on the depth range. The speed of the research boat was set to 3.5-4.0 knot during the survey. The ship's position and heading were provided with a Magellan Proflex 500 scientific GPS with an error of ±10 cm and stored in the headers of seismic data files. Gain correction, bandpass filter (10/15-1750/1900 Hz) and predictive deconvolution were applied to Chirp data. The data were processed using Kogeo Seismic Toolkit 2.7 and analyzed by "The Kingdom Suite" software.

5. RESULTS

Gas bearing sediments are widely observed, especially close to the southern coasts of the Sea of Marmara. These sediments are characterized by different acoustical reflections on the seismic data, such as acoustic turbidity, acoustic blanket, acoustic column, and chimney (Figs. 3a, b; 4, 5, 6).

Gas bearing sediments form transparent zones and mask deeper reflections on Chirp seismic sections. The interfaces between the gas bearing and

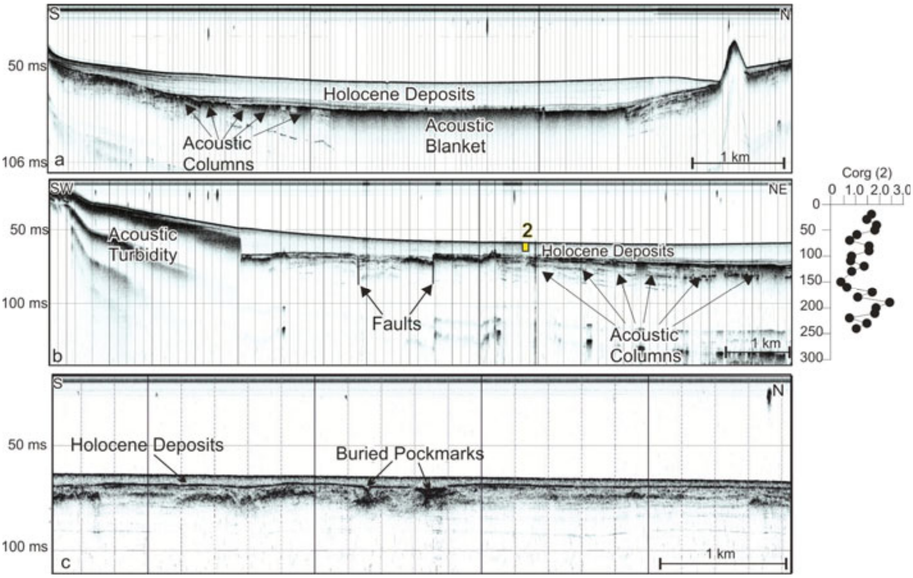

Fig. 3. Chirp seismic records from: (a) eastern, (b) central, and (c) western part of the Erdek Bay showing acoustically turbid sediments. See Fig. 1 for locations. Short (yellow) sticks stand for the sediments cores.

neighboring sediments are rather sharp and vertical. Other clues supporting the evidence of free gas in sediment are the pockmarks.

Depending on their different tectonic and depositional characteristics, seismic data from four regions were analyzed: Erdek Bay, Bandırma Bay, Kocasu River region, and Gemlik Bay.

Erdek Bay

Acoustic blanket can be identified at the SE part of Erdek Bay, implying gas content below the post-transgression marine deposits defined by Vardar *et al.* (2014) (Fig. 3a). The post-transgression marine deposits have low-amplitude and parallel inner reflections with an average thickness of 15-ms TWT. They become thicker in front of the river mouths, depending on the sea bottom morphology. Towards the southern part of this seismic section, some acoustic column type reflections show upward gas intrusions (Fig. 3a).

The sediments in front of the Gönen River cause acoustic turbidity as wide as 3 km and even intruded into the post-transgression marine deposits up to 2-2.5 m (3 ms TWT) below the seafloor (Fig. 3b). At the northern part of this section, towards the Kapidağ Peninsula, acoustic column type reflections become dominant (Fig. 3b). In addition, several buried pockmarks were observed at the boundary between post-transgression marine deposits and the

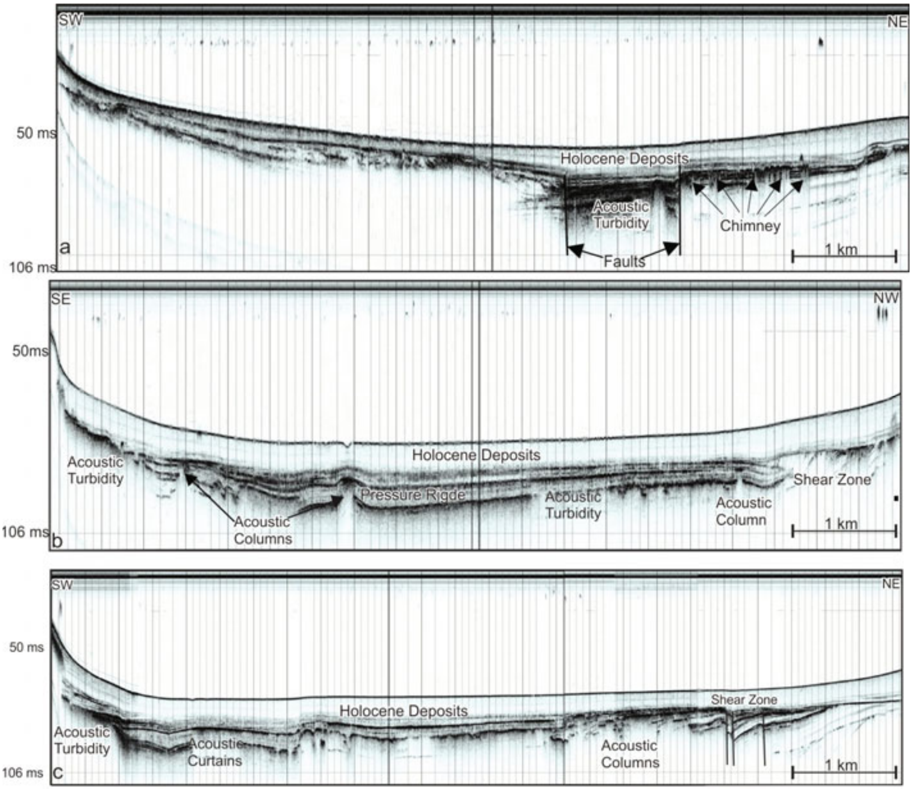

Fig. 4. Chirp seismic records from: (a) western, (b) central, and (c) eastern part of the Bandırma Bay showing acoustically turbid sediments. See Fig. 1 for locations.

underlying units (Fig. 3c). The mean diameter of the pockmarks distributed at the southern margin of the Avşa and Paşalimanı islands is approximately 20 m.

Bandırma Bay

Acoustic turbidity, column, and curtain reflections are observed locally in the Bandırma Bay (Fig. 4). Acoustic turbidity in the seismic profiles recorded at the central part of the bay can be seen below the Holocene (Vardar *et al.* 2014) deposits and are characterized by diffuse top reflections. Some local gas chimneys characterized by relatively high seismic amplitude are observed, implying fluid migration pathways (Fig. 4a). The tectonic deformations, such as shear zone in the north which is a main strike-slip fault, bounding normal faults and a pressure ridge in the central part, are the most important characteristic features in the Bandırma Bay (Fig. 4) (Vardar *et al.* 2014).

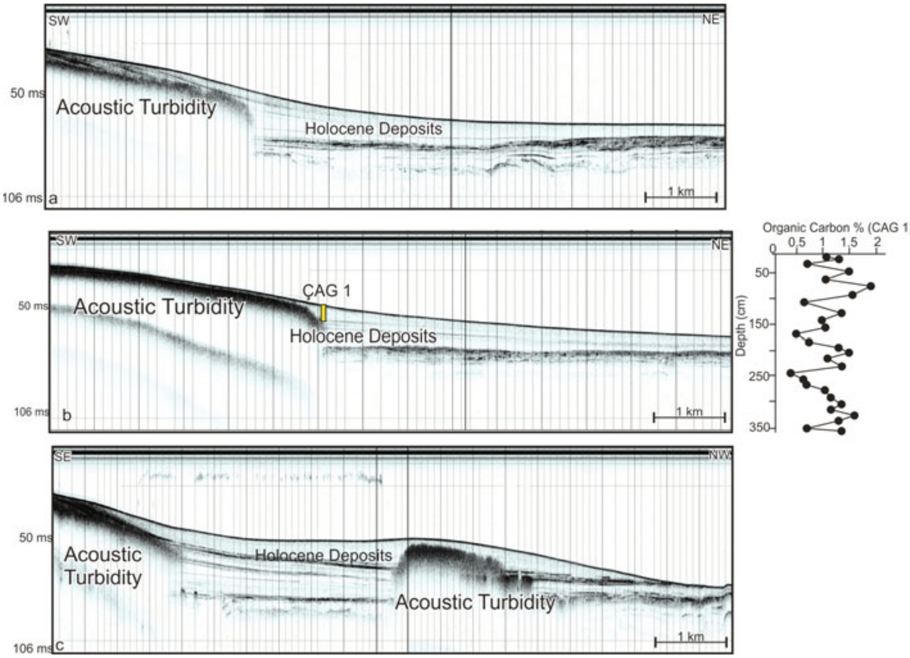

Fig. 5. Chirp seismic records from: (a) western, (b) central, and (c) eastern part offshore Kocasu River showing acoustically turbid sediments. See Fig. 1 for locations.

Offshore Kocasu River

An acoustic turbidity zone in recent deposits exists in the areas in front of the Kocasu River at water depths up to 75 m along the continental shelf (Fig. 5). Its areal distribution looks like a triangle with a height of 7 km at the river mouth and a width of 31 km along the WE oriented base line, mostly in the eastern part of the river. The areal distribution may depend on the amount and direction of the suspended load transported by the Kocasu River. The strong top reflections of the acoustic turbidity are in the Holocene deposits and reach to a level of 2 ms TWT below the sea bottom. These reflections may imply organic-rich muddy sediments underlying thin surficial sediments.

Gemlik Bay

The gas bearing sediments, mainly acoustic blankets in reflection character, are distributed widely at the Gemlik depression zone bounded by –110 m isobath. They are located below the Holocene marine transgressive deposits, Unit 3 as defined by Kuşçu *et al.* (2009), which are 12-14 ms (TWT) thick in the central part of the bay (Fig. 6a, b). Acoustical column-shaped reflections

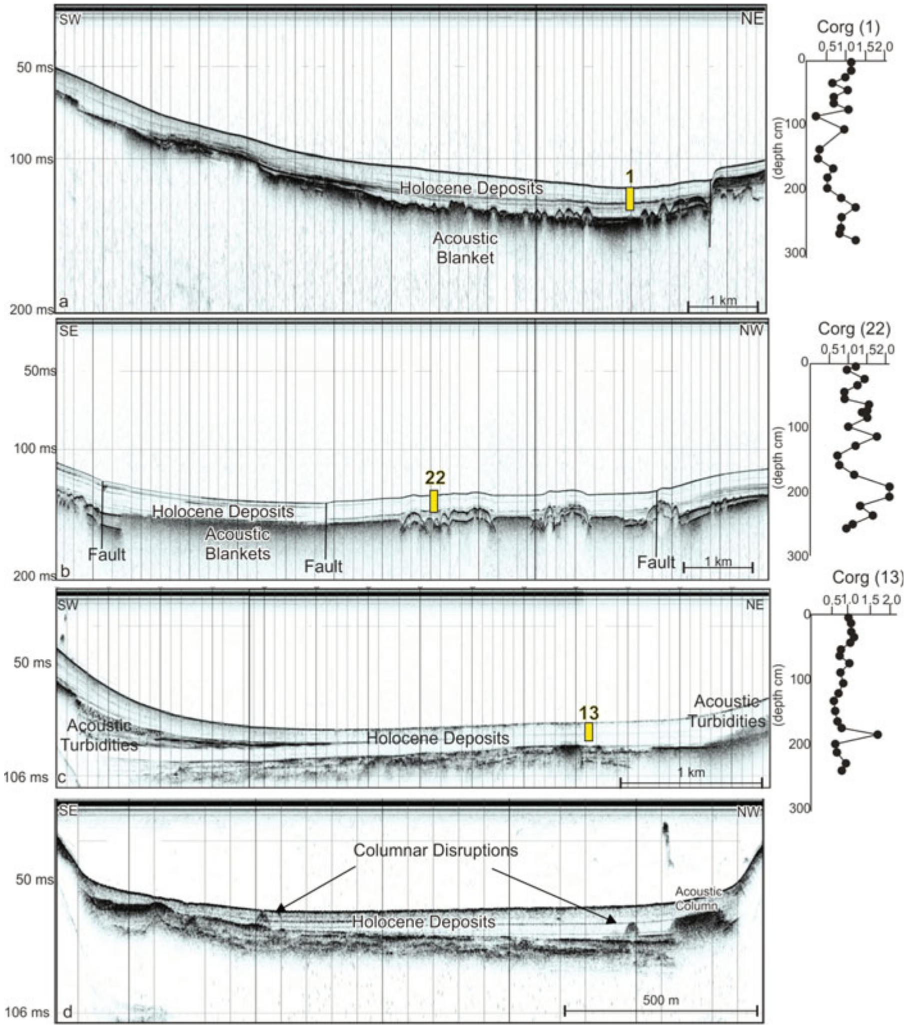

Fig. 6. Chirp seismic records from: western (a), central (b), and eastern (c and d) margins of the Gemlik Bay showing acoustically turbid sediments. See Fig. 1 for locations.

and columnar disruptions intruding into the upper deposits exist at the inner part of the bay (Fig. 6d).

6. DISCUSSION AND CONCLUSION

High-amplitude signatures of acoustic anomalies due to the presence of gas in sediments cause distinct and typical characteristic disturbances in the seismic records. In this study, the Chirp data allows a close observation of

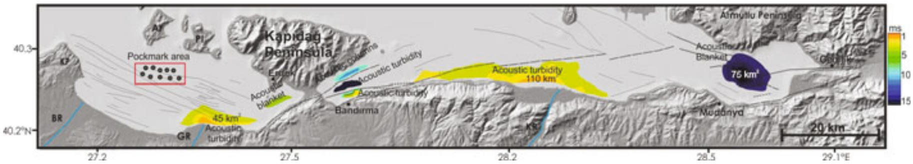

Fig. 7. Distribution of gas accumulations in the study area. Colors stand for the depths of gas accumulations from the seafloor. The lineaments show the faults given in Vardar *et al.* (2014). AI – Avşa Island, PI – Paşalimanı Island, KP – Karabiga Promontory, BR – Biga River, GR – Gemlik River, KR – Kocasu River.

the different shapes and geometries of some typical gassy structures such as acoustic turbidity, acoustic blanket, acoustic column, and chimney.

The gas bearing sediments in the Erdek Bay are widely distributed from the Gönen River to the Kapidağ Peninsula, as well as in front of the Biga River (Fig. 7). The acoustic turbidity observed in front of the Gönen River covers an area of 45 km^2 and implies organic-rich muddy sediments transported by the Gönen River itself. Its areal distribution is similar to the distribution of the high total organic carbon content in the sea bottom sediment given by Balkıs and Çağatay (2001). The total organic carbon (TOC) content at the near-surface sediments in the Erdek Bay implies biogenic gas (Çağatay *et al.* 1999). The TOC concentrations along the muddy layers of Core-2 (Fig. 3b) which approximately represents the latest 5000 years B.P. vary between 0.4 and 2.5%, with maximum peaks at the sapropelic layers (Çağatay *et al.* 1999) suggesting increased organic productivity during the deposition of these sapropelic layers. In this period, which covers the early phase of latest sea level rise, a riverine regime existed in the region with wetlands and poorly drained marsh areas (Vardar 2013). The buried pockmarks which were observed in the vicinity of the NW-SE oriented faults at the southern margin of the Avşa and Paşalimanı Island may have been originated during possible overpressure conditions provided by the strong historical earthquakes which affected the western part of the Sea of Marmara, *e.g.*, those given by Altınok and Alpar (2006).

Shallow gas accumulation in sediments of the Bandırma Bay is related to seismic images similar to horizontal stripes (Fig. 7). The source of free gas might be the lacustrine sediments which were deposited in a paleolake which existed in the region during the period of last glacial maximum, as it was isolated from the paleo-Marmara Lake by the Imrali sill (Vardar *et al.* 2014). In addition, some high concentrations of total organic carbon content (> 1.9%) were reported within the surficial sediments along the northern margin of the Bandirma Bay (Mülayim *et al.* 2012). Therefore, the gas bearing sediments in the Bandirma Bay can be assigned to biogenic origin, especially those at the northern and southern margins. The origin of the acoustic turbidity zone at the center, which is bounded by normal faults of a rectangular transpressional basin (Fig. 4a), might also be thermogenic.

The gassy sediments in front of the Kocasu River cover an area of sea floor of about 110 km^2 and have a triangular shape (Fig. 7). Çağatay *et al.* (2004) reported high level of organic carbon concentrations (C_{org} > 1%) recorded at depths of 50-80, 100-120, 170-210, and 270-320 cm along the ÇAG-1 core (Fig. 5b) which stays within the gassy sediments zone in front of the Kocasu River. In addition to these high levels of C_{org} concentrations in the sediments, high amount of terrestrial sediments transported by this river (Table 1) supports the idea that the gas source is biogenic.

The Gemlik Bay opened by a pull-apart mechanism and is still under the control of right-stepping strike-slip faults which affect the sea bottom (Yaltırak and Alpar 2002, Kuşçu *et al*. 2009, Vardar *et al.* 2014). The gas bearing sediments have been observed locally within the deep central part of this basin. It covers only an area of about 75 km^2 and similar in shape to the Gemlik Bay's main basin morphology. Gas masks mainly the lower units, below Holocene deposits, and no gas front reaching to the sea bottom was observed. The organic carbon values in the sea bottom surficial sediments were measured between 0.07 and 3.05% (Ünlü and Alpar 2006). The highest concentrations (> 2%) were from deep trough of the basin, offshore Kocasu river and local areas just in front of Gemlik and Mudanya due to harbor activity. On the basis of Chirp data collected by using SP (Sono Probe)-3 system, gas bearing sediments were also reported previously by Kuşçu *et al.* (2009). The researchers defined a similar gas bearing zone in the central basin without giving the chemical nature of the gas. The C_{org} content along the muddy layers of Core-1 (Fig. 6a) located at the western margin of the Gemlik deep through (water depth 72 m) is low, but increasing at the bottom of the core (> 2.5 m below sea floor) (Çağatay *et al.* 1999). On the other hand, the C_{org} content of Core-22 (Fig. 6b) located in the center of Gemlik deep through (water depth 110 m) varies between 0.7 and 2.1%, with maximums between depths of 200 and 240 cm, which represents 4000-5000 years B.P. (Çağatay *et al.* 1999). At the inner part of the Gemlik Bay (Core-13, Fig. 6c) where the water depth is 70 m, the highest C_{org} content (1.7%) has been measured within the 15-cm thick sapropelic mud horizon (1.8-2.0 m below sea floor) which represents 3500 years B.P. (Çağatay *et al.* 1999). Therefore, the gas bearing sediments may be assigned a biogenic origin even though thermogenic origin gas may take part due to active tectonic elements in the region.

Acoustic turbidity is widely distributed along the Southern Marmara Sea shoreline and indicates the presence of free gas in the near surface muddy sediments. The seismic signatures of gas bearing sediments can possibly be linked to the presence of a thin peat-rich layer. On the basis of their studies in the Western Baltic, Abegg and Anderson (1997) indicated that acoustic turbidity may even occur with less than 0.5% gas in shallow fine-grained sediments. Sedimentological studies have shown that high amounts of organic-rich sediments have been transported on the southern Marmara shelf by the rivers (Çağatay *et al.* 2007). Beyond fluvial transportation, sedimentation in the deeper basins on the southern Marmara shelf was developed under the lacustrine conditions that occurred during the last glacial maximum (Vardar *et al.* 2014). Because of the low-energy hydrodynamic conditions in the southern Marmara paleo-lakes, the deep waters became oxygen-depleted and organic-rich material sank to the bottom of the lake floor and has been preserved there.

The gassy areas in the studied region have been distributed in near shore and deep depositional basins which are controlled by fluvial and lacustrine regimes (Fig. 7). These areas are usually marked as acoustic turbidity and acoustic blanket and they are believed to be associated with the biogenic gas. The organic-rich sediments which were observed in the sediment cores also support the idea that the gassy areas in shallow sediments have been produced by bacterial degradation of the organic matter at low temperatures. Even though some thermogenic gas seepages may be derived from the underlying Tertiary sedimentary rocks, especially at some local places in the Gemlik and Bandirma Bays where still active tectonic faults are intersected, the gas accumulated locally in the shallow organic-rich sediments is believed to be biogenic in origin. Some active seafloor venting sites and deep-sourced fluids including thermogenic gas were reported in the deep troughs in the Sea of Marmara (Tryon *et al.* 2012).

The acoustic turbidity zones that prevail in front of the Gönen and Kocasu river mouths (Fig. 7) indicate the presence of free gas. These gassy packages are characterized by strong reflections at the top and masking deeper reflectors even they have high acoustical impedance. It is generally believed that relatively low concentrations of discrete gas voids in shallow fine-grained sediments causes such kind of acoustic turbidity zones (Hovland and Judd 1988).

However, it has been shown that sediments with small amount of gas may yield similar seismo-acoustic response to that of seismic units with higher gas saturation (Judd and Hovland 1992, Missiaen *et al.* 2002). Therefore, it is not easy to estimate the amount of shallow gas in sediment solely on the basis of the available seismic data. Further geotechnical (drilling and recovering core samples) and biogeochemial (gas chromatography to obtain the origin of gas) studies are needed for more definitive descriptions.

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