Control of active faults and sea level changes on the distribution of shallow gas accumulations and gas-related seismic structures along the central branch of the North Anatolian Fault, southern Marmara shelf, Turkey

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Detailed reviews of multichannel seismic reflection, sparker, chirp and multibeam data that were collected on the southern Marmara Sea shelf revealed various shallow gas indicators and related sedimentary structures, including enhanced reflections, seismic chimneys, acoustic blanking, bright spots, pockmarks, mound-like features and seeps. Seismic attribute analyses were applied to characterise the existence of gas-bearing sediments. The distribution of shallow gas indicators provides important insights into their origin and the geological factors that control them. Prominent gas accumulations and seeps are observed along the profiles that cross the branches of the central segment of the North Anatolian Fault Zone, which indicates that the gas seeps are controlled by active faulting. This indicates that the faults act as conduits through the sedimentary column. The dense occurrences of gas directly off the river mouths along the shallow bays provide clues about the organic-rich carbon content of the sediments and biogenic methane generation. In some areas, the gas-related acoustic anomalies are mostly located in the upper sediments below the marine unit, which indicates that the gas emissions in these areas were terminated as a result of the increased overburden pressure after the Holocene sea level rise and the deposition of the marine unit.

Keywords: shallow gas distribution; seismic attribute; bright spot; mound; central branch of NAF; Marmara Sea

1. Introduction

Investigations of shallow gas and gas-bearing reserves are geologically and economically important because shallow gas is widespread and easy to explore and produce. Thus, it could be an important energy source for the future. For example, shallow biogenic gas has been produced from late Quaternary sediments in the Qiantang River estuary area of eastern China (Lin et al., 2010). However, the gas and gas fluids may a dangerous natural hazard for offshore drilling because of their ability to generate submarine landslides and destructive blowouts. They also pose a major threat to the global carbon cycle because continuous methane seepage may influence the atmosphere and contribute to global warming (Judd & Curzi, 2002). Biogenic (microbial) methane is usually generated approximately 100 metres below the sea floor and is considered to form shallow accumulations (Judd, Hovland, Dimitrov, Garcia-Gil, & Jukes, 2002). In contrast, thermogenic hydrocarbon gases are produced by the catagenesis of sedimentary organic matter at high temperatures and pressure from several hundreds of metres to kilometres below the sea floor (Schoell, 1988).

Many academic investigations have focused on the occurrence of shallow gas around the world (Casas, Ercilla, & Baraza, 2003; Çifçi, Dondurur, & Ergün, 2003; Fleischer, Orsi, Richardson, & Anderson, 2001; Garcia-Gil, Vilas, & Garcia-Garcia, 2002; Gay, Lopez, Berndt, & Séranne, 2007; Hovland & Judd, 1988; Judd & Hovland, 1992; Kim et al., 2004; Naudts, De Batist, Greinert, & Artemov, 2009; Sun, Wu, Cartwright, & Dong, 2012). These studies primarily used high-resolution acoustic methods to identify shallow gas and gas-related structures. The presence of free gas in sediments scatters acoustic energy and results in significant disturbances to seismic reflections. Characteristic shallow gas indicators include acoustic blanking, enhanced reflections, gas seeps, gas chimneys and pockmarks. Enhanced reflections, which are characterised by very high-amplitude reflections (Schroot & Schüttenhelm, 2003), occur in shallow sedimentary sections. In contrast to enhanced reflections, bright spots that are strongly related to the existence of free gas are characterised by high-amplitude reflections accompanied by polarity reversals at both ends (Brown, 2011). Pockmarks are described as seafloor depressions of variable size. They mostly occur in fine grained, unconsolidated young sediments and are created by fluid or gas seepage into the water column (Hovland & Judd, 1988; Hovland et al., 2005). Harrington (1985) suggested that pockmarks are formed by pore water expulsion during sediment compaction. Vertical narrow acoustic alterations have been interpreted as gas chimneys in several previous studies (Heggland, Meldahl, de Groot, & Aminzadeh, 2000; Meldahl, Heggland, Bril, & de Groot, 2001). Chimneys are

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associated with features that are related to fluid or gas seepage, such as pockmarks, mud volcanoes and authigenic carbonates (Heggland, 1998; Heggland et al., 2000).

Hovland and Judd (1988) stated that the frequency content of enhanced reflections due to gas accumulations is usually lower than that of the original reflections. Negative anomalies on apparent polarity sections reflect low acoustic impedance and thus indicate the presence of gas. Instantaneous amplitudes or envelopes mark the strength of the reflection impedance contrasts that are caused by gas accumulations, unconformities and changes in lithology (Brown, 2000).

Alpar (1999) and Kuşcu et al. (2005) observed widespread free gas emissions in the Gulf of Izmit, Sea of Marmara, after the Mw = 7.4, 1999 İzmit earthquake and interpreted that earthquakes have a considerable influence on gas accumulations. Armijo et al. (2005), Géli et al. (2008) and Zitter et al. (2008) documented gas emissions along active faults in the deep basins and on pressure highs of the Sea of Marmara. In particular, gas emissions marked by acoustic anomalies were observed on the most active northern branch of the North Anatolian Fault (NAF; the Main Marmara Fault of Le Pichon et al., 2001). Furthermore, on the southern part of the Tekirdağ Basin, active seeps were detected along the main Marmara Fault and on the central and western highs (Géli et al., 2008). Burnard et al. (2012) observed mantle methane in the western part of the Tekirdağ Basin. Gas hydrates and thermal hydrocarbon gas bubbles were also observed along the NAF system by Bourry et al. (2009), and Kuşcu et al. (2009) documented extensive gas masking on chirp profiles in Gemlik Bay on the southern shelf. In this study, we present the first data of seismic anomalies and morphological features that are associated with shallow gas on the southern Marmara shelf using high-resolution multichannel seismic reflection (MCS), sparker, multi-beam bathymetric and chirp sub-bottom data. We further discuss the influence of tectonic activity and sea level changes on the formation of pockmarks, seepage and the gas distribution along different segments of the central branch of the NAF in Gemlik Bay, the vicinity of İmralı Island, Bandırma Bay, İmralı Ridge, the area between the Kapıdağ Peninsula and Marmara Island, and Erdek Bay (Figure 1). This paper also contributes to the definition of useful seismic attributes that can be used as indicators of shallow gas accumulations and emissions.

2. Regional setting and tectonic framework of the study area

The 1200-km-long North Anatolian Fault Zone (NAFZ) controls the morphology of the Sea of Marmara and accommodates approximately 20–25 mm/yr of dextral strike-slip motion between the Anatolian and Eurasian plates (Armijo, Meyer, Navarro, King, & Barka, 2002; Mcclusky et al., 2000; Reilinger & Mcclusky, 2011) (Figure 1(a)). It bifurcates into a horse-tail splay around Bolu, east of the Sea of Marmara and the width of the fault zone in the Sea of Marmara reaches 100 km in the N-S direction (Şengör et al., 2005) (Figure 1(b)).

Numerous studies have investigated the central branch of the NAFZ (Figure 1(b)) (e.g. Adatepe, Demirel, & Alpar, 2002; Aksu, Calon, Hiscott, & Yaşar, 2000; Aksu, Hiscott, & Yaşar, 1999; Alpar & Çizmeci, 1999; Barka & Kadinsky-Cade, 1988; Barka & Kuşcu, 1996; Gasperini, Polonia, Çağatay, Bortoluzzi, & Ferrante, 2011; Kurtuluş & Canbay, 2007; Kuşcu et al., 2009; Le Pichon, İmren, Rangin, Şengör, & Siyako, 2014; Vardar, Öztürk, Yaltırak, Alpar, & Tur, 2014; Yaltırak et al., 2002). It extends westward along Lake İznil (Öztürk, Yaltırak, & Alpar, 2009), Gemlik Bay (Yaltırak & Alpar, 2002) and the southern coast of Bandırma Bay. Its orientation changes to south-westward in the eastern part of Erdek Bay (Vardar et al., 2014). According to Kavuşu (1990), the central branch enters the Sea of Marmara in Gemlik Bay and then continues on land to the north of Mudanya (Figure 1).

The southern shelf of the Sea of Marmara covers a broad area (4194 km²) with an average width of 20 km (Gazoğlu et al., 2002). The sub-basins of Bandırma (−51 m) and Gemlik (−110 m) Bays are the most distinctive basins (Vardar et al., 2014). The study area covers three sub-basins (Figure 1(c)), Erdek, Bandırma and Gemlik Bays. The main freshwater and sediment inputs along this part of the southern shelf are from the Gönen, Biga and Kocasu Rivers, of which the Kocasu River is most important (Figure 1(c)). In addition, Kocadere Stream enters Gemlik Bay from the east after originating in İznil Lake. The sedimentary sequences in Gemlik and Erdek Bays are mainly composed of terrigenous material that consists of an admixture of sand, silt, clay and gravel (Balkıs & Çağatay, 2001; Çağatay et al., 2015; Ünlü & Alpar, 2006).

The study area includes the entire southern Marmara Sea shelf. The Marmara Sea lies between the Black and Aegean Seas, to which it is connected through the straits of Bosphorus and Dardanelles, respectively, which have sill depths of ~35–40 m and 65–70 m, respectively (Aksu et al., 2002; Çağatay et al., 2009). During the last glacial period (70–12.6 ka BP), global sea level was lower than the depth of the Bosphorus and Dardanelles sills (Deschamps et al., 2012; Lambeck, Sivan, & Purcell, 2007). The Marmara Sea has undergone significant water level and environmental changes due to climate oscillations. Several studies have found that the Sea of Marmara reached a low water level of approximately −105 m during the last glacial period (Aksu et al., 1999; Çağatay et al., 2003; Eriş, Ryan, Çağatay, & Sancar, 2007; Hiscott et al., 2007; McHugh et al., 2008). At that time, the shelf areas, including the study area, was subaerially exposed beyond the shelf break and small lakes were present in Gemlik and Bandırma Bays (Vardar et al., 2014). Chirp data indicate that Erdek Bay was
partially a lake and that some parts were sub-aerially exposed. As the sea level overtopped the Çanakkale sill at approximately 12.6 ka BP (Çağatay et al., 2015), the water level in the Sea of Marmara rose in tandem with global sea level. Gemlik Bay became marine approximately 1000 years later (11,250 ± 60, 14C ka BP; Gaperini et al., 2011; Taviani et al., 2014) because of the 50 m sill at the western end of the bay.

Evidence of water level oscillations is found in multichannel seismic profiles in the form of alternating lowstand deltas and onlapping sequences. Seismic reflectors that are related to the lowstand deltas north of İmralı Island were dated as far back as 500 ka BP by Sorlien et al. (2012) based on the global sea level curve, the volume of deltaic units and the rate of sediment input. However, these age data have not been confirmed by stratigraphic core analysis. The detailed chronostratigraphic core data from the southern shelf extend back to only 15 ka BP (Çağatay et al., 1999; McHugh et al., 2008; Taviani et al., 2014). Due to the lack of core stratigraphic evidence on the southern shelf, we use the reflector ages of Sorlien et al. (2012) with jump correlations to seismic lines that are connected to well data in this study.
3. Data acquisition and methods

This study is based on the following four data-sets: (1) approximately 1000 km of high-resolution (MCS) profiles, (2) ~900 km of sparker profiles, (3) ~1300 km of chirp data and (4) multibeam echosounder data (Figure 1c). The MCS, chirp and multibeam data were acquired simultaneously during a research cruise in 2013, and additional sparker data were collected in 2014 using R/V K. Piri Reis, which belongs to Dokuz Eylül University, Institute of Marine Sciences and Technology. Both data-sets were collected by the Seismic Laboratory (SeisLab) team in the framework of the bilateral TÜB- TAK-NSF Project (project code: 112Y026) on the South Marmara shelf and are called the Southern Marmara (SoMAR) cruises.

The MCS reflection system has a Hydroscience Seaman recording unit with 900-m-long 144 and 1050-m-long 168 channel digital streamers. The group interval was 45 + 45 inch, and the Generated Injected (GI) gun source was 45 + 45 inch and was fired every 12.5 or 18.75 m to produce high-resolution seismic signals at frequencies of 10–250 Hz. The recording length was 3000 ms, the sampling rate was 1 ms and the minimum offset was 50 m. The seismic lines had a penetration depth of approximately 170–450 m over the entire survey area, but the penetration depth in some areas was 20–40 m due to the bedrock strata of the shelf and basement highs just below the seafloor.

A conventional data processing flow was applied to all of the MCS data, including data importation, geometry definition, bandpass filter, F-K filter, true-amplitude recovery, kill trace, mute, sort, velocity analysis, NMO analysis and stack and time migration. Several special processing methods for seismic attributes were also applied to the MCS data, such as complex trace attributes (reflection strength, average energy, instantaneous frequency, instantaneous phase and apparent polarity). The seismic data were processed using the ProMax software. The IHS Kingdom Suite software was used for the interpretation and mapping of the seismic data. No multiple elimination methods were used to remove multiples from the real reflections. However, high velocities were chosen in the velocity analysis to determine the appropriate velocities for the reflections because the acoustic basement is very close to the seafloor, and the velocities in the southern Marmara shelf are higher than expected.

A single channel streamer (17 m) and a 1000 J energy source were used during the sparker data acquisition. The acquisition parameters were set at a shot interval of 1000 ms, a recording length of 1000 ms and a sampling rate of 0.25 m. The penetration depth was 40–75 m below the seafloor. The following data processing steps were applied to the sparker data: data importation, geometry definition, bandpass filter, trace kill, trace mix, mute and Stolt migration.

The shallower sediments were surveyed with a Bathy 2010 side-mounted chirp sub-bottom profiler system with nine transducers that produced a sweep signal between 2.75 and 6.75 kHz with a 3.5 kHz centre frequency. The recording length was 500 ms, and the penetration depth below the seafloor in the study area was 15–45 m. The applied data processing steps included gain correction, de-chirping and amplitude envelope. No processing steps were applied to the chirp data after the acquisition, but an instantaneous amplitude (envelope) was applied to the data during acquisition by the Bathy 2010 software.

The multibeam bathymetric data were collected simultaneously with the MCS profiles using a hull-mounted ELAC SeaBeam 1050D multibeam bathymetry system. The system operated at 50 kHz and had 126 beams with a 1.5° resolution that allowed a 153° swath coverage. The data were processed using the Carabes software. The processing steps were as follows: data importation, correction of navigation errors, navigation and bathymetry data merge, de-spiking and gridding with a 25-m grid interval.

4. Observations and interpretations

Based on the resolution of the seismic methods that were employed, several seafloor and subsurface features related to the presence of gas were identified and mapped.

4.1. Seismic indicators of shallow gas

The features include acoustic blanking, chimneys, enhanced reflections, bright spots and seeps. Figure 2 shows the distribution of shallow gas-related structures that were identified on the seismic, sparker and chirp data.

4.1.1. Acoustic blanking

Acoustic blanking is the most common feature that was observed in the chirp, sparker and MCS data; it was identified at more than 100 locations (Figure 2). Acoustic blanking zones are imaged as severely dimmed or acoustically transparent reflection zones on the seismic sections (Figures 3–6). They usually occur beneath enhanced reflections and terminate at different stratigraphic levels. They also appear as thin vertical columnar disturbances or chimneys (Figures 3 and 6). The widths of the acoustic blanking zones vary between 200 and 4000 m. Their upper boundaries are located at depths of less than 5–40 m (assuming a sound velocity of 1500 m/s) below the seafloor. On most of the chirp lines, the acoustic blanking areas are located below the marine transgressive sediments. In addition, acoustic blanking anomalies with enhanced reflections are observed around faults over the entire study area. Figure 6 shows a 1600-m-wide acoustic blanking zone that is accompanied by bright spots and enhanced reflections at its top on the outer shelf. This acoustic blanking
zone appears to be cut by a steep fault, which suggests that the origin of the gas accumulations in this area could be related to deeper structures.

4.1.2. Enhanced reflections

High-amplitude reflections, which are termed enhanced reflections, are observed in the shallow sediments (Figures 4–7). They are identified at more than 120 locations and are the most dominant features in the study area (Figure 2). These features appear to extend laterally and have sharp cut-off edges. They are usually concordant with the host sedimentary strata and are located directly above acoustic blanking zones and chimneys that are associated with faults (Figures 3, 5 and 8(e)). In addition, enhanced reflections and columnar disruptions are generally observed in shallower sediments in the upper parts of the sections (Figures 7, 9 and 10). They extend laterally for 300 to 1300 m and from the seafloor to a depth of 30 m. However, the lateral extent of a few individual anomalies can reach up to 3000 m in the sparker lines.

Some enhanced reflections occur in the deltaic deposits, which suggest that these deposits, and particularly the pro-delta facies, have the potential to act as gas reservoirs (Figure 7). Enhanced reflections are also observed near fault zones, which suggest that faults are the natural conduits for the upward transport of gases.

Figure 2. Distribution maps of acoustic blanking, seismic chimneys, enhanced reflections, bright spots, pockmarks, buried pockmarks and mound-like features on (a) chirp, (b) sparker and (c) MCS reflection data in the study area. Note that the sparker data do not cover the entire survey area.

Figure 3. Acoustic blanking characterised by transparent seismic sediments with an enhanced reflection at the top and chimneys that disturb parallel bedding in sediments near the faults on chirp line 08. The solid black lines show interpreted faults. MS = marine sediments; LS = areas in green are lacustrine sediments.
4.1.3. Bright spots

Bright spots are generally observed at depths of between 15 and 60 m from the seafloor and can reach up to 300–750 m in width. Figure 7 shows an excellent example of a seismic anomaly that is accompanied by polarity reversals at both ends as well as a velocity pull-down below it. The pull-down effect that is observed below some enhanced reflections represents gas-bearing sediments because the gas in the overlying sediments reduces the acoustic velocity. The bright spot on the MCS line in Figure 5(b) is not observed on the chirp line (Figure 5(a)) because the penetration depth of the chirp section is approximately 220 ms, and the bright spot is located 235 ms below the seafloor. Some bright spots occur with columnar disturbances under lacustrine sediments in Gemlik Bay, which indicate the existence of underlying free gas (Figure 9).

4.1.4. Seismic chimneys

Seismic chimneys were identified at more than 30 locations in the study area (Figure 2). They are commonly associated with enhanced reflections at their tops (Figures 3 and 6). The gas chimneys that are shown in Figure 3 appear to be accompanied by columnar acoustic blanking near the faults. Assuming a sound velocity of 1500 m/s, the width of the chimneys ranges from 40 to 200 m and the heights range from 10 to 15 m (Figures 3 and 6). Seismic chimneys are not common in the survey area and are densely observed only in Gemlik Bay, and they are associated with faults to the west of Marmara Island (Figures 6, 8 and 10). Chimneys that are associated with faults may represent vertical vents or conduits for fluid or gas emission from deeper sources.

4.1.5. Seeps

Gas seeps are observed as dark columns that rise from the sea floor up to 50 m into the water column. These features are located above gas-bearing sediments or pockmarks (Figures 3, 6(c) and 8(f)). They are rarely observed in the study area (Figure 2) except in Gemlik Bay and east of Marmara Island, where many seeps are observed (Figures 2(a) and 8(f)).

4.2. Morphological indicators of shallow gas-related seismic structures

4.2.1. Pockmarks

On the chirp and seismic sections, the pockmarks appear as V-shaped depressions that range from 3 to 6 m in depth and from 80 to 200 m in width (Figures 2, 6 and 7). Some of them are located directly above shallow gas accumulation zones (Figures 6(b) and 8(d)). Buried pockmarks are observed mostly in Erdek Bay and to the east of Marmara Island at depths between 2 and 7.5 m below the seafloor (Figure 8a and 8(c)). Some are located immediately next to mound-like features (Figure 7(b) and (c)), and all of the buried pockmarks are located immediately below the marine unit on the last lowstand erosional surface. On the multibeam bathymetric data, they have circular morphologies in plan.
view (Figure 6(e)). Some of the seismic lines show buried pockmarks in the deeper strata (Figures 6 and 9). Active pockmarks on the seafloor are common along faults in Gemlik Bay (Figures 6 and 8(f)), whereas buried pockmarks are present in Erdek Bay (Figure 7(c) and (f)). Some of the active pockmarks in Gemlik Bay are clearly associated with acoustic blanking zones and acoustic chimneys. In some areas, the chimneys below the pockmarks can be traced down to acoustic blanking zones (Figure 6(c)) and are interpreted as gas seeps. The hyperbolic distortions on the seafloor of the chirp data could be indicators of previous seep zones because of the existence of narrow high reflectivity columnar zones below them (Dondurur, Çifçi, Drahor, & Coşkun, 2011). They can therefore be used to identify inactive pockmarks (Figure 5(a)).

Vardar et al. (2014) suggested that Erdek Bay is a passive basin because the chirp data show that faults do not deform this region. In addition, the buried pockmarks that are preserved indicate rapid sedimentation conditions; thus, the shallow gas accumulations in Erdek Bay appear to have been formed by the rapid influx of highstand deposits that were transported through the Çanakkale strait and from the Biga and Gönen Rivers.

Figure 5. (a) Chirp line15 illustrating pockmarks on the seafloor above an acoustic blanking zone that is bounded by fault zones. (b) MCS line GM13–15, which was acquired simultaneously with chirp line 15, showing an acoustic blanking zone with a bright spot and enhanced reflections on the outer shelf. The solid black lines show interpreted faults. The dashed box illustrates the sea bed with a positive polarity and a bright spot with a negative polarity. The area that is bounded by the red-dashed box shows the section of the profile that the complex trace attributes were applied to. Red horizon is the 110 ka age which is explained in Figure 12. HS = Holocene sediments.
To the east of Marmara Island, buried pockmarks and active pockmarks are nearly vertically stacked but are shifted 200 m laterally (Figure 8(a)). This phenomenon may be explained as follows. In shallow sediments, active tectonics can easily change the local permeability of micro-faulted zones, and the area southeast of Marmara Island can be interpreted as an active zone in which the gas migration pathways could vary easily over geological history. Çifçi et al. (2003) described the formation of ‘vertically stacked’ pockmarks as periodical successive occurrences of disruption and reactivation of gas expulsions through the pockmarks. Similarly, Dondurur, Çifçi, Drahor, and Çoşkun (2011) explained the formation of inactive pockmarks in Izmir Gulf as lateral variations of gas migration pathways from inactive to active pockmark zones.

4.2.2. Mound-like features

Mound-like features, which may be indicators of vertical fluid flow, were observed on the seafloor in several locations (Figures 2 and 8(b)–(e)). Acoustically, they are characterised by high-amplitude bright reflections at their tops and acoustic columns below them. Many of these mounds rise 3–6 m above the seafloor in the chirp profiles. Sea floor mound-like features are only identified in Gemlik Bay, and buried mounds are only identified in Erdek Bay. The observed mound-like structures are associated with pockmarks in some areas (Figure 8(b) and (d)). Some were buried by recent sediments (Figure 8(c) and (d)). They are well preserved and indicate high deposition rates of sediments after the last lowstand in the Sea of Marmara. They are approximately 2–6 m high and 125–500 m wide.
The mounds are interpreted to be related to gas or fluid seeps because they are located directly below pockmarks and near areas of buried pockmarks. They may be evidence of fluid or gas expulsion activity and chemosynthetic fauna and/or carbonate buildups that formed on the sea floor during the last lowstand period because the buried mounds are located in Erdek Bay. Fu, Aharon, Byerly, and Roberts (1994) and Roberts and Aharon (1994) suggested that chemosynthetic microbial metabolism related to microbial degradation of hydrocarbon gases creates calcium–magnesium carbonates that cause the formation of a variety of seafloor features, including hard grounds and mounds with varying dimensions. In the northern Marmara Sea, Zitter et al. (2008) observed that authigenic carbonate chimneys are associated with the water seeps and visible water outflows in the Tekirdağ and Central Basins; the pore fluid chemistry data show that the water that is expelled at these sites is brackish water that was trapped in the sediment during lacustrine times (before 14 cal kyr BP).

Alternatively, on the northern shelf near Büyük Çekmece, isolated mounds and small ridges up to 4 m high were observed by Çağatay et al. (2009) on high-resolution chirp seismic profiles, who interpreted them as Holocene age bioherms. They sampled the interior of the mounds and recovered a rich abundance of shells over a rough erosional surface that was observed in the seismic sections. Figure 8(b) shows a bioherm-like mound with a similar internal structure that overlies a reflector similar to those in the northern shelf that were observed near pockmarks. Cores are needed to analyse these features, which differ between the different bays on the southern Marmara shelf.

In particular, pockmarks and mounds on and below the seafloor were clearly identified in the chirp data, while the seismic and sparker images provide useful information about the deeper parts of the surveyed lines. Therefore, sparker and MCS methods should be used in such surveys to address deeper gas indicators.

Figure 11 schematically summarises the seismic evidence of the gas-related structures that were observed in the study area in an ideal block diagram. It also illustrates the deep and shallow gas/ﬂuid migration systems within the shallow sediments and seafloor. The diagram shows interpreted schematic NW–SE and W–E transects (not to scale) in the study area.

The uppermost layer in the study area represents the Holocene sedimentary unit (Figures 3, 4, 6(c), 8, 9 and 10). The base of the uppermost marine unit has been dated in cores to between 11 and 12 ka BP by several authors (Çağatay et al., 2000; Gasperini et al., 2011; Vardar et al., 2014). The boundary between the marine and the underlying lacustrine unit is a low-stand erosional surface over the shelf areas (Figure 8(b)–(d)). In some parts of Erdek Bay, marine unit cover the fluviolacustrine depositional units. The marine unit is thicker in Gemlik Bay than in Erdek Bay. Vardar et al. (2014) interpreted this lowstand erosional surface as the upper surface of the Early–Middle Pleistocene sediments, which is more than 30,000 years old.

Our multichannel seismic data from Erdek and Gemlik Bays penetrate much deeper than the seismic lines in previous surveys (Kuşçu et al., 2009; Vardar et al., 2014; Yalırak et al., 2002) and show deep faults and the acoustic basement between 400 and 700 m (Figures 9 and 10). The acoustic basement is interpreted...
to be Miocene based on the erosional character of the reflection. The southern shoreline shows well-preserved evidence of Messinian fluvial erosion followed by post-crisis marine reflooding (Çifçi, 2015). Basement uplifts are located around the small islands to the east of Kapıdağ Peninsula between Bandırma and Gemlik; in addition, basement outcrops to the seabed between Marmara Island and the small islands.

Figure 12 shows the sequence stratigraphic interpretation of a seismic line that extends across the outer shelf area and involves parts of three intersecting lines. We used the reflector ages with jump correlations from a seismic line that is located north of Imralı Island to line Gm13–15, which intersects well data. The reflections are correlated from sequence boundaries from the existing seismic stratigraphic age model of Sorlien et al. (2012). The deltas and regional unconformities guided the sequence stratigraphic interpretations with a correlation of the ages in the Marmara 1 petroleum test well, which is located near the edge of the southern continental shelf. In the well 51–112 m of undifferentiated brackish Quaternary (possibly Pliocene in lower part) sediments were
recovered and Sorlien et al. (2012) correlated their sequences to the section above 127 m where there is a major unconformity.

The stratigraphic correlation includes five 540,000-year-old and younger horizons from the North Imrali slope basin onto the outer and middle shelf.

Figure 9. Seismic reflection line GM13–38 showing bright spots that are located under lacustrine sediments with underlying columnar disturbances. The faults disturb the deeper sediments and do not deform the Holocene deposits. Acoustic basement is visible between 400–500 ms and is also affected by faulting.

Figure 10. Seismic reflection line GM13–02 from Gemlik Bay area showing the acoustic blanking area between offsets 3300–5900 m that are associated with faults. Enhanced reflections are present on the horizons at approximately 100–150 ms under the lacustrine sediments. Acoustic basement is visible between 400 and 700 ms.
Figure 11. Schematic 3D box of NW-SE and W-E transects showing seismic evidence of gas-related structures in the study area, including the deep and shallow gas/fluid migration systems within the shallow sediments. The faults provide pathways for the migration of thermogenic gas and fluids. The shallow fluid flow systems (minor faults, pockmarks and mounds) are controlled by the stratigraphy and hydrostatic pressure conditions during changes in sea level.

Figure 12. Stratigraphic correlation of horizons from North İmrali Basin slope to outer shelf area where line GM13–15 intersects Marmara 1 well data. This multichannel seismic reflection profile is located in the inset map by red line between A and A’. Profile intersections are shown with black arrows at the top of profile. Faults are shown in the inset map. Colours correspond to ages in Sorlien et al. (2012).
The ~110,000-year-old ‘red’, ~250,000-year-old ‘blue’, ~340,000-year-old ‘yellow’, ~430,000-year-old ‘purple’ and ~540,000-year-old ‘green’ horizons were correlated across the İmralı fault zone. The western part of line A-A’ represents line GM13–15, and the stratigraphic age of the bright spot reflection corresponds to the green horizon. On line GM13–15, the İmralı fault is interpreted to bound the acoustic blanking zone and the bright spot reflection. This fault might provide pathways for deeper gas/fluid migration in the outer shelf area, while the shallow fluid flow system (minor faults, poikilomarks and mounds) could be controlled by stratigraphy and hydrostatic pressure conditions during sea level changes. Fluid/gas migration could therefore have been triggered by several factors, including active tectonics, overpressure, gas generation and high sedimentation rates.

The stratigraphic ages of the other lines in this study are not correlated because the sequences on the seismic lines are deeper than the existing piston cores. In addition, there are no wells in Erdek and Gemlik Bays.

4.3. Seismic attribute analysis of gas-related seismic structures

In this study, the most frequently used and stable attributes (instantaneous frequency, envelope and apparent polarity) are applied to interpret the characteristics of the high-amplitude seismic anomalies that are observed in the study area (Figure 13).

A bright spot is observed in the middle part of the migrated section of line GM13–15 (Figures 4(b) and 10(a)) between CDPs 650 and 2200 (~4700 m wide). The envelope section (Figure 13(b)) suggests that the amplitude of this bright spot is approximately 10 times stronger than the surrounding reflections. The anomalous local low-frequency zone below the bright spot in the instantaneous frequency section (Figure 12(c)) indicates that gas accumulation causes considerable attenuation of the seismic signal.

The seafloor reflection in the MCS data has a positive wavelet shape (Figure 13(a)), and the polarity attributes (Figure 13(d)) reveal that the seafloor reflection has a negative polarity (shown in blue), whereas the bright spot anomaly that is directly above the gas accumulation zone has a positive polarity (shown in red). The seafloor has a different appearance in the gas-rich areas with a more complicated wavelet shape and/or reversed polarity.

5. Discussion

5.1. Origin of gas

The origins of gas in shallow marine sediments are described by Missiaen, Murphy, Loncke, and Henriet (2002) as follows: (1) biogenic gas, which is the output of the bacterial decomposition of organic matter at low temperatures and (2) thermogenic gas, which forms by crackling of organic compounds at high temperatures at greater depths. The interpretations in the study area suggest possible deep thermogenic gas as well as biogenic gas has accumulated in shallow organic-rich sediments. Unfortunately, we do not have any data on the chemical composition of the gas in the study area. However, the geology of the study area does not suggest the possibility of deep thermogenic sources. Instead, it appears likely that gas has accumulated in situ in the shallow organically rich sediments, where faults delimit the boundaries of the acoustic blanking zones in the outer shelf area. Armijo et al. (2005), Henry and Marnaut Scientific Party (2007) and Géli et al. (2008) proposed that the main path for fluid expulsion is the main strike-slip NAF in the ridge areas (highs). Mantle helium is observed in the western part of the Tekirdağ Basin near the Ganos bend and on the Prince Island segment (Burnard et al., 2012), thermogenic gases are emitted along the Western High and Central High segments, and predominantly biogenic methane emissions occur in the southern Çınarcık Basin (Boutry et al., 2009).

On most of the faults of the central strand of the NAF, the vertical displacements increase with depth, which suggests that extension occurred during Pliocene to Holocene time. The Kapıdağ Fault and İmralı Ridge Fault both exhibit vertical separation of the acoustic basement (Okay, 2015).

In addition, the shallow gas accumulations on the outer shelf are generally located 60 m below the seafloor, and the reflections from the top of the gas accumulation zone are distinguished by their apparent negative polarity. The top of the gas-bearing zone includes high amplitudes with a bright spot. Bright reflections are clearly distinguished on the seismic envelope and polarity sections (Figure 13), and acoustic blanking zones are observed below these bright reflections. The instantaneous frequency sections show local low frequency anomalous zones, which indicate greater attenuation of the seismic signal due to gas accumulation. Although the gas composition, and hence the origin of the gas in these sediments, is still unknown, the existence of deep faults that penetrate layers as deep as 1 km may allow thermogenic gas to percolate upward. In addition, the linear alignment of gas accumulations along faults in Gemlik Bay and south of Marmara Island may indicate that both thermogenic and biogenic gas is present because of the presence of rivers around Gemlik Bay (Figure 5(a) and (b)).

To the east of Marmara Island, an unconformity surface that represents the last glacial maximum (LGM) is clearly imaged above the palaeolake (lacustrine) deposits (Figure 4). The source of free gas might be the lacustrine sediments that were deposited in a palaeolake environment during the last glacial period. The existence of deltaic deposits that are associated with enhanced reflections suggests that these deposits, particularly the pro-delta sediments, have the potential to trap and produce gases.

Because the delta progradations are located near and over zones of gas accumulation, their origins could be
interpreted as biogenic. The mound-like features appear to be related to biologic activity because they are accompanied by enhanced reflections and pockmarks, which suggest that the emitted gases are produced in the uppermost levels of the sediment column.

5.2. Factors controlling the distribution of gas-related structures and seepage

5.2.1. Sea level fluctuations

The Marmara Sea is affected by the exchanges of water between the Mediterranean and Black Seas, which are controlled by the Istanbul (Bosphorus) and Çanakkale (Dardanelles) Straits, respectively. It underwent significant sea level fluctuations and experienced lacustrine environments during the lowstand periods (Aksu et al., 1999; Çağatay et al., 2000).

The upper boundaries of acoustic blanking zones are located below the last lowstand deposits. In addition, buried pockmarks and buried mounds are present on the last lowstand erosional surface and in deeper strata on the seismic lines in some areas. These features indicate that there was a relationship between changes in the hydrostatic pressure and the activation of gas accumulations.

Figure 13. Attribute analysis of the bright spot between CDPs 650 and 2200 on line GM13–15.
and gas/fluid migration during the sea level changes in the Sea of Marmara. Falls in sea level decrease the hydrostatic pressure, which decreases the gas solubility; this results in gas migration and increases the amount of free gas in the subsurface sediments, which results in gas/fluid seepage from underlying sedimentary structures via pockmarks or faults.

5.2.2. Active tectonics and seismicity

Figure 14 shows the shallow gas indicators superimposed onto the fault map of Sorlien et al. (2012). These maps clearly show that the highest gas accumulations occur on the strands of the central branch of the NAF in Gemlik, Bandırma and Erdek Bays and around Marmara Island. This illustration strongly suggests the control of tectonics on the distribution of shallow gas. The association of many active seeps and pockmarks with faults in Gemlik Bay and east of Marmara Island indicates the ongoing seismic activity of the central branch of the NAF.

After the 1999 Kocaeli earthquake, an increase in the number of gas bubbles being released into the water column was observed in the Gulf of Izmit (Alpar, 1999; Kuşçu et al., 2005). Similarly, the occurrence of gas expulsions appears to be correlated with the distribution of micro-seismicity. Figure 13(b) shows the M >2 earthquakes in the Marmara Sea between January 2000 and February 2015. The gas indicators on the map are clearly consistent with the ongoing seismic activity. The presence of seeps and active pockmarks in Gemlik Bay may be related to active branches of the central branch of the NAF (Figure 14). Some of the pockmarks are related to the nearby vertical faults, which have displacements on the order of metres. These indicators of gas features that are related to active faults are important in the prediction of seismic hazards and the emplacement of deep seafloor seismometers.

The acquired seismic data indicate that all of the sequences between the Armutlu Peninsula and Bandırma have a prominent dip towards the south. The dip angle decreases to the west, and at Erdek Bay, no dip could be traced on the sections. These observations indicate that the subsidence rate was greater in Gemlik Bay.

The most significant observation from the chirp sections is that sea floor mounds are only located in Gemlik Bay, and buried mounds and buried pockmarks are only located in Erdek Bay. We propose a scenario to compare Erdek and Gemlik Bays that consists of three phases (lowstand, transgression and deposition of marine unit) for the temporary gas accumulations, gas/fluid seepage pathways and the influence of the LGM on the formation of the pockmarks and mounds (Figure 15).

During the LGM in the Marmara Sea at 30–12.6 ka BP a significant increase of pore pressure was caused by the decrease in the hydrostatic pressure due to falling sea level, which significantly decreased the effective load (Figure 15(a), Phase 1). Lowstand conditions caused an expansion of sediment-trapped bubbles within the shallow subsurface reservoirs. Pockmark formation occurred by the eruption of gas or pore water through the seafloor in Erdek and Gemlik Bays. Seafloor mounds formed as chemosynthetic fauna and/or carbonate buildups due to microbial oxidation of hydrocarbons on the sea floor of Erdek Bay. The existence of mounds could be explained.

Figure 14. Distribution map of all of the shallow gas indicators on the published fault map of Sorlien et al. (2012) of the central branch of the North Anatolian Fault. The red lines are the published faults, and the black lines are the faults that are mapped with our database. The blue lines show the rivers that flow into the southern Marmara Sea. GB = Gemlik Bay; BB = Bandırma Bay; EB = Erdek Bay; İİ = İmralı Island; GF = Gemlik Fault; İF = İmralı Fault; İRF = İmralı Ridge Fault; KF = Kapıdağ Fault.
by the high total organic carbon distributions of surface sediments in Erdek Bay. Balkış and Çağatay (2001) identified high total organic carbon distributions of the surface sediments at the mouths of rivers in Erdek Bay. Vardar et al. (2014) suggested that Erdek Bay was not a palaeolake during the early phase of sea level rise and that a riverine regime with poorly drained marsh areas and plains was dominant. This could explain why mounds formed in Erdek Bay but not in Gemlik Bay when it was a lake during the lowstand period.

The level of the Sea of Marmara increased with global sea level during the transgression (Figure 15 (a), (b); Phase 2). Slow hemipelagic deposition occurred in both basins throughout the Holocene (Figure 15 (a), (b), Phase 3), and the pockmarks and mounds in Erdek Bay were buried. The preservation of buried pockmarks indicates rapid sedimentation; thus, shallow gas accumulations were formed due to the rapid influx of highstand deposits from the Çanakkale Strait and the Biga, Gönen and Kocasu Rivers. Due to the load of the highstand water mass, the hydrostatic pressure increased, and the underlying sediments were charged with gas. In Phase 3 (Figure 15(b)), both Erdek and Gemlik Bays became marine. In Gemlik Bay, the increase in hydrostatic pressure may have controlled the formation of the shallow gas accumulations, but could not have controlled the seepage because it is a tectonically active bay with Holocene active faults. The seafloor mounds formed near active pockmarks after the marine unit deposition, possibly because no fluid/gas expulsion occurred in Gemlik Bay during last low stand time to form carbonate buildups on the sea floor.

No active faults or seeps through pockmarks are visible on chirp and sparker lines in Erdek Bay, which indicates that Erdek Bay was active before the Holocene and that gas accumulations cannot migrate to the seafloor in this area. Erdek Bay is a more passive bay than Gemlik Bay.

6. Conclusions

Shallow gas indicators along the southern shelf of the Marmara Sea were mapped, and the presence of shallow gas is indicated by acoustic anomalies, such as enhanced reflections, bright spots, acoustic blanking, pockmarks, seeps and chimneys. Based on the high-resolution seismic records, the gas accumulations migrated through chimneys to the top of the sediments to form gas seeps on the seafloor. The formation and distribution of shallow gas can be explained by the combined effects of
several factors, including global sea level changes and tectonic activity.

Although the entire southern Marmara shelf has experienced sea level changes over the same time periods, each bay has been affected differently. Buried pockmarks are present on the last lowstand erosional surface, and no active faults affect the Holocene sediments. In addition, buried pockmarks are present near the faults in Erdek Bay. Thus, it is likely that gas/liquid seepage was controlled by both sea level changes and active faulting during pre-Holocene time. At present, Erdek Bay is interpreted to be more passive than Gemlik and Bandırma Bays.

The high-resolution data reveal chimneys and seeps in the faulted areas of Gemlik Bay and east of Marmara Island, which indicates that seepage in this area is controlled by faults.

Erdek Bay was active before the Holocene, but the chirp and sparker data show that no active faults affect the Holocene sediments in this area.

The existence of numerous active and inactive pockmarks around faults in Gemlik Bay and the area to the east of Marmara Island indicate the reactivation of seismicity on the central branch of the NAF. Changes in the sea level and the migration of gas via active faults are a possible explanation for the inactive pockmarks. Periodical sea level changes are interpreted as the reason for vertically stacked pockmarks.

In the outer shelf area, sequence stratigraphic age correlations of horizons show that bright spot reflections above acoustic blanking zones correspond to a ~540,000-year-old horizon and that the İmrı leaves the acoustic blanking zone. This fault provides pathways for the migration of deep gas and fluids.

Acoustic blanking zones that are imaged as dimmed or transparent reflections are observed across the study area. Most of the boundaries of these zones coincide with the last lowstand horizon, which suggests that the source of the gas accumulations is below this horizon. The rapid sedimentation of the marine sediments during the transgression and sea level changes may have controlled the gas accumulations and the migration of gas through the sediments, which resulted in these gas indicators on the seismic data. The complex trace attribute analysis that was applied, which included instantaneous polarity, phase and instantaneous frequency techniques, demonstrated the presence of gas-bearing sediments in the study area.

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