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Geophysical evidence for gas geohazards off Iskenderun Bay, SE Turkey

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Abstract

High-resolution seafloor and sub-surface data were acquired as part of a site survey in Iskenderun Bay, SE Turkey to characterize the geohazards at the location of the proposed drilling site. A 3 km×3 km geophysical study reveals a pockmark field which trends NE and NNE, similar to the trend of major fault systems in the area. The pockmarks, with an average diameter of 35 m, reach their highest density in the northern part of the detailed survey area, with 13 features/km^2. Acoustic anomalies in the seismic records (acoustic turbidity, blanking, enhanced reflectors) below the proposed drilling site indicated potential shallow gas beneath it. The local seismic anomalies (amplitude and frequency) parallel to stratigraphy were assigned a low gas risk. As a result of the active neotectonics in the area, the pockmark field presented a potential hazard for drilling at the original location. The geohazard study resulted in moving the proposed drilling site eastward to an area of fewer pockmarks, less sub-surface seismic anomalies, and thus a location interpreted as a lower geohazard environment.

Keywords: Pockmarks; Acoustic anomalies; Geohazards; East Mediterranean Sea

1. Introduction

The eastern Mediterranean tectonic framework has recently been the focus of several seismic refraction and reflection studies (Aksu, Calon, Piper, Turgut, & Izdar, 1992a; Aksu, Ulug, Piper, Konuk, & Turgut, 1992b; Ben-Avraham, Ginzburg, Makris, & Eppelbaum, 2002; Kempler & Garfunkel, 1994; Vidal, Alvarez-Marron, & Klaeschen, 2000).

Extensional structures are prominent in the NE Mediterranean, a unique sector of the Africa–Eurasia plate convergence zone. The structural settings are different on the two sides of the NE Mediterranean triple junction. On the east, structures controlled by strike-slip and compression coexist, whereas on the west compression is less conspicuous. Here, deep basins separated by a partly submerged ridge are prominent (Kempler & Garfunkel, 1994).

Southeastern Turkey represents an active tectonic regime with a long history of seismicity. Turkey's active tectonics is the manifestation of collisional intracontinental convergence and tectonic escape-related deformation ongoing since the Early Pliocene (Bozkurt, 2001). Three major structures govern the neotectonics of Turkey (Fig. 1a); they are the dextral North Anatolian Fault Zone (NAFZ), the sinistral East Anatolian Fault Zone (EAFZ) and the Aegean–Cyprean Arc. Also, the sinistral Dead Sea Fault Zone plays an important role. The Anatolian wedge between the NAFZ and EAFZ moves westward away from eastern Anatolia, which is the locus of collision between the Arabian and the Eurasian plates. Ongoing deformation along, and mutual interaction among, these plates has resulted in four distinct neotectonic provinces, namely

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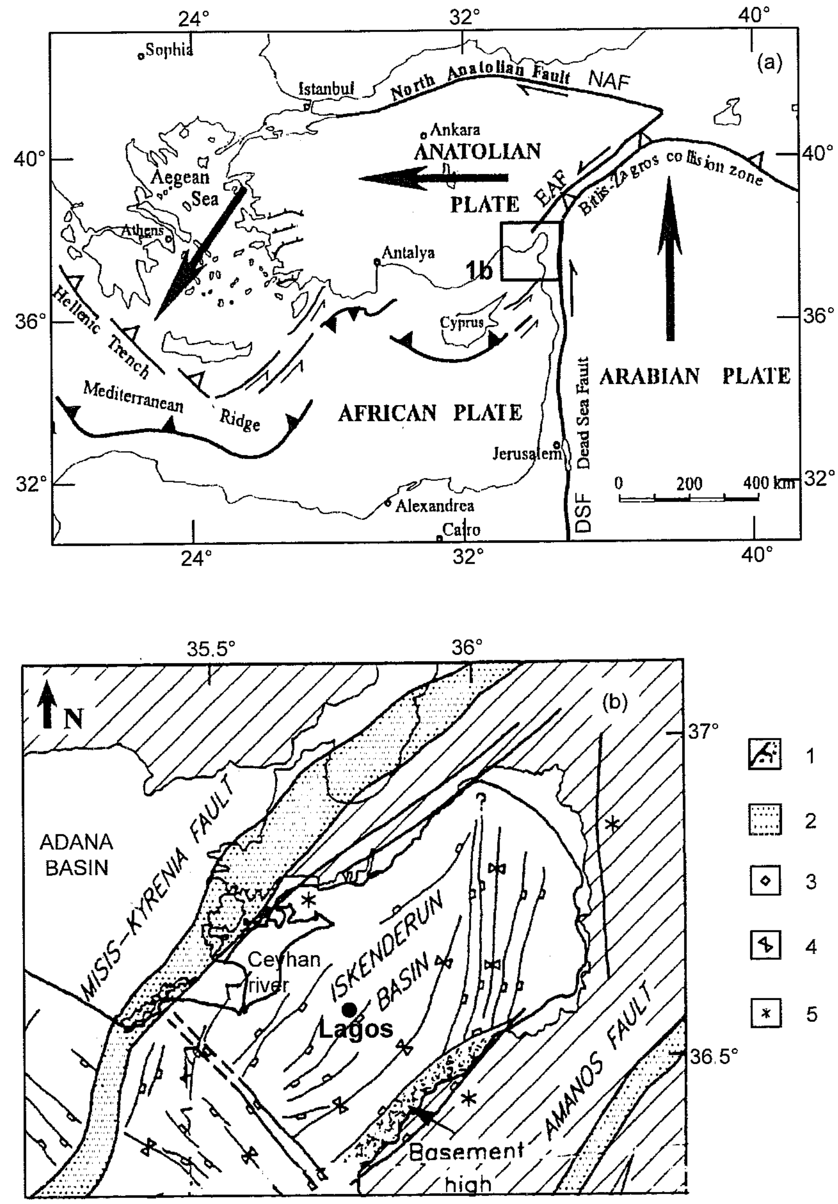

Fig. 1. (a) Tectonic framework of NE Mediterranean modified from Dählmann and de Lange (2003) and Kuşçu et al. (2002). Lines with filled triangles show active subduction zones, the ones with open triangles are active thrust faults at continental collision zones, and lines with tick marks are normal faults. The large solid arrows indicate the sense of motion of the lithospheric plates. DSF, Dead Sea Fault; EAF, East Anatolian Fault; NAF, North Anatolian Fault. (b) Location of Iskenderun Basin and Lagos site. Regional neotectonic setting of the area modified from Aksu et al. (1992a): (1) basement high, (2) Misis-Kyrenia and Amanos faults, (3) anticlinal axes, (4) basinal axes, and (5) faults taken from Perinçek and Çemen (1990).

the East Anatolian contractional, the North Anatolian, the Central Anatolian 'Ova' and the West Anatolian extensional provinces (Bozkurt, 2001).

The area is also seismically active, with common earthquakes of magnitude 6 or more (Ambraseys & Finkel, 1987; Barka & Reilinger, 1997; Koral, 2000). The magnitude 7.4 İzmit earthquake was the largest and most deadly earthquake in Turkey in the past 60 years, and it is remarkable in being the latest in a series of 11 major ($M>6.7$) earthquakes that have ruptured more than a 1000 km length of the North Anatolian fault from near the Karliova triple junction in eastern Turkey to the Aegean Sea (Reilinger, Toksoz, McClusky, & Barka, 2000).

2. Study area: Iskenderun Bay

Iskenderun Bay is located at the edge of the Anatolian platform, immediately southwest of the Africa–Arabia–Anatolia triple junction (Fig. 1). Seafloor morphology in the northeastern Mediterranean Sea is controlled mainly by large-scale tectonics and by the rivers that flow into the region and Iskenderun is one of several Middle–Late Miocene Basins which evolved as a result of intraplate extension associated with displacements around the triple junction (Aksu et al., 1992b; Ben-Avraham et al., 1995; Dählmann & de Lange, 2003; Kempler & Garfunkel, 1994; Kuşçu, Okamura, Matsuoka, & Awata, 2002).

In the Iskenderun Bay area, the continental shelf is generally less than 5 km wide, but widens considerably to 15–45 km off the mouth of present-day deltas, where the shelf gradient ranges from 1:220 to 1:300 (Aksu et al., 1992b). Chronology suggests that Iskenderun Basin is subsiding at rate of 0.33 m 1000 yr^{-1}. Seismic reflection profiling shows that delta architecture in that basin is mainly controlled by glacio-eustatic sea-level fluctuations and continuous basin subsidence (Aksu et al., 1992b).

This basin is bounded along its long sides by the Misis lineament to the northwest and a fault-controlled, shore-parallel basement high that flanks the Amanos Mountains to the southeast (Fig. 1b). Its southwestern boundary is marked by a 1–2 km wide zone of SW-dipping listric normal faults (Aksu et al., 1992a). Within the basin two families of steep normal faults are recognized in the Quaternary succession. One set of NE-trending faults with both northwestern and southeastern vergence run parallel to the Misis lineament. This family is also recognized on land (Gökçen, Kelling, Gökçen, & Floyd, 1988). The other set of faults splays from the southeastern boundary fault and runs in a northerly direction. This set forms a fan which shows steep to moderate easterly dips, easterly vergence and a listric geometry (Aksu et al., 1992a).

The inner Iskenderun Basin (Fig. 1b) is a rectangular-shaped embayment in which the water depth is generally less than 70 m. A 1–5 km wide and <10 m deep prodelta platform encircles the entire coastline off the present-day delta plain. The compound deltaic complex of the Tarsus, Seyhan and Ceyhan exhibits a wave-dominated delta front morphology, i.e. well-developed beach ridges and several rows of coastal dunes in the microtidal setting of the eastern Mediterranean (Russell, 1954).

The southern Turkish rivers (mainly the Goksu, Tarsus, Seyhan and Ceyhan) discharge vast quantities of sediment into the eastern Mediterranean. These four rivers are the main suppliers of siliciclastic sediments into the Iskenderun Basin, with a combined annual sediment yield of 13.315×10^3 t (Aksu et al., 1992b). Modern sediment input is particularly high in the winter months and in the past, sediment influx was especially high during periods of lower sea level (Aksu et al., 1992b). Over time this supply of land-derived debris has been supplemented by planktonic and benthic organisms, and has the potential to produce significant quantities of both biogenic gas and thermogenic hydrocarbons.

Within this context, El Paso Production Company in partnership with the Turkish Petroleum Corporation held a lease to explore this portion of the Turkish shelf and slope. Prior to exploration drilling in 2001, El Paso conducted a geophysical site survey to evaluate geohazards at proposed well sites on the shelf and slope. We will focus on the Lagos well site in this paper, located within Iskenderun Bay at ~80 m water depth (Fig. 1b).

3. Methodology

El Paso conducted a geophysical site survey to evaluate geohazards at a proposed well site on the continental shelf. The survey was conducted over an area measuring 3 km × 3 km, centered on the proposed well location with main survey lines orientated 24/204° in a grid pattern.

Geophysical data acquired includes multi-beam bathymetry and backscatter, sidescan sonar, sub-bottom profiler (pinger), and high-resolution 2D multi-channel seismic (HR2D) data. The reference point was the mean echo sounder transducer position at the waterline. The primary positioning system was Racal Survey's Skyfix DGPS service (multi-reference solution).

A heave compensated dual frequency Atlas Deso 15 single beam echo sounder was used to determine water depths within the survey area. Its transducer frequencies were 33 and 210 kHz with a digital output frequency of 33 kHz. A Simrad EM1000 multi-beam echo sounder provided multi-beam bathymetry and backscatter data, with a 95 kHz transducer frequency and 140° angular coverage.

A dual frequency GeoAcoustics sidescan sonar was also used. With 100 kHz frequency, it had a range of 200 m per channel. For the sub-bottom profiling system, a nine element hull mounted pinger with a band pass filter of 2–4 kHz was used.

For the 2D high-resolution seismic (HR2D), a 4×40 cubic inch TI Sleeve Gun array was used as a source with a shot interval of 12.5 m. The receiver had 96 channels, an active length of 1200 m, and a 12.5 m group interval. HR2D seismic lines were spaced 50–150 m apart in grids centered on the proposed well site. Also, existing exploration 2D multi-channel seismic (MCS) data were used to extend high-resolution interpretations, and to provide regional structural and stratigraphic context.

For ground-truthing the geophysical information, the seabed was sampled by means of a Kullenberg corer with 3 m core barrel length and 83 mm core diameter (Gardline Surveys Limited, 2001).

4. Results: Lagos site

Multi-beam data collected in a 3 km × 3 km area surrounding the well site indicate a relatively flat seafloor with a very gentle (1:2000) slope to the south. Shaded-relief multi-beam bathymetry revealed a dense field of circular, negative relief pockmarks, 0.5–1.5 m deep, aligned parallel

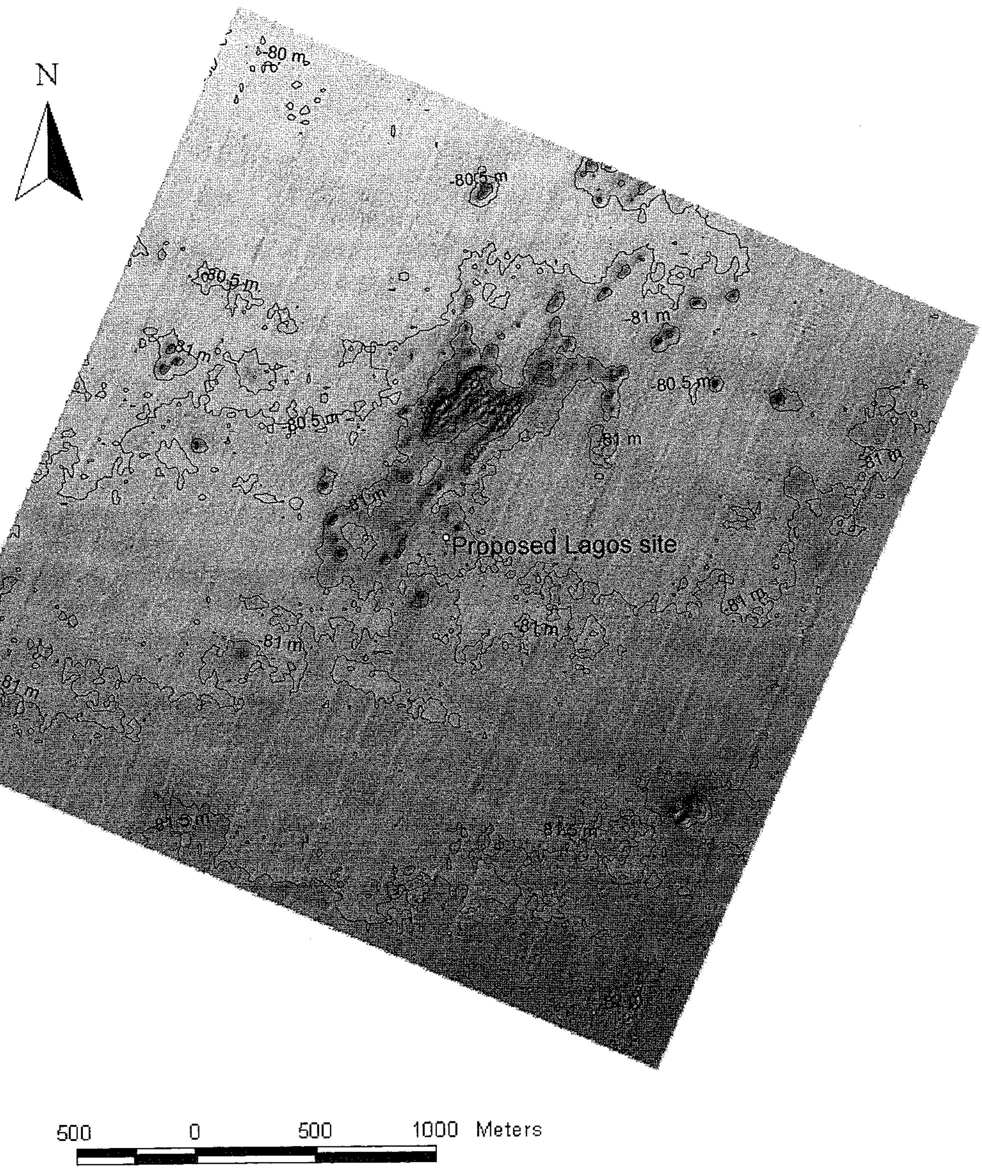

Fig. 2. Multi-beam bathymetry of the seafloor surrounding the proposed Lagos well site, Iskenderun Bay, offshore southeastern Turkey. Area shown is 3 km × 3 km. The seabed north and west of the proposed well site was characterized by numerous pockmarks aligned roughly NE–SW. Many of the pockmarks were characterized by high backscatter (imaged in both multi-beam backscatter and side scan data). Deeper water in darker colors. Water depth at well 81 m and contours every 0.5 m.

to the trend of the main fault systems (NE and NNE) identified in the area (Fig. 2).

The pockmarks have an average diameter of 35 m. Pockmarks are concentrated in the north–northwestern portion of the detailed study area and have an average density of 13 features/km^2, which is comparable with pockmark densities observed in other shallow localities (Hovland, Gardner, & Judd, 2002). Multi-beam backscatter and side scan data both document the presence of anomalously high backscatter within many of the pockmarks, particularly in the region showing the highest density. These pockmarks, therefore, represent a good example of 'eyed pockmarks' (Hovland et al., 2002).

In the side scan sonar data, the seabed generally presents low to moderate reflectivity, with trawl scars across much of the site and no apparent bedforms. Within that pattern, a large number of reflective contacts are observed. These contacts are of very high reflectivity, are 5–10 m in diameter and generally exhibit depths below surrounding seabed of 0.5–1.5 m. Although discrete, they are found in high density concentrations, in the northern part.

Pinger data document the existence of abundant sub-surface acoustic anomalies in the pockmark region (see Figs. 3 and 4). These acoustic anomalies consist of acoustic blanking, acoustic turbidity, and some enhanced reflectors (Hovland & Judd, 1988). Most of the sub-surface acoustic

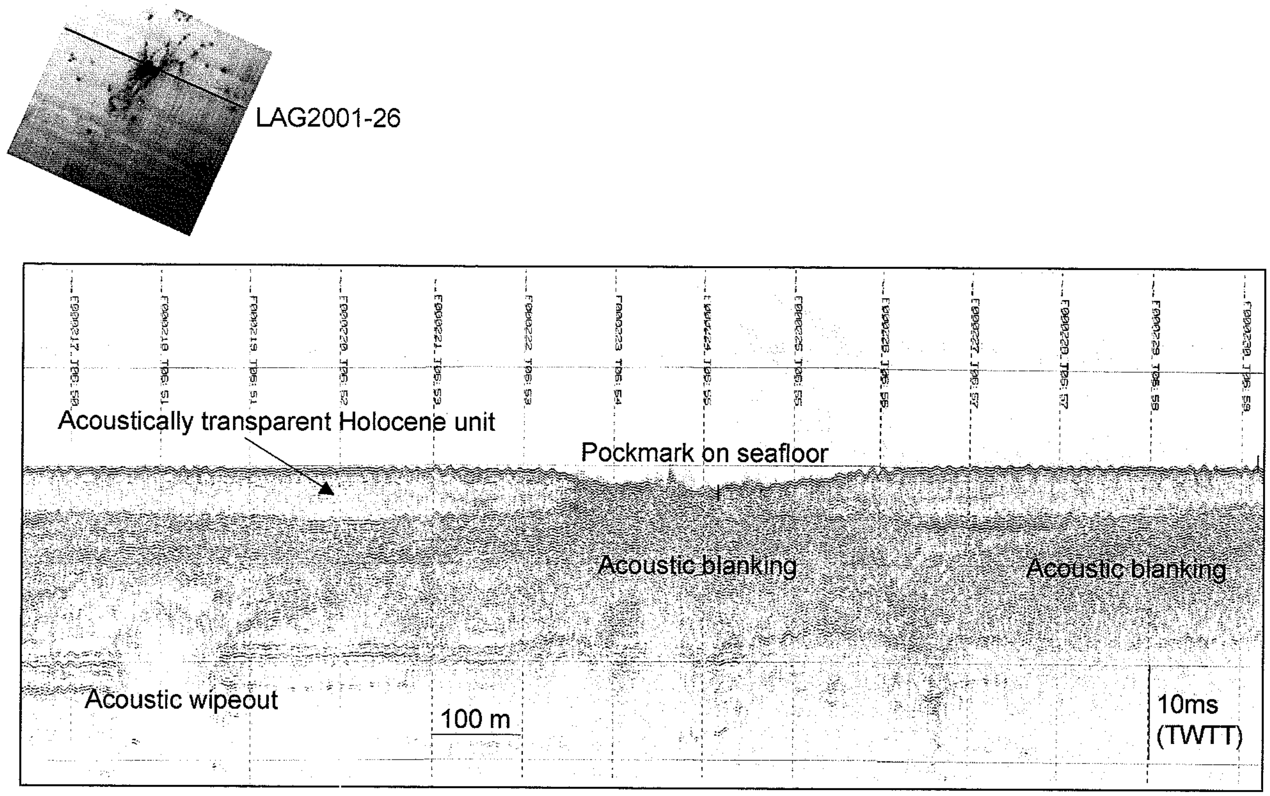

Fig. 3. Sub-bottom seismic profile line LAG2001-26 (3.5 kHz) crossing the pockmark field in the Lagos wellsite area (WNW–ESE). Notice the acoustic blanking below the pockmark reaching the seafloor and the acoustic wipeouts nearby.

anomalies occur in the region of highest pockmark concentration (and eyed pockmarks with high backscatter within them). Pockmarks occur elsewhere in the study area, but are fewer and farther between (Fig. 2). Sub-surface acoustic anomalies also occur elsewhere in the study area, but again are less common. Zones of acoustic blanking typically occur greater than 4–5 ms (TWTT) below the seafloor. In some cases, especially in the vicinity of the observed pockmarks, acoustic blanking extends to the seafloor (see Figs. 3 and 4).

Although the penetration of the pinger system in the area is sometimes limited to 25 m, up to 7 seismic units can be distinguished in the Lagos site area. The uppermost unit (3–5 m thick) is acoustically transparent and continuous across the area. Where acoustic anomalies are not present, the other seismic units are visible, internally chaotic, with an average thickness of 4 m. Cores acquired during the survey program yielded very soft clay from the upper 3 m of section.

Neither exploration 2D nor HR2D data show large acoustic vertical anomalies in the sub-surface within the study area surrounding the Lagos well site. Instead, HR2D data show relatively subtle regions of acoustic turbidity associated with high-angle faults. In Fig. 5, some amplitude anomalies occur just below the pockmarks at the seafloor. HR2D data also show local increases in amplitude and variations in frequency at stratal boundaries, and in particular at horizons located 0.10–0.12, 0.2–0.25, 0.4–0.42, 0.58–0.6, 0.90, and 1.10s TWTT below the sea surface (Fig. 6). Two-dimensional exploration data shows high-angle faults near the Lagos site (Fig. 7) and also, subtle amplitude anomalies in the sub-surface.

5. Discussion

At seismo-acoustic frequencies, typically a few hundred hertz to a few tens of kHz, acoustic propagation in sediments is severely affected by the presence of gas. Bubble layers act as scatterers of acoustic energy, effectively impeding the acoustic characterization of sediments below the gas horizon, and giving rise to clearly recognizable seismic features, i.e. acoustic turbidity, acoustic blankings, etc. (Fleischer, Orsi, Richardson, & Anderson, 2001; Hovland & Judd, 1988). Pockmarks, seeps, and other seabed features have been associated with the expulsion of fluids (in particular methane) from the seabed (Hovland & Judd, 1988; Judd, 2003).

Multi-beam bathymetry data indicated the presence of a pockmark field immediately N and W of the proposed Lagos well site. The sub-surface geophysical data, points out the numerous acoustic anomalies as potential gas accumulations in the sub-surface data in the Lagos site area. Also, multi-beam backscatter and side scan data both document the presence of anomalously high backscatter within many

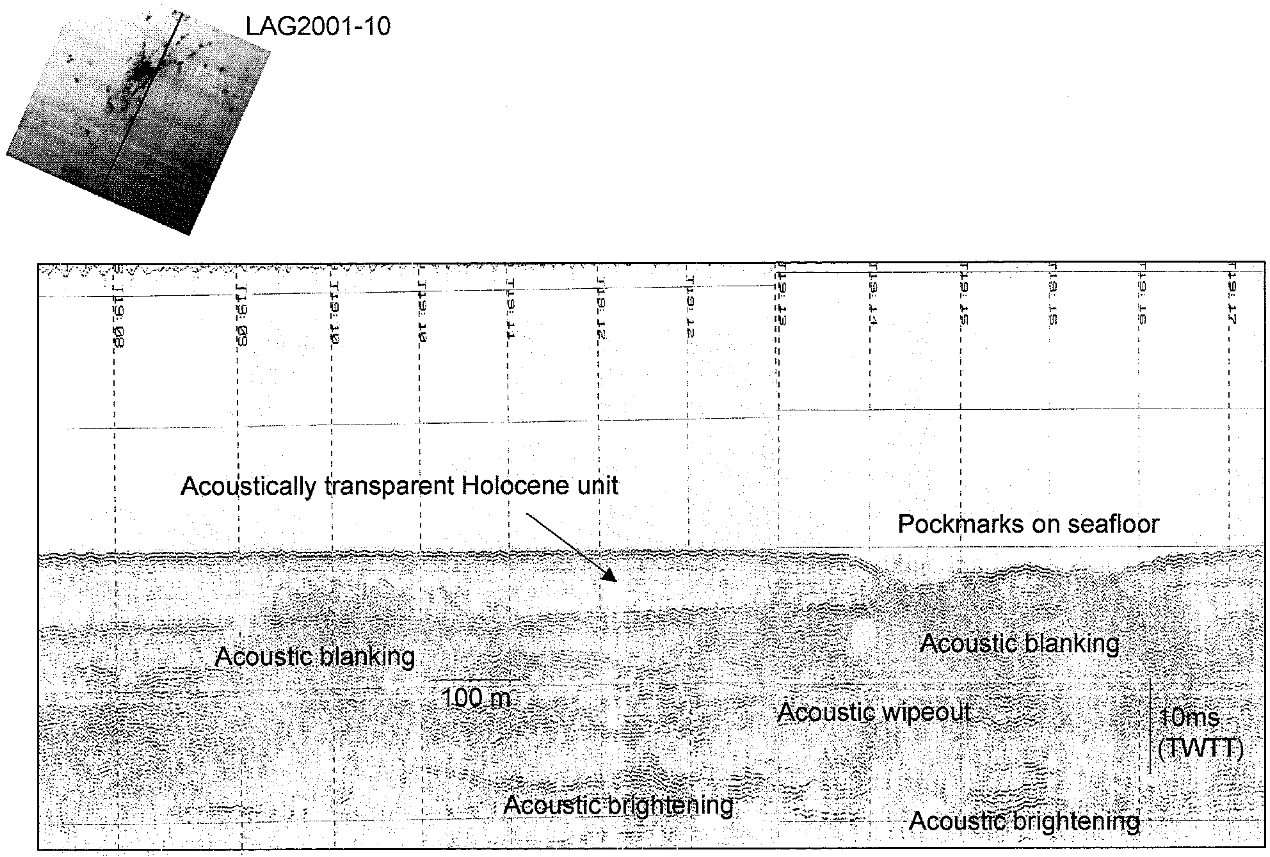

Fig. 4. Sub-bottom seismic profile LAG2001-10 (3.5 kHz) crossing the pockmark field in the Lagos wellsite area (NNE–SSW). Notice the acoustic blanking below the pockmark reaching the seafloor and the close acoustic wipeouts and local acoustic brightening.

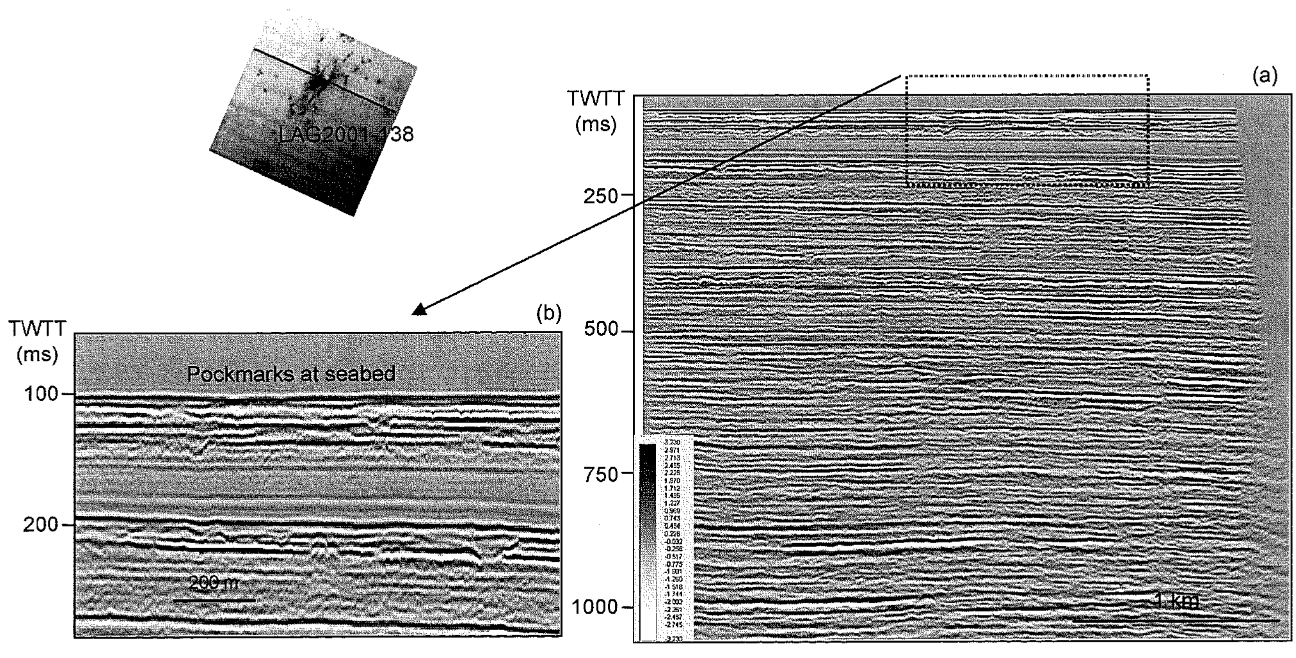

Fig. 5. (a) High-resolution 2D MCS line LAG2001-138 across the Lagos well site area (location shown in inset). Although HR2D data did not show prominent gas columns, they did show subtle acoustic anomalies, as well as localized amplitude anomalies at distinct stratal zones (0.10, 0.20, 0.40, 0.60, 0.70, 0.90, and 1.0s TWTT). In the figure shown, the acoustic anomalies and stratal brightening underlie a pockmark at the seabed; (b) detail of pockmarks at seabed.

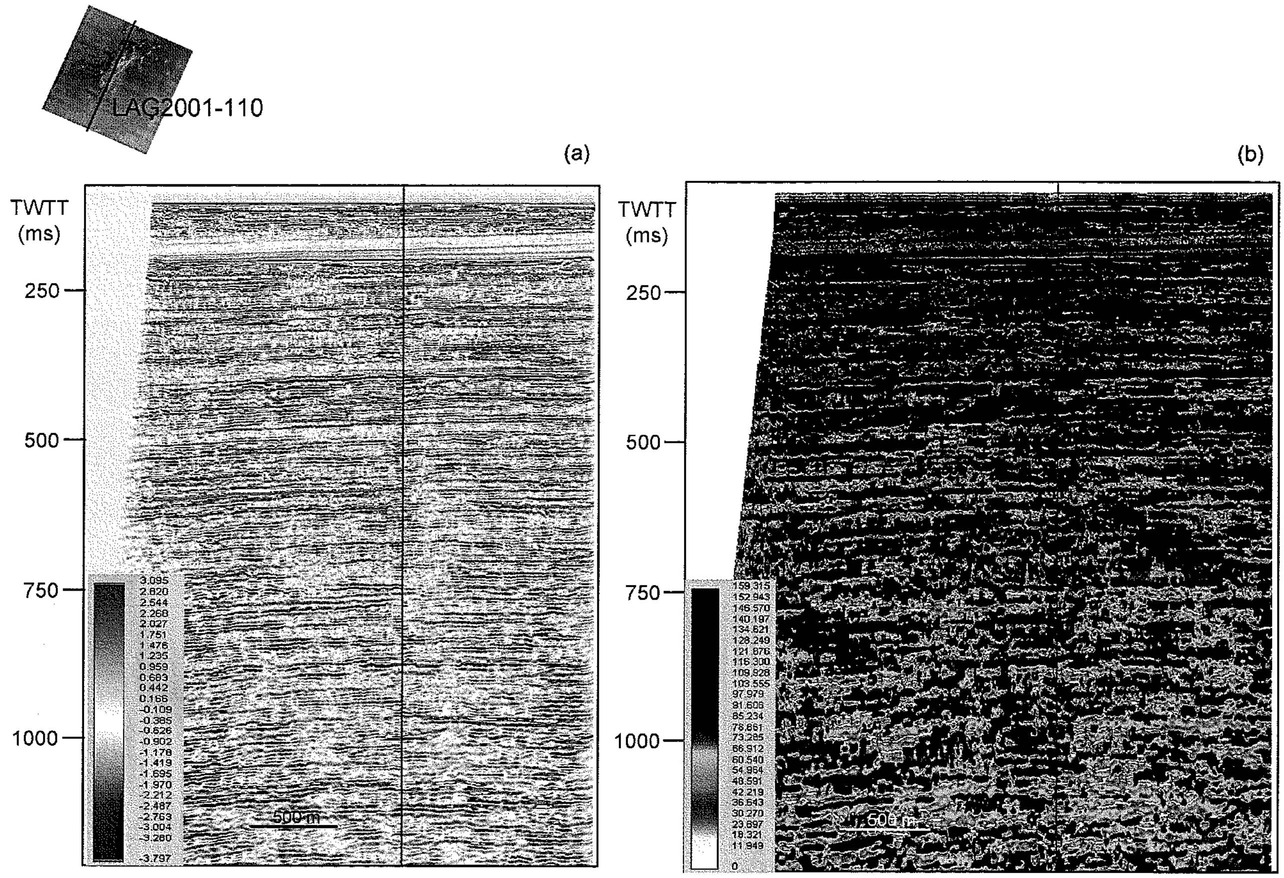

Fig. 6. High-resolution 2D MCS line LAG2001-110 across the Lagos well site area (location shown in inset) crossing 2D HR line LAG2001-138 (see Fig. 5); (a) HR2D data shows localized amplitude anomalies (yellow colors) at 0.10, 0.20, 0.40, 0.60, 0.90, and 1.10s (TWTT); (b) color indicated low frequency anomalies in the same line.

of the pockmarks, which is interpreted to be due to the presence of authigenic carbonate, which would suggest long-lived hydrocarbon seepage.

The low to moderate reflectivity outside the pockmarks in the side scan sonar records is consistent with superficial sediments comprising very soft clays. Also the moderate fishing activity in the area could explain the common trawl marks.

North and west of the proposed well site, the 'eyed' pockmarks showed regions of high seafloor backscatter within them, and were associated with sub-surface acoustic anomalies interpreted as gas columns, acoustic turbidity or enhanced reflectors in the sub-bottom profiler data (Figs. 3 and 4). The stratigraphic unit immediately below the seafloor is acoustically transparent and its base is inferred to be the Pleistocene–Holocene transition, which may provide an effective stratigraphic seal for the gas below. Below it we have been able to identify six other seismic units, which are generally internally chaotic and disturbed by the presence of gas, although Aksu et al. (1992b) points out up to nine seismic sequences in the area. The penetration of the pinger system in the area is sometimes limited due to the coarse nature of the sediment and signal absorption caused by gas within the sediments (acoustic blanking).

The sub-surface gas columns (in pinger data) and stratal brightening (in HR2D) suggest that diffuse gas has risen through the more porous Pliocene and Pleistocene section and has been trapped at various levels in the surface, including the base of the soft Holocene clay. The gas may originate in the biodegradation of organic matter discharged into Iskenderun Bay by the four main rivers of southern Turkey, as well as the planktonic and benthic organisms. Locally, this gas (of probable biogenic origin) penetrated the clay, and pockmarks containing authigenic carbonate cementation formed where gas-charged fluids exited the seafloor. No evidence of gas in the water column was detected in single beam or side scan data.

These observations suggested that the pockmarks formed as a direct result of protracted seepage of gas-charged fluids. The lack of significant gas columns on the HR2D data may indicate that the source of the gas is quite shallow or that these pockmarks are dormant, although the local amplitude anomalies parallel to stratigraphy in the HR2D data suggests that gas may be ponding at discrete intervals in the sub-surface. Regardless of whether the pockmarks are actively

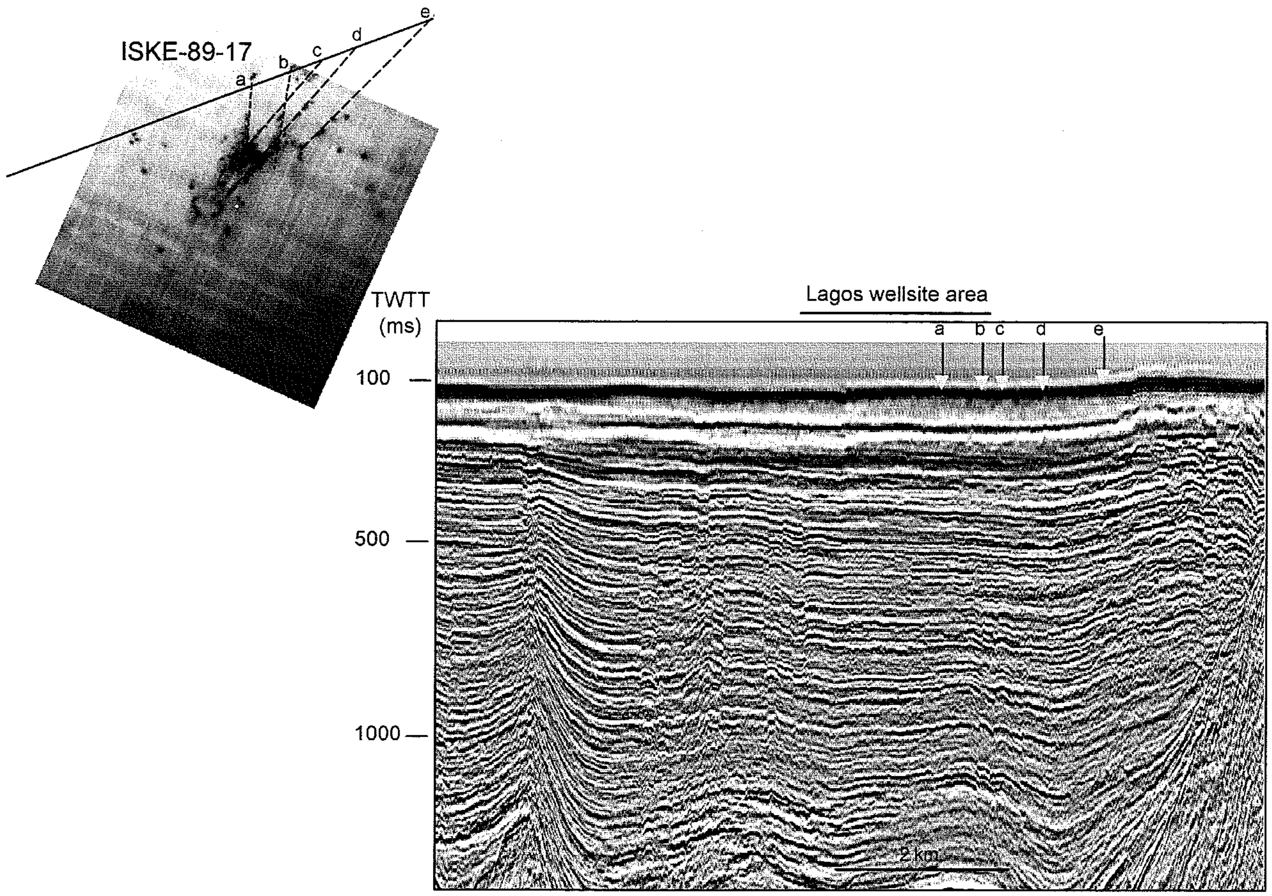

Fig. 7. 2D exploration seismic line ISKE-89-17 near Lagos site. Notice the multiple high-angle faults occurring near the site and the NNE trend of the lineations in pockmarks at the seafloor in the inset. Letters 'a' to 'e' indicate where the interpolated faults would cross the seismic line.

seeping gas, authigenic carbonate within eyed pockmarks provides an attractive target for obtaining information on the petroleum system (for example, to determine if thermogenic gas or fluids were involved in the expulsion).

HR2D data show relatively subtle regions of acoustic turbidity associated with high-angle faults. These and the NE/NNE trend of the fault system of the area (Aksu et al., 1992a; Bozkurt, 2001) suggest these faults act as pathways for gas migration through the sub-surface and escape to the seafloor. One evidence of this would be the alignment of the seafloor pockmarks (Fig. 2).

The local seismic anomalies located 0.10–0.12, 0.2–0.25, 0.4–0.42, 0.58–0.6, 0.90 and 1.10s TWTT below the sea surface and parallel to stratigraphy cannot not be attributed to primary depositional fabric, and were interpreted to be the result of gas ponding, and were assigned a low gas risk in the preliminary geohazard report (Gardline Surveys Limited, 2001).

If the Iskenderun pockmarks are not presently active, then one possibility is that the activity is associated with seismicity because the neotectonic activity in the area is very high (Bozkurt, 2001; Koral, 2000). The linear trend of the pockmarks corresponds to the trend of the main faulting systems in the area, suggesting a relationship between pockmark formation and tectonics. Sub-surface fault zones may provide preferential conduits for gas migration, or may be hydraulically active during or shortly after earthquakes. Thus, the degassing may be episodic and related to periods of seismicity. Other pockmarks related to faulting systems, and active during/after earthquakes in the eastern Mediterranean have been studied by Dimitrov and Woodside (2003).

A positive correlation between neotectonic activity and gas movements in time has been studied by Laier, Jørgensen, Buchardt, Cederberg, and Kuijpers (1992). Earthquake activity is a direct trigger for gas seepage (Dando et al., 2000; Field & Jennings, 1987; Hasiotis, Papatheodorou, Kastanos, & Ferentinos, 1996; Laier et al., 1992; Papatheodorou, Hasiotis, & Ferentinos, 1993; Soter, 1999). Earthquakes can increase internal fluid pressure and provoke seepage from the shallowest gas accumulations in the area as well as resuspend fine-grained material, temporarily reducing lithostatic pressure (Papatheodorou et al., 1993). In fact, Hasiotis et al. (1996) report that the majority of pockmarks they studied in the Gulf of Patras showed gas seepage some days after a M5.4 earthquake. Iskenderun Bay frequently experiences earthquakes significantly stronger than these

(Koral, 2000; Reilinger et al., 2000). The area also supports a very active fishing activity and that could also trigger gas seepage in zones where the gas is shallow enough (García-García, García-Gil, & Vilas, 1999).

Given the distribution of pockmarks and sub-surface acoustic blanking, and in particular the eyed pockmarks with high backscatter within them in the north–northwestern part of the field area, these features were considered to pose a potential hazard to exploration drilling. Pockmarks and anomalous seafloor backscatter occurred within 150 m of the planned well location. The full suite of geophysical data was evaluated, and the well location was moved to the southeast. The final well location took into account the distribution of pockmarks, eyed pockmarks, shallow acoustic turbidity zones and anomalous sub-surface amplitudes. Exploration drilling results and observations at the revised location were consistent with the features identified on the seafloor (or lack thereof) and the sub-surface geohazard predictions.

6. Conclusions

High-resolution seafloor and sub-surface seismic and acoustic data acquired as part of a site survey in Iskenderun Bay, SE Turkey, were sufficient to characterize the geohazards in the location of the proposed drilling site. A prominent pockmark field area (average pockmark diameter of 35 m and average density of 13 features/km^2) in the northern part of the site was discovered. Acoustic anomalies in the seismic records (acoustic turbidity, blanking, enhanced reflectors) below the proposed drilling site indicate potential shallow gas beneath it. The local seismic anomalies parallel to stratigraphy were assigned a low gas risk, with numerous faults underneath providing a preferential pathway for the gas to migrate and/or escape. Based upon the proximity of the proposed well to anomalous seafloor and sub-surface features, the proposed site was moved eastward to an area with a lower geohazard environment.

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