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High-resolution surveys for geohazards and shallow gas: NW Adriatic (Italy) and Iskenderun Bay (Turkey)

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Abstract

The need for quantifying and understanding the distribution of shallow gas is both of academic interest and of relevance to offshore facilities. The combination of seafloor mapping, subbottom profiling, and multi-channel seismic data can provide information on regions of possible shallow gas, where the gas impacts the acoustic properties of the host material and the seafloor. In this paper, we present two case studies – one academic and one industry – that evaluate the distribution of shallow gas in two field areas in the Mediterranean. In the first case study, geophysical data from Iskenderun Bay, southeastern Turkey, indicate the presence and distribution of shallow gas. Pockmarks on the seafloor are associated with acoustic wipeout in the shallow subbottom data. Although deeper seismic data do not show bright spots or other indicators of possible gas, instantaneous frequency analysis clearly shows laterally restricted anomalies indicating gas-rich zones. The interpretation of possible shallow gas resulted in moving a proposed drilling location to a nearby area characterized by fewer (but still present) shallow gas signatures. In the second case study, cores acquired in the Po Delta, Adriatic Sea, provide quantitative ground-truthing of shallow gas – as suggested by geophysical data – and provide minimum estimates of the percentage of gas in the subsurface. Cores targeted on anomalous subbottom data yielded up to 41,000 ppm methane; cores with anomalous gas content are associated with thick recent flood deposits which may effectively isolate reactive terrigenous organic matter from biologic and physical re-working.

Introduction

In offshore industries, a geohazard is a seafloor or subsurface geologic feature (or man-made infrastructure or debris) that could pose a threat to, affect the stability of, or constrain the operation of an offshore engineered structure (Trabant, 1984). Much of the work for offshore geohazards serves the offshore oil and gas industry. As the resolution

and quality of geophysical data has improved, so has the recognition that the seafloor and shallow subsurface can be extremely complex. Seafloor geologic conditions, for instance, can include irregular topography, steep slopes, faulting, vents, mud volcanoes, salt diapirs, rapid sediment accumulation, pockmarks, shallow gas and (in the appropriate pressure and temperature conditions) gas hydrates (Campbell, 1999). Some of these

features are associated with biologically diverse chemosynthetic communities deriving their energy from reduced fluids exiting the seafloor (hydrogen sulfide, oil, gas) at near-ambient temperature conditions (these are referred to as 'cold seeps'; Paull et al., 1984; Suess et al., 1985; Kulm et al., 1986; Paull and Neumann, 1987; Roberts and Neurauder, 1990; Neurauder and Roberts, 1994; Reilly et al., 1996; MacDonald, 1998).

Offshore structures are today being installed over a wide range of water depths from shallow water to depths of 3000 m. The scale and complexity of some offshore engineered structures is impressive, and is in part related to the complexity of the geohazard environment. The scale and complexity has also been driven by the use of subsea wells, which are operated remotely and tied back to a separate processing facility over distances that can exceed tens of kilometers. The high cost of such seafloor facilities drives the need for high quality data acquisition, and in turn, increases the importance of geohazard evaluation. Specific geohazard issues can include: shallow soils and their variability, steep slopes, slope stability, seafloor seeps, chemosynthetic communities, faulting, subsurface lithology, overpressured shallow brine sands at a proposed well bore, shallow gas, and gas hydrate (in shallow water in high latitudes and in deepwater at all latitudes).

Geohazard studies and geophysical tools

Geophysical tools for surveying the seafloor and subsurface have evolved as the industry's needs have evolved. Most of the early acquisition systems – echo sounders, side-scan sonar, and sub-bottom profilers – were adaptations of technology developed by the military. The development of swept frequency (chirp) subbottom profiling systems, 3D seismic, and high-resolution 2D (HR2D) multi-channel seismic have increased the tools available for analyzing the seabed and subsurface. Table 1 presents the array of acoustical (geophysical) systems used for geohazard evaluation with their frequency range, typical penetration, and applications. In general, the lower the frequency, the deeper the penetration below the seafloor (due to attenuation). High-resolution and very high-resolution 2D (HR2D and VHR2D) multi-channel

seismic were adapted from methods used for exploration seismic, with the seismic sources modified to produce the higher frequencies necessary to increase the vertical resolution of the seismic data in the shallow section. Exploration seismic data can also be reprocessed to enhance the high frequency content either by extracting the near-traces, or by spectral whitening.

The widespread use of 3D seismic data within the geohazard industry began in the mid-1990s (Roberts et al., 1996). The availability of these data, and their suitability to detect hazardous shallow gas accumulations (Hill, 1996), significantly impacts how geohazards are interpreted today. The vertical resolution is less than subbottom profiling systems, but the increase in lateral resolution provides great advantages (Campbell, 1999). One advantage is that geohazards interpreters can use seismic workstations with increasingly sophisticated and powerful software for seismic interpretation. Today all of the geophysical data can be brought into a common interpretation environment. The advantage of integrating these data cannot be underestimated. Not only can data be screened for high amplitudes that may indicate shallow gas, but geologic and geomorphic features that are imaged in different data sets can be readily compared at different resolutions.

Geohazard studies and shallow gas

Shallow gas identification and assessment is one of the most important tasks in a geohazard evaluation. Gas in the shallow subsurface can undermine an offshore structure or cause a gas blowout that can result in not just loss of investment and property, but loss of life. Shallow gas blowouts are usually caused when slightly overpressured gas pockets are encountered in shallow formations (typically between 200 and 1000 m below the mudline) during drilling operations. In this paper, we will discuss the high-resolution data acquisition and interpretation that were used in combination with exploration seismic data to evaluate two proposed well sites in Iskenderun Bay, offshore southeastern Turkey.

High-resolution seafloor and subbottom imaging tools, combined with exploration or high-resolution seismic, can provide imagery suggestive of the presence of gas. If close enough to the

Table 1. Geophysical sensors and seismic data with their frequency range, typical penetration, and applications (adapted from Trabant, 1984).

System	Frequency range	Typical penetration	Application
Echo sounder; single beam or multibeam	10–250 kHz	0–1 m	Echo sounder data can be used to image gas bubbles in water column. All systems can provide data on seafloor bathymetry. Multibeam systems, due to their inherent high data density, and provide detailed data on seafloor bathymetry. Pseudo Side Scan.
Side-scan sonar, multibeam backscatter	100–200 kHz; 10–100 kHz	cm's to dm's (low frequency systems [5–12 kHz] may penetrate m's)	Seafloor Morphology-Debris, depressions. Co-registered multibeam backscatter data, if properly processed, can image lateral changes of seafloor material. Side scan (and multibeam systems) provide information regarding seafloor impedance, roughness, and volumetric scattering (with the depth of penetration a function of frequency and sediment physical properties; Gardner et al. 1991).
Subbottom profiler	1–10 kHz;	< 100 m;	Very shallow stratigraphy, gas bubbles in water column, shallow channels, landslides, gas bearing sediments, identification of seafloor faults. Assessment of recent fault activity.
High and Very High-resolution 2D seismic (HR2D and VHR2D)	< 1 kHz; 1–6 kHz;	1000 m; < 100 m;	Detection of shallow gas, fault mapping, sequence stratigraphic interpretation, lithology prediction, geotechnical properties, correlation and calibration with 3D seismic data.
Conventional 3D seismic	40–70 Hz	~8000 m or more	Detection of hazardous shallow gas, fault mapping, sequence stratigraphic interpretation, seismic geomorphology, attribute analysis, visualization.
Reprocessed 3D seismic	50–80 Hz	~5000 m or more	Detection of hazardous shallow gas, fault mapping, sequence stratigraphic interpretation, seismic geomorphology, attribute analysis, visualization.
High and Very High-resolution 3D seismic (HR3D and VHR3D)	< 1 kHz; 1–6 kHz;	~1000 m; < 100 m;	Detection of shallow gas, detailed fault mapping, high-resolution sequence stratigraphic interpretation, high-resolution seismic geomorphology, geotechnical properties, attribute analysis, visualization.

seafloor, such anomalies can be sampled using well-placed cores. Headspace gas analyses of cores can provide a minimum estimate for the percentage volume of gas present in the sediment. If cores come from deep water, de-gassing of the pore water with a decrease in confining pressure may release some of the gas. Headspace gas samples can, however, provide valuable information on the presence or absence of gas, its distribution, and composition. If sufficient quantities of gas are sampled, additional analyses can be conducted in order to determine the isotopic composition of the gas.

One of the tools used in industry to evaluate the presence of gas involves attribute analysis of

the seismic data in the frequency domain. Gas reservoirs are detectable even when they are thinner than their tuning thickness, as they can create acoustic impedance anomalies and low instantaneous frequency attributes (Adriansyah and McMechan, 2002). Instantaneous frequency, in the range of ~5–100 Hz, is a very useful and practical seismic attribute for evaluating possible gas-rich zones because the presence of gas leads to a loss of high frequency energy due to absorption; the presence of gas in reservoir acts as a natural low-pass filter (Taner et al., 1979; Chen and Sydney, 1997). Attenuation of high frequencies occurs in a more pronounced way with increased

gas saturation within a reservoir. Instantaneous frequency analyses for shallow gas accumulations may show distinct low frequency shadow zones, for example beneath especially distinct bottom simulating reflectors (BSRs) related to gas ponding below the base of the gas hydrate stability zone (Vanneste et al., 2001, 2002). We emphasize that in some areas, the presence of gas-rich zones may be interpreted in the frequency domain, even if there is no corresponding bright spot or wipeout (or any other possible indication of gas) in the amplitude or reflection strength data. Searching for low frequency shadow zones as a possible indicator of gas reservoirs is an interpretation tool long used in the exploration industry (Taner and Sheriff, 1977) that can be applied to potential geohazards in the shallow section.

The U.S. Navy's Office of Naval Research has been funding work into the origin of stratal formation on margins (previously STRATAFORM and currently EuroSTRATAFORM). One of the objectives of this work is to understand how geologic processes create and modify seafloor and subsurface acoustic properties, and, by extension, how to differentiate between natural and

anthropogenic features. Gas in the shallow subsurface has a significant impact on subbottom profiler data, and it can also impact the acoustic signature of seafloor mapping systems. Our work with EuroSTRATAFORM addresses the role of gas in affecting shallow subbottom and seafloor acoustics. In this paper, we will show an example from the Po Delta, offshore northeastern Italy where a combination of geophysical surveys, sedimentology and headspace gas analyses link modern flood-driven sediment accumulation with shallow gas formation, and quantify the amount of gas required to get acoustic blanking in the subsurface.

Study Area 1: Iskenderun Bay

Iskenderun Bay is located at the edge of the Anatolian platform offshore southeastern Turkey, near the Syrian border (Figure 1). Seafloor morphology in the northeastern Mediterranean Sea is mainly controlled by large-scale tectonics and by the rivers that flow into the region. Iskenderun Bay is one of several Middle–Late Miocene basins, which

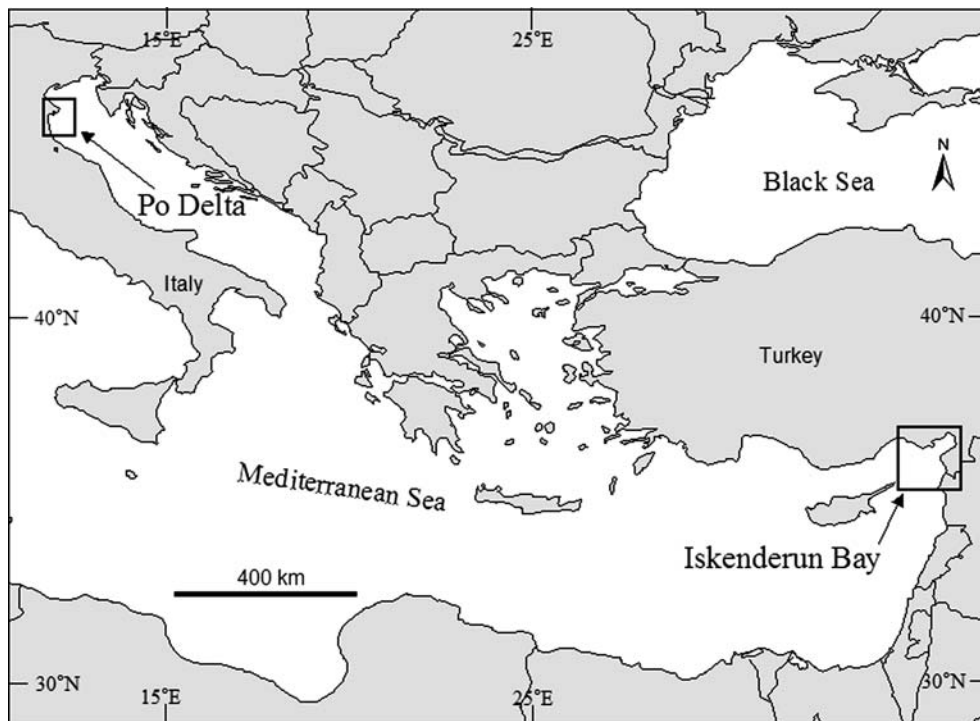


Figure 1. Location of Po Delta (Italy) and Iskenderun Bay (Turkey).

evolved as a result of intraplate extension associated with displacements around the Africa–Arabia–Anatolia triple junction (Aksu et al., 1992b).

Offshore southeastern Turkey 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). Seismic reflection profiling shows that sediment accumulation is mainly controlled by glacio-eustatic sea-level fluctuations and continuous basin subsidence (Aksu et al., 1992b). Within the basin two families of steep normal faults are recognized in the Quaternary succession. One set of northeasterly trending faults with both northwestern and southeastern vergence run parallel to the Misis lineament (Aksu et al., 1992a). This family is also recognized on land (Gökçen et al., 1988). A second set of faults splays from the southeastern boundary fault and runs in a northerly direction (Aksu et al., 1992a).

The inner Iskenderun Basin 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 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 13.315×10^6 kg (Aksu et al., 1992b).

Within this context, El Paso Energy Company in partnership with the Turkish Petroleum Corporation held a lease to explore this portion of the Turkish shelf and slope. Exploration seismic data obtained in the Iskenderun Bay area were acquired by the M/V Geco Sapphire using two 5100 m streamers separated by 100 m, and a 3397 cubic inch Bolt/sleeve gun array. The group interval was 12.5 m, and the shot interval 25 m. The data were sampled at 2 ms. Based upon evaluation of the 2D exploration seismic data, El Paso and TPAO selected a series of targets for exploration drilling. Prior to explor-

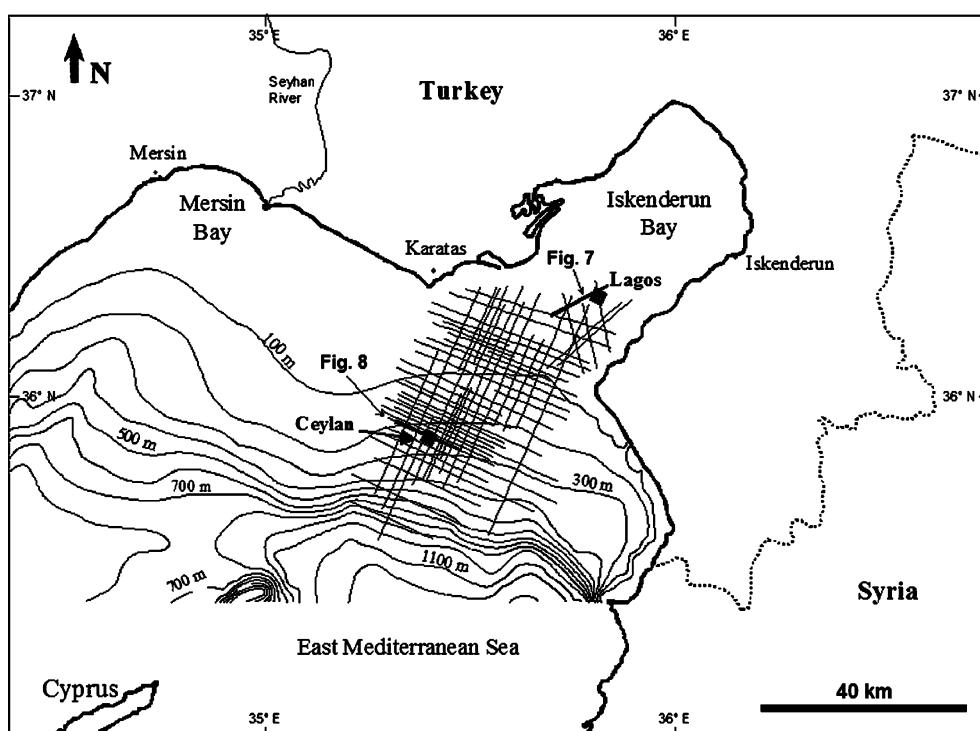


Figure 2. Location of Lagos and Ceylan drilling sites in the eastern Mediterranean Sea. Location of exploration 2D seismic lines shown as solid lines; high-resolution lines and subbottom profiles are constrained in a square of 3×3 km around each of the proposed drilling sites. 2D exploration lines used for instantaneous frequency analysis (Figures 7 and 8) indicated.

atory drilling in 2001, El Paso conducted a geophysical site survey to evaluate geohazards at each well site on the shelf and slope (Gardline Surveys Limited, 2001). We will focus on the Lagos and Ceylan well sites in this paper, located within Iskenderun Bay at ~80 m water depth and off Iskenderun Bay at ~230 m water depth respectively (Figure 2).

Iskenderun Bay-Lagos and Ceylan sites

To evaluate the geohazards in the region of the proposed drill site a survey was conducted over an area measuring 3×3 km centered on each proposed well location, with lines spaced 50–150 m apart (close spacing near the well, farther apart farther away). Geophysical data acquired included multibeam bathymetry and backscatter (Simrad EM1000), side-scan sonar (GeoAcoustics), sub-bottom profiler (pinger), and HR2D multi-channel seismic data (4×40 cubic inch sleeve gun array with a 96 channel, 1200 m streamer; group and shot interval of 12.5 m). All of the geohazard survey geophysical data were acquired simultaneously, with the maximum line spacing constrained by the range limits of the multibeam system. Note that at the narrow line spacing (required by the HR2D) the side-scan and multibeam systems provided substantial overlap.

Seafloor mapping (Lagos Site)

Multibeam data at the Lagos site indicate a relatively flat seafloor with a very gentle (1:2000) slope to the south, and a dense field of circular, negative relief pockmarks, 0.5–1.5 m deep (Figure 3), aligned parallel to the trend of the main fault systems (NE) identified in the area. The pockmarks have an average diameter of 35 m. Pockmarks are concentrated in the north-central portion of the detailed study area and have an average density of 13 features per km², which is comparable with pockmark densities reported by Hovland et al., (2002). Multibeam backscatter and side-scan data both document the presence of anomalously high backscatter within many of the pockmarks, particular 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 this pattern, a large number of reflective contacts are observed. These anomalous backscatter contacts are located within the pockmarks, of very high reflectivity, 5–10 m in diameter and with heights above seabed of 0.5–1.5 m. Pockmarks and isolated backscatter anomalies occur elsewhere in the study area, but are fewer and farther between.

Subbottom profiling (Lagos site)

Pinger data document the existence of abundant acoustic anomalies in the pockmark region (Figure 4), including acoustic blanking, acoustic turbidity, and some enhanced reflectors (Hovland and Judd, 1988). Most of the anomalies occur in the region of highest pockmark concentration. Subsurface acoustic anomalies also occur elsewhere in the study area, but are less common. Zones of acoustic blanking typically occur greater than 4–5 ms two way travel time (TWTT) below the seafloor. In some cases, especially in the vicinity of the observed pockmarks, acoustic blanking extends to the seafloor (see Figure 4).

Although the penetration of the pinger system 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 all of the area. Where acoustic anomalies are not present, the other seismic units are visible, commonly internally chaotic, and with an average thickness of 4 m. Cores acquired during the survey program yielded very soft clay at these depths.

HR2D seismic and exploration 2D seismic data

Neither exploration 2D data nor HR2D data show prominent acoustic anomalies in the subsurface within the study area surrounding the Lagos well site. Instead, HR2D data show relatively subtle regions of acoustic turbidity, and laterally restricted amplitude anomalies immediately below, associated with the pockmarks at the seafloor in the amplitude data (Figure 5). Exploration 2D data in Iskenderun Bay show high-angle faults in the subsurface data (e.g., Lagos site, Figure 6). Based upon the evidence of possible gas on the

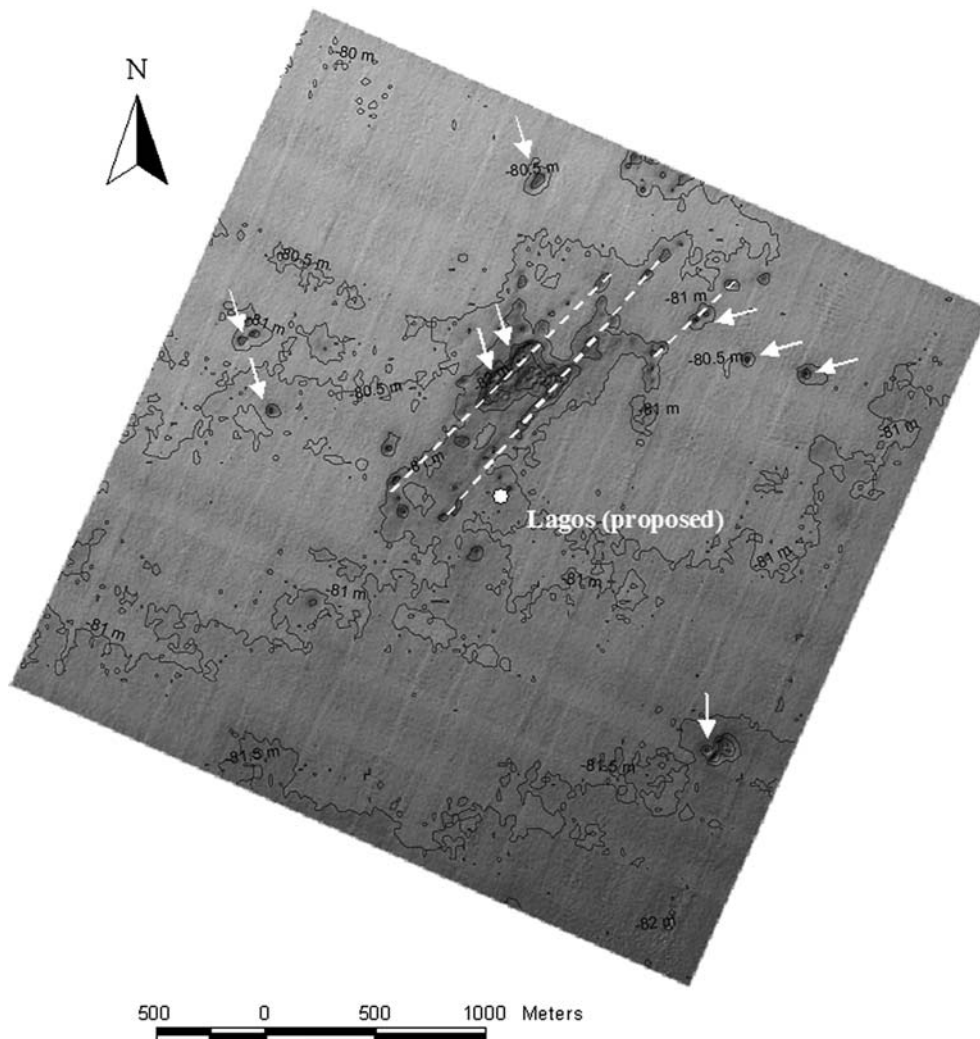


Figure 3. Shaded relief multibeam bathymetry of the seafloor surrounding the proposed Lagos well site, Iskenderun Bay. Area shown is 3×3 km. The seabed in the north-central portion of the survey area was characterized by numerous pockmarks aligned roughly NE-SW, parallel to a regional fault trend. Many of the pockmarks were characterized by high backscatter (imaged in both multibeam backscatter and side-scan data).

seafloor and subbottom profile data, yet relatively subtle features in the seismic amplitude data, we applied instantaneous frequency analysis to look for the presence of possible shallow gas in the seismic data. At both well locations (Lagos and Ceylan), reflection strength sections were additionally calculated from the migrated 2D seismic data to show amplitude–frequency relationship for two different sub-sets of each seismic line. Given the relatively gentle dipping seismic reflectors, side-by-side windows were selected to compare seismic attributes. This allowed frequency analyses to be compared and contrasted within the same lithofacies.

(a) Lagos site

At the Lagos site, the exploration seismic data show no obvious anomalies in the selected sub-areas A and B in either the amplitude or reflection strength data (Figure 7a and b; reflection strength = amplitude of the envelope of the seismic wave). However, in the frequency domain, by using a color palate that accentuates lower frequency energy, we see that the horizon at 380–400 ms TWTT is much brighter in sub-area A than the same horizon in sub-area B (Figure 7c). A quantitative analysis (power spectra) of the two sub-areas shows that sub-area A has less attenuation of lower frequencies than

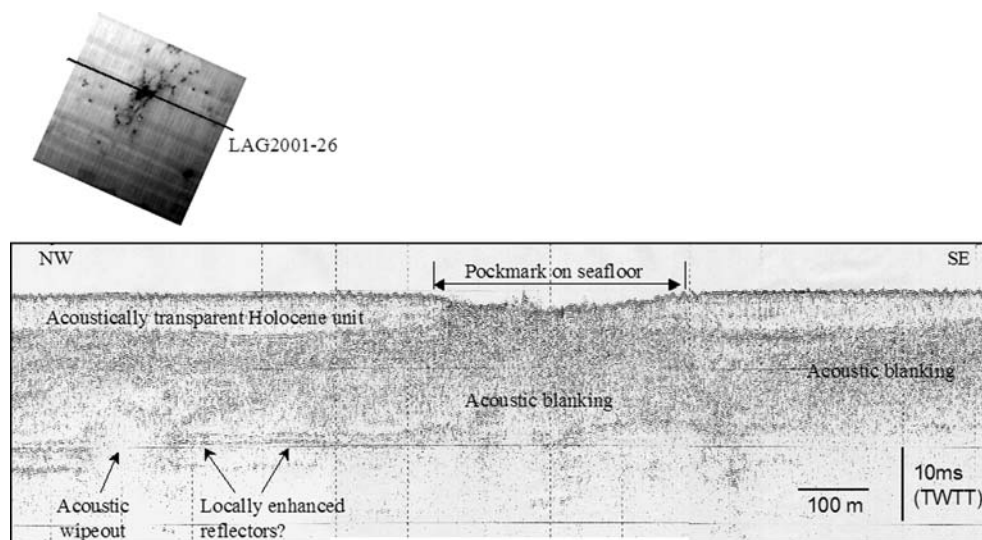


Figure 4. Subbottom seismic profile (3.5 kHz) crossing the pockmark field at Lagos site (location of the profile within the detailed survey area shown in inset). Notice the acoustic blanking below the pockmark reaching the seafloor, as well as the nearby locally enhanced reflectors and acoustic wipeouts.

sub-area B, specifically in the range of 10–30 Hz (Figure 7d).

Drilling at the Lagos site was conducted through sub-area A following the geohazard survey and the above evaluation. During drilling a number of gas kicks were encountered in the well, indicating a fair amount of gas in the upper section. These gas kicks were expected given the above analysis, which allowed the drilling engineers to be prepared for the gas and to plan their drilling activity (mud weight, casing depth, etc.) accordingly.

(b) Ceylan site

At the Ceylan site, the exploration seismic data again show no obvious anomalies in the selected sub-areas C and D in either the amplitude or reflection strength data (Figure 8a and b). Again using a color palate that accentuates lower frequency energy, we see that the horizon at 430–450 ms TWTT is much brighter in sub-area C than the same horizon in sub-area D (Figure 8c). The low frequency portion in sub-area C is proximal to a high-angle fault cutting through the section, with the brightest (lowest frequency) portion of the horizon proximal to the fault. A quantitative analysis (power spectra) of the two sub-areas shows a much more dramatic difference in the range of 10–30 Hz between the two sub-areas. Energy of the low frequencies (10–30 Hz) within

window C is clearly higher than that within window D of the Ceylan site (Figure 8d). This suggests that the frequency spectrum of the seismic energy is affected by a shallow gas accumulation. Note, however, that the presence of such a frequency ‘flag’ may not provide information regarding the saturation of this accumulation.

The low-frequency anomaly is confined to one of the main branches of a young normal fault system observed in the Ceylan site. The position of this anomaly, and other low frequency anomalies proximal to similar fault systems, suggests that this fault system is an effective conduit of gas and possibly hydrocarbons from depth. Lower frequency zones along fracture surfaces are due to seismic energy scattering confined to such surfaces (Taner, 2001). The seafloor distribution of pockmarks at Lagos, parallel to fault trends in the area, also argues for fracture permeability as the primary mechanism for vertical migration of gas in the area. Regional evaluation of the exploration 2D data also indicated that high-angle fault zones may provide the primary conduit for gas migration from deeper in the basin to the near-surface. Faults may act as preferential conduits if oriented at high angles to the minimum horizontal compressive stress. Closer to the surface, where the vertical effective stress is lower, we suggest that the gas can move laterally into more permeable units.

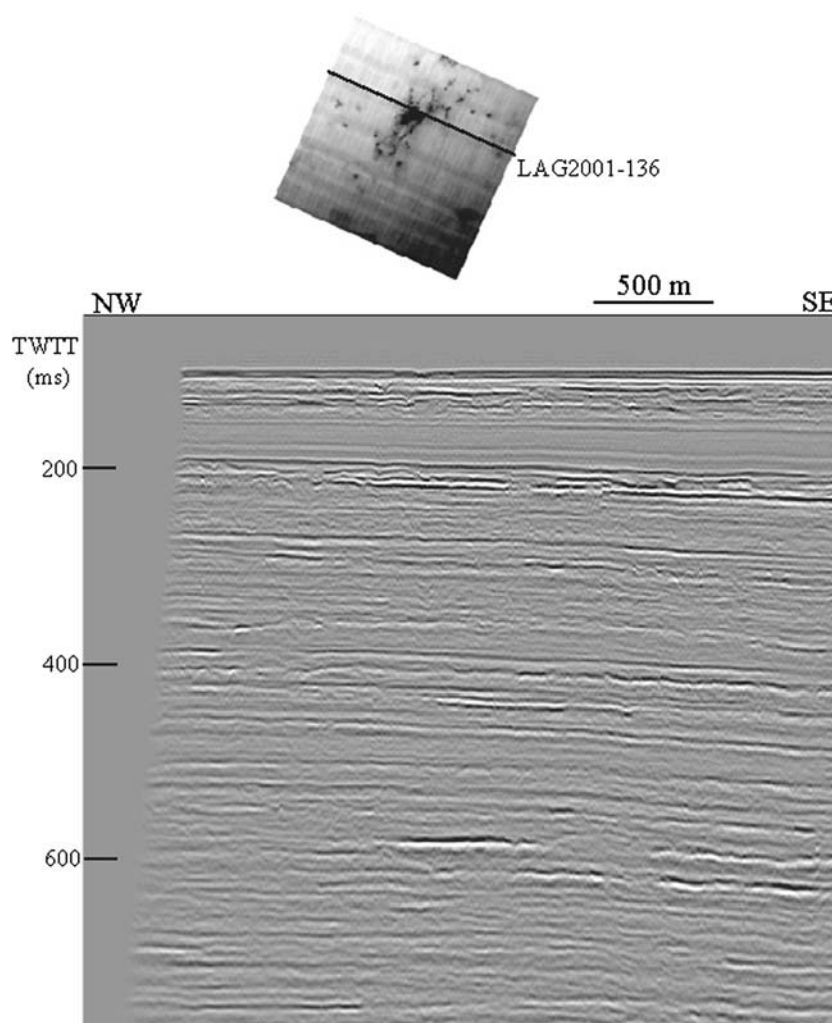


Figure 5. High-resolution 2D multi-channel seismic line (amplitude domain data) across the Lagos well site (location shown in inset). Notice amplitude anomalies at 0.10, 0.20, 0.40, and 0.60 s (TWTT).

The Ceylan well was drilled through sub-area D. No significant gas kicks were encountered in this well, although anomalous gas was detected in chromatograph readings.

Anomalous instantaneous frequency, however, does not necessarily indicate the presence of gas. Instantaneous frequency is also an effective lithology discriminator where low frequencies may indicate sand-rich bedding (Taner, 2001). When Ceylan and Lagos well locations are compared, the anomaly proximal to the fault at the Ceylan site is consistent with the petroleum system model, and therefore likely indicates a shallow gas accumulation because of its relationship with the fault

system. At the Lagos site, however, highly porous channelized sandstone may be the reason for the low frequency anomaly in sub-area A. The drilling indications of gas, the anomalous subbottom profiler data (acoustic wipeout), and the presence of pockmarks, however, supported a gas interpretation for these frequency anomalies as well.

Study Area 2: Po Delta

The Po Delta system represents the northern portion of a late-Holocene highstand systems tract (HST) growing along the Western Adriatic

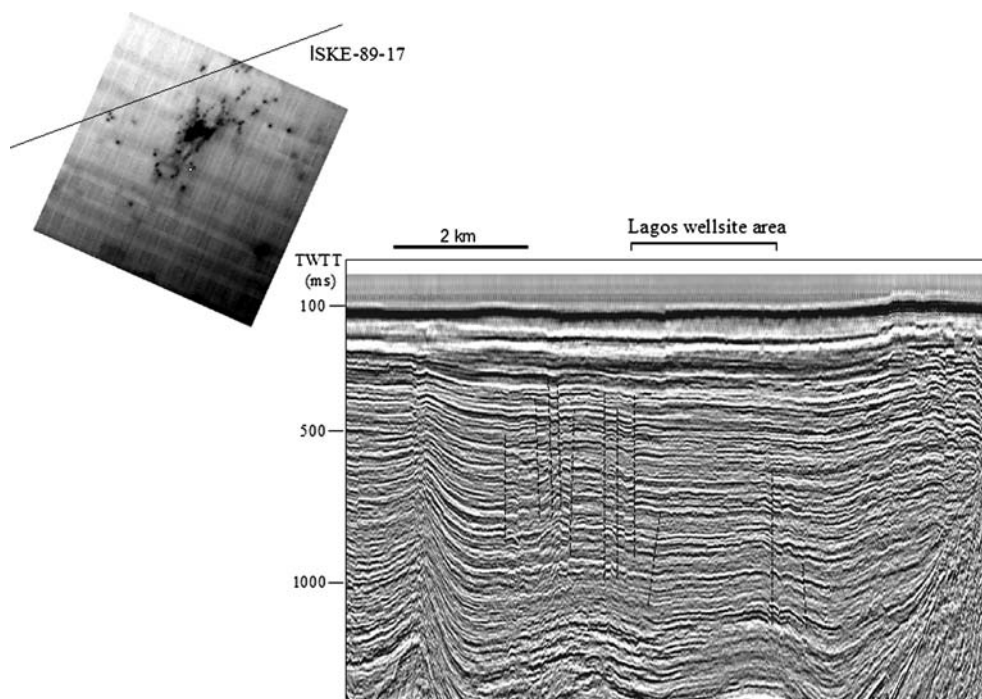


Figure 6. Exploration 2D seismic line near Lagos site (location shown in inset). Note the high-angle faults imaged in this section (in dashed lines). By combining vertical seismic sections with seafloor maps (inset), faults imaged in the subsurface could be more confidently assigned orientations in map view. Strike-slip deformation on some of the fault traces is suggested by differing throw down section (apparent down to the east in the upper section, and up to the east in the lower section), and by contrasting thicknesses of seismic packages on either side of a fault.

Sea (Figure 1). The modern Adriatic Sea is a narrow epicontinental basin, $\sim 160,000 \text{ km}^2$, with a low longitudinal topographic gradient ($\sim 0.02^\circ$) (Cattaneo et al., 2003). The two main sediment source regions for the Adriatic basin are the Po river ($15 \times 10^9 \text{ kg year}^{-1}$ from a single entry point) and the eastern Apennine rivers ($32.2 \times 10^9 \text{ kg year}^{-1}$). The drainage area of the eastern Apennine rivers is less than half of that of the Po river, whereas their sediment load is greater (Cattaneo et al., 2003).

Human manipulation and redirection of the river flow over the last 400 years has resulted in the formation of the present day delta (Gandolfi et al., 1982) with five distributary channels. Human impact on the Po river regime has had three main effects: an increase in river sediment yield due to deforestation phases since $\sim 3\text{--}4000$ year BP (Oldfield, 1996; Oldfield et al., 2003); a control on river avulsion with enhanced sediment bypass to the sea through artificial banks $\sim 2500\text{--}1500$ year BP, with maximized

effects 650–150 year BP (Ciabatti, 1967); and river bed excavation and/or river damming particularly during the last ~ 50 years, leading to a marked decrease in sediment supply (IDROSER, 1983). Nevertheless, the Po river seems to have undergone a less significant decrease in sediment load compared to other major Mediterranean rivers (Cattaneo et al., 2003).

During a EuroSTRATAFORM cruise on board the RV Seward Johnson II in the Adriatic Sea a coring program was conducted in order to evaluate the presence and distribution of shallow gas in the area, and its association with anomalous seafloor and subbottom acoustic data (Figure 9; Trincardi et al., 1996). Subbottom data from the area had identified regions of anomalous to occluded subsurface reflectivity which had been interpreted to be due to the presence of shallow gas (Trincardi et al., 1996). These areas were sampled during the cruise, as well as areas devoid of anomalous subbottom acoustic signatures suggestive of gas. The productivity of the Northern

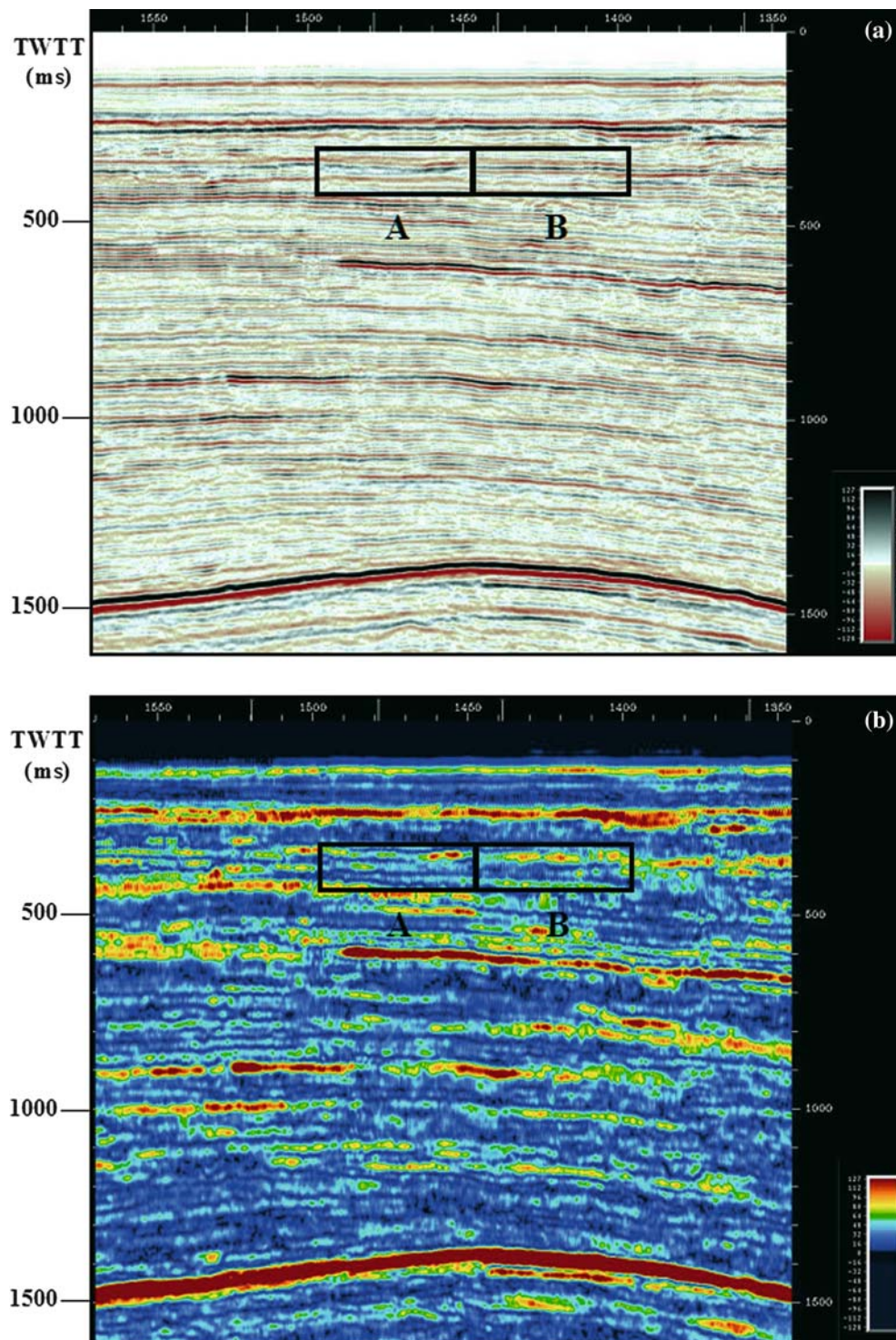


Figure 7. Seismic attribute analysis of the Lagos site exploration data (see Figure 2 for location). (a) Amplitude-domain data, indicating the two sub-areas of interest (A and B). Data are migrated, and shown in TWTT (time in milliseconds). Note that there is no obvious difference between the two sub-areas; (b) Reflection strength, again showing no obvious difference between the two sub-areas; (c) Instantaneous frequency, with a color palate designed to accentuate lower frequency energy. Sub-area A shows lower frequencies than sub-area B. Attenuation of high frequencies within gas-rich horizons leads to such low frequency shadow zones; (d) Power spectra of sub-areas A and B. Sub-area A shows much more energy in the 10–30 Hz range.

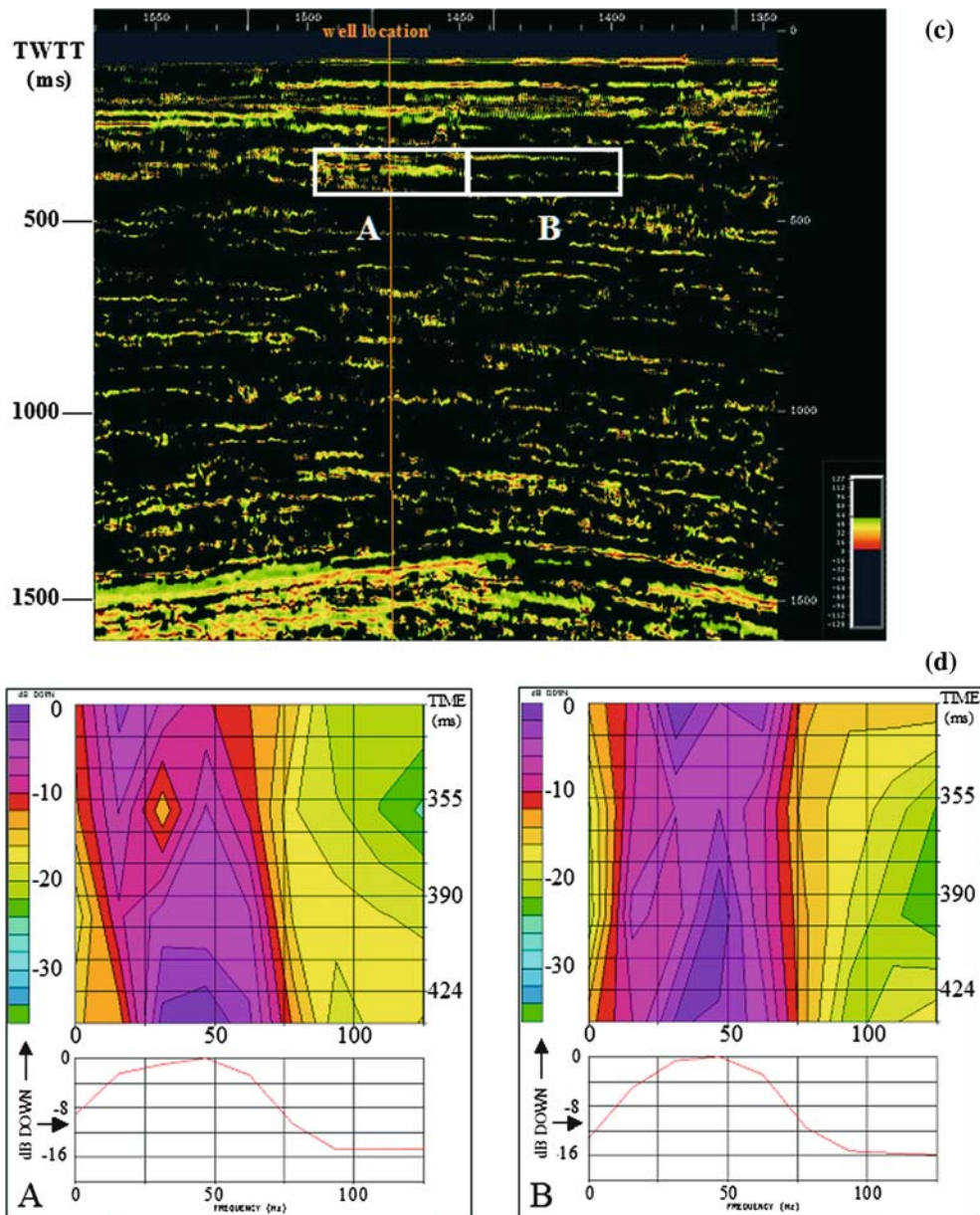


Figure 7. Continued.

Adriatic is among the highest in the Mediterranean Sea (Giordani et al., 2002), yet the geophysical data indicated that the region of anomalous subbottom reflectivity was restricted to a relatively narrow portion of the Po Delta (Cattaneo et al., 2002; Correggiari et al., in press). Specifically, the anomalous subbottom images were associated with the transition from the topset to the foreset in an area of the delta closest to the active Po di Pila channel (Correggiari et al., in press).

Subbottom profiling

Gas seeping from the Adriatic seabed was first reported by Morgante (1940) where distinct and continuous bubbling was observed at the sea surface. Since that time there have been numerous reports of gas seeps and gas within the shallow sediments (Trincardi et al., 1996; Conti et al., 2002). Numerous high-resolution subbottom profile lines acquired off the Po Delta (Cattaneo et al.,

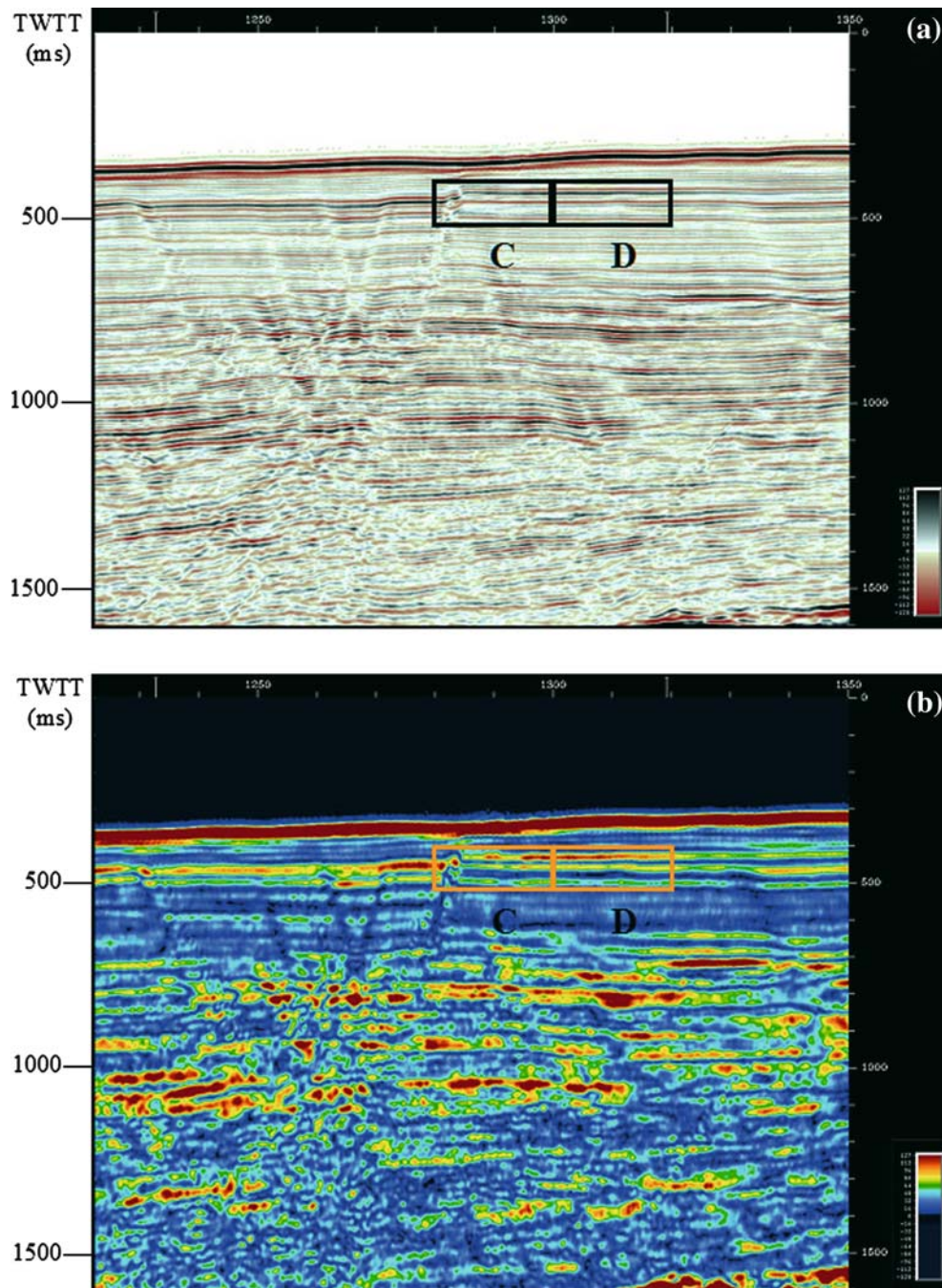


Figure 8. Seismic attribute analysis of the Ceylan site exploration data (see Figure 2a for location). (a) Amplitude-domain data, indicating the two sub-areas of interest (C and D). Data are migrated, and shown in TWTT (time in milliseconds). Sub-area C is in the footwall of, and proximal to, a fault clearly imaged in the data. Note that there is no obvious difference between the two sub-areas; (b) Reflection strength, again showing no obvious difference between the two sub-areas; (c) Instantaneous frequency, with a color palate designed to accentuate lower frequency energy. Sub-area C shows lower frequencies than sub-area D, with the anomalous frequency content increasing toward the fault zone. Attenuation of high frequencies within gas-rich horizons leads to such low frequency shadow zones, and suggests that the fault zone is propagating gas from depth; (d) Power spectra of sub-areas C and D. Sub-area C shows much more energy in the 10–30 Hz range.

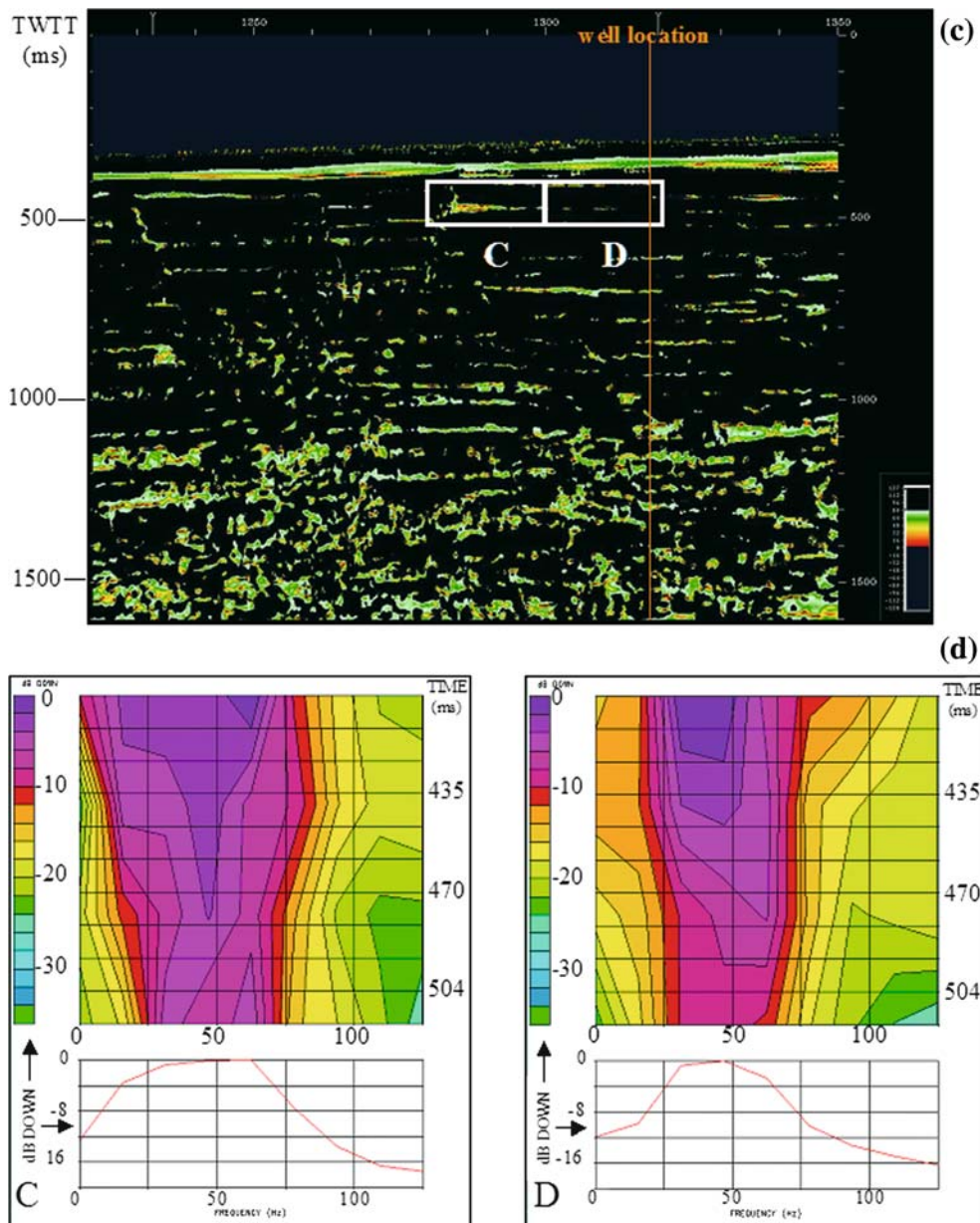


Figure 8. Continued.

2002) and elsewhere in the western Adriatic (Trincardi et al., 1996) have imaged acoustic anomalies interpreted to be due to shallow gas. Chirp sub-bottom profiler records (Figure 10) imaged seismic reflectors in the Po Delta region that were at times masked by acoustic blanking inferred to be due to gas-prone deltaic deposits (Hovland and Judd, 1988). Note that in order to get an anomalous signature in seismic amplitude, there still must be 1–2% gas in the form of bubbles, and the bubbles

must be of varying sizes in order to cause incoherent scattering (Løseth et al., 2003).

Ground-truthing gas with cores

The coring program included 28 cores from 17 unique locations offshore from the Po in the northern Adriatic Sea (Figure 9). Because deeper cores have a higher probability of yielding gas, gravity and kasten cores were acquired in

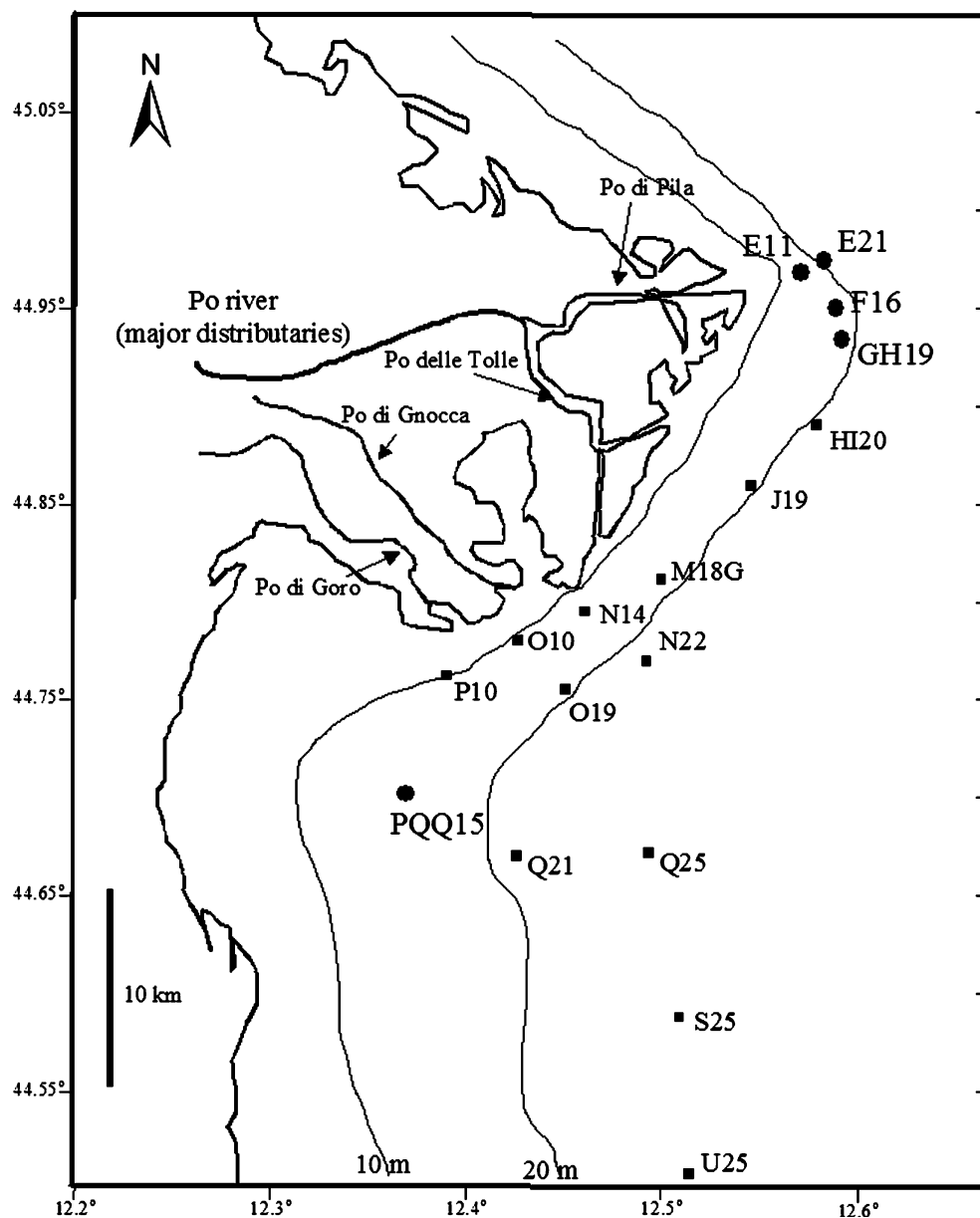


Figure 9. Coring sites of EuroSTRATAFORM cruise off the Po Delta. Bigger dots represent sites with high methane content (>90 ppm C_1). Station locations are designated by a letter indicating the coring transect (with letters ascending from north to south; each transect is oriented approximately perpendicular to isobaths), and a number indicating approximate water depth (e.g., core F16 was acquired on the 'F' transect in approximately 16 m of water). Bathymetric contours (10 and 20 m) are also shown.

addition to box cores in some locations. Core recovery on all samples was excellent, with up to 240 cm in the kasten cores, up to 450 cm in the gravity cores, and 30 cm in box cores. The average recovery of the box cores was 60%. Box cores were acquired in order to evaluate detailed sedimentological and acoustic properties. Box cores were sub-sampled using slabs for X-ray

analysis, which may provide additional evidence of gas such as bubbles or 'cracking' within the sediment.

The base of each core was sub-sampled using standard headspace gas techniques, using salt as a bactericide. In the laboratory, the partitioned hydrocarbon gases in the headspace were analyzed for methane through hexane (C_1 – C_6),

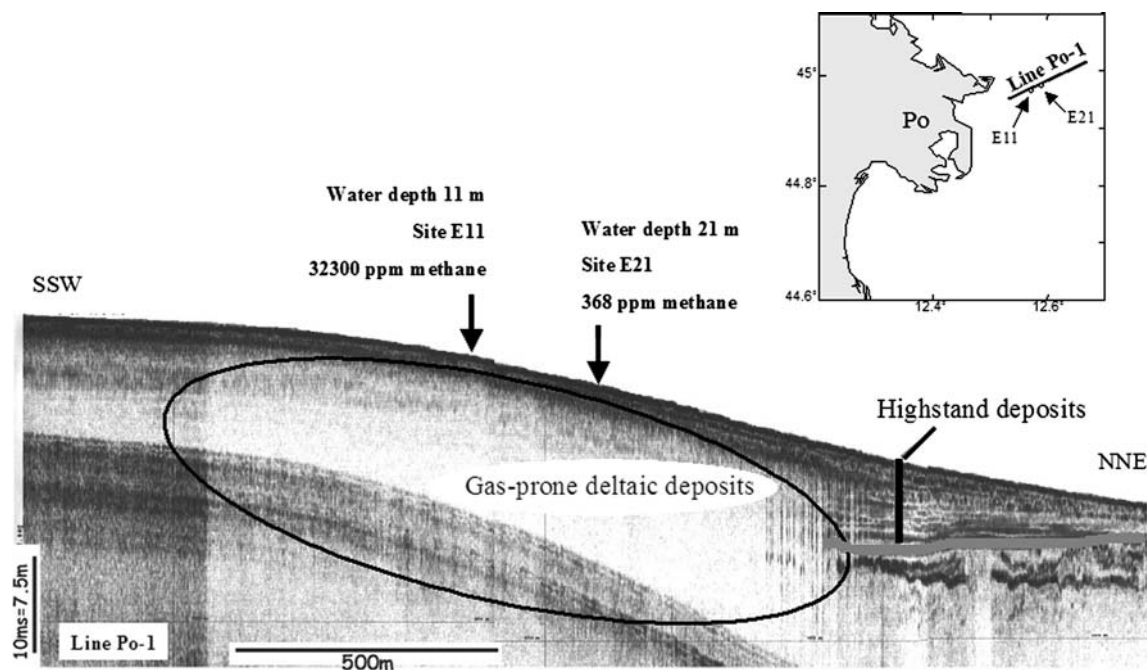


Figure 10. Chirp profiler line off the Po Delta (Correggiari et al., in press). The line shown crosses two coring sites (see map, inset and Figure 9) which yielded anomalous concentrations of gas (primarily methane). Water depths are 11 m at E11 site and 21 m at E21 site. Headspace analyses of sediment recovered at these two core locations yielded anomalous gas, with the location of the cores on the chirp line and methane concentrations shown.

carbon dioxide (CO_2), and hydrogen sulfide (H_2S), by gas chromatography. In most of the Po samples the sediment was dark colored, with a moderate to strong H_2S smell. In areas with more coarse sediment near the mudline, the oxic-anoxic boundary was very close to the seabottom (Figure 11).

Brief discussion of anomalous gas

The Po Delta cores were analyzed in the lab for C_1 – C_6 , CO_2 , and H_2S . The highest values of methane (CH_4) and CO_2 were associated with anomalous subsurface returns imaged on sub-bottom profiler data (suggestive of shallow gas) and the high sediment accumulation rate sediments of the Po Delta. Of the 17 unique sites (28 cores) analyzed, 5 sites (9 cores) had more than 90 ppm of CH_4 and of those, 3 sites (4 cores) had more than 13,800 ppm CH_4 (maximum = 41,385 ppm); the lack of higher order hydrocarbons (C_{2+}) in the headspace gas analyses suggests a microbial origin for the gas detected off the Po. Both sites sampled along the chirp line shown in Figure 10 had anomalous

gas, with 32,300 ppm of CH_4 at E11, and 368 ppm at E21.

All of the highest gas concentrations were found off the active channel of the Po Delta (Po di Pila outlet; Figure 9), with one anomalous sample obtained off an abandoned channel. The highest gas values were found in the gravity cores, whereas the box cores gave high results only where the gas was very shallow in the section. The Po di Pila outlet has been the most active delta channel during the last century (Correggiari et al., in press; Nelson, 1970). The cores come from 11 to 21 m water depth on the foreset of the subaqueous clinoform that characterizes the prodelta. The anomalous gas samples on the Po Delta are spatially associated with the region where the 2000 flood deposits exceed 10 cm in thickness, and suggest that flood deposits of this thickness may effectively isolate reactive organic matter from biologic and physical reworking, and thus are available for methanogenesis (Orange et al., in press).

Due to their high methane content, five samples were further analyzed for the isotopic signature of the gas. The results show values that are typical for shallow marine sediments higher in

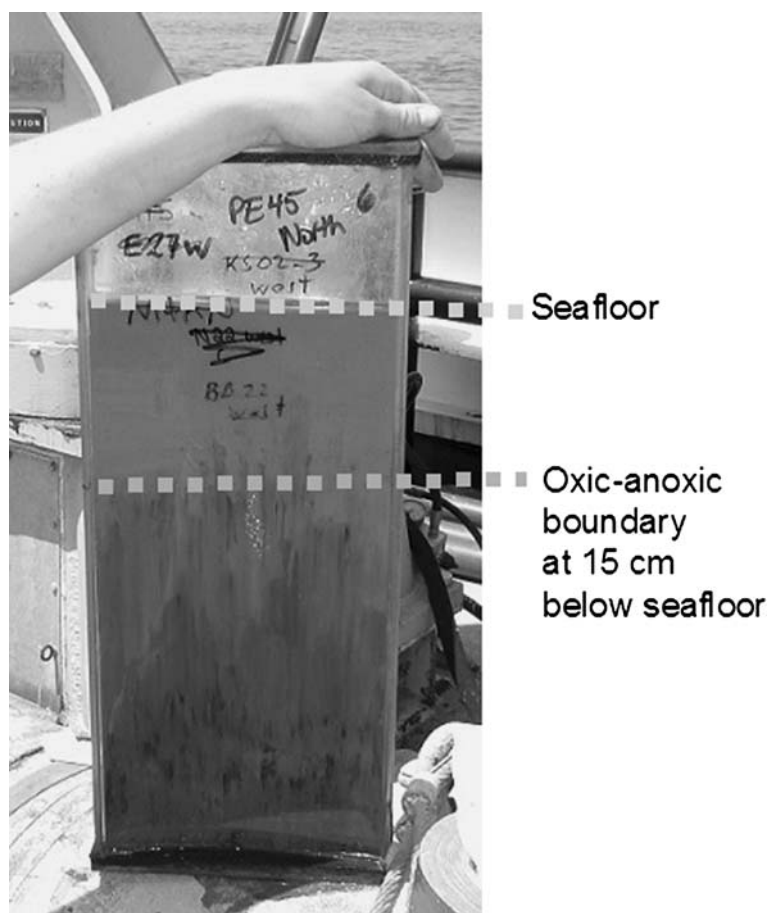


Figure 11. Coring program off the Po Delta. Box cores recovered up to 30 cm of sediment. The dark sediment in the box core slab suggests that in this sample the redox boundary is close to the sediment-water interface. Reducing conditions typically yield better gas samples.

organic matter ($>1\%$ total organic carbon (TOC)). $\delta^{13}\text{CH}_4$ values range from -70 to -92 ; these values further support a microbial gas source. Note that there is thermogenic hydrocarbon production in the Adriatic, as indicated by numerous active oil/gas platforms. The combination of $\delta^{13}\text{CO}_2$ and $\delta^{13}\text{CH}_4$ values can be used to define which bacterial process is responsible for the formation of the methane. In the case of the Po samples ($\delta^{13}\text{CO}_2 = -8$ to -24), carbonate reduction ($\text{CO}_2 + \text{H}_2 = \text{CH}_4$) is interpreted to be the microbial process generating methane.

Conclusions

High-resolution seafloor and subsurface data acquired as part of a site survey in Iskenderun

Bay, SE Turkey, were used to characterize the geohazards in the locations of proposed drilling sites. Multibeam bathymetry, multibeam backscatter and towed side-scan data all imaged a prominent pockmark field area where the pockmarks showed an average diameter of 35 m and average density of 13 features per km^2 . Pockmarks are located parallel to regional fault trends, suggesting some structural control to gas seepage from depth. Acoustic anomalies in the high-resolution seismic records (acoustic turbidity, blanking, enhanced reflectors) from both pinger and HR2D surveys in the area indicate the potential for shallow gas below the proposed drilling site. Exploration seismic data image faults in the area, but do not show prominent bright spots or acoustic turbidity that might indicate the presence of gas. Instantaneous frequency analysis

of these same data, however, image laterally restricted regions of high frequency absorption. Instantaneous frequency analysis can identify possible gas-rich regions because the presence of gas in a reservoir leads to loss of high frequency energy via absorption, and the gas-rich zones effectively act as natural low-pass filters. Frequency data may indicate the distribution of gas-rich zones even if there is no corresponding anomaly in the amplitude domain. Frequency analysis can therefore be used to identify regions that may pose a hazard to drilling that might otherwise be overlooked. Although frequency analysis is a routine exploration tool in reservoir evaluation it is rarely applied to geohazard studies.

Based upon the proximity of the proposed well to anomalous seafloor and subsurface features, the proposed Lagos site was moved eastward to an area with an interpreted lower geohazard environment. Gas kicks were still encountered in this well, but because the drilling engineers were prepared for the gas (and aware of its location) they were able to plan and execute the well accordingly. At a second well in the area (Ceylan), instantaneous frequency analysis suggested the presence of gas-rich zones proximal to a high-angle fault. This again supports a model of structurally controlled gas migration from depth. The well at this location was sited to avoid the possible gas-rich zones imaged in the frequency domain. No significant gas kicks were encountered in this well, although anomalous gas was detected in chromatograph readings.

Very high-resolution geophysical data were used to evaluate the sea floor and shallow subsurface for an academic project offshore the Po Delta, NW Adriatic. Very high-resolution subbottom profiler data in the area showed areas of acoustic wipeout associated with the topsets of prograding delta structures. These regions of wipeout were interpreted to be due to shallow gas, and were the target of a coring program carried out in 2002. All of the anomalously high gas concentrations were indeed found to occur in areas where subbottom data show anomalous acoustic features. These anomalous gas and subbottom areas are located proximal to the active Po Delta where flood-prone deposition results in high sediment accumulation rates. High sediment accumulation rates may isolate reactive organic matter from biological or physical re-working, with more organic matter

therefore available for methanogenesis. The absence of higher order hydrocarbons (C_{2+}) and the isotopic signature of the methane ($\delta^{13}CH_4 = -70$ to -92) indicates a biogenic origin for the gas found in the sediments off the Po Delta.

Both the Iskenderun Bay and Po Delta study areas demonstrate that the presence of gas in the subsurface (both shallow and deep), and the interaction of gas with the seafloor, affect acoustic properties. On the seafloor, gas expulsion can modify the shape of the seafloor, creating either negative relief pockmarks, and/or positive relief mounds. Both pockmarks and mounds may be associated with variations in seafloor backscatter. In the subsurface, gas can create anomalous features in the amplitude domain and the frequency domain, although gas imaged in the frequency domain may not show significant anomalies in the amplitude domain.

The combination of geophysical surveys of the seafloor, high-resolution subbottom profile data, exploration and high-resolution seismic data can be used to identify regions of possible shallow gas and study the impact on the acoustic properties. These regions can be evaluated with cores, geotechnical boreholes, or drilling to ground-truth the presence, distribution, and concentration of shallow gas. Gas-prone horizons can be identified prior to drilling so that wells can be moved to avoid such features if possible. If the well location is constrained, the distribution of potential gas-prone horizons can be communicated to the drilling engineers so that they can be prepared to handle any potential gas hazard before it is encountered.

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References

- Adriansyah, A. and McMechan, G.A., 2002, Analysis and interpretation of seismic data from thin reservoirs: north-west Java Basin, Indonesia, *Geophysics* **67**, 14–26.
- Aksu, A.E., Calon, T.J., Piper, D.J.W., Turgut, S. and Izdar, E., 1992a, Architecture of late orogenic Quaternary basins in northeastern Mediterranean Sea, *Tectonophysics* **210**, 191–213.
- Aksu, A.E., Ulug, A., Piper, D.J.W., Konuk, Y.T. and Turgut, S., 1992b, Quaternary sedimentary history of Adana, Cilicia and Iskenderun Basins: northeast Mediterranean Sea, *Mar. Geol.* **104**, 55–71.
- Campbell, K.J., 1999, Deepwater geohazards: how significant are they?, *Leading Edge* **18**(4), 514.
- Cattaneo, A., Correggiari, A., Langone, L. and Trincardi, F., 2003, The late-Holocene Gargano subaqueous Delta, Adriatic shelf: sediment pathways and supply fluctuations, *Mar. Geol.* **193**, 61–91.
- Cattaneo, A., Trincardi, F., Correggiari, A., Marsset, T. and Masson, D.G., 2002, Growth of mud reliefs within the Adriatic late-Holocene prodelta deposits through sediment load and fluid escape processes, in Briand, F. (Eds.), *Mediterranean and Black Sea Turbidite Systems and deep-sea fans*, Proceedings of CIESM Workshop Series 17, Bucharest, 5–8 June 2002 CIESM, Monaco France, pp. 33–36.
- Chen, Q. and Sidney, S., 1997, Seismic attribute technology for reservoir forecasting and monitoring, *Leading Edge* **16**(5), 445–456.
- Ciabatti, M., 1967, Ricerche sull'evoluzione del Delta Padano, *Giornale di Geologia* **34**, 381–406.
- Conti, A., Stefanon, A. and Zuppi, G.M., 2002, Gas seeps and rock formation in the northern Adriatic Sea, *Cont. Shelf Res.* **22**, 2333–2344.
- Correggiari, A., Cattaneo, A. and Trincardi, F., Depositional patterns in the late Holocene Po Delta system. in Bhattacharya, J. and Giosan, L. (Eds.), *SEPM Special Publication on Deltas: Modern and Ancient*, in press.
- Gandolfi, G., Mordenti, A. and Paganelli, L., 1982, Composition and longshore dispersal of sands from the Po and Adile Rivers since the pre-Etruscan age, *J. Sediment. Petrol.* **52**, 797–806.
- Gardline Surveys Limited, 2001, Lagos-1 prospect site survey, February–March 2001; survey report. Gardline internal project reference 5589: pp 49.
- Gardner, J.V., Field, M.E., Lee, H., Edwards, B., Masson, D.G., Kenyon, N. and Kidd, R.B., 1991, Ground-truthing 6.5 kHz side scan sonographs: what are we really imaging? *J. Geophys. Res.* **96**, 5955–5974.
- Giordani, P., Helder, W., Koning, E., Miserocchi, S., Danovaro, R. and Malaguti, A., 2002, Gradients of benthic–pelagic coupling and carbon budgets in the Adriatic and Northern Ionian Sea, *J. Marine Syst.* **33–34**, 365–387.
- Gökçen, S.L., Kelling, G., Gökçen, N. and Floyd, P.A., 1988, Sedimentology of a late Cenozoic collisional sequence: the Misis Complex, Adana, southern Turkey, *Sediment. Geol.* **59**, 205–235.
- Hill, A.W., 1996, The use of exploration 3D data in geohazard assessment: where does the future lie? Proceedings of Offshore Technology Conference, Houston, Texas, 6–9 May 1996, OTC 7966.
- Hovland, M. and Judd, A., 1988, *Seabed Pockmarks and Seepages. Impact on Geology, Biology and the Marine Environment*. London: Graham & Trotman Ltd, pp. 294.
- Hovland, M., Gardner, J.V. and Judd, A.G., 2002, The significance of pockmarks to understanding fluid flow processes and geohazards, *Geofluids* **2**, 127–136.
- IDROSER, 1983, Piano progettuale per la difesa della costa adriatica Emiliano-Romagnola IV. Il trasporto fluviale nei bacini tributari dell'Adriatico, pp 429.
- Kulm, L.D., Suess, E., Moore, J.C., Carson, B., Lewis, B.T., Ritger, S.D., Kadko, D.C., Thornburg, T.M., Embley, R.W., Rugh, W.D., Massoth, G.J., Langseth, M.G., Cochran, G.R. and Scamman, R.L., 1986, Oregon subduction zone: venting, fauna, and carbonates, *Science* **231**, 561–566.
- Løseth, H., Wensaas, L. and Arntsen, B., 2003, Gas chimneys – indicating a fractured cap rock. American Association of Petroleum Geologists, Abstracts with Programs, 2003.
- MacDonald, I.R., 1998, Habitat formation at Gulf of Mexico hydrocarbon seeps, *Cahiers de Biologie Marine* **39**, 337–340.
- Morgante, S., 1940, I 'bromboli' delle coste istriane, *Notiziario dell' Istituto de Biologia Rovigno* **16**(2), 1–12.
- Nelson, B.W., 1970, Hydrography, sediment dispersal, and recent historical development of the Po River Delta, In: Morgan, J.P. (Eds.), *Deltaic Sedimentation: Modern and Ancient*, Society of Sedimentary Geology, New York, pp. 152–184.
- Neurauter, T.W. and Roberts, H.H., 1994, Three generations of mud volcanoes on the Louisiana continental slope, *Geo-Mar. Lett.* **14**, 120–125.
- Oldfield, F., 1996, The PALICLAS project: synthesis and overview, *Memorie Istituto Italiano di Idrobiologia* **55**, 329–357.
- Oldfield, F., Asioli, A., Juggins, S., Langone, L., Rolph, T., Trincardi, F., Wolff, G., Gibbs, Z., Vigliotti, L., Frignani, M. and Post, K., 2003, A high resolution Late-Holocene palaeo-environmental record from the Adriatic Sea: core RF 93-30, *Quaternary Sci. Rev.* **22**, 161–184.
- Orange, D., García-García, A., Lorenson, T., Nittrover, C., Milligan, T., Miserocchi, S., Langone, L., Correggiari, A. and Trincardi, F., Shallow gas and flood deposits on the Po Delta. ComDelta special issue. *Mar. Geol.*, in press.
- Paull, C.K. and Neumann, A.C., 1987, Continental margin brine seeps: their geological consequences, *Geology* **15**, 545–548.
- Paull, C.K., Hecker, B., Commeau, R., Freeman-Lynde, R.P., Neumann, C., Corso, W.P., Golubic, S., Hook, J.E., Sikes, E. and Curran, J., 1984, Biological communities at the Florida Escarpment resemble hydrothermal vent taxa, *Science* **226**, 965–967.
- Reilly, J.F., MacDonald, I.R., Biegert, E.K. and Brooks, J.M., 1996, Geologic controls on the distribution of chemosynthetic communities in the Gulf of Mexico, In: Schumacher, D. and Abrams, M.A. (Eds.), *Hydrocarbon Migration and*

- its Near-surface Expression, American Association of Petroleum Geologists, Tulsa, OK, pp. 38–61.
- Roberts, H.H. and Neurauter, T.W., 1990, Direct observations of a large active mud vent on the Louisiana continental slope, *Am. Assoc. of Petr. Geol. Bull.* **74**, 1508.
- Roberts, H.H., Doyle, E.H., Booth, J.R., Clark, B.J., Kaluza, M.J. and Hartsook, A., 1996, 3D-seismic amplitude analysis of the seafloor: an important interpretive method for improved geohazards evaluations, Proceedings of Offshore Technology Conference Houston, Texas 6–9 May 1996, OTC 7988, pp. 283–292.
- Suess, E., Carson, B., Ritger, S.D., Moore, J.C., Kulm, L.D. and Cochrane, G., 1985, Biological communities at vent sites along the subduction zones off Oregon, *Bull. Biol. Soc. Washington* **6**, 475–484.
- Taner, M.T., 2001, Seismic attributes, *CSEG Recorder* **26**(7), 48–56.
- Taner, M.T., Koehler, F. and Sheriff, R.E., 1979, Complex seismic trace analysis, *Geophysics* **44**(6), 1041–1063.
- Taner, M.T. and Sheriff, R.E., 1977, Application of amplitude, frequency and other attributes to stratigraphic and hydrocarbon determination, In: Payton, C.E. (Eds.), *Seismic Stratigraphy – Applications to Hydrocarbon Exploration*, AAPG Memoir 26, Tulsa, USA, pp. 301–327.
- Trabant, P.K., 1984, *Applied High-resolution Geophysical Methods*. Boston: International Human Resources Development Corporation, pp. 265.
- Trincardi, F., Cattaneo, A., Asioli, A., Correggiari, A. and Langone, L., 1996, Stratigraphy of the late-Quaternary deposits in the central Adriatic basin and the record of short-term climatic events, *Memorie Istituto Italiano di Idrobiologia* **55**, 39–70.
- Vanneste, M., De Meersman, K., Guidard, S., Versteeg, W., Golmshtok, A.Y., Kremlev, A.N. and De Batist, M., 2001, Multi-frequency seismic study of the gas hydrate accumulations in Lake Baikal, Siberia. European Union of Geosciences (EUG) XI meeting, Strasbourg, France, 8–12 April 2001. Journal of Conference Abstracts 6: 153.
- Vanneste, M., Mienert, J., Guidard, S. and HYDRATECH-INGGAS partners, 2002, “Arctic” gas hydrates offshore Western Svalbard, Norway: Preliminary Results. Proceedings of the 4th International Conference on Gas Hydrates. Yokohama, Japan, 19–23 May 2002, pp. 222–227.