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Acoustic evidences of gas in the continental slope sediments of the Gulf of Cadiz (E Atlantic)

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Abstract Detailed reviews of high-resolution acoustic studies in the continental slope of the Gulf of Cadiz has revealed the following gas-related features: acoustic turbidity and blanking, bright spots, ancient and modern pockmarks, high-amplitude diffractions, acoustic plumes and turbidity in the water column, and BSRs. The origin of the gas is believed to be biogenic and thermogenic. The BSR-like acoustic anomalies occur intermittently in some areas of the upper slope and tend to occur in the volcanoes/diapirs. The pressure–temperature conditions deduced for the location of those acoustic anomalies do not correspond to the conditions of stability of gas hydrates. It is suggested that these volcanoes/diapirs intrusions may locally induce anomalously higher pore pressure conditions on the immediately surrounding sediments, affecting the stability field of the gas hydrates.

Introduction

High and very high-resolution reflection seismic investigations have revealed the presence of gas-charged sediments around the world oceans at water depths, from coastal to deep water environments (Hovland 1983; 1984; Söderberg and Flodén 1992; Taylor 1992; Solhøim and Elverhøi 1993; Chow et al. 2000; Judd and Curzi 2002). The gas-related acoustic features observed include mainly acoustic turbidity and blanking, bright spots, strong multiple reflections, pockmarks, acoustic plumes and turbidity in the water column, bottom simulating reflectors (BSRs), among others.

The BSRs are associated with the presence of gas hydrates. Gas hydrates are solid, ice-like substances formed by penta-hexagonal closed structures of water

molecules that form cavities where gas molecules—essentially methane—are trapped. They are stable under conditions of high pressure and low temperature, and occur naturally where these appropriate conditions of temperature and pressure co-exist, such as the deeper sectors of the continental margins, and in deep ocean basins (Sloan 1990). In the marine environment, gas hydrates are present in the sediments of continental margins below some hundred meters down to 1,500 m water depth, and from the seafloor down to 500 m deep in the sediment column. The scientific study of the formation and stability of methane hydrates has increased largely in recent years (Henriet and Mienert 1998; Max 2000). The interest in gas hydrates is due to several factors, among which their use as a potential energy resource (Kvenvolden et al. 1993; McDonald 1990; Max and Lowrie 1993), their influence on seafloor slope stability (Kayen and Lee 1993; Popenoe et al. 1993; Kvenvolden 1998), and the implications as a control factor on the global climate change and the greenhouse effect (Kvenvolden and McMenamin 1980; McDonald 1990; Nisbet 1990; Kvenvolden 1993, 1998) can be cited.

Although the direct evidence for the presence of gas hydrates in marine sediments has only been obtained through drilling and coring (Kvenvolden and Barnard 1983; Kvenvolden 1993), they can also be identified by means of acoustic methods using high-resolution seismic tools (Paull and Dillon 1981; Popenoe et al. 1993; Schmuck and Paull 1993; Kvenvolden 1998). The solid and rigid structure of the gas hydrates is characterised by a very high acoustic velocity (avg. 3.3 km/s) compared to the surrounding, hydrate-free sediments (avg. 1.7 km/s), and this results in a strong acoustic impedance contrasts. The presence of free gas in the sediment pores below the hydrate stable zone produces a strong decrease in the P wave velocity (Gregory 1977), which provides an even greater acoustic impedance contrast with hydrate-bearing sediments. This velocity contrast results in a high negative amplitude (Wood et al. 1994; Andreassen et al. 1995) and polarity (Neben et al. 1998),

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a very strong reflection paralleling the surface of the seafloor known as “Bottom Simulating Reflector” (BSR) which marks the base of the stable hydrate layer (Kvenvolden and Barnard 1983).

The aim of this work is to review in detail the previous acoustic evidence published by Baraza and Ercilla (1996), to analyse the possible evidence in the form of BSR-like acoustic anomalies seen on existing seismic records, and provide new insights on evidences supporting the existence of gas hydrates on continental margin sediments.

Methods

The present study is mainly based on the interpretation of seismic reflection profiles collected during several oceanographic cruises in the Gulf of Cadiz onboard the B/O *Garcia del Cid* between 1986 and 1991 (Fig. 1). The main geophysical systems used on these surveys were bathymetric echosounder, high-resolution ORE 3.5 kHz sub-bottom profiler, Geopulse boomer, and a 20–40 cu. in airgun array. The vessel speed was 5.5–6.0 knots, and the shooting interval was 1 to 3 s. The receiver consisted of a 200-m-long, single-channel streamer containing two active sections, each with 40 hydrophones. After being filtered with a 200-Hz low-pass and 300-Hz high-pass filter, the reflected signal was stored as an analogic record on an EPC 4800S graphic recorder. Depending on the sedimentary cover thickness, the penetration

achieved reached up to 700 ms with a vertical resolution of up to 6 m. Navigation was controlled by MAXIRAN, Loran C, and Transit satellite. The thickness of individual units has been calculated by converting travel time to thickness using an average acoustic velocity of 1,600 m/s.

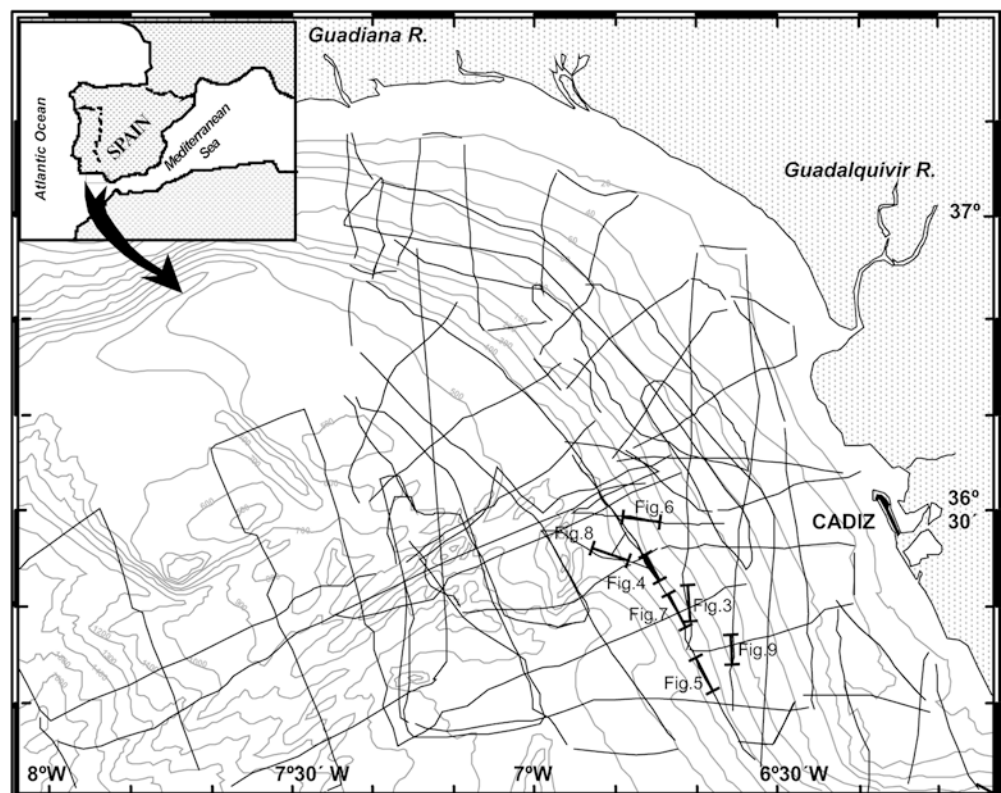
Geological and oceanographical background

Geological background

The Gulf of Cadiz (Fig. 1) occupies a focal position between the westernmost segment of the Mediterranean and the Iberian-African boundary, and records a complex tectonic history including several phases of extension, convergence and strike-slip motion, and the tectonic emplacement of a large olistostrome following the westward thrust of the Gibraltar Arc (Maldonado et al. 1999). Such a tectonic complexity is reflected on the present seafloor morphology and structure of the Gulf, characterized by a prograding margin with a central slope area occupied by elongated highs of shale-diapiric/volcanic nature, separated by narrow, steep-walled valleys (Maldonado et al. 1992; Nelson et al. 1993; Baraza et al. 1999; Somoza et al. 2002).

Different aspects related to the Neogene and Quaternary seismic stratigraphy and architecture of the Gulf of Cadiz slope and deep areas have been already discussed elsewhere (Nelson et al. 1993, 1999; Riaza and

Fig. 1 Bathymetric map (in meters) of the Gulf of Cadiz showing the location of seismic profiles. *Thick black short lines with numbers* refer to seismic lines shown in Figs. 3, 4, 5, 6, 7, 8, 9



Martínez del Olmo 1996; Rodero et al. 1999). The Messinian deposits in the Gulf of Cadiz correspond to clays and interbedded sand lenses with up to 450 m in thickness that fill most of the existing irregularities and depressions and prograde into the basin deposits, draping the top of the allochthonous units (Maldonado et al. 1999). The sand units represent depositional fan lobes derived from the northern Gulf of Cadiz margin and mainly from the two major rivers in the area (Guadiana and Guadalquivir, Fig. 1) and contain substantial amounts of gas (Riaza and Martínez del Olmo 1996; Maldonado et al. 1999). The top of these deposits is a basin-wide erosional unconformity above which the Lower Pliocene deposits are represented by a uniform unit between 50 and 300 m in thickness characterised by continuous stratified, parallel reflectors of high amplitude (Maldonado et al. 1999). These correspond to clays with interbedded sandy clays and some turbidite sand deposits (Riaza and Martínez del Olmo 1996). The Upper Pliocene deposits are aggradational above the Lower Pliocene unit or onlap onto the pre-existing slopes. They reach from 150 to more than 500 m in thickness and consist of interbedded clays and sands corresponding to hemipelagic deposits, turbidite sands and current-drift deposits. On seismic profiles, these deposits appear as a sequence with transparent to discontinuous reflectors at the bottom, and higher amplitude, interfingered reflectors at the top, following an overall cyclic pattern (Maldonado and Nelson 1999; Rodero et al. 1999; Hernández-Molina et al. 2003). On top of these deposits there is an unconformity over most of the basin that corresponds to the base of the Quaternary, above which there is a prograding and onlapping package consisting on several units of shelf margin deltas showing variations in facies and thickness that are controlled by the physiography of the margin, sediment sources and the intensity of bottom currents (Nelson et al. 1993; Rodero et al. 1999).

Oceanographic setting

The characteristic oceanographic setting and water mass structure of the Gulf of Cadiz is dominated by the plume of dense Mediterranean water that spreads westwards from Gibraltar Strait and descends the continental slope in the center of the Gulf. The presence of an eastward-moving upper layer of light and cold Atlantic water, and a westward-moving lower layer of dense and warmer Mediterranean water characterises a dynamic system of water masses whose vertical profiles in temperature and salinity depend on the geographical location, the physiography and the sea-level position (Zenk 1970; Baringer and Price 1999). The present sea-bottom topography has a very important effect upon the dynamics and path of the Mediterranean outflow water, and hence influences the sediment transport and grain size, bedform formation and gradation (Nelson et al. 1993; Baringer and Price 1999; Nelson et al. 1999). Temperature profile

transects give temperatures for bottom waters ranging from 12.5 to 10.5 °C between 400 and 1,100 m water depth (Madelain 1970). During the geologic past, however, the Atlantic and Mediterranean water-mass exchange may have been reduced due to smaller effective cross sections through the Gibraltar Strait, resulting from a lower sea-level position. Under these conditions, the strength and volume of the Mediterranean outflow as well as its interaction with the seafloor may have been different (Maldonado and Nelson 1999). All these factors may have altered the characteristics of the water masses and their distribution and mixing along the Gulf of Cadiz, and would have resulted on very different temperature profiles compared to the present ones.

Geophysical evidences of gas in the Gulf of Cadiz

There are a number of geophysical evidences that support the presence of gas in the sediments of the Gulf of Cadiz slope (Fig. 2). The typical acoustic masking on seismic records caused by interstitial free gas, gas-escape craters (pockmarks), and free gas seeps through the water column have been already described by Baraza and Ercilla (1996). They are reviewed in detail in this section.

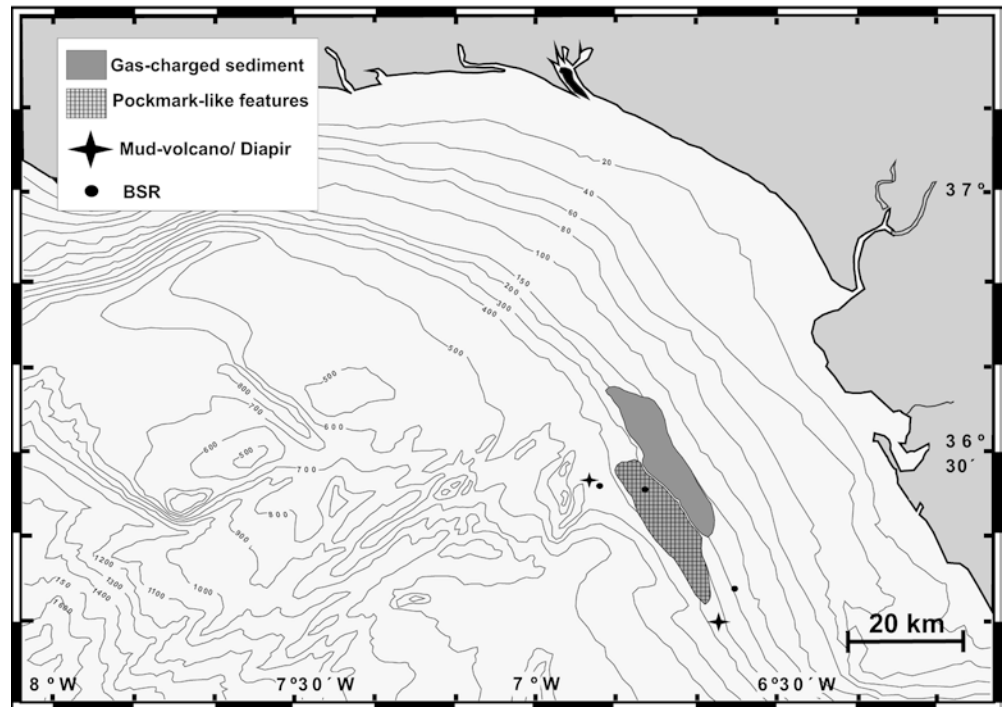
The area with gas charged sediments

The area with interstitial free gas is identified in the form of a “blanket” feature that appears as an acoustic turbidity on the seismic records (Fig. 3). It occurs on the uppermost slope between 130 and 300 m in water depth forming a 35-km-long by 5 to 7-km-wide belt trending approximately parallel to the slope contours that covers an approximate area of 210 km² (Fig. 2). This feature indicates the presence of free gas within the sediments and forms by the absorption of nearly all the seismic energy (Field et al. 1980). The acoustic turbidity appears mostly free of seismic reflections in the central zone although locally some reflections can be identified in the external zones. Enhanced reflections are locally observed at the top of the acoustic turbidity and also in the lateral extremes, indicating a local high concentration of gas. The upper limit of the acoustic turbidity is irregular and averages 20 m of the seabed surface. The area with free gas is locally affected by gravitational processes in the form of slumps (Baraza et al. 1999). Likewise, slumps occur downslope to the westwards of the acoustically turbid zone. Locally, in the most proximal parts of the slumps, they are underlined by gas and/or enhanced reflections in the form of bright spots.

Pockmark area

With respect to the pockmarks they occur in a 30-km-long by 2 to 7-km-wide belt in the central-east upper slope (Fig. 2) between 300 and 400 m of water depth,

Fig. 2 Bathymetric map (in meters) of the Gulf of Cadiz showing the location of the areas with gas-charged sediments, pockmarks, BSRs and some of the mud volcanoes/diapirs identified in this study



and display a wide range of sizes, with lengths between 125 and 850 m and depths between 1 and 19 m. The existence of seismic profiles that cut to those features approximately downslope (Fig. 3) and alongslope (Fig. 4) supports the interpretation that they are closed depressions (Baraza and Ercilla 1996). The pockmarks are both modern (Figs. 3 and 4) and ancient (Fig. 5), and they are similar in shape cross sections. Their size is variable and some ancient pockmarks grow in the vertical and have surficial expression whereas others are fossilised at different depths (Figs. 5 and 6). The pockmark area develops downslope from the gas-charged sediment area and surrounding diapirs (Figs. 2 and 6). Associated to the pockmarks there are acoustic distur-

bances with a narrow vertical column structure distributed along the vertical pockmark arrangements. These acoustic disturbances appear as diffractions mostly of high amplitude. These vertical acoustic anomalies may represent gas columns related to gas expulsion through the pockmarks (Figs. 5 and 6). Likewise, acoustically transparent columnar disturbances or wipe-outs are present in certain areas, immediately below and adjacent to the pockmarks (Fig. 5). They are interpreted as being caused by the presence of gas within the sediment. Enhanced reflections in the form of bright spots also occur in the vicinity of the ancient pockmarks in the sediment column, which indicate local high concentration of free gas.

Fig. 3 GeoPulse seismic profile showing gas-charged sediment and pockmark-like features. Seismic line in Fig. 1

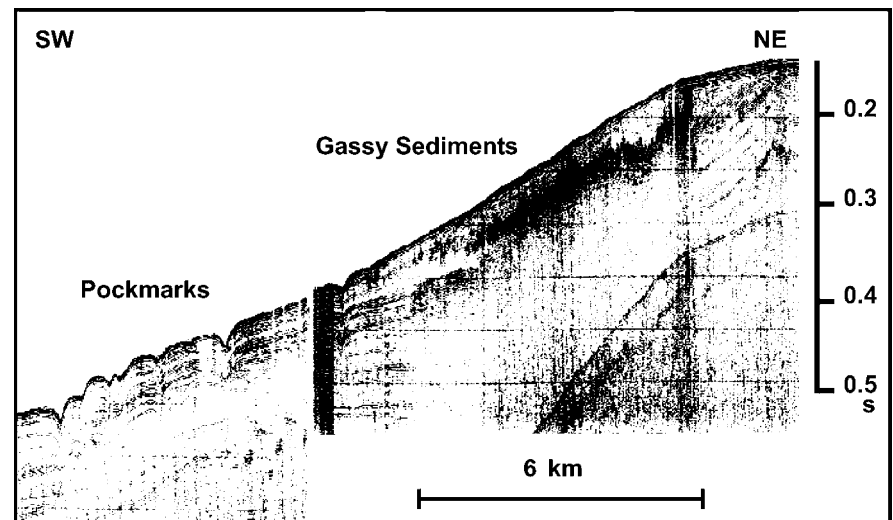


Fig. 4 Detail of a 3.5-kHz seismic profile showing modern pockmarks (*P*) and acoustic turbidity in the form of acoustic plumes (*arrows*) in the water column caused by ascending gas bubbles. Seismic line in Fig. 1

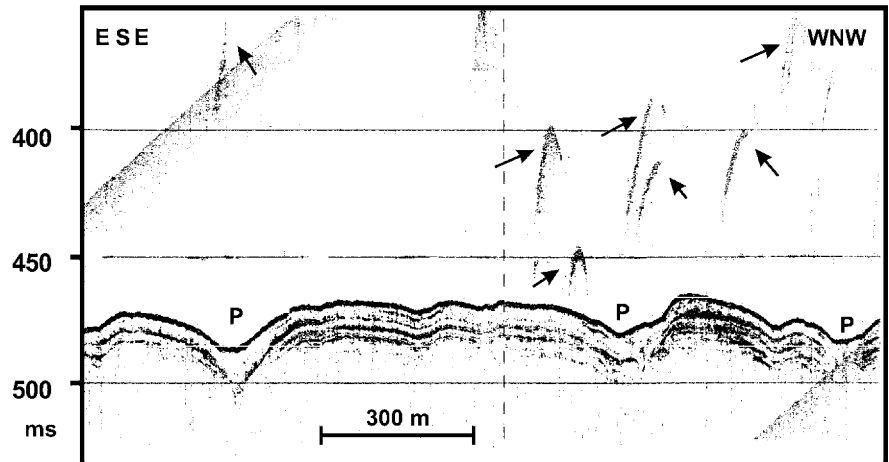
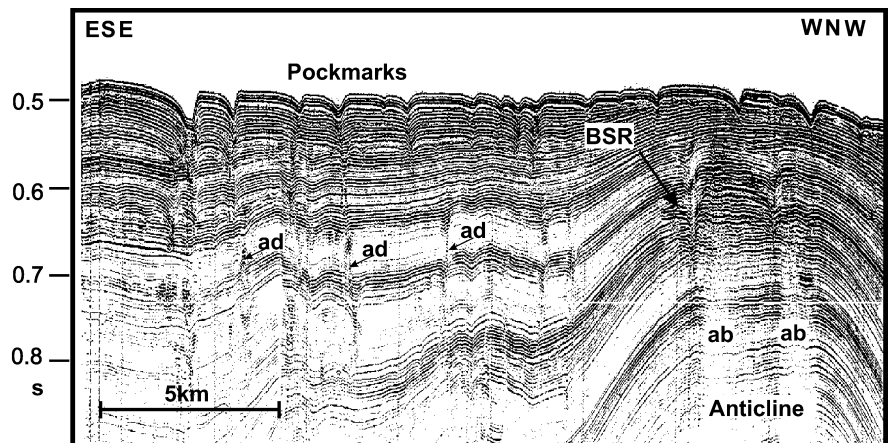


Fig. 5 Detail of an airgun seismic profile showing the pockmarks, and the presence of a BSR-like feature on top of an anticline feature. Note the presence of acoustic disturbances (*ad*) that occur along the vertical arrangement of pockmarks, and of acoustic blanking (*ab*) below the BSR-like feature. Seismic line in Fig. 1



Gas seepage area

Acoustically reflective plumes in the water column have been observed immediately above the pockmarks, suggesting that these plumes represent the actual seepage from the near-surface upper slope sediment (Baraza and Ercilla 1996). This gas seepage was observed in 3.5-kHz seismic profiles (Fig. 4). Moreover, the new analysis of bathymetric echosounders records also illustrates a possible indication for the actual seepage of gas from near-surface sediments on the upper slope and shelf-break sediments (Fig. 7). They appear as dark hyperbolas and columns ascending from the seafloor up to 50 m. Similar features can be caused by the presence of fish shoals or concentrations of suspended sediment among other things (Hovland and Sommerville 1985). But, in this case, the dark features extend vertically, seem to be bilaterally symmetrical, and are located above gas charged sediments and pockmarks. These observations suggest that the mentioned acoustic anomalies are gas plumes ascending along the water column (Judd et al. 1997).

Together with the above mentioned acoustic evidence of sediments containing free gas, or features that sup-

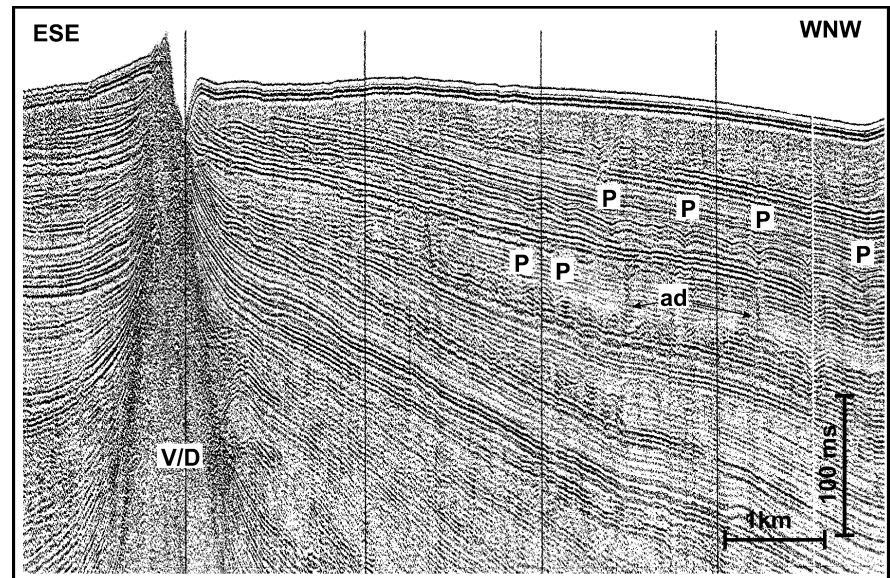
port the actual and past escape of gas from the sediments in the Gulf of Cadiz, there is new evidence in the form of acoustic anomalies comparable to BSRs. They may constitute a proof for the presence of gas in the form of gas hydrates on the same area (Ercilla et al. 2002). These acoustic anomalies are described in the detail below.

BSR-like reflections

A detailed review of the existing seismic database from the Gulf of Cadiz reveals several local examples of acoustic anomalies similar to what are interpreted as indicative of the presence of gas hydrates in the sediment column. These appear mainly in the form of high-amplitude reflections and BSRs identified on high-resolution, single-channel airgun seismic records.

A strong, discontinuous, high-amplitude reflection about 3 km long appears in a location of the central upper slope of the Gulf of Cadiz in the same area where both surficial and buried pockmarks develop (Fig. 5). This reflector appears parallel to the seafloor surface in an area where the stratification shows clear dipping. By

Fig. 6 Airgun seismic profile showing ancient pockmarks (*P*) fossilised at different depths and their close relationship with volcanic/diapir feature. Note the presence of acoustic disturbances (*ad*) in the form of high amplitude diffractions that occur along their vertical arrangement. Seismic line in Fig. 1



its disposition with respect to both the surrounding reflectors and the seafloor surface, and, following the terminology of Shipley et al. (1979), the reflector can be identified as a BSR. This BSR develops above an anticline structure on which other evidences for the presence and escapes of gas have also been identified (Baraza and Ercilla 1999) (Fig. 5). Acoustic anomalies in the form of column-shaped acoustic wipe-outs develop immediately below the BSR, on what seems the evidence of free gas within the sediments below the hydrate zone. The area where the BSR is located lies at a water depth of 388 m, and a depth below the seafloor of about 150 ms. Assuming an average sonic velocity of 1,600 m/s, and that both the hydrostatic and lithostatic pressure gradients are 0.1 atm m^{-1} , a pressure of about 50.8 atm can be expected at the depth of the acoustic anomalies. The Gulf of Cadiz area overlies a “normal” continental crust, and then an average geothermal gradient of $30 \text{ }^\circ\text{C/km}$ can be assumed for this area. This will imply a temperature increase of about $3.6 \text{ }^\circ\text{C}$ from the seafloor

surface to the depth where the acoustic anomaly or BSR is located. Without applying any correction for the presence of seawater, rather than pure water within the sediment pores, this leads to a temperature range estimate between 14.1 and $16.1 \text{ }^\circ\text{C}$ for the position within the sediment column where the acoustic anomaly is located.

There is a second example of acoustic anomaly found in the upper slope of the Gulf of Cadiz. This has been identified on different locations along airgun seismic profiles obtained immediately below an outcropping volcano/diapir ridge on the Gulf of Cadiz slope (Fig. 8). The anomalous reflection shows a clear reverse polarity, compared to the seafloor reflection. The BSR is at 340 m water depth and about 80 ms deep in the sediment column and extends for about 3.5 km (Fig. 8). The volcano/diapir appears as a penetrative structure cutting through more than 600 m of sedimentary units, probably along a fault that has been successively reactivated since the Pliocene. The sedimentary units are progressively thinner towards the diapir and show well-stratified, parallel seismic reflectors that abut against the diapir. Stratification is planar and horizontal and becomes more inclined, even sub-vertical, near the contact with the diapir, reflecting the simultaneity and continuity between sedimentation and diapir uplift (Fig. 8). Assuming the above mentioned values for average sonic velocity and hydrostatic and lithospheric pressure gradients, this acoustic anomaly would, theoretically develop at pressure of 40.4 atm under temperature conditions between 12.4 and $14.4 \text{ }^\circ\text{C}$.

New examples of acoustic anomalies are found towards the SE along the upper slope of the Gulf of Cadiz, but these occur in locations where no diapirs or other gas-related features (pockmarks) appear. The more evident of these acoustic anomalies on the airgun seismic profiles appear in an area between the

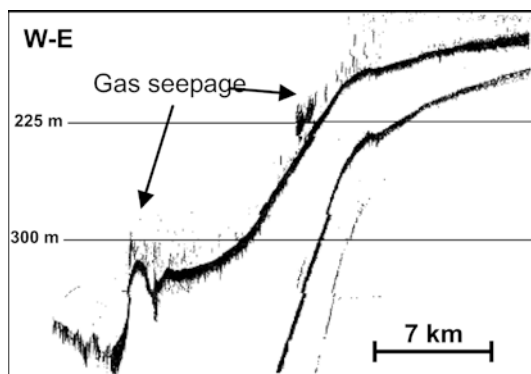
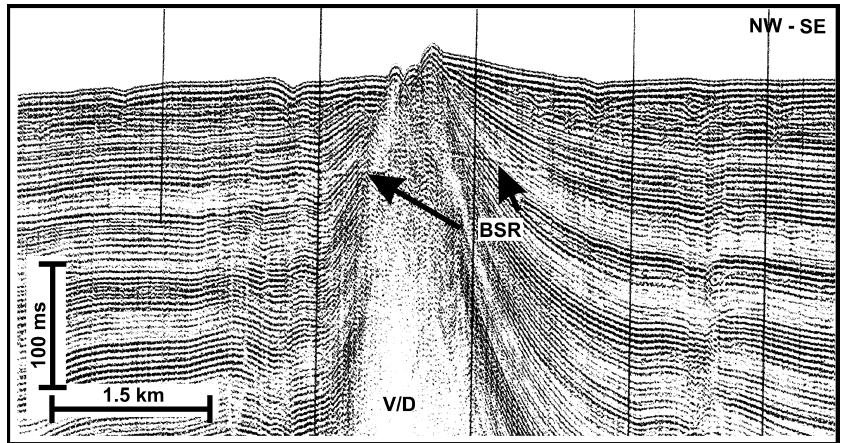


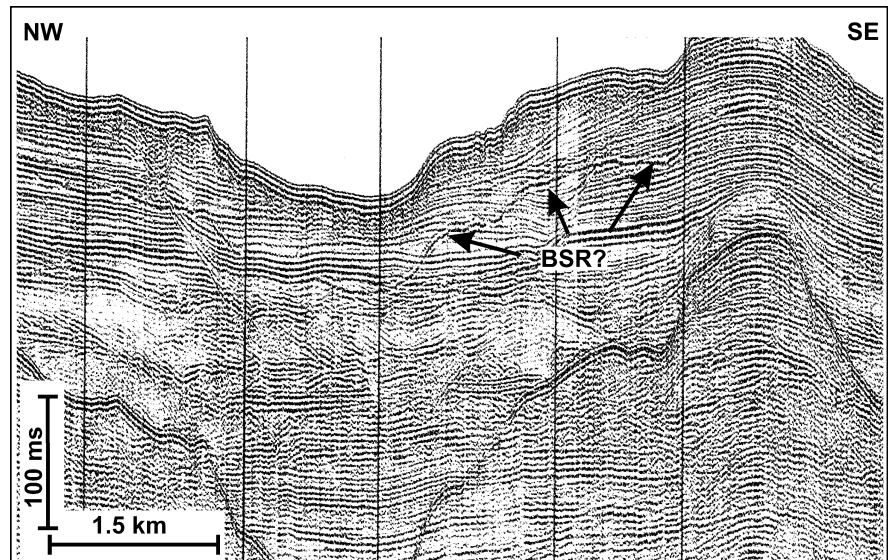
Fig. 7 Bathymetric echosounder profile showing acoustically reflective plumes in the water column. Seismic line in Fig. 1

Fig. 8 Detail of an airgun seismic profile showing the location of the BSR-like feature around the top of a mud volcano/diapir (V/D). Seismic line in Fig. 1



uppermost slope and the shelfbreak, between 140 and 220 m in water depth (Fig. 9). The erosion caused by the strong Mediterranean Undercurrent affects the upper slope in this area. This is reflected in an irregular topography, the truncation of the reflectors of the surficial seismic units, the presence of seismic facies with acoustic signatures and features typical of high-energy environments, internal erosional surfaces, cut and fill features...etc. Under these reflections, an acoustic anomaly that cuts through the stratification extends for more than 12 km. The acoustic anomaly has a reverse polarity compared to the seafloor reflection, and appears parallel to the seafloor at a very continuous depth of 80 ms (Fig. 9). Assuming the above mentioned values for average sonic velocity and hydrostatic and lithospheric pressure gradients, these acoustic anomalies would, theoretically, develop at pressure conditions between 20.4 to 28 atm, and, given their location closer to Gibraltar Strait (and hence near the direct impact of the Mediterranean Undercurrent), under temperature conditions of pressure conditions between 12.4 and 14.4 °C.

Fig. 9 Detail of an airgun seismic profile showing the location of the BSR-like feature, which mimics the morphology of the seafloor. Seismic line in Fig. 1



Discussion

The review of geophysical evidence that supports the presence of gas in the sediments of the Gulf of Cadiz slope by Baraza and Ercilla (1996), together with the recent publications about direct evidence of gas on the Gulf of Cadiz (Kenyon et al. 2000; Mazaurenko et al. 2002; Somoza et al. 2002) have provided new information and evidence about the presence of gas and its origin.

Yun et al. (1999) infer the relative distribution of gas in the subsurface based on differences in seismic features displayed by the gas charged sediments: highly gas-charged areas, when the subsurface appears to be acoustically impenetrable; areas of abundant gas, when acoustically turbid is present but coherent reflectors can be still discerned; and zones of sparse to no gas, where reflectors are coherent. In the sense of Yun et al. (1999), we may suggest that the concentration of gas within the area with charged sediment is higher in the central zones because the acoustic signal is totally obliterated;

contrasting, the concentration is lower in the external zones because it is possible to see traces of acoustic reflections. The presence of free gas within the sediment could have played an important role in the formation of slumps. Free gas within sediment increases pore pressure and in consequence reduces its shear strength favouring sediment faulting and gas migration and expulsion (Kayen and Lee 1993). In fact, enhanced reflections are still identified in proximal parts of slumps. Therefore, gas release can also occur through the slump development, and not only through pockmarks.

The new analysis suggests that the presence of pockmarks is not only related to sediment sorting, but they also seem to be related to diapirs. Baraza and Ercilla (1996) proposed that pockmarks occur where the near-surface sediments are sandier due to the action of the Mediterranean Undercurrent outflow (Nelson et al. 1999); the sandier sediments have high porosity, allowing the interstitial gas to escape. We note that pockmarks presence could be related also to diapir structures. Recent studies have indicated that some of these diapirs correspond to mud volcanoes (Kenyon et al. 2000; Mazurenko et al. 2002; Somoza et al. 2002). In fact, these studies have demonstrated the presence of gas hydrates, degassing structures, chemosynthetic fauna, and autigenic carbonates from samples recovered on the mud volcanoes. Our results also indicate the presence of gas and possible BSR features on the top of anticline structures. Then, we can tentatively consider that those pockmarks nearest to mud volcanoes/diapirs could be attributed to the expulsion of gas and/or fluids through migration paths related to the mud volcano/diapir structure. In fact, faults have been identified in the area where pockmarks develop (Baraza and Ercilla 1996; Baraza et al. 1999). The fossilisation of the pockmarks at different depths would indicate gas and/or fluids expulsion was episodic, their activity ceased at different times and then migration paths also had a temporal character.

Baraza and Ercilla (1996) proposed a biogenic origin for the gas in the Gulf of Cadiz, resulting from the decay of organic matter contained within the rapidly developed regressive shelf-margin deltas. This origin can be attributed for the interstitial free gas identified in the uppermost slope area where the shelf-margin deltas develop. But, recent geochemical data on gas-hydrate samples from mud volcanoes/diapirs indicate that gas has also a thermogenic origin (Mazurenko et al. 2002). Then, the origin of the gas responsible of the pockmark formation can be both, biogenic for those pockmarks close to the gas-charged sediments, and thermogenic for those pockmarks adjacent to mud volcanoes/diapirs.

The analysis of bathymetric echosounder records indicate that the gas seepage area is present not only above the pockmark area, but also above the gas-charged sediments. The presence of this acoustic anomaly in the water column above the pockmarks is because the gas is venting through them. The presence of gas seepage above that area with free gas within the sediments could be linked to slump development (above

mentioned) and permeability. Gas venting could occur through micro-faults and -fractures formed by elevated gas pressures and/or paths formed through interconnected pore spaces, which act as permeable conduits reaching the seafloor.

Some of the most interesting new data obtained from the detail review of acoustic records has been the identification of BSR-like reflections. In the following paragraphs we discuss in the detail the possible origin of this anomaly.

Origin of the BSR-like reflections: gas hydrate evidence?

The development of BSR-like reflections in the Gulf of Cadiz is constrained to very limited sectors of the upper slope that have some particular geological features. The most likely BSRs appear above anticline-like features and are associated to mud volcanoes/diapirs (Figs. 5 and 8).

The P–T conditions in the area where the BSRs occur are apparently contradicted by their location on the hydrate P–T stability diagram where their positions are not within the methane hydrate stability zone (Fig. 10). The Gulf of Cadiz acoustic anomalies plot on the areas of the P–T diagram where no stable gas hydrates are supposed to occur. Only one (maybe two) of the locations (those related to anticline or volcano/diapir structures) may really account for real BSRs caused by the presence of hydrates, providing that anomalous pressure or temperature conditions exist.

As is shown on the seismic profiles, the lateral termination of the BSR appears to be very abrupt. But the seismic facies surrounding the BSR and the BSR-free sectors, which are related to overall changes in sediment type or composition, change sufficiently to explain this significant feature. Chemical composition of the gas could have displaced the hydrate stability field, but the high concentration of methane (81%) measured in hydrates from a mud volcano in the Gulf of Cádiz by Mazurenko et al. (2002), does not explain satisfactorily the BSR depths observed in this study (Lerche and Bagirov 1998). Thus, pressure, the third critical component in the stability field of gas hydrate, and the deep structure of the area may be the responsible factors that we can tentatively consider.

Mud volcanoes/diapirs are commonly developed as a result of sediment deformation and fluid escape from underconsolidated sediments under the weight of the overlying sediments or under tectonic stress. As a result, excess pore pressure develops, which reduces the strength of the sediment and forces the sediment to deform and behave in a plastic way. Excess pore pressure can also dissipate along the sediment column in the vicinity of the diapirs, especially if geological discontinuities (such as faults or sharp lithologic contrasts) exist. Then, the pressure conditions in the vicinity of a mud/shale volcano/diapir may eventually differ (being locally higher), compared to the normal range controlled by the

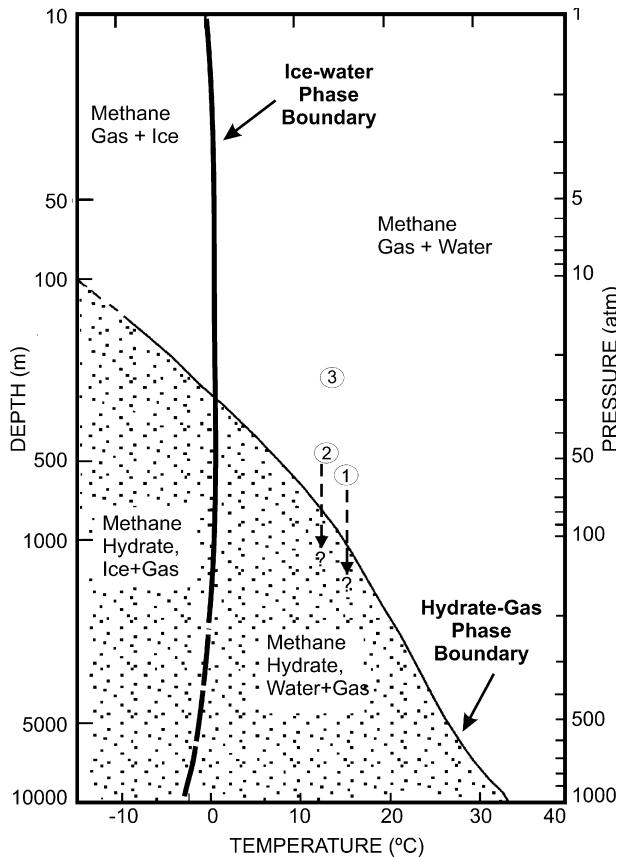


Fig. 10 Phase diagram showing the boundary between free methane gas (*no pattern*) and methane hydrate (*pattern*) for a pure water and methane system. Depth scale assumes lithostatic and hydrostatic pressure gradients of 10.1 kPa-1. (from Kvenvolden 1998). The dots 1, 2 and 3 represent the local P-T conditions for the three examples BSR-like features discussed on the text. 1 corresponds to the BSR-like feature in Fig. 7, 2 in the Fig. 8 and 3 in Fig. 9

lithostatic/hydrostatic pressure conditions. However, there are examples that show that diapirs may have the opposite effect on the stability field of gas hydrates. The thermal conductivity of a salt diapir is greater than that of the surrounding muddy sediment, resulting in a local increase in heat flow away from the diapir and a compression of the isotherms above it (MacLeod 1982). Contrasting, the low thermal conductivity of muds leads to a low temperature gradient which can contribute to the concentration of the hydrates at or near the crests of the mud/shale diapirs (Barker 1972; Lerche and Bagirov 1998).

This process, in conjunction with the doming of the surrounding strata by the diapir, forms a trap for gas released by disintegrating gas hydrate above the diapir and gas migrating updip from strata surrounding the diapir. A fast decrease of pressure can, then, bring the hydrates to the zone of instability and, in such a case, explosive dissociation of the hydrates can occur, especially where their concentration is very high, resulting in the expulsion of gas onto the water column where venting takes place and the formation of pockmarks

occurs (Fig. 5). For example, the tops of mud volcanoes/diapirs are very saturated in gas and the gas in the Gulf of Cadiz may get trapped by the doming of the gas hydrate-bearing sediment due to diapirism, as it has been observed in other areas (Dillon et al. 1980; Schmuck and Paull 1993). Significant gas accumulations can then occur in the rotated strata around the diapirs and above large diapirs in domed strata forming anticline-like structures. Gas occurrences in similar geologic settings have already been cited for the head of Cape Fear Slide area, US Atlantic margin (Schmuck and Paull 1993).

The areas where the acoustic anomalies are not in relationship with diapir uplift or deformation do not appear to be the result of hydrate-bearing sediments (Fig. 9). The P-T conditions corresponding to the location of these anomalies are far from the stability conditions of hydrates, which makes very unlikely their interpretation as a result of impedance contrasts at the base of the gas hydrate. These anomalous reflections may be the result of some kind of reverberation of the received acoustic signals or their interaction with the geometry of the source-receiver-vessel system.

Conclusions

1. The detailed review of the acoustic evidences previously identified in the Gulf of Cadiz has led to the acquisition of further evidence of the presence of gas. The gas-related features observed on the seismic records include acoustic turbidity and blanking, bright spots, ancient and modern pockmarks, high amplitude diffractions, acoustic plumes and turbidity in the water column, and BSRs.
2. This indirect evidence plus the recent sampling of sediment containing gas hydrate suggest the origin of the gas in the Gulf of Cadiz is not only biogenic as it has been suggested by Baraza and Ercilla (1996) whether thermogenic (Mazurenko et al. 2002).
3. The formation of pockmarks seems to be related to expulsion of biogenic gas and also to thermogenic gas coming from the volcanic/diapir fluids.
4. The emission of gas to the water column occurs through permeability conduits (micro-fractures and -faults and interconnected pore paths) in the area of gas charged sediment, and through slump and pockmark development.
5. The BSR-like acoustic anomalies occur intermittently in some areas of the upper slope, between 140 and 388 m water depth, and at 80 to 150 ms (65 to 120 m) deep in the sediment column. This anomaly tends to occur in the vicinity of volcanoes/diapirs or immediately above anticline features formed as a result of diapir uplift.
6. The P-T conditions deduced for the location of the acoustic anomalies do not correspond to the conditions of stability of gas hydrates, although some of the observed examples plot close to the boundary

between hydrates and free-gas. It is suggested that these diapiric intrusions may locally induce anomalously higher pore pressure conditions on the immediately surrounding sediments, affecting the stability field of the gas hydrates.

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