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Seismic expression of gas and gas hydrates across the western Black Sea

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Abstract:

This study is a synthesis of gas-related features in recent sediments across the western Black Sea basin. The investigation is based on an extensive seismic dataset, and integrates published information from previous local studies. Our data reveal widespread occurrences of seismic facies indicating free gas in sediments and gas escape in the water column. The presence of gas hydrates is inferred from bottom-simulating reflections (BSRs). The distribution of the gas facies shows (1) major gas accumulations close to the seafloor in the coastal area and along the shelfbreak, (2) ubiquitous gas migration from the deeper subsurface on the shelf and (3) gas hydrate occurrences on the lower slope (below 750 m water depth). The coastal and shelfbreak shallow gas areas correspond to the highstand and lowstand depocentres, respectively. Gas in these areas most likely results from in situ degradation of biogenic methane, probably with a contribution of deep gas in the shelfbreak accumulation. On the western shelf, vertical gas migration appears to originate from a source of Eocene age or older and, in some cases, it is clearly related to known deep oil and gas fields. Gas release at the seafloor is abundant at water depths shallower than 725 m, which corresponds to the minimum theoretical depth for methane hydrate stability, but occurs only exceptionally at water depths where hydrates can form. As such, gas entering the hydrate stability field appears to form hydrates, acting as a buffer for gas migration towards the seafloor and subsequent escape.

Introduction

For a long time the Black Sea has attracted interest regarding different aspects of gas-related processes, as several factors favour the generation of shallow gas in this basin: the supply of abundant organic matter from major rivers, rapid sediment deposition in a subsiding basin, and cyclic periods of anoxia. The high gas content of sediments has been inferred from observations of intense gas escape from the seafloor (Polikarpov et al., 1989; Luth et al., 1999; Kutas et al., 2002; Dimitrov, 2002; Egorov et al., 2003; Shnyukov et al., 2003; Naudts et al., 2006), mud volcanism (Ivanov et al., 1996; Limonov at al., 1997; Bohrmann et al., 2003), or gas hydrate sampling (Ginsburg and Soloviev, 1998; Vassilev and Dimitrov, 2002; Mazzini et al., 2004). Geophysical studies have described the acoustic signature of free gas in the sediment pore space (Gaynanov et al., 1998; Ergün et al., 2002; Ion et al., 2002; Kutas et al., 2002), as well as Bottom-Simulating Reflections (BSRs) suggesting the presence of gas hydrates (Ginsburg and Soloviev, 1998, and references therein; du Fornel, 1999; Ion et al., 2002; Lüdmann et al., 2004; Popescu et al., 2006).

Here we present a synthesis of the main gas features in recent sediments at the scale of the western Black Sea basin, based on investigation of an extensive seismic dataset (Fig. 1), integrated with published data and results. We used high-resolution reflection seismic data acquired during the BlaSON surveys of IFREMER and GeoEcoMar (1998 and 2002). Data were obtained using consecutively two seismic sources: a GI gun (central frequency 70 Hz) and a miniGI gun (central frequency 150 Hz). The receiver was a 300 m long 24-channel streamer. We processed the data using Promax software. The conventional processing flow included CDP gather formation, velocity analysis, removal of noisy traces, normal moveout correction and stacking, migration, and seabed mute. To investigate the shallow sediments we used 3.5 kHz sub-bottom profiles collected by GeoEcoMar in 1979-1983 across the Romanian shelf (Fig. 1).

Background

The Black Sea originated from back-arc extension associated with the northward subduction of the Thetian plate (e.g. Robinson et al., 1995). The Western Black Sea is structurally distinct from the Eastern Black Sea, as these two basins have different ages and coalesced only in their post-rift phases. The Western Black Sea opened in the Cretaceous (Upper Barremian to Cenomanian) and is thought to be floored by oceanic crust (Finetti et al., 1988). Thick sedimentary successions have infilled the basin since the Late Cretaceous, and reach ca. 13 km in the centre of the basin (Robinson et al., 1996; Finetti et al., 1988). Until the Miocene, regional compression affected the margins of the basin to the south (in the Pontides), south-west (in the Balkanides) and north-east (in Crimea), but had only a minor effect on its north-western part (Robinson et al., 1995). The morphology of the basin reflects this evolution: the continental shelf is narrow along the surrounding compressional belts (20 to 40 km), and considerably wider in the north-western Black Sea (up to 170 km; Fig. 1). A relatively steep slope (2.5%) lies between the shelfbreak (100-140 m water depth) and a flat abyssal plain (2200 m water depth; Ross et al., 1974). Significant sediment supply from major rivers such as the Danube, the Dniepr and the Dniestr, contributed to the shaping of the north-western Black Sea margin from the coastal area, marked by deltaic deposits, down to the deep basin, where large deep-sea fan complexes formed. Additionally, this river input constantly introduced high amounts of organic-rich material into the basin. The specific history of the Black Sea, including times of periodical sea bottom anoxia, created particularly favourable conditions for the decomposition of organic matter and for gas generation.

Results: Gas-related seismic facies in the Black Sea

The presence of free gas in sediments significantly affects the acoustic properties of the sub-bottom (Anderson and Hampton, 1980), and creates a variety of seismic gas signatures, frequently referenced in the literature (e.g. synthesis of Anderson and Bryant, 1990; Judd and Hovland, 1992). Our study reveals widespread occurrences of these types of seismic facies in the recent sediments of the Black Sea.

Most commonly, free gas dispersed in sediment scatters acoustic energy and results in a variable degree of disturbance of the seismic reflections. This effect is usually described as “acoustic turbidity” (Judd and Hovland, 1992; Figs. 2, 3, 4, 5). Turbidity often fades out to areas of complete “wipeout” where sediments appear to be acoustically impenetrable (Figs. 2, 5), in relation to high gas content (e.g. Yun et al., 1999). This association of facies is completed with anomalously high amplitude “enhanced reflections” or “bright spots” (Figs. 2, 5), which are thought to result from free gas pooling below a horizon and increasing the impedance contrast across that horizon because of the anomalously low velocity of gas-bearing sediments (e.g. Orange et al., 2002).

Extensive areas are marked by a succession of strong “multiples” both on high-resolution data (Fig. 2a) and on higher frequency sub-bottom profiles (Fig. 2b). Repetition of the sea floor reflection is caused by very gassy sediment layers located close to the sea floor, that reflect most of the acoustic energy, which is further re-reflected at the sea surface (Anderson and Bryant, 1990).

Columnar disturbances by upward fluid migration disrupt the normal sequence of seismic reflections (Hovland and Judd, 1988; Figs. 3, 4). The disturbances originate from a source deeper than the penetration limit of our profiles (ca. 2 s), and either reach the sea floor, or terminate within the sediment layers. These disturbances appear most often as narrow pipes, described elsewhere as “acoustic columns” or “acoustic chimneys” (e.g. Garcia-Gil et al., 2002). Locally, columns occur in association with wider turbid “acoustic curtains” with irregular tops (Fig. 4).

On 3.5 kHz seismic profiles “acoustic plumes” rising from the sea floor indicate gas escape to the water column (Fig. 5). Plumes may occur singly or in groups, and are usually up to 100 m high on the continental shelf. However, higher plumes have been previously described on the upper slope by Shnyukov et al. (2003). Acoustic plumes commonly correspond to areas where acoustic columns or turbidity reach the sea floor (Fig. 3). At some places, alignments of seeps follow the direction of recent faults, with gas escape clearly originating from the fault displacement (Fig. 5a).

Occurrences of gas hydrates in sediments are inferred from observations of BSRs. It is currently considered that a BSR marks the base of the gas hydrate stability zone as it reflects the acoustic impedance contrast at the interface between sediments containing gas hydrates and the underlying low-velocity gas-charged sediments. Due to its pressure-temperature dependence, the BSR approximately parallels the sea floor and crosscuts the acoustic bedding structure of the sediments. On our data, BSRs appear either as a distinct reflection with reversed polarity, or as an upper limit of enhanced reflections, mimicking the sea floor (Fig. 6). The sub-bottom depth of the BSR increases with water depth thus with pressure from 190 ms (ca. 150 m) at 750 m water depth, to 460 ms (ca. 370 m) at 1800 m water depth. Free gas is inferred to occur beneath the BSR, as indicated by high amplitude anomalies, acoustic turbidity and wipeouts. Locally, multiple BSRs occur beneath the equilibrium BSR (Fig. 6). They form successions of two, three or four distinct BSR-type reflections with similar amplitude, all of them showing the same characteristics as the upper equilibrium BSR: sub-parallel to the seafloor, reversed polarity and crosscutting of the sedimentary structure (see Popescu et al., 2006 for a detailed description). Multiple BSRs are an exceptional feature that has not been observed anywhere else. They are thought to represent most probably relics of former long-lived positions of the base of the hydrate stability zone (Popescu et al., 2006). However, their origin is far from being fully understood.

Discussion

Distribution of the gas facies

Shallow gas

Two major gas accumulation areas occur in the shallow sediments of the western Black Sea. The first shallow gas zone is located along the coast, whereas the second one lines up along the shelfbreak (Fig. 7). The seismic data from these areas are characterized by repeated multiples, associated with acoustic turbidity, wipeouts and enhanced reflections, masking almost completely the structure of the sedimentary systems (Fig. 2). The gas front, defined as the top of this association of facies, lies close to the sea floor.

Widespread shallow gas up to 1.3-4 ms (1-3 m) beneath the sea floor has accumulated in front of the Danube Delta (Fig. 7). This gas zone corresponds geographically to the Danube delta front and inner prodelta, and it extends southward following the direction of the present coastal flow. The coastal flow is associated with the Danube and Dniepr Rivers and is restricted to a very narrow coastal zone (Panin, 1996). A similar gas area covers most of the south-western shelf along the Bulgarian shore (Fig. 7). Dimitrov (2002) described this as a layer of “Holocene gas-charged sediments” up to 10-12 m thick, showing that its extent coincides with an area of unusually high deposition from the South Black Sea current, which transports fine material mainly from the Danube River.

There is also evidence for shallow gas accumulation along the shelfbreak, including the outer shelf and the upper slope down to ca. 750 m water depth. Gas occurrences follow the shelfbreak all along the western Black Sea basin in a band with variable width, from 3 km in front of the Bulgarian coast to ca. 50 km on the northern Romanian shelf (Fig. 7). The gas front is relatively flat and close to the sea floor (ca. 20-40 ms/15-30 m depth) on the outer shelf, and becomes more irregular and deeper (up to 300 ms/ca. 220 m) on the upper slope. Gas accumulations in this setting represent the most prolific gas discharge areas across the western Black Sea (Fig. 7). Several thousand of seeps have been reported, especially along the Ukrainian shelfbreak (Kutas et al., 2002; Egorov et al., 2003; Shnyukov et al., 2003; Naudts et al., 2006).

Between the coastal and shelfbreak gas areas, there is an uneven shallow gas front (1.3-13 ms/1-10 m depth) on 3.5 kHz profiles where there are localised acoustic turbidity and enhanced reflections, generally allowing recognition of the stratigraphic reflections. Lower frequency seismics penetrates this gas. This characteristic may indicate lower amounts of gas in sediment pores.

Deep gas

Acoustic columns occur ubiquitously on the western Black Sea shelf on high-resolution reflection seismic data (Fig. 7). Two distinct settings can be distinguished: (1) the inner shelf, where most of the columns terminate upwards against a major unconformity interpreted previously as the limit between the Oligocene and the Middle-Upper Miocene (Badenian-Sarmatian, see Gillet et al., 2003; Gillet, 2004), and (2) the outer shelf, where columns penetrate this stratigraphic surface and reach the seafloor (Fig. 3). Whether gas migration reaches the seafloor or not is essentially a function of the permeability of the base of the Miocene sediments. Several patches of columns reaching the seafloor occur inside the zone with buried columns, possibly in relation with higher gas supply, and often correspond to gas seeps at the seafloor (Figs. 3, 7). Some of these areas are situated above known deep oil and gas fields such as Lebada (Fig. 7). Wider areas of deep gas coincide usually with the location of major paleocanyons buried in the Plio-Quaternary deposits of the north-western Black Sea shelf (Fig. 4). However, gas supply does not originate in the canyon fill, but the canyons seem to form in areas with a stronger gas supply. The modern Danube Canyon also developed along a narrow zone with subsurface gas and a seepage alignment (Fig. 7; Popescu et al., 2004). This preferential location of major shelf-indenting canyons (both modern and buried) suggests that instability due to the presence of this gas may have acted as one of the canyon-forming forces.

Our results are in agreement with previous studies that have suggested vertical gas migration along faults or more permeable paths from the deeper sediments of the Black Sea (Ion et al., 2002; Kutas et al., 2004). It was also noted that some of the gas venting sites occurred near the Delfin and Komsomol’skoye hydrocarbon fields on the northern shelf (Kutas et al., 2002). Another indication of deep gas is the alignment of gas seeps along major faults, such as Peceneaga-Camena (Popescu et al., 2004; Fig. 8) and the Kalamit Ridge bounding fault zone (Peckmann et al., 2001). A deep gas supply was demonstrated in the central Black Sea at 2000 m water depth, where mud volcanoes occur in association with gas venting and pockmarks (Ivanov et al., 1996; Limonov et al., 1997).

Gas hydrates

We mapped several areas with BSR occurrences between ca. 750 m and 1900 m water depth. The three southern areas are located in the Danube deep-sea fan. The northern area, previously reported by Lüdmann et al. (2004), is situated in the Dniepr fan. We did not find evidence of BSRs on the southern Bulgarian slope, nor in front of the Bosphorus, as indicated by Vassilev and Dimitrov (2002). In the Danube fan, BSRs and associated free gas facies are confined within distinct channel-levee systems and follow their direction, which is reflected by the elongated shape of the BSR areas. The acoustic signature of free gas below the base of the hydrate layer is concentrated mainly in the coarser-grained deposits at the channel axis (Fig. 6). The BSR corresponds to the depth of the hydrate stability limit calculated for methane hydrates (Popescu et al., 2006). Paleo-BSRs possibly reflecting former stable P-T conditions have also been preserved within these gassy channel-levee systems (Popescu et al., 2006).

BSR areas are of minor extent at the scale of the western Black Sea. However, the presence of gas hydrates is not restricted to these areas, but is probably much more extensive, as near-surface hydrate samples have been reported widely and randomly across the basin, including areas well outside the BSR and mud volcano areas (Fig. 7).

Generally, gas hydrates can exist without a BSR, since the BSR is reflective only if free gas occurs below a stable interface with gas hydrates (Holbrook et al., 1996).

The upper limit of the BSR areas coincides roughly with the minimum theoretical depth of methane hydrate formation in the Black Sea (725 m, Naudts et al., 2006). Incidentally, this depth is also the lower limit of intense gas seepage all over the western Black Sea basin. Thus, gas release at the sea floor occurs regularly (and almost exclusively) outside the area where hydrate formation is possible (Fig. 7). There is no evidence of free gas presence within or migration through the hydrate stability zone, though free gas underlies the hydrate layer (Fig. 6). Therefore, any gas entering the hydrate stability zone appears to form hydrate. In this respect, we argue that gas hydrates in the western Black Sea act as a buffer that absorbs gas and thus prevent gas migration towards the sea floor. The main exception is the mud volcano area in the central basin, where gas and material extruded from deep layers most probably change the local heat flow and the stability conditions of hydrates.

Origin of the gas

Our seismic data provide evidence for both shallow and deep gas in sediments. Nevertheless, “deep gas” does not necessarily signify “thermogenic gas”, as biogenic gas can also occur in the deep subsurface (Kotelnikova, 2002). Complementary information, such as the concentration of methane relative to other hydrocarbons and the isotopic composition of methane is necessary to distinguish the origin of the gas. Most of the geochemical studies of core and drilling samples from the western Black Sea have indicated that gas in sediments is mainly methane of biogenic origin (Hunt, 1974; Ross, 1978; Ivanov et al., 1983; 2002; Dimitrov, 2002; Neretin et al., 2004).

Methane is also the main component of gas hydrates in the Black Sea (Ginburg and Soloviev, 1998; Vassilev and Dimitrov, 2002). However, the presence of higher hydrocarbons and methane isotope signatures indicating a contribution of thermogenic gas have been reported from the mud volcanoes in the central Black Sea (Limonov et al., 1997), and from one location on the northern upper slope (Mazzini et al., 2004; Kruglyakova et al., 2004).

Coastal gas accumulations have a shallow sub-bottom depth and they are located in areas currently characterized by high depositional rates associated with the organic-rich sediment input from the Danube River. Isotopic compositions of methane sampled from near-surface sediments from this zone have indicated a microbial origin (Ivanov et al., 1983; 2002). We thus conclude that the source of this gas is most probably related to in-situ degradation of high amounts of organic matter contained in river-fed sediments.

During lowstand times, the Black Sea water level was ca. 100 m lower than at present (e.g. Ryan et al., 2003; Popescu et al., 2004, and references therein; Lericolais et al., In Press). The shelf-edge area was then a paleocoastal environment, accumulating major river-born sediment discharge and thus high amounts of organic matter. Consequently, the shallow gas accumulations along the shelfbreak are likely to represent the lowstand equivalent of the coastal gas area. However, gas derived from in situ organic-rich paleocoastal sediments may coexist with gas migrating from the deeper subsurface, as suggested by the wide occurrence of upward gas migration on the rest of the shelf, and by the preferential location of gas seeps and sub-bottom gas along deep fault directions. Moreover, the lower limit of this area usually coincides with the upper limit of hydrate stability. As gas hydrates in the pore space of the sediments may focus fluid flow (Bouriak et al., 2000), part of this gas may have formed in the deeper basin and subsequently migrated upslope along the base of the hydrate stability zone. Gas from the shelfbreak area is mainly methane (Michaelis et al., 2002), and was proposed to derive from organic-rich sediments with a possible contribution of thermogenic gas (Peckmann et al., 2001).

Upward gas migration from a deep source is common on the western Black Sea shelf. This area is known to contain hydrocarbon fields (Fig. 7), some of which produce oil (Lebada) and gas condensate (Golitsyna). The main regional hydrocarbon source is the Maikopian facies, an Oligocene-Early Miocene (Jones and Simmons, 1997) or Upper Eocene (Robinson et al., 1996) black mudstone-dominated unit with a high organic carbon content. The Maikopian is considered to be the source rock for most of the petroleum occurrences around the Black Sea (Robinson et al., 1996), including the Lebada field on the Romanian shelf, where it is known as Histria Formation (Dinu et al., 2005). An Upper Devonian source may have generated gas condensate on the Ukrainian shelf (Robinson et al., 1996). Other intervals with source potential have been suggested for the Bulgarian shelf, such as Neogene, Palaeocene, Cretaceous, Upper Triassic, Lower Carboniferous, and Devonian (Dimitrov, 2002). Our data show that upward gas migration affects sedimentary successions as old as the Eocene (based on the stratigraphic study of Gillet, 2004; Figs. 3, 4). The source of this gas is thus Eocene or older, though it is situated below the penetration depth of our profiles.

The origin of the gas that generated hydrates in the Danube and Dniepr deep-sea fans seems to be mostly related to in situ biogenic methane (Ginsburg and Soloviev, 1998; Vassilev and Dimitrov, 2002; Neretin et al., 2004). There are no indications of vertical gas migration in this area. Interestingly, we did not identify seismic indicators of gas or hydrates in the deep flat central basin, between the lower limit of BSR occurrence and the mud volcano area. Free gas and BSRs may be more difficult to identify in this area because the sedimentary facies change, and the sea floor becomes parallel to the sedimentary layers. Alternatively, gas in sediments may be quantitatively less significant in this area. The latter option appears more likely, as it is consistent with the geochemical study of Reeburgh et al. (1991) which showed that deep basin sediments acted as methane sinks, while shelf and slope sediments were methane sources.

Conclusions

Our seismic data provide evidence for both shallow and deep gas in the western Black Sea sediments. Shallow gas concentrates especially in coastal and in shelfbreak areas, corresponding to the highstand and lowstand depocentres respectively. The coastal gas accumulation is mainly in situ biogenic methane derived from abundant organic matter deposited in the coastal zone. The gas accumulation at the shelfbreak appears to have a more complex origin, probably including a contribution from deep gas reservoirs. Upward gas migration from a deep source is ubiquitous on the western shelf. On the outer shelf gas reaches the sea floor and frequently escapes into the water column, whereas on the inner shelf migration is usually stopped at the base-Miocene unconformity. Some of the areas where gas migration penetrates this boundary correspond to deep oil and gas fields. Below ca. 750 m water depth BSRs occur in the Danube and Dniepr fans, but gas hydrates previously sampled in BSR-free areas suggests that hydrate distribution is much more extensive. A unique pattern consisting in a succession of up to five BSRs occurs repeatedly in association with distinct channel-levee systems of the Danube fan. Gas release at the sea floor occurs only exceptionally at water depths greater than the minimum theoretical depth for methane hydrate formation, although it is abundant at shallower depths. As such, gas entering the hydrate stability field probably form hydrates, which imply that gas hydrates may act as a buffer for gas migration towards the sea floor.

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Figure captions

Figure 1. Location of seismic profiles across the western Black Sea. Solid lines indicate high-resolution BlaSON data, thin dotted lines indicate 3.5 kHz GeoEcoMar data. The dashed line marks the shelfbreak. The inset box shows the location of the study zone in the Black Sea.

Figure 2. Gas-related seismic facies in the western Black Sea: multiples, acoustic turbidity, wipeout, enhanced reflections. The location of the profiles is shown in Figure 7. Note the different horizontal and vertical scales.

A. Part of high-resolution reflection seismic profile b008-miniGI.

B. Part of 3.5 kHz sub-bottom profile 10/80.

Figure 3. Gas-related seismic facies in the western Black Sea: acoustic columns, acoustic turbidity. The figure shows part of high-resolution reflection seismic profile b038-GI, location in Figure 7. Acoustic columns reach the sea floor on the outer shelf (right part of the figure), whereas on the inner shelf they usually terminate against the regional Oligocene/Miocene unconformity. Locally, acoustic columns on the inner shelf may, however, penetrate this surface and rise up to the sea floor, in areas which correspond with gas seepage. Stratigraphic limits are from Gillet et al. (2003) and Gillet (2004).

Figure 4. Gas-related seismic facies in the western Black Sea: acoustic columns, acoustic curtains, acoustic turbidity. The figure shows part of high-resolution reflection seismic profile b005-miniGI, location in Figure 7. Areas with particularly high gas supply from the deep subsurface often coincide with the location of major paleocanyons. Stratigraphic limits are from Gillet et al. (2003) and Gillet (2004).

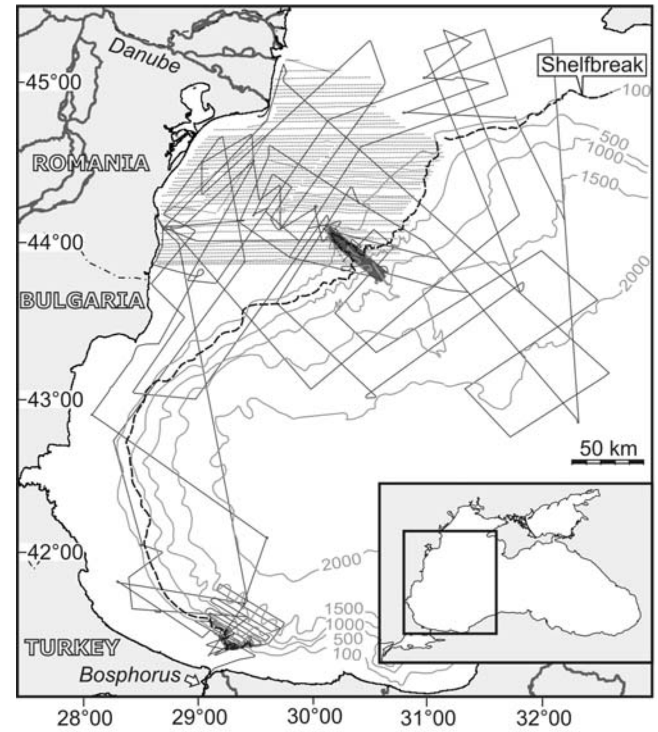
Figure 5. Gas-related seismic facies in the western Black Sea: acoustic plumes, acoustic turbidity, wipeouts, enhanced reflections. The location of the profiles is shown in Figure 7.

A. Part of 3.5 kHz sub-bottom profile 4/82. The acoustic plume originates from an active fault visible at the sea floor.

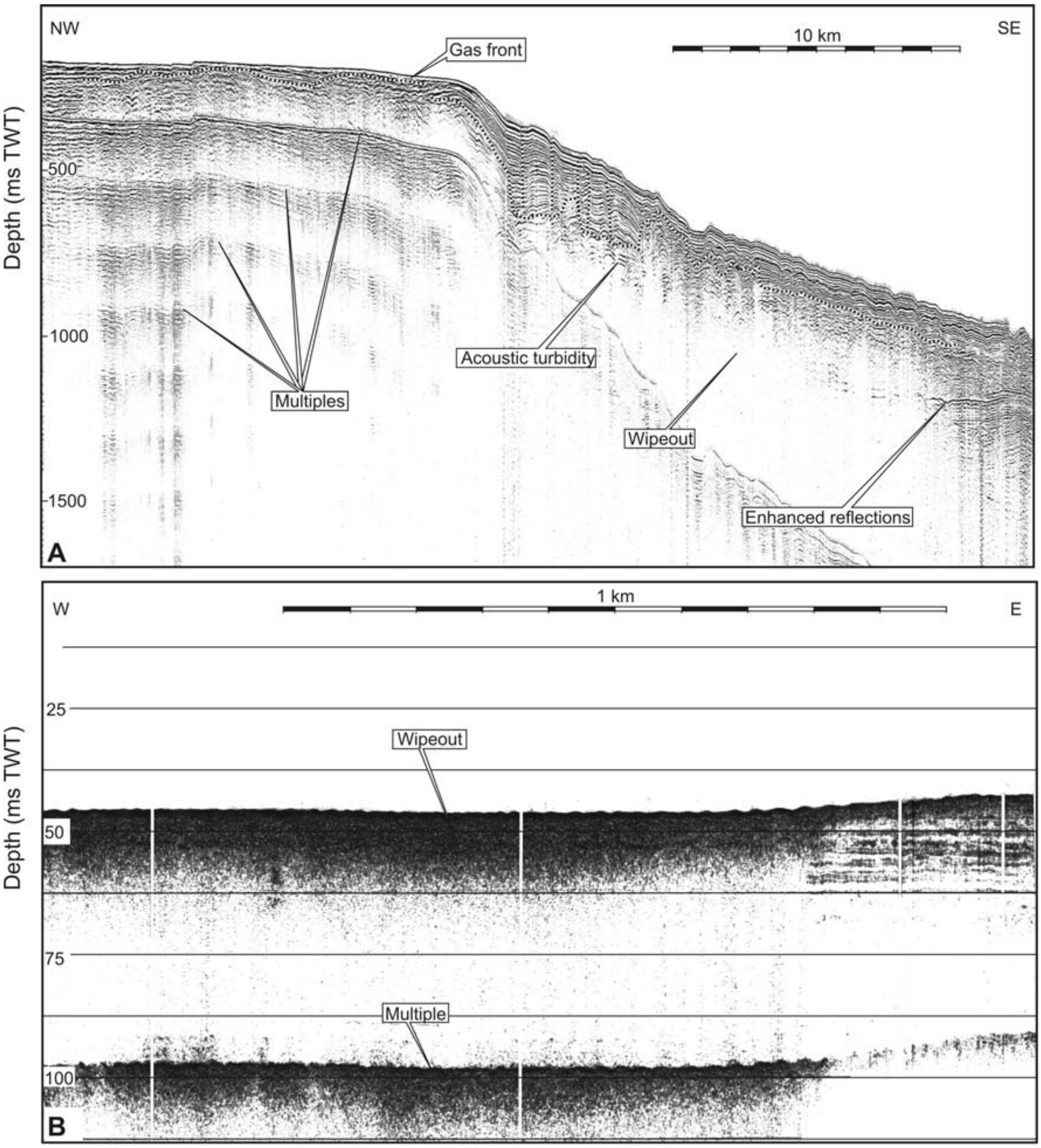
B. Part of 3.5 kHz sub-bottom profile 5/82. The acoustic plumes are located near the head of the modern Danube canyon, but outside the main erosional canyon trough.

Figure 6. Bottom-Simulating Reflections (BSR) in the western Black Sea. BSRs appear either as a distinct reflection with reversed polarity, or as the top of enhanced reflections. Multiple BSRs occur beneath the upper equilibrium BSR. Gas occurrence below the hydrate layer is indicated by acoustic turbidity and enhanced reflections. BSRs and gas facies are confined inside a channel-levee system, with free gas mainly concentrating at the channel axis. The figure shows part of high-resolution reflection seismic profile b039-GI, location in Figure 7 (after Popescu et al. 2006).

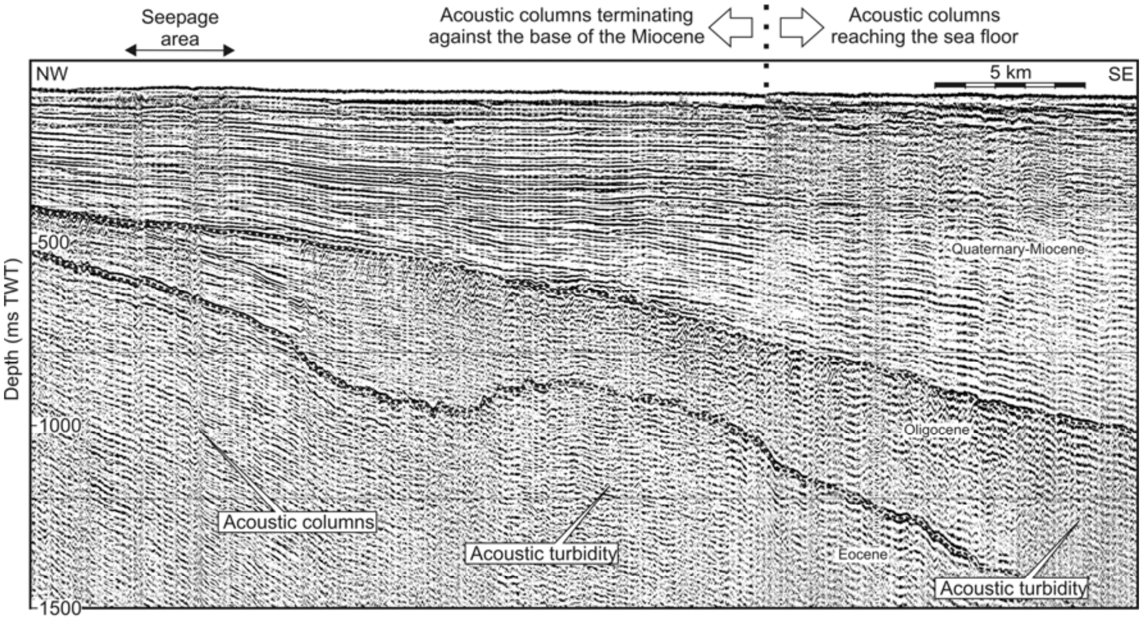
Figure 7. Distribution of the gas-related seismic facies and BSRs in the western Black Sea. Dotted grey line shows the minimum theoretical water depth for methane hydrate stability in the Black Sea. We also indicate the location of gas seeps (including information from Egorov et al., 2003; Shnyukov et al., 2003; Naudts et al., 2006), gas hydrate samples (after Vassilev and Dimitrov, 2002; Mazzini et al., 2004), mud volcanoes (after Gaynanov et al., 1998) and oil and gas exploration fields (after Robinson et al., 1996; Dinu et al., 2005). Thin dashed line around the BSR area in the northern basin shows BSR occurrence after Lüdmann et al. (2004). White arrows indicate the present coastal flow (after Panin, 1996). The inset box is a detail of the Danube Canyon area, showing the location of the buried Peceneaga-Camena (P-C) Fault (after Dinu et al., 2005), as well as active faults affecting the sea floor northward of the canyon. Note that alignments of seeps correspond in some cases with fault directions.



Popescu et al., Figure 1



Popescu et al., Figure 2



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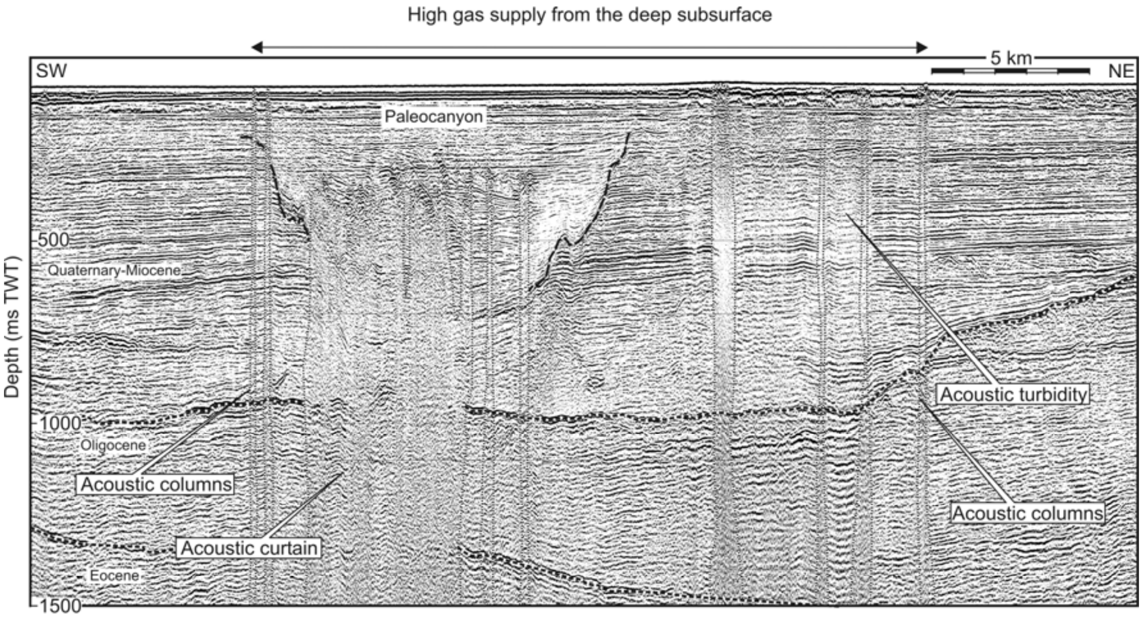

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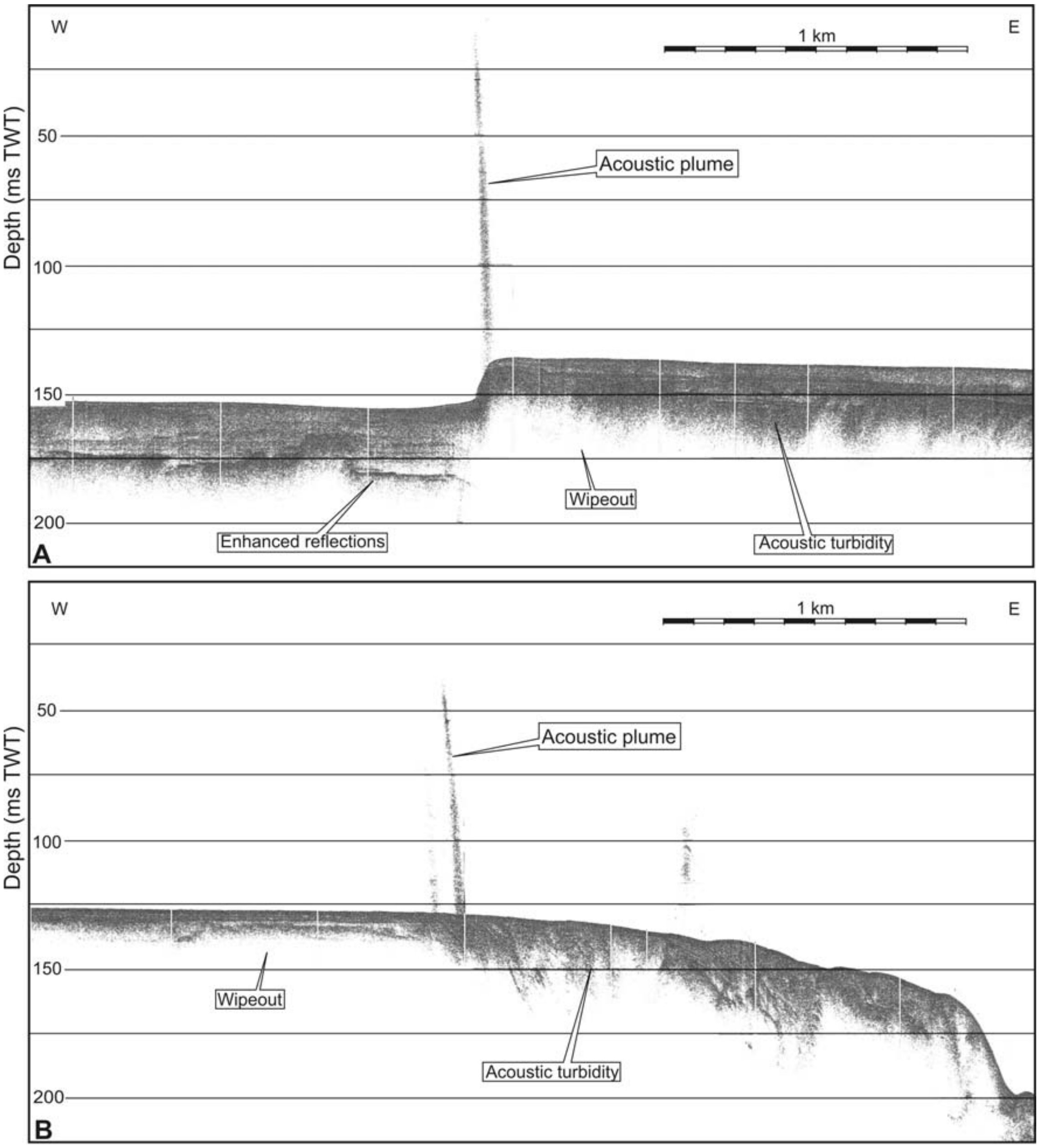

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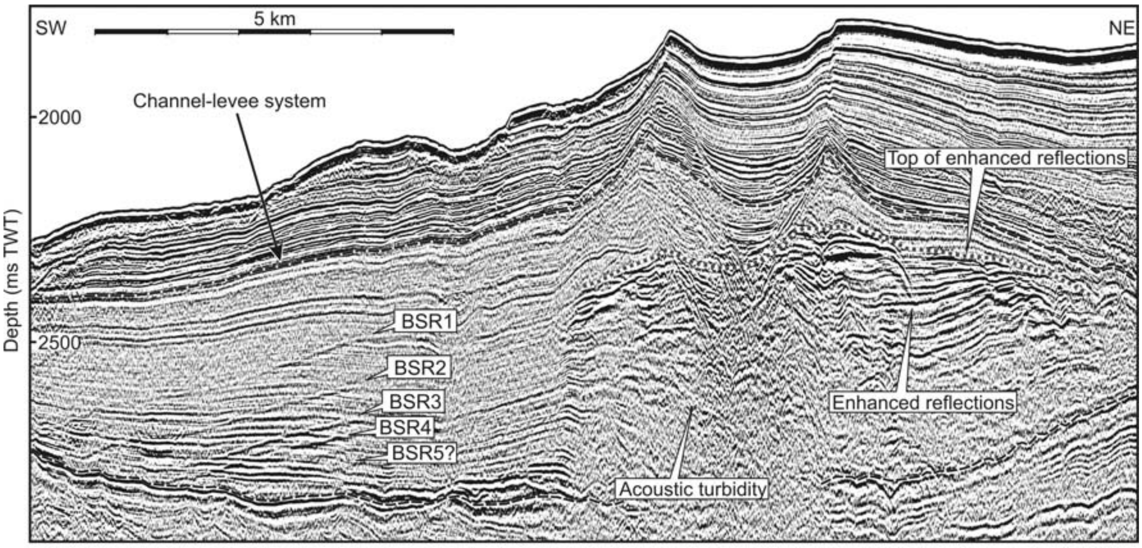
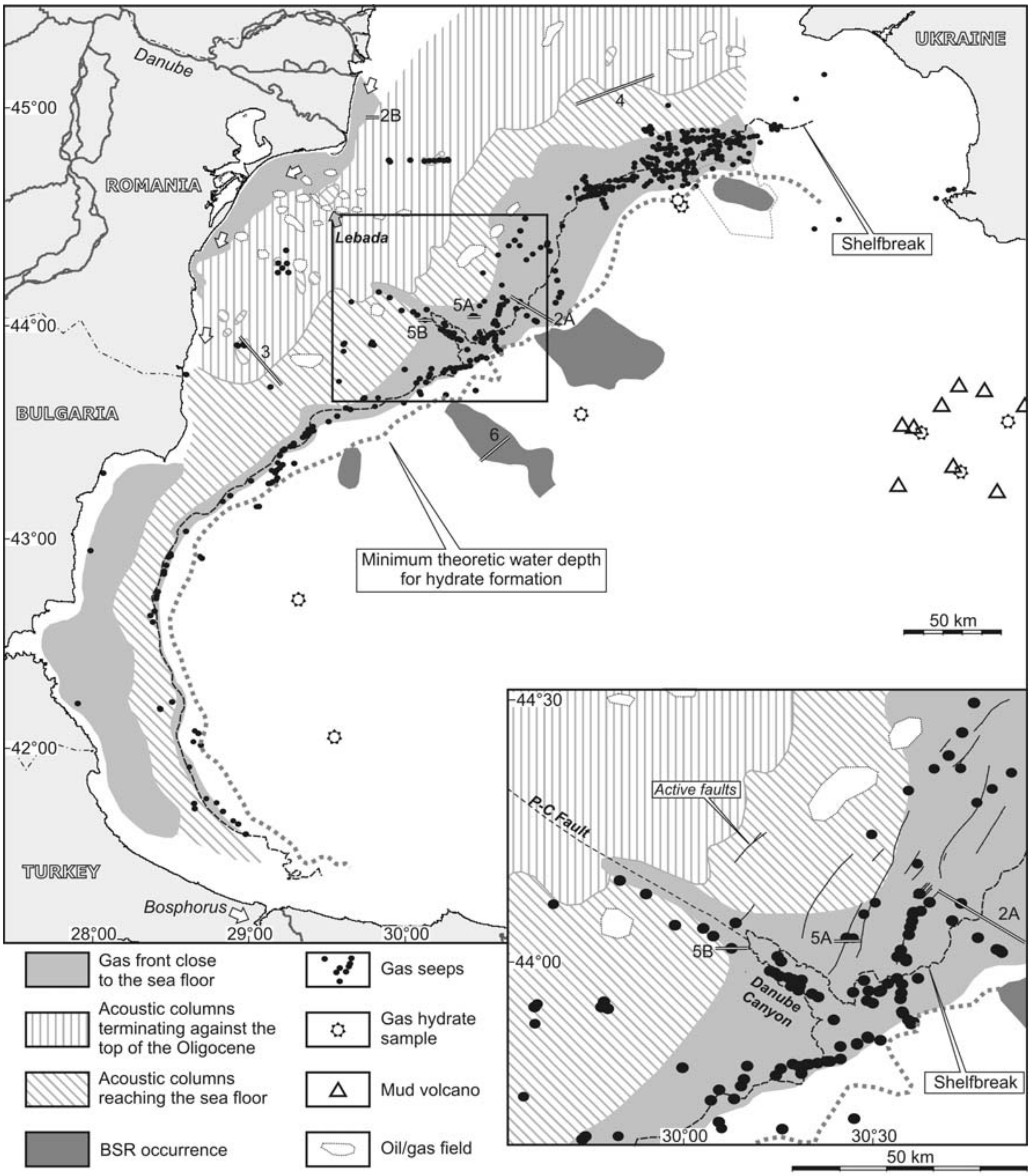


Popescu et al., Figure 6



Popescu et al., Figure 7