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Seismic evidence of shallow gas in the sediment on the shelf off Trabzon, southeastern Black Sea

M. Okyar*, V. Ediger

Middle East Technical University, Institute of Marine Sciences, P.O. Box 28, 33731-Erdemli/İçel, Turkey

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Abstract

High-resolution seismic surveys carried out on the shelf off Trabzon (southeastern Black Sea) show that the sub-bottom stratigraphy consists of two main depositional sequences (A and B) one of which contains zones of acoustic turbidity. Of these, the upper depositional sequence (A) is thought to comprise Holocene sediments, while the lower depositional sequence (B) is interpreted as approximating to the Pleistocene. The boundary between these sequences is defined by a reflector (R), which is interpreted as the pre-Holocene erosional surface. The acoustic turbidity observed on seismic profiles is interpreted as representing gas accumulations in the sediments of the upper depositional sequence. Previous geochemical investigations in the area indicate that acoustic turbidity implies biogenic methane gases in bubble form. On the basis of published hypotheses on the generation of the methane gases, it is suggested that the upper boundary of the zone of acoustic turbidity on seismic profiles in this study corresponds to the boundary between a biogenic sulfate-reducing zone and the underlying carbonate-reducing zone. Apart from acoustic turbidity, some bright spot anomalies which are also interpreted to arise from the presence of methane gases within the upper depositional sequence are observed on the seismic records collected from the shelf off Trabzon.

1. Introduction

The presence of gaseous hydrocarbons in near-surface sediment has been a source of considerable interest to the petroleum community for two main reasons (Kvenvolden et al., 1981). First, in some instances gaseous hydrocarbons signal the existence of deeper and more extensive hydrocarbon accumulations in frontier basins. Secondly, gaseous hydrocarbons may represent a hazard for drilling operations and offshore construction. For example, in circumstances where gas is trapped and accumulates

* Corresponding author.

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under an impermeable layer, the gas pressure can cause blow-outs during drilling. Similarly, increase of pore pressure resulting from an accumulation of gas decreases the shear strength of the sediment which may cause the collapse of an offshore structure (Davis, 1992).

The evidence for shallow gas in marine sediments recorded in high-resolution seismic reflection profiles has been demonstrated in detail by several investigators (Schubel and Schiemer, 1973; Siddiquie et al., 1981; Kang and Chough, 1982; Carlson et al., 1985; Hovland, 1992; Long, 1992; Taylor, 1992). They and others have attempted to develop classifications based on the various types of seismic signature which might provide a standard to which other records can be compared. Such studies have made an important contribution to the identification of gas-charged marine sediments. The origin of the gas is attributed to either low-temperature biogenic processes (bacterial activity) or thermogenic processes being essentially temperature and pressure dependent (Davis, 1992). In both cases the gas is derived from organic material (Davis, 1992).

The Black Sea Basin has been subjected to several studies of gas seeps and gas-charged sediments (Dimitrov, 1996) and also to studies pertaining to gas hydrates (Byakov and Stupak, 1987; Nomokonov and Stupak, 1988; Korsakov et al., 1989). On the basis of multi-channel seismic and high-frequency acoustic surveys Korsakov et al. (1989) reported on the occurrence of gas hydrates in the Black Sea Basin. Crystalline hydrates mainly occurred in Quaternary sediments. However, detailed studies concerning shallow gases in shelf sediments of the Black Sea, in particular adjacent to the North Anatolian coast, are rather limited (Okyar et al., 1994).

The main purpose of the present paper is to describe and discuss high-resolution seismic reflection anomalies in Holocene sediments. In addition, this paper will discuss aspects of the origin of gas-charged sediments in the region related to changing depositional regimes in response to the late Pleistocene–Holocene climatic changes. The presented interpretation is based on high-resolution, shallow-seismic reflection profiles collected from the shelf off Trabzon in the southeastern Black Sea (Fig. 1) some of which have been published previously (Okyar et al., 1994).

1.1. Late Pleistocene–Holocene depositional history

Late Quaternary sedimentation in the Black Sea is intimately linked to eustatic sea level changes and the supply of terrigenous sediments from rivers (Ross and Degens, 1974).

According to Milliman and Emery (1968), the sea level was lower than the critical sill depth (40 m) of the Bosphorus during the period from about 22 000 yr BP until 9000 yr BP. Investigation of sediments from the deep parts of the Black Sea basin have indicated that the Black Sea was an aerobic freshwater lake in the period from 22 000 to 9000 yr BP (Ross and Degens, 1974). During this period, however, the shallow (< 40 m) water areas of the Black Sea basin were exposed and subaerially eroded. During the Last Glacial maximum at about 18 000 yr BP the shoreline shifted to the 130 m depth contour (cf. Pfannenstiel, 1950). Because of the lowering of sea level, all the river valleys that enter the Black Sea extended across the continental shelf

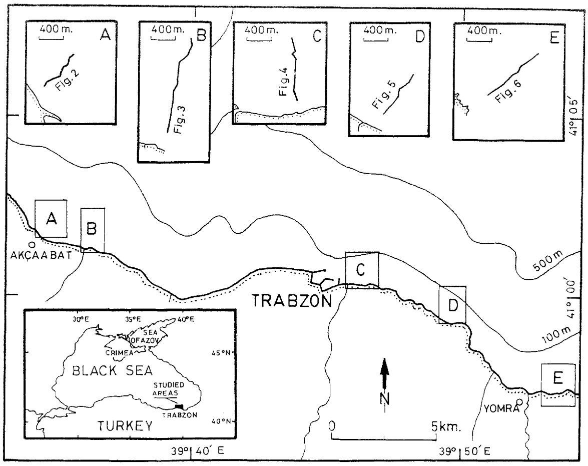

Fig. 1. Location map showing the areas surveyed seismically (A, B, C, D and E) on the Trabzon shelf. Seismic reflection profiles presented in this paper are marked by thick lines and by the corresponding figure numbers. Contours are in meters.

(Caspers, 1957). The present estuaries occupy the deeply eroded valleys formed at the Last Glacial maximum (Caspers, 1957). As the valleys became eroded the sedimentation rate in the deep basins of the Black Sea reached its maximum value of 90 cm/1000 yr. However, this started to decrease (40 cm/1000 yr) as sea level rose over the last 5000 yr of the phase (9000–14 000 yr BP) (Ross and Degens, 1974).

At about 9000 yr BP, seawater occasionally spilled over the Bosphorus sill and entered the Black Sea as a result of sea level rise (Ross and Degens, 1974). The entrance of this water initiated the change from the freshwater, well-aerated phase to the marine stagnant phase. By about 7000 yr BP an H_2S zone was well established in the deep basin. A reduction in the sedimentation rate (10 cm/1000 yr) in the deep basin coincided with these changes in environment. As the sea level rose, the detritus supplied by rivers was retained on the shelf and in the estuaries (Caspers, 1957). The conditions that now characterize the Black Sea were reached at about 3000 yr BP (Ross and Degens, 1974).

1.2. Shelf deposits

There is a sharp difference between the shelf and the deep sea deposits of the Black Sea due to the steep increase in gradient of the sea bottom from 180 to 2000 m and the H_2S poisoning of the water in the deeper zones (Caspers, 1957).

In general, fine-grained sediments are accumulating on the shelves of the Black Sea and there is an extraordinarily high rate of deposition of silt and clay in the estuaries (Caspers, 1957). Sedimentological analyses of surface sediments from the southern Black Sea shelf (Yücesoy and Ergin, 1992) show that the sediments off the mouths of the major rivers on the southern coast, the Kızılırmak, Yeşilırmak and Sakarya, are characterized by relatively high mud (silt plus clay) fractions (94–99% of bulk samples). High mud percentages are also prominent in sediments from relatively deep waters (>100 m) and in areas of quiet deposition (off the southwestern coast and off Amasra). On the other hand, coarse sediments, composed of terrigenous sand, are found off the Rize region. Gravel-sized materials, which are mainly located off the Bosphorus–Sakarya coast, seem to be controlled by both terrigenous and biogenic factors (Yücesoy and Ergin, 1992).

2. Materials and methods

Data used in this investigation were collected during the cruises of the vessel "Eyüpoğlu" in January 1992 (Fig. 1).

An EG and G Uniboom high-resolution shallow seismic system was used with a resolution of about 30 cm and an effective acoustic frequency of 400 Hz–14 kHz. Depth conversions from time sections were made using sound velocities of 1500 m/s in water and 1700 m/s in sediments (Okyar et al., 1994). Bathymetric data were collected using a Raytheon (210 kHz) precision depth recorder operated along the seismic lines. Positioning was maintained using a Del Norte Trisponder system (accuracy of about ± 3 m).

3. Interpretation and discussion of data

3.1. Seismo-stratigraphic setting

Criteria for the recognition of depositional sequences and the interpretation of the resulting seismic stratigraphy, along with data from an offshore well, are presented in detail elsewhere (Okyar et al., 1994).

Seismic reflection profiles in the area show two distinct depositional sequences (A and B) separated by an irregular reflector (R) (Figs. 2–6). The upper sequence A, is generally characterized by parallel/subparallel coherent reflections which imply uniform rates of deposition on a uniformly subsiding shelf setting (Mitchum et al., 1977). Based on nomenclature suggested by Folk (1974), the granulometric analysis of the surface sediments shows that sequence A consists of slightly gravelly muddy sand in near-shore areas grading into mud offshore (Ergin et al., 1992a).

Sequence B, which underlies sequence A, has commonly a chaotic reflection character which is interpreted either as strata deposited in a variable energy setting or as initially continuous strata that have become deformed. In contrast, some parallel oblique patterns within this sequence indicate a high-energy sedimentary regime at the time of deposition (Mitchum et al., 1977). The upper boundary of sequence B (reflector R) which is delineated by the downlap terminations of acoustic foresets within the overlying sequence (A) represents an erosional unconformity (Figs. 3 and 6). Similar seismic boundary relationships and erosional unconformities to reflector R have been reported in many areas, e.g. on the Rhone continental shelf (Tesson et al.,

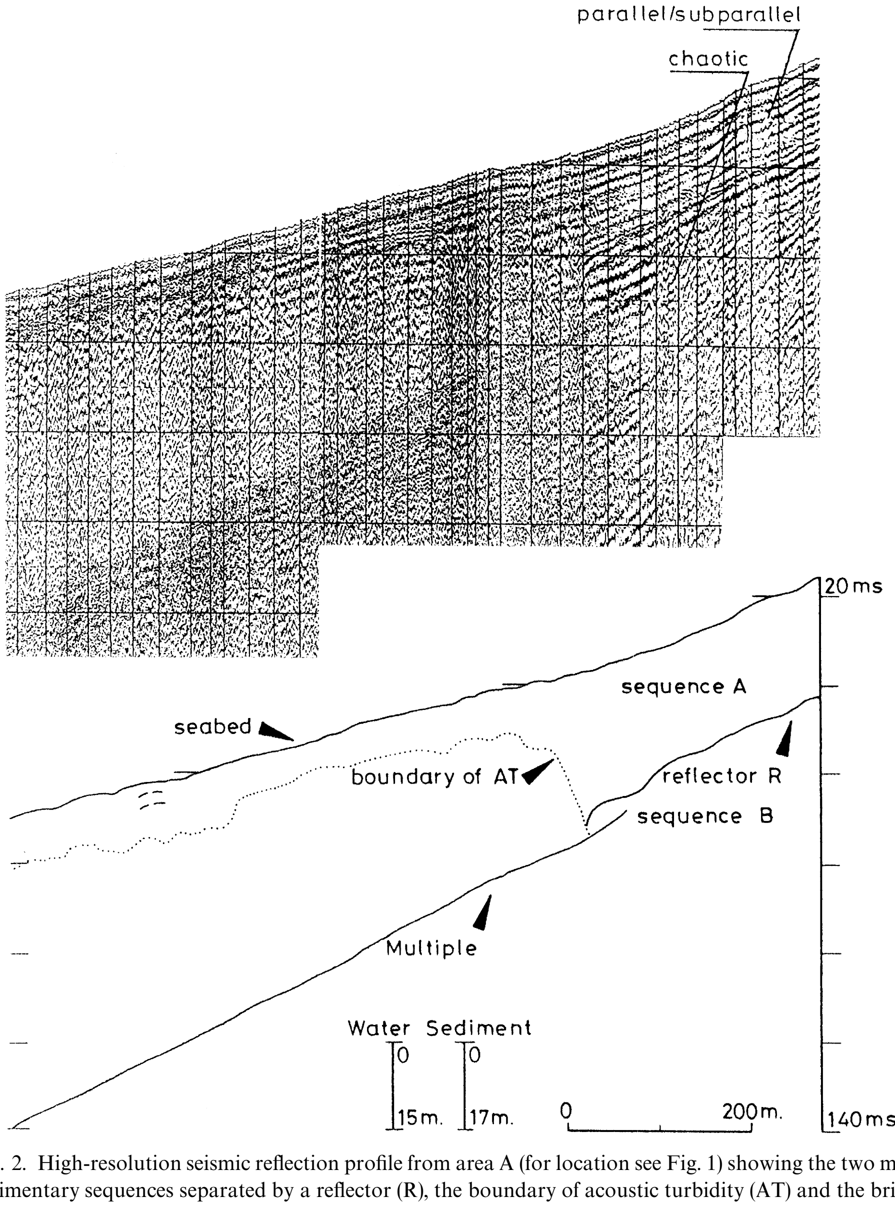

Fig. 2. High-resolution seismic reflection profile from area A (for location see Fig. 1) showing the two main sedimentary sequences separated by a reflector (R), the boundary of acoustic turbidity (AT) and the bright spot (dashed).

1990), offshore Mersin Bay (Okyar, 1991; Ergin et al., 1992b), on the Korea Strait (Park and Yoo, 1988) and in the North Sea (Salge and Wong, 1988), and represent pre-Holocene surfaces produced by the subaerial fluvial erosion of the continental shelves at the time of the last glacial maximum. Based on borehole data, sequence B

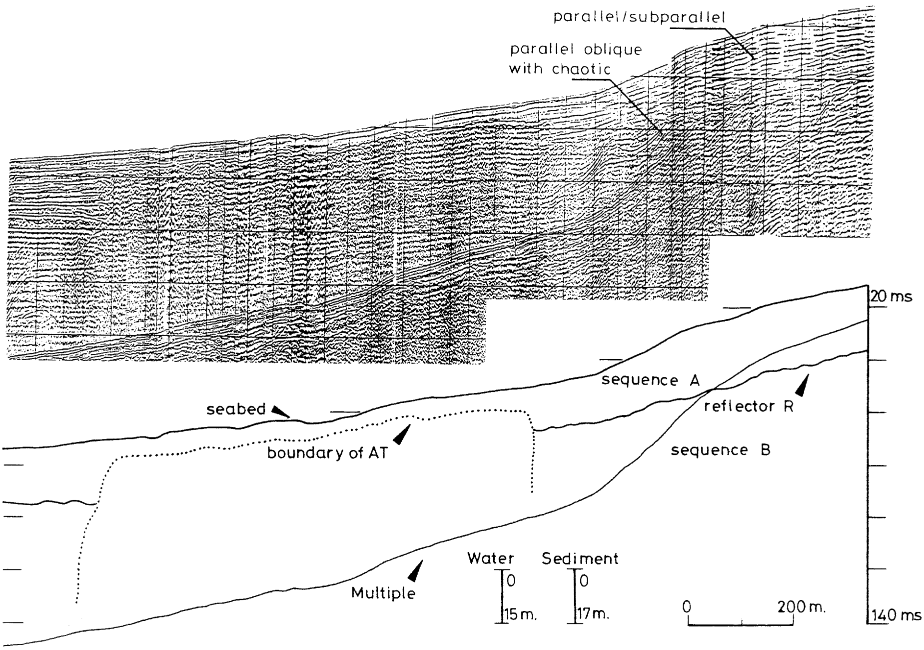

Fig. 3. High-resolution seismic reflection profile from area B (for location see Fig. 1) showing the two main sedimentary sequences separated by a reflector (R) and the boundary of acoustic turbidity (AT).

is composed of fragments of basalt, agglomerate and tuff respectively (Okyar et al., 1994).

Based on the above evidence it is reasonable to be confident in interpreting the reflector R in the seismic profiles of this study as a late Pleistocene and early Holocene erosional surface formed at a lowered sea level but now buried beneath the sediments of the subsequent post-glacial transgression (Okyar et al., 1994). Thus, the sedimentary sequence B is thought to represent the Pleistocene while sequence A is interpreted as the Holocene (Okyar et al., 1994).

3.2. Seismic anomalies

Many of the high-resolution seismic profiles collected in the surveyed areas (Figs. 2–6) contain anomalous zones or sections. These are very similar to features, described in other regions, that have been confirmed as being due to the presence of gas in the sediments (Carlson et al., 1985; Judd and Hovland, 1992; Taylor, 1992; Long, 1992; Hovland, 1992; Schubel, 1974; Korsakov et al., 1989). In this area therefore, the observed anomalous zones have been interpreted as representing gas accumulation in the sediments of the upper depositional sequence A (Okyar et al., 1994) and are referred to as zones of “acoustic turbidity (AT)”. The term “acoustic turbidity” refers to those parts of the seismic section where subbottom detail is lost

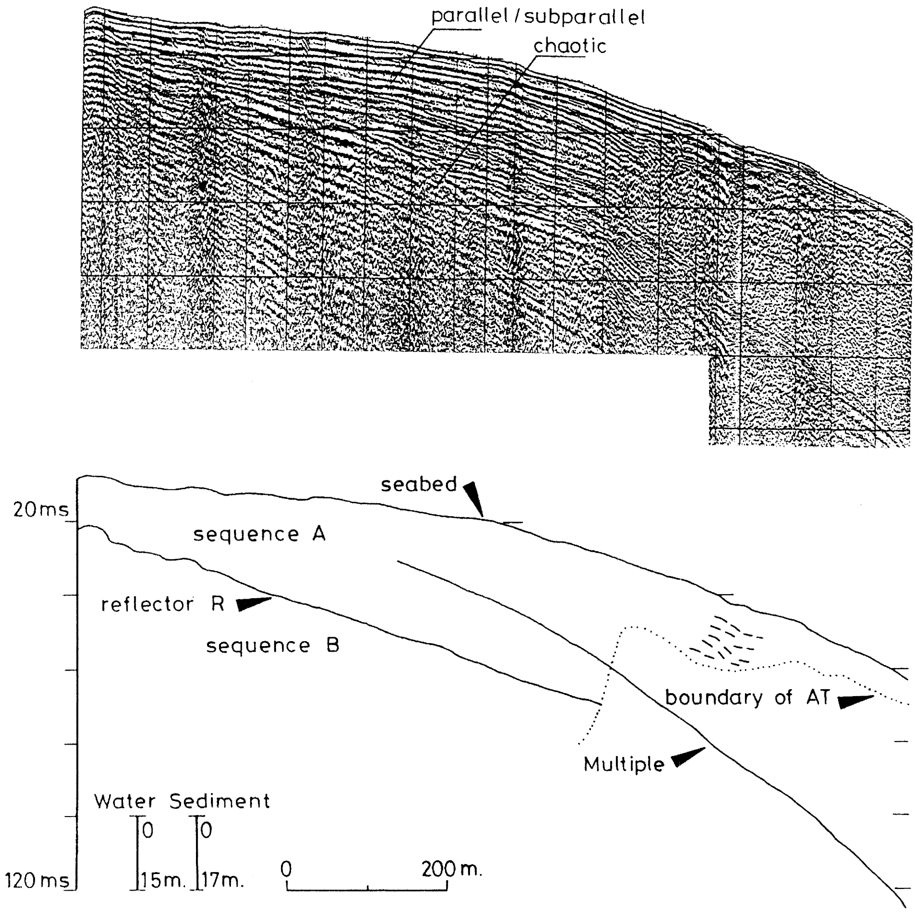

Fig. 4. High-resolution seismic reflection profile from area C (for location see Fig. 1) showing the two main sedimentary sequences separated by a reflector (R), the boundary of acoustic turbidity (AT) and the bright spot (dashed).

due to the effects of suspected gas bubbles within the sediment pore space (Davis, 1992). It has been found that acoustic turbidity may occur when there is as little as 1% of gas present (Fannin, 1980).

The acoustic turbidity observed on the seismic profiles (Figs. 2–6) is roughly confined to the upper sequence A, rising to within 2–15 m of the seabed but in no case reaching the surface. The lateral terminations of these turbid zones are steep, almost vertical. On the other hand, the seismic reflections on adjacent sections of acoustic turbidity zones mostly exhibit "pull-down" (Judd and Hovland, 1992). As these reflections extend towards the zones of acoustic turbidity they are apparently deflected downwards by the decrease in the acoustic velocity in the gas-bearing zone. According to Holmes and Thor (1982), the gas does not need to be in the free state

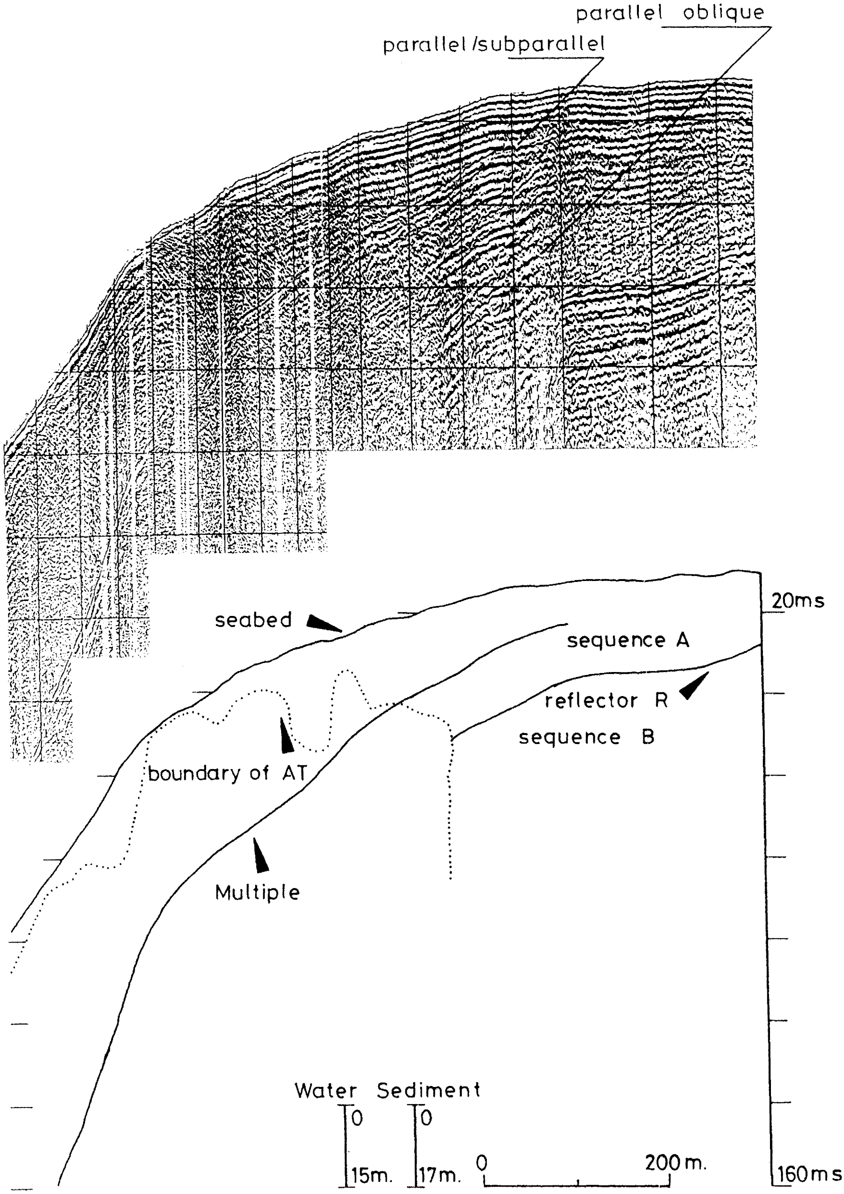

Fig. 5. High-resolution seismic reflection profile from area D (for location see Fig. 1) showing the two main sedimentary sequences separated by a reflector (R) and the boundary of acoustic turbidity (AT).

(bubble phase); however, the velocity decrease would be more pronounced if free gas were present. On the other hand, some of the high-resolution seismic profiles in the surveyed areas (Figs. 2 and 4) contain the low-frequency, high-amplitude ("bright spot" of Judd and Hovland (1992)) reflections (Hovland, 1998, pers. comm.). These

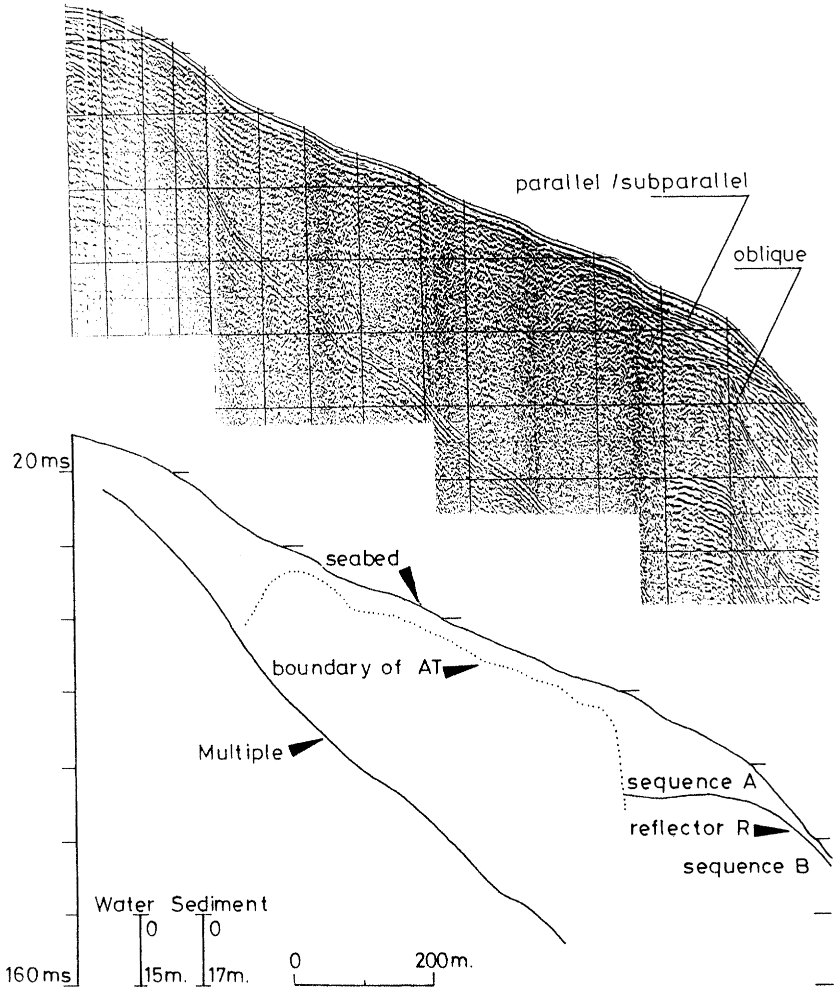

Fig. 6. High-resolution seismic reflection profile from area E (for location see Fig. 1) showing the two main sedimentary sequences separated by a reflector (R) and the boundary of acoustic turbidity (AT).

reflections are also indicative of gas-charged sediments (Judd and Hovland, 1992). It is stated that the bright spots are usually associated with porous (silt and sand-rich) sediments, while acoustic turbidity mostly occurs in finely disseminated (clay-rich) impervious sediments (Judd and Hovland, 1992).

According to Jones et al. (1986), typical gases found in marine sediments may include hydrogen, carbon dioxide, nitrogen, ammonia, hydrogen sulphide, methane and heavier hydrocarbons. These gases can originate from either bacterial activity (biogenic) in shallow sediments or thermogenic processes occurring at greater depths (>1000 m) and higher temperatures within sedimentary rock (Floodgate and Judd,

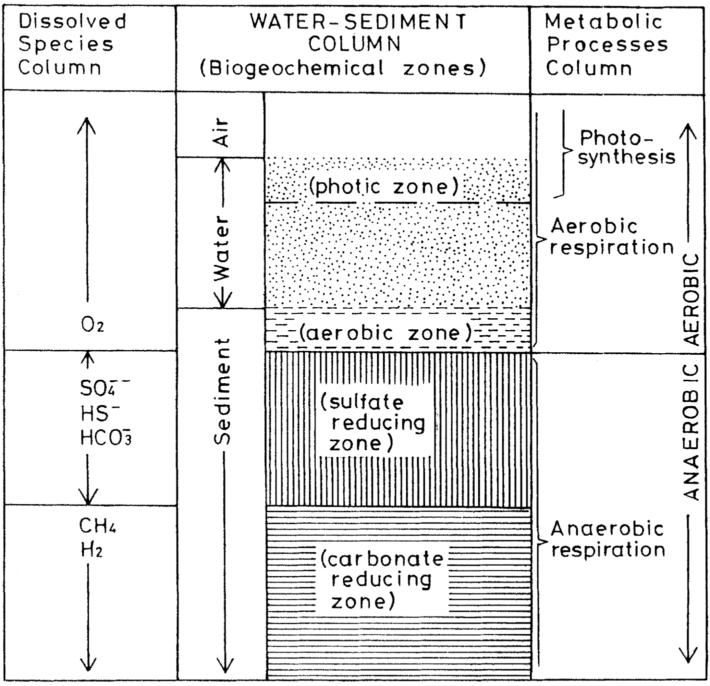

Fig. 7. Diagrammatic cross section showing the microbial ecosystems that lead to methane generation (modified from Rice and Claypool, 1981).

1992). However, of these gases the only one to be found in considerable quantity is methane (Davis, 1992; Floodgate and Judd, 1992).

Geochemical studies on core samples from the Black Sea have shown the gases in sediments to be mainly methane of biogenic origin (Hunt, 1974; Hunt and Whelan, 1978). Moreover, the shelf and slope sediments of the Black Sea have been regarded as a source of methane by Reeburgh et al. (1991). Therefore, the source of the zone of anomalous reflections "acoustic turbidity (AT)" on seismic records has tentatively been interpreted as biogenic methane gases. Additionally, the acoustic turbidity seen on the seismic profiles in this study (Figs. 2–6) is commonly found at water depths greater than 35 m. This may imply that the sediments rich in organic matter, which lead to methane formation, are generally deposited in the deeper (>35 m) parts of the southeastern Black Sea shelf. According to Shimkus and Trimonis (1974), sediment distributions in the Black Sea are controlled by the shelf dynamics (waves, currents and topography) and sedimentation processes (sediment type and sedimentation rate).

Rice and Claypool (1981) point out that the biogenic gas in marine sediments is produced by immature organic matter. They also indicate three distinct zones (aerobic zone, anaerobic sulfate-reducing zone and carbonate-reducing or methane-production zones) at different depths in marine sediments during the immature stage (Fig. 7). The transitions between these zones are a geochemical consequence of environmental changes induced by microorganisms. The aerobic zone in marine sediments is usually about 0.2–0.5 m thick (Hovland and Judd, 1988; Premchitt et al., 1992). During aerobic respiration oxygen is rapidly used up in this zone. After oxygen has been consumed, sulfate reduction becomes the dominant form of respiration. Below the sulfate-reduction zone, CO_2 reduction (via hydrogen produced by anaerobic oxidation of organic matter) results in methane formation. Thus, the conclusion from this discussion is that in areas where the boundary of acoustic turbidity is observed as a semi-parallel reflector to the seabed, on the seismic sections in southeastern Black Sea (Figs. 2–6) it corresponds to the boundary between a sulfate-reducing zone and an underlying carbonate-reducing zone (e.g. Siddiquie et al., 1981).

On the other hand, the Holocene deposits around the eastern Black Sea have total organic carbon (TOC) values in the range from 0.69 to 3.09 (Ergin et al., 1996) and this appears to be another significant factor leading to gas formation since biogenic gas occurrences have indeed been found in older deposits with TOC $> 0.5\%$ (Rice and Claypool, 1981).

4. Conclusions

High-resolution sub-bottom profiles acquired on the shelf off Trabzon (south-eastern Black Sea) have revealed the existence of acoustic turbidity which is caused by enhanced gas content in the Holocene sediments (sequence A). Seismic and previous geochemical evidence seems to indicate that the gas in the shelf off Trabzon is mainly methane of biogenic origin. No gas seepages have been observed in the seismically surveyed areas.

At the near-shore sections of seismic profiles, the areas of acoustic turbidity approximately start at water depths greater than 35 m. This indicates that the organic matter, forming methane gases, is mostly deposited in the deeper (<35 m) parts of the shelf off Trabzon. This depositional mechanism is related to the shelf dynamics and the sedimentation processes, prevailing in the southeastern Black Sea shelf.

In this study, the boundary of the acoustic turbidity on the seismic records is interpreted as the boundary between the sulfate-reducing and the underlying methane horizon. This conclusion is based on published hypotheses (Rice and Claypool, 1981) on the generation and seismic signatures (e.g. Siddiquie et al., 1981) of shallow gas bearing marine sediments.

The bright spot anomalies observed on the seismic records also imply the presence of gases within the Holocene sediments (sequence A). According to Judd and Hovland (1992), the bright spot anomalies mostly appear within the porous sediments, while acoustic turbidity is usually seen in the impervious sediments. This may indicate that the Holocene sediments in the shelf off Trabzon have different characters in terms of their contents and grain sizes.

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