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Acoustic investigations of mud volcanoes in the Sorokin Trough, Black Sea

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Abstract The Sorokin Trough (Black Sea) is characterized by diapiric structures formed in a compressional tectonic regime that facilitate fluid migration to the seafloor. We present acoustic data in order to image details of mud volcanoes associated with the diapirs. Three types of mud volcanoes were distinguished: cone-shaped, flat-topped, and collapsed structures. All mud volcanoes, except for the Kazakov mud volcano, are located above shallow mud diapirs and diapiric ridges. Beyond the known near-surface occurrence of gas hydrates, bottom simulating reflectors are not seen on our seismic records, but pronounced lateral amplitude variations and bright spots may indicate the presence of gas hydrates and free gas.

Introduction

Mud volcanoes are found all over the world in different tectonic settings in the submarine and subaerial environment. They have been studied intensively for many years because they are related to the occurrence of hydrocarbons and fluid discharge (mainly methane and CO_2), which is possibly an important component of global cycles (e.g., Higgins and Saunders 1974; Rakhmanov 1987; Milkov 2000; Kopf 2002). Kopf (2002) shows in a recent synopsis that mud volcanoes are mainly found in compressional tectonic systems. They vary in size and geometry and show a great diversity regarding the origin of the fluid and solid phases. The region with by far the most mud extrusions known to date is the Tethyan Belt extending from the Mediterranean Sea to the Makran coast, the Black Sea being part of this belt.

Most recent studies of mud volcanoes in the Black Sea concentrate on the central part of the Black Sea. Nine large mud volcanoes were identified west of the Crimea fault (Ivanov et al. 1996; Limonov et al. 1997; Gaynanov et al. 1998). The Sorokin Trough is the second main area with abundant mud volcanoes (Ginsburg et al. 1990; Soloviev and Ginsburg 1994; Woodside et al. 1997). Gas hydrates, bacterial mats, and authigenic carbonate crusts have been collected from the flanks of some of these mud volcanoes (Bouriak and Akhemtjanov 1998; Ivanov et al. 1998). Other areas with mud volcanoes in the Black Sea include the coast off Bulgaria, Russia, and Georgia. Abundant subaerial mud volcanoes are found along the coast of the Crimea Peninsula, especially at its southeastern end, the Kerch Peninsula (e.g., Akhmetjanov et al. 1996). We present newly collected seismic, sediment echo-sounder, and side-scan sonar data, which image the mud diapirs and mud volcanoes in the Sorokin Trough in great detail.

Geological setting

The geology of the Black Sea has been studied for many years (e.g., Ross et al. 1974; Finetti 1988; Okay et al. 1994). The Black Sea is generally considered to be a result of back-arc extension associated with northward subduction of the African and Arabian plates. Although this basin is primarily of extensional origin, most of the Black Sea margins are characterized by compressive deformation.

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The Sorokin Trough (Figs. 1 and 2) is located along the southeastern margin of the Crimean Peninsula and is bordered by the Cretaceous–Eocene Shatsky Ridge and Tetyaev Rise in the southeast. The trough is one of the large depressions in the deep part of the Black Sea; it has a length of 150 km and a width of 45–50 km (Tugolesov et al. 1985). Furthermore, the Sorokin Trough is considered to be a foredeep of the Crimean mountains; its formation started in the Oligocene. The inner structure of the Sorokin Trough was produced by lateral compression in a SE–NW direction, created by movement of the Shatsky Ridge and Tatyaev Rise. Overpressured fluids created some specific features of the inner structure, such as mud volcanoes.

Recent geophysical studies in the Sorokin Trough were carried out during the Training-Through-Research-Cruises (TTR) 6 and 11. Seismic profiling allowed to distinguish two main units in the sedimentary cover (Woodside et al. 1997): the lower unit is likely to represent the Maikopian series (Oligocene–Lower Miocene) as well as Pliocene deposits and is intensively folded and disturbed by numerous faults, which can also be traced into the upper unit (Limonov et al. 1997). The Quaternary deposits, representing the upper unit, are characterized by subparallel bedding and form a blanket covering the lower unit.

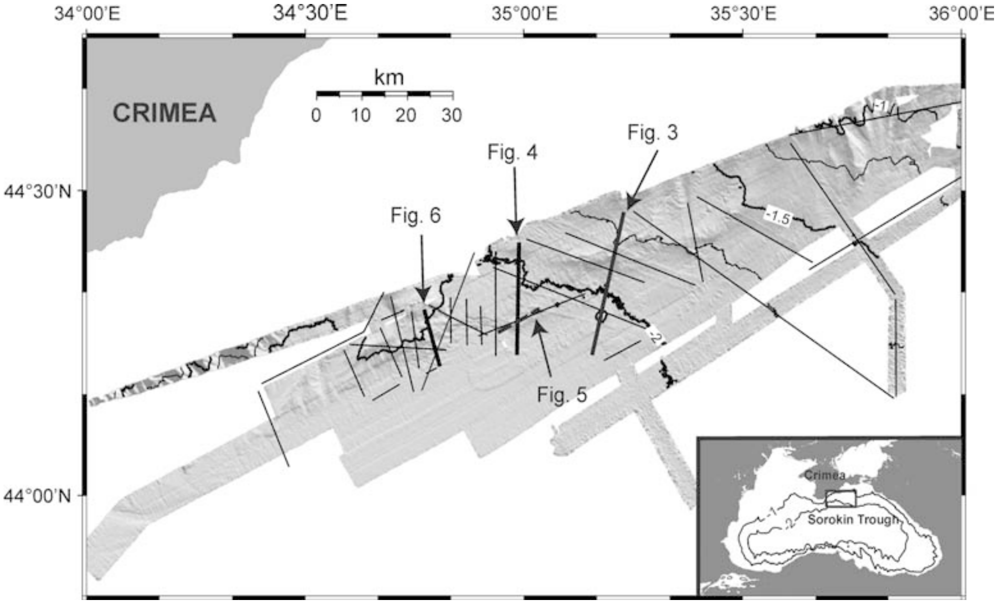


Fig 1 Shaded bathymetric map of the Sorokin Trough. The plot is shaded by artificial illumination from NNE. Contour interval is 0.25 km. The *continuous lines* are seismic profiles collected during Meteor cruise M52/1 (*thick lines* are shown for this study). The *dashed line* is the location of the side-scan image of Fig. 5

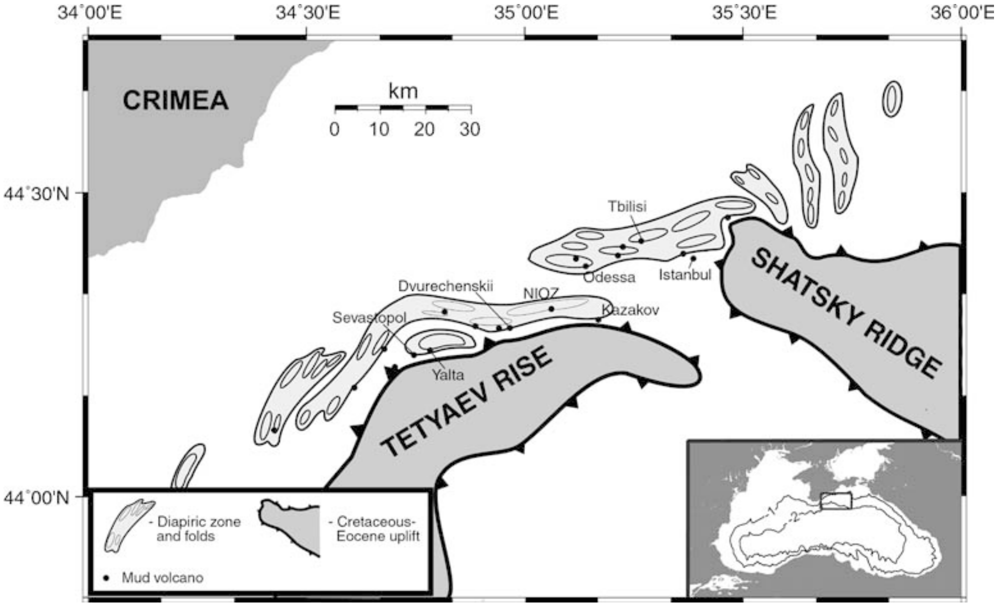


Fig. 2 Location of mud volcanoes and diapric zones/folds in the Sorokin Trough (modified after Woodside et al. 1997)

Materials and methods

The acoustic data used in this study were collected during cruise TTR-6 aboard the RV Gelendzhik in summer 1996 (Woodside et al. 1997), and Meteor cruise M52/1 in early 2002 (Bohrmann and Schenck 2002). Deep-towed MAK-1 high-resolution side-scan sonar images were collected in the Sorokin Trough during the TTR-6 cruise. The records of MAK-1 are collected with a frequency of 30 kHz in a medium-range mode with a swath range of 2 km, and at 100-kHz frequency in a high-resolution mode with a swath range of 500 m. The MAK-1 system is also equipped with a subbottom profiler operating at frequencies of 5.5–6.0 kHz. High-resolution seismic data were collected during Meteor cruise M52/1. A GI-Gun with a 0.4-l chamber (100–800 Hz) and a Sodera water gun (200–1,600 Hz) were used in an alternating mode along all seismic lines. The data were recorded by means of a 600-m-long Syntron streamer equipped with separately programmable hydrophone subgroups. Forty-eight groups of 6.25-m length at a group distance of 12.5 m were used for the GI-Gun, while ~2.5-m-long groups were used for recording the water-gun signal. Remotely controlled birds kept the streamer depth within a range of 1 m, and magnetic compass readings allowed determination of the position of each streamer group relative to the ship's course. The seismic data were stacked at a CMP-distance of 10 m and time migrated. Digital sediment echosounder data were acquired with Parasound/ParaDigMa at 4 kHz simultaneously to the seismic surveys. Bathymetric data were obtained with a Simrad EM-12 multibeam system during the TTR-6 cruise, while the Krupp Atlas Hydrosweep system was used onboard of R/V Meteor. GPS was used for navigation. Thirty-three seismic profiles were recorded in the survey area. The locations of the profiles are shown in Fig. 1, together with the recorded bathymetry.

Results

Types of mud volcanoes

Numerous mud volcanoes were identified on the bathymetric map and the seismic profiles. A map with the locations of all mud volcanoes is shown in Fig. 2. A detailed description of some of the identified mud volcanoes is given below.

Seismic line GeoB 02-003 (Fig. 3) shows typical features identified in the study area. Three mud volcanoes were imaged on this seismic line. The large structure at the southwestern end is the Kazakov mud volcano, which

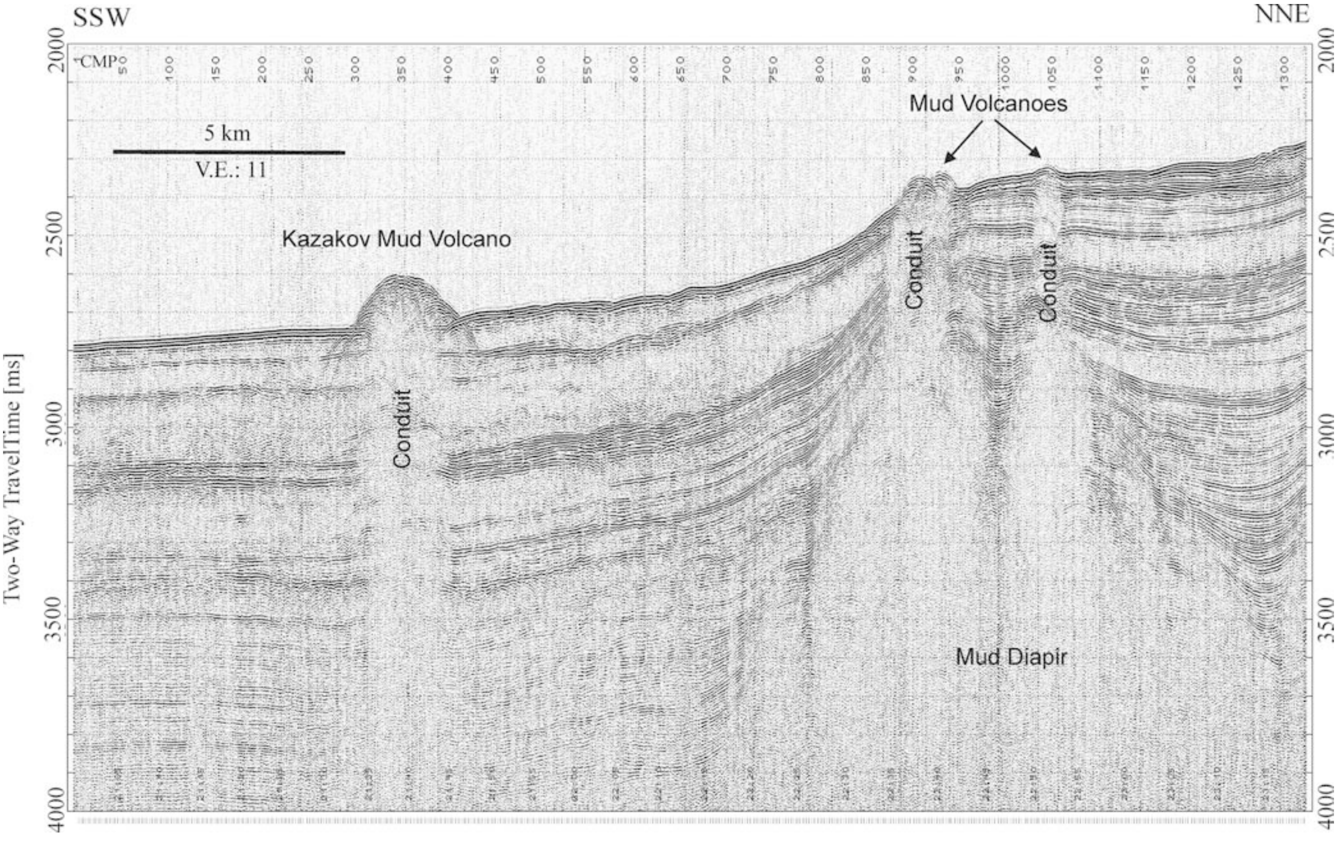


Fig. 3 CMP stack of seismic profile GeoB 02-003. The Kazakov mud volcano, with a diameter of 2.5 km and a height of 120 m, is the largest mud volcano in the survey area. The smaller mud volcanoes in the east, which are underlain by mud diapirs, are more typical for the study area. The location of the profile is shown in Fig. 1

is cone-shaped with a diameter of ~2.5 km and a height of ~120 m above the surrounding seafloor. The area beneath the Kazakov mud volcano is characterized by a transparent zone with a width similar to the diameter of the mud volcano, probably serving as the main feeder channel. Some short stretches of weak reflectors are imaged in the generally transparent zone, but in principle the transparent zone can be vertically traced for ~1,400 ms up to 4,000 ms two-way travel time (TWT), which is the maximum seismic penetration of the presented data. The root of this mud volcano is therefore not recognized, but it may exceed 7–9 km (Limonov et al. 1994). The upper 700 ms of the sediments around the Kazakov mud volcano are characterized by relatively thick (~100 ms) transparent units, which are separated by strong reflectors. Reflectors beneath this unit are closely spaced and show a good continuity. No major offsets of reflectors were identified across the Kazakov mud volcano, and therefore it is probably not located on a fault zone. The Kazakov mud volcano is by far the largest mud volcano in the Sorokin Trough.

Two smaller and more typical mud volcanoes are located between Common Mid-Points (CMP) 850 and 1100 on profile GeoB 02-003 (Fig. 3). They belong to a belt of mud volcanoes associated with a morphological step. Diameters range from ~1 km for the mud volcano located around CMP 900 to 500 m for the mud volcano at CMP 1050; the heights are 45 and 15 m, respectively. The feeder channels in the upper 300–400 ms TWT reveal about the same diameters as the mud volcanoes themselves. Diapirs are clearly imaged beneath each of the mud volcanoes. A narrow sedimentary basin separates the diapirs but, at a depth of about 3,300 ms TWT, the diapirs seem to be connected to a larger diapiric structure that is more than 8 km across. The flanks of the mud diapirs are onlapped by well-stratified sediments.

Another type of mud volcano is shown on profile GeoB 02-043 (Fig. 4). The flat-topped feature around CMP 550 is the Dvurechenskii mud volcano. The feeder channel and a mud diapir are clearly imaged beneath. The Dvurechenskii mud volcano is described in detail below. Two other diapirs are located on profile GeoB 02-043. Small faults and indications of fluid flow can be identified above the top of the diapir around CMP 1200, but no mud volcano is located above this diapir. The Parasound profile shows that the fault reaches to the seafloor (Fig. 4).

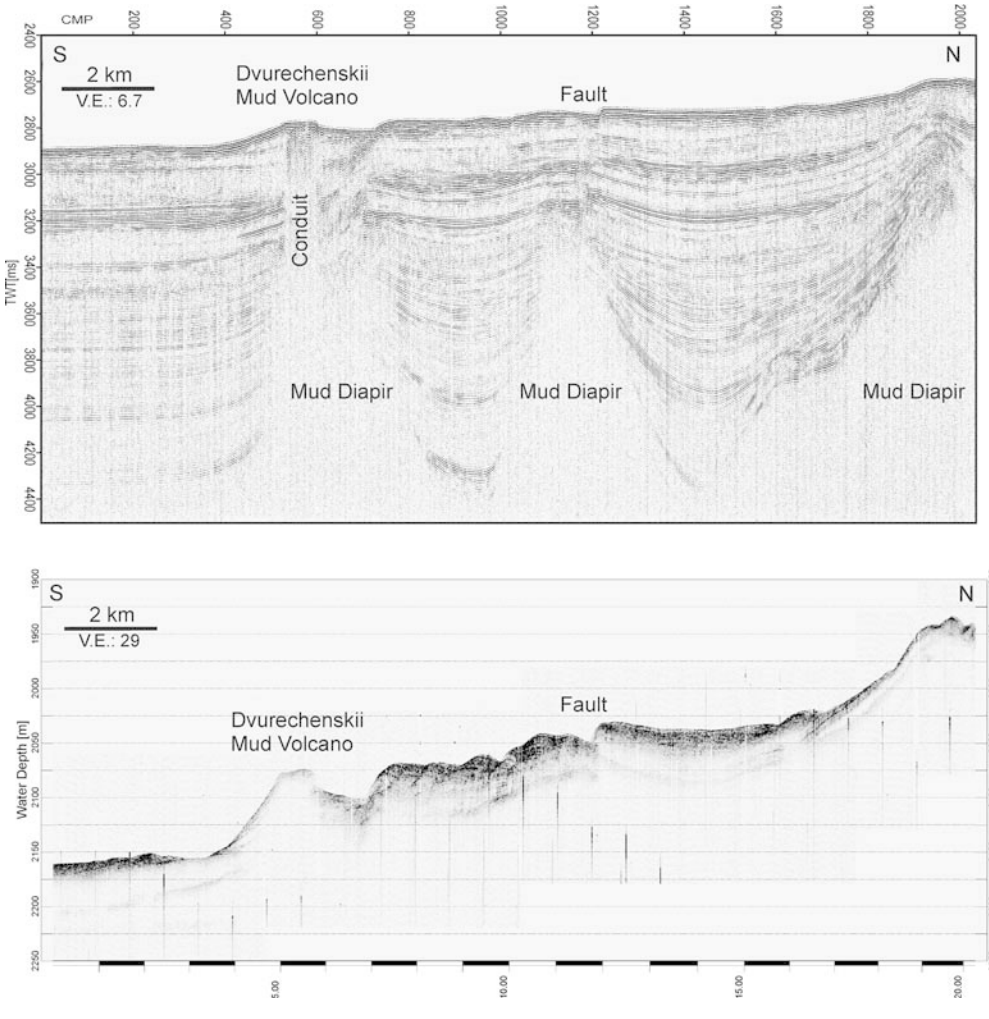


Fig. 4 *Top* Migrated seismic profile GeoB 02-043. *Bottom* Parasound image of the same profile. Note the different vertical exaggeration of the images. The location of the profile is shown in Fig. 1

Mud volcanoes and diapirs were identified in the entire survey area. Most of them are cone-shaped, and some are characterized by depressions in the seafloor (pockmarks); the Dvurechenskii mud volcano is the only flat-topped mud volcano. Mud diapirs are imaged beneath all the mud volcanoes, with exception of the Kazakov mud volcano where the base of the feeder channel is not visible on our seismic data (Fig. 3).

Previous work already mapped an elongated distribution of diapirs in the Sorokin Trough being coaxial to the strike of the trough (Tugolesov et al. 1985). The diapiric ridges are clearly imaged on our new seismic profiles. In the central survey area between 34°30′ and 35°30′E, the diapirs are orientated in W–E direction. The strike directions change toward the east and west following the flanks of the buried Tetyaev Rise and Shatsky Ridge.

Figure 2 maps the locations of the main tectonic features, mud diapirs, and mud volcanoes. The mud volcanoes are mainly located on the top or edges of the diapiric ridges. More mud volcanoes probably exist in the survey area but could not be identified, since side-scan sonar coverage is not complete and the resolution of the bathymetric systems is limited.

The Dvurechenskii mud volcano

The Dvurechenskii mud volcano (DMV) was imaged with different acoustic systems. Multichannel seismic data (Fig. 4) show the mud volcano itself and the sedimentary structure beneath it. The width of the flat top on the seismic line is ~800 m. The feeder channel is imaged as a transparent zone with a similar diameter, although some short stretches of reflectors are visible beneath the top of the mud volcano within the upper 200 ms TWT. The transparent zone can be traced down to 600 ms TWT beneath the seafloor. At this depth the transparent zone widens to almost 4 km. This is a typical dimension for mud diapirs also found in other locations in the survey area. Thick transparent units separated by bands of high-amplitude reflections characterize the upper part of the sedimentary section around the mud volcano. This pattern changes beneath 400–500 ms TWT subseafloor. Reflectors with medium amplitudes and very good continuity are characteristic for this part of the sequence. These reflectors are curved upward at the edges of the mud diapir. Although it is not possible to trace reflectors through the feeder channel of the mud volcano, characteristic reflection patterns show an offset of about ~100 ms TWT north and south of the mud volcano, indicating that the DMV is probably located on a fault zone.

The Parasound record of profile GeoB 02-043, acquired simultaneously with the seismic data (Fig. 4), shows that the seafloor reflection of the almost flat top of the DMV has a relatively low amplitude. No subbottom reflectors are visible beneath the top or the flanks. The flanks reveal varying reflection amplitudes. The slope angle of the southern flank has a relatively uniform value of 2.5° and a height of ~80 m. The northern flank is only 25 m high, but slope angles reach 5.5°. A prolonged seafloor reflector and a weak reflector some 30 m beneath the seafloor characterize most of the Parasound profile. The subbottom reflector is interrupted beneath the DMV.

The dataset showing the highest structural resolution was obtained by the deep-towed MAK-1 side-scan sonar (Fig. 5). The top of the DMV shows uniform backscatter values without any structural variability. Therefore, the top of the DMV seems to consist of relatively homogenous mud. At the center of the DMV, active seepage through centimeter- to decimeter-sized patches was observed by a video sled (Bohrmann et al. 2003, this volume), but these patches may be too small to be imaged by the side-scan sonar. The shape of the top of the DMV is oval with diameters of 1,000 and 800 m along the long and short axes, respectively. A major deviation from the general circular shape is visible at the northeastern flank. A mud flow of ~450 m length originating at this incision is imaged by higher backscatter values on the sonographs. A much smaller incision can be seen at

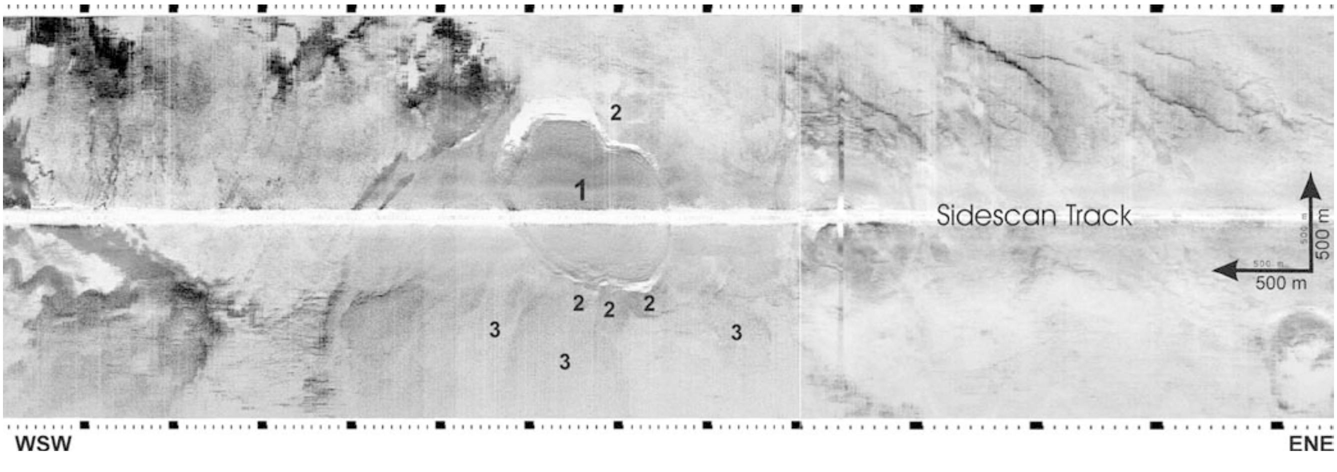


Fig. 5 Side-scan sonar image of the Dvurechenskii mud volcano. *Dark shading* are areas of high backscatter. *1* Flat top of the Dvurechenskii mud volcano, *2* young, small mud flows, *3* larger, older mud flows. The location of the image is shown in Fig. 1

the southern flank, where another small mud flow occurs. Larger, but probably older mud flows were identified south and west of the DMV (Fig. 5).

Discussion

Distribution, origin, and types of mud volcanoes

Abundant mud volcanoes of various morphology and size are present in the Sorokin Trough. The largest mud volcano is the Kazakov mud volcano (~2.5 km diameter) but this feature seems to be unique because it is the only mud volcano for which no underlying mud diapir was imaged on our seismic data, although a diapir may exist at greater depth. This is supported by Milkov (2000) who indicates that most mud volcanoes are associated with diapirs. In terms of size and depth of the feeder channel, the Kazakov mud volcano is comparable to the mud volcanoes in the central Black Sea (Ivanov et al. 1996; Limonov et al. 1997; Gaynanov et al. 1998).

Typical mud volcanoes in the Sorokin Trough are up to 1 km in diameter and up to ~100 m high. Three morphological shapes can be distinguished: cone-shaped, flat-topped, and collapsed structures. Most of the mud volcanoes are cone shaped, some show depressions and only one mud volcano has a flat top, the DMV.

The morphology of mud volcanoes generally reflects their evolution (e.g., Limonov et al. 1997). Key factors for the evolution of mud volcanoes and the resulting morphology are the viscosity and permeability of the mud, the latter being the primary control over the fluid flow (Brown 1990; Kopf et al. 1998; Kutas et al. 2002). Low permeability can seal the conduit, which leads to the buildup of excess pore fluid pressure and usually results in violent eruptions. These eruptions often form pockmarks, while medium flow velocities result in mud pies or cones with low slope angles. High-permeability mud leads to more effusive eruptions forming domes with relatively steep slopes ($>5°$). These different types of eruptions result in the various morphologies of the mud volcanoes in the Sorokin Trough. The large number of cone-shaped mud volcanoes indicates a relatively quiet evolution. Geological and geochemical investigations at the DMV show a seepage area with high flux rates (Bohrmann et al. 2003, this volume). This interpretation is well supported by the acoustic data. We interpret the flat top of the DMV that shows no relief and a low reflectivity as consisting of a very fluid mud of low viscosity. Eruptive activity leads to mud flows, which usually occur at incisions of the flanks. Pockmarks indicating high fluid flow velocities were mainly found in the western survey area. In this area bright spots were recognized that may be related to gas hydrate occurrences. A possible relationship between pockmarks, bright spots, and gas hydrates is discussed below.

All mud volcanoes in the Sorokin Trough, except for the Kazakov mud volcano, are located above shallow (<500 m beneath the seafloor) mud diapirs or diapiric ridges. These mud diapirs consist of Maikopian clay and are the result of a compressional tectonic regime between the Tetyaev Rise and Shatsky Ridge in the south and the Crimean Peninsula in the north (Fig. 2). Faults are often located above the diapirs, possibly acting as pathways for fluids. Mud volcanoes may form as result of this focused fluid flow above or on the edges of the diapirs. We also, however, observe fault zones reaching to the seafloor, but no mud volcano is found in their vicinity (Fig. 4). Preexisting faults above a diapir may be necessary for the formation of mud volcanoes, but the reasons for the formation of mud volcanoes at particular locations remain unclear. We are also not able to link the different mud volcano morphologies to subsurface structures. The DMV seems to be very active compared to most other mud volcanoes in the Sorokin Trough (Bohrmann et al. 2003, this volume), but the size of the conduit as well as the depth and dimensions of the underlying mud diapir are comparable to other mud volcanoes in the Sorokin Trough. One difference may be the relatively large offset (~75 m) between reflectors north and south of the DMV. Hence, a large fault zone, which is a potential pathway for fluids, is probably located beneath the DMV, resulting in high fluxes.

We interpreted the transparent zones beneath the mud volcanoes as feeder channels with a diameter similar to the size of the mud volcanoes themselves (see above), but theoretical considerations (Kopf and Behrmann 2000) for Mediterranean Ridge mud volcanoes indicate conduit diameters of 2–3 m. These observations correspond with surface observations at other locations (e.g., Stamatakis et al. 1987). Diameters of several hundreds of meters would result in astronomic flow rates, even if only small density contrasts exist as driving force (Kopf 2002). Therefore, the conduits must be smaller, at least near to the seafloor. A closer look at the seismic section of the DMV (Fig. 4) reveals short stretches of reflectors beneath its top. Hence, the transparent zone may consist of a number of much smaller conduits, which cannot be resolved by the seismic and the Parasound system. The diameter of the transparent zone would then correspond to an area riddled with small conduits, although not all conduits have to be active.

Sedimentary basins are typically located next to the mud diapirs (Figs. 3 and 4). While uplift was associated with the growth of the mud diapirs, subsidence may have occurred nearby, leading to the formation of the sedimentary basins. Such mechanisms are very comparable to salt diapirism.

Indications for gas hydrate occurrences in the seismic data

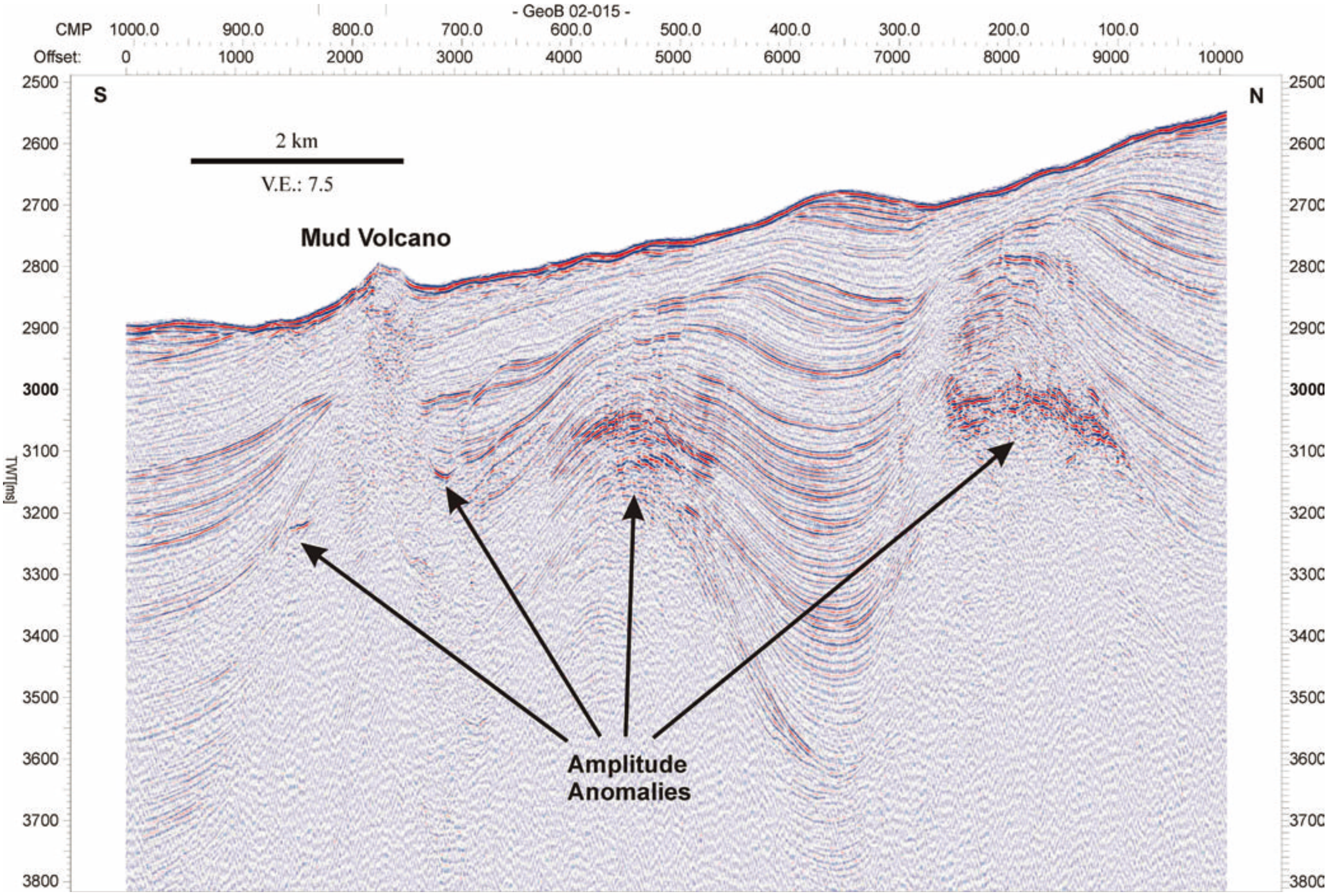
Gas hydrates in marine sediments of the Black Sea were already found 30 years ago (Yefremova and Zhizhchenko 1974). Since then, near-surface gas hydrates were discovered at various locations in the Black Sea, including the Sorokin Trough (Soloviev and Ginsburg 1994; Ivanov et al. 1998). Gas hydrates in the Sorokin Trough were sampled during Meteor cruise M52/1 from several mud volcanoes, for example, the Dvurechenskii, Yalta, and Odessa mud volcano as well as from an unnamed mud volcano (Bohrmann et al. 2003, this volume).

Bottom simulating reflectors (BSRs) in seismic records are often used to identify gas hydrates in sediments by means of acoustic measurements. A BSR is a reflector with a negative reflection coefficient usually occurring at the base of the gas hydrate stability zone (e.g., Dillon and Paull 1983), but in some cases no BSR is found on seismic sections, despite gas hydrates being present in the sediments (Paull et al. 1996).

BSRs are essentially absent in the Sorokin Trough. Despite the known near-surface occurrence of gas hydrates, bottom simulating reflectors have not been identified on any seismic line in the Sorokin Trough to date, but pronounced lateral amplitude variations and bright spots have been found, especially in the western survey area (Fig. 6). These amplitude anomalies are probably caused by free gas in the sediments. The amplitude anomalies are located either in the cores of anticlinal structures or at the updip terminations of strata with diapirs. These are the locations where the trapping of gas would occur if a seal exists. It is interesting to note that the amplitude anomalies occur at a relatively constant depth of ~300 ms TWT (~250 m) beneath the seafloor. We speculate that the top of these amplitude anomalies represents the base of the gas hydrate stability zone and that gas hydrates, acting as seal, are present above.

Heat flow measurements show that the base of the gas hydrate stability zone can be expected at a depth of ~400 m beneath the seafloor (Bohrmann et al. 2003, this volume). The amplitude anomalies seem to be somewhat shallower, but sediments above the anomalies are certainly in the gas hydrate stability zone. Several small faults are imaged above the amplitude anomalies, which may act as flow paths. They may allow a sufficient amount of gas to migrate into the gas hydrate stability zone and to form gas hydrate under the presence of water. It seems that the base of the gas hydrate zone is shallower than predicted from the surface heat flow measurements. The heat flow measurements, however, are sparse and more detailed measurements may result in a shallower depth for the base of the gas hydrate stability zone. Some pockmarks were identified in the area of the amplitude anomalies. If gas hydrates are present in this zone, they may occasionally seal the conduits (Reed et al. 1990; Bouriak et al. 2000), which can result in violent eruptions and the formation of pockmarks.

Fig. 6 Migrated seismic profile GeoB 02-015. Amplitude anomalies occur in the approximate depth of the base of the gas hydrate stability zone



Conclusions

We studied numerous mud volcanoes in the Sorokin Trough with seismo-acoustic methods. The use of different seismic and acoustic systems allows us to image the structure as well as the morphology of the mud volcanoes and their roots in great detail.

1. A variety of mud volcanoes were identified in the Sorokin Trough. Most are cone-shaped, some are collapsed, and one mud volcano, the Dvurechenskii mud volcano, has a flat top.
2. All mud volcanoes, except for the Kazakov mud volcano, are located above shallow mud diapirs or diapiric ridges. The tops of the diapirs are located ~400 m beneath the seafloor. Faults are often located above the diapirs and act as preferred pathways for fluids.
3. Transparent zones identified on seismic records reach from the diapirs to the mud volcanoes. They have approximately the same diameter as the mud volcano itself. The transparent zones probably consist of a number of small conduits (<10 m), which cannot be resolved by the seismic and the Parasound system.
4. The Dvurechenskii mud volcano reveals recent activity through several young mud flows imaged on the side-scan sonographs.
5. Despite the known near-surface occurrences of gas hydrates, bottom simulating reflectors were not recognized on our multichannel seismic data, but bright spots—indicating free gas—were identified in the approximate depth of the base of the gas hydrate stability zone. We speculate that gas hydrates are present above these zones.

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