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Mud volcanoes and gas hydrates in Anaximander Mountains (Eastern Mediterranean)

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ABSTRACT

Detailed multibeam, sedimentological, and geophysical surveys within the framework of the EU Project 'ANAXIMANDER' provided ample new data to confirm that the E. Mediterranean (Anaximander Mountains) is an important site for active mud volcanism and gas hydrate formation. More than 3000 km of multibeam track length was acquired during the two missions and 80 gravity and box cores were recovered. Major outputs: 1) Detailed bathymetry/morphology and backscatter data of the greater area compared to previous surveys; 2) Very detailed morphology of the known targeted mud volcanoes (Amsterdam, Kazan and Kula) especially the Amsterdam "crater" and the related mud breccia flows; 3) Gas hydrates were collected repetitively from a larger area of Amsterdam mud volcano at a subbottom depth of around 0.3-1.5 m; 4) Gas hydrates were sampled for the first time at Kazan MV; 5) New mud volcanoes were identified on the basis of multibeam backscatter intensity. They were sampled, documented as active and named ***"Athina"*** and ***"Thessaloniki"***. Gas hydrates were sampled also in Thessaloniki MV, the shallowest (1264 m) among all the active Mediterranean sites, at the boundary of the gas hydrate stability zone.

INTRODUCTION

Since the initial discovery of mud volcanoes in the eastern Mediterranean during the late 1970s (Cita *et al.,* 1981), mud volcanoes, mud diapirism and fluid seeps have been found in a number of different environments in the area. Most have been found on the accretionary prism of the Hellenic Arc (Mediterranean Ridge) and within the Anaximander Mountains (Woodside *et al.,* 1998); but they have also been found from offshore Sicily (Holland *et al.,* 2003) to the Nile Deep Sea Fan (Loncke, 2002; Loncke *et al.*, 2004), as well as along the Florence Rise (Zitter *et al.,* 2003) and in SE Aegean sea (Perissoratis *et al.,* 1998). International interest resulted in ODP

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drilling on the Napoli and Milano mud volcanoes in the Olimpi Field on the central Mediterranean Ridge in 1995 (Cita *et al.,* 1996; Robertson *et al.,* 1996a; Robertson and Kopf, 1998). To some degree the increased interest was fuelled by the inferred presence of gas hydrates based on chlorinity decrease and $\delta^{18}O$ increase in pore waters from Milano Mud Volcano (de Lange and Brumsack, 1998), whereas only a recent isotopic study showed that the fresher pore water originates from clay mineral diagenesis rather than gas hydrate dissociation (Dählmann and de Lange, 2003). However, gas hydrates were sampled in 1996 at Kula Mud Volcano in the Anaximander Mountains (Woodside *et al*., 1997, 1998). The discovery of mud volcanoes in the Anaximander Mountains was a result of a multibeam survey conducted as part of the Dutch ANAXIPROBE project in 1995 and from a follow-up survey in 1996 with seafloor sampling and deep-tow side scan imagery (Woodside *et al*., 1997, 1998).

Following these investigations the latest European effort regarding the gas hydrate research in the Eastern Mediterranean was the EU funded project 'ANAXIMANDER' (EVK3-2001-0001233000) .

The Anaximander Mountains comprise a group of three main seamounts located between the Cyprus and Hellenic arcs (Figure 1). They are currently undergoing a neotectonic deformation characterized by strike slip faulting (Zitter *et al*., 2003; Ten Veen *et al*., 2004) between the westerly moving Anatolian Plate and the African Plate (McClusky *et al*., 2000). The Anaximander Mountains are described as large faulted and tilted blocks that originally were geologically continuous with south-western Turkey.

The mud volcanoes of Anaximander Mountains were unexpectedly discovered in 1995 during a detailed multibeam bathymetric survey with the swath system Simrad EM-12 of the French research vessel *L'Atalante* in the framework of the Dutch ANAXIPROBE project. In 1996, the combined expedition of the ANAXIPROBE project and the International Training Through Research programme (TTR-6), aboard the Russian research vessel R/V *Gelendzhik*, used the MAK-1 deep-tow side scan sonar, sub-bottom profiling and detailed dredging and sampling, to verify the presence of the mud volcanoes, and sampled the first gas hydrates in the Mediterranean, from the Kula Mud Volcano (Woodside *et al*., 1997, 1998). Furthermore in 1998, the MEDINAUT programme using the submersible Nautile, deployed by the French research ship *Nadir*, performed a closer examination and took site-specific samples (MEDINAUT/ MEDINETH Shipboard Scientific Parties, 2000; Olu *et al*., 2004; Charlou *et al*., 2003). In 1999, cruises with the Russian R/V *Professor Logachev*, investigated mud volcanism through high-resolution side-scan sonar (O.R.E. Tech), sediment core recovering and specific measurements of

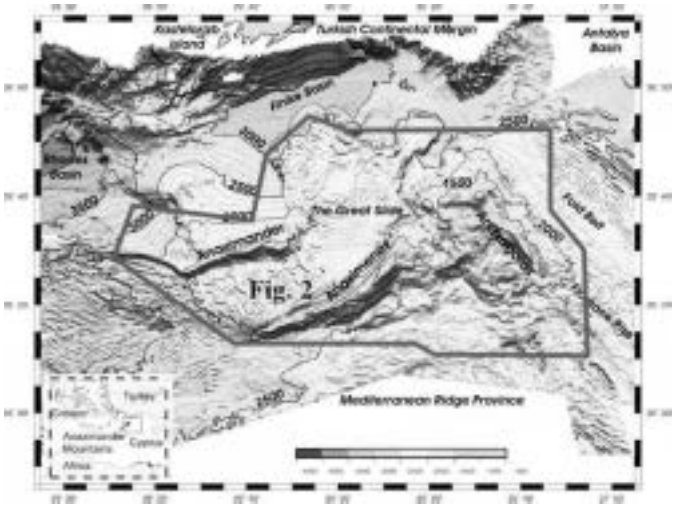


Fig. 1. Bathymetric map and major morphological features of the Anaximander Mountains and the surrounding basins acquired during the 1995 multibeam survey by R/V *L'Atalante* (Woodside *et al.,* 1997, 1998). The area enclosed by the frame was surveyed in detail by multibeam of R/V *Aegeo* during the Anaximander cruises.

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methane in the water column above the mud volcanoes (MEDINAUT/ MEDINETH and SMILABLE Shipboard Scientific Parties, 2000). Several mound-like features, expressed as high reflectivity patches on EM-12D backscatter intensity maps, were examined, but only seven were proven by sampling to be mud volcanoes at that time; and two of them were identified as bearing gas hydrates – the Amsterdam and Kula mud volcanoes. Gas hydrates, first sampled from Kula mud volcano during the 1996 ANAXIPROBE/TTR-6, were sampled again at Kula during the 1999 MEDINAUT/MEDINETH expedition as well as at Amsterdam mud volcano.

DATA AND METHODS

The data presented in this study were acquired during the two cruises of the ANAXIMANDER project in the Anaximander Mountains, in May 2003 (Lykousis *et al.,* 2003) and October-November 2004.

The seafloor bathymetry/backscatter survey was carried out using a SEABEAM 2120 swath system installed on the Greek research vessel *Aegaeo* of the Hellenic Centre for Marine Research. The high resolution seismic profiling system used during the first expedition,was an analog recorder $10in^3$ air gun system (PAR BOLT US). Digital data acquired, using a Delph (Triton Ellics) system.

In both expeditions, a total of 64 sediment gravity cores and 17 box-cores were recovered at "targeted" sites, selected primarily on the assessment of their backscattering intensity map.

RESULTS AND DISCUSSION

Amsterdam mud volcano

The Amsterdam mud volcano, the most prominent mud volcano in the Anaximander Mountains, is located on the southern flanks of the Anaximenes Mountain (Figure 2). It appears as a flat-topped circular-shaped mound, extending over an area of about 6 km^2, at a water depth on its summit of 2025 m. At the periphery of the mound, a ring-shaped sea-floor depression is formed, creating a relatively deep (50 m) moat northwards. Detailed morphological analysis of the Amsterdam MV indicated that there are two discrete craters the "external" and the "internal" that merge to the southeast. Both are sub circular with dimensions of 6 x 5 km and 4 x 3.3 km respectively, slightly elongated in an N-S direction. One common morphological feature is that the craters are open in the southernmost part and directly connected to the slope with a 400 m wide canyon extending down to a depth if 2250 m.

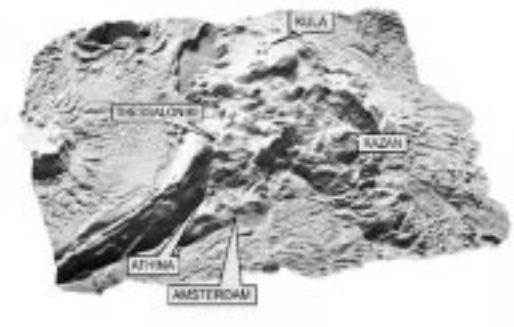


Fig. 2. Multibeam 3-D map of the Anaximander region indicating the three known (Amsterdam, Kazan, Kula) and the two newly discovered (Athina, Thessaloniki) mud volcanoes. For regional location see Figure 1.

Sediment containing gas hydrates has been sampled since 1999 at two sites, during the MEDINETH and SMILABLE cruises with R/V *Professor Logachev* and during the two cruises of R/V *Aegaeo*. During the later, seven cores containing gas hydrates from five new sites were recovered from Amsterdam MV (Figure 3).

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Fig. 3. Gas hydrate lump (8 X 5 X 4 cm) (center) and broken in pieces (lower) recovered from one of the cores from Amsterdam mud volcano. Successive measurements upon recovery of sediment cores bearing gas hydrates provided minimum temperatures around 3-4 º C.

Kazan mud volcano

Kazan is an isolated hill with a hight of 50 m, lying on the edge of a relatively flat plateau of 1750 m average depth (Figure 2). The plateau lies on the southern flanks of the Eastern Anaximander Mountains, and eastwards from a major NW-SE trending fault zone separating Anaximenes from Anaxagoras SMs. It is an oval 0.6 x 0.9 km dome aligned in a N-S direction.

Gas hydrates were recovered for the first time at Kazan MV during the first cruise. Overall, during both missions, gas hydrates were sampled in 6 gravity and one box corers from four different sites on the summit. The gas hydrate crystals appeared as small rice-like lumps and were rather regularly dispersed throughout the sediment matrix deeper than about 0.3 m of core depth.

Kula mud volcano

The Kula and San Remo mud volcano cluster lies on a small triangular plateau bounded to the east and south by seamounts at the northern tip of the Anaxagoras SM range. Four mound-type edifices have been defined on the bathymetry map (Figure 2). The eastern one, closer to the Anaxagoras slope, is an irregular feature with a summit depth of 1650 m which continues northeastwards as a low elevation ridge. West of it, Kula MV is a larger circular dome-shaped mount, with a diameter of 1 km and a height of 100 m (Woodside *et al.,* 1998). Northwestwards, a cone-shaped mound of 50 m height and about 1 km in diameter corresponds to the San Remo mud volcano (Woodside *et al.,* 1997).

The sediment cores recovered from the summit of the Kula mud volcano show mud breccia to be exposed at the sea bottom only at the very top of the mud volcano.

Athina mud volcano

The newly discovered Athina MV (Lykousis *et al.,* 2004) is located at the south-eastern slope of the Anaximenes SM. The whole topography is rather complicated with steep slopes, two isolated deep basins and two mound-like topographic features along the top of the rise that separates the two basins. Both mounds display at least two distinct summits at water depths of about 1800 m, with a relative height of 10-100 m. Four sediment cores were recovered from both summits of the northward-located mound. Typical mud breccia from gravity cores on the south-western and the north-eastern summit confirmed mud volcanism and active methane seepage (Lykousis *et al.*, 2004). The core from the south-western summit (water depth 1798 m) recovered 1 m of mud breccia with a greyish matrix supporting angular-sub angular clasts of mudstone The soupy structure with high amounts of water that appeared locally in the middle of the core may be indicative of hydrate dissociation (Lykousis *et al.*, 2004). The core taken from the water depth of 1783 m consisted mostly of fragments of authigenic carbonate crust, bivalves (*Lucinoma kazani)*, and worm tubes characteristic of active venting sites (Salas and Woodside, 2002).

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Thessaloniki mud volcano

North-eastwards of Athina MV, at a distance of 9 km along the south-eastern slope of the Anaximenes Mountain, and at a depth of 1260 m, a small circular dome with a radius of 1.5 km, defines the Thessaloniki mud volcano. Four sediment cores were recovered from the Thessaloniki MV, all with textures of active mud volcanism (mud breccia, gas hydrate, dissociation features, etc.). From two of the sediment cores gas hydrates were collected identifying Thessaloniki as the fourth mud volcano bearing gas hydrates in the Mediterranean. Small gas hydrate lumps or flakes were dispersed in the fluidised mud. This fluidised muddy structure rich in free methane and small gas hydrate crystals was not observed previously, at least among the mud volcanoes of the European margins, indicating freshly emitted mud during a very recent activity. The unexpected discovery of gas hydrates in the Thessaloniki MV is of great importance since it is a fairly shallow MV (1260 m) and it just falls near the borders of the stability/instability zone of gas hydrate stability diagram (bottom temperature 14^{o}C).

CONCLUSIONS

During the two recent research cruises of R/V *Aegaeo* in May 2003 and October-November 2004, the Anaximander Mountains were surveyed by sea-beam bathymetry and detailed seabed backscatter imagery, extensive sea bed sampling and (locally over mud volcanoes) by high resolution seismic profiling. The multibeam topography/imagery accurately delineated not only new morphological features of the greater Anaximander Mountains but also detailed morphological and acoustic characteristics of each individual mud volcano. The analysis of the seabed backscattering indicated potential new mud volcanoes that were confirmed by sediment gravity coring (Athina and Thessaloniki MVs). The Amsterdam mud volcano displays a well-developed almost flat-topped central dome while the Kazan, Kula, Thessaloniki and Athina MVs are rather mound-like conical mud volcanoes, probably indicating lower intensities of activity, and lower reactivation periods, narrower feeder channels, or extrusion of mud with higher shear strength, in comparison with Amsterdam mud volcano.

The large number of the sediment cores recovered enables the extension of the active mud volcanism, the delimitation of the gas hydrate field and the verification of new gas hydrate sites like the Kazan and Thessaloniki MVs. The Amsterdam MV is the most active mud volcano in the Anaximander Mountains in terms of volume and extent of erupted mud breccias and the extent of gas hydrate occurrence. A prominent characteristic is the southward moving mud flow that bears gas hydrates. This probably implies that a predominantly methane gas supply from deeper formations is located not only within the central active part, but also in the slope south of the Amsterdam MV. On the basis of systematic sampling it appears that gas hydrates occur mostly towards the central and north-eastern parts of the central dome of Amsterdam MV. Gas hydrates were also sampled, for first time, at Kazan and Thessaloniki MVs, while gas hydrate dissociation structures were found within the sediment cores from Kula and Athina MVs. Gas hydrates were observed and sampled at various depths within the sediment cores but were present usually deeper than 0.4 m from the seabed surface. The texture resembles compacted snow and the external morphology is like flakes, lumps (nodular aggregates), or big rice crystals (Kazan MV). Gas analyses on hydrate and sediment samples will be performed in order to draw a solid picture of the gas hydrate characteristics at the specific sites and will be published elsewhere (Dählmann *et al*., 2005).

The sediment cores from the Thessaloniki MV contained gas hydrates and implied recent activity. This is the shallowest mud volcano bearing gas hydrates in the Mediterranean (1260 m) at the edge of the stability zone determined by depth and seafloor temperature (~14^{o}C). The gas hydrates at Thessaloniki MV are thus sensitive to temperature and sea level fluctuation. Therefore this MV could be regarded as an ideal site for studies of mud volcano activity, and their environmental impact, and gas hydrate stability.

Acknowledgements

This work is a part of the EC ANAXIMANDER project (EVK-CT-2002-00068). The European Commission is acknowledged for their financial contribution to the project. The officers and the

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crew the R/V *Aegaeo* are gratefully acknowledged for their important and effective contribution to the field work and sampling. The Dutch Council for scientific research NWO is thanked for its support during Medineth and Smilable cruises.