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Mud volcanoes and gas hydrates in the Anaximander mountains (Eastern Mediterranean Sea)

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ABSTRACT

Detailed multibeam, sedimentological, and geophysical surveys provide ample new data to confirm that the Anaximander Mountains (Eastern Mediterranean) are an important area for active mud volcanism and gas hydrate formation. More than 3000 km of multibeam track length was acquired during two recent missions and 80 gravity and box cores were recovered. Morphology and backscatter data of the study area have better resolution than previous surveys, and very detailed morphology maps have been made of the known targeted mud volcanoes (Amsterdam, Kazan and Kula), especially the Amsterdam "crater" and the related mud breccia flows. Gas hydrates collected repeatedly from a large area of Amsterdam mud volcano at a sub-bottom depth of around 0.3–1.5 m resemble compacted snow and have a rather flaky form. New gas hydrate sites were found at Amsterdam mud volcano, including the mud flow sloping off to the south. Gas hydrates sampled for the first time at Kazan mud volcano are dispersed throughout the core samples deeper than 0.3 m and display a 'rice'-like appearance. Relative chronology and AMS dating of interbedded pelagic sediments (Late Holocene hemipelagic, sapropel layer S1 and ash layers) within the mud flows indicate that successive eruptions of Kula mud volcano have a periodicity of about 5–10 kyrs. New mud volcanoes identified on the basis of multibeam backscatter intensity were sampled, documented as active and named "*Athina*" and "*Thessaloniki*". Gas hydrates were sampled also in Thessaloniki mud volcano, the shallowest (1264 m) among all the active Mediterranean sites, at the boundary of the gas hydrate stability zone. Biostratigraphical analyses of mud breccia clasts indicated that the source of the subsurface sedimentary sequences consists of Late Cretaceous limestones, Paleocene siliciclastic rocks, Eocene biogenic limestones and Miocene mudstones. Rough estimations of the total capacity of the Anaximander mud volcanoes in methane gas are 2.56–6.40 km^3.

1. Introduction

Mud volcanoes (MVs) are the most important pathway for degassing of deeply buried sediments and are mainly found around subduction zones and orogenic belts where lateral tectonic compressional stress is dominant (Milkov, 2000; Kopf, 2002). Recent estimations of methane flux from shallow offshore mud volcanoes range from 0.42 to 0.96 Mt/yr, which is almost the 10% of the total global CH_4 flux from the onshore–offshore mud volcanoes (6–9 Mt/yr after Etiope and Milkov, 2004). High seafloor methane fluxes are associated with the mud volcanoes as well as with the accompanying cold vents and seeps (Charlou et al., 2003). The available gas provides energy for a rich benthic ecology, which includes chemosynthetic symbiotic fauna (Olu-Le Roy et al., 2004). Carbonate crusts are also formed by anaerobic oxidation of methane in these environments (Aloisi et al., 2002).

Mud volcanoes are widespread in the Eastern Mediterranean and may host large masses of solid gas hydrates of potentially high economical interest or/and may represent significant sources of natural pollutants (e.g. hydrocarbons) (Woodside et al., 1998; Mascle et al., 1999). Mud volcanism associated with the Mediterranean Ridge is initiated when overpressured fluid muds originating within the décollement zone, rise through the deformed sediments of the Ridge and reach the seafloor (Robertson et al., 1996; Robertson and Kopf, 1998). Brine lakes have also been observed mainly in association with mud volcanoes or along fault lineaments where Messinian evaporites are present in the

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subsurface (Woodside et al., 1999; MEDINAUT/MEDINETH Shipboard Scientific Parties, 2000; Woodside and Volgin, 1996). The faults can serve as channels for seawater to circulate through the upper sediments to the Messinian salt and back, or for hypersaline water to flow to the seafloor.

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 the SE Aegean sea (Perissoratis et al., 1998). International interest resulted in ODP 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., 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-scans 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) (Perissoratis et al., 2003). This paper presents the major results of the two ANAXIMANDER project cruises in 2003 and 2004, based on the interpretation of the detailed multibeam mapping, the extensive seabed sampling and the site survey seismic profiling. The paper demonstrates that active mud volcanism and the presence of gas hydrates in this sector of Eastern Mediterranean are considerably more extensive than previously thought, with several new sites where gas hydrates were sampled.

2. Geological setting

The Anaximander Mountains comprise a group of three main seamounts located between the Cyprus and Hellenic arcs (Fig. 1). They are currently undergoing a neotectonic deformation characterized by strike slip faulting (Zitter et al., 2003, 2006; Ten Veen et al., 2004) between the westerly moving Anatolian Plate and the African Plate (McClusky et al., 2002). The Anaximander Mountains are described as large faulted and tilted blocks that originally were geologically continuous with SW Turkey. They are composed of three distinct seamounts (SMs): Anaximander in the west, Anaximenes in the south and Anaxagoras in the east (Fig. 2). Anaximander and Anaximenes SMs can be correlated with the neritic limestones of the Bey Dağları Unit of SW Turkey (Poisson, 1977; Gutnic et al., 1979), whereas the Anaxagoras SM is a continuation of the ophiolitic Antalya Nappes Complex (Gutnic et al., 1979; Robertson and Woodcock, 1980; Woodside et al., 1997; Ten Veen et al., 2004; Zitter et al., 2005). The whole area has been undergoing complex multiphase deformation in its neotectonic development (Ten Veen et al., 2004). A kinematic change in the latest Miocene, related to the onset of the westward motion of Anatolia, marked the start of differential subsidence that resulted in the formation of the Anaximander Mountains (Ten Veen et al., 2004). These

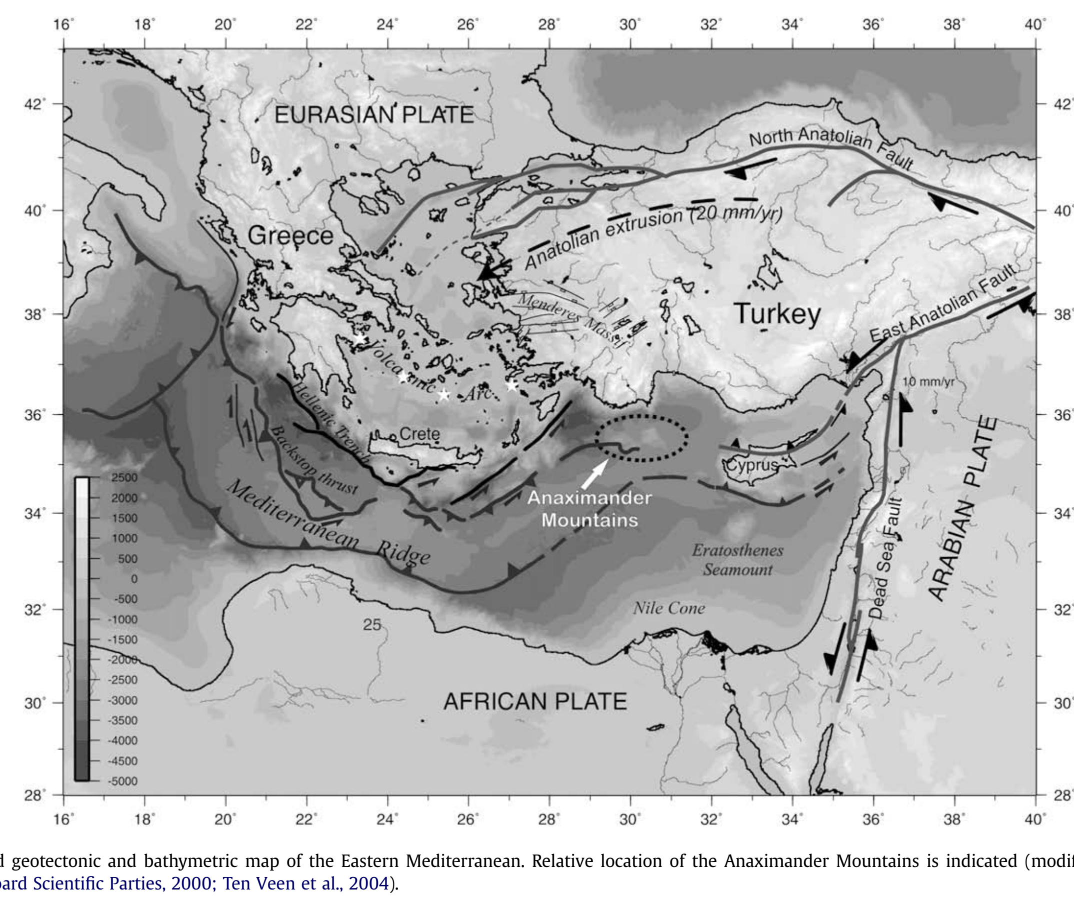

Fig. 1. Generalized geotectonic and bathymetric map of the Eastern Mediterranean. Relative location of the Anaximander Mountains is indicated (modified after MEDINAUT/MEDINETH Shipboard Scientific Parties, 2000; Ten Veen et al., 2004).