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Tectonic control on mud volcanoes and fluid seeps in the Anaximander Mountains, eastern Mediterranean Sea

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ABSTRACT

Deep-tow sidescan sonar and subbottom profiler data (from the 1999 MEDINETH survey), together with observations from the submersible *Nautile* (from the 1998 MEDINAUT survey), have been used to examine the occurrence of mud volcanoes in the Anaximander Mountains and along the Florence rise in the eastern Mediterranean Sea. This area, located at the intersection of the Hellenic trench and the Cyprus arc, is undergoing complex crustal deformation as a result of transpressional and transtensional tectonics, in response to collisional plate interactions. Widespread fluid escape through mud volcanoes and cold seeps occurs within the main wrench zones along the western branch of the Cyprus arc. Fault zones are inferred to provide pathways for overpressured mud and fluids. Mud volcanoes are spatially associated with both major and secondary faults within the regional stress field. This analysis reveals the fundamental role of transcurrent and extensional faulting in the extrusion of mud and the formation of mud volcanoes.

Keywords: mud volcano, strike-slip faulting, sonar mapping, submersible observations, eastern Mediterranean Sea

INTRODUCTION

Mud volcanoes and fluid vents occur worldwide, predominantly in areas undergoing collisional tectonics, and are commonly observed in close association with active faulting (Barber et al., 1986; Brown and Westbrook, 1988; Reed et al., 1990; Hieke et al., 1996; Robertson and Kopf, 1998b). However, a relationship between the types of faulting, the mechanisms of mud extrusion, and the distribution of mud volcanoes is not clearly established in the literature. It is inferred that the principal mechanism responsible for the development of mud volcanoes within convergent margins is lateral shortening (Limonov et al.,

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1996). In accretionary prism, thrusts and backthrusts are reported to provide natural pathways for mud, either extruded from the décollement level (Camerlenghi et al., 1995) or squeezed from higher levels in the accretionary wedge (Robertson and Kopf, 1998b). The significance of extensional and strike-slip deformation for the extrusion of mud within compressional environments is less well known but has been discussed with respect to mud volcanoes in Indonesia (Barber et al., 1986), Barbados (Faugères et al., 1997; Sumner and Westbrook, 2001), the Carribean Colombian margin (Vernette et al., 1992), the Alboran Sea (Pérez-Belzuz et al., 1997), and the Mediteranean Ridge (Rabaute et al., 2003; Huguen et al., 2004).

In the eastern Mediterranean Sea, the initial stages of continental collision between the Africa and Eurasia plates, and the resulting lateral escape of the Anatolia platelet into the Aegean domain (Taymaz et al., 1991; Le Pichon et al., 1995), led to the development of two highly curved arc systems along which convergence takes place: the Hellenic arc to the west and the Cyprus arc to the east. The study area discussed in this article (i.e., the Anaximander Mountains and the nearby Florence rise) is located at the cusp of these two arcs (Fig. 1) and forms a zone that accommodates the different tectonic regimes. The complex tectonics there is associated with various types of evidence of mud volcanism, release of methane, seep-related chemosynthetic communities, and the development of authigenic carbonate crusts (Woodside et al., 1998; MEDINAUT/MEDINETH shipboard scientists, 2000; Lykousis et al., 2004; Zitter, 2004).

Our recent work in this critical area discussed the strain pattern and the recent neotectonic evolution of the region (Woodside et al., 2002; Zitter et al., 2003; ten Veen et al,. 2004) and revealed the predominance of strike-slip tectonics along that plate boundary. In light of these studies, and specifically the structural analysis conducted by ten Veen et al. (2004), this article evaluates the relationships between mud volcanoes and tectonics, particularly the potential influence of strike-slip faulting. Our study is based on a wide geophysical data set obtained during various marine expeditions (ANAXIPROBE, ANAXIPROBE-TTR6, PRISMED2, MEDINAUT, and MEDINETH), allowing a multiscale analysis of the tectonic control on seep areas. The distribution of mud volcanoes within the regional tectonic setting is observed in the EM12D swath mapping data. Focused high-resolution sidescan sonar data are used to map the faults in the vicinity of several mud volcanoes (MV) and cold seeps of the study area (Fig. 2): Amsterdam MV, Kazan MV, Kula MV, Saint Ouen l'Aumône MV, Tuzlukush MV, Texel MV, and the Faulted Ridge seeps. Of special importance in this study is the use of groundtruth data to obtain direct seafloor evidence for a connection between tectonic features and seeps using submersible observations. Finally, we discuss a model for the remobilization and subseafloor pathways of overpressured fluids and mud for this area.

Figure 2. (A) Multibeam bathymetric map of the Anaximander Mountains with N90° illumination (created using GMT software; Wessel and Smith, 1998) with reference to the features cited in the text. (B) Structural scheme of the study area, interpreted from multibeam bathymetry and imagery and seismic profiling, and compiled from Zitter et al. (2003) and ten Veen et al. (2004), showing the main faulting, the mud volcanoes and cold seep areas (1—Amsterdam MV; 2—Kazan MV; 3—Tuzlukush MV; 4—St Ouen l'Aumône MV; 5—Kula MV; 6—San Remo MV; 7—Texel MV; 8—Harderwijk MV; 9—Faulted Ridge), and the high-backscatter patches inferred to relate to mud volcanism activity (white stars). Abbreviations are as follows: BD—Bey Dağlari; SZD—Suzuz Dağ.

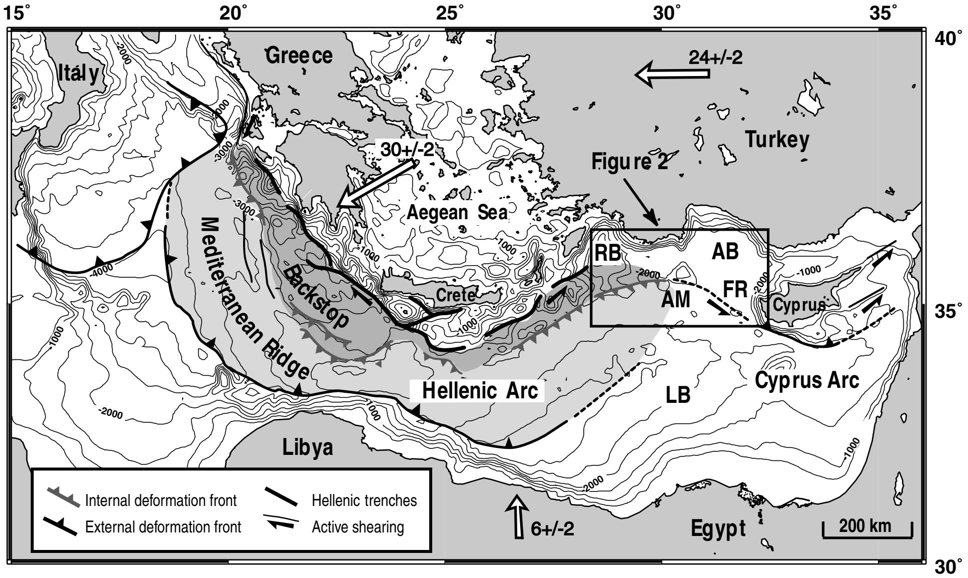
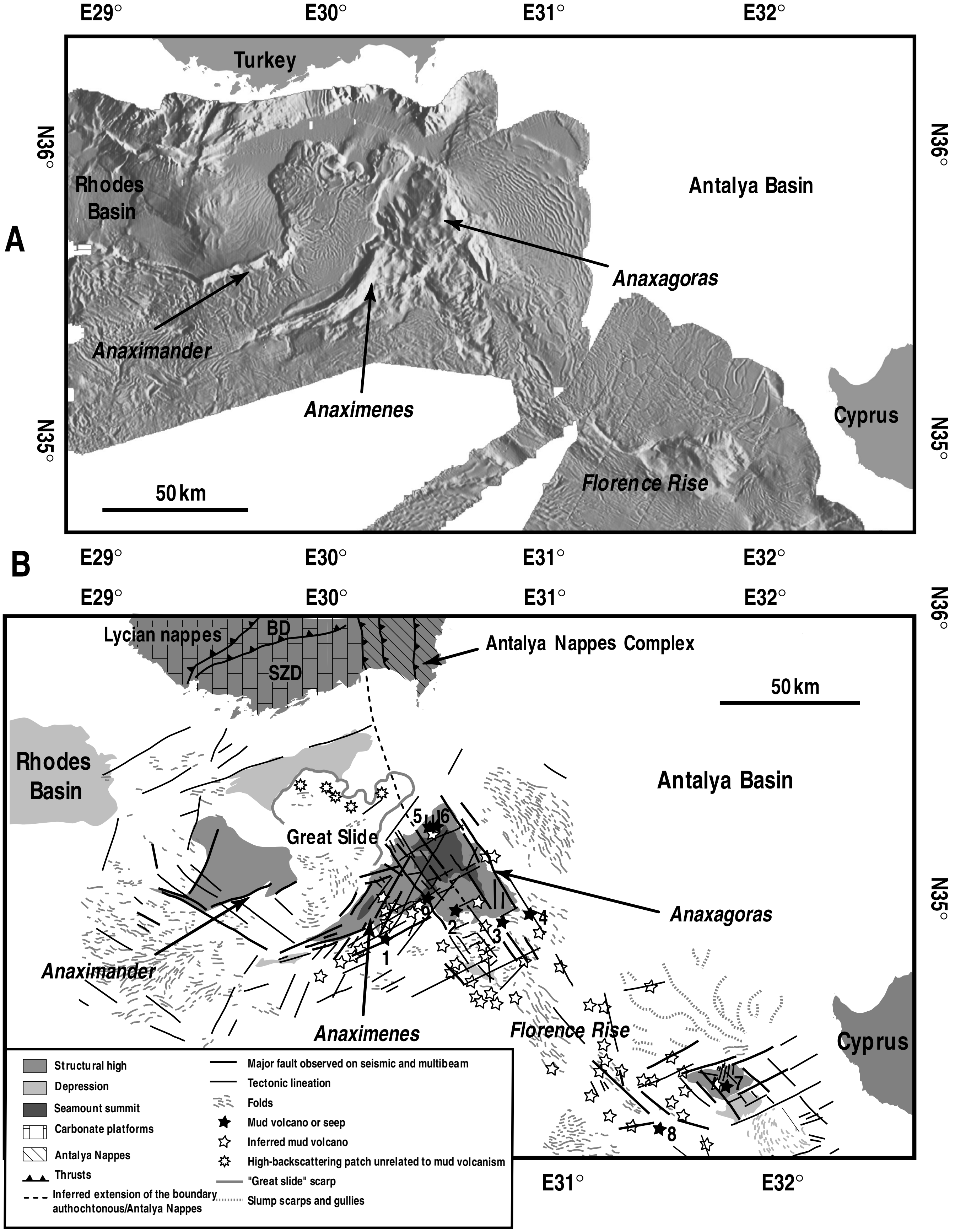


Figure 1. General geodynamic context of the Eastern Mediterranean Sea (modified after Huguen, 2001; Zitter et al., 2003; ten Veen et al., 2004), with the locations of the main features cited in the text and those of the study area (Fig. 2). The white arrows indicate the approximate sense of motion of the lithospheric plates relative to Eurasia, with rates in mm/yr (from McClusky et al., 2000). Abbreviations are as follows: AB—Antalya basin; AM—Anaximander Mountains; FR—Florence rise; LB—Levantine basin; RB—Rhodes basin.


A
E29°
E30°
E31°
E32°
N36°
N35°
Turkey
Rhodes Basin
Antalya Basin
Anaxagoras
Anaximander
Anaximenes
Cyprus
Florence Rise
50 km
B
Lycian nappes
BD
SZD
Antalya Nappes Complex
50 km
Rhodes Basin
Antalya Basin
Great Slide
Anaxagoras
Anaximander
Anaximenes
Florence Rise
Cyprus
1
2
3
4
5
6
7
8
Structural high
Depression
Seamount summit
Carbonate platforms
Antalya Nappes
Thrusts
Inferred extension of the boundary authochtonous/Antalya Nappes
Major fault observed on seismic and multibeam
Tectonic lineation
Folds
Mud volcano or seep
Inferred mud volcano
High-backscattering patch unrelated to mud volcanism
"Great slide" scarp
Slump scarps and gullies

TECTONIC FRAMEWORK

The Anaximander Mountains, between the Rhodes and Antalya basins (Fig. 1), are composed of three distinct seamounts (i.e., Anaximander in the west, Anaximenes in the south, and Anaxagoras in the east; Fig. 2) rising more than 2000 m above the surrounding seafloor. Sampling and dredging from the joint ANAXIPROBE-TTR6 expedition have shown that these mountains are crustal blocks rifted away from southern Turkey, because the recovered basement rocks have an affinity with the Taurus Mountains (Woodside et al., 1997). The two westernmost mountains (Anaximander and Anaximenes) are related to the autochthonous units, the Bey Dağlari and Susuz-Dağ carbonate platforms, which form a wide anticline structure onshore (Poisson, 1977; Gutnic et al., 1979), whereas the allochthonous Antalya nappes complex (Gutnic et al., 1979; Robertson and Woodcock, 1980; Woodside et al., 1997) extends southward beneath Anaxagoras (ten Veen et al., 2004).

The area, situated at the intersection of the Hellenic and Cyprus arcs, forms a broad zone of deformation defining the plate boundary (Zitter et al., 2003; ten Veen et al., 2004) and has been undergoing complex multiphase deformation during its neotectonic development. During the late Miocene, crustal extension created N120°-oriented grabens that developed into a vast subaerial to shallow marine area comprising the southern Aegean (ten Veen and Postma, 1999), Rhodes (ten Veen and Kleinspehn, 2002), and the present-day Anaximander Mountains (ten Veen et al., 2004). The Miocene–Pliocene transition marked a kinematic change within the southern Aegean region partly related to the lateral extrusion of Anatolia (McKenzie, 1972; Le Pichon et al., 1995). Subsequently, the Anaximander Mountains area as well as the adjacent Rhodes basin was affected by strong post-Miocene differential subsidence (Woodside et al., 2000; Zitter et al., 2003; ten Veen et al., 2004), as proved by the absence of Messinian evaporites throughout the area and the unconformably overlying Pliocene sediments. Since the Pliocene, progressive adjustment to the collisional plate interaction raised transtensional stresses in the western Anaximander Mountains and more transpressional tectonics in the eastern Anaximander (Zitter et al., 2003; ten Veen et al., 2004). Strike-slip deformation is confirmed by the source mechanisms of recent seismic events in the southwestern part of Cyprus (Ardvisson et al., 1998; Pilidou et al., 2004), showing mostly right lateral strike-slip faulting but exhibiting as well the complex characteristics associated with strike-slip, thrust, and normal faulting, especially for earthquakes with shallow focal depth (Yolsal and Taymaz, 2004).

Recent Simrad EM12D multibeam swath mapping and seismic profiling (from ANAXIPROBE and PRISMED2 expeditions) have provided essential new information about the prevailing strain pattern in the Anaximander Mountains (Fig. 2) and along the western branch of the Cyprus arc (Woodside et al., 2002; Zitter et al., 2003; ten Veen et al., 2004). The Cyprus arc is an arcuate feature strongly dominated, bounded, and transected by N150° and N70° lineaments and scarps (Fig. 2) extending from the Anaxagoras seamount to the north to the Florence rise southward (Woodside et al., 2002; Zitter et al., 2003). The N150°E-trending fault zones are probably related to preexisting thrust faults from the middle Tortonian Aksu phase that emplaced the Antalya nappes complex (Poisson, 1977; Glover and Robertson, 1998). Along the Florence rise, these N150°-oriented lineaments are characterized on the seismic profiles by anastomosing subvertical patterns and pop-up structures, indicating strike-slip faulting (Woodside et al., 2002; Zitter et al., 2003). The plate boundary there is thus characterized by pure sinistral wrench tectonics (Woodside et al., 2002; ten Veen et al., 2004). The strike-slip component decreases northward toward Anaxagoras, and the N150°-trending faults are mainly characterized by normal offset in bathymetry and seismic profiling. The N070°-trending faults are related to the development of N70°-trending sinistral strike-slip fault zones along the western branch of the Hellenic arc, in the Rhodes basin, and in the western Anaximander Mountains since the late Pliocene (ten Veen et al., 2004). The N070° strike-slip faults extend largely into the Anaxagoras domain (eastern Anaximander), where a stepwise northwestward increase in relief along the N070°-oriented scarps suggests a normal component along these faults. In the western part of the Anaximander Mountains, the onset of the N70° shear was associated with extensive N020° normal faulting in the early Pliocene and followed by N120° dextral strike-slip in the late Pliocene (ten Veen et al., 2004). Large-scale N20° extension-related structures are absent in the eastern domain, but short north-south extensional faults are segmented by N150° faults and are therefore probably secondary Riedel faults associated with them (ten Veen et al., 2004).

MUD VOLCANO DISTRIBUTION IN THE ANAXIMANDER MOUNTAINS

Structural Distribution of Mud Volcano Deposits

The mud volcanoes are identified on the EM12D multibeam acoustic data as high-backscattering patches (Volgin and Woodside, 1996), associated with subcircular positive relief in the multibeam bathymetry (Fig. 3). From these data, more than thirty mud volcanoes were identified (Fig. 2b) in the Anaximander Mountains and along the Florence rise. They are especially concentrated on the Anaxagoras seamount and south of Anaximenes.

Six mud volcanoes (numbered 1–6 in Fig. 2B) were the targets for numerous detailed surveys (Zitter et al., 2005). The largest one, Amsterdam MV, is up to 3 km across, with high-backscattering mud flows to the south, covering an area of more than 50 km^2. It is located on the southeastern flank of Anaximenes seamount, along a N70°-trending fault zone (Fig. 2). This fault zone has a pronounced morphological expression in the multibeam bathymetry and merges to the northeast with the Faulted Ridge, which is one of the major scarps shaping the

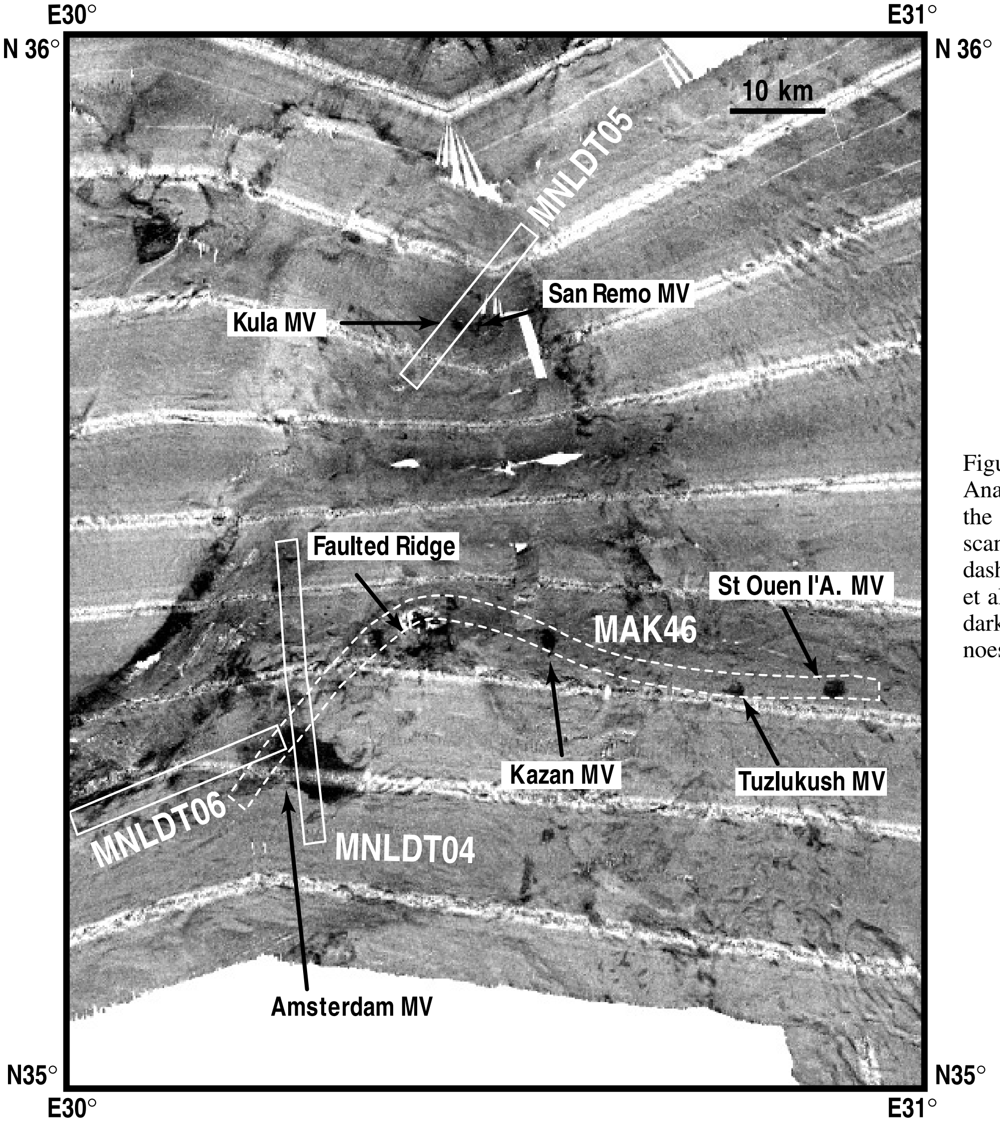


Figure 3. Multibeam imagery map of the Anaxagoras seamount with the locations of the mud volcanoes and the deep-tow side-scan sonar lines (plain—O.R.E.Tech lines; dashed—MAK line), modified after Zitter et al. (2003). High backscatter is shown as darker shades of gray; thus, the mud volcanoes appear as black patches.

Anaxagoras seamount (Fig. 2A), with a vertical relief of more than 500 m (Woodside et al., 1997). On the basis of high backscattering in the sonar imagery and acoustic wipeouts in deep-tow subbottom profiles, it was identified as a potential dredging target during ANAXIPROBE because of the likely presence of basement outcrops. Dredging here during the TTR6-ANAXIPROBE cruise recovered basement rocks and some tubeworms, and a *Nautile* dive confirmed the existence of numerous seeps along this scarp (number 9 in Fig. 2B). Eastward, the mud volcanoes of the southeastern part of Anaxagoras—i.e., Kazan MV, Tuzlukush MV, and Saint Ouen l'Aumône MV—are located at the intersection of the major N150° and N70° strike-slip faults. To the north, Kula MV and San Remo MV are sited at the northern end of the Anaxagoras seamount, in an area dominated by short north-south-oriented normal faults. Several small mud volcanoes are clustered on a small plateau there (Fig. 3).

Within the Florence rise area, the mud volcanoes also appear to be associated with the main strike-slip fault system (Fig. 2B). Two of them were sampled during the MEDINETH cruise in 1999 (numbers 7 and 8 in Fig. 2B). Texel MV is situated on a plateau at the top of the highest part of the Florence rise, together with another small, rounded dome inferred to be a mud volcano. This topographic high is an angular block bounded by N150° and N70° faults and referred to as the DSDP block (Woodside et al., 2002) because of the existence of DSDP (Deep Sea Drilling Project) drillholes there (Hsü et al., 1973). However, Texel MV appears to be more closely related to short north-south normal faults transecting the summit of the block, in a similar fashion to Kula MV and San Remo MV on Anaxagoras seamount. Harderwijk MV is situated in a small depression at the intersection of two strike-slip faults trending N70° and N135°.

Geological Distribution of Mud Volcano Deposits

The variation of clast lithologies within the mud breccia of the Anaximander Mountains mud volcanoes indicates that the erupted material has passed through different lithological units during mud ascension. Kula and San Remo MVs are situated above the extension of the Antalya nappes complex because their erupted mud breccia contains some ophiolite clasts gathered during mud ascension through the ophiolite-bearing allochthonous units. In the Kula mud breccia, some limestone, sandstone, chert, serpentine, and serpentinized peridotite were recovered (Woodside et al., 1997). Some clasts from Kula exhibit a dense network of fractures with calcite recrystallization and are dated as Campanian from nannofossil analysis (Huguen et al., 2001b). Cross-cutting veinlets and calcite joints observed on the surface of the clasts are inferred to indicate the hydrofracturing that formed with the release of pressure during the eruption of mud volcanoes (Robertson and Kopf, 1998a). In the San Remo mud breccia, red and green cherts were recovered as well (Woodside et al., 1997). In contrast, the clasts from the Amsterdam and Kazan mud breccia show an affinity with the typical succession of the Bey-Dağları massif (Woodside et al., 1997). The Amsterdam clasts include detrital limestone, siltstones and sandstone, and black claystone and marlstone, attributed to a middle Miocene (Serravalian) flysch and Eocene neritic limestones (Woodside et al., 1997, 1998). Clasts from Kazan MV show similar lithologies, but with ages as old as Maastrichtien (Huguen et al., 2001b). Dredging on the Faulted Ridge also recovered similar lithologies, with the predominance of dark marlstones (Woodside et al., 1997). The Tuzlukush and Saint Ouen l'Aumône mud flows contain clasts of limestone, sandstone, siltstone, claystone, and volcanic rock fragments (Woodside et al., 1997).

MORPHOTECTONIC ANALYSIS FROM DEEP-TOW SIDESCAN RECORDS

High-resolution sidescan sonar data consist of 2-km swath profiles acquired with MAK1 and O.R.E.Tech deep-tow sidescan sonar devices during the TTR6 and MEDINETH cruises (Fig. 3). The technical details of these devices are given elsewhere (Zitter et al., 2005). On deep-tow sidescan records, many linear features can be detected, commonly associated with shadows that reflect small-scale relief on the seafloor or enhanced backscatter, indicating scarps or inhomogenities of the insonified ocean bottom (Fig. 4). The enhanced backscatter could also be caused by the cementation of sediments by Mg-calcite within cracks and fractures (Hieke et al., 1996). The features may show a morphological expression on the seafloor, with scarps and small steps associated with a hyperbolic acoustic facies on the subbottom profiler (SBP). Although the SBP cannot resolve the continuation of these features at depth, they can be interpreted as an expression of faulting on the basis of analogies with features seen on both EM12D acoustic imagery and seismic profiles; they also show a good correlation with the main regional fault directions.

The lineaments observed on the sidescan sonar records were mapped across and in the vicinity of different mud volca-

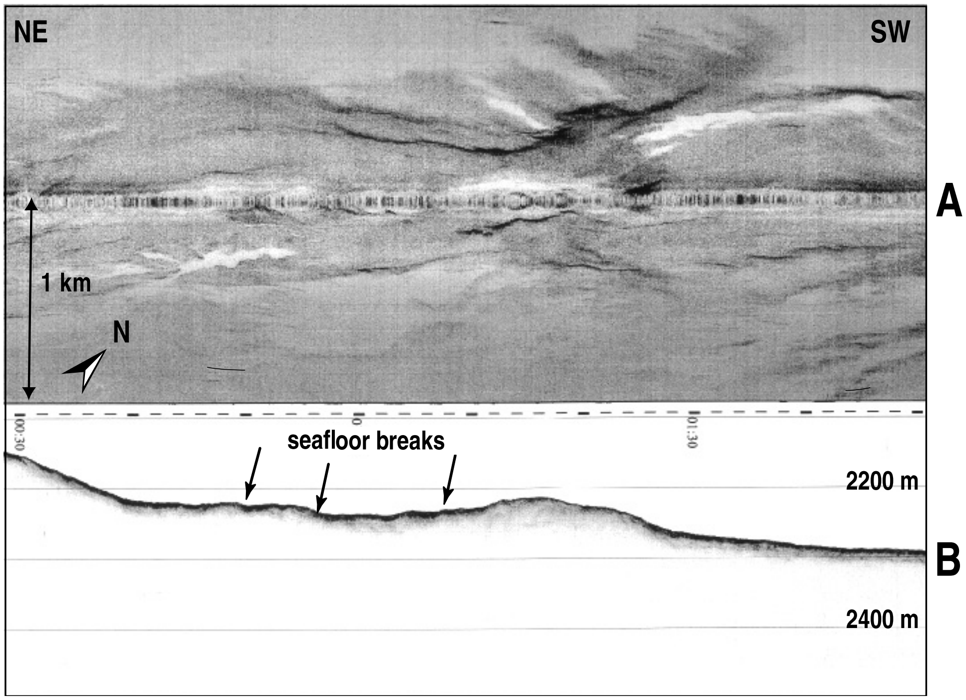


Figure 4. (A) Sidescan sonar image and (B) sub-bottom profiler record of a section of line MNLDT06 south of the Anaximenes seamount illustrating the acoustic signature of the faults on sonar records.

noes. Across Amsterdam MV, they were mapped on a section of line MAK46 and along the O.R.E.Tech sonar lines MNLDT04 and MNLDT06, respectively, running to the north and to the west of the mud volcano. They were mapped along line MNLDT05 for Kula MV. For Kazan MV, Saint Ouen l'Aumône MV, and Tuzlukush MV, they were also mapped from sections of line MAK46. The length and frequency distribution of all the mapped lineaments are presented as rose diagrams for each mud volcano (Fig. 5).

Trying to fit the morphotectonic directions into the regional tectonic setting (Zitter et al., 2003; ten Veen et al., 2004; Table 1), we deduce that:

1. The most important types of faults observed in connection with the mud volcanoes are related to the N70° sinistral strike-slip faults (Figs. 6, 7, and 8). They were recognized on all of the deep-tow records, though not always with the same significance (Fig. 5), and thus they appear the preferential path for mud extrusion.
2. N120°-oriented faults are commonly observed in relationship with mud volcanism. They are best expressed in the southern part of the Anaxagoras seamount, especially at the junction of Anaxagoras with Anaximenes, and therefore may relate to the major dextral transtensional faults occurring in the western part of the Anaximander Mountains (ten Veen et al., 2004).
3. A third trend, commonly observed in connection with the mud volcanoes, is N40–50°; these faults could correspond to synthetic faults (R-shear) associated with the N70° sinistral strike-slip faults.
4. The N150° faults are less commonly observed on the deep tow records, as seen along line MNLDT05 running across

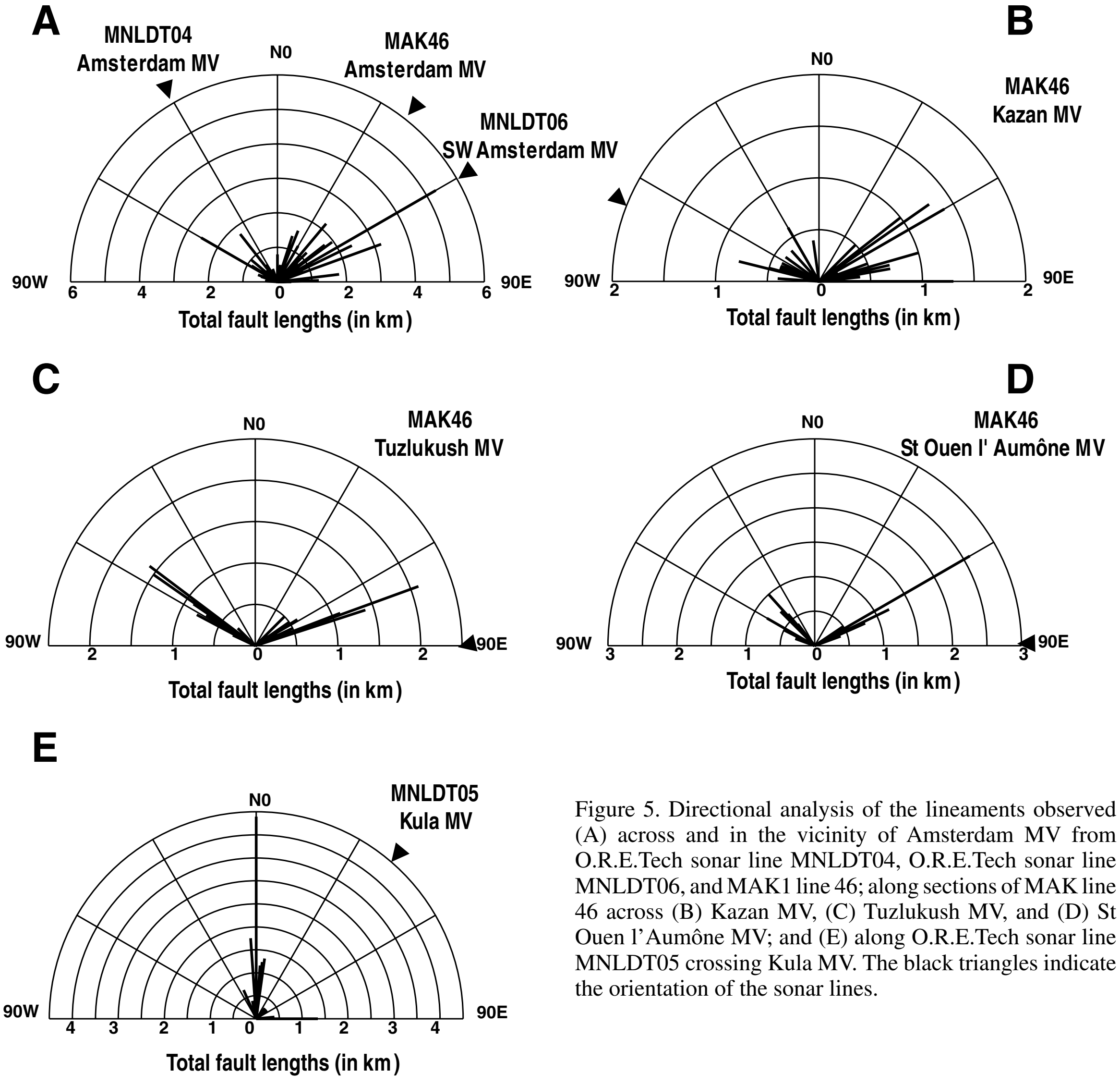


Figure 5. Directional analysis of the lineaments observed (A) across and in the vicinity of Amsterdam MV from O.R.E.Tech sonar line MNLDT04, O.R.E.Tech sonar line MNLDT06, and MAK1 line 46; along sections of MAK line 46 across (B) Kazan MV, (C) Tuzlukush MV, and (D) St Ouen l'Aumône MV; and (E) along O.R.E.Tech sonar line MNLDT05 crossing Kula MV. The black triangles indicate the orientation of the sonar lines.

Kula MV, or southwest of Amsterdam MV, on line MNLDT06. They may be more difficult to see, because they relate to prior thrusting (i.e., the last emplacement phase of the Antalya nappes complex; Poisson, 1977; ten Veen et al., 2004). However, these faults are presently reactivated as normal or transcurrent faults and have a clear expression in both the multibeam bathymetry and imagery.

5. North-south to N10°-oriented faults are of less importance with respect to the mud volcanoes, but they are worth mentioning because they are the dominant faults associated with the emplacement of Kula MV in the north of Anaxagoras. They show significant vertical offset on the SBP (up to 8 m of vertical displacement) and are inferred to be secondary normal faults related to the N150° faulting.
6. Large-scale N20° normal faults occurring in the western Anaximander domain are observed only in connection with Amsterdam MV.
7. Although thrust tectonics is inferred to occur in the area, thrust faults do not seem to be linked with mud volcanoes and may be restricted to the small N90° faults observed in connection with some of the mud domes (e.g., Kazan and Kula MVs).

SEAFLOOR EVIDENCE FOR TECTONIC CONTROL ON MUD VOLCANOES

Mud Flows

Mud flows are commonly emplaced along tectonic lineaments (Mascle et al., 1999; Kopf et al., 2001). Mud breccia may fill faults and fractures, and the resulting backscatter enhancement makes them easier to distinguish in the sidescan sonar data. Kula MV is the best example of such tectonically driven mud emplacement (Fig. 9), because a network of crosscutting high-backscatter lineaments can be observed on the deep-tow record on the top of this MV. These lineaments, associated with small steps on the seafloor, are inferred to be faults. They control the repartition of the high-backscattering patches and are thus inferred to channel the extrusion and flow of the mud breccia. They act as pathways for mud ejection as well as for the release of fluids and gases. The injected mud flows along faults can also be observed on Texel MV; near the western termination of a high-backscattering tongue-shaped mud flow, a 1-km-long narrow high-backscattering lineament suggests that the mud breccia is filling up a fault (Fig. 10). On Saint Ouen l'Aumône MV, several high-backscattering spots are lineated in a N85° direction, suggesting tectonic emplacement of the mud flows as well (Fig. 7).

Tectonic control of mud flow emplacement is best observed on mud volcanoes displaying weak or limited areas of backscattering. It is probable that massive and recently extruded mud flows have the tendency to cover and attenuate the visibility of deep-seated faults except where the faults are clearly observed on either side of the mud volcano.

Seeps and Scarps

Fault scarps observed during the *Nautile* dives attest to the intense tectonic activity. The largest one is the Faulted Ridge, explored by submersible between 1760 and 1280 m water depths (Fig. 11). Different parts of the scarp observed during the dive include (1) steep slopes with large pieces of fallen rocks, commonly associated with shells and debris of tubeworms; (2) scarps with outcropping stratified rocks, disrupted by fractures and dusted by hemipelagic sediments; and (3) actual cliffs or walls, up to 100 m high, displaying intensively fractured layered dark rocks. Fluid seeping through the scarp is indicated by patches of concentrated chemosynthetic-based fauna. Shells are observed in several different places, but are particularly concentrated at the base of the cliffs. More intensive fluid emissions are inferred to occur in two places (Fig. 11): (1) between 1660 and 1560 m water depth, along a cliff displaying tubeworms and active seeps characterized by purple reduced sediments and bacterial mats, and (2) at 1440 m water depth, on a wall where the greatest abundance of living vestimentiferans can be observed. The tubeworms are commonly located within the fractures or along the bedding planes, suggesting active fluid seepage along them. In some places, bunches of hundreds of living vestimentiferans are settled along fractures (Fig. 11).

On a smaller scale, many scarps from a few tens of centimeters to a few meters were observed. On Kazan MV, at least two linear N55°-trending scarps disrupt the seafloor with ~20- and 50-cm offset (Fig. 12), showing the present-day activity of the faults. The importance of active tectonics on this mud volcano is also indicated by numerous ridges on the seafloor, mainly corresponding to the regional tectonic direction: N120° and N50–70°. Kula MV also reveals some scarps and surface deformation that correlate with the fault directions observed on the sidescan sonar record (Zitter et al., 2005).

The majority of the scarps result from regional faulting, but some of them are related to local deformation within the mud volcanoes. Mass wasting processes are commonly found in association with mud volcanoes (Vogt et al., 1999). The dive observations indeed reveal scarps or faults developing from mass destabilization in response to the volume change of the mud volcano or due to the creeping on the steep flanks of the mud volcanoes (MEDINAUT/MEDINETH shipboard scientists, 2000; Zitter et al., 2005). This destabilization process is well imaged on Amsterdam MV, with the numerous concentric ridges and crevasses developing in the outer part of the summit (Fig. 6). Although not related to deep-seated tectonics, the folding and crevassing induced by the mud movement within the mud volcano control the local seep distribution. Active seeps with massive carbonate crusts and tubeworms were frequently observed on top of the ridges developing around Amsterdam MV (Zitter et al., 2005). These ridges, located in the inner part of the alternating high- and low-backscatter ring surrounding the summit, were probably built initially as eruptive ridges, but the faulting related to peripheral collapse structures may also

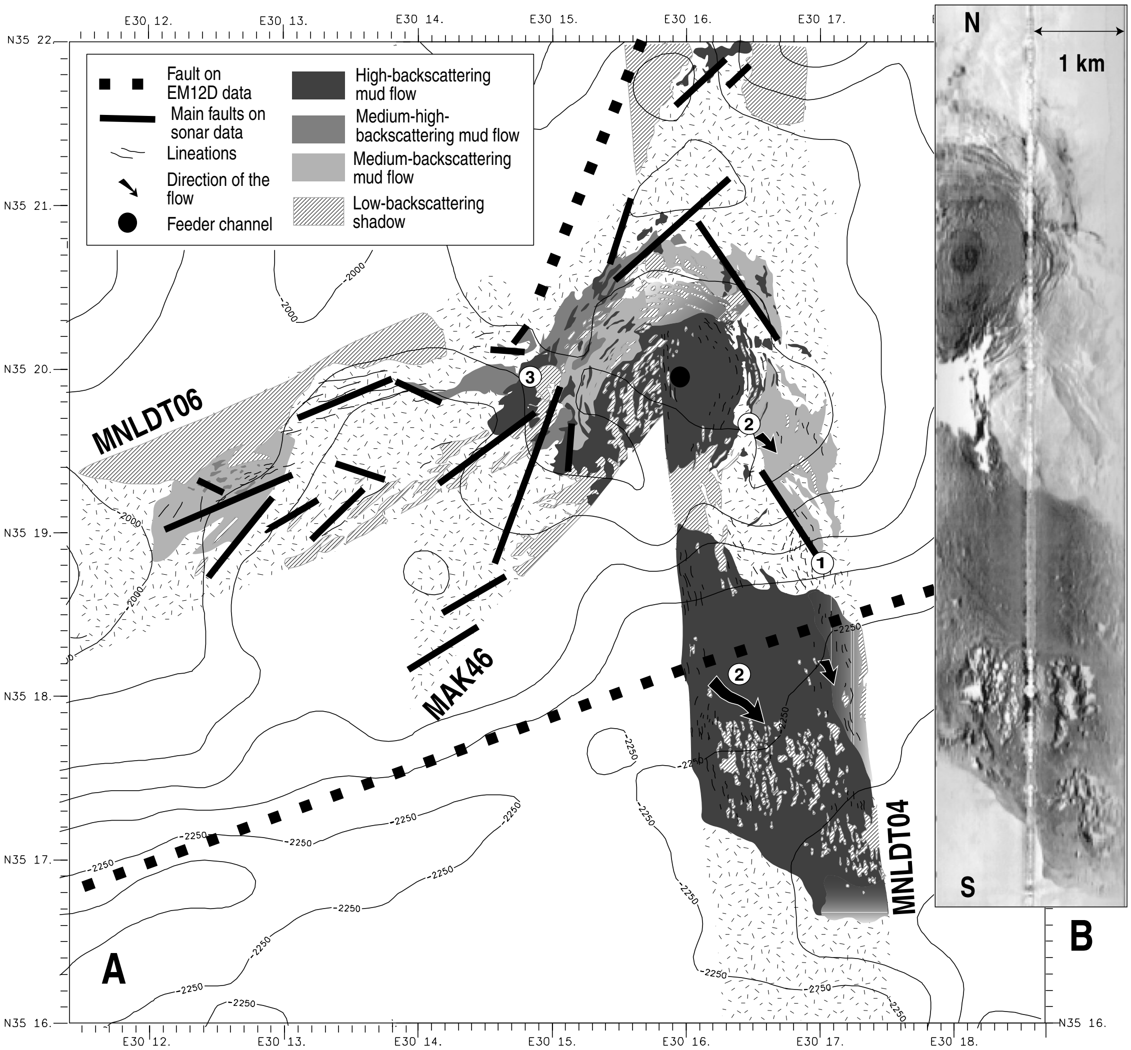


Figure 6. (A) Map of Amsterdam MV and its surroundings, with the interpreted mud flows and tectonic lineations observed from the sidescan sonar, superimposed on multibeam bathymetry with the major regional faults mapped from EM12D data. Note the relationship between the faults ①, the mud flows and the structuring of the slope ②, or the tectonically controlled eruptive parasitic center ③. (B) Sidescan sonar record of part of O.R.E.Tech line MNLDT04 showing the mud flow and the eastern side of the summit of Amsterdam MV. Note the very high-backscattering dark patch of the feeder channel.

facilitate superficial focused fluid flow. However, active seeps are not observed in the external part of the mud volcano in relationship with the outermost crevasses, except on a parasitic eruptive cone that is associated with the interaction of N20° and N50° regional faults (Fig. 6).

DISCUSSION

Tectonic Control of Distribution of Mud Volcano Deposits

In the Anaximander Mountains, mud volcanism occurs in the strongly tectonized eastern domain, along a former thrust belt (i.e., along the Cyprus arc). Compression appears as an important parameter for overpressuring sediments at depth. However, this thrust belt is now reactivated as a normal or transcurrent system (Zitter et al., 2003; ten Veen et al., 2004). In addition, most of the surveyed mud volcanoes of the Anaximander Mountains show a close relationship with strike-slip and normal faults (Table1). Compression alone is thus insufficient for the occurrence of mud volcanoes; a good plumbing system must exist as well.

The N70°-oriented strike-slip faults appear most significant in controlling the occurrence of mud volcanoes, probably because they are the most active faults in the area. They have a

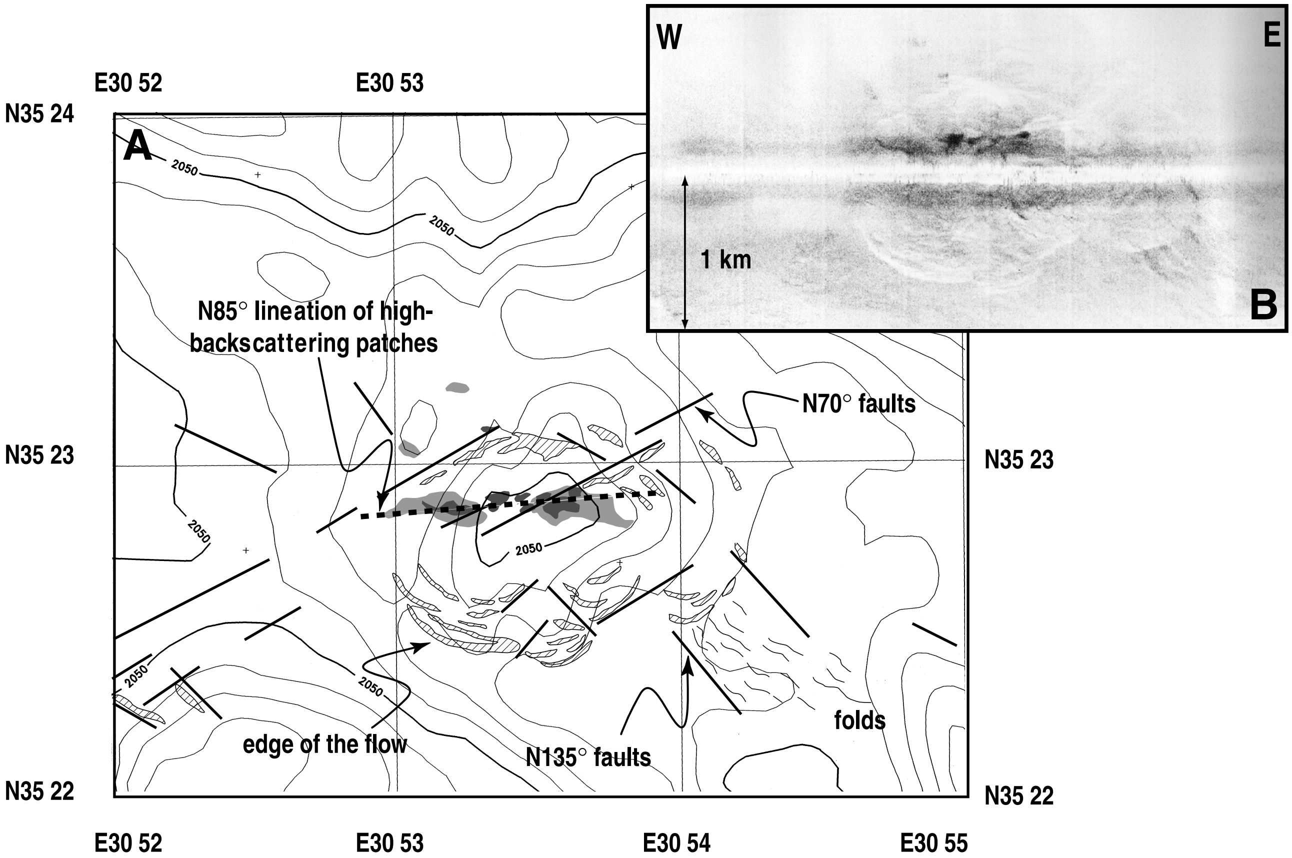


Figure 7. (A) Multibeam bathymetric map of Saint Ouen l'Aumône MV with interpreted faults (lines), folds, high-backscattering patches (gray scale), and acoustic shadows (hatched) outlining the edges of the old mud flows. For legend, see Figure 6. (B) Corresponding sidescan record.

strong topographic expression in the multibeam bathymetry (e.g., the Faulted Ridge bathymetric offset), and they are the youngest faults, for they are observed to crosscut the other faults. Although the precipitation of authigenic carbonates from circulating fluids tends to reduce the permeability within fault zones, fault activity will obviate this and create or rejuvenate such conduits for fluid flow. Therefore, active faults are important to control mud and fluid expulsion. The N70° strike-slip faults probably also facilitate the mud extrusion when compared to thrust faults that are tighter because of the compression across the fault. Finally, these faults relate to the plate boundary deformation and are likely to be deep-seated faults reaching both the source of the fluids and the level of remobilized mud (Zitter, 2004).

The source of the fluids is constrained by pore water geochemistry to originate from a depth zone where formation water temperatures are calculated to be between 80 and 150 °C and to relate to clay mineral dehydration (Haese et al., 2006). The solid phase of the mud breccia is, in contrast, derived from shallower units, which can be remobilized episodically although the source of the fluids is persistent (Zitter, 2004). Overpressured mud then uses the pre-existing faults to reach the surface, as in the case of Kula MV, which is associated with short north-south extensional faults that are secondary to the N150° oblique faulting in the northern part of Anaxagoras. This suggests that mud volcanoes are linked not only with major faults but also with smaller and probably shorter faults or fractures that may be under less compression, acting as a better conduit for mud extrusion.

In the Anaximander Mountains, mud volcanoes are also frequently located at the intersection of strike-slip and extensional faults. The interaction between different faults, and the fracturing resulting from this interaction, is an important factor in localizing the mud extrusion. In the southern part of Anaxagoras, where Amsterdam MV and Kazan MV occur, the observed faults indicate complex deformation related to the interplay of

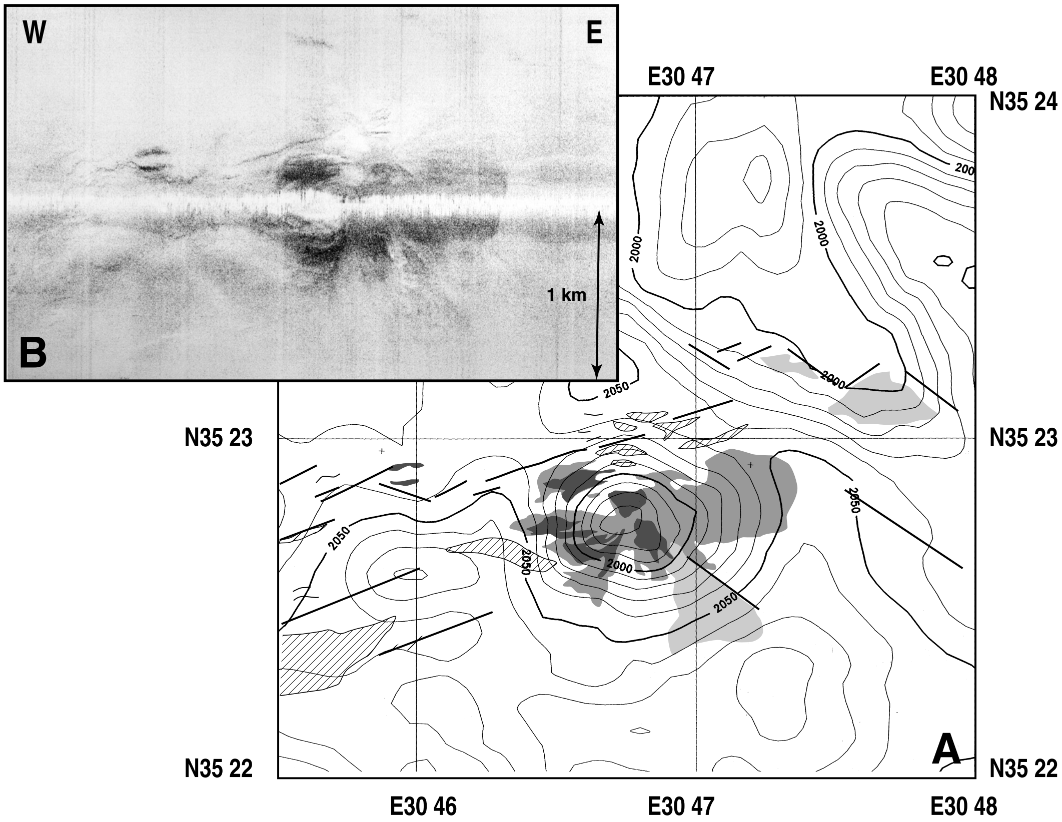


Figure 8. (A) Multibeam bathymetric map of Tuzlukush MV with the interpretation from the sidescan sonar record (B). The lines represent tectonic lineations, and the different patterns indicate different mud flows (gray scale) and acoustic shadows (hatched). For legend, see Figure 6.

both transpressional and transtensional tectonic regimes. The faults involved in this are mainly N120° dextral strike-slip faults, N150° oblique faults, and N50° synthetic Riedel faults. Active fracturing occurs where the stresses, especially tensile stresses, are more concentrated (Scholz et al., 1993). These regions of concentrated stresses, also called the breakdown regions, are found (1) at the termination of faults; (2) in the area of interaction between two or more faults, where the fault terminations are in close proximity or overlap (e.g., zones of relay); (3) at the intersection of several faults; or (4) along the fault trace, because friction during slip can form localized fracturing along the fault zone (Scholz et al., 1993; Curewitz and Karson, 1997). According to Curewitz and Karson (1997), fluid flow occurs preferentially within an interaction zone such that the three first structural settings are more permeable for focusing the fluid flow than the fracturing along the fault zone. Recent studies on the central domain of the Mediterranean Ridge (Huguen et al., 2004) as well as within its western branch (Rabaute et al., 2003; Chamot-Rooke et al., 2005) also emphasize the correlation of the shear strain component with mud output and the importance of the relay zones between the strike-slip faults for the localization of mud volcanism.

Tectonic Control on the Nature of Fluid Emissions and Mud Volcanism

A wide diversity of mud volcano morphologies is represented in many areas around the world (see Higgins and Saunders, 1974). For example, on the Barbados accretionary prism, several main types of observed mud structures include (1) active circular mud volcanoes that show extruded mud flows, (2) concentric flat-topped “mud pies” settled below the seafloor within subsiding basins, (3) piercing mud diapirs or mud mounds, and (4) up to 18-km-long mud ridges extruded from thrust faults and anticlinal crests (Brown and Westbrook, 1988; Henry et al., 1990; Le Pichon et al., 1990). The parameters that

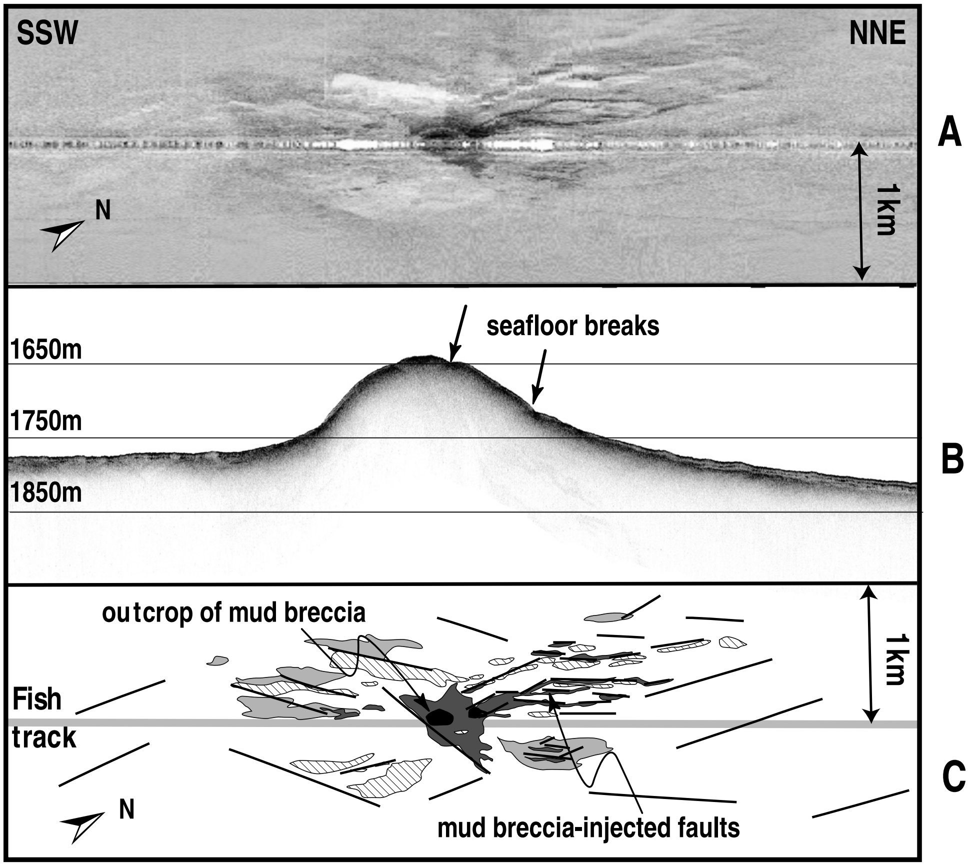


Figure 9. (A) Sidescan sonar image and (B) subbottom profiler record of Kula MV with (C) the interpretation. The different patterns indicate different mud flows (gray scale) and acoustic shadows (hatched). For legend, see Figure 6.

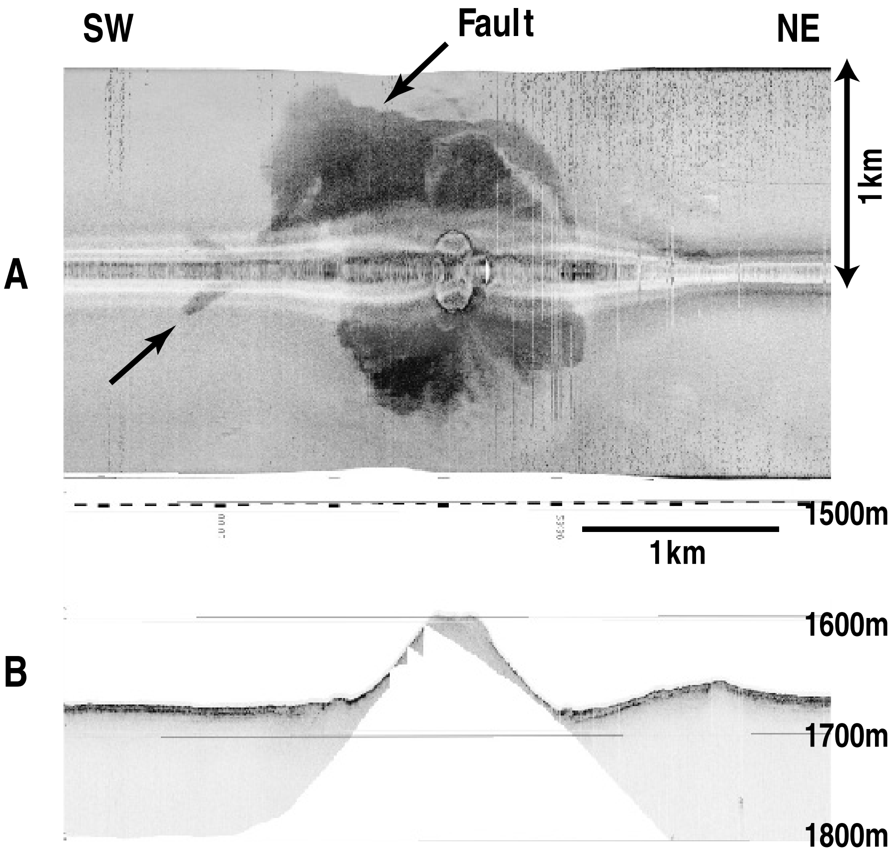


Figure 10. Sidescan sonar image (A) and subbottom profiler record (B) of Texel MV, modified after Woodside et al. (2002).

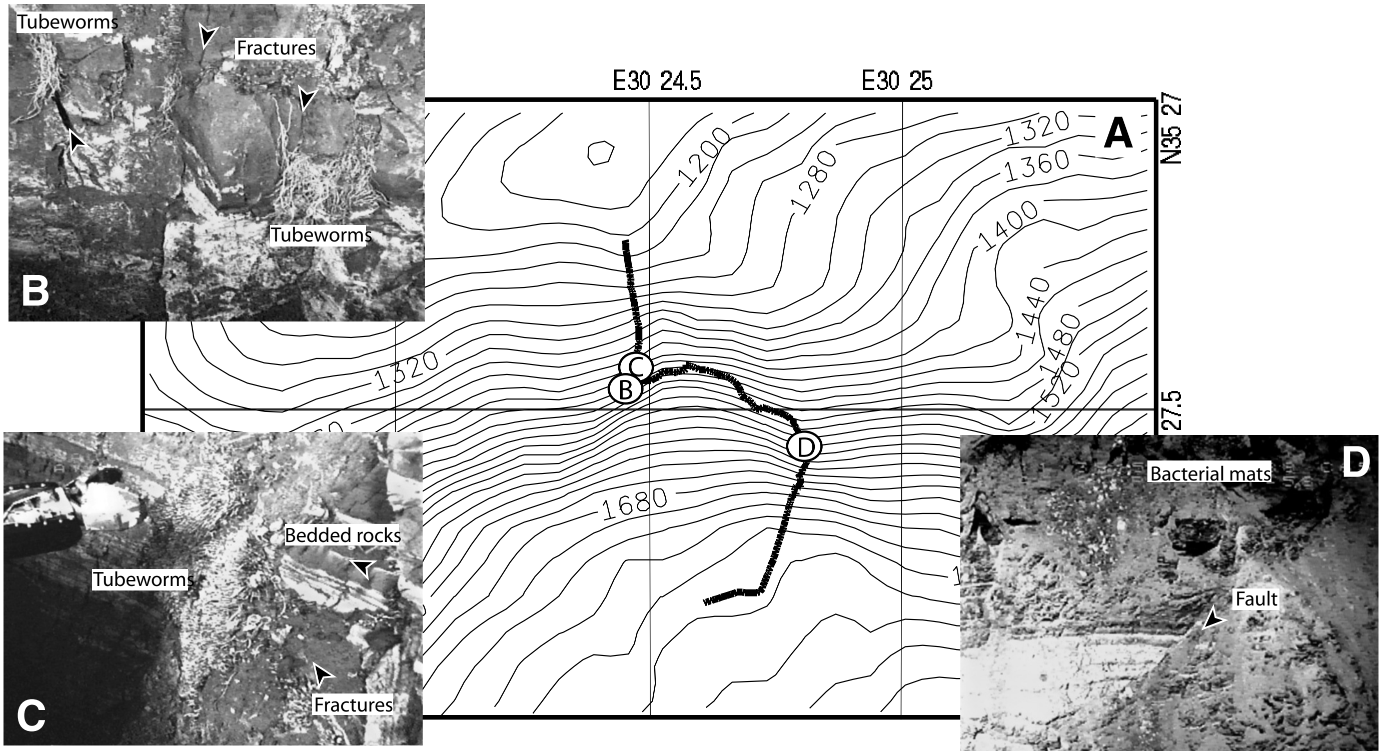


Figure 11. (A) Multibeam bathymetry map of the Faulted Ridge with the track of the *Nautile* dive and the location of the seafloor image showing: (B) the cliff and the tubeworms located within the fractures; (C) a bunch of living tubeworms at the intersection of fractures and beddings; and (D) bacterial mats on the cliff.

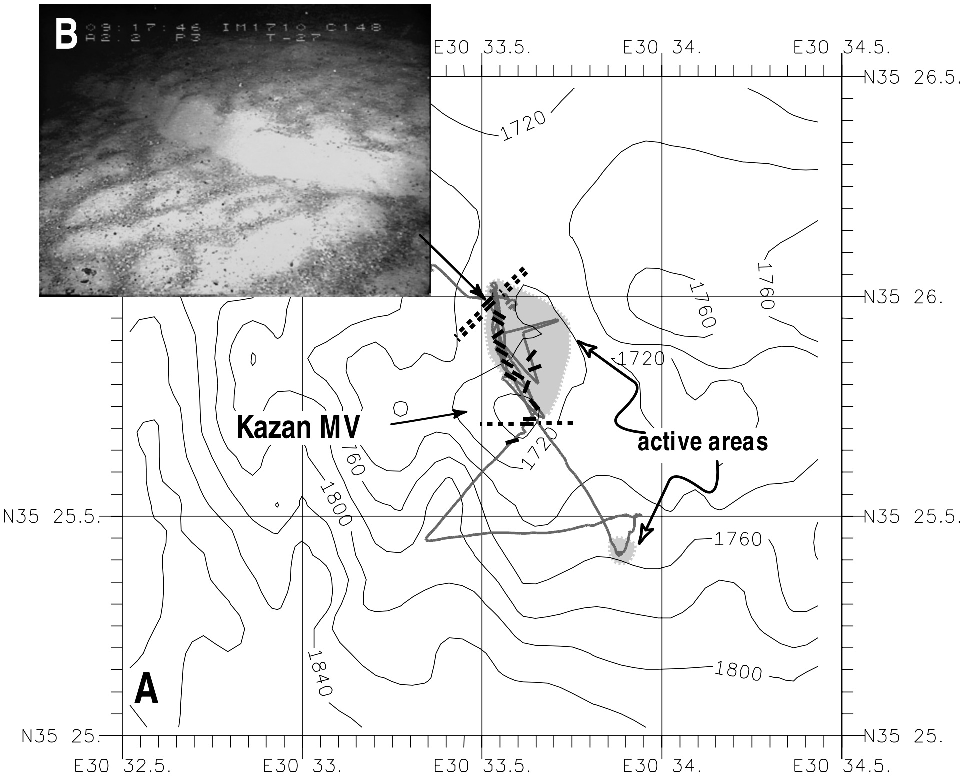


Figure 12. (A) Multibeam bathymetry map of Kazan MV with the direction of ridges (small lines) and scarps (dashed lines). (B) Seafloor image during dive 11 on Kazan MV, showing a fresh scarp of ~20 cm.

TABLE 1. FAULT DIRECTIONS MAPPED ALONG THE SONAR LINES IN THE SURROUNDINGS OF THE DIFFERENT MUD STRUCTURES

Mud volcanoes	Fault directions observed on EM12D	Sonar line	Fault directions observed on sonar	Signification into regional tectonics (ten Veen et al., 2004)
Amsterdam	N70°	MNLDT04	N60°–70°	N70° sinistral strike-slip
	N20°–30°	MNLDT06	N120°	N120° dextral transtensional
		MAK1-46	N20°–30°	N20° normal faults
			N140°–150°	N150° oblique faults
			N40°–55°	N50° synthetic shear
			N-S	
			N90°	
Kazan	N70°	MAK1-46	N50°–60°	N50° synthetic shear
			N70°	N70° sinistral strike-slip
			N110°–120°	N120° dextral transtensional
			N150°	N150° oblique faults
				N90°
Tuzlukush	N70°	MAK1-46	N70°	N70° sinistral strike-slip
	N150°		N50°–060°	N50° synthetic shear
			N120°–130°	
Saint Ouen l'Aumône	N150°	MAK1-46	N60°–70°	N70° sinistral strike-slip
	N70°		N110°–120°	N120° dextral transtensional
			N135°–150°	N150° oblique faults
Kula	N-S	MNLDT05	N-S	N-S normal faults
			N40°–60°	N50° synthetic shear
			N90°	
			N150°	

Source: ten Veen et al. (2004) and the present study.

control such diversity are unknown, as is the influence of the tectonic style on the nature of fluid emissions and the morphology of mud volcanoes. On the Mediterranean Ridge, the mud volcanoes also occur as highly variable structures, e.g., 2–8 km circular domelike structures (Napoli MV, Milano MV, and Maidstone MV), ridges (Moscow MV), large low-relief structures with strong acoustic backscatter from mud flows (Gelendzhik MV), wide flat extrusions of low-backscatter mud flows ("pies" of the eastern Mediterranean Ridge branch; Huguen et al., 2001a; Kopf et al., 2001). The viscosity and density of the mud probably largely control the geometry of the mud volcanoes (Brown, 1990). However, it is inferred that tectonics partly controls these morphological varieties (Kopf et al., 2001; Huguen et al., 2004).

In the Anaximander Mountains, mud volcanoes are morphologically less differentiated, although they also present differences in seeping activity, morphologies, and geophysical characteristics. Amsterdam MV stands out on account of its particular size (up to 3 km across), extensive associated mudflow to the south, and "mud pie" shape. This mud volcano is linked with large-scale deep-seated N20° normal faulting, providing a wide conduit for mud ascent. From theoretical calculations based on fluid dynamics (Kopf and Behrmann, 2000), it appears that the size and volume of the mud features are a function of the size of the feeder channel, and that large features generally relate to wider conduits.

The evidence for the seep activity of the Anaximander Mountains mud volcanoes, based on their geology (Zitter et al., 2005), associated chemosynthetic fauna (Olu-Leroy et al., 2004), and amount of degassing CH_4 (Charlou et al., 2003), indicates that the intensity of fluid emissions is highly variable. Fluid emissions appear very active in western Anaxagoras, especially near its intersection with Anaximenes seamount, at both Amsterdam and Kazan MV, as well as on the Faulted Ridge. On the other hand, Tuzlukush, Saint Ouen l'Aumône, and Kula MV appear less active or even dormant. Two parameters might constrain this difference in the nature of seeping: (1) the complex deformation at the interaction between the western Anaximander and the eastern Anaximander stress fields and (2) the differences in lithologies of the underlying units. Autochthonous limestones or other such brittle rocks take a longer time to become sealed by fluid precipitates, and hence they facilitate fluid seeps longer compared to more ductile units. Furthermore, thrusts separating the nappes sheets may provide a basis for later faulting and fluid pathways.

CONCLUSIONS

The Anaximander Mountains area displays evidence for active mud volcanism in an oblique convergent zone along the dominant structural trend of the western branch of the Cyprus arc. This plate boundary is defined by a broad wrench system accommodating precollisional deformation. The relationship between mud volcanism and neotectonic structures is observed from multibeam data and deep-tow sidescan sonar, as well as directly from a submersible. Numerous faults or fissures are observed in connection with the mud volcanoes that serve as conduits for mud ejection and the release of fluids. The faults linked with the occurrence of mud volcanoes depend on the tectonic setting, which is more extensional in the western part of the Anaximander Mountains and more transpressive along the Florence rise. However, mud volcanoes appear to be associated predominantly with the interplay of the dominant N70° sinistral shearing and with some major or minor extensional or transtensional faulting (N150° oblique faults, N120° dextral faults, or north-south to N20° normal faults). Thus, the extensional constraints generated by transtensive faulting appear to be the major conditions for mud extrusion. We propose a model whereby fluids from deep origin, derived from intraplate diagenetic deformation, are channeled along deep-seated crustal strike-slip faults (N70°, N120°, and N150°) and whereby remobilization of mud occurs at a shallower level and uses secondary faulting (north-south, N40–50°, N90°) and hydrofracturing as pathways.

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REFERENCES CITED

Ardvisson, R., Ben-Avraham, Z., Ekstrom, G., and Wdowinski, S., 1998, Plate tectonic framework for the October 9, 1996, Cyprus earthquake: Geophysical Research Letters, v. 25, no. 12, p. 2241–2244.

Barber, A.J., Tjokrosapoetro, S., and Charlton, T.R., 1986, Mud volcanoes, shale diapirs, wrench faults and melanges in accretionary complexes, eastern Indonesia: Bulletin of the American Association of Petroleum Geologists, v. 70, p. 1729–1741.

Brown, K.M., 1990, The nature and hydrogeologic significance of mud diapirs and diatremes for accretionary systems: Journal of Geophysical Research, v. 95, no. B6, p. 8969–8982.

Brown, K.M., and Westbrook, G.K., 1988, Mud diapirism and subcretion in the Barbados Ridge Complex: The role of fluids in accretionary processes: Tectonics, v. 7, p. 613–640.

Camerlenghi, A., Cita, M.B., Della Vedova, B., Fusi, N., Mirabile, G.L., and Pellis, G., 1995, Geophysical evidence of mud diapirism on the Mediterranean Ridge accretionary complex: Marine Geophysical Researches, v. 17, p. 115–141, doi: 10.1007/BF01203423.

Chamot-Rooke, N., Rabaute, A., and Kreemer, C., 2005, Western Mediterranean Ridge mud belt correlates with active shear strain at the prism-backstop geological contact: Geology, v. 33, no. 11, p. 861–864.

Charlou, J.L., Donval, J.P., Zitter, T., Roy, N., Jean-Baptiste, P., Foucher, J.-P., Woodside, J., and MEDINAUT Scientific Party, 2003, Evidence of methane venting and geochemistry of brines on mud volcanoes of the eastern Mediterranean Sea: Deep Sea Research I, v. 50, no. 8, p. 941–958.

Curewitz, D., and Karson, J.A., 1997, Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction: Journal of Volcanology and Geothermal Research, v. 79, p. 149–168, doi: 10.1016/S0377-0273(97)00027-9.

Faugères, J.C., Gonthier, E., Bobier, C., and Griboulard, R., 1997, Tectonic control on sedimentary processes in the southern termination of the Barbados Prism: Marine Geology, v. 140, p. 177–240.

Glover, C., and Robertson, A., 1998, Neotectonic intersection of the Aegean and Cyprus tectonic arcs: Extensional and strike-slip faulting in the Isparta Angle, SW Turkey: Tectonophysics, v. 298, no. 1–3, p. 103–132, doi: 10.1016/S0040-1951(98)00180-2.

Gutnic, M., Monod, O., Poisson, A., and Dumont, J.-F., 1979, Géologie des Taurides occidentales (Turquie): Mémoires de la Société Géologique de France LVIII, v. 137, Paris, 112 p.

Haese, R.R., Hensen, C., and de Lange, G., 2006, Pore water geochemistry of eastern Mediterranean mud volcanoes: Implications for fluid transport and fluid origin: Marine Geology, v. 225, p. 191–208.

Henry, P., Le Pichon, X., Lallemant, S., Foucher, J.-P., Westbrook, G., and Hobart, M., 1990, Mud volcano field seaward of the Barbados Accretionary Complex: A deep-towed side scan sonar survey: Journal of Geophysical Research, v. 95, no. B6, p. 8917–8929.

Hieke, W., Cita, M.B., Mirabile, G.L., Negri, A., and Werner, F., 1996, The summit area (Antaeus / Pan di Zucchero) of the Mediterranean Ridge: A mud diapir field?: Marine Geology, v. 132, p. 113–129, doi: 10.1016/0025-3227(95)00156-5.

Higgins, G.E., and Saunders, J.B., 1974, Mud volcanoes: Their nature and origin: Verhandlungen der Naturforschenden Gesellschaft in Basel, v. 84, p. 101–152.

Hsü, K.J., Cita, M.B., and Ryan, W.B.F., 1973, The origin of the Mediterranean evaporates, *in* Ryan, W.B.F., et al., eds., Initial reports of the DSDP 13: Washington, DC: U.S. Government Printing Office, p. 1203–1231.

Huguen, C., 2001, Déformation récente à actuelle et argilo-cinèse associée au sein de la Ride Méditerranéenne (Méditerranée Orientale) [Ph.D. thesis]: Université Paris 6, Paris, 260 p.

Huguen, C., Mascle, J., Chaumillon, E., Woodside, J.M., Benkhelil, J., Kopf, A., and Volkonskaya, A., 2001a, Deformational styles of the eastern Mediterranean Ridge and surroundings from combined swath mapping and seismic reflection profiling: Tectonophysics, v. 343, no. 1–2, p. 21–47, doi: 10.1016/S0040-1951(01)00185-8.

Huguen, C., Benkhelil, J., Giresse, P., Mascle, J., Muller, C., Woodside, J., Zitter, T., and the Medinaut Scientific Party, 2001b, Échantillons rocheux provenant de "volcans de boue" de Méditerranée orientale: Oceanologica Acta, v. 24, no. 4, p. 349–360.

Huguen, C., Mascle, J., Chaumillon, E., Kopf, A., Woodside, J., and Zitter, T., 2004, Structural setting and tectonic control of mud volcanoes from the Central Mediterranean Ridge (Eastern Mediterranean): Marine Geology, v. 209, p. 245–263, doi: 10.1016/j.margeo.2004.05.002.

Kopf, A., and Behrmann, J.N., 2000, Extrusion dynamics of mud volcanoes on the Mediterranean Ridge accretionary complex, *in* Vendelille, B.C., et al., eds., Salt, shales and igneous diapirs in and around Europe: Geological Society of London Special Publication 174, p. 169–204.

Kopf, A., Klaeschen, D., and Mascle, J., 2001, Extreme efficiency in dewatering accretionary prisms: Earth and Planetary Science Letters, v. 189, p. 295–313.

Le Pichon, X., Foucher, J.P., Boulègue, J., Henry, P., Lallemant, S., Benedetti, M., Avedik, F., and Mariotti, A., 1990, Mud volcano field seaward of the Barbados Accretionary Complex: A submersible survey: Journal of Geophysical Research, v. 95, no. B6, p. 8931–8943.

Le Pichon, X., Chamot-Rooke, N., and Lallemant, S., 1995, Geodetic determination of the kinematics of central Greece with respect to Europe: Implications for Eastern Mediterranean Tectonics: Journal of Geophysical Research, v. 100, no. B7, p. 12,675–12,690, doi: 10.1029/95JB00317.

Limonov, A.F., Woodside, J.M., Cita, M.B., and Ivanov, M.K., 1996, The Mediterranean Ridge and related mud diapirism: A background: Marine Geology, v. 132, p. 7–19, doi: 10.1016/0025-3227(96)00150-8.

Lykousis, V., Alexandri, S., Woodside, J., Nomikou, P., Perissoratis, C., Sakellariou, D., de Lange, G., Dählmann, A., Casas, D., Rousakis, G., Ballas, D. and Ioakim, Chr., 2004, New evidence of extensive active mud volcanism in the Anaximander mountains (Eastern Mediterranean): The "ATHINA" mud volcano: Environmental Geology, v. 46, p. 1030–1037.

Mascle, J., Huguen, C., Benkhelil, J., Chamot-Rooke, N., Chaumillon, E., Foucher, J.-P., Griboulard, R., Kopf, A., Lamarche, G., Volkonskaia, A., Woodside, J., and Zitter, T., 1999, Images may show start of European-African plate collision: Eos (Transactions, American Geophysical Union), v. 80, no. 37, p. 421, 425, 428, doi: 10.1029/99EO00308.

McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., and Veis, G., 2000, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus: Journal of Geophysical Research, v. 105, no. B3, p. 5695–5719, doi: 10.1029/1999JB900351.

McKenzie, D.P., 1972, Active tectonics of the Mediterranean region: Geophysical: Journal of the Royal Astronomical Society, v. 30, p. 109–185.

MEDINAUT/MEDINETH Shipboard Scientists: Aloisi, G., Asjes, S., Bakker, K., Bakker, M., Charlou, J.-L., De Lange, G., Donval, J.-P., Fiala-Medioni, A., Foucher, J.-P., Haanstra, R., Haese, R., Heijs, S., Henry, P., Huguen, C., Jelsma, B., de Lint, S., van der Maarel, M., Mascle, J., Muzet, S., Nobbe, G., Pancost, R., Pelle, H., Pierre, C., Polman, W., de Senerpont Domis, L., Sibuet, M., van Wijk, T., Woodside, J., and Zitter, T., 2000, Linking Mediterranean brine pools and mud volcanism: Eos (Transactions, American Geophysical Union), v. 81, no. 51, p. 625, 631–633.

Olu-Leroy, K., Sibuet, M., Levitre, G., Gofas, S., Salas, C., Fiala-Médioni, A., Foucher, J.-P., and Woodside, J.M., 2004, Cold seeps communities in the deep eastern Mediterranean Sea: Composition and spatial distribution on mud volcanoes: Deep-sea Research, Part I: Oceanographic Research Papers, v. 51, no. 12, p. 1915–1936, doi: 10.1016/j.dsr.2004.07.004.

Pérez-Belzuz, F., Alonso, B., and Ercilla, G., 1997, History of mud diapirism and trigger mechanisms in the Western Alboran Sea: Tectonophysics, v. 282, p. 399–422, doi: 10.1016/S0040-1951(97)00226-6.

Pilidou, S., Prietsley, K., Jackson, J., and Maggi, A., 2004, The 1996 Cyprus earthquake: A large, deep event in the Cyprean Arc: Geophysical Journal International, v. 158, p. 85–97, doi: 10.1111/j.1365-246X.2004.02248.x.

Poisson, A., 1977, Recherches géologiques dans les Taurides occidentales (Turquie) [Ph.D. thesis]: Université Paris 11, Paris.

Rabaute, A., Chamot-Rooke, N., and the DOTMED Team, 2003, Tectonics and mud volcanism at the western Mediterranean Ridge: Backstop contact: Geophysical Research Abstracts, v. 5, p. 12,007.

Reed, D.L., Silver, E.A., Tagudin, J.E., Shipley, T.H., and Vrolijk, P., 1990, Relations between mud volcanoes, thrust deformation, slope sedimentation, and gas hydrate, offshore north Panama: Marine and Petroleum Geology, v. 7, p. 44–55, doi: 10.1016/0264-8172(90)90055-L.

Robertson, A.H.F., and Kopf, A., 1998a, Origin of clasts and matrix within the Milano and Napoli mud volcanoes, Mediterranean Ridge accretionary complex, *in* Robertson A.H.F., et al., eds., Proceedings of the ODP, Scientific Results: College Station, Texas (Ocean Drilling Program), v. 160, p. 575–595.

Robertson, A.H.F., and Kopf, A., 1998b, Tectonic setting and processes of mud volcanism on the Mediterranean ridge accretionary complex: Evidence from Leg 160, *in* Robertson A.H.F., et al., eds., Proceedings of the ODP, Scientific Results: College Station, Texas (Ocean Drilling Program), v. 160, p. 663–680.

Robertson, A.H.F., and Woodcock, N.H., 1980, Strike-slip related sedimentation in the Antalya Complex, SW Turkey: Special Publication of the International Association of Sedimentologists, v. 4, p. 127–145.

Scholz, C.H., Dawers, N.H., Yu, J.Z., Anders, M.H., and Cowies, P.A., 1993, Fault growth and fault scaling laws: Preliminary results: Journal of Geophysical Research, v. 98, p. 21,951–21,961.

Sumner, R.H., and Westbrook, G.K., 2001, Mud diapirism in front of the Barbados accretionary wedge: The influence of fracture zones and North America–South America plate motions: Marine and Petroleum Geology, v. 18, p. 591–613, doi: 10.1016/S0264-8172(01)00010-1.

Taymaz, T., Jackson, J., and McKenzie, D., 1991, Active tectonics of the north and central Aegean Sea: Geophysical Journal International, v. 106, p. 433–490.

ten Veen, J.H., and Kleinspehn, K.L., 2002, Geodynamics along an increasingly curved convergent plate boundary: Late Miocene–Pleistocene Rhodes, Greece: Tectonics, v. 21, no. 3, doi: 10.1029/2001TC001287.

ten Veen, J.H., and Postma, G., 1999, Rollback controlled vertical movements of outer-arc basins of the Hellenic subduction zone (Crete, Greece): Basin Research, v. 11, no. 3, p. 243–366, doi: 10.1046/j.1365-2117.1999.00098.x.

ten Veen, J.H., Woodside, J.M., Zitter, T.A.C., Dumont, J.-F., Mascle, J., and Volkonskaia, A., 2004, Neotectonic evolution of the Anaximander Mountains at the junction of the Hellenic and Cyprus arcs: Tectonophysics, v. 391, p. 35–65, doi: 10.1016/j.tecto.2004.07.007.

Vernette, G., Mauffret, A., Bobier, C., Briceno, L., and Gayet, J., 1992, Mud diapirism, fan sedimentation and strike-slip faulting: Caribbean Colombian Margin: Tectonophysics, v. 202, p. 335–349, doi: 10.1016/0040-1951(92)90118-P.

Vogt, P.R., Gardner, J., and Crane, K., 1999, The Norwegian-Barents-Svalbard (NBS) continental margin: Introducing a natural laboratory of mass wasting, hydrates, and ascent of sediment, pore water, and methane: Geo-Marine Letters, v. 19, p. 2–21, doi: 10.1007/s003670050088.

Volgin, A.V., and Woodside, J.M., 1996, Sidescan sonar images of mud volcanoes from the Mediterranean Ridge: Possible causes of variations in backscatter intensity: Marine Geology, v. 132, p. 39–53, doi: 10.1016/0025-3227(95)00152-2.

Wessel, P., and Smith, W.H.F., 1998, New, improved version of the Generic Mapping Tools released: Eos (Transactions, American Geophysical Union), v. 79, p. 579.

Woodside, J.M., Ivanov, M.K., and Limonov, A.F., 1997, Neotectonics and fluid flow through seafloor sediments in the Eastern Mediterranean and Black Seas, Part I: Eastern Mediterranean Sea: IOC Technical Series (Intergovernmental Oceanographic Commission, UNESCO), no. 48, UNESCO, Paris, 128 p.

Woodside, J.M., Ivanov, M.K., and Limonov, A.F., 1998, Shallow gas and gas hydrates in the Anaximander Mountains region, eastern Mediterranean

Sea, *in* Henriet, J.P., and Mienert J., eds., Gas hydrates: Relevance to world margin stability and climate change: Geological Society of London Special Publication 137, p. 177–193.

Woodside, J.M., Mascle, J., Huguen, C., and Volkonskaia, A., 2000, The Rhodes Basin, a post-Miocene tectonic trough: Marine Geology, v. 165, no. 1–4, p. 1–12, doi: 10.1016/S0025-3227(99)00140-1.

Woodside, J.M., Mascle, J., Zitter, T.A.C., Limonov, A.F., Ergun, M., and Volkonskaia, A., 2002, The Florence Rise, the western bend of the Cyprus Arc: Marine Geology, v. 185, no. 3–4, p. 177–194, doi: 10.1016/S0025-3227(02)00194-9.

Yolsal, Y., and Taymaz, T., 2004, Seismotectonics of the Cyprus Arc and Dead Sea Fault Zone: Eastern Mediterranean: Eos (Transactions, American Geophysical Union), v. 85, no. 47, fall meeting supplement, Abstract T 52B-06.

Zitter, T.A.C., 2004, Mud volcanism and fluid emissions in Eastern Mediterranean neotectonic zones [Ph.D. thesis]: Vrije Universiteit, Amsterdam, 144 p.

Zitter, T.A.C., Woodside, J.M., and Mascle, J., 2003, The Anaximander Mountains: A clue to the tectonics of Southwest Anatolia: Geological Journal, v. 38, p. 375–394, doi: 10.1002/gj.961.

Zitter, T.A.C., Huguen, C., and Woodside, J.M., 2005, Geology of mud volcanoes in the Eastern Mediterranean from combined sidescan sonar and submersible surveys: Deep Sea Research, Part I, v. 52, no. 3, p. 457–475, doi: 10.1016/j.dsr.2004.10.005.

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