Western Mediterranean Ridge mud belt correlates with active shear strain at the prism-backstop geological contact

N. Chamot-Rooke
A. Rabaute } Laboratoire de Géologie, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris cedex 05, France
C. Kreemer Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada 89557, USA

ABSTRACT

A high-resolution swath-mapping survey conducted in the deep waters of the eastern Mediterranean Sea allowed mapping of active faults and mud volcanism along a sizable portion of the Mediterranean Ridge. Active shear is localized at the prism-backstop contact, a major dextral flower structure and a site of massive mud expulsion. We investigate the relationship between the mud output rate and horizontal strain rate by combining the mud volume estimate from sea-bottom reflectivity with kinematic modeling based on far-field global positioning system data and local fault and strain patterns. We find a direct correlation between maxima of mud output and maxima of the shear component of strain at the backstop contact. Mud volcanism may reflect the abundance of solid (mud) and fluid (methane) sources combined with a favorable tectonic regime established at the prism-backstop contact in post-Pliocene time, in relation to plate tectonic changes.

Keywords: mud volcanism, active tectonics, accretionary prism, Mediterranean Ridge.

INTRODUCTION

Little is known about the nature of the relationship between active faulting and mud volcanism, although these processes are frequently associated (see review in Kopf, 2002). Remote sensing surveys in shallow and deep marine waters provide the unique opportunity to map active faults and mud features. Multibeam sonar mapping and sidescan sonar mapping at convergent margins, in particular, are effective tools to detect sites of mud expulsion and to delineate active faults that may act as conduits to drive mud, fluid, and eventually gas to the surface. The best-documented examples are the Barbados (Stride et al., 1982; Brown and Westbrook, 1988) and Mediterranean Ridge (Kastens et al., 1992; Fusi and Kenyon, 1996; Huguen et al., 2001) accretionary prisms. The occurrence of mud volcanism at convergent margins has been related to a variety of potential faults, including deep décollements (Westbrook and Smith, 1983; Camerlenghi et al., 1995), splay faults (Henry et al., 2003), incipient and intersecting thrusts (Breen et al., 1986; Silver et al., 1986), strike-slip faults (Huguen et al., 2004), zones of extension (Costa et al., 2004), and back thrusts at the contact between prism and backstop (Camerlenghi et al., 1995; Kopf et al., 1998). There is little evidence for a hierarchy in these conduits.

Here we combine quantitative studies of mud volume (Rabaute et al., 2003) and active fault kinematics (Kreemer and Chamot-Rooke, 2004), both sharing the same extensive side-scan sonar and bathymetric data collected over the Mediterranean Ridge. Mud volume computations are based on image analysis of the backscatter intensity (reflectivity) of the seafloor, while kinematics of major faults were modeled by combining structural mapping of fault traces with far-field kinematic boundary conditions obtained by the global positioning system (GPS) and orientation of seamount tracks traveling into the wedge (Fig. 1). This quantitative approach allows us to investigate the relationships between mud output rate and horizontal strain rate over a sizable portion of an active accretionary prism.

MARINE DATA SET

The survey (Médée Cruise, conducted in 1995) covers a large portion of the Mediterranean Ridge from trench to backstop, including the Kephalonia, Cobblestone, and Pan di Zucchero mud fields (Camerlenghi et al., 1992; Cita et al., 1981) (Fig. 1). Bathymetric and seabed reflectivity data (using the Simrad EM12 system of the RV *L'Atalante*), complete with near-vertical seismic data, were used to produce a synthetic structural map of major active faults (Fig. 2).

Reflectivity mosaics were further analyzed in terms of high-reflectivity patches. Several features at the seafloor can cause high reflectivity, including mudflows, landslides, steep slopes, fault traces, and gas seeps (Volgin and Woodside, 1996). Mudflows were identified by cross-checking high backscattered signals, multibeam morphology, slopes (removed above 10°), and coring. We found that the backscattered level anticorrelates with the depth of the mud breccias-hemipelagites contact, and that the limit of detection of this contact by the EM12 sonar is near 80–100 cm (Rabaute et al., 2003).

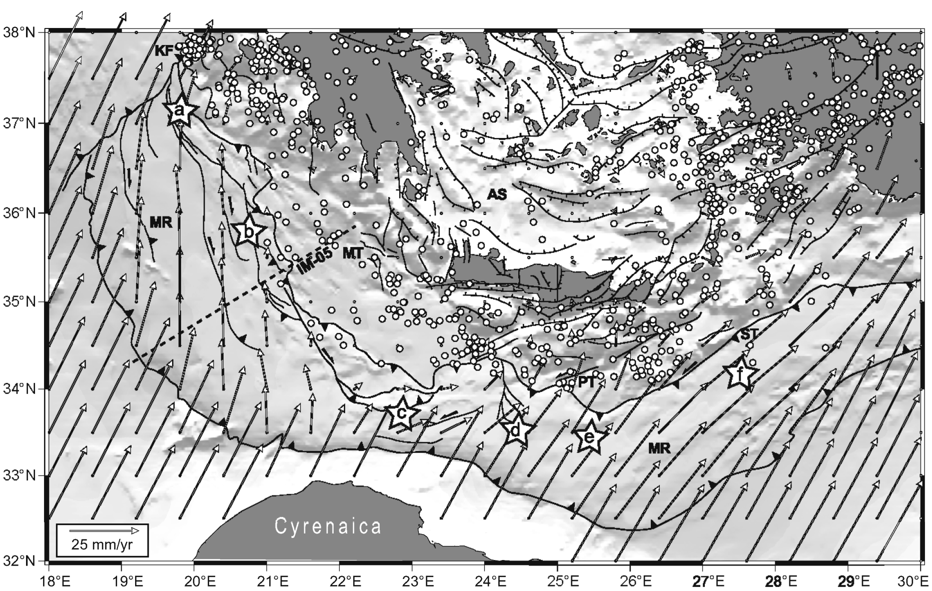

Figure 1. Horizontal velocity field over Mediterranean Ridge (Kreemer and Chamot-Rooke, 2004). Motion is given with respect to backstop. Stars locate mud fields of eastern Mediterranean: a—Kephalonia field; b—Cobblestone field; c—Pan di Zucchero field; d—Prometheus II and Olympi fields; e—United Nations field; f—Strabo field. Open dots—shallow seismicity (M > 4 and depth <20 km). MR—Mediterranean Ridge; AS—Aegean Sea; KF—Kephalonia fault; MT—Matapan trench; PT—Pliny trench; ST—Strabo trench.

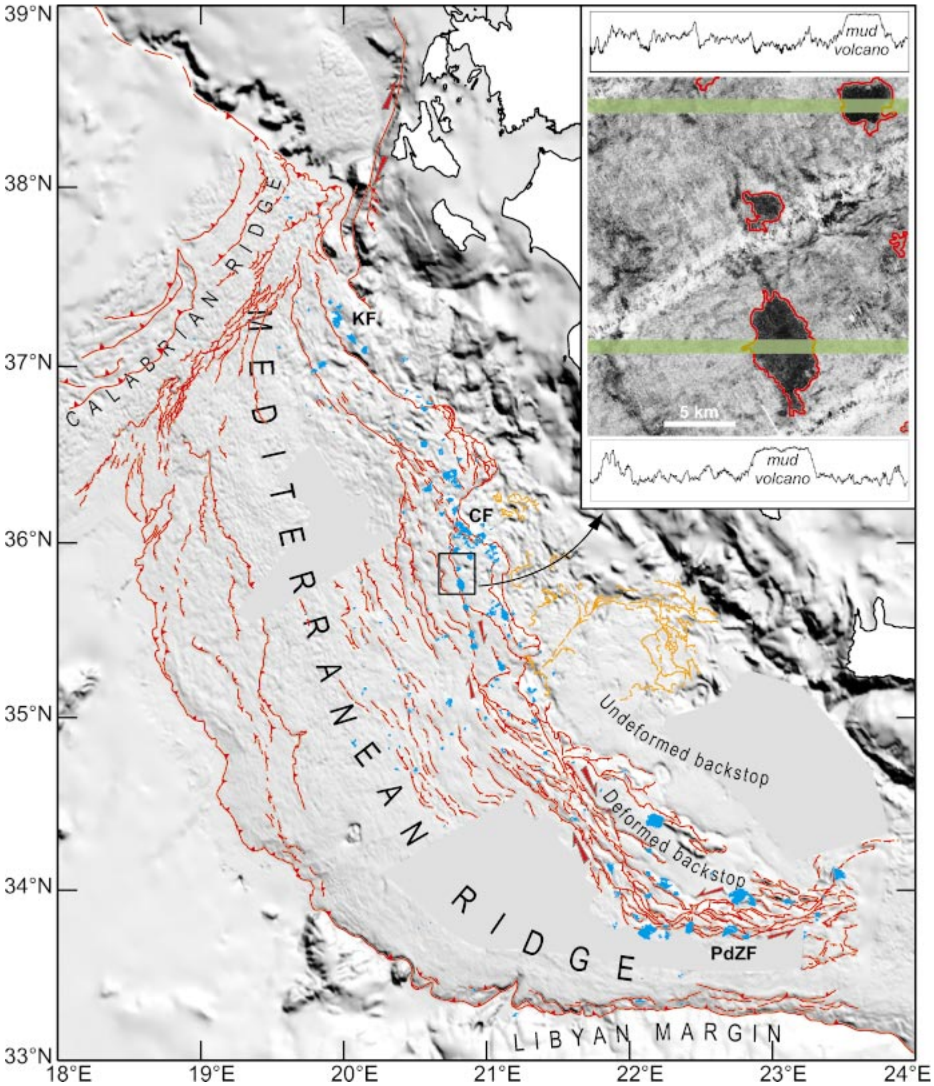

Figure 2. Simplified tectonic map of western Mediterranean Ridge showing inferred active faults with style (strike slip and thrust) (red) and mudflows (blue patches). Salt-related structures within backstop are shown in orange. Inset: extract of reflectivity map, with mud flows contoured in red; backscattered signal extracted along two profiles (green) crossing mud volcanoes.

Mudflows are not evenly distributed over the Mediterranean Ridge (Fig. 2). They concentrate into a narrow 500-km-long mud belt extending from Pan di Zucchero in the southeast to the seaward extension of the Kephalonia fault in the northwest, and are associated with active strike-slip faults located near the wedge-backstop contact, interpreted as a major transpressive dextral shear zone. Detailed mapping suggests that most of the mud volcanoes are located in areas of interaction between faults (releasing and restraining steps), rather than on the traces of the faults. Fault interaction areas are known to be stress concentrators and may thus act as preferential fluid paths (Curewitz and Karson, 1997). Qualitative interpretation of the marine data set thus confirms the link between the wedge-backstop tectonic contact and massive eruption of mud.

MUD OUTPUT RATE

We identified 215 mudflows summing to a total extruded mud surface of almost 1500 km^2 (Rabaute et al., 2003). Because we are interested here in the relative distribution of mud rather than the absolute volume, the surface covered by mudflows is used as a proxy for the rate of output. Using the limit of detection of the mud breccias by the EM12 sonar, and reasonable sedimentation rates, we find that the identified mud volcanoes have been active at least once during the past 27 ± 9 k.y. Although the periodicity of mud eruption remains largely speculative, superposition of flows is recognized along the flank of some of the larger mud volcanoes. This periodicity is smaller than the corresponding time slice investigated by the sonar, thus the relative distribution of sonar-detected mudflows reflects spatial variation in mud output rate.

To investigate the distribution of mud output, we computed the surface covered by mudflows inside 27.5×27.5 km cells (the same cell size is used in the kinematic model). Results are displayed in Figure 3A. Cells are shown only if the surface covered by mudflows is greater than zero (i.e., at least one flow identified within it). The number in the center of each cell indicates the surface covered by the mud (in square kilometers). Finally, we superimposed contours of the grid-cell mud surface (in percent) to better visualize variations in the amount of expelled mud. The surface covered by mud exceeds 10% for the Cobblestone and Pan di Zucchero mud fields.

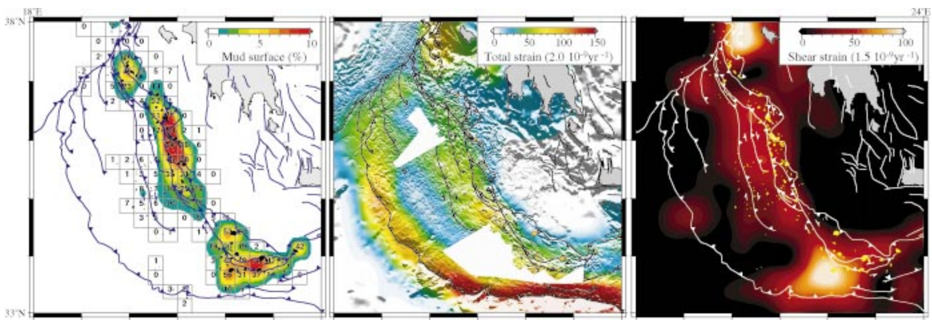

Figure 3. A: Mud output rate given as percentage of seafloor surface covered by mudflows. Numbers indicate mud surface within cell (in km^2). Major faults are shown and mudflows identified as black patches. B: Total horizontal strain rate obtained by kinematic modeling, given as second invariant of modeled strain rate field (in yr^{-1}). Bathymetry is superimposed as shades, mudflows in yellow. C: Shear strain component of horizontal strain rate (in yr^{-1}).

WEDGE AND BACKSTOP HORIZONTAL STRAIN RATES

The Mediterranean Ridge accretionary prism is the result of the ongoing convergence of Nubia (Africa) with the Aegean block (Aegean Sea and Hellenic Arc). The horizontal strain rate was obtained by combining the active fault maps with available kinematic indicators (Kreemer and Chamot-Rooke, 2004, and references therein). GPS measurements place strong far-field constraints while seamount track orientations—or asperities carried by the African plate and traveling through the wedge—can be used to constrain the local direction of convergence. Faults are introduced into the inversion as zones of weakness, and their style is specified. Their relative importance was evaluated through structural mapping, and the structural scheme was further simplified into a limited set of major faults prior to inversion (Kreemer and Chamot-Rooke, 2004).

The results of the kinematic modeling are shown as velocities with respect to the Hellenic backstop (Fig. 1) and total strain rate, i.e., the second invariant of the model strain rate field (Fig. 3B). We also extract the shear component (Fig. 3C). High shear strain at the wedge-backstop contact is the result of partitioning of the oblique subduction of Africa with respect to the Hellenic margins. Our kinematic modeling predicts ~2 cm/yr of dextral motion at the western Mediterranean Ridge–backstop contact and the same amount of sinistral strike slip at Pliny and Strabo trenches along the eastern Mediterranean Ridge (Kreemer and Chamot-Rooke, 2004).

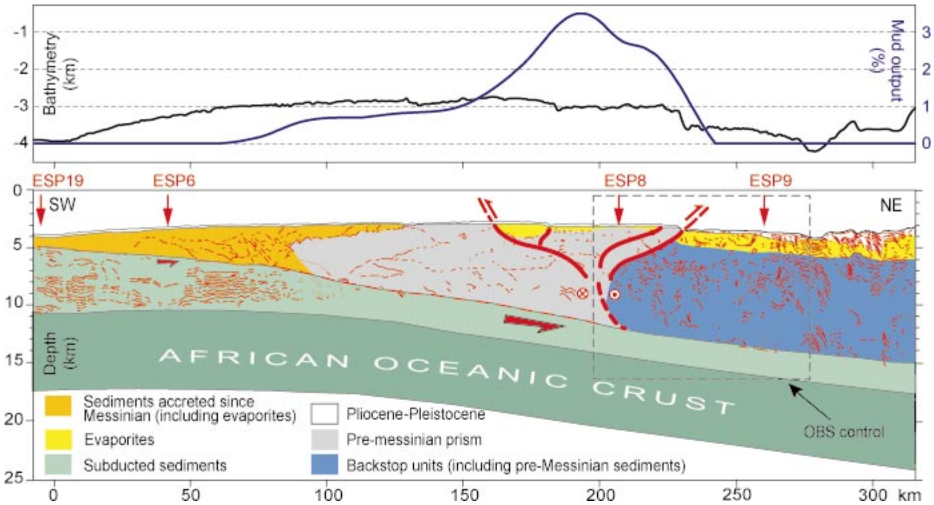

Figure 4. Interpretation of a deep seismic profile across accretionary prism and Hellenic backstop (IM-05, located in Fig. 1). Bathymetry along profile and rate of mud output are shown above. ESP—expanding spread profiles; OBS—ocean bottom seismographs.

CORRELATION BETWEEN MUD OUTPUT RATE AND HORIZONTAL STRAIN RATE COMPONENTS

Properties of the model strain rate field include high deformation in the frontal portion of the wedge roughly coinciding with the post-Messinian portion of the wedge and a band of weakly deforming prism ~100 km inward of the front, covering the Miocene prism. Both portions of the prism show very few mud volcanoes. Shear strain is high at the boundary between prism and backstop, in relation to the high number of strike-slip faults recognized here. Deformation is strongest immediately north of the Cyrenaica promontory, as expected from the short distance there between the Hellenic continental backstop and the African margin engaged in the subduction.

Mud output rate in the Cobblestone field is as high as in the Pan di Zucchero field: mud volcanism does not decrease away from the precollision zone, at variance with the generally accepted view of a direct link between Africa precollision and massive mud eruption. A striking result is the high degree of correlation between the mud output rate and the shear component of the strain rate field. The two areas of very large mud expulsion (Cobblestone and Pan di Zucchero mud fields) coincide with two maxima of the shear strain.

DISCUSSION

In the Barbados accretionary prism, maximum mud volcanism seems to be in the areas of high accretion rates and high shortening rates, i.e., the first 100–150 km of the frontal wedge (Brown and Westbrook, 1988), although sparse mud volcanism also occurred ~200 km from the front (Biju-Duval et al., 1982). Hydrofracture mechanics suggest that the portions of the prism under extensional and strike-slip regimes are efficiently vented sites, because fractures are easier to open (Behrmann, 1991; Moore and Vrolijk, 1992; Tobin et al., 1993). Conversely, hydrofracturing requires near-lithostatic fluid pressure under a thrust regime, and the subhorizontal orientation of the hydrofractures may not be optimal for fluid escape. These poorly vented portions of the prism are potential sites of pressure buildup in the footwall of thrust faults (Hayward et al., 2003), ultimately leading to mud volcanism (Behrmann, 1991).

The hydrofracture model is challenged by the contrasting proportions of the volume of mud erupted in the frontal portion of Barbados (virtually all) and Mediterranean (only a few percent of the total emitted volume) prisms. Camerlenghi et al. (1995) proposed that the Messinian evaporites prevent extrusion of deeper overpressured sediments to the surface, so that mud volcanoes would exclusively pierce where evaporites are thin or absent. The distribution of mud volcanoes that we obtain here shows a small increase of mud at the transition between the post-Messinian wedge and pre-Messinian wedge ~80 km from the front (Fig. 4) (Reston et al., 2002). However, most of the mud volcanoes are far away from this boundary.

The estimated depth of the décollement below the area of intensive mud output is between 7 and 10 km (Fig. 4), somewhat deeper than the reported depth of fluid circulation (Deyhle and Kopf, 2001). Using an average geothermal gradient of 20–25°C/km (Camerlenghi et al., 1995), the temperature at the décollement is likely to be higher than 150°C. At these depth and temperature ranges, sediments have already undergone dehydration and low-grade metamorphic reactions (Moore and Saffer, 2001), and they should not be a large source of in situ fluid production. If the site of mud production coincides with the dewatering window, then the distance to the trench would be three to five times greater than that reported in other subduction zones (Silver et al., 2000; Moore and Saffer, 2001). However, our depth and temperature estimations are within the degassing window due to organic matter cracking (Luo and Vasseur, 1996), suggesting a link between enhanced methane production at depth and the location of maximum mud eruption at the surface.

Apart from the origin of the fluid component of the mud, high rates of mud output at the contact between the prism and backstop may also relate to the abundance of the solid source (Rabaute et al., 2003) combined with favorable tectonic regime. Mud volcanism triggered by recent plate motion changes has been proposed for the volcanoes found seaward of the Barbados front, in relation to strike-slip faulting affecting the oceanic crust (Sumner and Westbrook, 2001). Recent tectonics of the eastern Mediterranean suggest that the post-Pliocene kinematic reorganization due to the propagation of the North Anatolian fault in the Aegean, together with the complex shape of the backstop, changed the tectonic regime at the prism-backstop boundary from moderately compressive to highly compressive, then to highly sheared (Le Pichon et al., 1995; Kreemer and Chamot-Rooke, 2004; Huguen et al., 2004; Costa et al., 2004). This scenario would be compatible with pressure building during the compressive stage followed by mud and fluid escape during the wrench stage. It is also in agreement with the young age (1–2 Ma) of the Mediterranean mud volcanoes (Robertson and Ocean Drilling Program Leg 160 Scientific Party, 1996).

ACKNOWLEDGMENTS

We thank the crew and scientific members of the Médée Cruise onboard the RV *L'Atalante* and Ifremer Brest for multibeam data acquisition. The paper benefited from careful reviews by Angelo Camerlenghi, Graham Westbrook (who pointed out to us that large mud volcanoes do develop in the more landward part of the Barbados accretionary complex), and Pierre Henry (who drew our attention to the potential role of organic matter cracking).

REFERENCES CITED

Behrmann, J.H., 1991, Conditions for hydrofracture and the fluid permeability of accretionary wedges: Earth and Planetary Science Letters, v. 107, p. 550–558, doi: 10.1016/0012-821X(91)90100-V.

Biju-Duval, B., Le Quellec, P., Mascle, A., Renard, V., and Valery, P., 1982, Multibeam bathymetric survey and high resolution seismic investigations on the Barbados Ridge complex (Eastern Caribbean): A key to the knowledge and interpretation of an accretionary wedge: Tectonophysics, v. 86, p. 275–304.

Breen, N.A., Silver, E.A., and Hussong, D.M., 1986, Structural styles of an accretionary wedge south of the Island of Sumba, Indonesia, revealed by Seamarc-II side-scan sonar: Geological Society of America Bulletin, v. 97, p. 1250–1261, doi: 10.1130/0016-7606(1986)97<1250:SSOAAW>2.0.CO;2.

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

Camerlenghi, A., Cita, M.B., Hieke, W., and Ricchiuto, T., 1992, Geological evidence for mud diapirism on the Mediterranean Ridge accretionary complex: Earth and Planetary Science Letters, v. 109, p. 493–504, doi: 10.1016/0012-821X(92)90109-9.

Camerlenghi, A., Cita, M.B., Della Vedova, B., Fusi, N., Mirabile, 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.

Cita, M.B., Ryan, W.B.F., and Paggi, L., 1981, Prometheus mud breccia: An example of shale diapirism in the Western Mediterranean Ridge: Annales Géologiques Des Pays Helléniques, v. 30, p. 543–570.

Costa, E., Camerlenghi, A., Polonia, A., Cooper, C., Fabretti, P., Mosconi, A., Murelli, P., Romanelli, M., Sormani, L., and Wardell, N., 2004, Modeling deformation and salt tectonics in the eastern Mediterranean Ridge accretionary wedge: Geological Society of America Bulletin, v. 116, p. 880–894.

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.

Deyhle, A., and Kopf, A., 2001, Deep fluids and ancient pore waters at the backstop: Stable isotope systematics (B, C, O) of mud-volcano deposits on the Mediterranean Ridge accretionary wedge: Geology, v. 29, p. 1031–1034, doi: 10.1130/0091-7613(2001)029<1031:DFAAPW>2.0.CO;2.

Fusi, N., and Kenyon, N.H., 1996, Distribution of mud diapirism and other geological structures from long-range sidescan sonar (GLORIA) data, in the Eastern Mediterranean Sea: Marine Geology, v. 132, p. 21–38.

Hayward, N., Westbrook, G.K., and Peacock, S., 2003, Seismic velocity, anisotropy, and fluid pressure in the Barbados accretionary wedge from an offset vertical seismic profile with seabed sources: Journal of Geophysical Research, v. 108, ESE-3, doi: 10.1029/2001JB001638.

Henry, P., Ashi, J., Tsunogai, U., Toki, T., Kuramoto, S., Kinoshita, M., and Lallemant, S.J., 2003, Cold seeps and splay faults on Nankai margin: Geophysical Research Abstracts, v. 5, p. 10,246.

Huguen, C., Mascle, J., Chaumillon, E., Woodside, J.M., Benkhelil, J., Kopf, A., and Volkonskaia, A., 2001, Deformational styles of the eastern Mediterranean Ridge and surroundings from combined swath mapping and seismic reflection profiling: Tectonophysics, v. 343, p. 21–47, doi: 10.1016/S0040-1951(01)00185-8.

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.

Kastens, K.A., Breen, N.A., and Cita, M.B., 1992, Progressive deformation of an evaporite-bearing accretionary complex: SeaMARC I, SeaBeam and piston-core observations from the Mediterranean Ridge: Marine Geophysical Researches, v. 14, p. 249–298.

Kopf, A., 2002, Significance of mud volcanism: Reviews of Geophysics, v. 40, p. 1005, doi: 10.1029/2000RG000093.

Kopf, A., Robertson, A.H.F., Clennell, M.B., and Flecker, R., 1998, Mechanisms of mud extrusion on the Mediterranean Ridge Accretionary Complex: Geo-Marine Letters, v. 18, p. 97–114, doi: 10.1007/s003670050058.

Kreemer, C., and Chamot-Rooke, N., 2004, Contemporary kinematics of the southern Aegean and the Mediterranean Ridge: Geophysical Journal International, v. 157, p. 1377–1392, doi: 10.1111/j.1365-246X.2004.02270.x.

Le Pichon, X., Chamot-Rooke, N., Lallemant, S., Noomen, R., and Veis, G., 1995, Geodetic determination of the kinematics of central Greece with respect to Europe: Implications for eastern Mediterranean tectonics: Journal of Geophysical Research, v. 100, p. 12,675–12,690, doi: 10.1029/95JB00317.

Luo, X.R., and Vasseur, G., 1996, Geopressuring mechanism of organic matter cracking: Numerical modeling: American Association of Petroleum Geologists Bulletin, v. 80, p. 856–874.

Moore, J.C., and Saffer, D., 2001, Updip limit of the seismogenic zone beneath the accretionary prism of southwest Japan: An effect of diagenetic to low-grade metamorphic processes and increasing effective stress: Geology, v. 29, p. 183–186, doi: 10.1130/0091-7613(2001)029<0183:ULOTSZ>2.0.CO;2.

Moore, J.C., and Vrolijk, P., 1992, Fluids in accretionary prisms: Reviews of Geophysics, v. 30, p. 113–135.

Rabaute, A., Chamot-Rooke, N., and Deep Offshore Tectonics of the Mediterranean (DOTMED) Team, 2003, Tectonics and mud volcanism at the western Mediterranean Ridge–backstop contact: Geophysical Research Abstracts, v. 5, p. 12,007.

Reston, T.J., von Huene, R., Dickmann, T., Klaeschen, D., and Kopp, H., 2002, Frontal accretion along the western Mediterranean Ridge: The effect of Messinian evaporites on wedge mechanics and structural style: Marine Geology, v. 186, p. 59–82, doi: 10.1016/S0025-3227(02)00173-1.

Robertson, A., and Ocean Drilling Program Leg 160 Scientific Party, 1996, Mud volcanism on the Mediterranean Ridge: Initial results of Ocean Drilling Program Leg 160: Geology, v. 24, p. 239–242, doi: 10.1130/0091-7613(1996)024<0239:MVOTMR>2.3.CO;2.

Silver, E.A., Breen, N.A., Prasetyo, H., and Hussong, D.M., 1986, Multibeam study of the Flores backarc thrust belt, Indonesia: Journal of Geophysical Research, v. 91, p. 3489–3500.

Silver, E.A., Kastner, M., Fisher, A., Morris, J., McIntosh, K., and Saffer, D., 2000, Fluid flow paths in the Middle America Trench and Costa Rica margin: Geology, v. 28, p. 679–682, doi: 10.1130/0091-7613(2000)028<0679:FFPITM>2.3.CO;2.

Stride, A.H., Belderson, R.H., and Kenyon, N.H., 1982, Structural grain, mud volcanoes and other features on the Barbados Ridge Complex revealed by GLORIA long range side-scan sonar: Marine Geology, v. 49, p. 187–196, doi: 10.1016/0025-3227(82)90036-6.

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.

Tobin, H.J., Moore, J.C., Mackay, M.E., Orange, D.L., and Kulm, L.D., 1993, Fluid flow along a strike-slip fault at the toe of the Oregon accretionary prism: Implications for the geometry of frontal accretion: Geological Society of America Bulletin, v. 105, p. 569–582, doi: 10.1130/0016-7606(1993)105<0569:FFAASS>2.3.CO;2.

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.

Westbrook, G.K., and Smith, M.J., 1983, Long décollements and mud volcanos—Evidence from the Barbados Ridge complex for the role of high pore-fluid pressure in the development of an accretionary complex: Geology, v. 11, p. 279–283, doi: 10.1130/0091-7613(1983)11<279:LDAMVE>2.0.CO;2.

Manuscript received 27 December 2004
Revised manuscript received 8 July 2005
Manuscript accepted 11 July 2005

Printed in USA