Strike-slip faults mediate the rise of crustal-derived fluids and mud volcanism in the deep sea

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ABSTRACT

We report on newly discovered mud volcanoes located at ~4500 m water depth ~90 km west of the deformation front of the accretionary wedge of the Gulf of Cadiz, and thus outside of their typical geotectonic environment. Seismic data suggest that fluid flow is mediated by a >400-km-long strike-slip fault marking the transcurrent plate boundary between Africa and Eurasia. Geochemical data (Cl, B, Sr, $^{87}Sr/^{86}Sr$, $\delta^{18}O$, δD) reveal that fluids originate in oceanic crust older than 140 Ma. On their rise to the surface, these fluids receive strong geochemical signals from recrystallization of Upper Jurassic carbonates and clay-mineral dehydration in younger terrigeneous units. At present, reports of mud volcanoes in similar deep-sea settings are rare, but given that the large area of transform-type plate boundaries has been barely investigated, such pathways of fluid discharge may provide an important, yet unappreciated link between the deeply buried oceanic crust and the deep ocean.

INTRODUCTION

Fluid seepage and mud volcanism are common at active and passive continental margins (Kopf, 2002); typical driving mechanisms are (1) rapid sedimentation in combination with compaction and tectonic stress, (2) intrusive processes like salt diapirism, (3) dewatering of hydrous minerals, and (4) formation of hydrocarbons. These factors are met in the Gulf of Cadiz, where several kilometer-thick Mesozoic to Holocene sediments accumulated in an accretionary wedge, hosting numerous mud volcanoes (MVs) preferentially at fault intersections (Fig. 1; Magalhães et al., 2012). Proximal to the coast, MV fluids are strongly influenced by clay-mineral dehydration and leaching of Upper Triassic evaporites (Haffert et al., 2013). With increasing distance from the coast, the fluid signature changes, and fluid interaction with the underlying oceanic crust was postulated based on results from the Porto MV (Scholz et al., 2009). The occurrence of MVs located at water depths >2500 m is closely tied to the presence of active strike-slip faults (Duarte et al., 2013; Fig. 1), which provide deeply rooted fluid pathways (Hensen et al., 2007). In 2012, R/V *Meteor* cruise M86/5 was conducted to test hypothesized fluid seepage along deep-rooted strike-slip faults also in distal segments outside the accretionary wedge. Our findings call for a reappraisal of oceanic transform-type faults as fluid conduits and support current hypotheses about ongoing fluid circulation in "aged" upper oceanic crust.

GENERAL OBSERVATIONS

Acoustic backscatter anomalies recorded during previous bathymetric surveys led to the discovery of three new MVs on cruise M86/5: Abzu, Tiamat, and Michael Ivanov (ATI MVs hereafter; Fig. 1A) at water depths of ~4500 m at the southern rim of the Horseshoe Valley, ~90 km west of the deformation front of the accretionary wedge (Fig. 1A; Duarte et al., 2013). These MVs are smaller than those found on the accretionary wedge and consist of isolated cones (Fig. 1B) aligned on the Lineament South (LS) trend (Bartolome et al., 2012; Terrinha et al., 2009). The position of the MVs along the LS fault coincides with a seismically active zone with earthquakes of magnitudes $M_w \leq 6$ nucleating in the upper mantle between 40 km and 60 km depth (Fig. 1A; Geissler et al., 2010). This suggests a fault intersection scenario similar to the situation on the accretionary wedge. Five gravity cores of up to 4.75 m length were obtained from active fluid emanation sites at ATI and Porto MVs (see Appendix DR1 in the GSA Data Repository[1]). Pore water was extracted in intervals ≤25 cm and analyzed for major and minor element composition using standard ana-

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[1]GSA Data Repository item 2015124, supporting information on locations, fluid geochemical data, analytical methods, Sr-isotope data of mud clasts, and heat flow measurements, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

lytical procedures (Appendix DR2; e.g., Scholz et al., 2009). MV sediments typically consist of olive-gray mud breccias with claystone clasts of millimeter to centimeter size, and are highly enriched in H_2S and methane. Gas hydrates are found below the zone of anaerobic oxidation of methane (AOM). Dissolved methane escaping from the MV sediment forms plumes above the seafloor and feeds chemosymbiotic assemblages including several species of bivalves and tubeworms (Cunha et al., 2013).

FLUID SOURCES AND IMPLICATIONS

At ATI MVs, a shallow AOM zone prevails (40–200 cm sediment depth) due to advection of methane-rich fluids. Below the AOM zone, mixing with ambient bottom water is minor so that the chemical composition of rising deep fluids can be studied on samples from this depth, defined as "local endmembers" of a core (e.g., Scholz et al., 2009). Local endmembers from four cores sampled on cruise M86/5 at ATI MVs and one core from Porto MV were selected and compared to previously published (Hensen et al., 2007; Scholz et al., 2009) local endmembers from MVs on the accretionary wedge (Fig. 2; Appendix DR1; distal MVs: Carlos Ribeiro [CRMV], Bonjardim, Porto; proximal MVs: Mercator, Captain Arutyunov [CAMV]).

Fluid data reveal positive and negative correlations of $\delta^{18}O$ and Cl versus B (Fig. 2A) and $\delta^{18}O$ versus δD (Fig. 2B), respectively. Such trends are typical for clay-mineral dehydration, a major fluid source in the Gulf of Cadiz (Hensen et al., 2007). Clay dehydration causes freshening of fluids (depletion of conservative elements such as Cl), a characteristic signal of $\delta^{18}O$ above and δD below standard seawater composition (Vienna standard mean ocean water, VSMOW), as well as enrichments of boron and other fluid-mobile elements (Dählmann and de Lange, 2003).

Similarly, MV endmembers of Sr (Fig. 2C) and $^{87}Sr/^{86}Sr$ ratios (Fig. 2D) were plotted versus Cl. Data from non-ATI MVs in Figure 2C show a similar relationship as in Figures 2A and 2B,
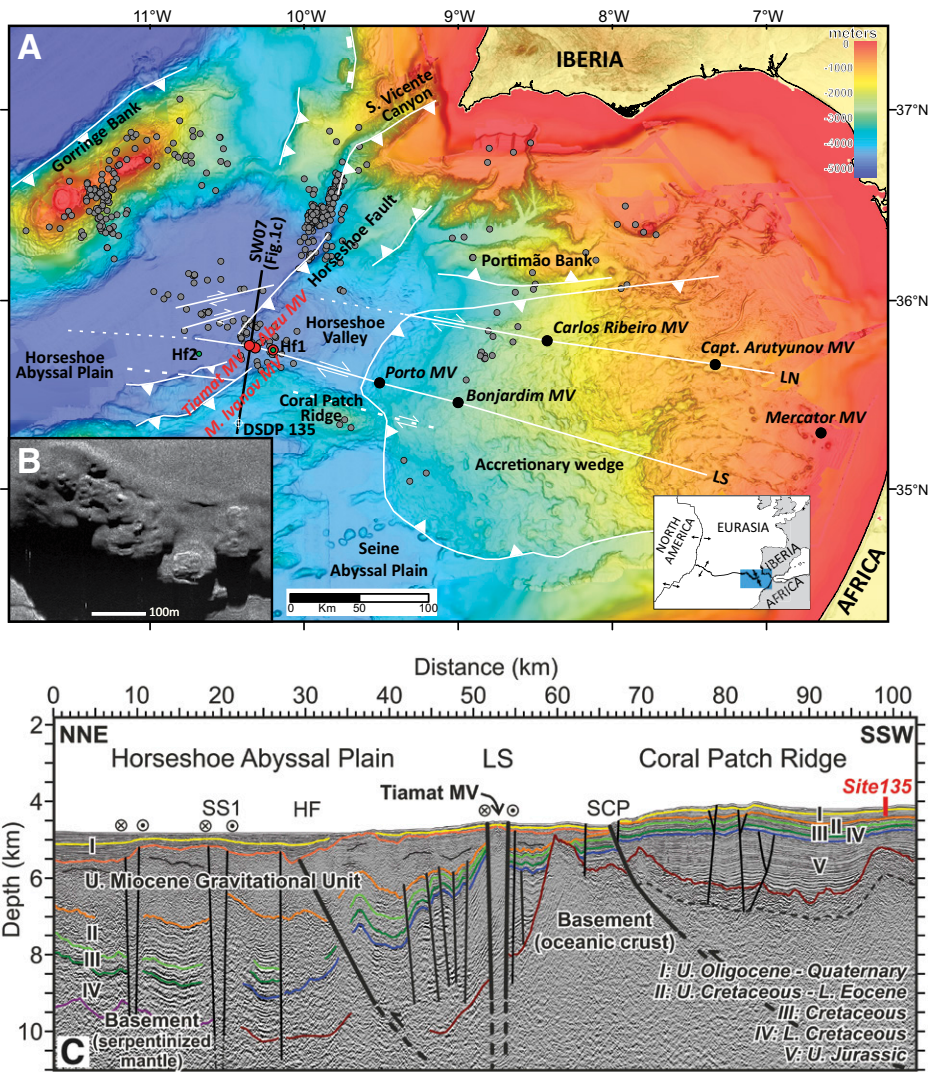
Figure 1. Study area, Gulf of Cadiz, and structural framework. A: Bathymetric map of the southwest Iberian margin from ~90 m digital grids (Zitellini et al., 2009); seismicity data (gray dots) from the NEAREST (Integrated Observation from Near Shore Sources of Tsunami) project temporary deployment; seismic profile SW07 (black line) running across the Lineament South (LS) and Deep Sea Drilling Project (DSDP) site 135; Hf1 and Hf2 (heat flow stations; Appendix DR4 [see footnote 1]). MV—mud volcano. Inset: Plate tectonic setting of the southwest Iberian margin (blue rectangle corresponds to the area depicted in A). B: Detail of a high-resolution sidescan sonar image of Michael Ivanov mud volcano. The entire structure consists of numerous single cones, being typically <100 m in diameter. C: Interpreted pre-stack depth-migrated seismic profile SW07 across the LS (at Tiamat MV), from the Coral Patch Ridge region to the Horseshoe Abyssal Plain. HF—Horseshoe fault; SS1—Strike-slip fault 1 (Martínez-Loriente et al., 2013); SCP—South Coral Patch Ridge fault; LN—Lineament North; U.—Upper; L.—Lower; vertical exaggeration: 5×.

most of the MV fluids. Therefore, oceanic crust is unlikely to be the dominant source of Sr at the ATI MVs. Pore waters of (pelagic) limestones can be enriched in Sr by >1 mM. The Sr enrichment is related to recrystallization (Gieskes and Lawrence, 1981) of Sr-rich, meta-stable aragonite to Sr-poor, stable calcite. The $^{87}Sr/^{86}Sr$ ratio of fluids affected by this process may be as low as 0.7068 ($^{87}Sr/^{86}Sr$ of Upper Jurassic seawater and carbonates; Banner, 2004). Seismostratigraphy calibrated with results of nearby Deep Sea Drilling Project (DSDP) Site 135 (Fig. 1) shows an exceptionally thick (2.5 km) sequence of Upper Jurassic sediments on top of the oceanic basement below the ATI MVs (Fig. 1C; Martínez-Loriente et al., 2013). Evidence from DSDP Site 105 (Hollister et al., 1972), the western Atlantic counterpart to Site 135, suggests that Upper Jurassic sediments in the study area are indeed pelagic limestones.

To further explore how potential sources may affect the MV fluid compositions, we examine a plot of Sr/B versus $^{87}Sr/^{86}Sr$ (Fig. 3). This combination of parameters allows for a clear discrimination between (1) clay (strongly radiogenic $^{87}Sr/^{86}Sr$), (2) carbonates ($^{87}Sr/^{86}Sr$ between present-day and the Late Jurassic Ocean; high Sr/B), and (3) oceanic crust (well-defined, strongly non-radiogenic $^{87}Sr/^{86}Sr$) as potential sources. The fluid composition of the proximal MVs is close to the suggested end-member of clay-mineral dewatering, while that of ATI MVs shows a strong imprint of recrystallization of Upper Jurassic carbonates (Fig. 3). The distal, non-ATI MVs plot within the binary mixing field of "clay" and "crust", suggesting a negligible influence of carbonate recrystallization there. This interpretation is in line with stratigraphic evidence for the subsurface extension of Upper Jurassic sediments (Fig. 4). Consequently, only ATI MVs receive the strong signal from carbonate recrystallization.

Unlike clay minerals, sedimentary carbonates do not store water in their lattice, and the process of recrystallization only enriches ambient pore waters in Sr. Therefore, an additional transport mechanism is required to carry the signal of carbonate recrystallization to the seafloor. Freshwater release from clay is presumably low in carbonate-rich sediments. In addition, clay-mineral dehydration occurs at temperatures between 60 °C and 150 °C (Hensen et al., 2007), which translates into sub-seafloor depths of ~1–3 km (geothermal gradient 45–50 K km⁻¹; Appendix DR4; Grevemeyer et al., 2009). Thus, there is only a limited overlap with the Upper Jurassic sediments (2–4.5 km sub-seafloor depth). As the Upper Jurassic unit corresponds to the deepest sedimentary deposits located right above the oceanic crust, only a scenario where crustal-derived fluids carry the geochemical signals upward (mixing of all three sources in Fig. 3) can explain observed
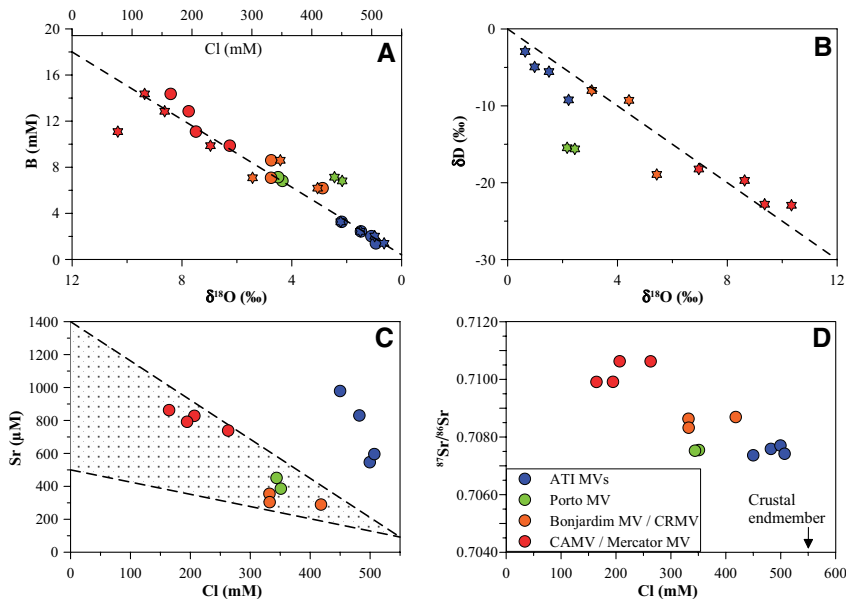
and can be defined by mixing between a certain range of Sr-enriched clay endmembers and seawater (shaded area Fig. 2C). This suggests that Sr is also derived from clay dehydration. By contrast, ATI MV fluids are clearly offset from this trend. Explaining this offset by mixing of clay-mineral–derived water and seawater would require an unrealistically strong Sr source in clays. Moreover, Sr released from clays has a high (radiogenic) $^{87}Sr/^{86}Sr$ ratio (Scholz et al., 2009; Appendix DR3) so that a strong Sr input from clays at ATI MVs should cause a positive offset in the isotopic signature, which is not the

case (Fig. 2D). Instead, the $^{87}Sr/^{86}Sr$ signal of fluids at all distal MVs indicate the decreasing influence of clay-mineral dewatering (Scholz et al., 2009) suggesting a low (less radiogenic) $^{87}Sr/^{86}Sr$ ratio of the source at ATI MVs. Two possible sources of Sr can induce such a low $^{87}Sr/^{86}Sr$ signal in this geological setting: deeply buried oceanic crust, and recrystallization of Mesozoic carbonates. Sr concentrations in hydrothermal vent fluids vary between 80 μM and 300 μM (Butterfield et al., 1994; Campbell et al., 1988; Mottl et al., 2000; Von Damm, 1990), which is below the level measured in

Figure 2. Endmember plots for various mud volcano (MV) fluids. A: δ¹⁸O versus boron (stars) and Cl versus boron. B: δ¹⁸O versus δD (stars). ATI MVs—Abzu, Tiamat, and Michael Ivanov MVs; CRMV—Carlos Ribeiro MV; CAMV—Captain Arutyunov MV. Dashed lines in A and B indicate trends with suggested endmember concentrations of clay-mineral–derived water (B = 18, Cl = 0, δ¹⁸O = 12; δD = −30) and seawater (B = 0.4, Cl = 550, δ¹⁸O = 0; δD = 0). C: Cl versus Sr. Shaded field between the dashed lines defines the mixing area between minimum and maximum Sr endmembers at Cl = 0 and seawater. D: Cl versus ⁸⁷Sr/⁸⁶Sr. Note that Cl⁻ concentrations for samples from Mercator MV and Captain Arutyunov MV (CAMV) in A were corrected using the equation of Hensen et al. (2007), because fluids at those sites were affected by salt dissolution (see Appendix DR1 in the Data Repository [see footnote 1]).

dehydration, are typical for mineral hydration processes such as the alteration of volcanic ash or oceanic crust (Gieskes and Lawrence, 1981). This trend is hardly visible at ATI MVs, likely due to the strong imprint of carbonate recrystallization favoring the formation of ¹⁸O-enriched fluids at elevated temperatures (Lawrence et al., 1975) and counteracting any negative crustal-derived δ¹⁸O signal.

In spite of the clear geochemical evidence, the precise mechanism driving fluid flow remains elusive. The major strike-slip fault (LS) provides a deep-reaching, permeable conduit that serves as pathway for ascending fluids. Strike-slip faulting has been previously suggested as a mechanism for the release of overpressure, eventually leading to pulses of fluid flow (Mazzini et al., 2009; Sibson, 1987; Viola et al., 2005). Deep seismic activity in the vicinity of ATI MVs (Fig. 1) indeed supports this hypothesis. In addition, pore water convection, related to the existence of local basement highs (e.g., Coral Patch Ridge; Figs. 1 and 4), could provide an alternative scenario of crustal-derived flow. To date, examples for fluid convection are mainly reported from the eastern Pacific, where pore fluids circulate through interconnected seamounts in young oceanic crust (Fisher et al., 2003).

CONCLUSIONS

Our findings confirm that seismogenic strike-slip faults provide pathways for deep-seated fluids, sustaining mud volcanism even in abyssal regions, outside areas of rapid sediment accumulation. Moreover, strike-slip faults tap fluid sources in oceanic crust older than 140 Ma, contradicting previous assumptions that fluid circulation terminates at a crustal age of ca. 65 ± 10 Ma (Stein et al., 1995). Although the exact mechanism remains poorly constrained, our data provide evidence for fluid flow within old oceanic crust in an area of strong topographic contrasts and deep basement faults as suggested by Von Herzen (2004). Interestingly, MVs expel-

Figure 3. Endmembers of mud volcano (MV) fluids (symbols) and assumed fluid sources (boxes). Ranges were derived as follows. Clay-mineral dewatering: Lower and upper boundary of ⁸⁷Sr/⁸⁶Sr = 0.7094–0.7150 (derived from clay clasts; see Appendix DR3 [see footnote 1]; Scholz et al., 2009), Sr/B from linear extrapolation of data to Cl = 0 mM (Figs. 2A and 2C). Carbonates: ⁸⁷Sr/⁸⁶Sr = 0.7068–0.7092 (range from Late Jurassic to contemporaneous seawater), Sr = 300–1500 µM, B = 0.43 mM (seawater). Crustal derived fluids: ⁸⁷Sr/⁸⁶Sr = 0.7040, Sr/B min/max derived from Butterfield et al. (1994), Campbell et al. (1988), Mottl et al. (2000), Von Damm (1990). Lines indicate two-end-member mixing of reservoirs: solid (clay-crust), stippled (clay-carbonate). Hatched line for clay-carbonate mixing uses the average value of all clast samples (⁸⁷Sr/⁸⁶Sr = 0.7120) and thus the most likely lower endmember value of clay clasts (indicated by faded red color below this value). ATI MVs—Abzu, Tiamat, and Michael Ivanov MVs; CRMV—Carlos Ribeiro MV; CAMV—Captain Arutyunov MV.

fluid compositions. Such a scenario is in compliance with the evidence for crustal alteration in MV fluids in the Gulf of Cadiz (Scholz et al., 2009). Our observations are summarized in a synthetic cross section (Fig. 4). Overall, fluids at Porto MV carry the strongest signal from oceanic crust alteration (Fig. 3), which is in agreement with the thinnest sediment cover at this site (Fig. 4). Compared to all other sites, there is also an obvious negative offset in δ¹⁸O values at this location. Negative shifts in δ¹⁸O, i.e., opposite to the effect observed during clay
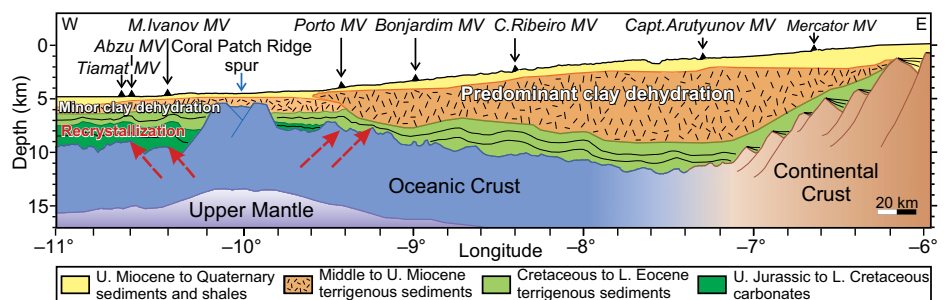

Figure 4. Regional synthetic (west to east) cross section from the continental shelf to the deep Horseshoe Basin north of Coral Patch Ridge (roughly following the Lineament South [LS]) illustrating major sources and processes affecting the fluid composition of distal mud volcanoes (MVs) in the Gulf of Cadiz. The largest potential for clay-mineral dehydration exists within the suitable temperature/depth range in the Middle to Upper Miocene terrigeneous units. MVs are projected along the profile. Note that Coral Patch Ridge is a prominent basement elevation appearing as buried spur and corresponds to a significant elevation of the seafloor, south of LS (Fig. 1). U.—Upper; L.—Lower. Vertical exaggeration: ~5×.

ling geochemically distinct fluids off the Barbados Accretionary Prism (Godon et al., 2004) are found in a tectonic setting comparable to that in the Gulf of Cadiz. Those are aligned along a major fracture zone and it was suggested that mud volcanism was initiated by changes in plate motion along this fracture (Sumner and Westbrook, 2001). Globally, transform-type plate boundaries are of similar length as divergent and convergent plate boundaries (Bird, 2003) and the latter are known for intense vent and seep activity. We suggest that transform-type plate boundaries and fracture zones may also provide important pathways for fluid exchange between the lithosphere and the deep ocean, and hence deserve more intense future exploration to evaluate their role in terms of heat and element exchange.

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Geology

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