Serpentinite Mud Volcanism: Observations, Processes, and Implications

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Abstract

Large serpentinite mud volcanoes form on the overriding plate of the Mariana subduction zone. Fluids from the descending plate hydrate (serpentinize) the forearc mantle and enable serpentinite muds to rise along faults to the seafloor. The seamounts are direct windows into subduction processes at depths far too deep to be accessed by any known technology. Fluid compositions vary with distance from the trench, signaling changes in chemical reactions as temperature and pressure increase. The parageneses of rocks in the mudflows permits us to constrain the physical conditions of the decollement region. If eruptive episodes are related to seismicity, seafloor observatories at these seamounts hold the potential to capture a subduction event and trace the effects of eruption on the biological communities that the slab fluids support, such as extremophile Archaea. The microorganisms that inhabit this high-pH, extreme environment support their growth by utilizing chemical constituents present in the slab fluids. Some researchers now contend that the serpentinization process itself may hold the key to the origin of life on Earth.

1. INTRODUCTION

Forearc: overriding plate region of an intraoceanic convergent plate margin between the ocean trench and the active volcanic arc

Subduction processes have important physical effects at intraoceanic convergent plate boundaries, changing the rheological aspects of the mantle wedge above the subduction zone that influence seismic activity, affecting melting conditions in the zone of arc magma genesis, and influencing convection patterns of the suprasubduction-zone mantle wedge. The chemical effects of these processes include the recycling of lithospheric constituents into the mantle, release of fluids from the subducting lithospheric plate into the over-riding plate, release of fluids and volatiles into the water column, and potentially interchange of these constituents with the atmosphere. Biological effects include the development of some of the most unique and extreme conditions for life that are known on the planet, including the highest pressure environments in the deep ocean trenches, the highest pH environment ever discovered at springs on the ocean floor, and seeps that vent direct, slab-derived fluids that can be found up to 90 km from the trench axis. The reaction of the Earth's mantle with these slab-derived fluids releases nutrients that are necessary for the development of novel microbial communities, and some researchers suggest that the origin of life may be tied to such environments because of their distinct physical and chemical characteristics.

The fluids released from the subducting lithospheric slab are of immense importance for determining the balance of inputs and outputs of slab constituents within subduction zones. For many years, there was controversy over an apparent disparity between the relatively low output of volatiles from volcanic arcs and the higher estimated inputs from the subducting slabs. These global mass-balance studies focused on the proposed reactions as pressure and temperature increased within the descending slab and on the diversity of plate materials being subducted worldwide. Heightened interest in the issue of controls over mass balance at convergent plate boundaries became one aspect of the National Science Foundation–funded MARGINS Program and its Subduction Factory Initiative. Two decades of intense surveying and sampling expeditions in the Mariana part of the MARGINS Izu-Bonin-Mariana focus area (**Figure 1**) have broadened our understanding of the subduction factory far beyond expectation. Studies of massive, active, serpentine mud volcanoes near the Mariana Trench (**Figure 2**) revealed information about reactions within the subduction zone, aspects of fluid release from subducting slabs, the tectonics of forearc regions (between the trench and arc), and extreme environments that support novel biological communities (Fryer 1996). This review presents an assessment of contributions from these and related studies and provides a perspective for potential future work.

2. BACKGROUND

2.1. Serpentinization

The mud volcanoes of the Mariana forearc are not likely to be unique occurrences in convergent plate margins throughout geologic history, but they do apparently occur only under certain geologic conditions. The only ones known to be active today are those of the Mariana forearc (Fryer 1996). The serpentinite mudflows that form the bulk of the edifices contain both finely comminuted matrix and rock clasts of serpentinized mantle peridotite. Serpentinization occurs at temperatures less than ~500°C, involving the hydration of mafic minerals. The formation and textures of serpentinites and the composition of serpentine phases have been discussed in depth elsewhere (see especially O'Hanley 1996). Recently, as interest has increased, several researchers have investigated the details of serpentinization and the formation of the three phases, antigorite (400°C–600°C), lizardite (0°C–300°C), and chrysotile [mainly at low temperatures, high-fluid flux, but unstable everywhere (Evans 2004)] (e.g., Normand et al. 2002; Bach et al. 2006; Frost & Beard 2007; Evans 2008, 2010; Beard et al. 2009; Klein et al. 2009).

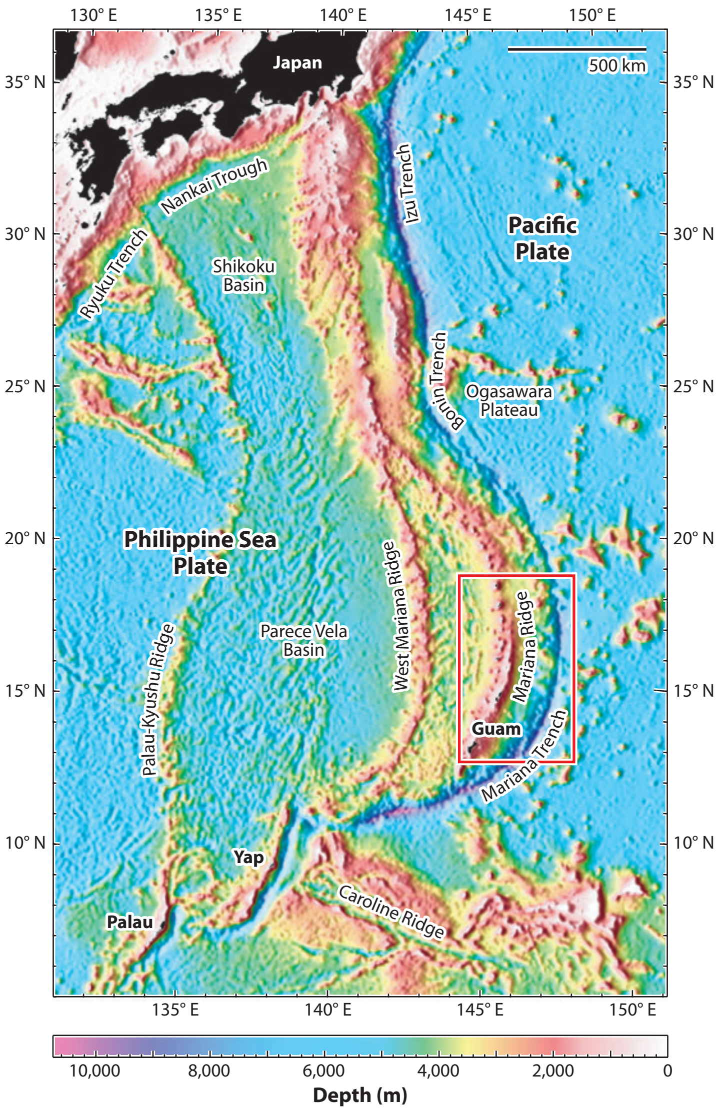


Figure 1

Color bathymetry map of the Philippine Sea region of the western Pacific. The red box shows the position of **Figure 2**.

Although the details of serpentine formation are strongly dependent on temperature, pressure, and silica activity, among other factors, the reaction is fundamentally understood. Serpentinization is an exothermic reaction. Serpentine forms by the hydration of various mantle peridotite minerals. The magnesian olivine mineral forsterite reacts with water to form magnesian serpentine and brucite:

$$2Mg_2SiO_4 + 3H_2O = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2.$$

The magnesian orthopyroxene enstatite reacts with water to form magnesian serpentine and talc:

$$6MgSiO_3 + 3H_2O = Mg_3Si_2O_5(OH)_4 + Mg_3Si_4O_{10}.$$

Silica activity: a measure of the effective concentration of silica in a mixture

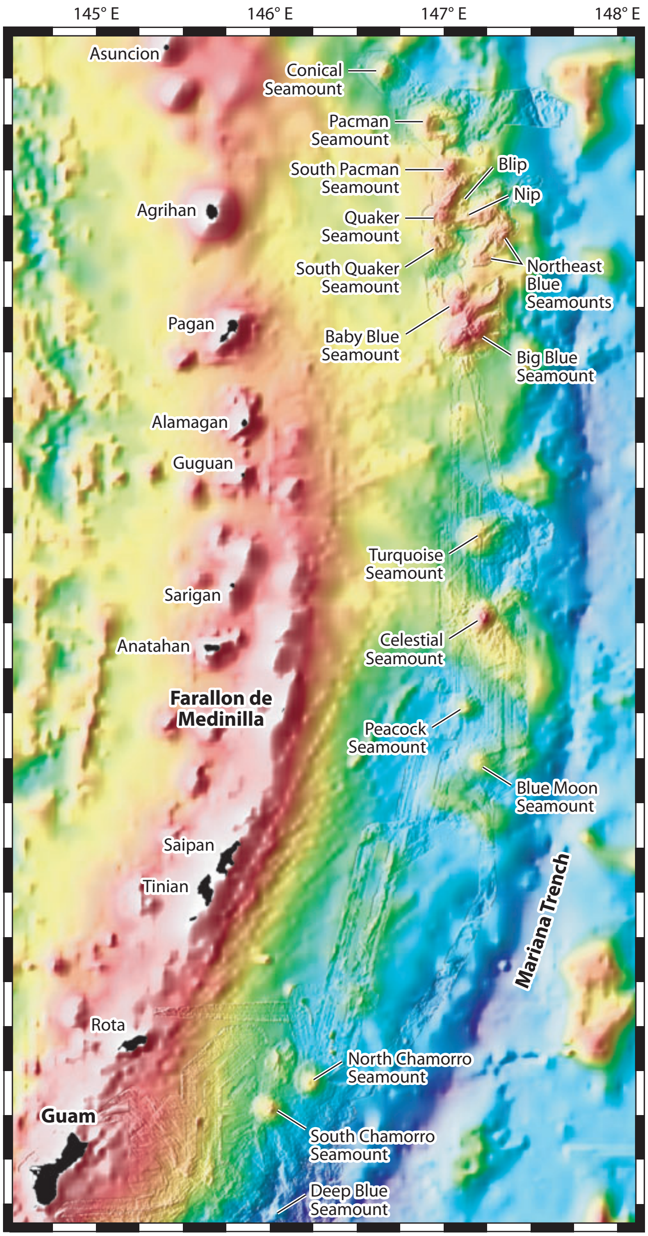


Figure 2

Color bathymetry map of the Mariana forearc region; shading shows illumination from the northwest. Serpentinite seamounts that have been sampled since 1981 are labeled.

Peridotite bearing both forsterite and enstatite can react with water to form serpentine alone:

$$Mg_2SiO_4 + MgSiO_3 + 2H_2O = Mg_3Si_2O_5(OH)_4.$$

Most olivine in Mariana forearc peridotites contains iron in amounts of ~10 mol%. The iron end member of the olivine series (fayalite) will react with water to produce magnetite, increase the silica activity of solutions, and release hydrogen:

$$3Fe_2SiO_4 + 2H_2O = 2Fe_3O_4 + 3SiO_2(aq) + 2H_2.$$

Hydrogen interacting with carbon dioxide released from the subducting slab (e.g., Fryer et al. 1999; Mottl et al. 2003, 2004) can produce methane abiotically:

$$4H_2 + CO_2 = CH_4 + 2H_2O.$$

At high pH, this is

$$4H_2 + CO_3^{2-} = CH_4 + H_2O + 2OH^-.$$

Frost & Beard (2007) argued that the serpentinization process is controlled mainly by low silica activity prompting the initial hydration of olivine to serpentine and brucite without magnetite production (or the release of H_2). Beard et al. (2009) observed that initial hydration in olivine troctolite samples produced olivine and iron-rich brucite (with no magnetite). Further reactions involved serpentinization inside the growing veins and the formation of magnetite. Based on the $Fe^{2+}Mg_{-1}$ exchange potential, Evans (2008) cautioned that a higher and variable ferric iron component in lizardite at the onset of serpentinization could explain an early lack of magnetite formation. This would also preclude H_2 release. He did note that control may be heavily influenced by a high fluid flux. In the Mariana seamounts, there is a ready supply of fluid, so hydrogen production is likely during serpentinization of the forearc mantle.

Hyndman & Peacock (2003) suggested that the amount of slab-derived fluid would be sufficient, over several tens of millions of years, to serpentinize the entire Mariana forearc mantle wedge. Furthermore, Tibi et al. (2008) showed seismic evidence for a widespread low-velocity zone in the Mariana forearc that suggests serpentinite. Most of the peridotitic clasts recovered from drilling efforts [Ocean Drilling Program (ODP) Legs 125 and 195] on the summits of Mariana serpentinite seamounts are indeed highly serpentinized (e.g., Saboda et al. 1992; Savov et al. 2002, 2005a; D'Antonio & Kristensen 2004). There are, however, many relatively fresh clasts of peridotite recovered from both drilling and dredges on the flanks of the mud volcanoes and on fault scarps that expose peridotites (Bloomer 1983; Fryer 1992, 1996; Michibayashi et al. 2007), suggesting that serpentinization may be localized around faults or conduits and may not be ubiquitous in the Mariana forearc mantle.

Rising fluids high in carbonate alkalinity react with seawater and/or sediment at the seafloor to precipitate carbonate. Large carbonate chimney structures were discovered on Conical Seamount's summit during Alvin dives (Fryer et al. 1990) and on South Chamorro Seamount on Shinkai 6500 dives (Fryer & Mottl 1997). The summits of all the seamounts are below the carbonate compensation depth, so the chimneys would dissolve if fluids were not continuously supplied. Crystals of aragonite are also common in the serpentinite mudflow cores collected from the seamounts sampled (e.g., Fryer et al. 1999).

2.2. Serpentinite Deposits Worldwide

Lockwood (1971, 1972) suggested that subaerial deposits of what was then termed sedimentary serpentinite were likely flows from mud volcanism that occurred in convergent margin settings. Many such deposits worldwide include marine fossils, peridotites that have suprasubduction-zone compositional characteristics, and clasts of other lithologies similar to those in the Mariana serpentinite mudflows. Thus serpentinite mud volcanism may have been more widespread in the geological past (Fryer et al. 2000). Care must be taken, however, as there is a vast array of types of exposures of serpentinite bodies in the oceans that can mimic a serpentinite mudflow deposit (e.g., Fryer 2002). Serpentinization primarily occurs at major fault structures where fluids can permeate the peridotite exposures. Such faults form at magma-starved mid-ocean ridges, in areas of offsets between slow-spreading ridge segments where the basaltic overburden is unroofed; at the transition from continental to oceanic lithosphere as ocean basins begin rifting; and within convergent plate boundaries, such as in the Mariana system.

A well-known recent discovery of serpentinized peridotite rock at a mid-ocean ridge is associated with the Lost City hydrothermal field at the southern margin of the Atlantis Massif (30° N) on the Mid-Atlantic Ridge (Kelley et al. 2001). This peridotite-hosted field supports the growth of impressive carbonate chimneys, as large as or larger than those of the Mariana serpentinite mud volcanoes. These structures differ dramatically, however, from chimneys formed at the high-temperature (∼325°C–350°C) Logatchev (15° N) and Rainbow (36° N) peridotite-hosted hydrothermal sites on the Mid-Atlantic Ridge. The latter have sulfide chimneys and black smokers (e.g., Rona et al. 1987, German et al. 1996, Barriga et al. 1997, Fouquet et al. 1997, Bougault et al. 1998, Fujioka et al. 1998, Mozgova et al. 1999, Cherkashev et al. 2000, Parson et al. 2000, Sudarikov & Roumiantsev 2000, Lein et al. 2001). The higher temperatures of these fields are likely related to the initial high-temperature emplacement of the peridotite bodies (Allen & Seyfried 2004). The differences between mid-ocean-ridge serpentinization sites and the mud volcanism sites of the Mariana forearc lie in the nature of the fluids interacting with the peridotite and in the composition of the peridotite protolith itself (seawater and abyssal peridotite versus slab-derived fluids and suprasubduction-zone peridotite, respectively).

During continental rifting, passive plate margins with low magma input, such as the North America/Europe margin between Newfoundland and Portugal/Spain, exposed upper mantle along deep faults. Galicia Banks, west of the Iberian Peninsula, provide access to ridges of serpentinized peridotite deposits. Initial interpretations suggested that the serpentinite recovered might be from diapiric or mud volcano emplacement. Eventually, however, geophysical surveys, dredging, submersible investigations, and two ocean drilling expeditions (Boillot et al. 1980, 1988; Mauffret & Montadert 1987; Beslier et al. 1993, 1996; Riegel 1994, 1998; Pinheiro et al. 1996) indicated that the ridges formed as continental mantle was serpentinized and deformed during the initial extension of the ocean basin.

Detailed studies of the relationships of sedimentary serpentinite bodies to the surrounding structures, of the peridotite clast compositions and textures, and of the nature of the nonperidotite lithology composing the entire formation can help to constrain emplacement processes. Even then, ambiguities can persist. For example, bodies of serpentinite in the Wilbur Springs area and the Mysterious Valley Formation in the California Coast Range serpentinite belt have been interpreted as representing mudflows similar to those of the Mariana seamounts (Carlson 1981, MacPherson & Phipps 1988, MacPherson et al. 1990). More recently, Hopson & Pessagno (2004, 2005) and Hopson et al. (2008) interpreted these bodies as the distal portions of huge volumes of debris shed from uplifted forearc ridges that exposed tectonically deformed Jurassic oceanic crust and upper mantle serpentinized by infiltrating seawater. Dilek & Furnes (2011) presented an overall framework for distinguishing the origins of ophiolite exposures. They recommended characterizing the exposures by the nature of their lithological assemblage, the related structures and textures of the materials, and the chemical compositions of the lithologies to identify the original tectonic setting. They note that this will help unravel the processes responsible for both the formation and exposure of the deposits. Their criteria can be applied to any ophiolite exposure, including ancient greenstone belts, and thus can even permit the characterization of oceanic lithosphere from Archean times.

2.3. The Izu-Bonin-Mariana Serpentinite

The serpentinite mud volcanoes of the Mariana convergent margin lie in the outer half of the 200-km-wide region between the Mariana Trench and the volcanic islands of the active arc. The most fully studied edifices are south of ~20° N (**Figure 2**). Sedimentary mud volcanoes observed at many convergent margins around the world normally reach a maximum size of a few hundred meters high and up to 10 km in diameter (e.g., Kopf et al. 2010). The mud volcanoes of the Mariana forearc reach heights of 2.5 km and diameters of 50 km. Carbonate chimney structures form on seamounts greater than 55 km from the trench (Fryer et al. 1990, Fryer 1992), and smaller chimneys of brucite form on those closest to the trench.

A ridge comprising largely serpentinized peridotite makes up the outer 50 km of the Izu-Bonin forearc (Fryer & Fryer 1987). The ridge has localized highs along its length that could be regions of locally greater degrees of serpentinization or mud volcanism. Drilling on ODP Leg 125 at one of these locations, Torishima Forearc Seamount (Shipboard Sci. Party 1990a,b), recovered serpentinite deposits similar to those of the Mariana seamounts. Horine et al. (1990) interpreted their multichannel seismic (MCS) surveys in the vicinity of Torishima Forearc Seamount to indicate that it may be similar in most respects to the Mariana forearc mud volcanoes. In more modern Mariana MCS data (Oakley et al. 2007), the reflectors from underlying forearc sediments can be traced unambiguously for many kilometers beneath the flanks of the edifices. None of the Izu-Bonin seamounts have been found to have active seeps or obvious mudflow structures, and all are restricted to the ridge on the inner trench slope. A refraction seismic transect across the Izu-Bonin convergent margin at 32° N shows low velocities in the outer 50 km of the forearc that have been interpreted as a serpentinite diapiric region (Takahashi et al. 1998), but detailed internal structures were not imaged in this data set. Thus more data are needed to determine unambiguously the nature of the Izu-Bonin seamounts. Both forearc regions show low-velocity suprasubduction zones (Fujie et al. 2002, Tibi et al. 2008). An interesting local exception is an MCS transect at ~26° N across the southern Izu-Bonin forearc that shows what Miura et al. (2004) interpreted to be a "rootless" serpentinite seamount. They suggested that the subduction of the western edge of the Ogasawara Plateau (**Figure 1**) has eroded away the plumbing system of the seamount.

Along the Izu-Bonin-Mariana forearc the entire intraoceanic, convergent plate margin is nonaccretionary; therefore, a significant amount of serpentinized mantle is exposed. Little of the sediment on the incoming Pacific plate is scraped off and accreted to the forearc toe (Uyeda 1982). Approximately half the convergent margins around the world are nonaccretionary. Faults on the inner trench slope of such convergent margins can expose deep sections of forearc lithosphere, including upper mantle, and provide avenues for the escape of fluids released from the subducting plate. Movement along these faults during earthquakes can shear peridotite, creating mylonite and fault gouge, and fluids rising along them can serpentinize and mobilize this material to create mudflows that erupt at the seafloor.

3. MARIANA SEAMOUNT OBSERVATIONS

3.1. Distribution and Morphology

The Mariana serpentinite mud volcanoes on the southern forearc tend to occur in clusters (**Figure 2**). Three are located between 13° and 14° N. More than 13 large and several very small ones are located between ~15° and 20° N. The scarp lineaments along the outer Mariana forearc south of ~20° N define what appears to be sets of conjugate faults with a dominant northeast-southwest trend (Stern et al. 2004). Between 21° and 24° N, most of the fault scarps in the outer forearc lie roughly parallel to the trench (Stern & Smoot 1998, Stern et al. 2004), and

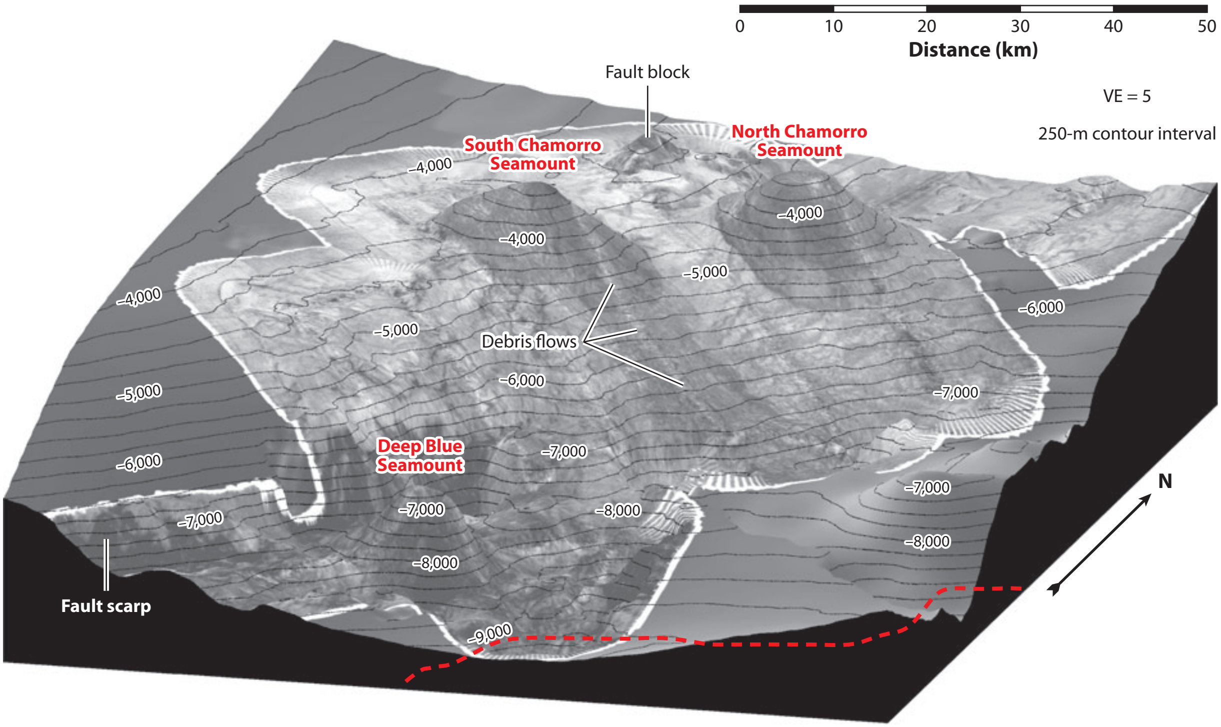


Figure 3

Perspective views from the southeast of South Chamorro Seamount from HMR-1 side-scan sonar backscatter imagery draped on topography for the three southernmost serpentinite mud volcanoes of the Mariana region. Darker shading indicates high backscatter. South Chamorro Seamount shows a darker (higher-backscatter) debris field (debris flows) extending ∼70 km from the summit southeastward toward the trench (*red dashed line*). Abbreviation: VE, vertical exaggeration.

there are four conical-shaped edifices along these scarps. These northern seamounts were dived on with the Shinkai 6500 submersible in 2009 and yielded serpentinized peridotite, metabasites, and other lithologies similar to those of mud volcanoes on the southern half of the forearc (H. Maekawa, personal communication, 2009).

Nearly all the seamounts are monogenetic. Deformation in response to gravity occurs throughout the lifetime of the edifices. Oakley et al. (2007) presented a model for the gravitational collapse of the edifices. They essentially flatten and expand laterally into, and thus deform, the surrounding forearc sediments. Most seamounts also have other types of flank disruption, and several show slump or sector collapse features. The entire southeastern flank of South Chamorro Seamount has seen a significant slumping event, and debris flows reach 70 km southeast of the seamount's summit toward the trench (**Figure 3**) (Fryer et al. 1999, Wheat et al. 2008). Slumps on the west side of Celestial Seamount (Fryer et al. 1999, Oakley et al. 2007) have eroded a channel in the west flank of the edifice. Discrete mud lumps up to 10 km away from the base of the edifice have varying degrees of backscatter (different amount of sediment cover) that suggest they were sloughed from the flank of the seamount at different times (**Figure 4** and **Supplemental Figure 1**; follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**). Alternatively, they may be small mud volcanoes. Pacman Seamount (**Figure 2**) has formed along an east-west trending fault that dips to the north (Fryer et al. 1990). Mudflows partially fill in the western side of the trough between the two fault blocks and give this seamount its unusual

Supplemental Material

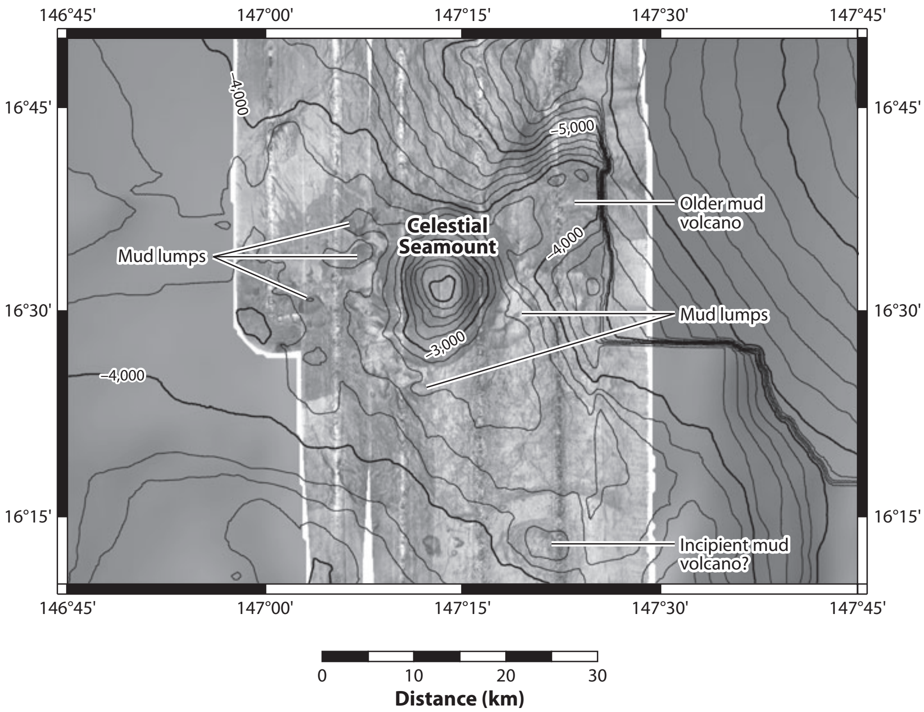


Figure 4

Celestial Seamount shown with a shaded (illumination from the northwest) bathymetry map (250-m contour interval) draped with HMR-1 side-scan sonar backscatter. An apparently older mud volcano lies to the northeast of Celestial Seamount, and there is a possible incipient one to the southeast. Numerous small mud lumps lie within ~10 km of the seamount base. These may represent either slump deposits from the main edifice or individual small mud volcanoes (see **Supplemental Figure 1**).

crescent shape. In some cases, fault scarps beneath the seamounts are entirely draped by mudflows (e.g., Conical Seamount), whereas at other edifices, underlying faults are evident and possibly still active beneath the flanks of the seamounts [e.g., Big Blue and Turquoise Seamounts (see Oakley et al. 2007)].

3.2. Lithology

The serpentinite mudflow matrix (**Figure 5**) of the seamounts sampled contains ~90% serpentine, mainly lizardite and chrysotile, with some antigorite (e.g., Fryer & Mottl 1992, Lagabrielle et al. 1992, Komor & Mottl 2005). Accessory minerals include magnetite, aragonite, calcite, brucite, talc, mixed-layer smectite/illite clays, chlorite, various amphibole grains, relict grains of olivine (Fo_{90-93}), enstatite and clinopyroxene, and minute amounts of garnets (Shipboard Sci. Party 1990c,d, 2002). Authigenic minerals in the muds include mainly aragonite and calcite, and in some seamounts these occur in significant amounts. A gravity core from Big Blue Seamount contained ~30% aragonite needles up to 2 cm long and 4 mm in diameter. The rock clasts included in the mud matrix of flows represent lithologies from both the subducted plate and the suprasubduction-zone mantle and crust. The peridotite clasts are dominantly harzburgite (~75% to over 90%) and dunite (~15% to less than 10%) (Shipboard Sci. Party 1990c,d, 2002; Ishii et al.

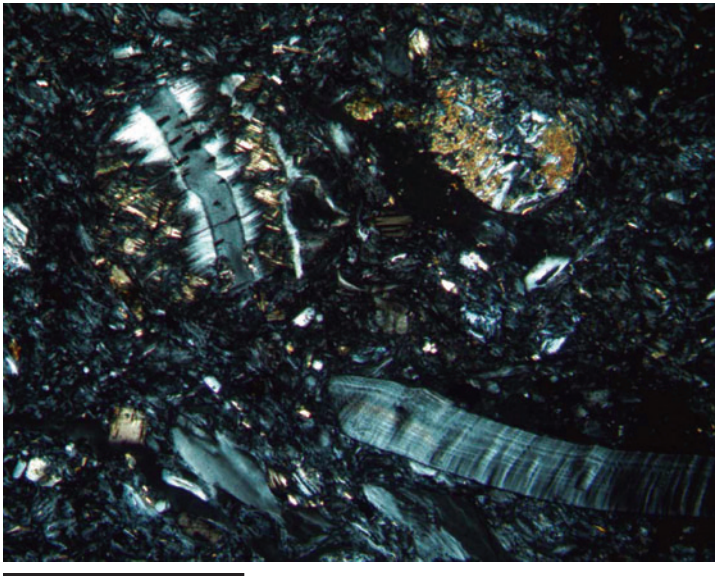


Figure 5

Photomicrograph of typically unsorted serpentinite mudflow matrix (sample 195-1200F-1H-4, 34–36 cm; crossed polarizers; and magnification of 10 times). The groundmass consists of various-sized serpentine grains and serpentinized lithoclasts (*upper left and right*, *white and gray interference colors*) with brucite (*brown interference colors*). Figure taken from Shipboard Sci. Party (2002), figure F9.

1992; Saboda et al. 1992). Most are between 70% and 100% serpentinized, but about one-third of the clasts are between 30% and 50% serpentinized (e.g., **Figure 6**), and some are as little as ∼15% serpentinized (e.g., Shipboard Sci. Party 1990c,d; Savov et al. 2005a). The muds contain a few percent of other lithologies, including ocean island basalts, normal mid-ocean-ridge basalts, transitional mid-ocean-ridge basalts, hemipelagic cherts (Johnson & Fryer 1990, Johnson 1992, Savov et al. 2005a), and the first discovery of blueschist facies rocks (Maekawa et al. 1992, 1993) from an active convergent plate margin. The muds contain island arc tholeiitic basalts and boninite from the forearc crust (Johnson & Fryer 1990) and a variety of schists derived from both basaltic and sedimentary protoliths (Fryer et al. 1999, Fryer et al. 2006, Gharib 2006). The paragenesis of the rocks helps to constrain the pressure and temperature of origin of these metamorphic schists. The incipient blueschist facies metabasites indicate temperatures of ∼175°C–250°C and pressures of 0.5–0.65 GPa (∼15–19.5 km) (**Figure 7**). A metabasite schist from South Chamorro Seamount includes epidote in equilibrium with magnesioriebeckite/barroisite amphibole and thus indicates a higher temperature of origin (250°C–300°C) at a pressure of ∼0.4–0.50 GPa (∼12–15 km) (Fryer et al. 2006). Savov et al. (2005a) performed mixing calculations to show that the mudflow matrix composition is essentially identical to the composition of the included clasts.

Paragenesis: a petrologic concept meaning an equilibrium assemblage of mineral phases; used in studies of igneous and metamorphic rock genesis

3.3. Chimney Structures

The carbonate chimneys discovered on Conical Seamount (Fryer et al. 1990) reach heights of more than 10 m (**Figure 8*a***), but they are generally surrounded by a field of large broken stubs, possibly broken off the main structure during small seismic events (**Figure 8*b***). Most chimneys vary from a few centimeters to a few meters high. Those on Conical Seamount have a dark manganese-oxide

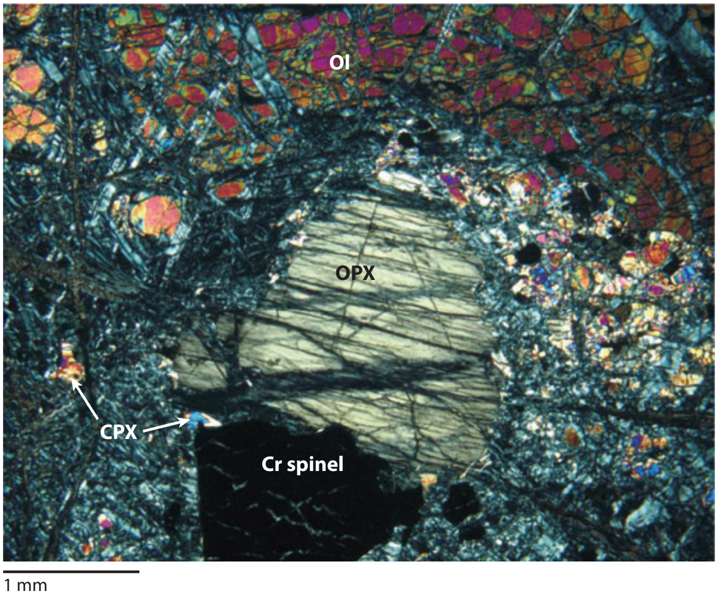


Figure 6

Photomicrograph of partially serpentinized harzburgite (sample 195-1200A-12R-1, 25–27 cm; cross-polarized light; 1-mm bar for scale). Abbreviations: CPX, clinopyroxene; Cr spinel, chromium spinel; Ol, olivine; OPX, orthopyroxene. Figure adapted from Shipboard Sci. Party (2002), figure F17.

coating at the base and white tips where carbonate, mainly aragonite, is actively precipitating. Root structures were recovered that show the intergrowth of carbonate and serpentinite mud in chimneys that were collected from the muds by the Alvin pilots (Fryer et al. 1990). Quaker Seamount chimneys (**Figure 8*c***) form along a fault trace on the eastern side of the summit region (Fryer et al. 2006). The summit of South Chamorro Seamount also has small carbonate chimney structures and armoring of the edges of fissures in the serpentinite mud (Fryer et al. 1999). Brucite chimneys on seamounts closer to the trench, such as the Cerulean Springs site on Pacman Seamount's southeast arm, are generally small, less than a few centimeters high (**Figure 8*d***). The lack of carbonate chimneys close to the trench (shallower depth to slab) suggests that decarbonation or carbonate dissolution reactions have not yet begun in the slab.

3.4. Pore Fluids

Analysis of pore fluids from Alvin push cores and ODP Leg 125 collected on Conical Seamount (Fryer et al. 1990; Shipboard Sci. Party 1990a,b) first established that fluids rising with the serpentine mudflows are slab-derived. The pore fluids from ODP Hole 780 at the summit of the seamount (within the conduit region) had a fluid alkalinity ranging from 2.5 to 34 and pH changing from 8 to 12.4 within a few meters of the seafloor. The fluids also showed rapid depletions in calcium and magnesium; increases in sulfate, potassium, and ammonia; and decreases in salinity and chlorinity (Mottl 1992). Subsequent studies of trace element and isotopic composition aspects of the pore fluids showed enrichments in potassium, rubidium, boron, iodine, fluorine, chlorine, bromine, hydrocarbons (methane, ethane, propane), ammonia, ^{18}O, and deuterium and depletions in strontium, lithium, silicon, phosphate, and ^{87}Sr, all consistent with a slab origin (Haggerty & Chaudhuri 1992; Haggerty & Fisher 1992; Mottl 1992; Mottl & Alt 1992; Ryan et al. 1996;

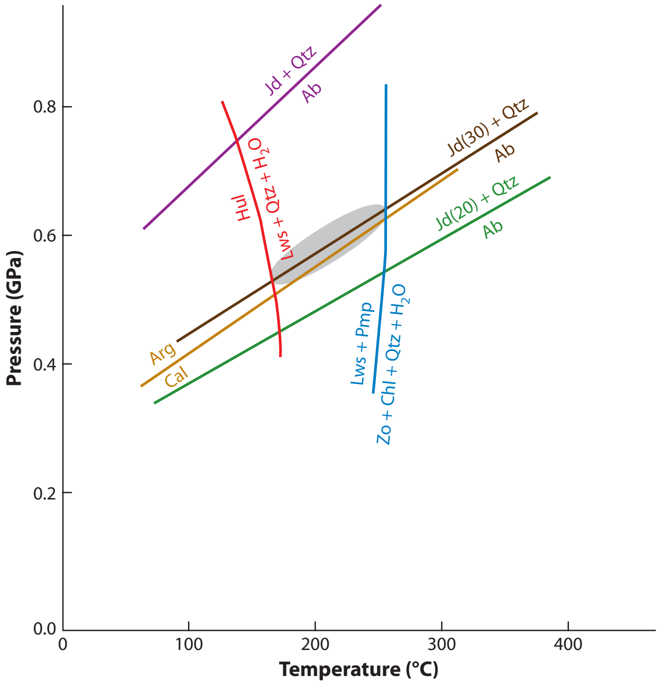


Figure 7

Gray shaded region is an estimate of 150°C–250°C and 0.5–0.6 GPa for conditions that formed the metabasite clasts recovered during ODP Leg 125 drilling of Conical Seamount. Abbreviations: Ab, albite; Arg, aragonite; Cal, calcite; Chl, chlorite; Hul, heulandite; Jd, jadite; Lws, lawsonite; Pmp, pumpellyite; Qtz, quartz; Zo, zoisite. Figure modified after Maekawa et al. (1992), figure 14.

Ishikawa & Terra 1999; Fryer et al. 1999, 2006; Benton et al. 2001, 2004; Mottl et al. 2003, 2004; Snyder et al. 2005; Wei et al. 2005; Savov et al. 2007; Wheat et al. 2008; Hulme et al. 2010). Sakai et al. (1990) analyzed the oxygen isotopic composition of serpentine mud and deduced that temperatures of dehydration reactions from the basaltic subducting slab were between 400°C and 500°C. However, studies of serpentine mineral separates (Alt & Shanks 2006) restricted the slab reactions to temperatures in the range of 300°C–375°C for antigorite formation and <200°C for chrysotile formation. These latter findings are consistent with temperature estimates based on mineral parageneses from schists within the serpentinite mud matrix (see Section 3.2).

Pore fluid compositions from all seamounts (Fryer et al. 1999; Mottl et al. 2003, 2004; Hulme et al. 2010) demonstrated a systematic variation with distance from the Mariana Trench, thus with depth to the slab (**Figure 9**). Predictions by Peacock (1990) and analyses of metasedimentary rocks from the Franciscan complex in California (Sadofsky & Bebout 2003, 2004) showed results consistent with variations observed in Mariana pore fluids with distance from the trench. The most recent data from trace element analyses, including rare earth elements (Hulme et al. 2010), provide more detail regarding reactions and temperatures at the source. Nearest the trench (e.g., Blue Moon Seamount), only calcium and strontium concentrations are greater than seawater, suggesting smectite collapse (Hulme et al. 2010). At Blue Moon Seamount, cesium is immobile, requiring a temperature of <80°C at the source. Further from the trench (e.g., Cerulean Springs on Pacman Seamount), cesium is mobilized, and temperatures >80°C at depths to slab of ~13–16 km are likely. With increasing distance from the trench equivalent to slab depths of

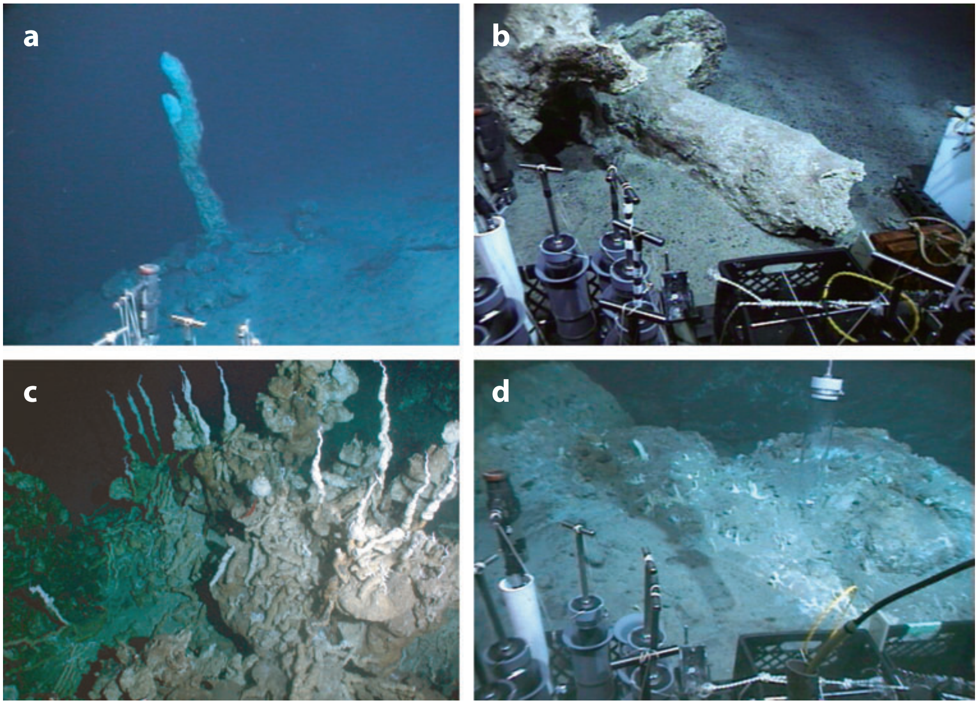


Figure 8

Jason 2 seafloor images. (*a*) A 10-m carbonate chimney structure on Conical Seamount. Large pieces of chimney lie around its base. The chimney has collapsed on occasion and then regrown. (*b*) Close-up of the large (0.7 m in diameter) broken fragments of carbonate chimney at the base of the structure shown in panel *a*. (*c*) Thin-diameter (∼1–3 cm) carbonate spires growing from a thicker 2–3-m-wide, 2–5-m-high base forming on a fault scarp at the summit of Quaker Seamount. (*d*) Minute (1–10 cm high, 1–4 cm in diameter) brucite chimneys on a seep (Celestial Springs) at the southeast tip of the Pacman Seamount.

∼17–24 km (e.g., Celestial Seamount), low rubidium/potassium and rubidium/cesium suggest that the pore-fluid source is the dehydration of altered clays at temperatures of <150°C (see also Plank & Langmuir 1998). At a depth to slab of ∼25 km (e.g., Big Blue and Quaker Seamounts), pore fluids show higher light rare earth elements relative to heavy ones, indicating temperatures of ∼200°C, and higher ratios of rubidium/potassium, reflecting a basaltic source. Variations in rubidium/cesium with distance from the trench limit slab temperatures beneath the seamounts furthest from the trench (South Chamorro and Conical Seamounts) to ∼350°C. These results are consistent with the paragenesis studies of minerals in schists enclosed in the mudflows on South Chamorro Seamount.

3.5. Eruptive Processes

Serpentinite mudflow eruptions on Mariana forearc seamounts are clearly episodic and must be directly related to episodic release of fluids from the subducting slab. We do not know the rate of eruption or the frequency, nor do we know how old most of the serpentinite mud volcanoes are. Studies of Deep Sea Drilling Project (DSDP) Leg 60 cores (the only ones to penetrate Mariana forearc basement rocks) suggest that at least Big Blue Seamount (**Figure 2**) may have been active since the Middle Eocene (∼45 Mya). Desprairies (1981) described sediments of that age directly

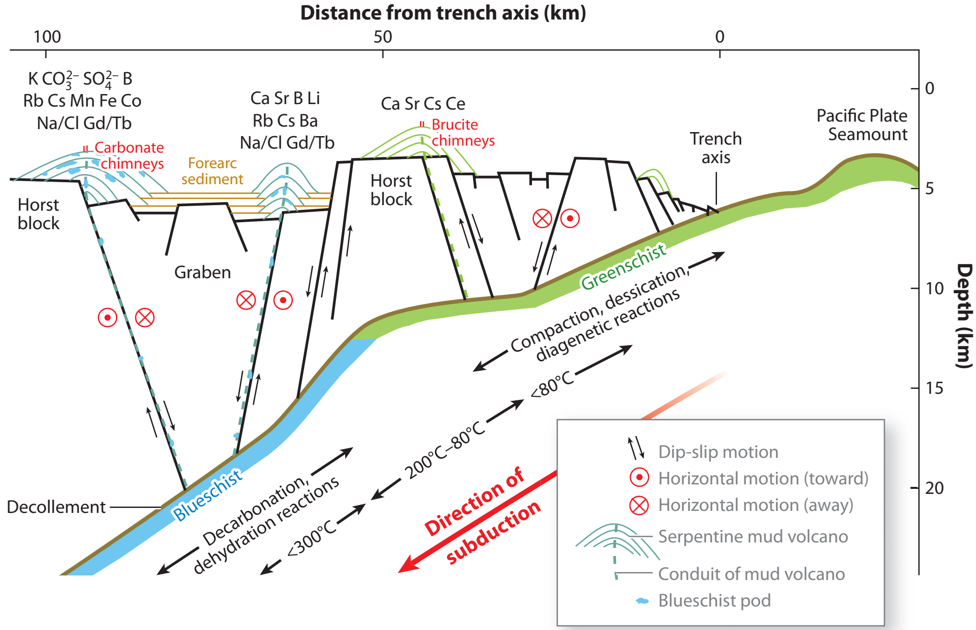


Figure 9

Schematic cross section of the Mariana forearc summarizing the structures, processes, physical conditions, and chemical species occurring at various distances from the trench. The elements and ions depicted above various seamounts represent those species that are enriched at increasing distances from the trench. The types of reactions taking place in the subducting slab are depicted, and the temperature ranges are indicated by the paragenesis of mineral species and reactions likely at different temperatures in the subduction zone. Figure modified after Fryer et al. (1999) and Hulme et al. (2010).

above the basement in Site 459 just to the south of Big Blue Seamount that contain 50% serpentine. If the serpentine is indicative of a mudflow, then Big Blue Seamount, or an earlier mud volcano in that region, became active almost at the inception of subduction (Fryer 1992).

Side-scan imagery (e.g., Fryer et al. 1990, 1999; Wheat et al. 2008), submersible dive observations (Fryer et al. 1990, Fryer & Mottl 1997), ODP drilling operations (Shipboard Sci. Party 1990c,d, 2002; Fryer 1992; Fryer & Mottl 1992; Lagabrielle et al. 1992; Fryer & Salisbury 2006), and MCS surveys (Oakley et al. 2007) point to the presence of multiple flow units on the flanks of the seamounts. Mottl et al. (2003) calculated that the upward seepage velocity of slab fluids at the South Chamorro summit vents is a few centimeters per year, based on profiles of pore-fluid advection. At Big Blue Seamount, the rate is higher, 36 centimeters per year (Wheat et al. 2008, Hulme et al. 2010). However, these are merely snapshots in time of systems that may be highly variable. The results of strontium isotope studies (Bickford et al. 2008) show that after eruptive episodes, mudflows exposed at the seafloor equilibrated with seawater and accumulating sediments. Subsequently, when these flows and enclosed small rock fragments were buried by additional serpentine mudflows, they began to re-equilibrate with the slab-derived pore fluids from the new flows. Together with experiments on strontium isotopic exchange, the study of the zonation of the strontium isotopic composition of the serpentinized peridotite clasts and serpentine fragments in the muds may make it possible to characterize the periodicity of fluid release at South Chamorro Seamount (Bickford et al. 2008). Such a characterization would provide the first

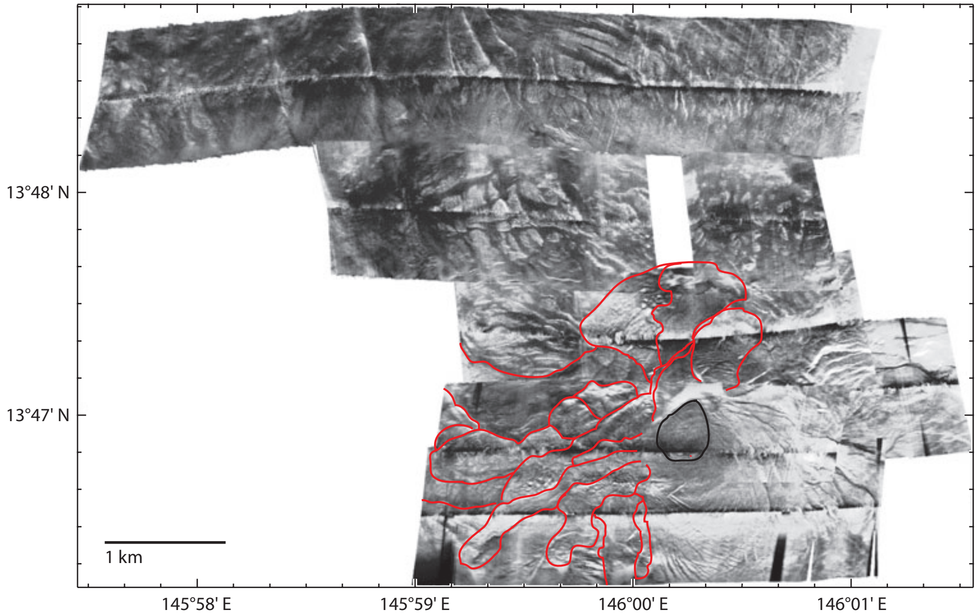


Figure 10

DSL120 backscatter side-scan imagery of the summit of South Chamorro Seamount. The mudflows outlined in red emanate from the summit knoll and overlap one another. The higher-backscatter region circled in black is the slight depression at the summit knoll in which there are active fluid vents; carbonate structures; armoring of fissures; and communities of mussels, gastropods, tube worms, and galatheid crabs.

time even an estimate of the rate of periodicity of eruption at one of these seamounts had been accomplished.

It is possible that we will find that some eruptive episodes bring muds up from great depth rapidly, on the order of weeks to years. The 200 m of thin (a few to several tens of centimeters) flows that penetrated at the summit knoll of South Chamorro seamount (Shipboard Sci. Party 2002) indicate a relatively rapid accumulation of numerous, small flows. High-resolution side-scan imagery of the summit knoll on this seamount (Fryer & Salisbury 2006, Wheat et al. 2008) shows some intricate overlap of these small flows on the west side of the knoll (**Figure 10**). Such interrelationships suggest rapid eruption; otherwise sediment accumulation would likely have muted these subtle features.

Mineralogic characteristics of the schists enclosed in the muds also point to relatively rapid eruption. Amphibole crystals in some schists enclosed in South Chamorro Seamount muds and single crystals in the mudflow matrix have sodic rims and calcic cores (Fryer et al. 1999, 2000; Gharib 2006), indicating nearly exclusively prograde reactions at incipient blueschist facies. At the lowest measured rates of fluid rise (~1 cm per year), it would take muds 1 to 2 million years to rise through 10 to 20 km of forearc lithosphere. It is well established that retrograde metamorphic reactions are generally sluggish and that high-pressure/low-temperature phases can persist metastably to low pressures, which is explained by metamorphism generally driving fluids out of a system, reducing the ease with which reactions can take place. The reduction in temperature and pressure with uplift also decreases the potential for retrograde reactions. We would expect, however, that serpentinite muds rising in a fluid-charged, highly reactive, and very dynamic conduit environment over 1 to 2 million years could readily experience retrograde metamorphism, especially of loose, individual, millimeter-size amphibole grains. Such grains observed in South Chamorro mudflows do not show evidence of this (Fryer et al. 1999). This suggests a relatively short residence time in the conduit during transport.

3.6. Biological Communities

Organisms such as small, high-spire gastropods, limpets, and shrimps were observed and recovered during Alvin dives on Conical Seamount in 1987 (Fryer et al. 1990) near the summit on the carbonate chimneys. A gelatinous ooze coating the exterior of the chimneys was presumed to be a microbial mat, but no microbiological studies were done on the samples at that time. Communities of mussels, larger gastropods, galatheid crabs, and tubeworms were observed and recovered during Shinkai 6500 dives at the active seeps on the summit of South Chamorro Seamount in 1996 (Fryer & Mottl 1997). Samples of serpentinite mudflows were recovered in 2003 from gravity and piston cores on seven of the mud volcanoes and from push cores by the remotely operated vehicle (ROV) Jason 2. These core samples, together with ODP Leg 195 drill core samples from the South Chamorro Seamount summit, reveal a microbial population that is dominated by Archaea, especially below ~3 m below the seafloor (archaeal biomass 571 to 932 times higher than bacterial biomass) (Mottl et al. 2003, Curtis & Moyer 2005, Curtis 2007). Pore fluid studies indicate that the Archaea are "oxidizing methane in the fluids to carbonate ion and organic carbon, reducing sulfate to bisulfide, and probably dissolved nitrogen to ammonia" (Mottl et al. 2003).

The unusual characteristics of the environment in which the microbial communities operate are that they do so at the highest pH (12.5) ever measured from a seafloor seep, the community is dominated by anaerobic methane-oxidizing (ANME) Archaea yet the setting is devoid of sedimentary organic carbon, and thus the typically accompanying ANME Bacteria are not observed (Mottl et al. 2003). In fact, Archaea dominate the microbial populations in all seven seamounts thus far sampled (Curtis & Moyer 2005). In samples from the South Chamorro Seamount summit, Curtis (2007) notes an increase in richness by about 33% of the clone library from ODP Hole 1200E (a few meters from an active spring) compared with that of Hole 1200D (80 m from the spring). Pore fluid advection rates at Hole 1200E are ~3 cm per year, whereas those at Hole 1200D are only 0.2 cm per year. This supports the interpretation that the archaeal population is supported by nutrients brought up by slab-derived fluids and products of the serpentinization process, and that the faster the flow, the more complex the community. This is also consistent with the nutrient source being the abiotically produced methane associated with serpentinization reactions (Mottl et al. 2003).

Curtis & Moyer (2005) performed an analysis of the Jason 2 core samples, including community fingerprinting of genomic DNA using terminal restriction length polymorphism. Compared with traditional clone library and sequence analysis of ODP Site 1200 core samples from South Chamorro Seamount, the data show that the dominant archaeal phylotypes clustered into two groups of novel Methanobacteria. They identified a third phylotype, associated with Crenarchaeota, a nonthermophilic marine group I that was exclusively detected at ODP Hole 1200D on South Chamorro Seamount. Their data suggest that a novel archaeal subsurface community has developed in the mudflows on at least three of the seven Mariana mud volcanoes sampled (South Chamorro, Big Blue, and Blue Moon Seamounts). Takai et al. (2005) also discovered a new species of alkaliphilic bacteria, *Marinobacter alkaliphilus*, present to ~3 m below the seafloor at South Chamorro Seamount. They found them to be psychrophilic (optimal temperatures of 30°C–35°C), halophilic (optimal NaCl concentration of 2.5%–3.5%), and uniquely alkaliphilic (optimal pH between 8.5 and 9.0, persisting to 11.4). Both the new alkaliphilic bacteria and the novel populations of Archaea in the deeper muds (Curtis & Moyer 2005) can survive only in the unique geochemical conditions created by the active egress of the slab-derived pore fluids. The microbial community at South Chamorro Seamount thus not only is extremophile, but also is dependent on chemical energy from a source as deep as 20 km (Oakley et al. 2007) below the seafloor (Mottl et al. 2003).

Decollement: a surface that acts as a gliding plane between two masses in a thrust fault relationship

4. CONTROLS OVER MUD VOLCANISM PROCESSES

4.1. Seismicity as an Eruptive Trigger?

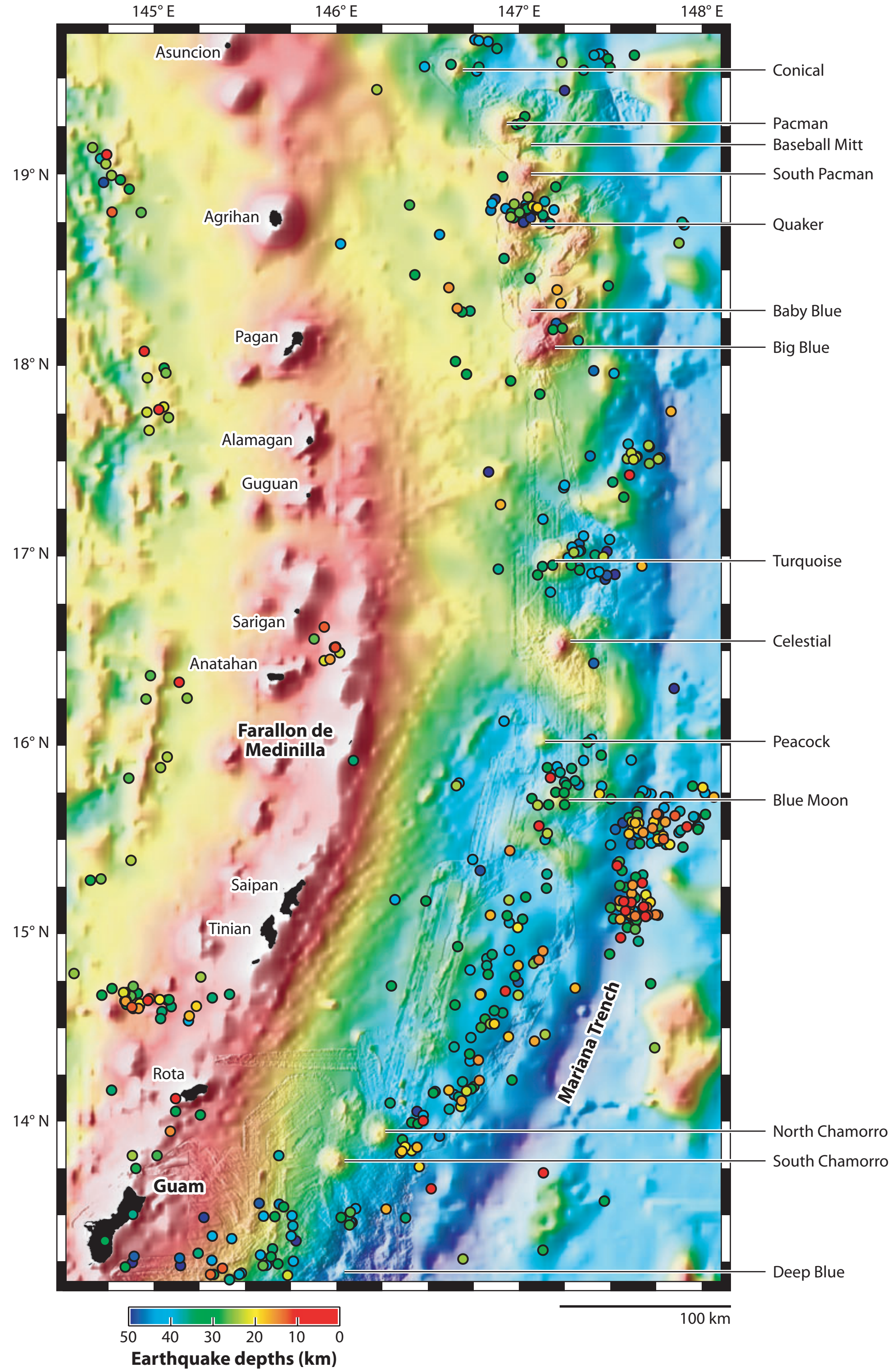
The serpentine mudflow material is less dense than surrounding peridotite (Ballotti et al. 1992) and should tend to rise because of gravitational instability, but a mixture of serpentinized fault gouge and slab-derived fluids would not be strong enough (e.g., Phipps & Ballotti 1992) to push, diapirically, through surrounding massive peridotite. A conduit for the rise of the serpentinite mud must be created, and extensional deformation is required for an eruption to be initiated. That the seamounts are mainly monogenetic suggests that the conduits are long-lived. The Mariana forearc is in extension both east-west and along its strike (Fryer 1992, Wessel et al. 1994, Stern et al. 2004). The Mariana serpentinite seamounts form along fault scarps and at the edges of horst/graben structures where it is most likely that conduits for fluid and mud release will develop (Fryer 1992).

Both the decollement and the overriding plate of the Mariana forearc are seismically active. Plots of relocated earthquakes from Engdahl et al.'s (1998) data sets for only the upper 50 km of the forearc region show clusters of earthquakes associated with some of the mud volcanoes, but other mud volcanoes appear to have no associated earthquakes (**Figure 11**). Depth determinations, even for relocated earthquakes in this region, can have errors of as much as $\pm$10 km, but the data show some temporal relationships between deep (slab) events and smaller shallow aftershock events in the overriding plate (**Supplemental Videos 1–3**). Shiobara et al. (2010) completed a one-year deployment of ocean bottom seismometer instruments across the Mariana forearc and arc recordings of over 3,000 events. If seismic activity within the decollement triggers fluid-release events, the fluids may mobilize gouge along faults within the forearc lithosphere beneath the seamounts (Fryer 1992). Mudflow matrix material and clasts could be derived from the footprint region of the event. As the muds rise, they can presumably also incorporate material from anywhere along the conduit. The variations in composition and mineralogy of materials from flow units in ODP cores (Fryer & Mottl 1992, Lagabrielle et al. 1992, Savov et al. 2005a), however, suggest that discrete source regions can be distinguished.

Supplemental Material

4.2. Dynamics of Serpentinized Mariana Forearc Mantle

Girardeau & Lagabrielle (1992) examined the microtextures of serpentinized ultramafic clasts from Conical Seamount. They noted the initial formation of the peridotite under high-temperature asthenospheric conditions, followed by the remelting and infusion of the peridotite with a fluid phase, which was accompanied by a period of high-temperature/low-stress deformation of the peridotite that occurred either before subduction began or during the initial stages of subduction and proto-arc formation. They identified ductile shear zones in clasts as having formed during a later phase of protracted retrograde metamorphism (serpentinization). Overprinting all is brittle failure of the serpentinized peridotite. These observations are consistent with serpentinization in the suprasubduction environment, extensional tectonics, and a mud volcanism emplacement of the clasts (Fryer 1992).


145° E
146° E
147° E
148° E
19° N
18° N
17° N
16° N
15° N
14° N
Asuncion
Agrihan
Pagan
Alamagan
Guguan
Sarigan
Anatahan
Farallon de Medinilla
Saipan
Tinian
Rota
Guam
Mariana Trench
Conical
Pacman
Baseball Mitt
South Pacman
Quaker
Baby Blue
Big Blue
Turquoise
Celestial
Peacock
Blue Moon
North Chamorro
South Chamorro
Deep Blue
100 km
50 40 30 20 10 0
Earthquake depths (km)

4.3. Rheology of Serpentine and Seismicity

Since the discovery of serpentinized peridotite in the Izu-Bonin-Mariana convergent margin (Ishii et al. 1992) and low velocities from seismic data in the forearcs (Sato et al. 2004, Tibi et al. 2008), several researchers have suggested that fluids and serpentine, especially chrysotile (e.g., Kamimura et al. 2002, Peacock & Hyndman 1999, Hyndman & Peacock 2003, Kasahara et al. 2003, Gerya & Meilick 2011), could essentially lubricate the decollement. The presence of chrysotile was thought to permit stable sliding and limit the upper boundary of great earthquakes at subduction zones. It is well known that chrysotile preferentially forms in veins in the latter stages of serpentinization and is associated primarily with high-fluid flux in general (e.g., Evans 2004), but Moore et al. (2001, 2004) concluded that all the serpentine phases would be relatively strong in the deeper parts of fault zones. They specifically examined chrysotile strength in laboratory measurements at various temperatures and pressures and determined that a given fault lined with chrysotile would pass through a strength minimum at a depth of 3 km, after which its strength would increase rapidly. At depths greater than ~3 km, unstable slip (i.e., earthquakes) could occur even in chrysotile-lined faults.

Other relatively weak minerals such as brucite and talc also occur in serpentinites and have been suggested as additional causes of stable sliding in subduction zones (Hyndman & Peacock 2003, Wang et al. 2009). Brucite is the weakest of these additional constituents of serpentinite bodies, but there are some problems with its facilitating stable sliding. Moore et al. (2001) suggested that although brucite does occur in quantities approaching 25% in some serpentinites, it would have to be "concentrated along the principal slip surfaces rather than mixed in with the serpentine minerals in order to substantially lower the strength of a serpentinite-filled fault." Laboratory analysis of microcrack formation in ultrabasic rocks shows that the cracks develop in a random orientation within serpentinized peridotites (Rigopoulos et al. 2011). Beard et al. (2009) demonstrated that in the incipient phases of the hydration of peridotite rocks, iron-rich brucite does indeed form preferentially along the fluid channels within the rocks, but in very small amounts (micrometer-width veinlets). With an increasing degree of serpentinization, the brucite becomes more randomly disseminated throughout the rock. Intimate intergrowth of brucite with highly serpentinized bodies is the rule rather than the exception (e.g., O'Hanley 1996); however, talc is a better candidate (Moore & Michael 2007, Moore & Lockner 2008, Wang et al. 2009, Soda & Takagi 2010). Once carbonate ion is present in the serpentinizing fluids, serpentine will react with it to yield talc and magnesite and release hydrogen via

$$2Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow Mg_3Si_4O_{10}(OH)_2 + 3MgCO_3 + 3H_2.$$

Talc, however, generally forms at temperatures greater than 350°C–400°C (e.g., Bucher & Frey 2002), and these temperatures are indicated only at serpentinite seamounts furthest from the trench, at depths greater than the generally accepted updip limit of seismicity. More seismic activity monitoring and laboratory studies on the rheological behavior of hydrated assemblages in shallow suprasubduction regions are needed.

Figure 11

Color bathymetry map of the Mariana forearc region with labels for the major serpentinite seamounts; shading shows illumination from the northwest. Earthquakes at depths from 0 to 50 km from Engdahl et al.'s (1998) relocated earthquake data set are plotted for the region as colored dots (see the color bar for corresponding depths). Clusters of events are primarily associated with Blue Moon, Turquoise, and Quaker Seamounts (see **Supplemental Videos 1–3**).

5. SUMMARY AND DISCUSSION

5.1. Mariana Serpentinite Mud Volcano Processes

Mélange: a regional-scale formation that lacks continuous bedding and includes fragments of rock of all sizes; contained in a fine-grained deformed matrix

Olistostrome: sedimentary submarine deposit of heterogeneous blocks and muds accumulated as a semifluid by gravity sliding or slumping of unconsolidated debris

Recognition that the Mariana forearc seamounts were large serpentinite mud volcanoes placed the association of serpentinite mélange/olistostrome formation within the context of an active convergent margin setting. Natland & Mahoney (1982) were the first to suggest that fluid from the subducting slab probably rose to crustal levels and caused the unusual alteration of basaltic lavas beneath forearc sediments at DSDP Sites 458 and 459. Submersible dives on Conical Seamount (Fryer et al. 1990) first discovered carbonate chimneys associated with active serpentinite seeps on the ocean floor. Cores of the mudflows collected on the seamounts provided pore-fluid samples that established the slab as a source of the serpentinizing fluids and related the change in composition of the fluids with depth to the slab beneath the forearc. One consequence was the recognition that chimney structures closer to the trench comprised brucite, whereas those further away were exclusively carbonate (Fryer et al. 1999). The episodicity of the eruptions from the seamounts was also clearly established. Attempts to determine the rate at which the fluids and muds rise have been hampered by the lack of advection or isotopic equilibration time-series data. The dynamics of the conduit processes are still unknown. Formation fluid pressure within the conduit of South Chamorro Seamount does respond to seismic events that occur in the vicinity of the seamount (Davis & Becker 2005). At ODP Hole 1200C, pressure sensors were deployed within the cased and CORKed Hole. Over the next year, two large (~7.0 Mb), deep (~70 km) earthquakes occurred within 200 km of the hole and produced seismic-frequency pressure variations and persistent positive pressure changes at the time of the events. Davis & Becker (2005) inferred that these signals reflected a local formation response to seismic surface waves.

Supplemental Material

Clusters of earthquakes occur on the Mariana forearc (**Figure 11** and **Supplemental Video 1**). Some serpentinite seamounts are associated with these earthquakes (especially Quaker, Turquoise, and Blue Moon Seamounts), while other seamounts do not have associated earthquake activity. It is interesting that, in some cases, large earthquakes along the decollement or within the subducting plate are followed by shallower earthquakes in the overlying forearc (**Supplemental Videos 2** and **3**). Does subduction-zone seismic activity trigger fluid-release events? A 40-day study of local seismicity near Big Blue Seamount (Pozgay 2007) determined that most events lie in a zone to the west of the seamount at depths between 30 and 100 km (within the subducting plate). Shiobara et al.'s (2010) data confirm these observations and lend credence to the potential effects of hydration-related processes on the updip limit of seismicity in subduction zones. If a mud volcano eruption could be captured through seafloor observatory efforts, the conduit of a seamount would likely produce only extremely small earthquakes (magnitude 0–1) from pressure changes and thermal stresses (Sohn et al. 1999, Wilcock 2004). An array of ocean bottom seismometer instruments around the flanks of the seamount could map activity at that level.

5.2. Subduction of Serpentinite

Serpentinite may be being recycled in the Mariana subduction system. Murata et al. (2009) examined microtextures in serpentinized peridotites from the Mariana forearc and concluded that higher-fayalite content (Fo_{86-90}) overgrowths on primary Fo_{90-92} olivine and the presence of lizardite and chrysotile veins, both pre- and postdating the formation of antigorite, indicate tectonic recycling of the mantle-wedge serpentinite. Several researchers studying the Mariana mudflow lithologies have noted the possibility that serpentinite formed near the shallower parts of the decollement may be carried deeper into the subduction zone and may contribute fluids and slab constituents to magma genesis at the arc and backarc regions (Kerrick & Connolly 2001; Snyder et al. 2005; Wei et al. 2005; Savov et al. 2005b, 2007).

5.3. Serpentinization and the Origin of Life

Within the past decade, serpentinization has enjoyed particular attention as a potential process supporting the evolution of life on Earth. Recently investigators (Holm & Charlou 2001, Sleep et al. 2004, Kelley et al. 2005, Schulte et al. 2006, Delacour et al. 2008, Martin et al. 2008, Proskurowski et al. 2008, Konn et al. 2009, Lang et al. 2010, Russell et al. 2010, Muntener 2011) suggested that serpentinization reactions, particularly in cool alkaline environments, could have resulted in a geochemical milieu, including hydrogen and low-molecular-weight carbon compounds that may have provided the ideal conditions for the earliest life forms. Most of these researchers favor an environment near a mid-ocean ridge. Seyfried et al. (2007) noted the complexity in the processes of serpentinization at such sites and urged caution in modeling alteration in peridotite-hosted ridge systems. Bada (2004) disagreed with the ridge origin, noting that those who favor it assume "that hyperthermophilic organisms form the root of the tree of life." Peresypkin et al. (1999) and Bada & Lazcano (2002) argued against a high-temperature origin, emphasizing that progenitor molecules for the formation of organisms are unstable at high temperatures. They suggested that there may have been times in the early history of Earth when serpentinization in cooler environments was prevalent. Ancient subduction zones are an obvious possibility. Subduction zones were present on the Hadean/Archean Earth, represented today by some ancient greenstone belts. The results of $\delta^{18}O$ analysis of zircon with ages of 4.4 billion years (Wilde et al. 2001) indicate that surface temperatures were cool enough in the late Hadean (4.6–3.82 Gya) for liquid water to have existed on Earth's surface and thus for life to have evolved (Valley et al. 2002). If this is so, and subduction processes were occurring on Earth, serpentinization would have been possible. Yoshida & Fujiura (2009) presented intriguing results from simulating earthquakes in an experiment to study the response to shaking of biofilms in serpentinite cracks. Their results suggest that seismic activity may facilitate bacterial genetic exchange, particularly when exposed to chrysotile needles.

There are some advantages to subduction zones as a site for the origin of life, but some problems too. Today serpentinization takes place at relatively low temperatures (~30°C) in the conduits of the seamounts (Shipboard Sci. Party 1990c,d, 2002). As mineral parageneses for the schists from the Mariana mud volcanoes shows, the maximum temperatures of metamorphism at the source of the muds are ~300°C–350°C (Fryer et al. 2006, Gharib 2006, Hulme et al. 2010). Evans (2010) recently suggested, however, that serpentinization in the suprasubduction-zone mantle wedge would likely take place at temperatures of 400°C–600°C, conditions under which the rates of magnesium/iron diffusion are so great that antigorite could be produced without the precipitation of magnetite, thus no release of H_2. This led him to conclude that the release of H_2 and the formation of abiogenic methane may not be accompaniments of mantle-wedge serpentinization. That antigorite is present in the matrix of Mariana serpentinite mudflows does suggest that some serpentinization took place at temperatures above ~300°C. However, the dominant serpentine phases present in the matrix of the mudflows on all seamounts is lizardite, and significant methane (Shipboard Sci. Party 1990a,b; Mottl 1992), as well as more evolved hydrocarbons (Haggerty & Fisher 1992), is present in the pore fluids. The question remains, with the likely higher geothermal gradients present in the earliest subduction zones, would serpentinization have taken place at temperatures low enough to provide the necessary geochemical and physical conditions to foster the evolution of living organisms?

SUMMARY POINTS

1. Mariana forearc mud volcanoes are likely long-lived (tens of millions of years) and are associated with major fault zones.

2. These mud volcanoes permit us to sample directly the entire forearc lithosphere, the downgoing Pacific plate, and slab-derived fluids. The included rock clasts provide a record of forearc and slab metamorphism.
3. Fluid compositions vary with distance from the trench (i.e., with depth to slab), recording changes in reactions with increasing pressure and temperature within the subducting lithospheric slab.
4. Eruptions from the seamounts are episodic and variable in volume and fluid content.
5. Extensional tectonics, not diapiric mechanisms (as in salt-dome formation), are required for serpentinite mud volcanism to occur.
6. Some seamounts are associated with clusters of earthquakes, whereas some are not. A linkage among seismic activity, variable-volume fluid-release events from the subducting slab, and activity on the mud volcanoes may exist.
7. The scope and complexity of biological communities associated with seeps on these mud volcanoes are likely controlled by the rate and composition of fluid release from active conduits.
8. The relatively cooler temperatures of subduction zones versus ocean ridges may afford a more promising locality for the early evolution of life on Earth.

FUTURE ISSUES

1. Additional laboratory experiments on mudflow products will enable a deeper understanding of the diversity of mantle composition and stress regimes along the Mariana plate margin and potentially reveal microbial processes in serpentinized peridotitic clasts.
2. Drilling through the flank of the seamount would provide much-needed age data, and establishing a seafloor observatory drill site at a seamount summit could monitor possible linkages among subduction events, seep activity, and biological responses.
3. The full-ocean-depth hybrid ROV Nereus will permit the exploration of geological and biological processes on seamounts closer to the trench. Such data would provide near-trench end-member fluid and mud samples for comparison with experimental data.
4. The potential exists for monitoring natural processes of carbon sequestration in these active serpentinization systems. Does the potential exist for the development of strategies for long-term storage of atmospheric CO_2 in these systems?
5. The study of microbiology in association with hydrothermal systems is a burgeoning field. How the process of serpentinization may relate to the proliferation of life at these sites is poorly understood, and whether early life-forms on Earth may have developed in such environments needs to be studied in greater detail.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Contents

Errata

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