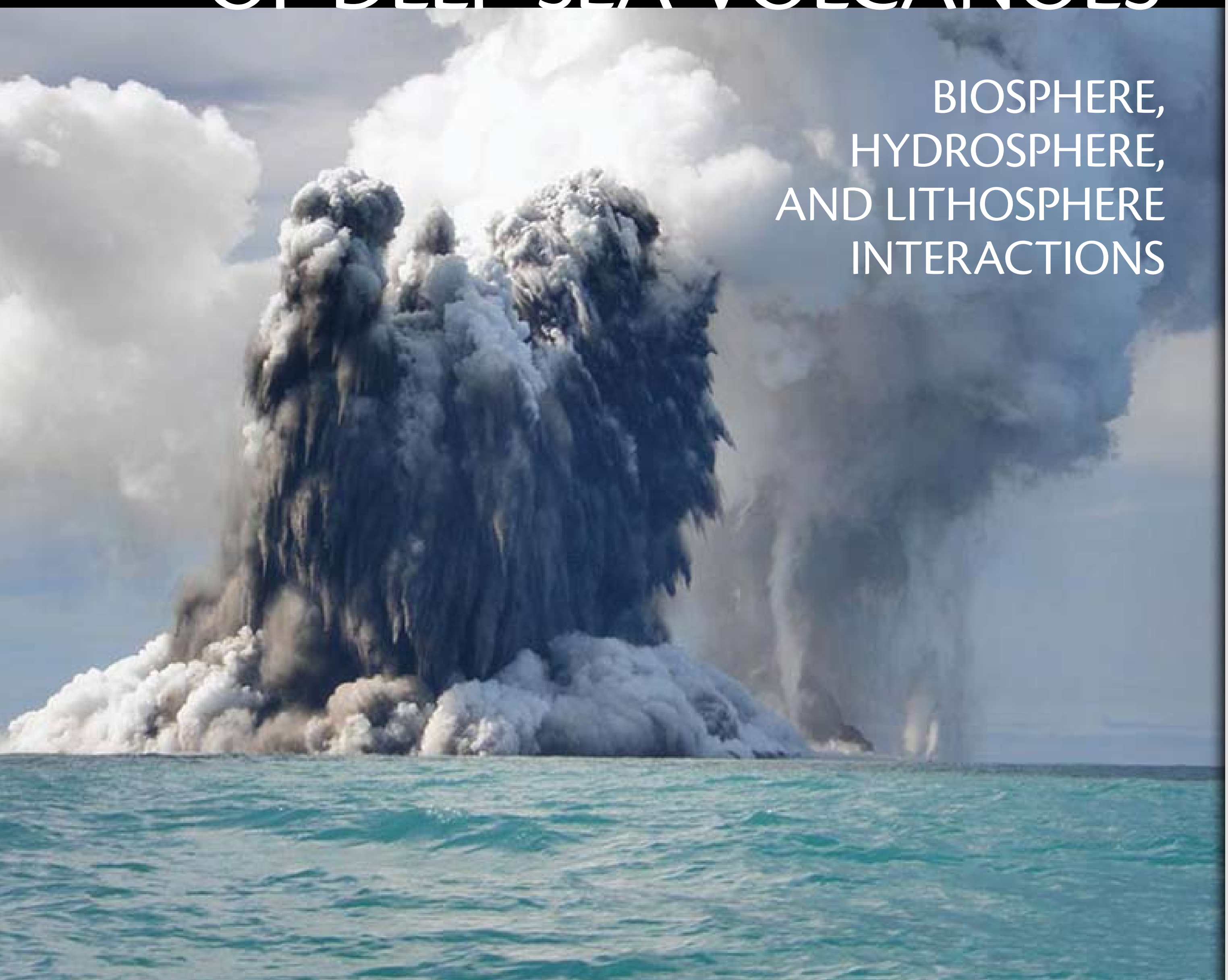
BY HUBERT STAUDIGEL AND DAVID A. CLAGUE

THE GEOLOGICAL HISTORY OF DEEP-SEA VOLCANOES

BIOSPHERE, HYDROSPHERE, AND LITHOSPHERE INTERACTIONS



Emergence of a submarine volcano near Nukualofa, Tonga, March 18, 2009. The eruption column displays two very characteristic features for shallow-submarine eruptions, base surges (light colored) that spread out horizontally at the base and "cocks' tail" tephra jets that emerge from the center of the column. *Photo credit: Dana Stephenson/Getty Images*

ABSTRACT. The geological evolution of seamounts has distinct influence on their interactions with the ocean, their hydrology, geochemical fluxes, biology, resources, and geohazards. There are six geological evolutionary stages of seamounts: (1) small seamounts (100–1000-m height), (2) mid-sized seamounts (>1000-m height, > 700-m eruption depth), (3) explosive seamounts (< 700-m eruption depth), (4) ocean islands, (5) extinct seamounts, and (6) subducting seamounts. Throughout their lifetimes, seamounts offer major passageways for fluid circulation that promotes geochemical exchange between seawater and the volcanic oceanic crust, and seamounts likely host significant microbial communities. Water circulation may be promoted by hydrothermal siphons in conjunction with the underlying oceanic crust, or it may be driven by intrusions inside seamounts from Stage 2 onward. Geochemical fluxes are likely to be very large, primarily because of the very large number of Stage 1 seamounts. Intrusive growth of seamounts also initiates internal deformation that ultimately may trigger volcano sector collapse that likely peaks at the end of the main volcanic activity at large seamounts or islands. Explosive activity at seamounts may begin at abyssal depth, but it is most pronounced at eruption depths shallower than 700 m. Wave erosion inhibits the emergence of islands and shortens their lifespans before they subside due to lithosphere cooling. Once volcanism ends and a seamount is submerged, seamounts are largely unaffected by collapse or erosion. Throughout their histories, seamounts offer habitats for diverse micro- and macrobiological communities, culminating with the formation of coral reefs in tropical latitudes. Geological hazards associated with seamounts are responsible for some of the largest natural disasters recorded in history and include major explosive eruptions and large-scale landslides that may trigger tsunamis.

INTRODUCTION

Seamounts are the least explored major morphological features on Earth. Hundreds of thousands of them are dispersed through the ocean basins, with less than 0.1% known from *any* direct observation such as an echosounding, or any kind of sampling. Most of what we know about seamounts comes from satellite observations that sense them indirectly from the centimeter-size deflections they impose on sea surface topography (e.g., Wessel et al., 2010). This indirect method reliably identifies only features larger than 1500 m in height and does not offer any topographic detail below this scale. This state of exploration reveals nothing about a seamount's geology. In fact, this lack of detail would be considered entirely unacceptable for topographic features on land, effectively all of which are now sampled and mapped by direct measurements with a resolution better than 30 m in vertical and 100 m in horizontal dimensions. Seamounts are the last major frontier in our exploration of Earth's surface.

The minimal level of seamount exploration contrasts with their significance to science and society. They have rich fisheries (Pitcher et al., 2010), are marine-biological and microbiological hotspots (Danovaro et al., 2009; Emerson and Moyer, 2010), and have a significant geochemical impact, with chemical fluxes that allow mantle-derived materials to interact with the hydrosphere (Fisher and Wheat, 2010). Hence, seamounts are key points of intersection among the biosphere, hydrosphere, and lithosphere, and they are globally relevant.

In this paper, we explore how seamounts grow, collapse, and age, and how these processes interact with the hydrosphere and impact biological processes. The reader is referred to earlier reviews by Batiza and White (2000), Schmidt and Schmincke (2000), and a recent monograph (Pitcher et al., 2007).

DEFINING A SEAMOUNT

There is no uniform definition for the term seamount that equally satisfies all scientific disciplines. Definitions reflect diverse interpretative perspectives and disciplinary approaches that can be quite specific to the needs of a particular scientific community (see Box 1 on page 20 of this issue [Staudigel et al., 2010a]). We use here a definition that centers on seamounts as isolated geological features on the seafloor. Seamounts are typically volcanoes that form on top of the oceanic crust with their own central magma supply and hydrothermal system. This simple distinction can become more complex when isolated volcanoes form right on the mid-ocean ridge axis, such as Axial Seamount on the Juan de Fuca

Ridge (see Spotlight 1 on page 38 of this issue [Chadwick et al., 2010a]).

Isolated volcanoes on the seafloor come in a range of sizes whereby the smallest ones are typically referred to as abyssal hills and the larger ones as seamounts. We use 100 m as the tallest abyssal hill and smallest seamount, following a definition of Schmidt and Schmincke (2000). By this definition, seamounts may form in any tectonic setting; they may have conical, flat-topped, or complex shapes; and they may or may not have carbonate or sedimented caps. We also include oceanic islands in our definition of a seamount, considering them as very large seamounts that breached the sea surface. Viewing islands as a subgroup of seamounts is unusual because most views focus on the distinct nature of islands in terms of their volcanic features, subaerial weathering, and land-based biology (see Gillepsie and Clague, 2009). However, our grouping makes sense from a geological point of view in which volcanic islands are the summit regions of very large seamounts that are temporarily exposed above sea level. Most oceanic islands start out as seamounts and turn back into seamounts toward the ends of their life cycles.

GEOLOGICAL SETTING

Seamounts form in an oceanic geological setting that is much more dynamic than the continents, resulting in much larger vertical and horizontal displacements. Oceanic crust flexes and bends relatively easily from the processes involved in seamount formation (see Koppers and Watts, 2010). It may bulge upward from the buoyancy of rising mantle or due to heating of the lithosphere from below. However, as soon as a seamount has reached a critical size, subsidence becomes the dominant vertical force, caused by the bending of the oceanic crust into the mantle as it yields to the seamount load (Watts, 2001). For example, data from drowning coral terraces on Hawai`i suggest a subsidence rate of 2.6 mm $yr^{-1}$ for the Island of Hawai`i (Moore and Fornari, 1984; Moore et al., 1996). However, on a much longer time scale extending millions of years, seamounts also subside owing to the cooling of the lithosphere they are built upon. Most seamounts are formed within a few hundred kilometers of mid-ocean ridges at roughly 2.5-km water depth. These seamounts will subside with the underlying cooling lithosphere to about 5-km water depth within 60 million years and possibly down to 10-km depth when they arrive at subduction zones. This journey from mid-ocean ridge to subduction zone may involve thousands of kilometers of horizontal displacement. For example, the majority of the seamounts in the central-western Pacific originally formed in the South Pacific 80–140 million years ago.

GEOCHEMISTRY

Seamount volcanoes are formed by two principal mantle melting processes. Mid-ocean ridge (MOR) basalt and oceanic intraplate volcanoes (OIVs) are formed by decompression melting of mantle materials that buoyantly rise in upward convective flow and/or in response to plate extension and thinning. Subduction zone volcano magmas are commonly formed by the lowering of the melting point of the sub-arc mantle due to addition of volatiles from the descending slab. These different melting processes have a profound impact on the chemistry of seamount rocks and the chemical evolution of the volcanoes formed.

Seamounts close to MORs and in OIV settings erupt mostly basaltic (tholeiitic and alkalic) magmas, whereas subduction zone volcanics are predominantly composed of calc-alkaline (andesitic or arc-theoleiitic) magmas. All seamount rocks are formed by mantle melting processes that involve smaller degrees of melting than are characteristic for the generation of the oceanic crust itself. As a result, their incompatible element abundances may be an order of magnitude higher, and seamount fluxes of these elements may dominate global mantle fluxes even though seamounts are substantially less voluminous than the elongated volcanoes forming the MORs themselves. Subduction zone magmas tend to have overall higher Si, alkali, and volatile abundances, and lower Mg contents, than OIVs and MORs. As a result, they are more explosive and tend to have higher viscosities.

OIVs display a characteristic geochemical evolution over their 5–20-million-year volcanic histories (Clague and Dalrymple, 1987). Four geochemical stages are commonly distinguished, originally defined for the Hawaiian Islands but also found to

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characterize many other OIVs (Konter et al., 2009). OIV formation at Hawai`i's most recent active volcano, Lō`ihi, starts with small erupted volumes of basaltic rocks with diverse compositions generated by small degrees of mantle melting. The subsequent main, shield-building stage then produces up to 98% of the entire volcano typically from rocks formed by relatively large melt fractions in the mantle, yielding tholeiitic or mildly alkalic basalts. This is closely followed by a cap of alkalic rocks that are formed by smaller degrees of partial melting than the shield magmas. Some OIVs have a last stage of post-erosional or rejuvenated volcanism, after a volcanic hiatus of 1.5–10 million years. Rejuvenated volcanism typically consists of very small volumes of highly alkalic lavas that often include mantle xenoliths. These stages of geochemical evolution provide insights into the temporal evolution of mantle melting with substantial implications for the geodynamic processes involved. An interesting fact is that the majority of seamounts have completed their geochemical evolutions, and hence their surfaces most likely display the latest stages of volcanism. As a consequence, the majority of their earlier shield-building evolution may be largely hidden from direct sampling.

LITHOLOGICAL ROCK TYPES

Seamounts, like all volcanoes, are formed by intrusive and eruptive processes, probably in roughly equal proportions, at least in larger volcanoes where these processes have been studied in more detail.

Intrusive rocks at seamounts include dikes, sills, and gabbroic to ultramafic intrusions. The intrusion of dikes is likely to be one of the key means of growth of volcanoes with pronounced rift zones such as Hawai`i's Kilauea Volcano (Dieterich, 1988; Leslie et al., 2004). Kilauea's East Rift displays volcanic spreading rates of about 10 cm yr^{-1}, pushing the whole volcano outward from Mauna Loa along a near-horizontal slip surface at 8–9-km depth (Hill and Zucca, 1987; Denlinger and Okubo, 1995; Delaney et al., 1998). Such spreading may be entirely intrusive, as indicated by the common earthquake swarms on the rift zones of Kilauea that are not associated with eruptions (Klein et al., 1987). Erosion has also exposed the rift zones on several extinct Hawaiian volcanoes, particularly Koolau on Oahu, that also show large volumes of dikes (Walker, 1987; Figure 1). At the uplifted La Palma seamount series (Canary Islands), sills are the dominant form of intrusion. Their cumulative thickness suggests uplift of the overlying volcano by about 2 km (Staudigel and Schmincke, 1984; Staudigel et al., 1986). Sills may also play a key role in the growth of some Galápagos volcanoes (Amelung et al., 2000; Chadwick et al., 2006).

The deeper portions of seamounts are likely to contain magma reservoirs that crystallize to gabbroic and ultramafic intrusions (Upton and Wadsworth, 1972). Such intrusions may occur at a range of depths below the summit and are commonly sampled as xenoliths in later lavas (Clague and Dalrymple, 1987). At La Palma, such intrusive rocks have been found at stratigraphic depths of almost 5 km below the likely original summit of the seamount (Staudigel et al., 1986), whereas active magma chambers at Kilauea may be only 800 m below the summit (Almendros et al., 2002). Intrusive activity at seamounts results in inflation, over-steepening of flanks, and ultimately flank collapse.

Figure 1. Dike intrusions (vertical and slanted features) into the Koolau volcanic shield, Oahu, Hawai`i. Photo taken during road construction where the road cut is defined by three, near-horizontal "staircase" steps. A person on the second terrace (circled) offers a scale.

Eruptive rocks dominate the surface and the upper portions of a seamount, hence they are the major *apparent* component of volcano growth, with two major submarine types: lava flows and volcaniclastics (Staudigel and Schmincke 1984; Batiza and White, 2000; Schmidt and Schmincke, 2000).

Pillow lavas are the most common submarine lava flows and may be found in almost any subaqueous setting (Figure 2A,B). Less abundant are sheet flows and massive flows that tend to indicate higher mass eruption rates. Sheet flows typically are found on shallow slopes and settings where they may be ponded (Figure 2C; Staudigel and Schmincke 1984, Clague et al., 2000, 2009). All submarine lava flows have pronounced, quenched, glassy margins. Pillow lavas are named after the curved, occasionally round, cross section of the lava tubes that form these flows. Pillow lava cross sections commonly display characteristic "V-shaped" bottoms as the lava tubes mold themselves to the underlying pillow lavas. Individual lava tubes may occur in a range of tube diameters, from a few tens of centimeters to 200 cm in diameter (Clague et al., 2009), decreasing in size with distance from the eruption center and upward in a section (Figure 7 in Staudigel and Schmincke, 1984).

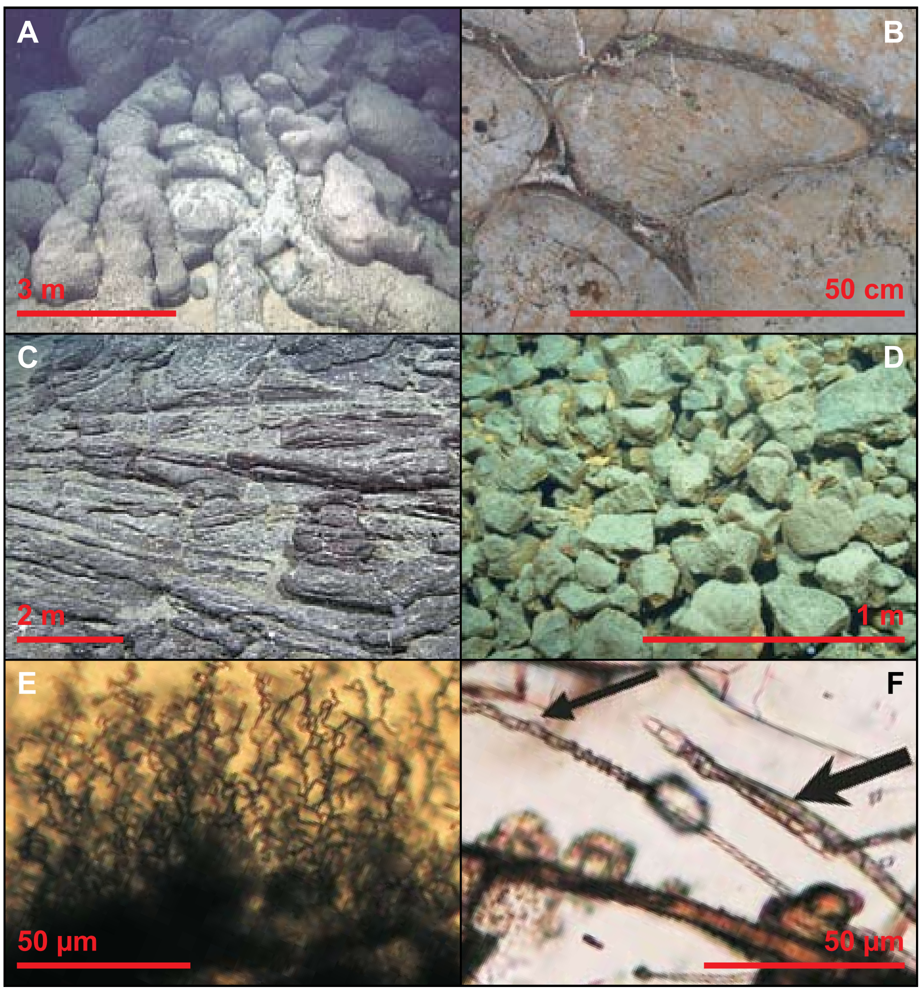

Figure 2. Field and microphotographs of submarine volcanic rocks: (A) Pillow lavas from submarine exposure at Vance Seamounts (1600-m water depth). (B) Dissected pillow formation from Archean pillow lavas in Pechenga, Russia. (C) Surface of a submarine sheet flow resembling a subaerial pahoehoe flow from Vance Seamounts (1712-m water depth). (D) Pillow fragment breccia from Lō`ihi Seamount, 1000-m water depth. (E) Tubular micro tunnels at a crack in a glassy pillow margin from Deep Sea Drilling Project Site 396B, 20R-3, piece 13, 108–112 cm. (F) Segmented tubular alteration and tubules with coiled bore from Troodos ophiolite. Tubular features in (E) and (F) are interpreted as trace fossils formed by microbial chemical drilling (Staudigel et al., 2008).

Seamount volcaniclastic rocks are sedimentary rocks formed by mechanical breakup of lava flows or by explosive-eruptive fragmentation mechanisms (Fisher and Schmincke, 1984); they are the most common volcanic rocks in shallow submarine volcanoes (e.g., Staudigel and Schmincke, 1984; Garcia et al., 2007). Mechanical fragmentation prevails during the collapse of unstable volcanic rock formations and spallation of pillow margins. Explosive fragmentation may be caused by the expansion of gas bubbles inside the magma, magma interaction with external water, or grain-to-grain interaction during an eruption. Although mechanical fragmentation processes have no (confining) pressure dependence, explosive fragmentation does. The water-depth dependence of explosive fragmentation processes is due to pressure dependence of magma volatile solubility and the pressure dependence of the extraordinarily large volume change in water when it transforms from liquid to gas. At one atmosphere pressure, this volume change is by a factor of 1600. It is important that the pressure dependence of gas solubility varies substantially with the dissolved species. CO_2 may outgas at relatively high pressures, whereas H_2O

and SO_2 tend to outgas at much lower pressures. Sulfur may separate from magma as an immiscible liquid at a wide range of pressures, but it contributes to the explosivity of lava only at low pressure when SO_2 bubbles can form in the magma. Geological observations and theoretical considerations point to a relatively consistent critical depth for the onset of major explosive activity. A more than 1800-m-thick section of seamount volcanic rocks at the La Palma seamount series shows a dramatic increase in volcaniclastic rocks at about 1000-m water depth (Staudigel and Schmincke, 1984). Theoretical considerations place the explosive transition closer to 700 m for explosions caused by the interaction of external water with magma (Peckover et al., 1973) as well as the explosive outgassing of magma itself (McBirney, 1963). However, some variance may be expected as a result of magma composition and eruption rates, and minor pyroclastic activity can be widespread even at abyssal depths (Clague et al., 2009).

Pillow fragment breccias are probably the most common mechanically fragmented volcaniclastic rocks at seamounts, often formed during the collapse of steep pillow lava flow fronts (Figure 2D). Pillow breccias may form when pillow lavas intrude into their own fine-grained volcaniclastics, with highly irregular, amoeba-shaped pillow cross sections that are completely enclosed in a hyaloclastite matrix. Pillows may also intrude into fine-grained epiclastic sediments (peperites). Explosive seamount volcaniclastics from magmatic outgassing may form highly vesicular scoria that may occur as nearly pumiceous deposits or be broken up into finer particles. The fragmentation of dense spatter may also be responsible for the formation of well-sorted, fine-grained hyaloclastite (glass sand; Clague et al., 2009). Most submarine volcaniclastics are missing most of the fine grain-size fraction, which remains suspended in turbulent waters and is deposited slowly in more distant areas surrounding the seamount eruption site. This lack of fine grains gives seamount volcaniclastics a relatively high permeability.

Lithology, particularly the abundance of coarser-grained volcaniclastic deposits, has a substantial impact on chemical fluxes and on the development of microbial habitats. Key controls include the high permeability of these deposits, which allows for seawater circulation, and a high abundance of volcanic glass, which is highly reactive with seawater. The alteration of volcanic glass is the primary process that controls low-temperature alteration fluxes between seawater and basalt (e.g., Staudigel and Hart, 1983), and glass is a particularly suitable material for colonization by microbial communities (Figure 2E,F), up to the moment they are sealed off by authigenic mineral deposition.

HYDROTHERMAL AND BIOLOGICAL ACTIVITY

Seafloor volcanism generally produces hydrothermal systems that are likely to be associated with substantial microbial and possibly macrobiological activity. Seamount hydrothermal water flow may be driven by intrusive activity, or the seamount may act as a "hydrothermal siphon" (Fisher and Wheat, 2010), allowing the recharge of seawater to the oceanic crust and the escape of oceanic crustal fluids that may be otherwise trapped by a blanket of impermeable sediments. Hydrothermal circulation at seamounts is significant, because they are made of rather permeable volcaniclastic rocks, and sediment cover does not significantly inhibit circulation. Seamounts also have a topographic advantage in that water can enter on the flanks and then rise within the seamount due to its raised geothermal gradients resulting from hydrothermal activity (Schiffman and Staudigel, 1994) or simply by their topography. Furthermore, seamount volcanic rocks are rich in volcanic glass, and their alteration contributes preferentially to hydrothermal chemical fluxes. Hence, seamount hydrothermal fluxes may be substantially more important than suggested by their volume relative to MORs. Some indications for large fluxes come from the large fluxes of ^3He or CO_2 (Lō`ihi; see Spotlight 3 on page 72 of this issue [Staudigel et al., 2010c]; Lupton, 1996; Hilton et al., 1998) or Mn and ^3He anomalies (Vailulu'u; see Spotlight 8 on page 164 of this issue [Koppers et al., 2010]; Hart et al., 2000; Staudigel et al., 2004). Together, seamount and oceanic crust hydrothermal systems play key roles in buffering the chemical composition of seawater, but the contribution from seamounts remains less well known and is likely to vary among elements.

Microbial communities have been documented from a range of seamounts, and there is abundant evidence that they might play a role in a potentially very large deep oceanic crustal biosphere. Emerson and Moyer (2010) review much of the evidence from microbiological studies at seamounts, showing that there are very diverse microbial communities, often with novel organisms with metabolic capabilities (including heterotrophy) and microbes that oxidize (and reduce) iron, manganese, and sulfur. Microbial communities may thrive, in particular, on the reducing potential of these elements in basalt, which is strongly enhanced by the high abundance of key nutrients in these rocks that are depleted in seawater (Fe, Mn, Ni, P). Fluids extracted from a sealed drillhole into Baby Bare Seamount (Cascadia Basin, Northeast Pacific Ocean) yielded a highly diverse microbial community (Cowen et al., 2003), suggesting that microbes are active inside the crust as well. The latter is also suggested by the study of microbial trace fossils in volcanic glass alteration that imply that bioalteration dominates glass alteration in the upper oceanic crust, at least to a depth of 500 m (Figure 2E,F; Furnes and Staudigel, 1999; Staudigel et al., 2008).

The interplay of ocean circulation and hydrothermal activity at seamounts also has a substantial impact on the macrofauna found at their surfaces. For example, the crater of Vailulu'u Seamount displays substantial metazoan mortality in the deepest part of the crater, whereas the summit of a new volcano growing in the crater displays a thriving population of eels (Staudigel et al., 2006). Similar complex benthic zonations likely occur at many other seamounts, such as the liquid sulfur lakes at Daikoku and Nikko volcanoes (Embley et al., 2007).

THE STRUCTURAL EVOLUTION OF SEAMOUNTS

Seamounts evolve in six stages that are structurally distinct (Figure 3). (1) Small seamounts (< 1-km tall) and abyssal hills (< 100-m tall) are seafloor volcanoes built on the oceanic crust largely by eruptive processes. (2) Mid-size seamounts are taller than about 1000 m and remain at eruptive depths deeper than 700 m, representing largely nonexplosive volcanoes with magmatic plumbing systems that become an increasingly important part of the seamount itself. (3) Explosive seamounts form at ocean depths shallower than 700 m and are mostly covered by volcaniclastics. (4) Islands form when a seamount breaches the sea surface, shifting to subaerial processes, including subaerial weathering, soil formation, and erosion. (5) Extinct seamounts have completed all volcanic activity and subsided below sea level, sometimes forming atolls. (6) Seamounts meet the end of their geological life during closure of an ocean basin or by subduction. Although these six stages describe the complete development of very large seamounts, most seamounts never reach the island stage. Smaller seamounts may be entirely buried by sediments by the time they reach a subduction zone.

Stage 1

Small seamounts with total heights of 100–1000 m are by far the most common type of seamount, even though they are often difficult to distinguish from the roughness of the abyssal oceanic crust topography that may occur on a similar scale. The key distinctive feature is their often circular morphology that is superimposed on a seafloor fabric that largely is made up of elongated MOR volcanoes or tectonic blocks. There may be as many as 25 million of them worldwide (Wessel et al., 2010). The majority of these seamounts form on relatively young crust, at water depths between 2–3 km, on bare rock, or on thinly sedimented seafloor. Their dominant eruptive lithologies include mostly pillow lavas and approximately 20% volcaniclastics (as found at Ocean Drilling Program/Deep Sea Drilling Project Site 417A and the deep-water section at La Palma; Staudigel and Schmincke, 1984). It is likely that seamounts on sedimented seafloor may initially form intrusions into the sediments and/or peperites, before they erupt pillow lavas that quickly cover these rocks. Small seamounts are likely to include almost no intrusive rocks, except for their feeder dikes, which has important consequences. The underlying oceanic crust controls these seamounts' plumbing systems and tectonics. There also is no or very little intrusive inflation of the freestanding part of the seamount, which makes it very unlikely that these volcanoes develop any major collapse features. And, finally, the reaction zone for their hydrothermal fluids is located inside the oceanic crust, and their hydrothermal venting is strongly linked to the hydrothermal cooling of the underlying oceanic crust. Intense low-temperature hydrothermal circulation in small seamounts results in extreme enrichments in seawater-derived chemical components, particularly in volcaniclastics but also in lava flows (e.g., Site 417A; Staudigel et al., 1996). It is quite likely that the very large number of small seamounts and their extreme alteration makes them major players in global geochemical cycles and as globally relevant habitats for microbial communities.

Stage 2

Mid-size seamounts are defined here as volcanic features that are tall enough (at least 1000 m in height) to have a magma plumbing system above the level of the oceanic crust, but that have not yet shoaled enough to be dominated by shallow-water explosive activity (which starts at ~ 700-m water depth). There may be hundreds of thousands of such seamounts (Wessel et al., 2010), and some of them may be quite large—all Hawaiian seamounts had to grow to 4000-m heights above the seafloor before they became explosive in Stage 3. Mid-size seamounts are likely to be mostly made of eruptive rocks, with an increasing fraction of intrusives as they increase in size. Based on observations at La Palma, the eruptive rocks on typical mid-size seamounts may consist of a majority of pillow lavas with about 20% volcaniclastics.

As seamounts increase in size, they begin to develop internal magma reservoirs above the oceanic crust. This attribute has two important consequences. First, intrusions begin to inflate the volcano, and this inflation soon dominates its internal stresses and determines the development of fissures and rift zones as well as, ultimately, the extent and geometry of volcano collapse. Second, intrusions introduce heat into shallower portions of the volcano, establishing hydrothermal convective cooling systems that are increasingly decoupled from the underlying oceanic crust. At Vailulu'u Seamount, earthquake locations cluster below hydrothermal vents along main structural trends defined by rift zones (Konter et al., 2004), indicating a close relationship among the development of permeability, intrusive geometry, and hydrothermal cooling. The depth of the earthquakes suggests

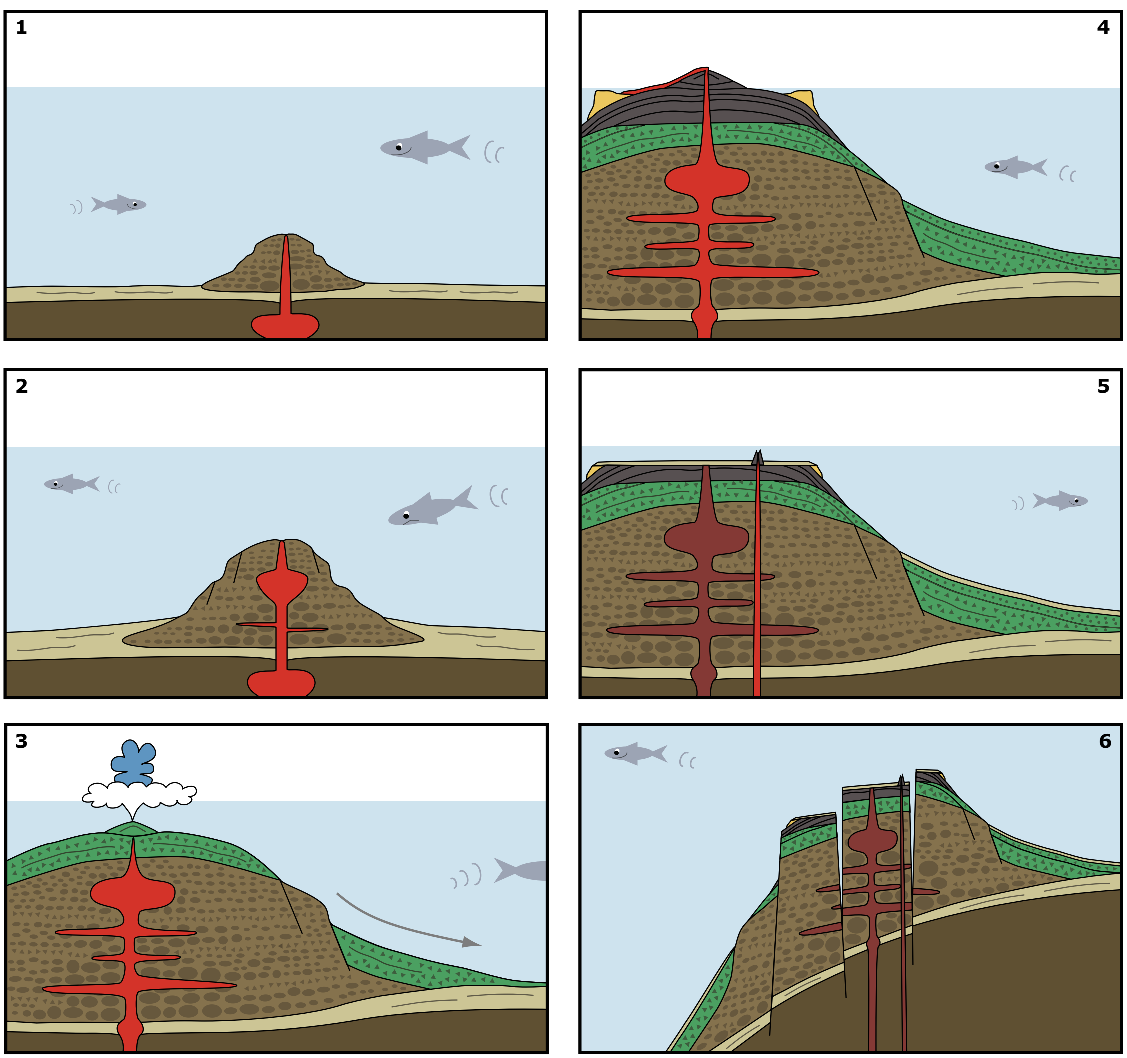

Figure 3. Six stages of seamount evolution are defined by seamount size, by the confining pressures at the time of eruption, and by exposure to seawater. Stage 1 represents the smallest seamounts (100–1000 m), whose magmatic plumbing systems are located in the oceanic crust, below the volcano. Stage 2 includes mid-size volcanoes exceeding 1000 m in height and with eruptive depths greater than 700 m, the likely critical depth for the beginning of explosive activity. Stage 3 describes the explosive stage of seamounts above 700-m eruption depth, and Stage 4 relates to seamounts with emerged summits forming islands and carbonate reefs. Stage 5 includes all seamounts that have reached the end of their magmatic activity. Stage 6 illustrates the breakup of a seamount before it is consumed by subduction.

that the hydrothermal reaction zone is likely centered well above the seafloor, probably guided by intrusive and recharge systems, including central and rift-related upwelling and recharge from flanks and radial fissures.

Mid-size seamounts have a substantial impact on ocean circulation and on the biosphere. They provide much larger obstacles to currents than small seamounts, and they are likely to locally enhance the amplitudes of internal ocean oscillations. As such, they contribute more to ocean mixing (stirring-rod effect) and they provide for potential development of seamount-encircling currents that may attract or trap pelagic life, including larvae. How seamount morphology and size determines ocean circulation remains a topic of active research (Lavelle and Mohn, 2010). Mid-size seamounts also provide a settling substrate for sessile benthic filter feeders (such as sponges and deep sea corals; Young, 2009), defining a biome that may exceed a surface area equivalent to that of Europe (see Box 12 on page 206 of this issue [Etnoyer et al., 2010]). These filter feeders record water characteristics that relate to ocean currents at their particular depth (Robinson et al., 2007). In addition, these seamounts support microbial habitats that may remain active for a long time because of slow, low-temperature water circulation.

Stage 3

Shallow seamounts are geologically distinct because relatively low hydrostatic pressures at depths less than 700 m may allow a substantial increase of explosive volcanism. They are less common than mid-size seamounts, and it is likely that the locations of *all* shallow seamounts are known from satellite observations, even though gravity anomalies yield only indirect and much-less-reliable depth estimates than echosoundings. Shoaling seamounts can pose navigational and geohazard risks. The collision of the submarine USS *San Francisco* with a seamount resulted in substantial damage and the death of one sailor, and a Japanese survey ship, *Kaiyo-maru No. 5*, was destroyed in 1952 by an eruption of Bayonnaise Rocks (Myojinshu), killing the crew of 31.

Volcaniclastics are the dominant eruptive rock types at shallow seamounts, as directly observed in Mariana Arc eruptions at Northwest Rota-1 (see Spotlight 10 on page 182 of this issue [Chadwick et al., 2010b]; Chadwick et al., 2008a; http://www.youtube.com/watch?v=1tPTsZ6PtR8&NR=1) and at Monowai in the Kermadec Arc (Chadwick et al., 2008b), and at an emerging seamount volcano near Tonga (see photo in opening spread). There is also abundant evidence from the modeling of seamount magnetic anomalies, which often require a "nonmagnetic top" that is probably best explained by highly altered volcaniclastics. At La Palma, the transition from mid-size to shallow seamount is characterized by an increase from 20% to more than 60% volcaniclastics, which are deposited on the summit, flanks, and, in particular, the surrounding aprons. It is well known from arc systems that volcaniclastics make up a very large fraction of the surrounding sediments. A similar situation may exist for the sediments surrounding very large seamounts where volcaniclastics are collected in the flexure moats caused by a deep flexing of the oceanic crust upon loading (Koppers and Watts, 2010). Eruptions from shallow seamounts can also produce pumice rafts that float great distances away from the volcano. Intrusives of shallow seamounts are likely not to be different from those of the Stage 2 mid-size seamounts, although it is likely that the overall fraction of intrusives increases with the size of the seamount.

The growth from mid-size to shallow and emergent seamounts involves a variety of changes in habitats. The increase in volcaniclastics results in enhanced production of volcanic glass that has a substantial effect on geochemical fluxes and provides an attractive substrate for microbial growth. It may play an important role within the seamount itself, on the summit and flank, and in the sediments surrounding the seamount. Exploration of the craters of mid-size and shallow seamounts shows that their unusual geochemical settings result in ecological conditions where some specialized biological communities thrive (e.g., polychaetes, demisponges), although there may be mass mortality for fish (e.g., Vailulu'u) due to extensive hydrothermal plume activity in an enclosed crater (Staudigel et al., 2006). Some unique habitats may result from the development of liquid sulfur lakes or the venting of buoyant liquid drops of CO_2, as found at a range of seamounts in the western Pacific (Lupton et al., 2006; Staudigel et al., 2006; Embley et al., 2007). As a seamount reaches the near surface, it may breach the oxygen minimum zone where microbial communities have to adjust to microaerophilic or anaerobic conditions. Finally, their summits may come close enough to the surface that photosynthesis becomes a viable energy source for carbon fixation. In tropical regions, this can result in the formation of massive carbonate reefs. Such reefs are among the most diverse and productive habitats on Earth.

Stage 4

Islands are born when shallow submarine volcanism allows a seamount to emerge above sea level and to transition into subaerial volcanic activity. This transition is a prolonged process. Historically, most newly born islands have disappeared shortly after their emergence (e.g., Metis Shoal of Tonga, Myojinsho of the Izu Ogosoawara group south of Japan, Graham Island in the Mediterranean Sea). They disappear because the continuous power of sea-surface wave erosion tends to out-compete constructive volcanic growth by minimally alteration-resistant volcaniclastic rocks. In fact, persistent emergence may only be possible during periods of very high eruption rates, and the formation of a more resistant lava veneer that protects the underlying clastic rocks from wave erosion. It is also conceivable that emergence is critically aided by intrusive activity that may lift the top of a seamount.

Emergence of a volcanic island has important geological consequences in terms of eruptive and intrusive processes and volcano collapse, erosion, and weathering. Eruptive rocks at ocean islands are dominated by lava flows that cool at substantially slower rates than their submarine equivalents. However, many of these flows enter the sea, where they produce large quantities of glass-rich volcanic rocks that are deposited on lava benches, submarine island flanks, or the surrounding seafloor. In particular, ocean arcs, but also ocean islands, may produce substantial explosive (Plinian) eruptions that can distribute volcanic ash as discrete layers up to 2000 km downwind from the source (Toba/Sumatra). These explosive eruptions constitute major volcanic hazards, particularly when hydrovolcanic processes resulting from contact with seawater amplify the eruptions. Major catastrophic eruptions include the 1630 BCE Santorini cataclysm that is likely to have terminated the Minoan culture, or the 1883 Krakatoa eruption that was associated with more than 30,000 casualties in the Indian Ocean area.

Intrusive activity at islands is demonstrably a major factor in their evolution and collapse. Collapse features are most likely and most prominent in the largest seamounts and islands with well-established, long-lived magmatic plumbing systems. They are most commonly found near the point of emergence of major rift zones from the main body of a volcano (Figure 4). Sector collapse may mobilize volumes up to 3000 km^3 (Satake et al., 2002), and the debris from such flows may cover an ocean area of 10,000–15,000 km^2 with > 1-km-size blocks up to 180 km from their site of origin (Moore and Clague, 2002). Such events leave a major scar on the side of the volcano, have a substantial effect on benthic life around the volcano, and result in catastrophic tsunamis that may have runups reaching inland to localities up to 400 m above sea level, constituting a major ocean-basin-wide

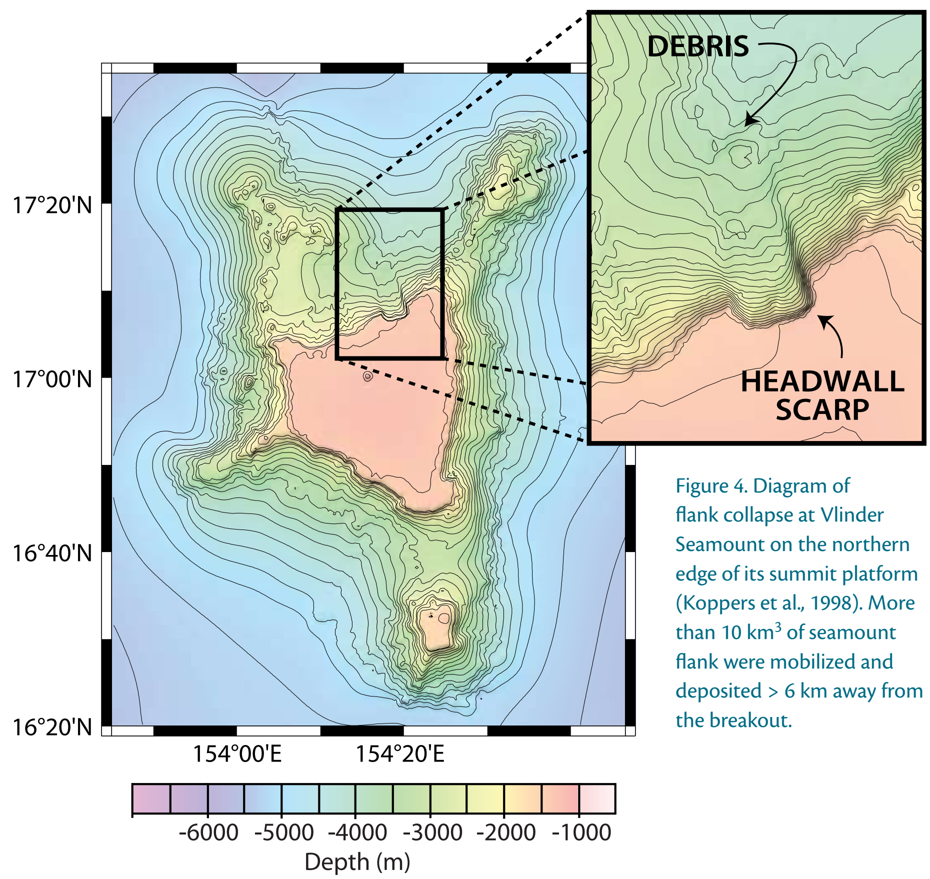

Figure 4. Diagram of flank collapse at Vlinder Seamount on the northern edge of its summit platform (Koppers et al., 1998). More than 10 km^3 of seamount flank were mobilized and deposited > 6 km away from the breakout.

natural hazard (e.g., at Kohala Volcano in Hawai`i; McMurtry et al., 2004).

As soon as islands are formed, they are subjected to weathering, soil formation, and erosion, as well as the development of groundwater, particularly in environments with significant rainfall. Weathering and erosion products introduce a range of new materials into the marine environment, including organic-rich soils and sands with highly reactive components (olivine, glass) that can support life in the ocean. In addition, the formation of groundwater on islands commonly creates a submarine freshwater lens that alters the hydrothermal reactions from a seawater-dominated environment to a freshwater system (Clague and Dixon, 2000). Other consequences of the freshwater lens include freshwater seeps in shallow marine settings, and the potential "lubrication" of faults at depth due to increased hydrostatic pressure from a groundwater table that commonly is located at elevations well above sea level.

Ocean islands and their coastal shallow submarine systems are biologically complex environments that benefit in particular from the availability of photosynthesis as an energy source, as well as from the fertility of volcanic soils. Ocean islands also often provide nesting grounds for seabirds whose presence can result in deposition of guano that may be introduced to the ocean by weathering or runoff, resulting in increased fertility on land and in the surrounding shallow ocean. Islands and volcanic reefs in tropical and subtropical climates provide substrates for carbonate reefs, that may range from minor shoreline reefs or massive coral reefs that eventually may cover the entire subsiding volcano. If conditions are met, reefs can get established fairly quickly, as is evident at the relatively recent Hawaiian volcanoes of Hualalai, Kohala, and Mauna Kea. Overall, coral reefs and volcanic ocean islands are among the most productive fisheries on Earth. This productivity may be a result of many processes and circumstances, including the constant volcanic input, photosynthesis, and complex local ocean circulation, due to the islands' roles as ocean "stirring rods."

STAGE 5

Once volcanism ceases, a volcanic island will eventually drown due to erosion and subsidence. Coral reefs will meet a similar fate if coral growth does not keep pace with subsidence. In some cases, volcanically dormant islands may show a short period of volcanic rejuvenation that may be reflected in the formation of volcanic cones that rise above the erosion surface of its otherwise flat top. Following cessation of volcanism, drowning islands and reefs eventually will become part of a diverse group of extinct seamounts that includes many that never reached Stages 2–4. Former islands and coral reefs can be recognized as seamounts with flat summits ("guyots"). After their submergence, all the extinct seamounts remain intact and virtually unchanged until they are consumed by subduction or ocean basin closure. Some may be older than 140 million years, giving us the oldest, most stable landforms on the planet.

Despite the absence of volcanism or erosion, extinct seamounts nevertheless serve some significant geological, hydrological, and oceanographic functions. With time, seamount surfaces are encrusted with ferromanganese oxides and phosphorites, depending on their chemical environment. These mineral groups potentially include very high concentrations of elements that are very scarce in seawater (Mn, P, Co, Ni, Ti, Pt, Th, Pb, rare earth elements; Hein et al., 1997), and thus seamount surfaces are likely to play a role in the geochemical budgets of these elements in seawater. Such surfaces provide some unique substrates for microbial growth and the basis for potential seafloor mining, in particular for Co and some high-tech metals such as tellurium (Hein et al., 2010).

Hydrologically, extinct seamounts may continue to act as long-term hydrothermal siphons (Fisher and Wheat, 2010), possibly providing the dominant mechanism for the exchange of fluids between seawater and sediment-covered old oceanic crust. This chemical exchange remains to be quantified but may be profound in terms of global geochemical budgets and in providing a habitat for microbial activity. Large submerged seamounts can substantively impact ocean circulation, including vertical mixing and the generation of turbulence that determines the sedimentation patterns at and down-current from the seamount (Lavelle and Mohn, 2010).

Extinct seamounts are considered biological hotspots (Danovaro et al., 2009), with thriving microbial communities and sessile megafauna colonizing their surfaces (see Box 7 on page 128 of this issue [Etnoyer, 2010]). Microbial communities are known to be associated with the venting or seepage of fluids from the seamount, but it is also likely that they form communities inside the seamount, taking advantage of a range of chemical nutrient or energy sources provided by hydrothermal circulation. Surface-colonizing fauna include, in particular, filter feeders such as deepwater corals, especially along ridges and rift zones where they are exposed to maximum flow of seawater. Deepwater corals are valuable recorders of paleoclimate for at least the past 200,000 years (Robinson et al., 2007), with individual corals recording climate information for their life spans of up to several thousand years.

Stage 6

Seamount life spans end when they reach a subduction zone or when their host ocean basin closes due to the collision of two continental plates. Tectonic processes that affect geohazards, as well as chemical fluxes and biological processes, mainly control this phase.

Seamount subduction may follow different paths, depending on subduction geometry. In arc systems with pronounced accretionary wedges, seamount subduction leaves prominent scars in the frontal portion of the wedge (e.g., Costa Rica). In the western Pacific, seamount subduction commonly begins with faulting and breakup (e.g., Capricorn and Osborne seamounts) before the seamount descends into the trench. As seamounts become entirely subducted, they can temporarily lift up segments of the overlying arc system, potentially creating a blockage to continued subduction that may be released in rupture and associated seismic activity (e.g., Scholz and Small, 1997; Watts et al., 2010). Descent of a major topographic feature, like a seamount chain, may have a profound impact on a subduction zone, potentially lifting up the entire arc and/or creating a slab window as in the Costa Rica arc at its intersection with the Cocos Ridge. The tectonism involved in seamount subduction also results in the opening of new fluid pathways and brings cold sediments and seamount materials into contact with warmer materials in the subduction system. These effects combine, cause top-down prograde metamorphism, and allow fluids to escape, potentially with consequences for substantial geochemical fluxes in an arc system (Staudigel et al., 2010b).

Although there is almost nothing known about the biology of this final stage of seamount evolution, it is very likely that the enhanced fluid flow also results in substantial microbial activity, perhaps providing a link between microbial activity and prograde metamorphism in the subducting slab.

> “FROM OVER HALF A CENTURY OF MODEST RESEARCH EFFORTS, IT IS CLEAR THAT SEAMOUNTS ARE MOST REWARDING AND INTERESTING TARGETS FOR FUTURE OCEANOGRAPHIC RESEARCH.”

CONCLUSIONS

Seamounts are geological and biological hotspots that connect lithosphere, hydrosphere, and/or biosphere in ways that evolve systematically as a seamount grows. These processes are likely to have a profound impact on geochemical fluxes and the development of seafloor communities and deep biosphere communities, and, finally, they may result in hazards to humankind.

Geochemical fluxes between seawater and seamounts are facilitated by their role as hydrothermal siphons and by their own hydrothermal convection systems. The latter is driven initially by intrusive activity in the underlying oceanic crust and then by intrusions into seamounts as they develop their magma plumbing systems. Fluxes are high because of the high permeability of the volcaniclastic rocks and their large volume fraction, and the lack of sedimentary cover that would impede fluid flow. Fluxes are relevant to ocean chemistry, arc mass balances, and the chemical heterogeneity of the mantle through seamount subduction.

Reactive surfaces and the chemical fluxes from hydrothermal flow support the development of biological communities that take advantage of the chemical energy and nutrients provided by seamounts. Small seamounts mostly act as portals to the underlying oceanic crust, whereas larger seamounts are likely to include their own deep biosphere. Both are likely to be important. Counting the larger seamounts alone, they represent a biome the size of Europe or larger (see Box 12 on page 206 of this issue [Etnoyer et al., 2010]).

Significant geohazards may be associated with very large seamounts, which pose navigational hazards and produce explosive activity and tsunamis associated with sector collapse. These hazards are responsible for some of the largest geologic disasters recorded in human history.

All three processes are likely to be globally relevant, but none are known to the extent needed to make meaningful estimate of fluxes, total biomass, extent of primary carbon fixation, or a realistic probability of geohazard threats. This lack of detail results from less than one percent of all seamounts having been studied even in a cursory way, and much of what we know of these processes is drawn from a few, often singular, well-studied examples. From over half a century of modest research efforts, it is clear that seamounts are most rewarding and interesting targets for future oceanographic research. This body of work points the way to a series of targeted investigations that have much potential for better understanding how Earth works.

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