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Chapter · May 2016

DOI: 10.1007/978-94-007-6644-0_28-3

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Encyclopedia of Marine Geosciences
DOI 10.1007/978-94-007-6644-0_28-3

Mid-Ocean Ridge Magmatism and Volcanism

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Definitions

Mid-Ocean Ridge. A linear, narrow volcanic and tectonic region which marks the constructive boundary between two tectonic plates. It is divided into segments by transform faults and other offsets. The global ridge system cuts through every major ocean basin and comes ashore in a few places like Iceland. It forms an approximately 65,000 km long, globe-encircling, largely submarine mountain chain.

Magmatism. Magmatism is the production and migration of magma, which is molten rock produced from the partial or complete melting of solid materials within a planetary body. When magma erupts on the surface, it is known as lava.

Volcanism. Volcanism is the eruption of molten rock, hot gases, or solidified rock fragments from an opening ("vent") in the Earth's crust. Volcanism occurs on Earth and other planets and moons. Most of the volcanism on Earth occurs at mid-ocean ridges, almost always sight unseen.

Mid-Ocean Ridge Magmatism. By far, the dominant type of lava resulting from magmatic activity at mid-ocean ridges is basalt, also called mid-ocean ridge basalt (MORB). However, small amounts of other extrusive magma types (predominantly andesite, dacite, and picrite) also erupt there. Variations in the rate and style of magma production, volcanism, and faulting result from variations in upper mantle temperature, upper mantle composition, and seafloor spreading rate through the ridge system, causing differences in igneous ocean crustal thickness, structure, and composition.

Mid-Ocean Ridge Volcanism. Volcanic eruptions at ocean ridges vary in style, intensity, and duration around the globe as a function of parameters such as magma chamber depth, magma supply rate, and eruption depth beneath sea level. Nevertheless, the dominant eruption styles either produce fissure-fed lava flows or point-source, single vent volcanic lava mounds. Nearly all volcanic products at ridges exhibit rapid quench textures, formed by the freezing of molten magma upon contact with cold seawater.

Introduction and History

Magmatism at mid-ocean ridges is one of our planet's most important geological processes, forming a dense, low-lying, igneous crust that floors the vast ocean basins, making up the solid rocks over nearly two-thirds of the Earth's surface. For most of geological history, the greatest number and volume of volcanic eruptions on Earth has occurred in the ocean, along mid-ocean ridges. Earth's globe-encircling volcanic system is a truly colossal geological structure (Fig. 1). Yet it is one that many people are not aware of because the global mid-ocean ridge system mostly lies beneath the sea (except in rare occurrences, such as in Iceland, where the mid-ocean ridge is exposed on land due to an anomalously thickened crust from the effects of the colocated Iceland Hotspot). Viewed from space and with the world's oceans stripped away, the mid-ocean ridge system would stand

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out as one of our planet's most prominent surface geological features. The ridge system generally produces a layered crust, with volcanic rocks on top, coarse-grained intrusive rocks at depth, and an intervening layer of dikes. Together, these layers form the igneous basement of the oceanic crust.

Mid-ocean ridges are segmented at various length scales into volcano-scale units as well as longer coherent segments that are separated by major offsets and discontinuities (e.g., Macdonald, 1982). Although at their upper surface mid-ocean ridges are dominated by volcanic rocks, the number and frequency of volcanic eruptions that formed them is not well known (e.g., Rubin et al., 2012). Compared to eruptions on land, we know less about submarine eruptions and the magmas that drive them, especially those that occur in the deep sea (here defined as below 500 m depth) because eruptions in the deep ocean are much more difficult to detect and observe (Fig. 1). Our first knowledge of submarine volcanic rocks from mid-ocean ridges probably comes from reports by deep-sea cable repair ships (Hall, 1876) and the Challenger Expedition (Murray and Renard, 1891), both of which recovered volcanic rocks from the seafloor in the 1870s. Thus, while geologists working on land have had thousands of years to develop an understanding of the magmatic processes that drive subaerial volcanism, marine geologists have had only a century or so. Still, concerted multinational efforts in the last 35–40 years have accelerated the pace of learning, with several marine expeditions to map, sample, and observe mid-ocean ridges occurring around the globe each year. Sampling campaigns over the past several decades have resulted in greatly increased, but highly uneven, sampling of the global ridge system. Some areas have few to no known rocks recovered from them, and at the other extreme, several locations have sampling density equivalent to the best-studied volcanoes on land (with 10–100 samples taken per km of ridge; Fig. 1).

Mid-ocean ridge basalt (MORB) is one of Earth's most common and most intensely studied rock types. Murray and Renard (1891) published an early account of the composition of MORB, demonstrating that it was similar in major element composition to basalts erupted on land. Major progress in understanding the range of compositions of volcanic rocks erupted on mid-ocean ridges began roughly 75 years later, with the exploration and sampling of ridges during the early years of testing and acceptance of the theory of plate tectonics. Initially, samples were collected mostly by dredging, although by the 1970s, scientists had also begun to deploy both human-occupied submersibles, such as *Alvin*, to directly observe and sample the seafloor (e.g., Ballard and Van Andel, 1977), and to use drilling, via the Deep Sea Drilling Project (DSDP) and its successor programs to recover intrusive rocks from beneath the seafloor. Evidence that these mid-ocean ridge volcanoes were underlain by active magmatic systems came via the discovery of warm springs on the Galápagos Spreading Center in 1977 (Corliss et al., 1979) and hot springs on the East Pacific Rise in 1979 (Spiess et al., 1980). Soon thereafter, ever-improving observational technologies paved the way for discoveries of specific eruptions (e.g., Embley et al., 1991; Haymon et al., 1993; see also reviews in Baker et al., 2012; Rubin et al., 2012). Exploration and monitoring of mid-ocean ridges continue to this day as we expand our understanding of magmatism and volcanism there. Current understanding of the recent volcanic history of several submarine mid-ocean ridge volcanoes now rivals that at volcanoes on land (Rubin et al., 2012; Clague et al., 2013).

Magma Generation at Mid-Ocean Ridges

Overview

Separation of tectonic plates causes compositionally heterogeneous mantle beneath mid-ocean ridges (e.g., Allègre et al., 1984) to rise and decompress, partially melting the upper mantle

DOI 10.1007/978-94-007-6644-0_28-3

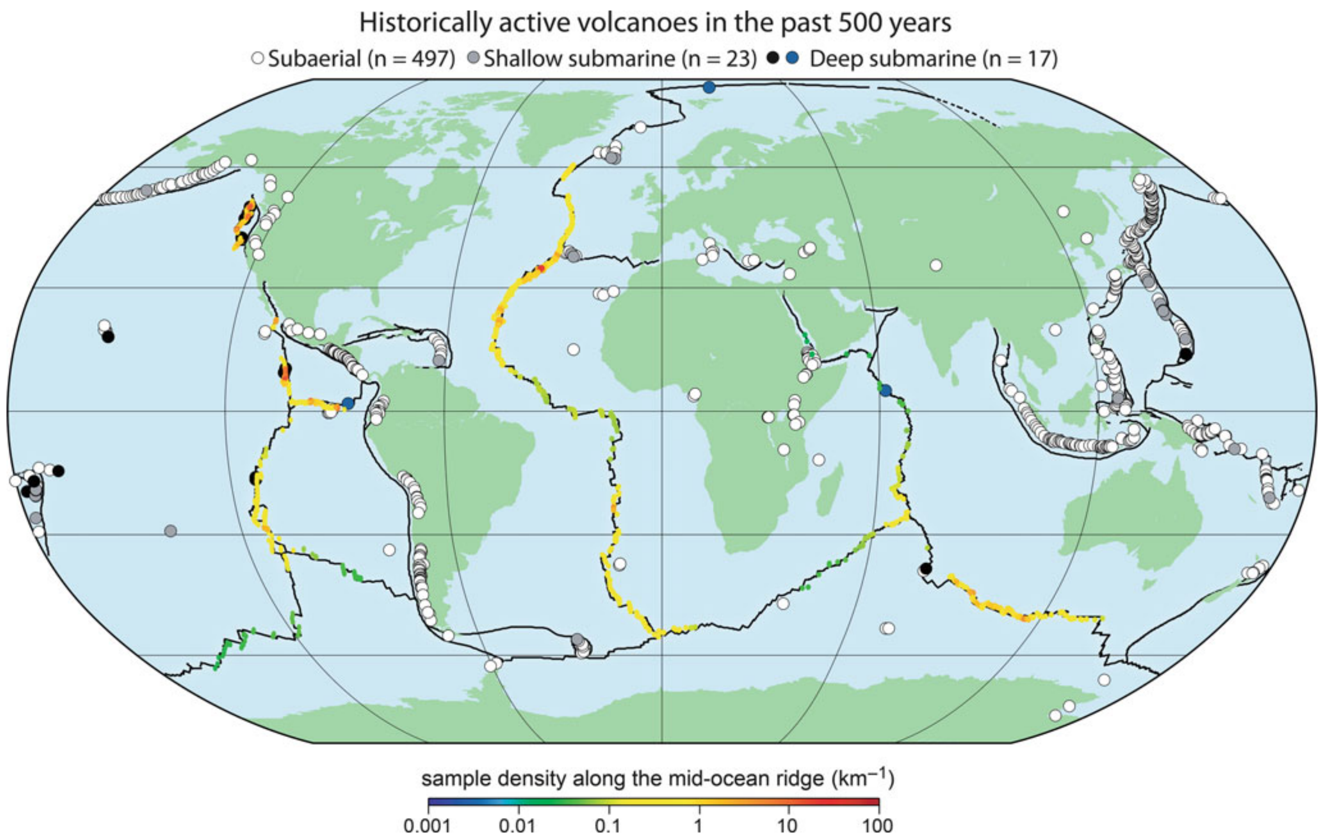

Fig. 1 Map of the world's continents (*green*) and oceans (*blue*) with major plate boundaries (*black lines*) and several types of volcano eruption and sampling data depicted. The *white*, *gray*, and *black circles* represent the locations of all documented volcanic eruptions on Earth over the past 500 years (as described in the caption of Rubin et al., 2012, Fig. 1), and the colored dots represent sampling density of lavas from the world's mid-ocean ridge system (as described in the caption of Rubin et al., 2009, Fig. 3; sample sites were compiled from the petrologic database, http://www.petdb.org). Notice that sample density along mid-ocean ridges varies by a wide range and that most of the ridge system is highly under-sampled (less than 1 sample per 10 km or not sampled at all). Notice also that there have been far more subaerial eruptions than submarine ones detected over the past 500 years globally, which is due to the much greater difficulty of identifying submarine eruptions, especially deep ones, and due to the relative youth of the field of submarine volcano studies. Shallow submarine eruptions leave a surface expression (as volcanic debris or ash/gas plumes) and are somewhat easier to detect and study than deep submarine eruptions. Most of the known deep submarine eruptions have occurred at mid-ocean ridges

(e.g., Klein and Langmuir, 1987; Kelemen et al., 1997) and producing basaltic parent melts (e.g., Elthon, 1979). Magmatic compositions are modified by multiple processes during ascent and storage prior to eruption (e.g., Klein and Langmuir, 1987; Sinton and Detrick, 1992; Rubin and Sinton, 2007). Mid-ocean ridge magma compositions therefore reflect a combination of magmatic processes related to (a) the composition and temperature of mantle beneath the ridge, (b) the volcanic plumbing system within ridge volcanoes, and (c) cooling from the infiltration of overlying seawater along faults and fissures in the upper crust leading to magma differentiation (e.g., Macdonald, 1982; Phipps Morgan and Chen, 1994). Variations in the rate and style of magma production, volcanism, and faulting result from upper mantle temperature and composition variations (e.g., Dalton et al., 2014) and a change in seafloor spreading rate from <1 cm/year to 20 cm/year through the ridge system, causing differences in igneous ocean crustal thickness (e.g., Bown and White, 1994), structure and morphology (e.g., Small, 1998), and composition (e.g., Rubin and Sinton, 2007).

Away from hotspots, magma supply to ridges from mantle melting covaries positively with spreading rate, so that high spreading rate generally equates to high magma supply. Superimposed on this plate-spreading-driven magma supply, differences in mantle composition, melting, and melt transport further modulate melt supply to the ridge axis along its length (e.g., Langmuir et al., 1986; Sinton et al., 1991), in turn producing physical and chemical segmentation of the mid-ocean ridge at 10–100 km length scales. Upward migration of MORB melts through the mantle, followed by accumulation in crustal magma bodies called magma chambers, results in magma differentiation and crystallization (e.g., Klein and Langmuir, 1987; Grove et al., 1992; Herzberg, 2004) and perhaps to melt-rock reactions (e.g., Lissenberg and Dick, 2008; Lissenberg et al., 2013) prior to either eruption or emplacement as a pluton within the oceanic crust. Structural and thermal conditions within the mantle and crust produce magma supply and magmatic differentiation variations at even smaller spatial scales (i.e., 1–10 km along the ridge axis), producing spatial patterns in erupted magma compositions akin to those found within and between neighboring terrestrial volcanoes (e.g., Reynolds et al., 1992; Perfit et al., 1994; Perfit and Chadwick, 1998). Studies of individual eruption deposits (e.g., Rubin et al., 2001; Bergmanis et al., 2007; Goss et al., 2010; Colman et al., 2012) and dikes that feed eruptions (e.g., Pollock et al., 2009) reveal spatial geochemical patterns that record variations in the delivery of individual magma batches to, and magma mixing and differentiation conditions within, subaxial magma reservoirs from which they erupt.

Magma and Mantle Source Compositions

Like all mafic magma generation on Earth, the major element composition of MORB magmas is largely set by the composition of the parent rock in the mantle source, the melting depth, and the degree to which the source rock is partially melted. MORB major element compositions vary less than basalts erupted on land, in part because the aforementioned melting parameters and source compositions are comparatively homogeneous beneath ridges and in part because the thinner and compositionally more uniformly oceanic crust imparts significantly less chemical variation to MORB magmas during magma accumulation and differentiation before eruption. Still, MORB display geographical variations in major element, trace element, and radiogenic isotopic compositions that reflect regional differences in mantle composition and melting conditions around the globe (e.g., Dupre and Allègre, 1980; Hamelin and Allègre, 1985; Klein and Langmuir, 1987; Mahoney et al., 1989; Asimow et al., 2004; Hanan et al., 2004; Niu and O'Hara, 2008), as well as the influence of near-ridge hotspots (e.g., Schilling, 1991; Cushman et al., 2004).

Globally, the trace constituents in MORB (trace elements and radiogenic isotopes) vary more significantly than the major elements. Petrologists use these constituents to understand the mineralogy, chemical composition, and history of a magma's mantle source rock, as well as to help track preeruptive magma differentiation and magma-host rock reactions in the crust. MORB have been widely used to identify variations in upper mantle composition although such mantle signatures in MORB still need to be distinguished from variations imparted to the magmas by melting, magma transport, melt-rock reactions, mixing, and magma differentiation (e.g., see review by Rubin et al., 2009). Of particular importance are the degree to which different types of mantle rocks (i.e., lithologies), also known as "mantle heterogeneities," melt at different rates and proportions (e.g., Ito and Mahoney, 2005; Stracke et al., 2006; Russo et al, 2009) and the extent of subsequent magma mixing and homogenization (Rubin and Sinton, 2007). The latter works to partially or fully obscure inherent mantle source rock variability in aggregated melts of the mantle, becoming more pronounced as magma supply increases.

Magma Chamber Processes

Nearly all MORB erupt bearing the chemical and mineralogical signatures of magma differentiation (e.g., olivine and plagioclase crystallization) and partial loss of initial melt magmatic gas loads, essentially requiring that these magmas accumulated and partially crystallized in magma bodies at one or more locations in the crust before eruption. There is considerable debate as to the nature of these magma bodies, where they reside, and how they impart structure to the oceanic crust (e.g., see discussion of the "gabbro-glacier" and "sheeted-sill" models in Coogan, 2007 and Keleman and Aharonov, 1998). An important characteristic of many mid-ocean ridges is the axial magma chamber (AMC), discovered in the 1980s by seismic reflection studies. The AMC represents the shallowest level of magma accumulation in the crust (Sinton and Detrick, 1992) and can be segmented at a variety of spatial and temporal scales (e.g., Carbotte et al., 2013). Far fewer AMC reflections have been detected at the ridges with very slow to slow-spreading rates (i.e., < 1–2 cm/year), despite most magmas erupted there showing the chemical and mineralogical signatures of differentiation at crustal pressures, which implies that the AMC bodies there are mostly too small and discontinuous to be seismically imaged. Where they can be detected, the size, continuity, and depth of the AMC vary substantially through the ridge system, but overall these parameters scale with spreading rate: the AMC generally becomes more continuous and shallower (as little as 1.5 or 2 km below the seafloor) at the fastest-spreading rates (Fig. 2). This depth variation has been successfully modeled as an interplay between the rate of magma supply from below and the intensity of hydrothermal cooling of the shallowest crust from above (Phipps Morgan and Chen, 1994).

Global MORB magma compositions support the Phipps Morgan and Chen (1994) heat supply model: MORB major element compositions display a general relationship between petrologic indicators of fractionation depth and spreading rate, with evidence for generally higher magma crystallization pressures (Sinton and Detrick, 1992; Michael and Cornell, 1998) and magmatic gas equilibration pressures (Paonita and Martelli, 2007) being more common at slow-spreading ridges. A more recent study found very regular variations in MORB chemistry with spreading rate and AMC depth in a large, 11,000 sample group of MORB from around the globe (Fig. 2). Here, the least differentiated MORB were found to occur at slow-spreading rates, becoming progressively more differentiated and erupting from a shallower AMC as spreading rate increases (Rubin and Sinton, 2007). This dichotomy, that cooler magmas generally erupt from ridges with the highest magma supply and hotter magmas from ridges with the lowest magma supply, demonstrates the importance of the AMC and its depth within the crust for modulating MORB composition.

At shorter temporal and spatial scales, chemical variations in MORB within and between successive historical eruptions at sites having an AMC show that magma chamber thermal

Encyclopedia of Marine Geosciences
DOI 10.1007/978-94-007-6644-0_28-3

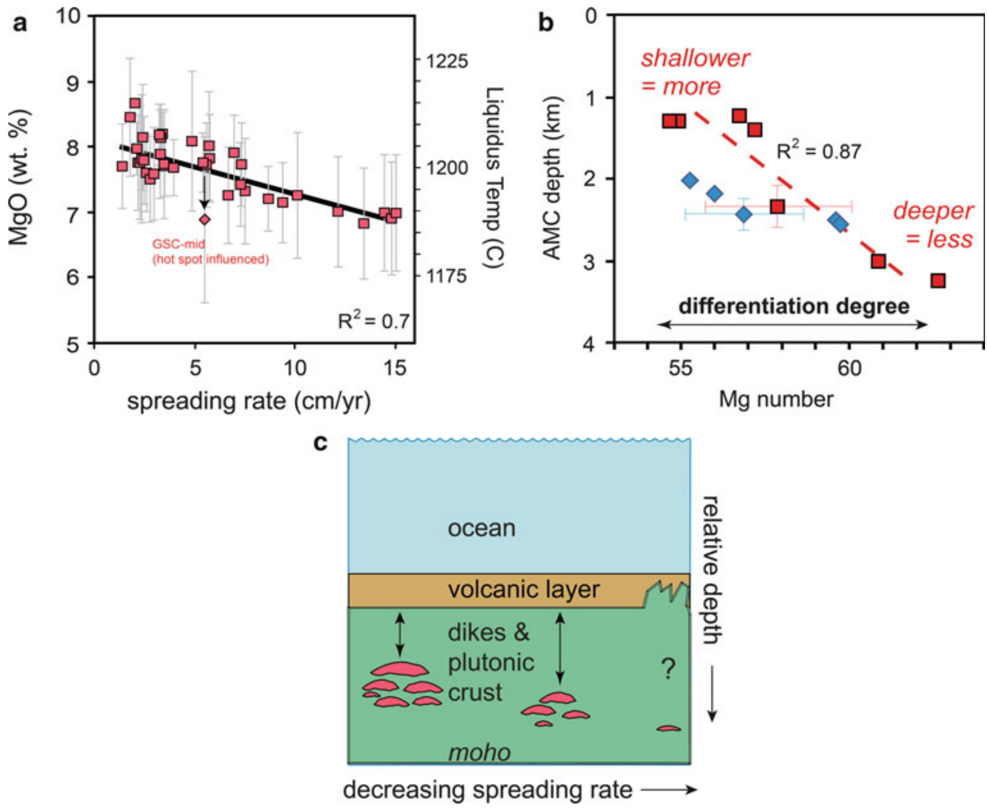

Fig. 2 Three diagrams depicting compositional attributes of mid-ocean ridge basalts that can be used to infer conditions of magma differentiation, as discussed in the text. *Panel a*, which is modified from Fig. 1 of Rubin and Sinton (2007) (see that paper for details of data analysis and spreading rate calculations), shows Mg variations and inferred eruption temperature in ridge section means from different geographic regions of the global mid-ocean ridge system using a >11,000 basalt glass database. Note the strong linear relationships with spreading rate (the *solid black line* is a linear regression to the data). *Gray bars* are 1 s deviations for each mean. Overall, erupted compositions are cooler and more differentiated at faster-spreading rate ridges and also more variable in differentiation-related parameters (see Rubin and Sinton, 2007 for a detailed discussion). The central Galapagos Spreading Center, which is an example of a hotspot-influenced ridge having anomalously high magma supply due to active upwelling, falls off the trend (*diamond symbol*). *Panel b*, axial magma chamber (AMC) depth versus Mg content of erupted MORB showing variations in both means of ridge sections (from *panel a*) also having AMC depth measurements (*red symbols*) and segments of the Juan de Fuca ridge having AMC depth (*blue symbols*). See the caption in Fig. 8 in Rubin and Sinton (2007) for details of data sources and handing. This panel shows that magmas erupted from deeper magma chambers are generally less differentiated. Magma chambers are generally shallower at higher spreading rates and deeper at slower-spreading rates, where overall melt supply is high and low, respectively. The linear regression includes the *red* symbols. *Panel c*, A generalized depiction of the greater depth, smaller size, and lower connectivity of AMCs at low spreading rates, as discussed in Rubin et al., (2009). A wide range of geophysical and geochemical parameters were used to infer these variations, as discussed briefly in this article and in detail in Rubin et al. (2009)

conditions were relatively constant at these few sites over this time interval, with just 10–20 °C of magmatic heat loss over one to two decades (e.g., at 9° 50′N East Pacific Rise, Goss et al. 2010; 17° S East Pacific Rise, Bergmanis et al., 2007; CoAxial segment of the Juan de Fuca Rise, Embley et al., 2000). Many of these same eruption deposits also preserve magma temperature gradients along the eruptive fissures that indicate thermal variations within the AMC along axis that are not mixed out during eruptions (e.g., Rubin et al., 2001; Sinton et al., 2002; Bergmanis et al., 2007; Goss et al., 2010).

Encyclopedia of Marine Geosciences
DOI 10.1007/978-94-007-6644-0_28-3

Evolved Magma Compositions

Small volumes of high-silica lavas (andesites and dacites) occur on mid-ocean ridges, often associated with ridge discontinuities such as propagating rift tips (e.g., Sinton et al., 1983), overlapping spreading centers (e.g., Wanless et al., 2010), and ridge-transform intersections (e.g., Schmitt et al., 2011); however, highly differentiated lavas can also occur in more "normal" ridge settings (e.g., Wanless et al., 2010) and at regions showing ridge-hotspot interaction (Haase et al., 2005; Colman et al., 2012). Many authors have suggested a tectonic control on the occurrence of highly differentiated lavas on mid-ocean ridges, primarily by allowing for extensive cooling of the AMC margins near places where magma supply might be lower. This promotes conditions that allow for extensive fractional crystallization of the magmas. Similar highly differentiated lavas also occur in Iceland, where strong shifts in oxygen isotopic composition relative to mantle values indicate a major role as well for the melting of altered crust (e.g., Martin and Sigmarsson, 2007). The bulk composition of many highly evolved mid-ocean ridge lavas is remarkably similar, and several different occurrences have been successfully modeled by a combination of extensive MORB fractional crystallization plus/minus partial melting and/or assimilation of seawater-altered oceanic crust (e.g., Haase et al., 2005; Wanless et al., 2010). Radiometric dating of zircons from dacite lava domes erupted near the intersection of the Juan de Fuca ridge and the Blanco transform (in the NE Pacific Ocean) indicates that this differentiation can occur rapidly (over just 10 millennia or so; Schmitt et al., 2011).

The Plutonic Crust

Beneath the volcanic carapace at mid-ocean ridges lies a thick plutonic crust. This intrusive material comprises roughly five times the volume of the extrusive (volcanic) section (White et al., 2006). Direct in situ observation of this crust is difficult, so that much of what we know about this relatively inaccessible material comes from drill hole studies. However, rare plutonic exposures on the seafloor occur in fracture zones and other faulting-exposed "tectonic windows," as well as in ophiolites (pieces of young oceanic crust obducted onto land, e.g., Cann, 1974; Pallister and Hopson,1981). Collectively, studies of these materials indicate a large range of lower crustal rock types, from mafic to evolved compositions, and a range of petrologic textures, some acquired during complex cooling and melt-reaction histories (e.g., Coogan, 2007; Coogan et al., 2007; Keleman and Aharonov, 1998; Lissenberg and Dick, 2008; Lissenberg et al., 2009; Suhr et al., 2008). The extent to which magmas erupted at the surface interact with and reflect this diversity of rocks in the lower crust is an area of active research.

Volcanic Eruptions at Mid-Ocean Ridges

Volcanic activity occurs predominantly on the axis of the mid-ocean ridge system with largely unknown frequency. Our understanding of how deep submarine volcanism has built structures on mid-ocean ridges has been greatly aided by sonar and visual mapping of submarine volcanic edifices and by sampling and compositional analysis of rocks there to learn the types and distributions of volcanic products that occur. There is a large literature on this subject, much of which is reviewed in Rubin et al. (2012). In summary, mid-ocean ridges produce low-lying elongate volcanoes from the combined effects of fissure eruptions of generally low viscosity magmas and the constant rafting away of eruption deposits due to plate separation. Bathymetric relief is lower at higher magma supply (e.g., faster-spreading) ridges because volcanic construction dominates over tectonic rifting processes (e.g., Buck et al., 1997; Macdonald, 1998). In fact, the boundaries of individual volcanoes and individual eruptions become more difficult to define at the fastest-spreading ridges because magma is erupted at relatively high frequency (e.g., Sinton et al., 2002; Bergmanis et al., 2007) from nearly continuous along ridge melt axial magma chambers (e.g., Singh et al., 1998) leading to axial high and mound-like topography (e.g., White et al., 2002). At slower-spreading rates, tectonic forces (faulting and plate separation) dominate over volcanic construction, leading to the common axial valley morphology of the ridge, with volcanic accretion commonly localized along smaller ridges within this valley (e.g., Searle et al., 2010; Yeo et al., 2012) and fault block-dominated rift valley walls. At the very slowest-spreading rates, volcanic activity appears to be discontinuous along the highly tectonized ridge axis, leading to exposures of volcanic, plutonic, and even mantle rocks on the seafloor (e.g., Michael et al., 2003; Cannat et al., 2008).

Eruption Products

The different styles of submarine volcanic eruptions and the deposits they produce are controlled by magma chemistry and physical properties, magma eruption rate, and physical conditions at the volcanic vent (e.g., Gregg and Fink, 1995; Perfit and Chadwick, 1998). The size, volume, thickness, and dispersal of both effusive and pyroclastic volcanic deposits provide key information about the conditions of the eruption(s) that produced them. Both effusive and explosive eruption styles are observed at mid-ocean ridges, although effusive lava flows are by far the dominant volcanic product of mid-ocean ridge eruptions. Lava flow thickness, run out, and surface morphology reflect variations in magma viscosity, effusion rate, local slope, topographic obstructions, and the sequence of emplacement events during individual eruptions (see discussion in Rubin et al., 2012 and references therein). Submarine lava flow morphologies are typically classified by the length scale of the quenched-crust units that collectively make up a lava flow, which themselves form as a function of flow rate and cooling rate. Common different types of lava deposits are known as pillow, lobate, and sheet lavas (see Fig. 3). Common methods of detection and mapping of these flow types involve direct or remote visual observation from submersibles and towed camera systems (see Rubin et al., 2012), although a recent development employs high-resolution sonar data from autonomous underwater vehicles that have been automatically classified by surface geometry and texture to generate detailed lava flow morphology maps over relatively large areas of seabed (McClinton et al., 2013). Volumetrically minor deposits of lapilli- to ash-sized explosive fragments also occur throughout the depth range of observations in the deep sea (e.g., Clague et al., 2009; Helo et al., 2011).

Eruption Frequency and Duration

Just like volcanoes on land, the periodicity of volcanism at mid-ocean ridges reflects the rate of magma input to the volcano, the buildup of tectonic stress, and conditions within the crustal magma reservoir. Marine scientists currently lack the information to determine eruption frequency, size, and duration for all but a very small number of submarine mid-ocean ridge volcanoes (reviewed in Rubin et al., 2012). Individual eruptions can last just days to perhaps a year. In terms of eruption frequency, many mid-ocean ridge volcanoes likely operate at a quasi-steady state (e.g., Wadge, 1982) in which eruption volume and repose (the time between eruptions) correlate positively as the result of a relatively constant magma flux. Using such a steady-state assumption and calculating magma supply rate from the spreading rate and an assumption of constant crustal thickness, the smallest average eruption repose interval (~10 year) should occur at the fastest-spreading rates (for instance, on the Southern East Pacific Rise; Sinton et al., 2002 or at Axial Volcano, a ridge-centered hotspot on the Juan de Fuca ridge with anomalously high magma supply). An average repose interval of roughly 1,000 years should occur on slower-spreading ridges like the Mid-Atlantic Ridge (see Perfit and

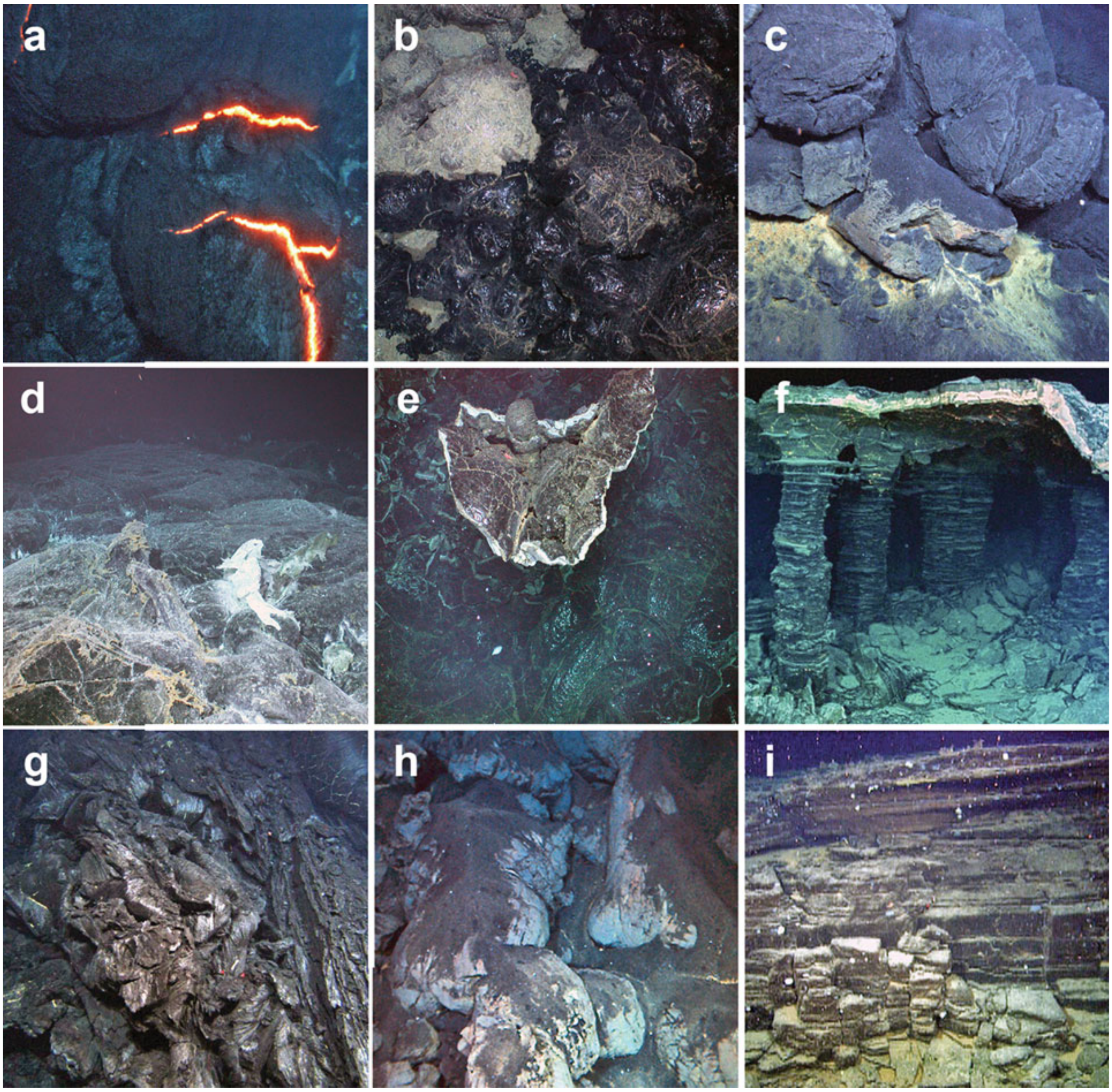

Fig. 3 Photographs of deep-sea eruption products roughly arranged by volcanic effusion rate (slowest at the *top* of the image) and/or eruption style (effusive or explosive). *Panels a*, *b*, and *c* depict pillow lavas which general extrude slowest and have the smallest cool units; the active pillow lava lobe inflating on a transverse and radial crack in *Panel a* is from West Mata volcano rather than a ridge setting, but the mode of emplacement is the same; *Panel b* shows a downward-looking view of 2005–2006 pillow lavas overlying older pillows at 9° 50′N EPR; *Panel c* shows a very young pillow lava at West Mata volcano colonized by an orange microbial mat. *Panels d*, *e*, and *f* depict lobate lavas, which have larger cooling units that often crust over and continue to flow underneath, leading to drainage of the interior and collapse of the surface crust; *Panel d* is of months old lobate lavas at 10° 45′N EPR covered by various microbial mats; *Panel e* is a downward-looking view of a remnant piece of lobate crust above the collapsed interior of lavas erupted in 2005–2006 at 9° 50′N on the East Pacific Rise; *Panel f* is a side-on view of 2–3 m tall lava pillars in the interior of the partially collapsed lobate lava flow erupted at Axial Seamount in 1998. *Panel g* shows a high-effusion-rate sheet flow from the NE Lau Spreading Center; *Panel h* shows young volcanic pyroclasts overlying pillow lavas from an eruption at Gakkel Ridge; *Panel i* shows a 1 m high section of consolidated pyroclastic deposit at one of the Vance Seamounts, near the JDFR. This figure is a modified subset of images of deep-sea eruptions in Rubin et al. (2012) [Photo sources: (**a**) Jason ROV dive J2-414, 2009; (**b**) WHOI TowCam, 2006; (**c**) Jason ROV dive J2-418, 2009; (**d**) Alvin HOV dive 3935, 2003; (**e**) WHOI TowCam, 2006; (**f**) ROPOS ROV dive R743, 2003 (**h**) Camper camera sled, 2007; (**i**) Tiburon ROV dive T1011, 2006]

Chadwick, 1998; Sinton et al., 2002 and references therein). The small number of direct eruption observations (there are two submarine mid-ocean ridge sites that have been observed to have erupted twice) and studies utilizing volcano-scale geological mapping and deposit dating via high-precision radiometric or paleomagnetic chronological methods indicate that volcanic eruption frequency and repose are likely not steady state at the individual eruption scale, but that averaged over several eruptions, they do occur at roughly the predicted steady-state interval (e.g., Rubin et al., 2012; Bowles et al., 2014).

Eruption Dynamics

Our understanding of the dynamics and mechanisms of submarine volcanic eruptions is informed by a relatively recent but growing body of direct and remote sensing observations. Intermediate- to fast-spreading mid-ocean ridges (i.e., the only places we have such observations) are dominated by short duration, high eruption rate events, or clusters of events (see Rubin et al., 2012 and references therein). Eruption rate variations produce a range of lava morphologies. Lava flows will advance for hours or days during each eruption pulse (e.g., Soule et al., 2012). Eruption pulses may continue if the pressure release was incomplete and/or pressure continues to build in the crustal melt lens by recharge. Widespread diffuse venting of hydrothermal fluids continues through the carapace of a new lava flow well after the eruption wanes. Focused flow hydrothermal activity (i.e., from chimneys) can persist at a site over multiple eruptions, although the character of fluids and chimneys at any given vent site is dominated by subterranean plumbing systems that are highly sensitive to changes that occur during eruptions (e.g., Von Damm, 2004).

Decadal-scale studies at several mid-ocean ridge sites with high melt supply reveal that magma chambers are persistent features over eruptive cycles (e.g., Carbotte et al., 2012). Magma chamber pressures increase over time (e.g., Chadwick et al., 2006), triggering increased seismicity rates along the ridge over several years (e.g., Tolstoy et al., 2006). When sufficient pressure has built in the magma body, diking initiates (e.g., Dziak et al., 2007) and may reach the surface given sufficient overpressure. Event plumes, which are thermally buoyant volumes of seawater carrying chemical signatures of volcanic and hydrothermal inputs, likely form at this time by advection of magmatic heat to the seafloor and/or discharge of hydrothermal fluids stored in the crust (e.g., Baker et al., 2011, 2012). The amount of magmatic gas within the system and the eruption depth will determine the extent of explosive activity that might accompany the effusive component of the eruption (e.g., Clague et al., 2009; Helo et al., 2011).

Eruption Detection

This discipline of submarine eruption detection and study is quite a bit younger than complementary studies of eruptions on land. The first evidence for an eruption at a mid-ocean ridge came in the form of a hydrothermal event plume detected along the Cleft segment of the Juan de Fuca Ridge (JdFR) in 1986 (Baker et al., 1987) – a follow-up study of the seabed led to the discovery of a series of pillow mounds up to 75 m high in the same area, making them the first young deep-sea lava flows of known age (Chadwick et al., 1991; Embley et al., 1991). In 1991, the Alvin submersible happened upon the aftermath of a volcanic eruption at 9°50′N on the East Pacific Rise, finding dead and charred tube worms strewn among and under fresh lava and “snowblower” hydrothermal vents diffusely spewing white sulfur-rich microbial floc (Haymon et al., 1993). Radiometric dating subsequently demonstrated that this discovery occurred just 2–4 weeks after the eruption had stopped (Rubin et al., 1994). The first remotely detected mid-ocean ridge eruption was in 1993, when scientists at NOAA/PMEL detected an earthquake swarm on the CoAxial segment of the Juan de Fuca Ridge within the first month of real-time acoustic monitoring using the US Navy Sound Surveillance System

(SOSUS) (Fox et al., 1994). Since then, multiple other eruptions have been detected and described by both remote and direct methods (see Rubin et al., 2012 for a full listing). For instance, the real-time hydroacoustic monitoring capability has led to multiple eruption discoveries and responses in the NE Pacific (e.g., Perfit and Chadwick, 1998; Dziak et al., 2007; Dziak et al., 2011; Baker et al., 2012).

Current Investigations and Controversies

The scientific community has learned a great deal about mid-ocean ridges over the half century, since the realization that they were centers of volcanism and seafloor spreading. Yet there is a great deal that is not well known about both volcanism and magmatism that occur in the Earth's most active and prolific volcanic province, so research continues on multiple fronts. These include the time-scales of magmatic processes, magmatic processes leading to intrusions, and the architecture of the ridge at depth, eruption characteristics, and what are the spatial scales of mantle heterogeneity and how is this heterogeneity sampled and modified by magmatic activity. This section highlights some of these current topics of investigation.

Magmatic Timescales

Researchers are actively developing and employing novel methods to unravel the timescales of magmatic processes at mid-ocean ridges, from the duration of melting to the rate of magma transport from mantle depths to the crust and the duration of magma residence in the crust before eruption. The nuclides of the naturally occurring U and Th decay series provide the best tracers for these applications because collectively they have a range of half-lives and chemical characteristics, hence varying recovery rates to secular equilibrium following chemical perturbations (where secular equilibrium is the condition of all isotopes in a chain decaying at the same activity, measured as decay constant multiplied by the number of atoms present). Recent U-series radioactive disequilibria studies have demonstrated that melting, melt extraction, and melt accumulation rates can range from millennial (Elliott and Spiegelman, 2007; Stracke et al., 2006; Sinton et al., 2002) to decadal timescales (Rubin et al., 2001; Bergmanis et al., 2007). For instance, covariation of short-lived ^{210}Pb–^{226}Ra disequilibria (half-life = 22 years.) and other compositional attributes of historically erupted MORB at intermediate to fast-spreading ridges indicate that magmatic conditions can fluctuate rapidly, even between successive eruptions separated by just a decade or two (Rubin et al, 2005; Bergmanis et al., 2007). And eruption of lavas with ^{226}Ra–^{230}Th disequilibria (half-life = 1,600 year.) far away from the axis of spreading implies eruption ages of one to eight thousand years even when located on crust of 75–100 kyr spreading age (i.e., assuming steady-state volcanism and post-eruption movement of lava flows by plate spreading; Waters et al., 2013 Standish and Sims, 2010). Despite these successes, it must be noted that the U-series constraints in the aforementioned studies and others like them are semi-quantitative and highly dependent upon model parameterizations of melting using imprecisely known melting rates, melt fractions, melt porosities, melt flow conditions, lithological diversity, and the spatial scales of mantle compositional and mineralogical variations, all of which are targets for future research.

At even finer temporal scales, the ^{210}Po–^{210}Pb dating method provides ultrahigh-resolution lava eruption ages (±1–3 weeks) by charting the post-eruption in-growth of initially degassed, volatile ^{210}Po from erupting magma. The method has been used on several submarine eruptions since its first use on the East Pacific Rise in 1994 (Rubin et al., 1994) to provide temporal constraint on post-eruption recovery of hydrothermal systems and biological colonization and ecological succession on newly emplaced seafloor (summarized in Rubin et al, 2012). Recent applications using large sample numbers along with detailed lava flow mapping by manned submersible and remotely operated vehicle (e.g., Soule et al, 2007) provided data to reconstruct eruption dynamics and the temporal and spatial evolution of a lava flow field. For example, detailed study of a lava flow erupted at 9° 50′N EPR showed that this long fissure eruption began in summer 2005, with subsequent smaller eruptive pulses from ever-shortening fissures, culminating in a small eruption in mid-late January 2006 (Rubin et al., 2015), with eruption pulses being correlated in time with hydrothermal fluid exit temperatures recorded in situ. Paleomagnetic intensity dating of lavas (e.g., Carlut et al., 2004; Bowles et al., 2006) and radiocarbon dating of planktonic and benthic foraminifera collected from lava flow tops (Clague et al., 2013) are two other methods that both show promise for developing site-specific century to millennial eruption histories.

Mantle Compositions and the Spatial Scales of Mantle Heterogeneities

Many researchers over the past several decades have been motivated to use MORB magmas to probe upper mantle compositional variations because of several factors that should simplify the connection of erupted magmas to their mantle source, including the common occurrence of relatively undifferentiated magmas, the thin and compositionally less variable oceanic crust (compared to the continents), and the broad spatial coverage of the upper mantle by mid-ocean ridges, which span much of the globe. Such studies have revealed many first-order variations in mantle compositions, as discussed above. More recently, studies addressing the physical nature and distribution of heterogeneities have shown that a few percent of highly fusible mantle pyroxenite veins can dominate aggregate melt composition but not melt flux (e.g., Russo et al, 2009) and that isotopic compositional domains along parts of the ridge system reflect stretching, thinning, and folding of compositionally distinct domains by mantle convection (Graham et al., 2006). Spectral analysis of MORB chemistry along the Mid-Atlantic Ridge has revealed mantle heterogeneity arising from modern hotspots as well as ancient heterogeneities preserved by incomplete mantle mixing during convection (Agranier et al., 2005) and perhaps different mantle-upwelling patterns beneath Indian and Atlantic mid-ocean ridges compared to those in the Pacific (Meyzen et al., 2007). New, high-quality trace element data sets from relatively large numbers of MORB have revealed variations in the degree of depletion of the MORB source mantle around the world (Arevalo and McDonough, 2010; O'Neill and Jenner, 2012) and a more refined definition of and characterization of "normal" MORB (aka N-MORB), as well as depleted and enriched MORB variants in a geographic framework (Gale et al., 2013).

Such studies will help researchers with their goal of understanding the spatial scale of mantle composition and lithology variations and how they are expressed in erupted MORB compositions. However, over the past decade, researchers have also come to realize that magmatic process produces significant overprinting of mantle compositional variations in MORB (e.g., Rubin and Sinton, 2007; Rubin et al., 2009; O'Neill and Jenner, 2012). For instance, the magnitude and temporal variability of melt supply largely affects the degree to which mantle heterogeneity is expressed in MORB magmas (Rubin and Sinton, 2007), which among other things produces reduced variance of mantle parameters in intermediate to high magma supply Pacific ridges compared to other ocean basins, an effect incorrectly assumed to reflect mantle heterogeneity or upwelling patterns in several of the aforementioned studies. The coupling of apparent mantle compositional homogenization with increased magma differentiation, which can be observed over a number of length scales (Rubin et al, 2009), implies that much of this mixing happens at shallow crustal levels, where magmas pool and differentiate in melt-rich lenses prior to eruption. O'Neill and Jenner (2012) argue that disruption of trace element variations in MORB occurs in frequently replenished, open-system magma chambers, although other authors have also argued that magma-rock reactions during intergranular porous flow deeper in the crust also modify the signatures of mantle source characteristics in the erupted MORB (Lissenberg et al., 2013). New advances in this area will likely require more eruption and volcano-scale studies using geological mapping, sampling, and chemical analysis to sort out the full range of processes that operate and under which conditions they occur.

Another way to get at the spatial scale of mantle composition and lithology variations is to look at mantle rocks themselves where they are exposed on the seafloor or in ophiolites. The mantle beneath mid-ocean ridges is thought to be largely depleted by melt prior extraction and magmatism, leading to, for instance, continental growth. But within this depleted matrix likely also lie veins and domains of enriched material injected into the mantle at subduction zones and slowly mixed and spread around by mantle convection. Studies of mantle rocks at ridges have shown that (a) they range in composition, from very melt depleted on ridges near hotspots to less so at locations away from hotspots (e.g., Dick et al., 1984), (b) a large proportion of the upwelling mantle beneath some ridges contributes little magma to the ridge axis because of extreme prior melt extraction (e.g., Liu et al., 2008), and (c) the average mantle beneath ridges may be far more isotopically depleted and compositionally more variable than inferred from erupted oceanic basalts (e.g., Stracke et al., 2011).

Eruption Detection and Response

Multidisciplinary studies at several focus sites around the world illustrate the important interplays between magmatism, hydrothermal activity, and biological processes at active and dormant mid-ocean ridge volcanoes (e.g., Kelley et al., 2002; Fornari et al., 2012). Mid-ocean ridge eruptions provide windows into rapidly changing magmatic, hydrothermal, and deep-sea biological processes (e.g., Delaney et al., 1998), so there has been great interest in detecting eruptions or intrusions, followed by rapidly organized seagoing response efforts to study these interplays (see reviews in Baker et al., 2012; Rubin et al., 2012). Such field studies, which began in the early 1990s, have largely been in response to remotely detected seismicity or serendipitous discovery. Despite the logistical difficulty of getting research vessels, equipment, and crew together on short notice, thirty-five recognized events have been responded to on submarine volcanoes over the world (i.e., at mid-ocean ridges and arc and intraplate seamounts; Baker et al., 2012). This list includes eleven historical eruptions at mid-ocean ridges (Rubin et al., 2012). As of this writing, the most recent of these eruptions, which occurred at Axial Seamount in 2011 (on the Juan de Fuca), was a triumph of prior planning and deployment of modern instrumentation, so that the geophysical, geodetic, and geological characteristics of the event were captured in exquisite detail (Caress et al., 2012; Chadwick et al., 2012; Dziak et al., 2012). The newest approaches in submarine eruption studies include autonomous detection stations, autonomous vehicle development for response efforts, and the establishment of permanent seafloor observatories. These will provide extraordinary research opportunities at a handful of sites, but active monitoring of most of the global ridge system will take a concerted effort by the international scientific community, as well as many more interested scientists and infrastructure to conduct these rapid response research efforts.

Summary

The global mid-ocean ridge system is a vast, complicated array of volcanoes, the great majority of which remain unvisited and sparsely sampled. Detailed studies at a few dozen sites reveal patterns of volcanic style, magmatic processes, and erupted compositions that generally reflect variations in

spreading rate, magma supply, mantle composition, and proximity to ridge discontinuities and hotspots. Such studies also reveal the range of site-specific geological conditions that affect MORB composition and mid-ocean ridge volcanism. These effects are being studied in ever more locales at ever higher resolution to understand the spatial and temporal scales of ocean ridge magmatic processes, revealing how mid-ocean ridge volcanoes operate and how they sample the underlying mantle. Combined petrological, geochemical, geophysical, and geological data about mid-ocean ridges indicate that inferred mantle compositions are significantly modified in range, magnitude, and length scale at mid-ocean ridges by preeruptive magmatic processes such as magma residence and transport through the upper mantle and lower crust. Submarine eruptions construct new ocean crust and are a primary agent for the transfer of heat, chemicals, and microbes from the Earth's mantle or crust into the overlying ocean. Studying these eruptions is therefore important as well for a complete understanding of the chemistry and biology of the deep sea.

Cross-References

▶ Axial Magma Chamber
▶ Axial Summit Trough
▶ Axial Volcanic Ridges
▶ Crustal Accretion
▶ Depleted Mantle
▶ Explosive Volcanism in the Deep Sea
▶ Hydrothermal Plumes Category
▶ Hydrothermal Vent Fluids (Seafloor)
▶ Lava Types
▶ Layering of Oceanic Crust
▶ Lithosphere - Composition and Formation (plus Lithospheric Mantle)
▶ Mid-Ocean Ridges
▶ Oceanic Rifts
▶ Oceanic Rift System/Mid-Oceanic Ridge
▶ Oceanic Spreading Center
▶ Peridotite
▶ Ridge-plume Interaction
▶ Spreading Rates and Ridge Morphology

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