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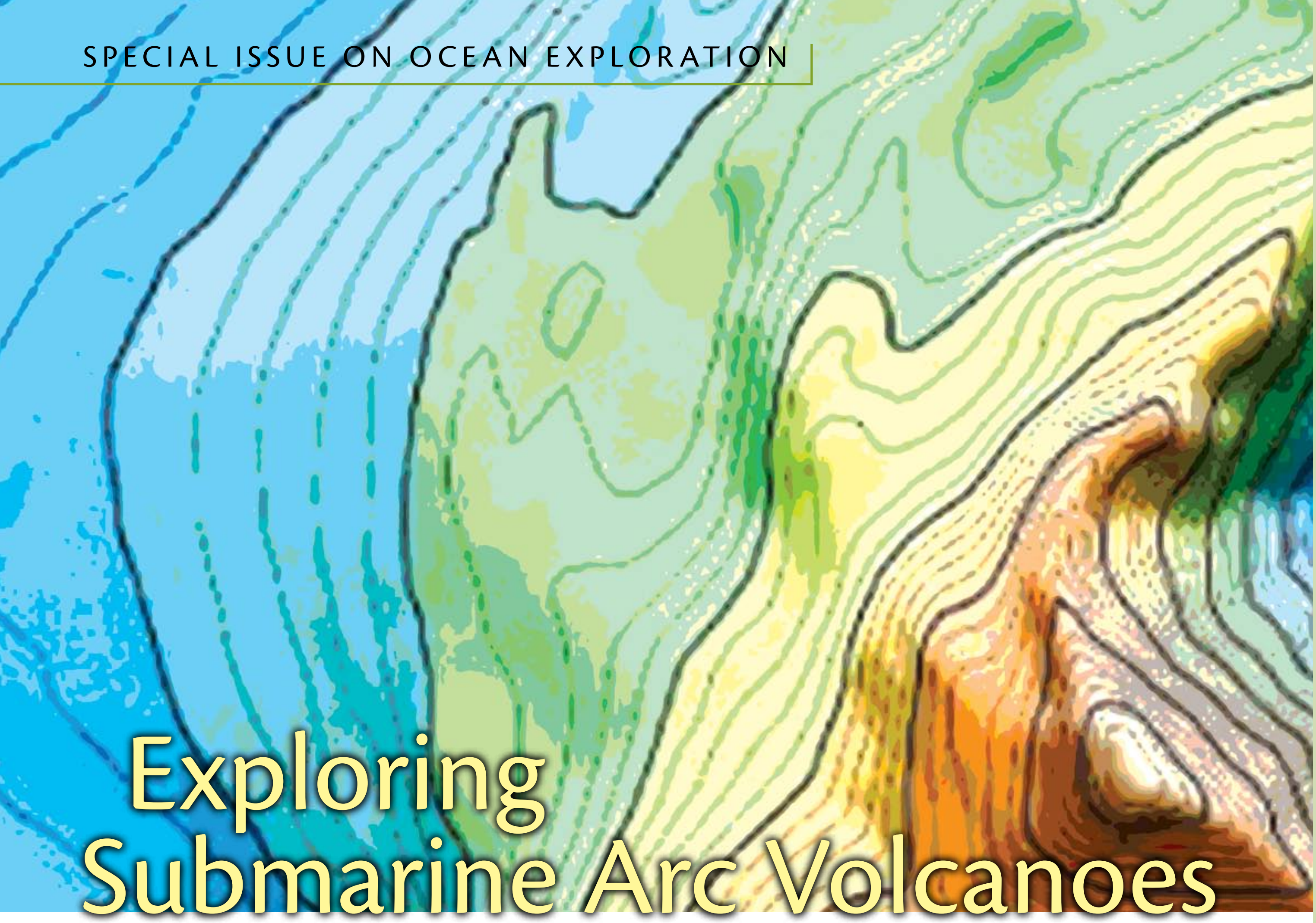


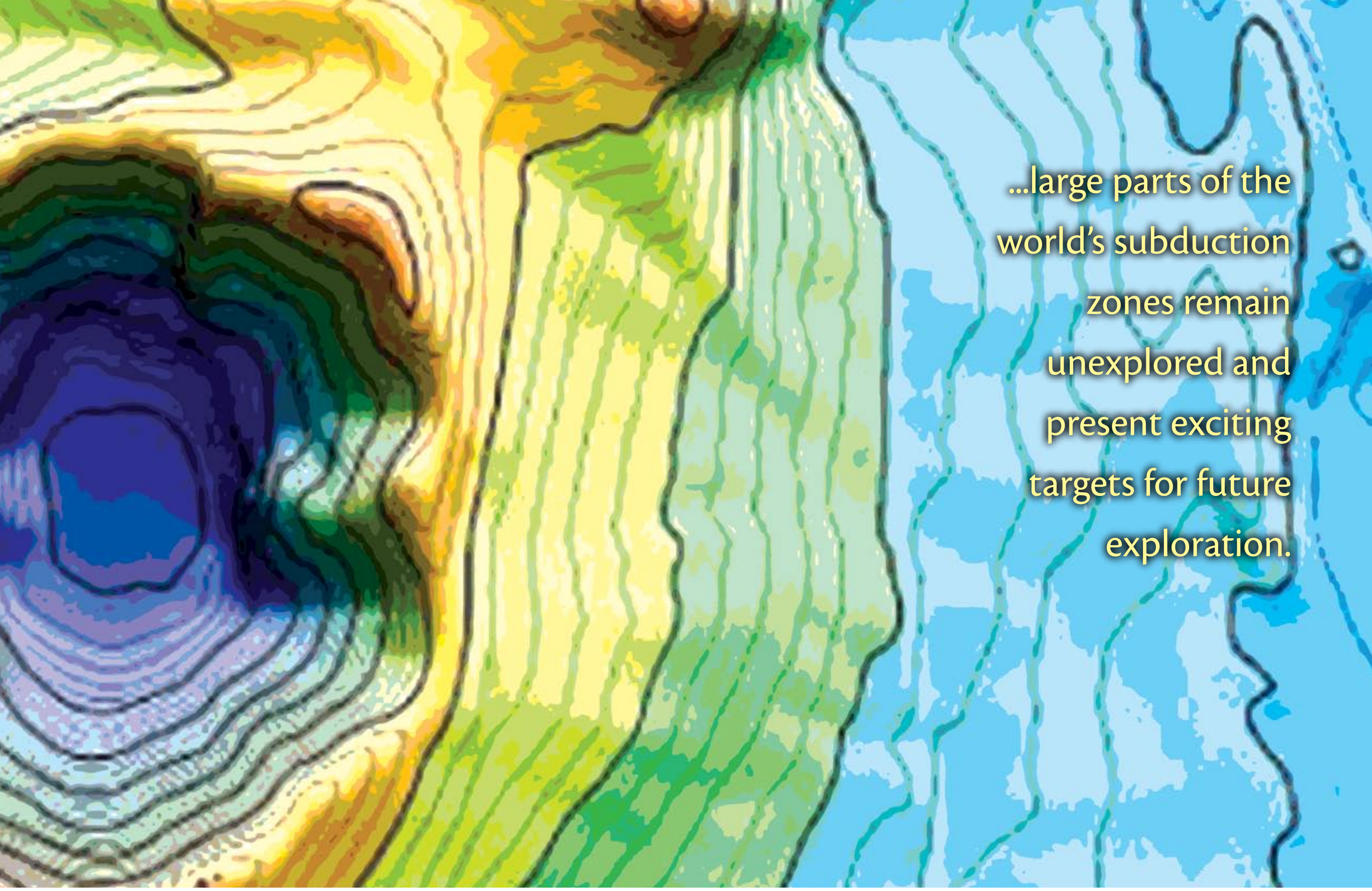
Exploring Submarine Arc Volcanoes

BY STEVEN CAREY AND HARALDUR SIGURDSSON

Three quarters of Earth's volcanic activity occurs beneath the sea, predominantly along the extensive mid-ocean ridge system that winds its way through the major ocean basins. The style of eruptive activity along mid-ocean ridges has been extensively studied and well characterized. Submarine eruptions at mid-ocean ridges are dominated by effusive production of pillow and sheet-flow lavas at water depths of several thousands meters. The other major style of submarine eruptions occurs along island arcs where subduction of oceanic crust triggers melting of mantle rocks by the release of volatile components, such as water and carbon dioxide. Submarine volcanism constitutes an important component of active island arc systems, although a significant part of arc volcanism can also occur subaerially.

Eruptions that take place beneath the sea in arcs contribute to the formation of thick sedimentary sequences (Wright, 1996), provide sites for hydrothermal mineralization (Iizasa et al., 1999; de Ronde et al., 2005), and may be responsible for the introduction of biogeochemically significant components such as Fe into the upper water column (de Ronde et al., 2001). The impact on biological production is likely to be accentuated in subantarctic and polar waters where Fe is a limiting constraint. In shallow water, the activity of submarine-arc volcanoes poses significant hazards from explosive eruptions that can breach the surface (Baker et al., 2002) and cause the generation of tsunamis (Latter, 1981). The loss of the Japanese survey vessel *Kaio-maru* in 1952 from an eruption of the shallow Myojinsho volcano underlines the dangers of submarine eruptions that reach the surface (Fiske et al., 1998).

Unlike mid-ocean ridges, the submarine eruptive styles and types of edifice construction within island arcs have only begun to be explored in detail. The Ocean Exploration program of the U.S. National Oceanic and Atmospheric Administration (NOAA) pioneered the systematic study of submarine arc volcanoes with expeditions in the western Pacific (Embley et al., 2004, 2006), Lesser Antilles (Sigurdsson et al., 2006a), and the eastern Mediterranean Sea (Sigurdsson et al., 2006b). Remarkable



...large parts of the world's subduction zones remain unexplored and present exciting targets for future exploration.

discoveries made on these expeditions provide new insight into the structure and behavior of submarine arc volcanoes. In particular, these discoveries have allowed scientists to better gauge the potential hazards, geological significance, and economic importance of these types of volcanic centers.

COLLAPSING EDIFICES

The presence of major horseshoe-shaped scars on many oceanic volcanoes led early workers to speculate that large-scale gravitational collapse of island flanks was responsible for these distinctive features (Fairbridge, 1950; McBirney, 1971). When the side of Mount St. Helens collapsed on May 18, 1980, and generated the largest rock avalanche of the twentieth century, volcanologists witnessed for the first time the devastating potential of unstable volcanic slopes. The resulting horseshoe-shaped scar would become the fingerprint of unstable-slope collapse at many volcanic centers. Such collapses may or may not be associated with eruptive activity. The recognition of numerous and extensive submarine debris avalanche deposits and slumps along the Hawaiian island chain confirmed their important role in the evolution of large intraplate oceanic volcanoes (Moore et al., 1994a). Such collapses are inferred to have produced enormous tsunamis that may have carried coral fragments up to 60 m above sea level on some of the Hawaiian islands (Moore et al., 1994b). Recognition of debris avalanche deposits in the deep sea has been facilitated by the use of side-scan sonar to identify the characteristic hummocky topography of their surfaces (Holcomb and Searle, 1991).

In island arcs such as the Lesser Antilles, slope collapse was first proposed for a number of volcanic centers on the islands of St. Lucia, Dominica, and St. Vincent (Roobol et al., 1983). Large arcuate depressions represented the

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scars of gravity slides that traveled into the back-arc Grenada Basin. In a recent study utilizing swath bathymetry, backscatter data, and seismic reflection profiles, large-scale, debris-avalanche deposits were found in the Grenada Basin west of the islands of Dominica, Martinique, and St. Lucia (Deplus et al., 2001). Sector collapse and the generation of submarine debris avalanches thus appears to be an important process for submarine and subaerial arc volcanoes (Coombs et al., 2007), as well as large oceanic islands such as the Hawaiian chain.

An excellent example of a young submarine arc volcano that illustrates this important process is Kick'em Jenny volcano located just off the island of Grenada in the Lesser Antilles (Figure 1). The volcano was discovered in 1939 when numerous earthquakes were felt, and tsunamis affected Grenada and the Grenadines, and reached as far as Barbados. An explosive eruption broke the surface and produced ash-laden columns that extended up to 300 m above the sea surface (Devas, 1974). There have been at least eleven eruptions since that event, some of which caused disturbances at the sea surface and small tsunamis. Other eruptions, with no surface manifestations, have been detected only by T-phase seismic signals (Shepherd and Robson, 1967).

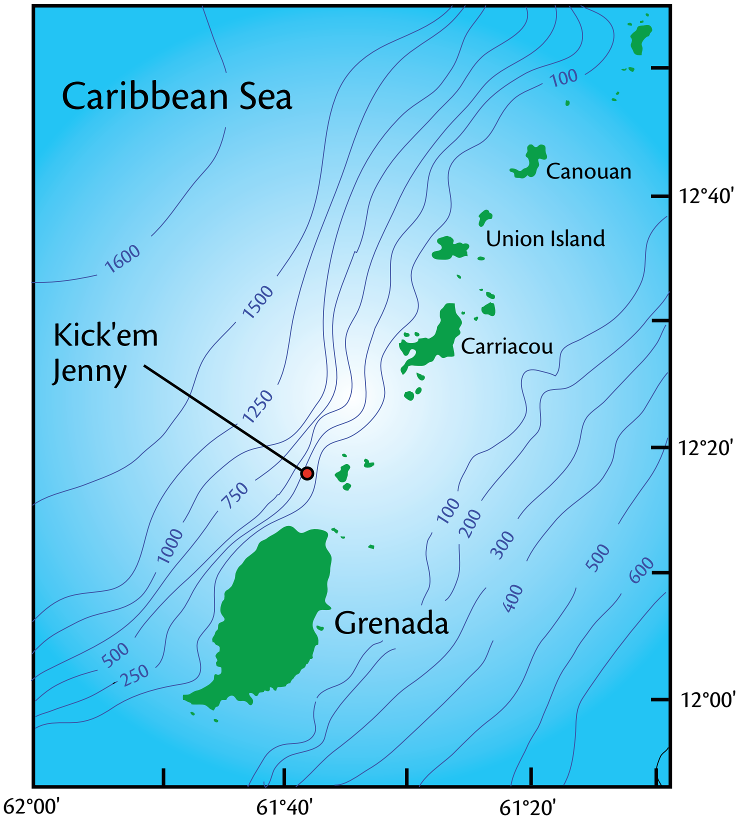

Figure 1. Location of Kick'em Jenny submarine volcano off the north coast of the island of Grenada in the Lesser Antilles island arc.

A reconnaissance survey in 1962 showed that the depth to the crater rim was 223–232 m. The depth decreased as a result of each successive eruption, reaching a minimum of 160 m by 1978. The first detailed survey of the volcano in 1972 revealed a 1300-m-high conical structure, constructed on the western flank of the arc (Sigurdsson and Shepherd, 1974). The summit crater was found at a depth of 190 m and was approximately 180 m in diameter. An eruption in 1977 resulted in shallowing of the volcano's summit to 160 m, and the summit region was more dome-shaped than distinct crater. The first multibeam survey of the volcano in 1985 confirmed the earlier findings, but showed that the region between the volcanic cone and the Grenada Basin to the west comprises irregular topography (Bouysse et al., 1988). Submersible dives in 1989, a few months after a 1988 eruption, revealed that the volcanic cone consisted of both pyroclastic deposits and pillowlike lava-flow units. The summit region exhibited the remnants of a lava dome and a breached crater.

Multibeam surveys were undertaken by the NOAA research vessel *Ronald H. Brown* following a December 2001 eruption. They yielded a high-resolution image of the volcano and the surrounding region and revealed important new details regarding its structure. The most striking feature is a large arcuate west-facing scarp that surrounds much of the volcanic cone to the south, west, and north (Figure 2). The new data show that the Kick'em Jenny volcanic cone is actually located inside a major 5-km-wide, horseshoe-shaped, west-facing amphitheater that most likely was formed by slope failure and associated

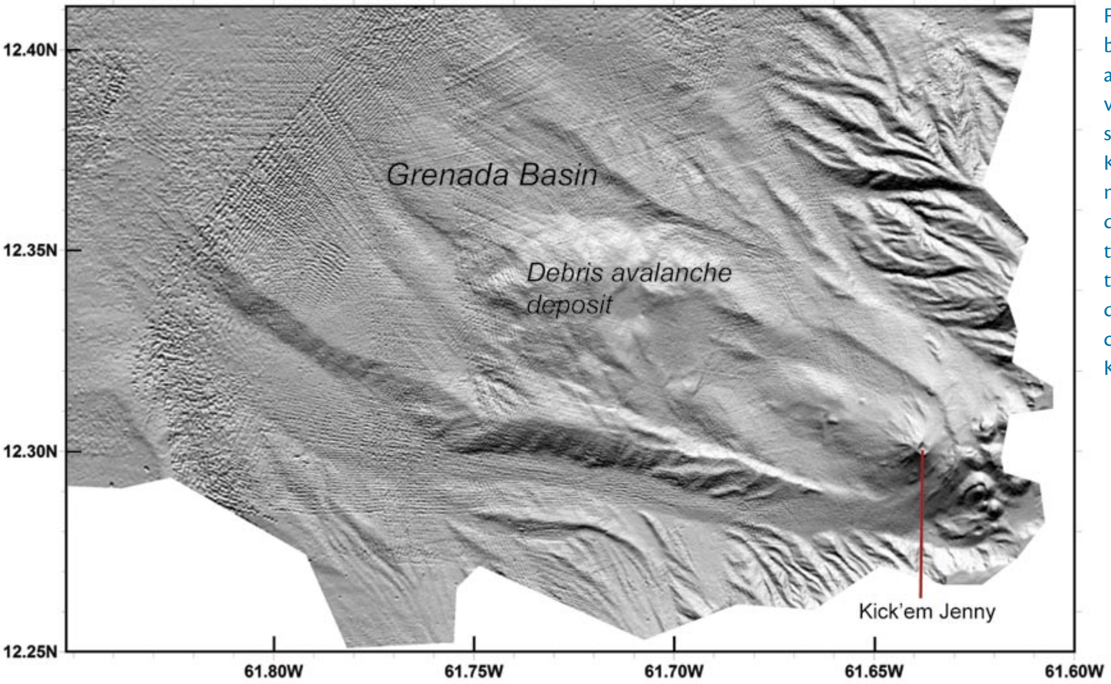

Figure 2. SeaBeam multibeam bathymetry shadow image in the area of Kick'em Jenny submarine volcano. Note the large horseshoe-shaped scar surrounding Kick'em Jenny and open to the northwest. The hummocky area downslope of the volcano in the Grenada Basin is interpreted to represent a debris avalanche deposit produced during the collapse of an ancestral cone of Kick'em Jenny.

debris avalanche. This debris avalanche deposit extends 17 km downslope into the back-arc Grenada Basin (Sigurdsson et al., 2006a). Empirical relationships suggest that the volume of the debris avalanche may be of the order of 10 km^3. The identification of a major arcuate scarp surrounding Kick'em Jenny volcano (Figure 2) suggests that the growth of the present cone has been controlled by this feature. The large inferred volume of the Kick'em Jenny debris avalanche raises questions about the nature of the structure that collapsed. For example, if the present cone of Kick'em Jenny was replaced by a 10 km^3 conical structure, it would likely form a subaerial edifice a few hundred meters above sea level. Thus, there is a possibility that a subaerial island was involved in the original collapse and that Kick'em Jenny is in the process of rebuilding a larger volcano.

SUBMARINE ERUPTION PROCESSES

Submarine explosive eruptions driven by the exsolution of primary gases such as H_2O and CO_2 constitute an important process in the growth of island arcs and, to a lesser extent, mid-ocean ridges and oceanic islands (White et al., 2003). The depth at which these eruptions can take place has been the subject of considerable debate (e.g., Burnham, 1983; Gill et al., 1990). Recent exploration of the Mariana island arc during the Ring of Fire 2006 NOAA cruise dramatically illustrated this phenomenon with the video recording of an actively erupting vent at NW Rota-1 submarine volcano (555 m water depth; Embley et al., 2006). In this case, the erupting magma was basaltic and the activity resembled energetic strombolian discharges.

Our understanding of submarine explosive activity suffers from a lack of visual observations and instead relies on inferring eruption processes from deposits in the geologic record (Kokelaar and Busby, 1992; Kano et al., 1996; Fiske et al., 2001). In the case of explosive eruptions of felsic (high-silica) magmas, there are no existing observations, and conceptual models have been qualitatively developed (Figure 3; Kano, 2003). The importance of submarine explosive activity in island arcs is probably underestimated because of the scarcity of direct observations. The presence of pumice rafts, gas bubbling on the sea surface, local seawater color changes (Hedervari, 1984; McClelland et al., 1989), and seismic activity (Talandier, 1989) are all direct indicators of submarine volcanic explosions.

The nature of submarine eruptions depends upon the water depth (hydrostatic pressure), composition, volatile content of the ascending magma, and

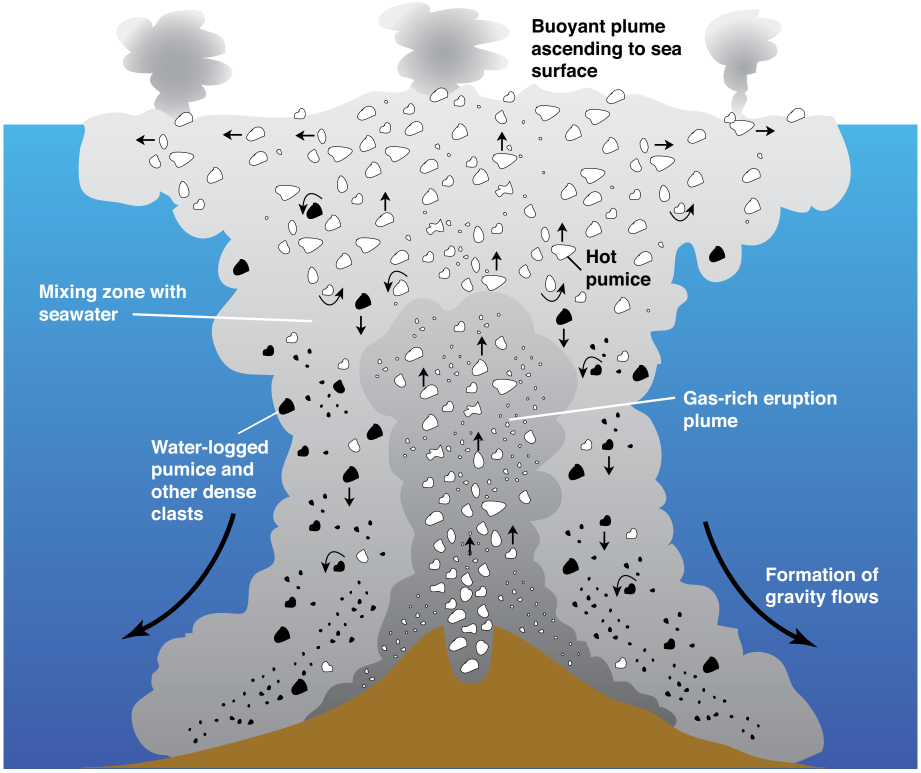

Figure 3. Schematic representation of a shallow-water, explosive eruption that generates pumice (*adapted from Kano, 2003*). The eruption produces a central gas-rich core that ascends and mixes with seawater. Some pumice continues to rise to the surface, but other clasts become waterlogged and sink. Mixing with seawater at the edges of the eruption column produces dense, particle-laden mixtures that collapse and flow down the submarine slopes.

rate of magma discharge (McBirney, 1963; Burnham, 1983; Stix, 1991; Cas, 1992; Head and Wilson, 2003; White et al., 2003). Gas expansion and resulting submarine volcanic explosions are theoretically possible down to a depth of 3000 m, which corresponds to the critical point of water, where the transition from water to vapor involves negligible expansion. It has been suggested that explosions could be possible at depths in excess of 3000 m, and that a wide range of pyroclastic deposits can be expected (Head and Wilson, 2003). Various methods of volatile concentration within the magma are called upon in order to achieve gas contents high enough to drive explosive volcanism at such great depths. Potential submarine explosive eruption styles include plinian (sustained discharge of volatile-rich magma; Kokelaar and Busby, 1992; Kano, 2003), vulcanian (short-lived explosion resulting from failure of a solid plug in the vent), strombolian (bursting of large bubbles in low-viscosity magma), and fire fountaining (eruption of low-viscosity magma in the form a spray; Mueller and White, 1992; Head and Wilson, 2003). Deposits of fragmented rhyolitic pumice and basaltic scoria that erupted subaqueously have been found in several places in the ocean, at depths up to 2000 m (Kato, 1987; Cashman and Fiske, 1991; Fiske et al., 1998). However, it appears that many subaqueous explosions resulting from primary gas exsolution preferentially occur at shallower depths, above the suggested maximum volatile fragmentation depth of several hundred meters (Fisher and Schmincke, 1984).

It is likely that island arcs may be the sites of more abundant submarine explosive eruptions than other volcanic environments owing to the volatile-rich nature of the magmas. Recent detailed exploration of submarine arc volcanoes in the Kermadec and Izu-Bonin island arcs shows a great abundance of geomorphic features such as craters, calderas, and pyroclastic deposits indicative of explosive activity (Fiske et al., 2001; Wright et al., 2003; Yuasa and Kano, 2003). Such submarine eruptions are likely to be more energetic than those at mid-ocean ridges and oceanic islands because of the higher magmatic volatile content, more viscous nature of the magmas, and larger individual volumes of magma batches that are involved in island-arc eruptions.

The nature and dynamics of submarine explosive pumice-forming (pyroclastic) eruptions is complex and still not well understood. The presence of water and the potential for the formation of steam results in a three-phase system (gas, particles, and water) that has novel sedimentation and transport behaviors (Cashman and Fiske, 1991; Fiske et al., 2001; Kano, 2003). Explosive eruptions of silicic magma will form submarine eruption columns that eject hot pumice and gas into the water column (Figure 3). If the mass flux is very high, a buoyant mixture of pumice, steam, and hot water will rise and potentially reach the surface where it will spread out to form a mushroom-shaped mixture of water and particles. If the pyroclastic mass flux is low and the submarine eruption column is able to entrain enough water, the steam phase may recondense and the bulk density will increase significantly. This will trigger collapse of the column to form syneruptive sediment gravity flows (Kano, 2003; Allen and Stewart, 2003). Even when parts of the column collapse, significant amounts of pumice and ash may still rise convectively, disperse, and then begin to fall out when they become saturated with water (Figure 3). Most pumice is initially less dense than seawater but will eventually become waterlogged by condensation of internal steam and absorption of water (Whitham and Sparks, 1986; Manville et al., 1998). Some pumice is able to rise to the surface, eventually becoming waterlogged and sinking. Other pumice can become negatively buoyant very quickly upon exposure to water within the eruption column. Thus, some pumice that initially rises in the water column will settle back to the seafloor, but at a much slower rate than in air. The time scale for the transition to negative buoyancy is proportional to the size of the pumice (Manville et al., 1998) and may thus result in reverse size grading of submarine fallout deposits.

Three quarters of Earth's volcanic activity occurs beneath the sea, predominantly along the extensive mid-ocean ridge system that winds its way through the major ocean basins.

These events are potentially important for deep-sea volcaniclastic sedimentation as they can produce large volumes of pumice and ash during single events. Fiske et al. (2001) estimate that a submarine eruption of Myojin Knoll caldera in the Izu-Bonin arc produced more than 40 km^3 of pumicieous tephra, and Wright et al. (2003) suggest that Healy caldera in the southern Kermadec arc discharged 10–15 km^3 of pumice at water depths of about 1000 m. The characteristics of submarine pumice deposits are likely to show both similarities to and differences from their subaerial counterparts. Fallout of pumice will form well-sorted and mantle-bedded sequences, although the size sorting of particles of different density will reflect settling through water as opposed to air, resulting in a smaller contrast between the size of pumice and denser fragments (Cashman and Fiske, 1991). In addition, the velocity of submarine gravity flows will be less than that of subaerial equivalents and thus may impart different bedding characteristics.

Remarkable new discoveries have resulted from detailed ROV exploration and high-resolution bathymetric mapping.

Recent remotely operated vehicle (ROV) exploration of Kolumbo submarine volcano in the Aegean Sea provides detailed views of the deposits associated with a shallow (< 500 m) island-arc center. Kolumbo is the largest of a line of submarine centers that extends 20 km to the northeast of the islands of Santorini (Figure 4). The line of volcanoes lies within a rift that ends in the southwest as normal faults that dissect the northern caldera wall of the island of Thera. Kolumbo consists of a 3-km-diameter cone with a 1500-m-wide crater, a rim as shallow as 10 m below sea level in the southwest, and a crater floor about 500 m below sea level. It was last active in 1650, when an explosive eruption produced hot surges that spread over the sea surface and caused 70 deaths on Thera and other extensive damage from tsunami inundation (Fouqué, 1879; Vougioukalakis et al., 1996, Dominey-Howes et al., 2000). During the 1650 eruption, the volcano broke the surface and produced an ephemeral pumice bank that was subsequently eroded below the surface. The submarine crater wall consists of a spectacular sequence of well-bedded dacite pumice deposits (Figure 5a) that was most likely formed by fallout from a submarine eruption column similar to that shown in Figure 3. A large part of the upper cone consists almost exclusively of very loose pyroclastic material that is actively slumping into the caldera. The deposits from Kolumbo volcano are important analogues for thick uplifted Pleistocene-age pumice deposits exposed on the Greek islands of Kos and Yali (Allen and Stewart, 2003).

HYDROTHERMAL VENTING AND MINERAL DEPOSITS

The discovery of hydrothermal venting and polymetallic sulfide deposits at mid-ocean ridge systems counts as one of the last two decades' most exciting facets of marine geological research (Tivey, 2007). Much is known about the distribution and composition of the hydrothermal systems that create these deposits (e.g., Humphries et al., 1995). Equally important is the recognition that these unique environments, created as a result of the thermal energy of volcanism, provide distinct habitats for exotic communities of biological organisms (Hannington et al., 2005). There have also been new discoveries of hydrothermal vents and polymetallic sulfide deposits in volcanic systems associated with subduction-zone environments. An actively growing Kuroko-type polymetal-

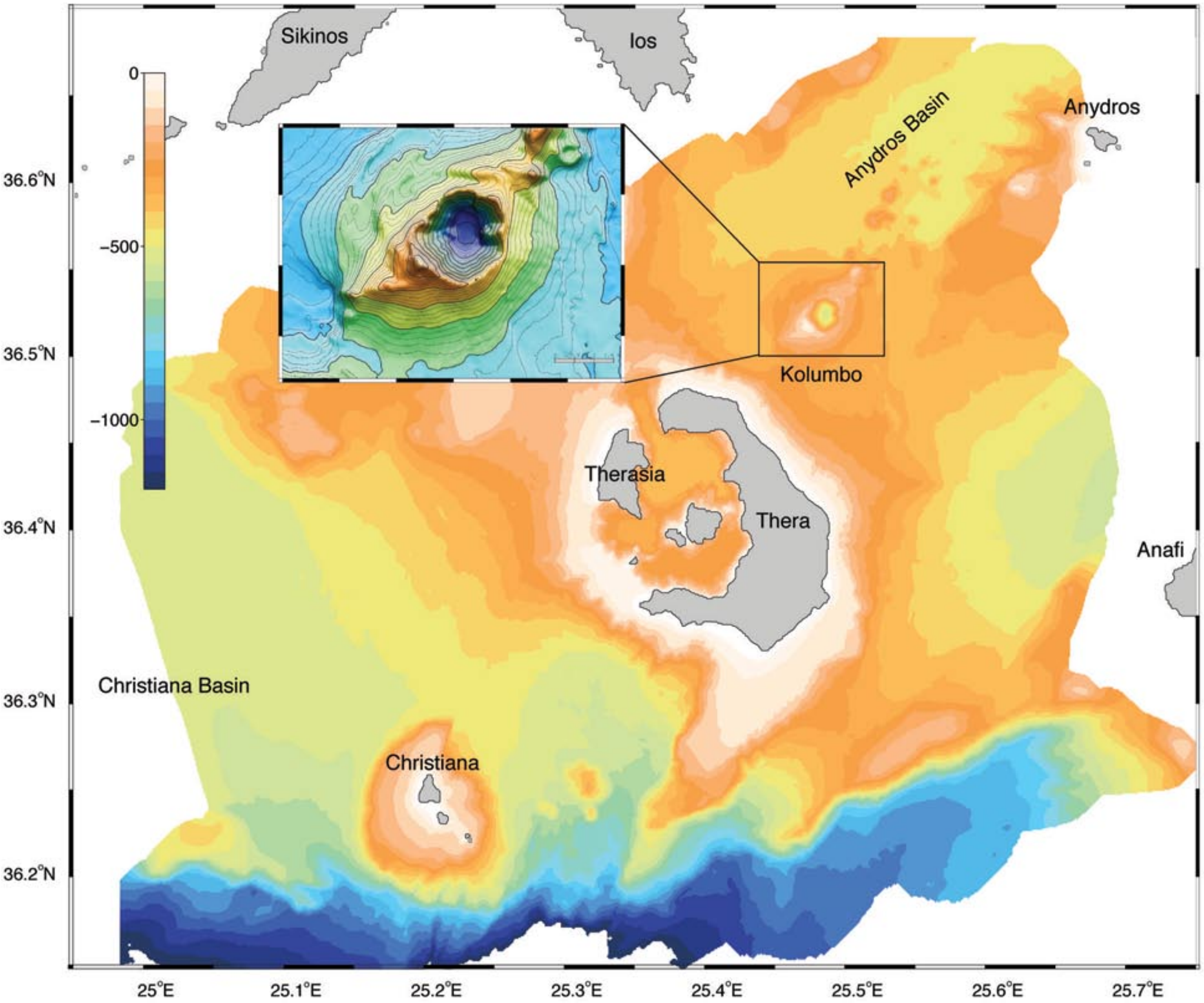

Figure 4. Location and morphology of Kolumbo submarine volcano to the northeast of the Santorini volcanic complex, Greece (Thera and Therasia). Water depth scale is in meters. *SeaBeam multibeam bathymetric map provided by the Hellenic Center for Marine Research, Greece*

lic sulfide deposit was discovered off of Japan in the submarine Myojin caldera (Iizasa et al., 1999). Numerous active chimneys and a 400-by-400-m area consisting of brecciated massive sulfide and manganese oxide were found on the caldera floor near an inferred caldera fault system. A similar deposit was also found in shallower water at the Bayonnaise caldera, also within the Izu-Ogasawara arc, but in a more back-arc rift environment (Iizasa et al., 2004). The most comprehensively described deposit occurs within the Brothers caldera of the southern Kermadec arc system (de Ronde et al., 2005). Compared to the polymetallic sulfide deposits of mid-ocean ridge systems, the subduction-related, Kuroko-type deposits are richer in Au, Ag, Zn, and Pb, but poorer in Fe and Cu (Iizasa et al., 1999).

In relatively shallow water, hydrothermal venting can include the discharge of gases in addition to metal-rich fluids (Dando et al., 1995). The gases may be derived directly by exsolution from subsurface magmas or boiling seawater. At Kick'em Jenny in the Lesser Antilles, bubbling vents were discovered in the crater at a depth of 250 m. Subsurface temperatures in the area of venting were inferred to be in excess of 270°C. The boiling point of seawater at the pressures of the inner crater of Kick'em Jenny (~ 250 m) is approximately 260°C. This is less than the inferred temperature of 270°C at a depth of 10 cm below the vent opening. Thus, seawater that is circulating through the porous volcaniclastic sediments of the inner crater may reach the boiling point and be converted to vapor that rapidly migrates to the sediment/water interface and forms streams of bubbles.

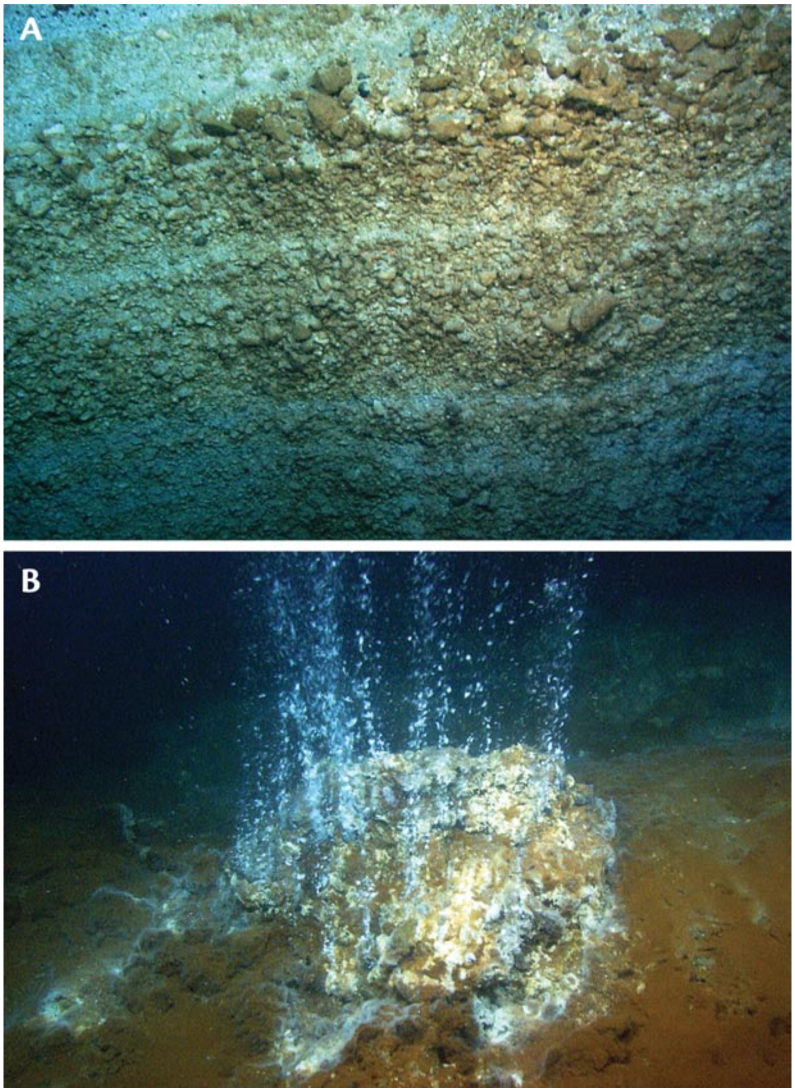

Figure 5. A) Bedded pumice deposits near the rim of Kolumbo submarine volcano. The largest pumice clasts are approximately 5 cm in diameter. B) Hydrothermal vent on the floor of Kolumbo submarine volcano discharging warm fluids and gas. The bubbling area is approximately 1–1.5 meters in diameter. I*mage courtesy of the Graduate School of Oceanography, University of Rhode Island, the URI Institute for Archaeological Oceanography, and the Mystic Aquarium Institute for Exploration (IFE)*

Recent marine geological investigations of the Kolumbo submarine volcano using ROVs reveal a very active high-temperature hydrothermal vent field that is about 25,000 m^2 in area in the northeastern part of the crater floor (Sigurdsson et al., 2006b). Vent chimneys up to 4-m high are vigorously emitting colorless gas plumes up to 10-m high in the water column (Figure 5b). Temperatures as high as 220°C were recorded in vent fluids. Some vents are in craterlike depressions that contain debris from collapsed extinct chimneys. Most chimneys show high porosity and are configured with a central conduit surrounded by an open and very permeable framework of sulfides and sulfates, aiding fluid flow through the chimney walls. In the sulfate-rich samples, blades of barite and anhydrite crystals coat the outside of the chimney wall, and layers of barite alternate with sulfide in the interior. The dominant sulfides are pyrite, sphalerite, wurtzite, marcasite, and galena (Sigurdsson et al., 2006c). Crusts on extinct and lower-temperature chimneys are composed of amorphous silica, goethite, and halite. Elevated levels of copper, gold, and silver are observed in the bulk composition of chimney samples.

> Our understanding of the growth and eruptive processes of submarine arc volcanoes has been greatly improved due to recent marine geological investigations carried out by the NOAA Ocean Exploration Program.

SUMMARY

Our understanding of the growth and eruptive processes of submarine arc volcanoes has been greatly improved due to recent marine geological investigations carried out by the NOAA Ocean Exploration Program. Remarkable new discoveries have resulted from detailed ROV exploration and high-resolution bathymetric mapping. However, large parts of the world's subduction zones remain unexplored and present exciting targets for future exploration. Shallow submarine-arc volcanoes are particularly interesting because of their potential hazards (tsunamis and explosive eruptions), mineral resources, geochemical fluxes to shallow water, and unique biological habitats. Much work is needed to understand the complex processes of submarine explosive eruptions and the types of deposits that they form. The high volatile content (H_2O and CO_2) of arc magmas that drive these explosive eruptions also contribute to the unique characteristics of the hydrothermal fluids and mineral deposits. Just as hydrothermal circulation at mid-ocean ridges was found to play a key role in global seawater chemistry, similar processes in submarine arcs will need to be similarly assessed in the future.

ACKNOWLEDGEMENTS

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