Marine Investigations of Greece's Santorini Volcanic Field

The most recent major explosive eruption of the Santorini volcano in Greece—around 3600 years before present (B.P.), often referred to as the Minoan eruption—is one of the largest volcanic events known in historical time and has been the subject of intense volcanological and archeological studies [*Druitt et al.*, 1999]. The submarine volcano Kolumbo, located seven kilometers northeast of Santorini and associated with Santorini's tectonic system, erupted explosively in 1650 A.D., resulting in fatalities on the island of Thera [*Fouqué,* 1879]. A large fraction of the erupted products from the Minoan eruption has been deposited in the sea but, up to now, only has been studied in distal marine sediments.

As part of a collaborative project between the University of Rhode Island (Narragansett), the Hellenic Centre of Marine Research (Athens, Greece), and the Institute of Geology and Mineral Exploration (Athens), a marine geological survey was conducted around Santorini from April to June 2006. The new work now shows that the volume of the Minoan eruption may be comparable to that of the largest known historical eruption, the 1815 eruption of Tambora in Indonesia [*Sigurdsson and Carey,* 1989]; provides insights into the depositional processes and size of the Minoan eruption; and led to the discovery of important submarine hydrothermal vents with active mineralization.

Submarine Pyroclastic Deposits

The Minoan eruption of the Santorini volcano has remained of great interest to geologists, historians, and archeologists because of its possible impact on the Minoan civilization in Crete and on the Cycladic islands. The eruption generated pyroclastic flows as well as widespread volcanic ash fallout. The volume of ash fallout from the Minoan eruption has been estimated previously to be 19 cubic kilometers dense-rock equivalent (DRE) [*Sigurdsson et al.*, 1990]. This result implied that the volume of submarine pyroclastic flows should be of the order of 20 cubic kilometers DRE, based on mass balance assumptions [*Sparks and Huang,* 1980]. Thus, the early estimate was a total of 39 cubic kilometers DRE for the eruption as a whole.

The recent marine seismic survey reveals a sediment sequence on the ocean floor around Santorini that is generally massive or chaotic (with highly irregular internal reflections), as is typical of submarine pyroclastic flow deposits. This sequence has a mean thickness of about 29 meters, but ranges up to about 80 meters in areas close to the coast of Santorini. The distribution of the sequence is greatly affected by seafloor topography, and mainly follows pre-existing submarine valleys (Figure 1). The unit has a total area of 1378 square kilometers inside the 10-meter thickness contour line, and the total bulk volume around Santorini is 54.5 cubic kilometers, or about 41 cubic kilometers DRE.

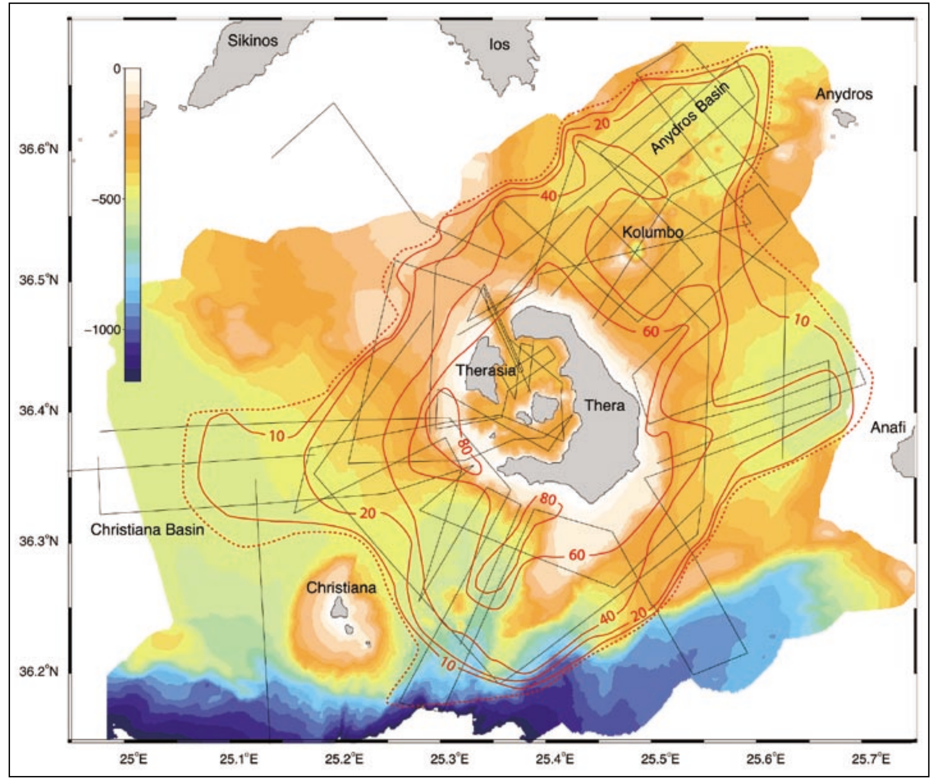

Fig. 1. Map of the Santorini region showing bathymetry (Seabeam), locations of seismic lines (black), and the distribution of inferred massive pyroclastic deposits from the Minoan eruption. The thickness of the surface sequence derived from the volcano is shown with 10-meter-spaced contours (red), and the outer limit of the deposit is shown by the red dashed lines.

The top of the sequence often is terraced or step-like, especially on the steep submarine slopes of the volcano, with steps that have a lateral extent of kilometers or more and heights of tens of meters. These morphological 'wrinkles' most likely are a result of downslope creep and slumping during or just after deposition. On some steep slopes, the terraces detach and the sequence is separated into distinct hummocks or blocks.

The origin of this extensive sequence, which clearly is derived from Santorini, can be

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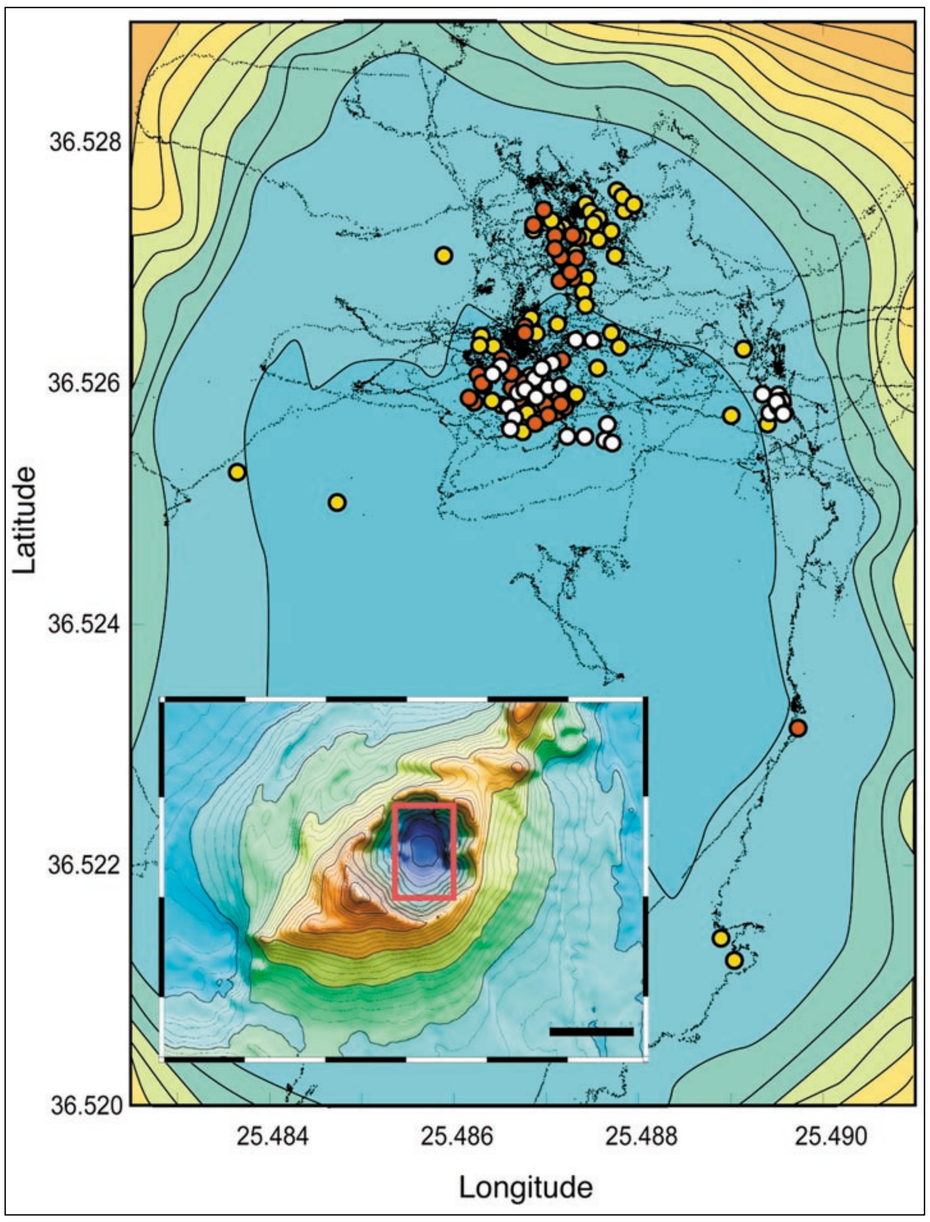

Fig. 2. Map showing the distribution of hydrothermal vents in the crater of Kolumbo submarine volcano and the track of the remotely operated vehicle (dashed/stippled black tracks). Shown are high-temperature chimneys (white circles), low-temperature chimneys (red circles), and areas of bacterial streams (yellow circles). Inset map shows Kolumbo volcano and the area depicted in the larger figure. The scale bar at the bottom right of the inset map is 1.5 kilometers.

interpreted as submarine pyroclastic gravity flow deposits by comparing this sequence with the character of the submarine deposits formed during the 1883 Krakatau eruption [*Sigurdsson et al.,* 1991]. The sequence is likely to contain several layers, as shown by some internal reflectors. These layers may consist of primary submarine pyroclastic flow deposits emplaced at high temperature or water-supported flows generated by transformation of hot flows as they entered the ocean.

This young, widespread sequence is likely to be related to the 3600 year B.P. Minoan eruption of Santorini and may have been generated as a result of massive pyroclastic flow discharge into the sea. If the sequence consists of dominantly juvenile material from the Minoan eruption, then this would increase the total volume of erupted material estimated for this event. Volumetrically, the Minoan eruption deposit consists of four components: plinian ash fall from the main eruption column (2 cubic kilometers DRE), ash fall associated with pyroclastic flows (17 cubic kilometers [*Watkins et al.,* 1978]), pyroclastic flow deposits on land on Santorini (1.5 cubic kilometers), and the newly mapped marine pyroclastic deposits around the volcano (41 cubic kilometers). Thus, the total volume of the event could be as high as 60 cubic kilometers DRE, nearly twice the previous estimate.

Hydrothermal Vents

The Santorini volcanic field extends 20 kilometers to the northeast, as a line of more than 20 submarine cones. The line of craters lies within a rift that dissects the northern caldera wall of Thera island (Figure 1). By far, the largest of these submarine craters is Kolumbo, a three-kilometer-diameter cone with a 1500-meter-wide crater, a crater rim as shallow as 10 meters, and a crater floor 505 meters in depth below sea level. Kolumbo last was active in 1650 A.D., when an explosive eruption produced hot surges across the ocean surface that caused 70 deaths on Thera [*Fouqué,* 1879]. Seismic monitoring by the Institute for the Study and Monitoring of the Santorini Volcano shows that seismicity in the region today almost is exclusively limited to Kolumbo and the northeast trending Kolumbo volcanic line.

A widespread hydrothermal vent field was discovered on the floor of the Kolumbo submarine crater during the recent marine survey (Figure 2). High-temperature venting occurs in the northern part of the crater, with vigorous gas emission plumes more than 10 meters above the crater floor, and fluid temperatures up to 220ºC from vent chimneys up to four meters in height that are constructed of polymetallic massive sulfides and sulfates. The exterior of most chimneys is densely covered with white, gray, and reddish filamentous bacteria. Some of the chimneys exhibit branching, trunk-like structures that have continuous gas and fluid streaming from multiple openings. Other chimneys consist of a series of tightly clustered, tapered spires that are up to one meter in height.

Lower-temperature chimneys and vents along the northern and eastern margins of the crater floor discharge clear fluids up to 70ºC and minor gas bubbles. The larger chimneys in this area are covered by reddish bacteria and sea squirts (glassy tunicates). The margins of the crater wall in the northeast have streams of white bacterial mats that are the colonization of fluid seeps moving downward toward the crater floor. In some of these areas, there are patches of gray, hydrothermally altered clays emitting shimmering water at temperatures up to about 70ºC. The entire crater floor of Kolumbo is covered by a reddish orange bacterial mat a few centimeters in thickness. In addition, the water column in the crater deeper than 250 meters is turbid with abundant bacterial filaments and other suspended particles.

In contrast to the high-temperature venting in Kolumbo, only low-temperature venting was observed within the Santorini caldera. Hydrothermal vents occur in both the North and South basins of the caldera. There is a vent field in the northeast part of the North Basin that is 200 by 300 meters in extent (Figure 3). The vents form hundreds of one- to four-meter-diameter mounds of yellowish bacterial mats that are up to one meter high. Temperatures in the mounds are around 15º–17ºC, or about 5ºC above ambient temperature. The North Basin hydrothermal vent field is located in line with the normal fault system of the Kolumbo rift, and also is near the margin of a shallow intrusion that occurs within the sediments of the North Basin. Similar vent mounds occur in the South Basin, where most of the low-temperature vents are seeps along a ridge separating the Aspronisi Basin and South Basin, and on the submarine flanks of the Kameni volcanic islands.

Seismic studies show that the three basins of the Santorini caldera have a post-Minoan sediment fill of about 200 meters. Diffuse hydrothermal activity has emanated through this fill, forming low-temperature vent fields in the North and South basins. These vent fields are characterized by mounds of yellowish bacterial mats, and the North Basin vents are located in line with the Kolumbo tectonic trend.

In contrast, the hydrothermal activity in the Kolumbo submarine crater includes high-temperature gas-emitting vents from one- to four-meter-high sulfide- and sulfate-rich chimneys at up to 220ºC. The different state of hydrothermal activity in the Santorini caldera versus the Kolumbo crater is attributed in part to the thick sediment fill that has accumulated in the caldera, and the much more recent submarine volcanic activity in the Kolumbo crater. Thus, Kolombo may be a modern analogue to conditions within the Santorini caldera just after the Minoan eruption. It is likely that after the Minoan eruption, the Santorini caldera was the scene of very vigorous hydrothermal activity, as the shallow magmatic system was cooling down. In the 3600 years since the eruption, the sea-floor hydrothermal activity has waned, because of heat-loss as well as because of the rapid burial of the caldera by a more than 200-meter thickness of sediment influx.

The results of the recent marine survey show that the Minoan eruption is now comparable in volume to the largest known historical eruption, that of Tambora in Indonesia in 1815 [*Sigurdsson and Carey,* 1989]. Furthermore, the submarine pyroclastic flow deposits from the Minoan eruption are even more extensive than those of the 1883 Krakatau eruption. These results imply that the direct hazard from pyroclastic flows entering the sea and flowing over the ocean surface is likely to be much greater than previously considered for this important eruption in the Late Bronze Age. Refinement of the erupted volume of the Minoan eruption also has implications for the assessment of the potential global environmental impact that was caused by this event.

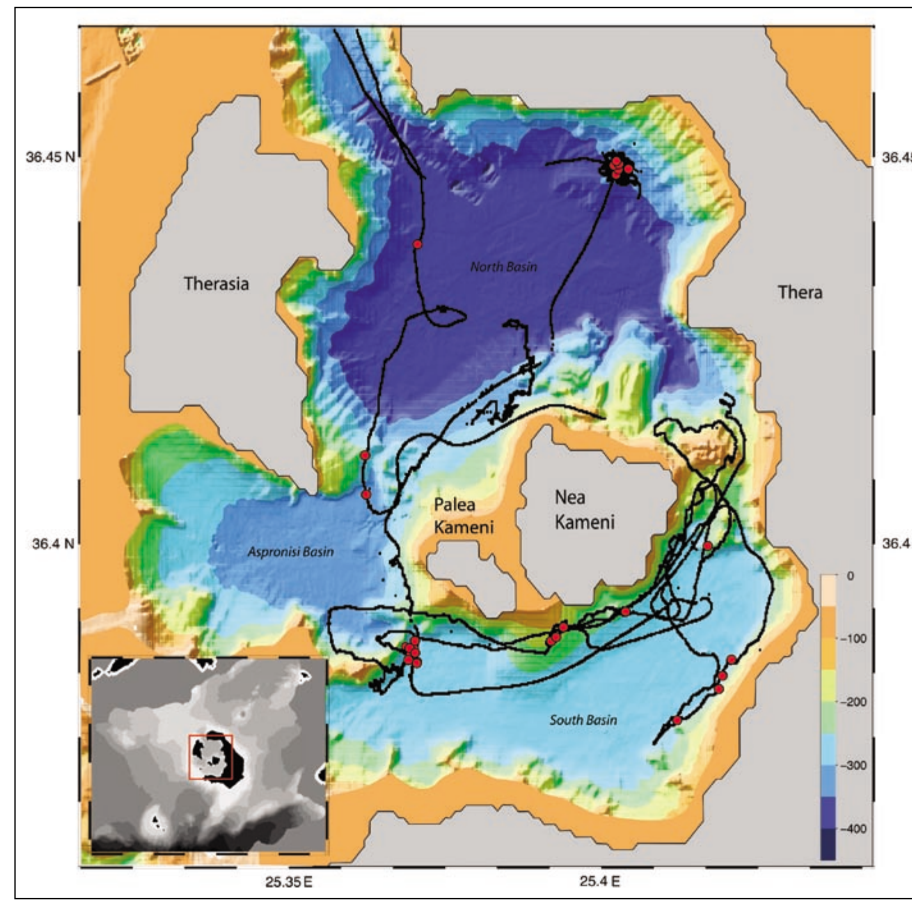

Fig. 3. Map showing the distribution of hydrothermal mounds (red circles) in the caldera of Santorini (Thera) and the track of the remotely operated vehicle (heavy black line). Principal fields occur in the northeast, southwest, and to a lesser degree to the south of the Kameni islands. Inset map shows the Santorini volcanic field and the area of the caldera shown in the larger figure.

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