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Toward a Risk Assessment of Central Aegean Volcanoes

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Active tectonic processes along the African-Eurasian collision zone are associated with catastrophic events including earthquakes, major volcanic eruptions, and tsunamis. Understanding how these processes can affect the eastern Mediterranean is of increasing scientific and public interest. The region includes a frequently crossed international sea traffic corridor and dense population centers. Furthermore, most of the small volcanic islands in the Aegean are major tourist attractions that contribute significantly to the wealth of this region.

One of these Aegean islands is Santorini, which is a major explosive volcano and possibly one of the most dangerous volcanoes in Europe. During the past 150 million years, Santorini has had 12 major eruptions, and several of them ejected large columns of ash and debris high into the atmosphere. It is widely believed that the eruption of Santorini about 3600 years before present (B.P.) destroyed the Minoan civilization of Crete.

In addition to the volcanic island, there are several submarine volcanic seamounts in the Aegean Sea. One of them, the Columbo seamount, is about eight kilometers northeast of Santorini, and recently has attracted attention due to the high earthquake activity of the Hellenic subduction zone [*Bohnhoff et al.*, 2006]. This activity is concentrated in an area northeast of Santorini, within the so-called Santorini-Amorgos zone.

The earthquakes occurred in the upper crust at a depth of 3–15 kilometers and are considered to be related to evolving volcanism and related magma or fluid migration. Whereas the potential risk of future eruptions of the Santorini volcano is well recognized by scientists and by Santorini residents, the Columbo underwater volcano never has reached a level of public risk perception that is adequate for its actual risk, despite the potential threat of underwater eruptions. For that reason, a multidisciplinary research initiative, begun in June 2006, is investigating recent tectonic and volcanic activity in this area and preparing a risk assessment for this region.

The newly completed first phase of the 'Inspecting Columbo' project consisted of an extensive marine geophysical survey that was carried out in order to map active tectonic and volcanic features. More than 1500 kilometers of seismic and magnetic data, as well as 2500 kilometers of gravity data, were collected in June 2006 during a cruise onboard the research vessel (R/V) *Poseidon*. On the basis of onboard processing, optimized locations for deploying five ocean-bottom seismometers and four newly developed ocean-bottom tiltmeters were determined. The retrieval of these instruments, scheduled for spring 2007, will initiate the second phase of the program.

Volcanic Complexes of the Santorini-Amorgos Zone

According to previous findings, the Santorini-Amorgos zone (SAZ) marks a major structural boundary in a dextral transtensional regime that subdivides the Hellenic volcanic arc into a seismically and volcanically quiet western and an active eastern part. The highest earthquake activity has been observed beneath the submarine Columbo volcano and northeast of it along the Santorini-Amorgos Ridge [*Perissoratis*, 1995], which terminates south of the island of Amorgos (Figure 1).

The activity close to the Columbo seamount is considered to be linked directly to a magma reservoir and to be influenced by the migration of magma and fluids toward the surface. Earthquakes northeast of the volcano also may result from magma and associated fluid migration toward the surface, according to some suggestions. The Santorini-Columbo volcanic complex includes one caldera at Santorini and one crater at Columbo. The caldera of Santorini is formed by four deep basins (from 290 to 390 meters deep). The Columbo volcano has a well-defined crater with a single basin (depth 500 meters). Until now, only a single underwater eruption has been reported for the Columbo volcano in 1650 A.D. [*Fytikas et al.*, 1990]. However, evidence for previously undiscovered activity in Colombo's past was expected on the seafloor surrounding the seamount.

Strategy for Geophysical Profiling

The general scientific objectives of the project's recently completed first phase included the investigation of shallow expressions of deep-rooted tectonic or magmatic intrusions, which may result in active faulting or fluid migration, respectively. During the research cruise, the Santorini-Columbo complex as well as the SAZ were mapped in detail by means of multichannel seismic reflection and magnetic (1500 kilometers each) and gravity (2500 kilometers) profiling (Figure 1). For the active seismics, a bubble free airgun with about 100-hertz main frequency served as the seismic source. In the sediment basins, the signal penetrated to a depth of more than one kilometer beneath the seafloor. Data were received by two seismic sensor cables (streamers) of 600- and 150-meter length, respectively.

The seismic data will help with (1) the identification of active tectonics; (2) the budgeting of pyroclastic deposits around Santorini and the Columbo volcano as well as in the SAZ; (3) the interpretation of individual eruption events of the Columbo and Santorini volcanoes; and (4) the detection of fluid migration paths and reservoirs associated with magmatic intrusions. The gravity and magnetic data will help to correlate shallow tectonic signals with deeper magmatic intrusions, and therefore determine the distinction between main faults above an intrusion or side branches.

Two examples elucidate the potential of the data. A seismic cross-section of the Santorini-Amorgos Ridge where the earthquake activity is highest, indicates that its sediment cover is highly and actively faulted (Figure 2). The presence of magnetic anomalies at

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the ridge's southeastern escarpment suggests that the earthquake activity and the active faulting are caused by magmatic processes. Initial modeling results suggest that the magnetic source body, such as a magma chamber, lies at a depth of five kilometers. This is consistent with previously published epicenter depths of a few kilometers.

A second example from a northwest-southeast striking line across the Columbo volcano elucidates the primary building blocks of the volcano. Two cone-like volcanoclastic deposits show that the Columbo volcano evolved from at least two eruptions. A bright spot about 200 meters beneath the caldera provides evidence for gassy and/or fluid charged sediments. The strong magnetic anomaly (~450 nanoteslas) above the caldera can be assumed to be caused by a magma chamber beneath the caldera. In addition, a depth for the magnetic body has been estimated at five kilometers. Southeast of the volcano, along the so-called Kameni line, an elongated dike intrusion, named the Poseidon Ridge, has been discovered about 100 meters beneath the seafloor. The ridge, six kilometers wide and more than 10 kilometers long, is characterized by a small magnetic anomaly of about 40 nanoteslas. An active extensional fault can be seen on the seafloor. A second extensional fault lineament is present northwest of Columbo, where initial faults already pierce the seafloor. Both of these examples prove that the SAZ is tectonically active and deserves constant monitoring.

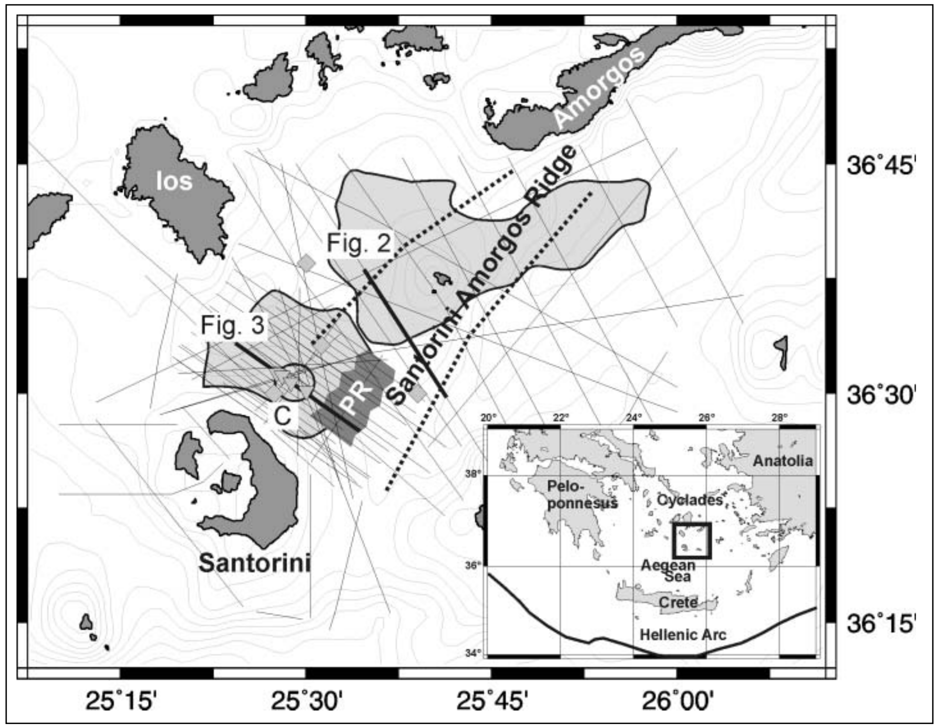

*Fig. 1. Map of the Santorini-Amorgos zone. Thin lines mark geophysical profiles (Multi-channel seismic reflection (MCS), gravity, magnetics). Bold lines show the locations of Figures 2 and 3. Triangles show ocean-bottom tiltmeters, and squares show ocean-bottom seismometers. Areas of high earthquake activity [*Bohnhoff et al., *2006] around the Columbo submarine volcano (cycle labeled C) and the Santorini-Amorgos zone are marked by two lightly shaded areas. The tectonically-active Poseidon Ridge (PR) is located southwest of the Columbo volcano. The Santorini-Amorgos Ridge is shown by dotted lines according to* Perissoratis *[1995].*

Seafloor Observation Systems

The second phase of the research initiative aims to understand possible correlations between earthquake and volcanic activities. To accomplish this, a network of ocean-bottom tiltmeters (OBT) and ocean-bottom seismometers (OBS) was deployed in the vicinity of the Columbo seamount. Altogether, five OBS and four OBT were deployed during the cruise in June 2006 (Figure 1). The instrument retrieval, scheduled for spring 2007, represents the kickoff of this second phase of the research initiative, which will examine the collected data.

As reported by other authors, the crustal uplift at Cape Columbo (northeastern part of Santorini Island) and a high seismicity rate in the vicinity of Columbo seamount caldera suggest the occurrence of offshore volcanic activity, such as dike intrusions accompanied by microearthquake clusters. The newly developed Hamburg OBT contains a two-component tiltmeter with a resolution of 10 nanorads and an absolute pressure sensor (Paroscientific) to detect uplift or subsidence. Additionally, each OBT observes seismic signals with a hydrophone (0.325 hertz). Four OBTs have been deployed on a profile perpendicular to the largest principal stress axis $\sigma 1$ near the summit of the Columbo seamount. A magma dike is supposed to ascend as a lens-like body with its maximal lateral extension parallel to the main stress

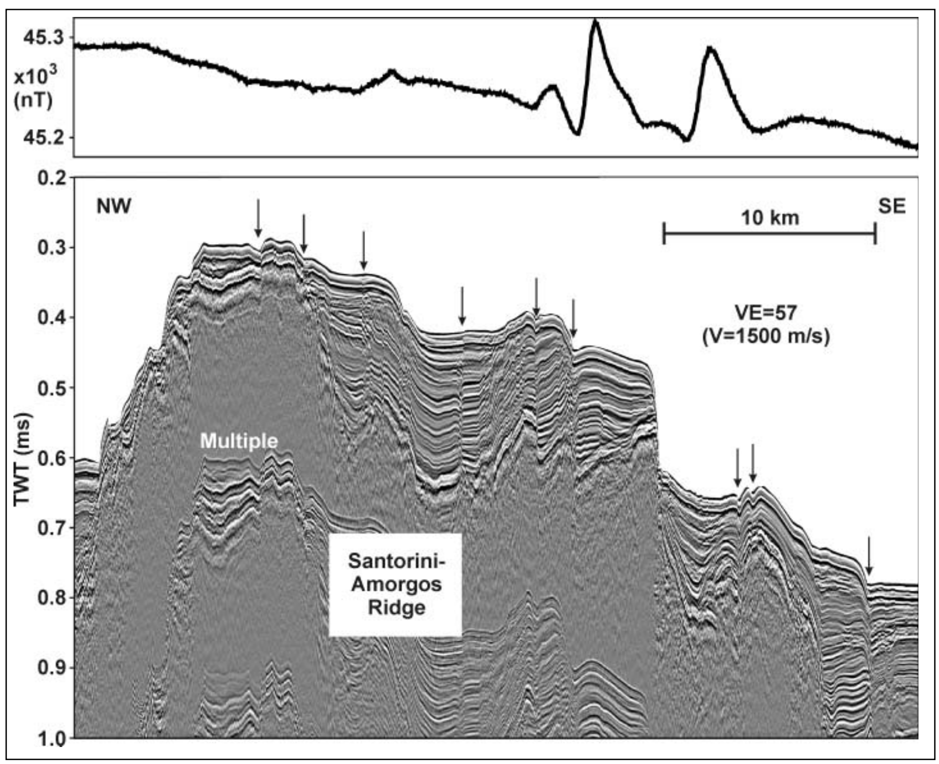

Fig. 2. Seismic (time-migrated section) and magnetic (gradiometer) data across the Santorini-Amorgos Ridge. In this region, abundant shallow earthquakes have been observed by Bohnhoff et al. *[2006]. Arrows point to near-vertical faults that represent shallow expressions of deep rooted processes. The magnetic anomalies of about 100 nanoteslas align on the southwestern shoulder of the Santorini-Amorgos Ridge. First modeling results suggest the magnetic source body, like magma chambers, at a depth of five kilometers, which is consistent with previously determined epicenter depth. For location, see Figure 1.*

direction and thus the strongest tilt signals and tilt gradients should appear on the flanks of the smallest lateral extension of the dike.

Furthermore, four OBS stations, two of them close to the seamount and another two at a distance of approximately 20 kilometers, enhance the aperture of the existing land-based seismic network. Closing the azimuthal gap to the northeast and covering the epicentral area could allow the observation of a higher number of events and the acquisition of accurate epicenter locations. Focal mechanisms will be calculated, and the tilt data will be examined closely to find correlations with tilt signals that could appear parallel to the events. The geometry of the OBS network has been designed according to the expected focal mechanisms, i.e., transform faulting in case of purely tectonic events along the Santorini-Amorgos Fault, and normal faulting in case of magma-induced crustal uplift.

The combined interpretation of multichannel seismic, gravity and magnetic profiles as well as seismological and tiltmeter data could help with unraveling the impact of tectonic and magmatic processes on the seafloor and adjacent islands. This research could represent a significant step towards an improved risk assessment for the Santorini-Columbo volcanic complex and, consequently, for the residents of the central Aegean region.

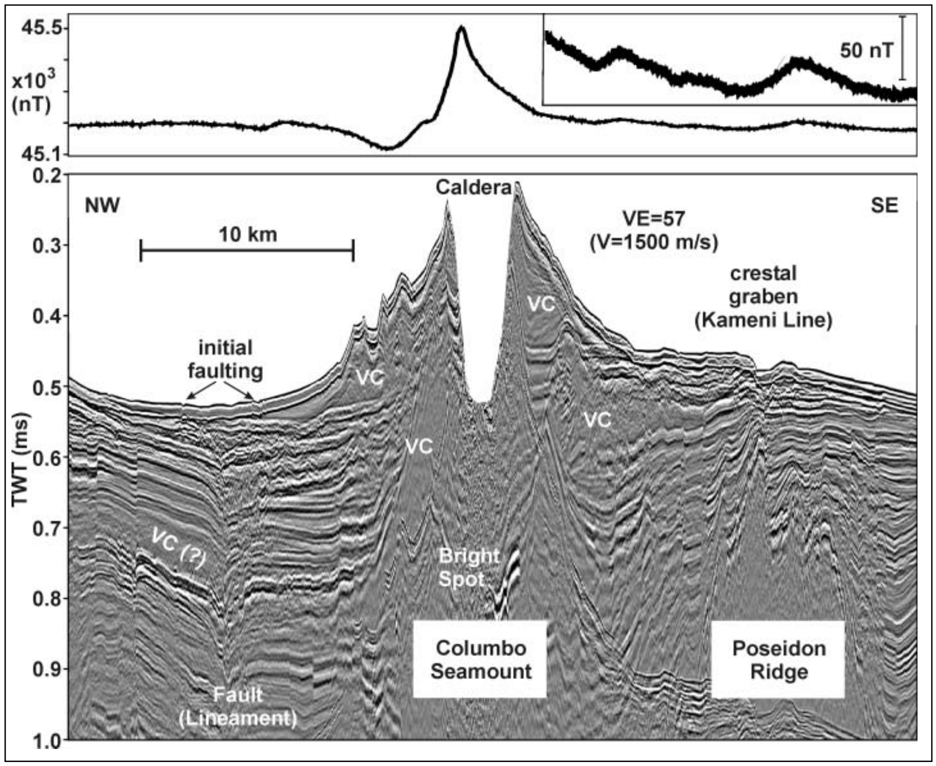

Fig. 3. Seismic (time-migrated section) and magnetic (gradiometer) data across the Columbo submarine volcano. Volcanoclastic (VC) deposits are characterized by weak and chaotic reflections. Two vertically stacked cones of VCs give evidence of at least two major outbursts. A bright spot beneath the caldera suggests the presence of fluids or gas about 200 meters beneath the caldera. The Poseidon Ridge aligns along the Kameni line. This magmatic ridge is tectonically active, as indicated by an extensional crestal graben. To the northwest, another elongated extensional fault starts to pierce through the uppermost sediments. For location, see Figure 1.

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