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# Submarine evidence of a debris avalanche deposit on the eastern slope of Santorini volcano, Greece

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ABSTRACT

Hummocky seafloor features were discovered on the eastern flank of Santorini volcano, Greece. Multibeam bathymetric mapping, airgun seismic profiling, side scan sonar survey, and remotely operated vehicle (ROV) dives have been carried out to characterize the nature of the hummocks. These hummocks appear to be composed of several tens of blocks that are up to several hundred meters in diameter, and are the surface expression of a much larger deposit than is observed in the bathymetry. The sidescan and airgun data show that the deposit covers an area of approximately 6 km wide by 20 km long, and is up to 75 m thick. We estimate the total volume of the deposit to be approximately $4.4 \times 10^9$ $m^3$. Sampling of these blocks show they are composed of pyroclastic flow deposits produced during the Minoan eruption of Santorini (ca. 3600 BP). We propose that the deposit is the result of a multi-stage landslide event that was caused by one of the several large earthquakes or volcanic eruptions that have occurred in the vicinity of Santorini since the Minoan eruption. One or more of these events likely triggered the destabilization of a part of the eastern flank of Santorini, which led to a debris avalanche, depositing blocks and forming a hummocky terrain at the base of the island's slope. The mass movement later evolved into a turbulent suspension flow that traveled 20 km or more from the presumed initial failure. Given the size of the landslide deposit, it might have a tsunami potentially affecting the islands across the southern Aegean Sea. The understanding of earthquake–landslide dynamics has important implications for hazard assessment in this seismically active, historical, and highly populated region of the world.



## 1. Introduction

Hummocky deposits were discovered on the eastern submarine slope of Santorini using multibeam bathymetric mapping and seismic profiling aboard the R/V *Aegaeo* in 2006 (Alexandri et al., 2001, 2006; Sigurdsson et al., 2006), and were further mapped with sidescan sonar and observed with remotely operated vehicles (ROVs) aboard R/V *Endeavor* in 2006 and E/V *Nautilus* in 2010. The hummocks are similar in morphology to debris avalanche deposits found in other volcanic arc environments, such as the Lesser Antilles, Nisyros, and the Aleutian Arc (Coombs et al., 2007; Deplus et al., 2001; Siebert, 1984; Tibaldi et al., 2008). We hypothesize that the hummocks are the result of a debris avalanche that was triggered by one or more of the several large earthquakes or volcanic eruptions that have occurred in the vicinity of Santorini over the past 3600 years (Papazachos et al., 2000b, 2007).

Debris avalanches are one of the most dangerous hazards in coastal volcanic environments. The large, catastrophic movement of volcaniclastic debris has the ability to bury entire towns (Catane et al., 2008), and are able to cause tsunamis that can devastate nearby coastal communities (Tappin et al., 2001; Tinti et al., 2008; Ward and Day, 2001; Whelan and Kelletat, 2003). Studying the characteristics of past events may allow us to more fully understand how these events are triggered and the potential dynamics of future events.

Recent studies have shown that the processes, magnitude, and characterization of submarine landslides are distinct from subaerial events (Hampton et al., 1996; Korup et al., 2007; Locat and Lee, 2002). Furthermore, Canals et al. (2004) have identified the need for criteria by which underwater debris flows and debris avalanches can be classified for further study. They have developed a classification scheme that includes the assessment of: (1) morphology and dimensions of failure deposits; (2) scars and slip plane geometries; (3) run-out distances; (4) and, triggering mechanisms and ages of slide events (Canals et al., 2004). We aim to apply these criteria to evaluate the hummocky deposits found east of Santorini using a combination of geophysical and geological data collected in 2006 and 2010. Each of the characteristics can be evaluated to varying degrees, depending on the data available.

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## 2. Geological setting

Located in the center of the Hellenic Volcanic Arc, Santorini has been the site of some of the largest explosive eruptions in the Mediterranean region (Figs. 1 and 2). The Hellenic Arc began to form approximately 25 to 30 Ma by the subduction of the African plate beneath the Aegean microplate (Horvath et al., 1981; Pe and Piper, 1972), and today stretches from Greece in the west to Turkey in the east.

Profitis Ilias, the highest point on Santorini, as well as a number of smaller outcrops is composed of pre-volcanic alpine basement that protrude on the southeastern side of the island (Papastamatiou, 1958). Large underwater spurs to the east of Santorini may represent the submarine extensions of these features (Fig. 3).

Santorini has been volcanically active since the early Pleistocene, with periodic cycles of volcanism and dormancy. During these cycles, there have been twelve major and several minor eruptions, as well as four caldera collapses (Druitt et al., 1999). The last major explosive eruption, known as the Late Bronze Age (LBA) or Minoan eruption, occurred approximately 3600 years before present (1627–1600 BC with 95% confidence) (Bond and Sparks, 1977; Friedrich et al., 2006). The eruption was one of the largest in human history, ejecting an estimated 60 $km^3$ dense rock equivalent (DRE) of volcaniclastic material (Sigurdsson et al., 2006). This eruption has been the subject of intense volcanological and archeological studies, as it is hypothesized to have caused the demise of the Minoan civilization in the Aegean, and may have had wide-spread repercussions across the ancient Mediterranean world (Dominey-Howes, 2004; Eastwood et al., 1998; Federman and Carey, 1980; Gorokhovich, 2005; Guichard et al., 1993; Sigurdsson et al., 1999).

The volcanic and tectonic activities of the region have defined Santorini's terrestrial and submarine structure (Druitt and Francaviglia, 1992; Druitt et al., 1999; Mellors and Sparks, 1991; Perissoratis, 1995; Sparks et al., 1983). In the area around Santorini, the most recent seismicity is focused along a northeast-striking fault system that includes Kolumbo submarine volcano (~7 km NE of Santorini) and a series of other smaller submarine cones in the Anhydros Basin (Bohnhoff et al., 2006; Nomikou et al., in press, 2013-this volume). Today's tectonic structure is characterized by these northeast-striking normal faults overlying older east–west normal faults (Perissoratis, 1995; Sakellariou et al., 2010). Subduction and changes in fault orientation have resulted in a high rate of earthquake activity; nearly ten thousand earthquakes with magnitude greater than $M_w = 4.0$ have been documented in the Aegean from 550 BC to 2007 AD, with a maximum magnitude of 8.0 for the same period (Papazachos et al., 2000a, 2007). Similar seismicity rates would be expected for the time period 1600 to 550 BC, but are not documented. These earthquakes, in turn, cause a significant amount of sediment movement and failure in the basins surrounding Santorini (Anastasakis, 2007; Piper and Perissoratis, 2003). Further, coastal and submarine sediment failures on and around Santorini have been shown to cause tsunamis that have affected the Aegean and eastern Mediterranean (Cita and Aloisi, 2000; Perissoratis and Papadopoulos, 1999).

One event has been hypothesized to have caused the largest known mass wasting feature in the Santorini–Amorgos region. The July 9, 1956, earthquake was the strongest shallow earthquake to take place in this region during the 20th century (Ambraseys, 1960; Papadopoulos and Pavlides, 1992; Papazachos et al., 1985; Perissoratis and Papadopoulos, 1999; Stiros et al., 1994). The main shock had a surface magnitude of $M_s = 7.5$, and the strongest aftershock took place 13 min later, with a magnitude of $M_s = 7.2$. The epicenter of the main shock was located 20 km south of the Island of Amorgos (36.64°N, 25.96°E), while the main aftershock was centered NE of Santorini (36.6°N, 25.7°E), very close to the location of the landslide deposit (Papazachos et al., 2000a, 2007). The earthquake was associated with a tsunami that affected islands across the southern Aegean, including nearby Amorgos and Astypalea, where the wave height was observed to be 20–25 m, all the way to Crete, where the wave was 1–2 m high (Ambraseys, 1960; Dominey-Howes, 1996; Dominey-Howes et al., 2000). As a result, numerous people and livestock were killed;

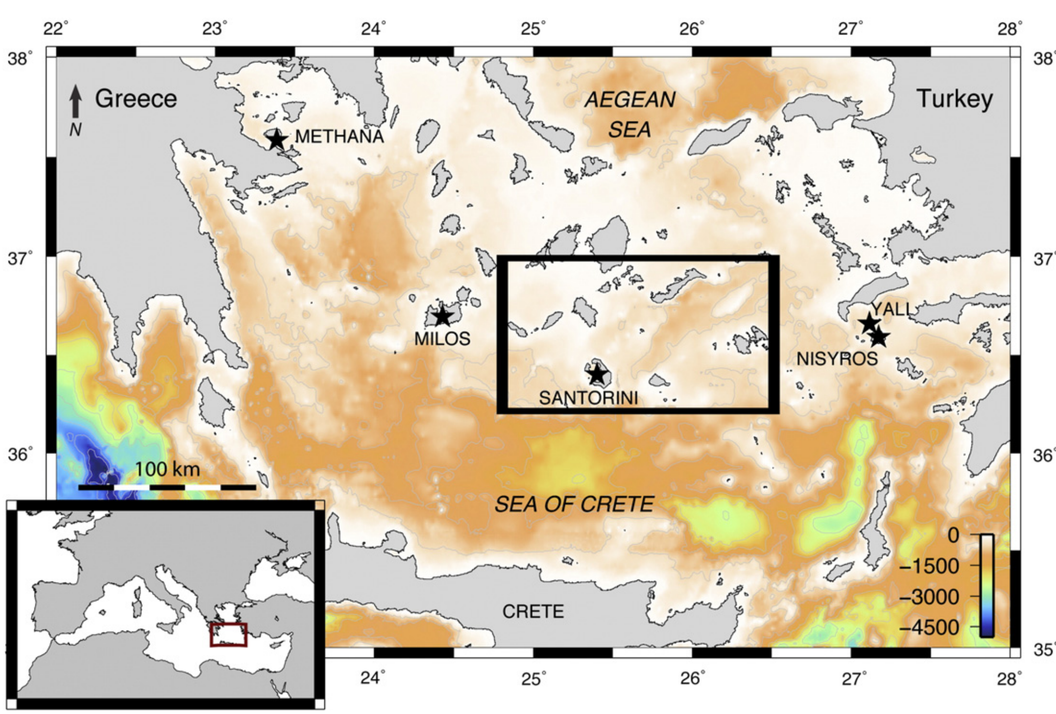


**Fig. 1.** Map of the southern Aegean Sea (GEBCO, 2009); stars indicate emission centers of the Hellenic Volcanic Arc active during the Holocene. Black box indicates bounds of Fig. 2.