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Seismic imaging of the upper crustal magma system and caldera at Santorini volcano, Greece

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Santorini is the most active arc volcano of the Hellenic subduction zone and has a history of alternating effusive, shield-forming eruptions and explosive caldera collapse. The most recent caldera-forming event is the well-studied 3.6 kyr Late Bronze Age (LBA/Minoan) eruption. In 2011-2012, the volcano experienced inflation and seismicity attributed to magma intrusion between 3.3 and 5.9 km depth. To investigate processes that control caldera formation and the accumulation of magma at arc volcanoes, we use a high-resolution, P-wave, seismic velocity model together with existing geological and geochemical constrains. The PROTEUS experiment collected dense, 3D, active-source marine-land seismic data using 90 ocean bottom seismometers, 65 seismic land stations, and ∼14,300 controlled-sound marine sources from the U.S. R/V Marcus Langseth. We use seismic tomography to invert >220,000 Pg travel times to image of the upper crustal structure to 7 km depth. Regional geology and tectonic features are reflected in the near-surface velocity structure. Magmatism has localized along NE-SW basin-like structures that connect the Christiana, Santorini, and Kolumbo volcanic centers, indicating a strong interaction between magmatism and tectonism. In the upper 3 km beneath the north-central caldera, we find a ∼3-km-wide, cylindrical low-velocity anomaly (-2 km/s) that lies directly above the pressure source of 2011-2012 inflation and between two NE-SW-striking tectonic lineaments. Vents that formed during the first three phases of the LBA eruption locate near the edges of the imaged structure. We infer that collapse of a limited area of the caldera floor resulted in a high-porosity, low-density cylindrical volume, which formed by either chaotic collapse along reverse faults, wholesale subsidence and infilling with tuffs and ignimbrites, phreatomagmatic fracturing, or a combination of these processes. LBA phase 4 eruptive vents are located along the margins of the topographic caldera and the velocity structure indicates that the wider topographic caldera formed by coherent down-drop following the more limited collapse in the northern caldera. This progressive collapse sequence is consistent with models for multi-stage formation of nested calderas along conjugate reverse and normal faults. The upper-crustal density differences inferred from the seismic velocity model predict differences in subsurface gravitational loading that correlate with 2011-2012 edifice inflation indicating that sub-surface density anomalies may influence present-day magma accumulation. Directly beneath this structure, we image a second low-velocity anomaly that is 3-6 km below the northern caldera basin, 3-5 km wide, and elongated ∼15 km NE-SW, parallel to tectonic structures. The largest-amplitude recovered velocity anomaly (-1 km/s) is consistent with 4-10% melt and coincides with the 2011-2012 Mogi pressure source. Significant ray bending indicates that the recovered size and amplitude of the low velocity volume are minimum bounds. We infer an upper-crustal intrusion rate (∼2.6 km^3/ky) consistent with the inferred long-term growth of the shallow magma system at Santorini. Future analysis of waveforms, reflectors, and shear waves, and full waveform inversion, will better constrain the melt content and distribution of crustal magma accumulation beneath Santorini.