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Spatio-temporal evolution of the Christiana-Santorini-Kolumbo volcanic field, Aegean Sea

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ABSTRACT

The Christiana-Santorini-Kolumbo volcanic field (CSKVF) in the Aegean Sea is one of the most active volcano-tectonic lineaments in Europe. Santorini has been an iconic site in volcanology and archaeology since the 19th century, and the onshore volcanic products of Santorini are one of the best-studied volcanic sequences worldwide. However, little is known about the chronology of volcanic activity of the adjacent submarine Kolumbo volcano, and even less is known about the Christiana volcanic island. In this study, we exploit a dense array of high-resolution marine seismic reflection profiles to link the marine stratigraphy to onshore volcanic sequences and present the first consistent chronological framework for the CSKVF, enabling a detailed reconstruction of the evolution of the volcanic rift system in time and space. We identify four main phases of volcanic activity, which initiated in the Pliocene with the formation of the Christiana volcano (phase 1). The formation of the current southwest-northeast–trending rift system (phase 2) was associated with the evolution of two distinct volcanic centers, the newly discovered Poseidon center and the early Kolumbo volcano. Phase 3 saw a period of widespread volcanic activity throughout the entire rift. The ongoing phase 4 is confined to the Santorini caldera and Kolumbo volcano. Our study highlights the fundamental tectonic control on magma emplacement and shows that the CSKVF evolved from a volcanic field with local centers that matured only recently to form the vast Santorini edifice.

INTRODUCTION

Located on the Hellenic volcanic arc (southern Aegean Sea), the Christiana-Santorini-Kolumbo volcanic field (CSKVF) is one of the most hazardous volcanic fields in the world, having produced >100 explosive eruptions in the past 650 k.y., including at least four caldera-collapse events (Druitt et al., 2019a). The iconic Minoan eruption 3600 yr ago may have contributed to the fall of the Minoan civilization, leaving its imprint on Greek mythology, archaeology, and volcanology (Druitt et al., 2019b).

The CSKVF is located in a 60-km-long, southwest-northeast–oriented rift zone and comprises the Christiana volcano, the Santorini caldera, the submarine Kolumbo volcano, and the Kolumbo chain that consists of 24 submarine cones (Fig. 1B) (Nomikou et al., 2019). The onshore geology of Santorini has been a focal point of geoscientific research for decades, resulting in a detailed chronostratigraphic framework constrained by field mapping and radiometric dating (Druitt et al., 1999). In contrast, only the latest of the as many as five eruptions of Kolumbo is dated by historic reports (Fouque, 1879), and the age of the Christiana volcano is unknown.

Our understanding of the thick volcano-sedimentary infills of the surrounding marine basins has so far been immature. Offshore constraints on the CSKVF chronology are sparse and based mainly on analog seismic data with limited resolution and penetration, which hampers imaging and identification of the commonly complex nature of volcanic structures. Piper et al. (2007) suggested that volcanism of the CSKVF initiated at Christiana during the early Pleistocene (ca. 1.7 Ma), with a main phase of activity at ca. 0.6 Ma. In this interpretation, the entire Kolumbo edifice represents a young volcanic episode contemporary with the Thera Pyroclastic Formation (<0.36 Ma) at Santorini. However, later studies show that the Kolumbo volcano is more complex than previously assumed, with five stacked volcanoclastic units from different eruptive cycles (termed K1–K5) for which two different chronologies with significantly different ages for the inception of Kolumbo volcanism (180 ka versus 1.6 Ma) have been proposed (Hübscher et al., 2015). This highlights large uncertainty in the chronological framework of the CSKVF and complicates the understanding of volcano-tectonic interactions in this densely populated region, which are crucial to understand for a more reliable hazard assessment.

We now have compiled the database necessary to resolve the debate over the chronology of the CSKVF. Through a regional and internally consistent seismic reflection data interpretation linked to onshore constraints, we identify the products of some previously unknown submarine volcanic centers and unravel how CSKVF volcanism has evolved in space and time.

DATA

Our seismic reflection data set comprises >3200 km of high-resolution multi- and single-channel profiles (Hübscher et al., 2006; Sigurdsson et al., 2006; Karstens et al., 2020) (Fig. 1B). We have established the regional stratigraphy for all basins of the CSKVF by identifying and mapping six seismic units characterized by distinct seismic reflection patterns. Ocean bottom seismometer–based (Karstens et al., 2020) ray-tracing analysis provided seismic velocities, which we used for thickness calculation of specific seismic units. We then estimated approximate ages assuming an average sedimentation rate of 10 cm/k.y., which has been used in previous studies in this area (Piper and Perissoratis, 2003; Anastasakis and Piper, 2005). For this calculation, we excluded all mass-transport deposits, volcanoclastic formations, and areas

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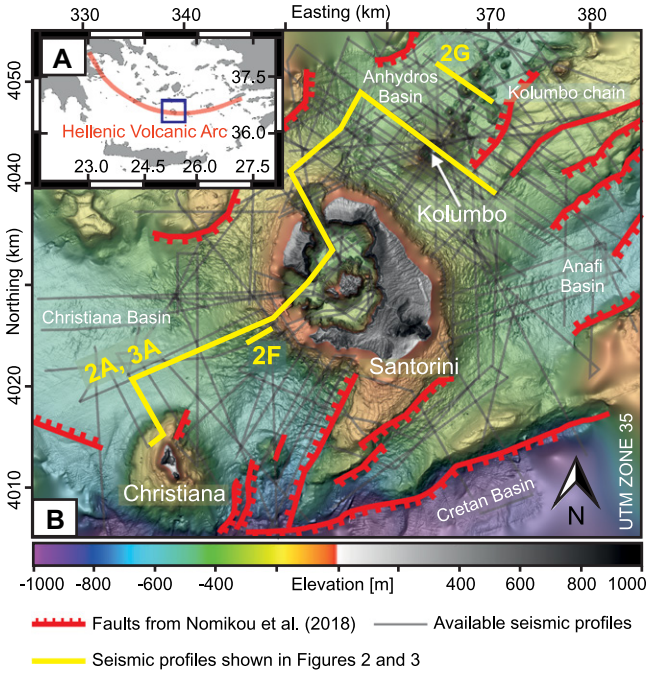


Figure 1. (A) Regional setting of the southern Aegean Sea with study area (blue box). (B) Morphological map of the Christiana-Santorini-Kolumbo volcanic field showing basins, volcanic centers, and volcanic lineaments. UTM—Universal Transverse Mercator.

with diverging reflections (for details, see the Supplemental Material[1]).

RESULTS

Stratigraphic Framework

A continuous seismic section across the CSKVF extends from the northern flank of Christiana through the Christiana Basin (markers T–V in Fig. 2A), crosses the Santorini caldera (V–X), enters the Anhydros Basin (X–Y), and covers the Kolumbo volcano (Y–Z). Two short seismic lines show additional volcanic cones from the Christiana Basin (Fig. 2F) and the Kolumbo chain (Fig. 2G).

We identify six marker horizons (h1–h6) in the Christiana and Anhydros Basins, which define the bases of six volcano-sedimentary units (U1–U6; Figs. 2B–2E). Figures 2B and 2C highlight the correlation of the marker horizons and seismic facies in the Christiana and Anhydros Basins. The uppermost unit (U6) comprises several high-amplitude subparallel reflections (Fig. 2E). While U6 is rather thin in the Christiana Basin (Fig. 2D), it forms a ~350-m-thick wedge northeast of Santorini (Fig. 2E), which pinches out toward the northern caldera breach and thins out toward the Anhydros Basin (Fig. 3A). Unit U5 is a well-stratified unit traceable throughout the whole study area with an approximately constant thickness (Figs. 2B and 2C). The underlying unit (U4) is weakly reflective, shows wavy top reflections in both basins, and has a distinct internal reflection in addition to some scattered reflections (Figs. 2B–2D). Units U2 and U3 consist of closely spaced reflections locally interrupted by several larger chaotic or transparent subunits (Figs. 2D and 3A). The lowermost unit (U1) has low-amplitude reflections; it is thick in the Christiana Basin but thin and hardly detectable in the Anhydros Basin (Fig. 3A). Deposits within the Santorini caldera are related to the Minoan eruption and the post-Minoan activity of the Kameni islands (Johnston et al. 2015).

Interpretation of Volcanic Features

Our seismic data reveal an abundance of volcanic features intercalated within different stratigraphic units of the Christiana and Anhydros Basins (Fig. 3A). In the western part of the profile, the flank of Christiana is defined by horizon h3, which represents a major onlap surface (Fig. 2D). There are several prograding reflections beneath h3 that are high amplitude and of positive polarity, indicating a high acoustic impedance (Fig. 2D). Based on these observations, we interpret them as talus deposits or lava flows from the Christiana edifice, which is consistent with the observation of westward-dipping lava flows of onshore Christiana (Puchelt et al., 1977).

Within unit U3, we identify a large subunit in the eastern Christiana Basin of Santorini (between the dotted blue lines in Fig. 2D). This subunit consists of several wavy and low-amplitude reflections (Fig. 2D), is ~150 m thick at the foot of Santorini, and thins toward the Christiana Basin. The wavy top and internal reflections are typical for volcanoclastic density-flow deposits, suggesting that this layer consists of volcaniclastics deposited by multiple eruptions (Pope et al., 2018). We observe anomalously high-amplitude reflections at its base (Fig. 2D), beneath which the reflections are very weak, implying pronounced signal attenuation. Hence, we tentatively interpret these reflections as sills or lava flows (Jackson, 2012; Bischoff et al., 2019), which form a volcanic center, hereafter referred to as the "Poseidon center" west of Santorini.

Unit U4 (Figs. 2D and 3A) is a thick, widespread, and weakly reflective deposit, which has been described by Tsampouraki-Kraounaki and Sakellariou (2018) in the Christiana Basin and interpreted as a volcanoclastic density-flow deposit. The chaotic internal seismic facies, however, also resembles that of debris-avalanche deposits (Watt et al., 2021). Given the distribution in both the Christiana and Anhydros Basins, the source for this deposit must have been located somewhere close to present-day Santorini.

Unit U6 comprises several pyroclastic deposits from the Thera Pyroclastic Formation. This is best visible at the northern caldera breach, where the thick wedge of alternating low-amplitude, chaotic, and wavy reflections is typical for pyroclastic deposits (Karstens et al., 2013; Pope et al., 2018) and resembles the stratified flanks of the caldera cliffs of the Santorini caldera (Fig. 2E) (e.g., Druitt et al., 1999). Like Piper et al. (2007), we find only a comparably thin cover of Thera Pyroclastic Formation deposits in the Christiana Basin (Fig. 2D).

The Kolumbo volcano dominates the bathymetry of the Anhydros Basin. The lowermost units K1 and K2 are within our unit U3, with K2 making up the largest part of the entire edifice (Fig. 3A). We identify a small, weakly reflective subunit between units K1 and K2, which we interpret as a mass-transport deposit. Unit K3 represents a smaller unit from Kolumbo that is intercalated within our stratified unit U5. Above that, unit K4 is a larger unit of Kolumbo, which is located within our unit U6. The most recent Kolumbo unit (K5), from the A.D. 1650 eruption, lies on top of our unit U6 (Fig. 3A).

Figures 2F and 2G illustrate previously unknown cones west of Santorini (Fig. 2F; *Aspronisi cones*) and from the Kolumbo chain (Fig. 2G), which strongly resemble other seismically imaged volcanic cones from different regions (e.g., Weiß et al., 2015; Bischoff et al., 2019). Onlap terminations indicate that there are relative age differences between these cones, yet all of them are within unit U5, as is unit K3 from Kolumbo (Fig. 3A).

DISCUSSION

The detail at which we can resolve volcanic structures and deposits depends on the vertical seismic resolution (~4–9 m), which means subresolution layers that would be obvious in the field cannot be resolved seismically. Further, minor volcanic centers could be missed depending on the survey layout. To overcome this limitation, extensive and costly three-dimensional seismic surveying would be required. Nevertheless, our

[1]Supplemental Material. Acquisition and processing parameters, as well as velocity, thickness, and age estimation. Please visit https://doi.org/10.1130/GEOL.S.16624534 to access the supplemental material, and contact editing@geosociety.org with any questions.

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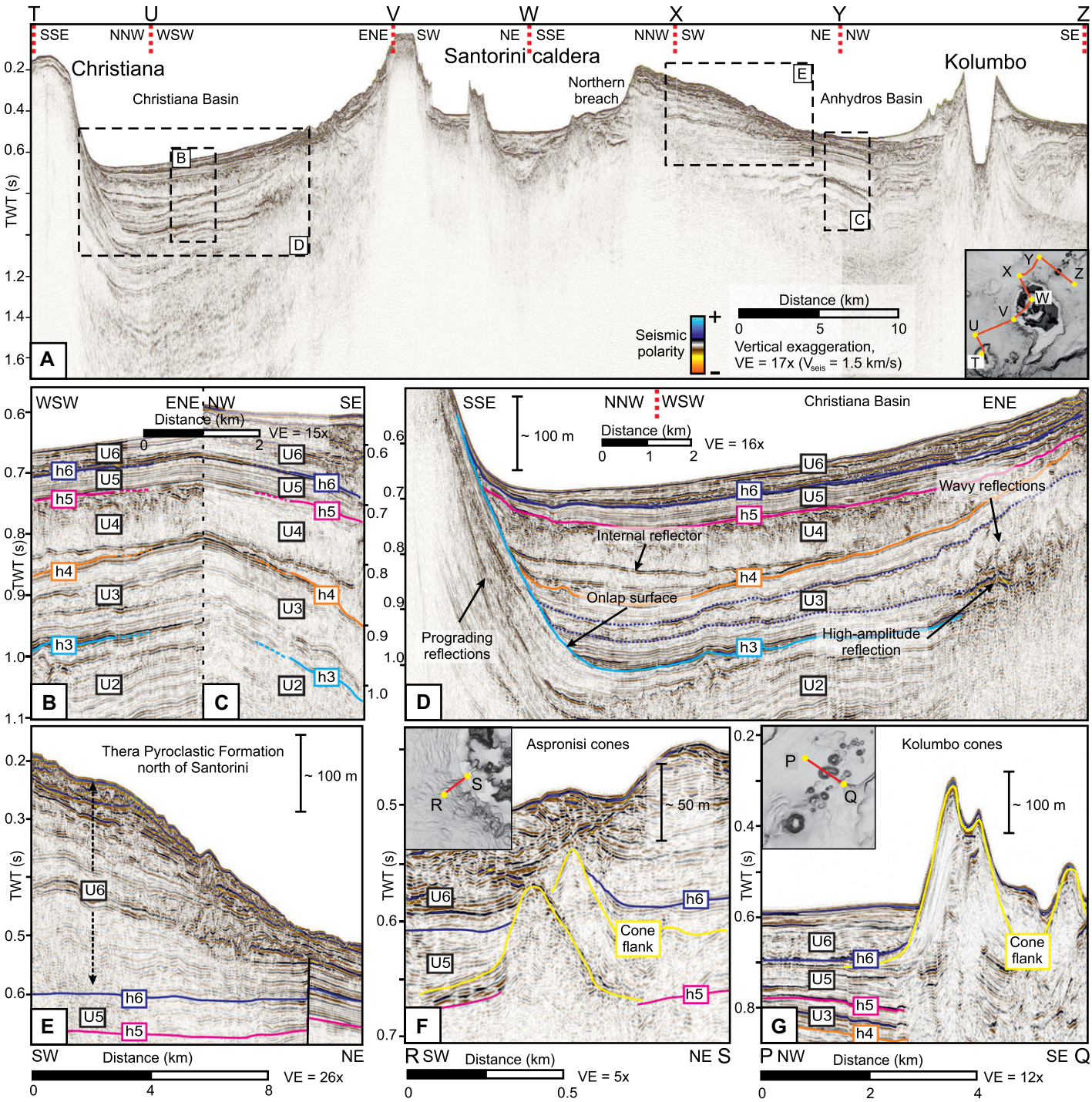


Figure 2. (A) Seismic profile connecting volcanic centers of the Christiana-Santorini-Kolumbo volcanic field. For location, see inset map and Figure 1. (B–E) Enlargements highlight stratigraphic correlation of the upper units of the Christiana (B) and Anhydros Basins (C), the internal architecture of Christiana Basin (D), and the northeastern flank of Santorini (E). (F,G) Additional seismic lines show Aspronisi cones (F) and examples of cones from the Kolumbo chain (G). TWT—two-way traveltime; V_{seis}—seismic velocity; h3–h6—marker horizons; U2–U6—volcano-sedimentary units.

seismic network is sufficiently dense to identify major volcanic centers (Fig. 1B).

Figure 3B illustrates the chronology of the volcanic features from the CSKVF. While the relative chronology is validated by the correlation of horizons in the Christiana and Anhydros Basins (Figs. 2B and 2C), absolute ages are subject to uncertainty due to lateral thickness variations and the assumption of a constant sedimentation rate, and they need to be tested by scientific drilling. Yet, our estimates are in good agreement with age constraints from previous studies. Our age estimate of ca. 0.35 Ma for horizon h6 agrees well with the onset of the Thera Pyroclastic Formation, while ca. 0.7 Ma for horizons h5 and h4 roughly corresponds to the onset of the Akrotiri volcano (0.65–0.55 Ma; Druitt et al., 1999). The estimated age of ca. 1.2 Ma for the Poseidon center roughly fits with age estimates from Seward et al. (1980) for a rhyodacitic tuff (dated at ca. 1 Ma) that discordantly underlies the products of Akrotiri onshore Santorini. Horizon h1 is the only stratigraphic marker that can be correlated with Deep Sea

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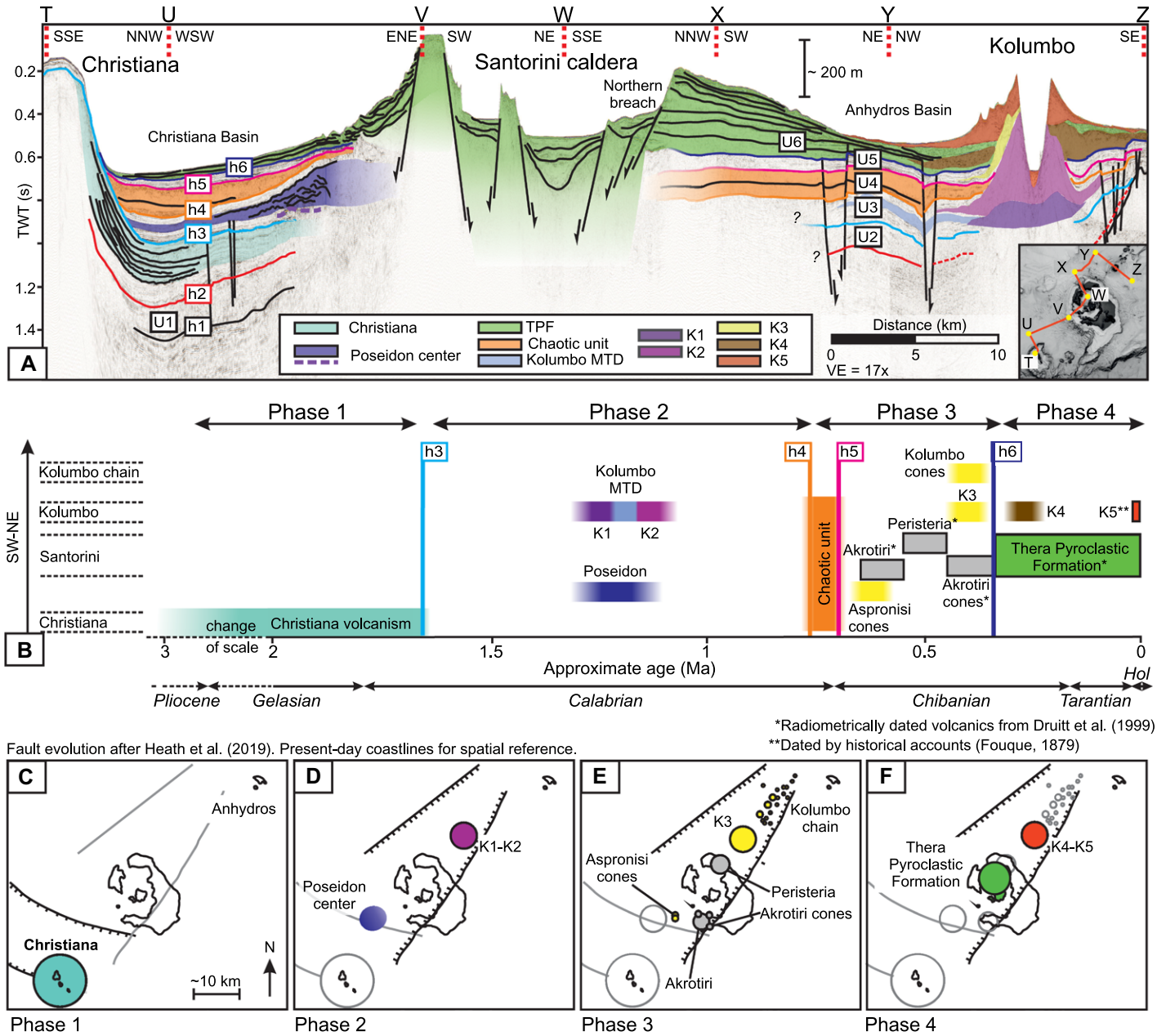


Figure 3. Interpretation of the seismic profile from Figure 2A. TWT—two-way traveltime; h1–h6—marker horizons; U1–U6—volcano-sedimentary units; TPF—Thera Pyroclastic Formation; MTD—mass transport deposit; K1–K5—Kolumbo units; VE—vertical exaggeration. (B) Schematic illustration of the chronology of volcanism at the Christiana-Santorini-Kolumbo volcanic field (CSKVF). Hol—Holocene. (C–F) Sketches of spatial distribution of the four main phases of volcanic evolution of CSKVF.

Drilling Project Hole 378 in the Cretan Basin (south of Santorini) (Shipboard Scientific Party, 1978), where it corresponds to the top of the Messinian. This is in agreement with our age estimate of ca. 5.4 Ma and interpretations of previous studies (Piper et al., 2007; Hübscher et al., 2015). There are no direct age constraints for horizons h2 and h3, but our framework suggests ages of ca. 3.4 Ma (h2) and ca. 1.6 Ma (h3).

We define four distinct phases of volcanic activity, which we relate to the tectonic model of the CSKVF from Heath et al. (2019). Phase 1 initiated during the late Pliocene with the formation of the Christiana volcano as a consequence of the intersection of the Miocene–Pliocene east-west–oriented fault regime and an emerging southwest-northeast–oriented fault system (Fig. 3C) initiating the rifting that shaped the basin system east of Santorini (Fig. 1B) (Hübscher et al., 2015; Nomikou et al., 2018). Given that the volcanic deposits from Christiana are intercalated within large parts of unit U2, the evolution of the Christiana volcano must have taken place over several hundreds of thousands of years. This phase terminated after horizon h3 at ca. 1.6 Ma, which fits well with the early Christiana series from Piper et al. (2007). However, in contrast to Piper et al. (2007), we do not see evidence for a second phase of activity from Christiana.

During the next volcanic phase (phase 2), the southwest-northeast–striking fault trend became the main pathway for magma ascent, which resulted in a southwest-northeast alignment of volcanism connecting the Poseidon center with the center of early Kolumbo (units K1 and K2; Fig. 3D). This volcanic lineament is roughly parallel to the present-day Kameni and Kolumbo lines, which are considered to be rooted on deep-seated extensional faults focusing magma emplacement (Heath et al., 2019; McVey et al., 2019). Our results agree with the long Kolumbo chronology from Hübscher et al. (2015).

The subsequent emplacement of the chaotic unit U4 at ca. 0.7 Ma occurred prior to volcanic

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phase 3 and is interpreted to be the result of large-scale mass-wasting or pyroclastic-flow events or a combination of both sourced from proto-Santorini. Afterwards, volcanism occurred across the whole rift system, extending from the newly discovered Aspronisi cones to the Kolumbo volcano (unit K3) and the Kolumbo chain (Fig. 3E). Approximately contemporaneously, the Akrotiri rhyolitic centers (0.65–0.55 Ma), the Peristeria stratovolcano (northern Santorini) (0.55–0.45 Ma), and the monogenetic cinder cones at Akrotiri (0.45–0.34 ka) erupted, these being the earliest-dated onshore activity on Santorini (Druitt et al., 1999). The existence of a field of monogenetic centers (cones of Aspronisi, Akrotiri, and Kolumbo chain) in between polygenetic centers (Akrotiri, Peristeria, Kolumbo K3) is a notable feature of phase 3.

The fourth and ongoing phase (phase 4) has seen a distinct shift in the volcanic behavior of the CSKVF as volcanism concentrated between the Kameni and Kolumbo lines (Fig. 3F). This ongoing phase has been characterized by tomographic observations from McVey et al. (2019), who revealed a low-velocity anomaly at 2.8–5 km depth below the northern caldera basin, which terminates northwest of Kolumbo. McVey et al. (2019) suggested that this zone is bounded by volcano-tectonic lineaments that provide pathways for melt to reach the surface. Our results indicate that this lineament represents a long-lived feeder system that has been active for as long as ~1.2 m.y., underlining the fundamental tectonic control of volcanism in the CSKVF.

IMPLICATIONS

For the first time, we establish the relative chronology of CSKVF volcanism, which complements onshore dating back to the Pliocene. We reconstruct the waxing and waning of volcanic centers of the CSKVF and show that these local centers matured only recently to form the vast Santorini edifice. This study highlights the potential of seismic reflection surveying to provide detailed insights into the spatio-temporal evolution of complex volcanic systems, even in an area as well studied as Santorini. Such detailed information is crucial for reconstructing eruption frequencies and for defining hazard scenarios, which are key for more reliable risk assessment. Given its comparably small extent and number of volcanic centers, the Hellenic volcanic arc offers the unique opportunity for a complete spatio-temporal reconstruction of an entire arc system. Extending our framework to the greater Hellenic volcanic arc centers should be a focus of future research.

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