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**DISTRIBUTION OF TEPHRA FROM THE 1650 AD
SUBMARINE ERUPTION OF
KOLUMBO VOLCANO, GREECE**

**BY
SARAH A. FULLER**

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTERS OF SCIENCE
IN
OCEANOGRAPHY**

UNIVERSITY OF RHODE ISLAND

2015

MASTER OF SCIENCE THESIS
OF
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UNIVERSITY OF RHODE ISLAND
2015

Abstract

Kolumbo submarine volcano, located 7 km northeast of Santorini in the Aegean Sea, last erupted in 1650 AD resulting in significant coastal destruction from tsunamis and about 70 fatalities on nearby Thera from gas discharge. Pyroclastic materials were reported as far south as Crete and as far northeast as Turkey. Tephra from the 1650 AD submarine eruption has been correlated in sediment box cores using a combination of mineralogy and major element composition of glass shards. The biotite-bearing rhyolite of Kolumbo can be readily discriminated from other silicic pyroclastics derived from the main Santorini complex. In general, the tephra deposits are very fine-grained (silt to fine sand), medium gray in color, and covered by ~10 cm of brown hemipelagic sediment. This corresponds to an average background sedimentation rate of 29 cm/kyr in the area. The distribution of the 1650 AD Kolumbo tephra covers at least 446 km² around the crater, nearly 5 times the approximated 97 km² previously inferred from seismic profiles on the volcano's slopes and in adjacent basins. Despite the expansion of the inferred deposition area, the estimated eruption volume is not enlarged significantly, and therefore remains a minimum estimate, because the box cores did not penetrate the bases of the tephra units. SEM images reveal particle morphologies attributed to multiple fragmentation mechanisms, including primary volatile degassing and phreatomagmatic activity. It is likely that phreatomagmatic activity became more important in the latter stages of the

eruptive sequence when eruptions column broke the surface and a small ephemeral island was formed.

We suggest that after the generation of a significant fine ash fraction during submarine and subaerial stages of explosive volcanism, the fines are efficiently removed from the vent area and transported by several mechanisms: (1) dominant local winds; (2) surges over the sea surface from subaerial eruption column collapse; (3) vertical gravity currents driven by Rayleigh-Taylor instabilities; and, (4) sediment gravity flows driven by submarine eruption column collapse. The fine-grained marine tephra deposits surrounding Kolumbo represent the complement to the very fines-poor proximal pumice sequence exposed in the crater walls.

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I would like to thank to my advisor and mentor, Steve Carey, for his expertise, guidance and patience through my time at the Graduate School of Oceanography. His ability to both appreciate and laugh at my obsession with detailed organization and his skill for reminding me of the bigger picture has been matched by no other.

I would also like to thank Kat Cantner for her artistic help in creating several of the key figures (Figures 1 & 15), as well as for being a valuable sounding board during the final stages of editing.

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Finally, thank you to my family and friends who have woven through GSO with me. I am forever indebted to you all for keeping my spirits high and reminding me that research is best accompanied with a smile.

Preface

This thesis is an integrated analysis of the 1650 AD eruption of Kolumbo submarine volcano, Greece. An abstract pertaining to the initial findings of this research was presented at the American Geophysical Union (AGU) fall meeting in 2013 under the title “Distribution of tephra from the 1650 AD submarine eruption of Kolumbo volcano, Greece”.

This thesis is presented in manuscript format and has been completed with the intention of submission to the Journal of Volcanology and Geothermal Research.

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**Distribution of tephra from the 1650 AD submarine eruption of
Kolumbo volcano, Greece**

by

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is formatted for submission to

Journal of Volcanology and Geothermal Research

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1. Introduction

In 1650 AD, the previously undocumented submarine volcano Kolumbo, erupted explosively and breached the surface (Fouqué, 1879). Over the course of four months, submarine and subaerial activity occurred at the volcanic center, located only 7 km northwest of the island of Santorini, Greece. Impacts on the surrounding communities included widespread pumice rafts, ash falls, tsunamis, and the deaths of approximately 70 people from the release of toxic gases (Fouqué, 1879; Vougioukalakis *et al.*, 1996; Vougioukalakis, 1996). The modern threat of such hazards is evidenced by recent seismic studies and active hydrothermal venting at Kolumbo, indicating the presence of a 5 km deep magma chamber beneath the crater (Bohnhoff *et al.*, 2006; Sigurdsson *et al.*, 2006; Dimitriadis *et al.*, 2010; Nomkiou *et al.*, 2012b). The 1650 AD submarine eruption provides an ideal opportunity to study processes of subaqueous explosive volcanism because of the relatively young deposits, reliable historic accounts (Fouqué, 1879), and recent remotely operated vehicle exploration of the vent area (Carey *et al.*, 2011; Cantner *et al.*, 2014).

The processes by which products of explosive volcanic eruptions are dispersed in the submarine environment are poorly understood owing to the limited number of direct observations. Consequently, proposed mechanisms for transport and deposition of this type of material are inferred by studying

deposits in the geologic record (*e.g.* Cashman & Fiske, 1991), theoretical predictions based on first order models (*e.g.* Head & Wilson, 2003), and analogue laboratory experiments (*e.g.* Allen *et al.*, 2008). In particular, fine tephra generated by submarine explosive eruptions can be transported in a variety of ways, including fallout, sediment gravity flows, and vertical gravity currents. Studies of proximal vent sequences (*eg.* Allen & McPhie, 2000; Fiske *et al.*, 2001; Cantner *et al.* 2014) have noted significant fines depletion. In this study, we investigate the distribution and transport mechanisms of fine ash from the 1650 AD Kolumbo eruption using 59 box and gravity cores on the flanks and in the craters of both Santorini and Kolumbo volcanoes, collected during the 2006 *R/V Aegeao* expedition. Tephra is correlated between cores using a combination of petrographic and geochemical data.

Updated tephra deposit isopachs are used to refine estimates of erupted volumes for the 1650 AD eruption (Vougioukalakis *et al.*, 1996; Nomikou *et al.*, 2012a), including previously unknown submarine flows and deposits. The results offer a comparison of fine-grained tephra distribution in a submarine environment versus the better-understood subaerial environment. Interpretation of the fractionation and transport of fine tephra from the 1650 AD eruption contributes to an enhanced understanding of Kolumbo's eruptive behavior, proposed eruption model, and the distribution of similar material at other submarine volcanoes with highly explosive activity.

2. Geologic Setting of Kolumbo

Kolumbo submarine volcano is located in the Hellenic Volcanic Arc of the eastern Mediterranean between Greece and Turkey (Figure 1). The Hellenic Volcanic Arc is separated from the Hellenic Sedimentary Arc by the Cretan Basin, a back-arc molassic basin (Kiliyas *et al.*, 2013). The volcanic arc, active from 5 Ma to the present, has developed in the thinned pre-Alpine to Quaternary continental crust of the Hellenic Subduction System (Papanikolaou, 1993; Royden & Papanikolaou, 2011). Kolumbo is at the southern end of the Cycladic Group in the Hellenic Subduction System, formed by subduction of the African Plate beneath the Aegean microplate (Le Pichon & Angelier, 1979). The major volcanic centers are aligned along NE-SW trending fault lines.

Within the Cycladic Group, Kolumbo lies in the transtensional Anhydros basin that is bordered and dissected by normal faults extending to the northeast, forming a neotectonic graben (Nomikou *et al.*, 2013). It is part of the Santorini volcanic field, dominated by a deep-seated NE-SW volcano-tectonic line (Sakellariou *et al.*, 2010). The Santorini volcanic group comprises three distinct volcanic structures: Christiana to the southwest, Santorini in the middle, and Kolumbo, 7 km to the northeast (Nomikou *et al.*, 2012b). *P* and *S* wave seismic velocity studies indicate the existence of a magma chamber 5 km beneath Kolumbo that is separate and distinct from the deeper magma

reservoir beneath the main island of Santorini (Bohnhoff *et al.*, 2006; Dimitriadis, 2010).

Kolumbo is the largest and most active of the identified submarine volcanic centers northeast of Santorini, the remainder of the field extends northeast for approximately 20 km. It is a linear grouping of over 20 individual submarine cones, which diminish in size and height further away from Kolumbo to the northeast (Nomikou *et al.*, 2013).

The shallowest point on Kolumbo's crater rim is 18 m below sea level and the center of the crater is 505 m deep. The cone is 3 km wide and the crater is approximately 1500 m in diameter (Nomikou *et al.*, 2013). Seismic reflection profiles show two cone-like volcanoclastic sequences, interpreted as the evolution/construction of Kolumbo volcano from at least two eruptive periods (Huebscher *et al.*, 2006; Bohnhoff, 2006). Layered or massive lavas form the base of the cone and the upper section is composed of tephra deposits produced during the 1650 AD eruption (Nomikou *et al.*, 2013; Cantner *et al.*, 2014). Post-eruption mass wasting events have created scalloped, knife-edges along the crater wall (Carey *et al.*, 2011).

In 2006, active hydrothermal vents were discovered in Kolumbo's center with massive sulfide deposits and highly diverse microbial communities (Sigurdsson *et al.*, 2006; Kiliyas *et al.*, 2013). The sulfide deposits, uniquely enriched in Sb, Tl, and Hg, do not conform geochemically to traditional volcanic-associated massive sulfide deposits. Instead, the deposits represent

a new hybrid active analogue style of epithermal volcanic-associated massive sulphide mineralization (Kiliyas *et al.*, 2013).

Vents discharge high temperature fluids at ~220°C with bubbles composed of ~99% CO₂ (Sigurdsson *et al.*, 2006; Carey *et al.*, 2013). The dissolution of the gases contributes to a highly stratified, acidic crater water column with bottom conditions as low as pH 5 (Carey *et al.*, 2013). The sequestered CO₂ in the crater has lead to the accumulation of acidic water and the potential for gas release at the surface if the water is overturned (Carey *et al.*, 2013).

3. The 1650 AD Explosive Eruption of Kolumbo

Historical accounts of the 1650 AD eruption were compiled by Ferdinand A. Fouqué in the 1879 publication *Santorini et ses eruptions*. Beginning in 1649 AD, Santorini regularly experienced violent earthquakes, worsening in March 1650 AD. The earthquakes were correlated to activity at Kolumbo on 27 September 1650 AD when shaking was accompanied by “clouds of dense smoke and flame[s]” rising from the sea (Fouqué, 1879). A subaerial edifice formed from which incandescence and flames were regularly observed. On 2 October 1650 AD, green seawater indicated foreign materials were dissolved in the water. The seawater did not return to its pre-eruption color until after 6 December 1650 AD (Fouqué, 1879).

Eruption columns repeatedly grew, “blotting out the entire sky”, and collapsed. Eruption column collapse likely would have caused pyroclastic flows and surges that could have traveled over the sea surface. Modern analogues like Krakatau in 1883, show that the surges flowing over the sea surface present a life-threatening hazard for nearby communities (Sigurdsson *et al.*, 1991; Nomikou *et al.*, 2013).

Continuing for four months, earthquakes, sky-darkening eruption columns, toxic gas clouds, pumice rafts, and tsunamis characterized the eruption. Hundreds of heads of cattle and ~70 people perished on Santorini as a result of toxic gases. The eruption culminated on 7 December 1650 AD, but signs of high temperatures and weak shocks lasted for several years (Fouqué, 1879).

Notably, Fouqué’s terminology is indicative of robust ash production during the 4-month eruption. The words “cloud”, “smoke”, “lightning”, and descriptions of green, yellow, or red water color, are likely related to high ash content. The only direct descriptions of discrete ash falls are from accounts at vineyards to the northeast in Anatolia, modern Turkey, a minimum distance of ~200 km from Kolumbo. A significantly high ash plume would be necessary to reach such distances (Carey & Sparks, 1986). Fouqué repeatedly references darkness and lightning during the 4-month eruption, reflective of dense ash content in the atmosphere. A bimodal distribution of ash plumes heights is associated with lightning, peaking at 7 – 12 km and 1 – 4 km (McNutt &

Williams, 2010). The former are similar to heights of typical water-associated thunderstorms, and the latter suggests major factors contributing to electrical activity originating at the vent site (McNutt & Williams, 2010).

Cantner *et al.* (2014) used historical accounts, stratigraphic observations from the crater walls, and geochemical/petrologic analyses to build a two-phase eruption model of the 1650 AD Kolumbo eruption. In this model, the first phase was almost completely submarine, driven by primary degassing that generated stable submarine eruption columns, which produced laterally continuous, well-sorted fallout deposits. A second phase was dominated by deposition from numerous sustained hybrid submarine/subaerial plumes in which fallout choked the water column and produced vertical density currents (Cantner *et al.*, 2014).

Recent seismic profiles of the basins surrounding Kolumbo reveal a conservative estimate for the pyroclastic deposits from 1650 AD to be about 5 km³ bulk volume or 2 km³ dense rock equivalent, assuming an average thickness of 50 m over an area of 97.4 km² (Nomikou *et al.*, 2012a). Thick (>200 m) pumice outcrops derived from the 1650 AD eruption on the crater rim represent the proximal facies of the erupted products and are believed to be a modern analogue for the uplifted, fines-depleted Yali pumice (Greece), whose components and lithofacies are a well-preserved subaqueous pumice breccia (Allen & McPhie, 2000). Pumices from the crater wall are generally crystalline-poor, well-vesiculated, high-K rhyolite with SiO₂ contents ranging from 73.7 to

74.2 wt.% (Cantner *et al.*, 2014). Petrographic analysis of the deposits identify the major mineral phases as plagioclase (7%), biotite (2%), and <1% magnetite, orthopyroxene and amphibole (Cantner *et al.*, 2014). Volcanic ash that is produced by explosive eruptions of nearby Santorini volcano do not contain biotite, indicating that the presence of biotite in marine ash layers uniquely identifies its source as Kolumbo (Druitt *et al.*, 1999).

4. Methods

In spring 2006, the Graduate School of Oceanography at the University of Rhode Island (URI-USA), the Department of Geology & Geoenvironment of University of Athens (NKUA-Greece), the Hellenic Centre for Marine Research (HCMR-Greece), the Institute of Geology and Mineral Exploration (IGME-Greece), and the Institute for Exploration (now, Ocean Exploration Trust) collaborated in an oceanographic expedition (AEG01, or “Thera Exploration 2006”) that investigated the region surrounding the Santorini volcanic complex, including Kolumbo submarine volcano, aboard the *R/V Aegeao*. Geologic samples collected during the expedition include 48 box cores and 18 gravity cores. All samples are curated at the Marine Geological Samples Lab (MGSL) at the Narragansett Bay Campus.

4.1 Core location and recovery

Core distribution was chosen to cover roughly 1278 km² around Kolumbo (Figure 2). Recovered gravity cores with polycarbonate liners were capped on both ends, transported to and split at the MGSL, then stored at ~5°C. While aboard the *R/V Aegaeo*, 12 cm diameter polycarbonate push cores were taken within the box cores. Cores were then capped on both ends, transported to and split at the MGSL, then stored at ~5°C.

4.2 Sedimentological and petrographic analyses

Sediment core examination and sampling was carried out using the core lab facilities of the MGSL. Core segments were described, photographed, and analyzed with a multisensor whole core logger (MSCL) for P-wave velocity, density, magnetic susceptibility, and resistivity.

Petrographic work on tephra samples used a Zeiss Axioscope microscope to determine the component abundances in smear slides from the tephra deposits. Samples from visible volcanic deposits were hydraulically sieved to < 63µm, 63 – 150 µm, and >150 µm, then made into smear slides for petrographic analysis.

Coarse-grained pumices were examined for mineralogical contents using a stereoscope.

4.3 Grain size analysis

A maximum average grain size was calculated for seven cores adjacent to Kolumbo's crater. In each core, the five largest individual grains found in the deposits were hand picked and the longest axis was measured. The maximum grain size and maximum average grain size were then recorded for each core.

Bulk grain size was determined for sixteen samples adjacent to Kolumbo's crater using a Malvern Mastersizer2000 and a Hydro2000G sampler-handling unit. The Mastersizer2000 laser diffraction-based particle size analyzer determines the size, sorting, and other granulometric characteristics based on the Fraunhofer approximation (opaque, disc-shaped particle). Sample preparation included: dissolution of carbonate with 1 N acetic acid, removal of grains >1000 μm by wet sieving, disaggregation with sodium hexametaphosphate (4 g/L), and sonication . The stirrer and pump on the Hydro2000G were set to maximum limit in the Standard Operating Procedures to ensure complete suspension of the largest grains during analysis. The Mastersizer2000 software calculated statistical parameters by the method of moments.

4.4 Electron microprobe analysis

Major elements were determined in deposit glasses using the Cameca SX-100 electron microprobe (EMP) at the Geological Sciences Department at Brown University following the methodology of Devine *et al.* (1995). An accelerating voltage of 15 kV, and a 10 nA beam current and 10 s count time were used. Beam diameter was set at approximately 3 μm and the Na-loss program of Nielsen & Sigurdsson (1981) was used to correct for Na-loss during analysis.

4.5 Scanning electron microscopy

Scanning electron microscope images were obtained on a JEOL JSM-5900 at the Sensors and Surface Technology Center at URI. Samples were wet sieved to $>63\ \mu\text{m}$ and mounted for SEM imaging of individual grains.

5. Correlation of Tephra Layers

Historical accounts of the 1650 AD Kolumbo eruption indicate that eruptive products were dispersed over a relatively large area of the Aegean Sea. Volcanic ash fallout occurred as far as western Turkey, $\sim 180\ \text{km}$ to the northeast, and floating pumice rafts washed ashore in Crete, $\sim 130\ \text{km}$ to the

south. Despite the young age of the eruption there has not been a systematic attempt to study the distal distribution of tephra from this event on the seafloor.

The composition and stratigraphic relation of Kolumbo eruptive products within the crater and on its proximal flanks were first studied in detail in order to reconstruct the eruptive processes of the 1650 AD event (Cantner *et al.*, 2014). Here we aim to correlate the proximal findings with the distal tephra deposits in order to evaluate the proposed eruption model and suggested depositional mechanisms. Nomikou *et al.* (2012a) published a seismic survey of the region proximal to the vent showing the distribution and thickness of pyroclastic deposits, which are assumed to be derived from the 1650 AD eruption. The deposits cover an area of about 97.4 km² with an average thickness of 50 m based on interpretation of seismic records (Nomikou, 2012a). Given the size of the survey area and the inability of the seismic profiling to detect pyroclastic deposits less than 10 m thick, box and gravity cores offer a valuable compliment to the estimates based on seismic data. The area covered by box and gravity cores is approximately 1278 km², over 13 times the area encompassed by the seismic profiling, including cores toward the western side of Santorini, and within the Santorini crater.

Submarine deposits were sampled using gravity and box cores that penetrated sediments up to 66 cm depth. There was a wide spatial distribution of sampling, but the cores were primarily from the northwest, northeast, and southeast of Kolumbo crater (Figure 3). Of the 66 box cores and gravity cores

collected, 26 contain distinct primary pyroclastic deposits capped with hemipelagic sediments. Table 1a gives the location, water depth and general characteristics of cores collected in the Kolumbo region. Ten additional cores contain evidence of reworked tephra deposits (Table 1b). The majority of the composition of the reworked, or secondary deposits, is hemipelagic and not enough material was collected to conclude direct correlation with Kolumbo deposits. The secondary deposits consists of CaCO_3 -dominated clay with various amounts of biogenic fragments (such as foraminifera, pteropods, spicules, and radiolaria) and are commonly mixed with glass grains, plagioclase, biotite, and lithics.

5.1 Facies

In general the stratigraphic character of the submarine pyroclastic deposits can be subdivided into two dominant facies: (1) massive facies, as demonstrated in 16 cores; and, (2) laminated facies, as seen in 10 cores (Figure 3). Massive deposits are generally medium gray, poorly sorted and normally graded, dominated by silt to large rhyolitic lapilli, and covered by ~10 cm of light to medium brown hemipelagic sediment. Laminated cores are similar in tephra composition, but exhibit internal layering alternating between fine-grained silt to sand and lapilli. Laminations vary in thickness from

millimeter scale to tens of centimeters. Sandy ash layers often underlie several to tens of centimeters of poorly-sorted silty ash.

Facies are additionally identified by variations in P-wave velocity down core. Massive facies exhibit relatively uniform P-wave velocities throughout the tephra deposit, represented by AEG01-53A-BC (Figure 4a). Laminated cores typically show variation in P-wave velocity with sharp decreases/increases through the tephra deposits, as represented by AEG01-20A-BC (Figure 4b).

Box cores are able to recover the sediment-water interface without disturbance and thus the most recent sediments are typically preserved.

Assuming that the top of the pyroclastic deposits represents the year 1650 AD, the thickness of the overlying hemipelagic sediment can be used to calculate the average sedimentation rate in the area. Using 26 cores, the average rate is 29 cm/kyrs +/- 10 cm. This rate is higher than typical deep-sea hemipelagic accumulation rates but not unexpected given the abundant supply of dispersed volcanic material that is continuously being eroded from nearby Santorini island.

5.2 Mineralogy

The submarine tephra of the 1650 AD eruption of Kolumbo contain a limited set of components, including: volcanic glass, lithics, hemipelagic materials, plagioclase, and biotite (Table 1a, Figure 5). Pyroxene and rutile are

rarely observed as accessory minerals. Smear slides of both hemipelagic and tephra deposits were examined for cores with sufficient fine-grained material. Depending on the length and internal structure of the core, up to 5 smear slides were analyzed for mineralogical composition. Cores with coarse grains were examined by stereomicroscope for the presence of biotite and other minerals within pumiceous clasts. Table 1a shows the average component assemblage for the primary tephra deposits. Cores with prominent internal structures displayed some variation in relative assemblage abundances.

Volcanic glass dominates the tephra, comprising 50% - 95% of the total assemblage, complemented by small amounts of the other components. Glass is translucent to light brown, and varies in size, vesicularity, and morphology. Plagioclase is the second most abundant component and typically displays flat, bladed, or tabular crystal morphologies. Biotite is light brown and varies in size from very small single-sheeted fragments to larger grains with excellent platy cleavage. Within the crater, biotite is altered from light brown to light green. Biotite is often 3% - 5% of total assemblage, rarely < 1%, and is less common than the plagioclase component. Biotite is the most important mineral indicator in the ash because its absence or presence distinguishes the tephra from volcanics produced by the adjacent Santorini volcano (Druitt *et al.*, 1999).

Lithics are generally fine and opaque, and some appear altered. Hemipelagic material consists of biogenic clasts and fragments, and nonbiogenic clay. Biogenic clasts and fragments are dominantly pteropod

shells, sponge spicules, foraminifera, radiolaria, and diatoms. Fragments are far more common than whole tests, displaying evidence of transport with rounded edges and occasional fragments are finer than the glass. Nonbiogenic clay is often clumped and shows signs of oxidation.

5.3 Geochemistry

The origin of tephra layers in the gravity and box cores was evaluated by comparison of the glass geochemistry to samples from identified pyroclastic deposits on Santorini (Druitt *et al.*, 1999) and the Kolumbo crater wall (Cantner *et al.*, 2014). Mineralogically correlated Kolumbo deposits had glass shards from both pumices and ash analyzed for major element composition (Table 2). SiO₂ contents range from 74.3 to 75.5 wt. % with an average of 74.7 wt. %. When compared to previously published major element analyses, the Kolumbo crater pumice glass and distal tephra deposits clearly correlate (Figure 6). Additionally, they can be discriminated from Santorini Minoan products by generally higher contents of SiO₂ and K₂O.

Correlation of tephra deposits by geochemical and mineralogical criteria greatly expands the distribution area inferred from seismic profiling data (Nomikou *et al.*, 2012a). 1650 AD Kolumbo eruption products are correlated in submarine cores at distances up to approximately 20 km from the vent,

expanding the coverage area by a factor of nearly 5, from 97.4 km² to approximately 446.3 km² (Figure 7).

6. Grain Size Analysis

6.1 Average maximum grain size analysis

Coarse tephra deposits were dominantly found in the massive facies of the cores, although two laminated facies also contain large pumice clasts. Seven cores with coarse-grained massive facies have an average maximum grain size between 1.6 mm to 22.2 mm (Table 3a). The coarsest deposits were within 2.1 km of the vent site, with a maximum grain size (largest single grain) of 40.0 mm and an average maximum grain size of 22.2 mm (Figure 8a). Coarse deposits were found as far as 13.9 km to the south-southeast of the crater. At this distance, the maximum grain size is 5.0 mm and the average maximum grain size is 3.9 mm.

Two laminated cores containing layers of large pumice lapilli have an average maximum grain size between 4.8 mm to 6.2 mm (Table 3b). Coarse grains recovered from laminated facies were found in basins up to 12.9 km from the center of the crater to the northeast (Figure 8a). At 12.9 km to the north-northeast, the maximum grain size reaches 8.0 mm and the average maximum grain size was 6.2 mm.

The maximum size of grains decreases in all directions away from the crater (Figure 8a) without any preferential direction as might be expected if the distribution was controlled solely by atmospheric dispersal and fallout. This result may suggest that sediment transport is influenced by both fallout and sediment gravity flow processes.

6.2 Bulk grain size analysis

Cores with massive facies have median grain sizes ranging from 12.3 to 65.4 μm with an average median grain size of 24.8 μm for 5 samples (Table 4a, Figure 8b). Values of inclusive mean size range from 4.50 Φ to 6.52 Φ with an average mean size 5.96 Φ for 5 samples. The massive facies are generally poorly sorted, as determined by values of inclusive graphic standard deviation, which range from 1.77 to 2.30 Φ . The facies exhibit coarse skewed to strongly coarse skewed, mesokurtic to platykurtic grain size distribution curves based on skewness values of -0.13 to -0.36 and kurtosis values of 0.90 to 0.94 Φ , indicating normal distribution of sorting with some better sorting in the tails than central portion of the distributions.

Within the 7 laminated submarine sediment cores, the bulk grain size analysis of 11 individual layers show mass median diameters ranging from 13.9 to 186.4 μm with average median grain size of 60.9 μm (Table 4b, Figure 8b). Values of inclusive mean size range from 2.56 Φ to 6.58 Φ with an

average mean size 4.90 Φ . The laminated facies are generally poorly to very poorly-sorted, as determined by values of inclusive graphic standard deviation, which range from 1.21 to 2.45 Φ . The facies exhibit near coarse skewed to very coarse skewed, mesokurtic to very leptokurtic grain size distribution curves based on skewness values of -0.12 to -0.50 and kurtosis values of 0.88 to 1.67 Φ , indicating some normal distribution of sorting.

Overall, the bulk tephra deposits exhibit three types of grain size distributions: unimodal fine, unimodal coarse, and laminated unimodal fine and unimodal coarse (Figure 9). The occasional weak bimodal distribution (Figure 9a, Figure 9b) is attributed to the poor to very poorly-sorted characteristic of the deposits. There is no clear relationship between the total grain size distribution and distance from the crater (Figure 10). Fine material is located at all distances from the crater with no clear preference for distal deposits, while sandy samples show a slight preference for distal deposits. Additionally, while a fine-grain tephra layer is often observed capping the tephra unit in distal deposits, it is not observed uniformly.

7. SEM Imaging of Tephra Particles

The shapes of volcanic ash particles are used to interpret the physical properties of an erupting magma and its volatile content, as well as the degree

of magma/water interactions. A single eruptive event can be driven by both the release of magmatic volatiles and explosive magma-water interactions. Therefore, identification of volcanic ash morphologies by SEM is important for interpretation of explosive eruption phenomena and can give clues about pyroclast transport mechanisms.

For this study, ash grains were wet sieved to $> 63 \mu\text{m}$ and then scanned by electron microscopy (SEM). From these SEM images, four dominant pyroclast morphologies were identified: (1) vesicular, irregular shapes; (2) very fine, platy, vesicle wall shard fragments; (3) pipe vesicular, elongate shapes; and (4) blocky, equant shapes (Figure 11). All morphologies have edges showing small chips and scratches and surfaces covered with fine ($< 5 \mu\text{m}$), adhering shards, especially in vesicle cavities.

Type 1 pyroclasts are the most frequently observed morphology of coarse ash, characterized by well-developed, coalesced vesicles with surfaces controlled by fairly thin vesicle walls. There are abundant vesicle surfaces producing irregular shapes with jagged particle outlines. Occasionally, threads and ribs of glass cross the cavities after coalescence. Vesicle edges range from occasionally sharp to rounded and smooth with irregular overall grain shape (Figure 11a).

In rare instances, two stages of gas exsolution are captured in an individual grain (Figure 12). One stage of exsolution resulted in large, coalesced vesicles measuring up to $50 \mu\text{m}$ across, and $< 150 \mu\text{m}$ long. The

bubble walls show characteristic glassy quench surfaces that do not intersect the significantly smaller vesicles within the wall fabric. The wall fabric supports round, non-coalesced vesicles, as small as $< 3 \mu\text{m}$ across, which are characteristic of a separate stage of gas exsolution (Figure 12).

Type 2 pyroclasts are very fine platy vesicle wall shard fragments ($> 10 \mu\text{m}$) often found adhered to the surface or trapped within vesicle embayments of the coarse-grained ash (Figure 11b). The fractured bubble walls are very angular, consisting of curved splinters and chips that appear to have brittly fractured.

Type 3 pumice pyroclasts have highly elongate, pipe vesicles with length to width ratios greater than 30:1 (Figure 11c). They have angular grain surfaces either parallel or normal to the long axes of the vesicles. The rounded parallel ridges are collapsed vesicle walls. Many of the vesicles show considerable coalescence.

Type 4 pyroclasts are characterized by their smooth surfaces and are slightly less common than the highly vesiculated pyroclasts (Figure 11d). The equant, blocky grains have both smooth and conchoidal fracture surfaces or curved surfaces where large ovoid vesicles were broken during fragmentation. The spacing between vesicles is often $> 10 \mu\text{m}$ resulting in thick walls that are cut by the curvilinear fracture surfaces. The geometries of Type 4 grains are either pyramidal or elongate in one dimension and shortened in the other two. Occasionally, grains exhibit characteristics of both Type 1 and Type 4

pyroclasts, resulting in blocky grains with medium vesicularity, indicating a transition zone from highly vesiculated grains to equant blocky grains (Figure 13).

8. Discussion

8.1 Transport and deposition of tephra

The distribution of the 1650 AD Kolumbo ash extends over an area larger than previously inferred from seismic profiles on the volcano's slopes and in adjacent basins. The cores contain volcanic ash deposits approximately 20 km from the crater, expanding the coverage area of 97 km² inferred from seismic profiling data to approximately 446 km² (Figure 7), for an increase of about 5 times. In plan view, the deposit displays a distinct bi-lobate distribution pattern with tephra concentrated in two basins to the northeast and southeast of Kolumbo.

Atmospheric dispersal of volcanic ash is largely controlled by winds during transport and typically the resulting deposits form a uni-lobate morphology expanding in the downwind direction (*e.g.* Sigurdsson *et al.*, 1980). With few exceptions, most marine tephra fallout patterns also are dominantly controlled by atmospheric transport with some modification by currents during settling in the water column (Carey, 1997). If dispersal of the

Kolumbo tephra was driven by atmospheric transport alone, then a uni-lobate pattern of dispersal would be expected in the area downwind of the volcano, based on the eruption column height and wind strength (Carey & Sparks, 1986). Additional historical accounts of ash fall in Turkey, would suggest a dominant wind direction to the northeast during some phase of the eruption (Fouqué, 1879). The absence of tephra deposits on bathymetric highs between basins suggests that the observed bi-lobate tephra deposit did not result from variations in wind direction during the course of the eruption (Byrne, 2007).

The preferential occurrence of the volcanic ash within basins, in conjunction with sedimentological features such as laminations, suggests that emplacement was dominated by sediment gravity flows generated from submarine and subaerial eruption plumes. Additionally, the distribution of massive and laminated facies shows significant local variability that can't be explained by fallout alone. We suggest that generation of the sediment gravity flows took place by collapse of submarine eruption columns and by Rayleigh-Taylor instabilities that formed on the sea surface as subaerial fallout accumulated from parts of the columns that breached the surface.

8.1.1 Submarine eruption column collapse

Distal tephra deposits likely represent many depositional events that occurred during the four-month 1650 AD eruption of Kolumbo, causing overlapping accumulation of tephra from different phases of the eruption. While the coarsest deposits are most proximal to the vent site, coarse grain sizes are also recovered from laminated facies found in basins up to 12.8 km from the center of the crater to the northeast and approximately 19.8 km to the southeast (Table 2, Fig. 4). Because the spatial distribution does not show any patterns consistent with fallout as the primary depositional mechanism, sediment gravity flows caused by eruption column collapse are more likely responsible for the distal distribution of coarse grains.

A factor likely to affect the distribution of sediment gravity flows in the region is the slopes of the local bottom topography (Sigurdsson *et al.*, 1980). The bottom topography surrounding Kolumbo consists of a series of steep slopes, multiple small submarine cones, and 2 basins, one to the north-northeast and the second to the southeast of the volcanic center (Figure 2). Pyroclastic material is notably absent from the bathymetric highs and is dominantly recovered in basins suggesting these features exert control on the pattern of the submarine deposits (Figure 7). The slopes surrounding Kolumbo are highly variable, ranging from a very shallow 0.3° in the distal northern basin to steeper slopes of 6.8° on the southeastern proximal flanks (Figure

14). To the north, the proximal flanks are steepest at approximately 5.1° ; however, starting at approximately 400 m depth, the slope quickly decreases to about 0.3° within the basin. Another possible pathway downslope into the northern basin lies to the east of the NE-SW volcano tectonic line. Proximal slopes are steeper than to the north, at 5.4° and shallow quickly to 0.4° before steepening again to 1.1° . The proximal slopes on the southeastern flanks are initially steeper than to the north, at 6.8° , and the slope within the southeastern basin also maintains a higher gradient ranging between 0.8° and 1.5° .

The northern distal tephra deposits are comprised of both massive and laminated coarse-grained tephra showing high degrees of vesiculation and abundant platy shards capped by laminated fine-grained silty ash. The characteristics of the deposit in conjunction with the exceptionally shallow slope in the northern basin indicate that the coarse-grained tephra was likely transported by sediment gravity flow following eruption column collapse (Figure 15). The coarse-grained units lack typical sedimentological features of coarse turbidites or grain flows such as rip-up clasts or crossbedding. Such features are likely to exist at deeper levels that could not be sampled by the box corer. The coarse-grained deposits support the eruption model developed by studies of the proximal crater deposits, which indicated frequent eruption column collapses generating deposition from subaqueous gravity currents

during the submarine phase of the eruption (Carey *et al.*, 1988; Cantner *et al.*, 2014).

8.1.2 Rayleigh-Taylor instabilities

In the distal southern basin, the 1650 AD tephra deposits are fine-mode dominated, virtually ungraded, laminated ash layers. The deposits are comprised mostly of glass, with sharp bases and bioturbated tops indicating they are deposited quickly (Carey, 1997; Sigurdsson *et al.*, 1980). These characteristics suggest transport may have been dominated by vertical gravity currents formed from Rayleigh-Taylor instabilities as subaerial fine ash accumulated on the sea surface.

Vertical gravity currents form in the water as a result of convective instability in a surface boundary layer caused by increasing particle concentration just below the surface (Carey, 1997). Downward fluxing of particles in the vertically travelling plumes can occur several orders of magnitude faster than individual particle settling predicted by Stoke's law (Wienser *et al.*, 2004; Carey 1997). The increase in effective settling velocities greatly reduces the residence time of fine-grained ash in the water column and mitigates the effects of tephra redistribution by ocean currents (Carey, 1997). However, it would be expected that deposition caused only by Rayleigh-Taylor instabilities of tephra fall on the sea surface would produce "fall-out" like

deposits on the seafloor with mantling relationships on bathymetric highs. As previously discussed, this is not an observed characteristic of the deposits surrounding Kolumbo. It is more likely that Raleigh-Taylor instabilities occur close to the source where sea surface fine-grain particle concentration is highest. The vertically descending plumes would then generate fine-grained sediment flows that propagate downslope upon contact with the seafloor (Figure 15).

8.2 Volume of fine ash

Original estimates of the erupted volume of the 1650 AD event based on crater volume suggested a total of 2 km³ (Vougioukalakis *et al.*, 1996). These estimates were later modified based on regional seismic profiles. The new estimate assumed a 50 m thickness over a 97 km² distribution area, resulting in a conservative estimate of approximately 5 km³ bulk volume (Nomikou *et al.*, 2012). With our new correlation of tephra from box cores around Kolumbo, the distribution area can be greatly expanded. However, to calculate a minimum estimate for the volume of fine ash produced by the eruption, the thickness of distal deposits must be assumed. This limitation will result in an underestimate as the base of the tephra units were never penetrated by the box cores.

Without recovering the base of the tephra deposits, we know that 19 km to the SSE there is a distal thickness of at least 20.1 cm. To the northeast, a distal thickness is at least 12.5 cm at 13 km NE (Table 1a). If we use the maximum distal thickness and assume there is a layer of tephra at least 20 cm thick over the entire new distribution region (446 km²), then the minimum bulk volume estimate would increase by approximately 0.1 km³.

Despite our finding that the tephra distribution area is larger than previously thought, by a factor of 5, the thin layer of tephra recovered from the box cores does not significantly increase the total eruptive volume beyond the seismically-inferred estimates.

8.3 Fragmentation mechanisms

SEM imaging can provide insights into the fragmentation mechanisms that occur during explosive eruptions. The four pyroclastic types described were found in both depositional basins, but each reflect different eruption stages. The fine detail provided by the images of the Kolumbo tephra illustrates a variety of glass morphologies that indicate significantly different fragmentation mechanisms during the course of the eruption.

Analyses of Kolumbo's rhyolitic pumice by Cantner *et al.* (2014) showed that the magma contained a sufficient volatile content to drive subaqueous fragmentation solely by primary degassing. The SEM images depicting highly vesicular grains (Type 1) are typical of this type of fragmentation that likely

dominated the opening stages of the eruption at depths of about 500 m (Figure 11a). These fragments would have been entrained into the rising warm water column and transported laterally. The observed chips and spalled surfaces on the glass walls further support the opening stages of the eruption model, where eruption column collapse would lead to abrasion on individual particles as sediment gravity flows moved away from the vent.

Type 2 clasts (Figure 11b) are shards that exhibit curvilinear fracture surfaces that additionally suggest the vesiculating magma fragmented in a brittle fashion upon interaction with water. The very fine shards ($> 10 \mu\text{m}$) adhered to the surface or trapped within vesicle embayments of the coarse-grained ash are additional evidence of high degree of fragmentation (Heiken & Wohletz, 1985).

Type 3 SEM images (Figure 11c) show highly vesicular particles with coalesced vesicles with more elongate hollows controlling much of the brittle fracture, and as a result, many of the grains are elongate broken parallel to the foliation (Figure 11c). The degree of vesicle elongation is characteristic of vesiculating magma that has been deformed within the conduit prior to discharge on the seafloor (Heiken & Wohletz, 1985).

SEM images reveal another important glass morphology, Type 4, with characteristics such as blocky, equant, and poor vesicularity, suggesting fragmentation by energetic water-magma interaction (Wohletz, 1983; Wohletz, 1986). As shown with Type 1 particles, some vesiculation of the magma

occurred earlier than the explosive interaction with water, and thus would have facilitated efficient fragmentation of the melt (Self & Sparks, 1978). Historical accounts of the eruption indicate that the activity progressively became more shallow and in part subaerial during the course of the event. The phreatomagmatic interactions thus became more important in the late stages of the eruption as the cone grew more shallow, causing a reduction of water pressure that would have otherwise impeded the explosivity of earlier magma-water interactions (Cantner *et al.*, 2014). Most vesicle growth was suppressed and rapid mixing of magma and water under lower pressure conditions produced the blocky glass clasts. Another factor that may have contributed to more blocky clasts at later stages of the eruption is that if most volatile components were concentrated in the top of the magma chamber, a highly vesicular froth is eventually depleted as the eruption proceeds.

In rare instances, two stages of gas exsolution are captured in an individual grain (Figure 12). The first stage of exsolution results in large, coalesced vesicles measuring up to 50 μm across, and < 150 μm long. The bubble walls show characteristic glassy quench surfaces that do not intersect the significantly smaller vesicles within the wall fabric. The wall fabric supports round, non-coalesced vesicles, as small as < 3 μm across, which are characteristic of the second stage of gas exsolution (Figure 12). The second stage of gas exsolution would have occurred within the heated plastic vesicle walls after the primary vesicles were depressurized and quenched.

8.4 Fate of fine ash during submarine explosive eruptions

There is a very strong contrast between proximal vent deposits in the crater and distal tephra deposits from the 1650 AD Kolumbo eruption. The fines-depleted pumice lapilli and block deposits proximal to the vent are attributed to rapid quenching of hot clasts during frequent collapses of unstable eruption column margins (Cantner *et al.*, 2014). During these events, strong size fractionation can occur with the rapid sinking of lapilli-sized clasts and the elutriation of fine ash due to the low settling velocity in water (Allen *et al.*, 2008; Allen & McPhie, 2009; Cantner *et al.*, 2014). Until now, the fate of fine ash produced during submarine explosive eruptions has been poorly understood and difficult to document. By analyzing medial and distal deposits recovered with box cores, the transport and dispersal of the fine-grained complement to the crater walls has been more clearly defined.

After the generation of a significant fine fraction during submarine and subaerial stages of explosive volcanism, the fines are efficiently removed from the vent area and transported by several proposed mechanisms: (1) dominant local winds; (2) surges over the seafloor from subaerial eruption column collapse; (3) vertical gravity currents driven by Rayleigh-Taylor instabilities; and, (4) sediment gravity flows driven by submarine eruption column collapse (Figure 15).

According to historical accounts, the dominant wind direction was to the northeast resulting in fine ash fallout in Turkey (Fouqué, 1879). The same accounts also discuss dilute surges reaching Santorini to the southwest, although there are no known geologic deposits of the surge events. The surges were likely generated by subaerial eruption column collapse and it is possible that the generation of steam at the flow/seawater interface may have resulted in a reduction in the sedimentation of particles (Carey *et al.*, 1996).

As previously discussed, vertical gravity currents and lateral sediment gravity flows appear to be the major transportation mechanisms for fine materials into deeper water surrounding Kolumbo. The fallout of pyroclasts on the water surface leads to Rayleigh-Taylor generated density gravity currents that transport particles faster than Stokes-Law settling behavior (Carey, 1997; Fiske *et al.*, 1998). Rather than mantling the bathymetry upon contact with the seafloor, vertical gravity currents continue down-slope as sediment flows. Similarly, submarine eruption column collapses generate sediment flows that propagate downslope. Therefore, seafloor tephras show little evidence for mantling the local bathymetry and instead, fine-grained submarine eruption products are recovered dominantly in adjacent basins.

9. Conclusion

The 1650 AD eruption of Kolumbo submarine volcano in the Hellenic Arc, Greece, took place over a four-month period characterized by earthquakes, tsunamis, surges, ash fall, and asphyxiation by noxious gases that were recorded by local populations. Previous examination of Kolumbo's interior crater walls revealed well stratified deposits of fines-depleted lapilli pumice likened to the uplifted Yali sequence, approximately 100 km to the northeast (Cantner *et al.*, 2014, Allen & McPhie, 2009). It was proposed that the crater wall deposits result from subaqueous fallout and eruption column collapses and are depleted in fine pyroclastic material because of hydraulic sorting during flow movement caused elutriation of the fine material (Cantner *et al.*, 2014). In this study, the complement to the fines-depleted subaqueous pumice cone of Kolumbo was recovered using box cores from a 1278 km² survey area.

Correlation of the recovered tephra to Kolumbo's 1650 AD crater wall pumice was accomplished by petrographic and sedimentological analyses, as well as by electron microprobe analyses of the glass components. Maximum average grain sizes were calculated by hand, and bulk grain sizes were calculated using a laser diffraction-based particle size analyzer. Additionally, scanning electron microscopy was used to examine individual ash grains for

morphological evidence of fragmentation methods and for confirmation of the proposed eruption model by Cantner *et al.* (2014).

Analyses of the tephra recovered from the survey area reveal a distribution area 5 times greater than the seismically-inferred pattern, resulting in 446.3 km² of primary 1650 AD deposits. The estimated sedimentation rate for the region is approximately 29 cm/kyrs +/- 10 cm based in the amount of post-eruption hemipelagic sediment accumulation. The mineralogical and geochemical analyses clearly align the new tephra analyses to the proximal deposits of Kolumbo and confirm the tephra as the compliment to the fines depleted crater walls.

SEM images reveal that the explosive interaction between the vesiculating rhyolitic magma and sea water generated ash particle shapes that vary from highly vesicular and pumiceous to low-vesicular and equant, blocky grains or shards. The presence of two contrasting glass morphologies supports the proposed eruption model for the 1650 AD submarine eruption of Kolumbo (Cantner *et al.*, 2014). Highly vesicular grains were produced by primary degassing during the initial subaqueous phase of the eruption. The blocky equant grains were formed later on during the eruption when the vent shallowed and reduced pressure allowed for violent phreatomagmatic activity that produced frequent subaerial eruption plumes.

Preferential deposition of fine tephra within two basins to the northeast and southeast of Kolumbo, coupled with sedimentological features of the

deposits, strongly indicate that the transport of tephra from the eruption was dominated by sediment gravity flows. Some were likely generated by collapse of submarine eruption columns, whereas others are attributed to Rayleigh-Taylor instabilities, generated by fallout of tephra on the sea surface from subaerial eruption columns. The striking contrast between the very coarse lapilli deposits in the crater wall versus the fine tephra only 20 - 30 kms from the vent highlights the very effective elutriation of fine ash from coarse material during submarine explosive eruptions, likely caused by variation in settling velocities between particles in water versus air.

The new distribution pattern of the 1650 AD Kolumbo tephra enhances our understanding of tephra transport and deposition in the submarine environment. Investigation of sediments surrounding similar volcanic environments would reveal more information to further our understanding of these processes. This knowledge can eventually serve to increase estimated eruption volumes and contribute to better hazard evaluation and disaster management for explosive submarine eruptions.

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Table 1a. Characteristics of primary tephra deposits.

Core no.	Depth below seafloor (m)	Depth of primary tephra deposit (cm)	Total length recovered tephra (cm)	Distance (km) and Direction from Caldera	General Component Assemblage	Characteristic Features
AEG01-01BC	402	11.9	20.1	19.01 SSE	G + Pl + B + L + H	laminated
AEG01-02BC	528	7.9	12.6	19.97 SE	G + Pl + B + L + H	laminated
AEG01-03BC	548	14.5	9.0	19.84 SE	G + Pl + B + H + Px + R	laminated
AEG01-05BC	404	10.9	8.1	13.94 SSE	pumice w/ B	massive (coarse)
AEG01-07BC	270	10.8	8.2	8.07 SSE	G + Pl + H + L + B + Px + R	massive (fine)
AEG01-08BC	271	11.2	30.3	8.07 SSE	G + Pl + B + L + H	massive (fine)
AEG01-09BC	359	12.2	9.8	7.68 ESE	G + Pl + B + H + L	laminated
AEG01-10BC	352	3.0	12.0	8.23 ESE	G + Pl + H + B	massive (fine)
AEG01-18BC	330	10.9	9.1	10.53 WNW	pumice w/ B	massive (coarse)
AEG01-19BC	340	7.1	20.9	8.78 W	pumice w/ B	massive (coarse)
AEG01-20BC	396	14.3	20.7	5.99 WNW	G + Pl + B + L + H + Px + R	laminated
AEG01-21BC	333	0.0	20.0	4.06 WNW	pumice w/ B	massive (coarse)
AEG01-22BC	458	10.5	12.5	12.93 NNE	G + Pl + H + B + L	laminated
AEG01-23BC	465	16.3	3.7	12.81 NNE	G + Pl + B + L	laminated
AEG01-24BC	347	8.0	29.0	3.69 ENE	G + H + Pl + B + Px	massive (fine)
AEG01-25BC	319	5.4	13.1	2.69 SE	pumice w/ B	massive (coarse)
AEG01-52BC	341	13.9	23.1	4.88 SE	G + Pl + H + B	massive (fine)
AEG01-53BC	381	8.9	23.1	5.22 NE	G + Pl + B + H	massive (fine)
AEG01-54BC	400	15.1	9.9	5.18 NNE	G + Pl + B + H + L	massive (fine)
AEG01-55BC	262	3.0	22.0	2.50 NW	G + L + B + Pl	massive (fine)
AEG01-56BC	277	2.0	9.0	2.07 SSE	pumice w/ B	massive (coarse)
AEG01-57BC	297	8.5	27.5	4.63 SSW	G + Pl + L + B + Px + R + H	laminated
AEG01-58BC	365	6.0	8.0	8.03 NE	G + Pl + B + H + L	laminated
AEG01-60GC	465	11.0	8.0	12.78 NNE	G + L + Pl + B + Px	massive (fine)
AEG01-61GC	346	4.9	60.1	5.82 NE	G + Pl + L + B + Px	laminated
AEG01-66BC	502	0.0	66.0	0.00 inside	G + Pl + B + L + bacteria	massive (fine, hydrothermally altered), bacterial filaments

^G, glass; Pl, plagioclase; B, biotite; R, rutile; Px, pyroxene; L, lithics; H, hemipelagic components

*Component assemblages are given in order of diminishing contents.

Table 1b. Characteristics of secondary tephra deposits.

Core no.	Depth below seasurface (m)	Total length of core (cm)	Distance (km) and Direction from Caldera	General Component Assemblage	Characteristic Features
AEG01-04BC	510	21.0	17.24 SE	G + H + Pl + B	massive mixed hemipelagic sediment
AEG01-06BC	375	18.0	13.42 SSE	H + L + G + Pl + B + R + Px	massive mixed hemipelagic sediment, many pumices
AEG01-11BC	353	24.0	8.27 ESE	G + H + Pl + B	massive mixed hemipelagic sediment
AEG01-12BC	255	9.0	11.99 ENE	H + G + Pl + B	massive mixed hemipelagic sediment
AEG01-16BC	111	17.5	17.67 W	H + G + Pl + B	massive mixed hemipelagic sediment
AEG01-29BC	285	23.0	26.22 S	H + G + Pl + B	massive mixed hemipelagic sediment
AEG01-30BC	305	34.0	24.99 S	H + G + Pl + B + L	massive mixed hemipelagic sediment
AEG01-50BC	355	27.5	24.90 S	H + G + Pl + B + R + L	massive mixed hemipelagic sediment, many pumices
AEG01-51BC	88	13.0	18.78 S	G + H + Pl + B	massive mixed hemipelagic sediment, pumice on the surface
AEG01-59GC	458	8.0	9.38 NE	H + L + G + B	massive mixed hemipelagic sediment

[^]G, glass; Pl, plagioclase; B, biotite; R, rutile; Px, pyroxene; L, lithics; H, hemipelagic components

*Component assemblages are given in order of diminishing contents.

Table 2. Representative electron microprobe analyses of glass from Kolumbo tephra.

Sample	SiO ₂	K ₂ O	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	P ₂ O ₅	Total
09BCgrn1	73.89	3.55	0.05	13.65	1.29	0.07	0.07	0.66	1.9	0.00	95.10
09BCgrn2	71.71	3.92	0.06	13.16	1.23	0.05	0.06	0.74	3.8	0.03	94.72
09BCgrn2	72.36	4.03	0.05	13.48	1.22	0.07	0.07	0.70	4.2	-0.02	96.20
09BCgrn2	71.82	4.12	0.05	13.07	1.15	0.08	0.04	0.68	4.1	-0.02	95.09
09BCgrn3	73.20	4.14	0.07	13.81	1.05	0.09	0.07	0.86	4.4	0.01	97.65
09BCgrn4	72.22	3.90	0.08	13.56	1.19	0.11	0.07	0.72	4.4	-0.02	96.25
09BCgrn6	73.69	4.10	0.08	13.56	1.39	0.08	0.07	0.74	4.3	0.03	98.08
21BCpum1	73.98	4.56	0.07	13.60	1.16	0.09	0.06	0.66	4.1	0.04	98.30
22BCgrn1	73.19	4.13	0.05	13.58	1.22	0.11	0.04	0.68	4.4	0.01	97.36
22BCgrn2	73.39	4.00	0.04	13.52	1.25	0.14	0.06	0.69	4.2	0.06	97.39
22BCgrn3	74.40	4.05	0.08	14.37	1.30	0.10	0.07	0.87	4.6	0.05	99.94
22BCgrn4	74.10	3.99	0.07	13.73	1.21	0.05	0.05	0.74	4.4	0.02	98.38
56BCpum1	71.94	4.15	0.05	13.34	1.27	0.09	0.05	0.68	4.2	0.00	95.78
56BCpum2	71.60	4.11	0.04	13.33	1.23	0.09	0.06	0.72	4.3	0.02	95.49
56BCpum3	72.17	4.10	0.05	13.27	1.06	0.08	0.06	0.77	4.3	0.01	95.91
56BCpum4	72.12	4.16	0.06	13.51	1.23	0.09	0.04	0.66	4.3	0.02	96.14
56BCpum5	71.98	4.07	0.07	13.44	1.17	0.05	0.05	0.67	4.4	0.05	95.95
56BCpum6	72.63	3.98	0.06	13.79	1.24	0.09	0.05	0.80	4.2	0.00	96.86
*S79-81	73.8	3.36									
**EN419-25	75.04	4.08	0.06	13.22	1.16	0.09	0.05	0.91	4.79	0.03	99.43

*Representative electron microprobe analyses of glass from Santorini Minoan pumice (Druitt *et al.*, 1999)

**Representative electron microprobe analyses of glass from Kolumbo pumice (Cantner *et al.*, 2014)

Table 3. Coarse grain size analysis from (a) massive and (b) laminated facies.

Sample type	Core No.	Depth below seasurface (m)	Depth of primary tephra deposit (cm)	Total length recovered tephra (cm)	Distance (km) and direction from Caldera	Max. coarse grain size (mm)	Avg. coarse grain size (mm)
(a) Massive Facies							
	AEG01-05BC	404	10.9	8.1	13.94 SSE	5.0	3.9
	AEG01-18BC	330	10.9	9.1	10.53 WNW	9.0	7.2
	AEG01-19BC	340	7.1	20.9	8.78 W	12.0	8.6
	AEG01-21BC	333	0.0	20.0	4.06 WNW	17.0	12.2
	AEG01-24BC	347	8.0	29.0	3.69 ENE	2.0	1.6
	AEG01-25BC	319	5.4	13.1	2.69 SE	6.0	5.5
	AEG01-56BC	277	2.0	9.0	2.07 SSE	40.0	22.2
(b) Laminated Facies							
	AEG01-57BC	297	8.5	27.5	4.63 SSW	5.5	4.8
	AEG01-22BC	458	10.5	12.5	12.93 NNE	8.0	6.2

Table 4. Bulk grain size analysis from (a) massive and (b) laminated facies.

Sample type	Core No.	Depth below seafloor (m)	Depth of primary tephra deposit (cm)	Total length recovered tephra (cm)	Distance from center of crater (km)	Mass Median Diameter (μm)	Inclusive Mean (ϕ)	Inclusive Standard Deviation (ϕ)	Inclusive Graphic Skewness	Inclusive Graphic Kurtosis (ϕ)
(a)										
Massive Facies	AEG01-08BC	271	34-35	30.3	8.1 SSE	16.3	6.19	1.77	-0.23	0.93
	AEG01-24BC	347	26-28	29.0	3.7 ENE	65.4	4.50	2.30	-0.36	0.90
	AEG01-52BC	341	30-31	23.1	4.9 SE	17.1	6.14	1.78	-0.24	0.93
	AEG01-53BC	381	26-27	23.1	5.2 NE	12.3	6.52	1.77	-0.15	0.94
	AEG01-60GC	465	12-13	8.0	12.8 NNE	12.7	6.46	1.83	-0.13	0.94
(b)										
Laminated Facies	AEG01-01BC	402	19-20	20.1	19.0 SSE	75.5	3.850	1.210	-0.350	1.67
	AEG01-03BC	548	19-20	9.0	19.8 SE	23.6	5.58	2.04	-0.13	1.03
	AEG01-20BC	396	14-16	20.7	6.0 WNW	107.4	3.56	1.70	-0.44	1.64
	AEG01-20BC	396	19-21	20.7	6.0 WNW	12.5	6.47	1.81	-0.12	0.94
	AEG01-22BC	458	18-19	12.5	12.9 NNE	186.4	2.56	1.39	-0.26	1.30
	AEG01-22BC	458	14-15	12.5	12.9 NNE	13.9	6.38	1.78	-0.19	0.90
	AEG01-23BC	465	15-16	3.7	12.8 NNE	48.7	4.48	1.33	-0.31	1.59
	AEG01-57BC	297	10-11	27.5	4.6 SSW	13.6	6.40	1.88	-0.16	0.88
	AEG01-57BC	297	31-32	27.5	4.6 SSW	11.0	6.58	2.03	-0.06	0.89
	AEG01-61GC	346	46-47	60.1	5.8 NE	108.3	3.95	2.45	-0.45	0.94
	AEG01-61GC	346	54-55	60.1	5.8 NE	69.3	4.44	1.93	-0.50	1.23

Figure 1. Geologic setting of Kolumbo within the Hellenic Arc of the southern Aegean Sea.

Figure 2. Location of all box and gravity cores in relation to Santorini and Kolumbo volcanoes, as collected during the 2006 *R/V Aegeo* cruise to the Kolumbo region.

Figure 3. Distribution of massive and laminated facies of 1650 AD Kolumbo primary tephra deposits.

Figure 4. Core logging data of massive, well-sorted facies (a) and stratified ash deposits (b). Deposit data includes measurements of P-wave velocities, densities, magnetic susceptibility, and resistance. Layer composition is also noted.

Figure 5. Example from AEG01-02BC at 20 cm core depth showing typical mineralogy of tephra deposits with high abundance of volcanic glass, followed by plagioclase, biotite, a few oxides, and lithics. Photographs taken at 10x objective on a Zeiss Axioscope; image diameters are 920 – 930 μm . Upper photograph is under regular light, lower photograph is shown in polarized light.

Figure 6. Geochemical analyses of SiO_2 and K_2O wt. % show volcanic glass from the newly cored tephra deposits fall in the same field as the previously published pumice glass collected from the crater wall of Kolumbo. The SiO_2 and K_2O wt. % are easily discriminated from published analyses of Santorini Minoan products that generally have lower contents of both SiO_2 and K_2O .

Figure 7. Primary and secondary 1650 AD Kolumbo deposits, as noted by red stars and green squares, respectively. The newly correlated distribution area (red outline) is nearly five times the area than the seismically-inferred distribution area (blue outline), as previously identified by Nomikou *et al.* (2012a).

Figure 8. Distribution of (a) maximum average grain size, and (b) bulk median grain sizes within massive and laminated facies.

Figure 9. Whole grain size analyses representing (a) unimodal fine bulk tephra deposits, (b) unimodal coarse bulk tephra deposits, and (c) laminated unimodal fine and unimodal coarse bulk tephra deposits.

Figure 10. Ternary diagram of bulk median grain size, with ratios of sand, silt and clay within tephra deposits, in relation to approximate distances from the crater. There is no clear relationship between the total grain size distribution and distance from the crater.

Figure 11. Four glass morphologies as distinguished by SEM images: (A) Type 1 are vesicular, irregular shapes as represented in core AEG01-01BC; (B) Type 2 are very fine, platy, vesicle wall shard fragments as represented in core AEG01-03BC; (C) Type 3 are pipe vesicular, elongate shapes as represented in core AEG01-01BC; (D) Type 4 are blocky, equant shapes as represented in core AEG01-

Figure 12. Two stage gas exsolution demonstrated in vesicle walls of pyroclasts from core AEG01-57BC.

Figure 13. Particle showing a transitional texture between Type 1 and Type 4 morphologies, from core AEG01-20BC.

Figure 14. Average slope angles from bathymetric highs to bathymetric lows illustrate the likely paths of sediment gravity currents away from the Kolumbo crater.

Figure 15. Cartoon illustrating the proposed tephra transport mechanisms: dominant local winds; surges over the seasurface from subaerial eruption column collapse; vertical gravity currents driven by Rayleigh-Taylor instabilities; and, sediment gravity flows driven by submarine eruption column collapse.