TECHNICAL UNIVERSITY OF CRETE

MAPPING OF PYROCLASTIC FLOWS DEPOSITS AND RELATED SLOPES FAILURE PHENOMENA NE OF SANTORINI ISLAND

INTERGRATED MASTER MINERAL RESOURCES OF ENGINEERING TECHNICAL UNIVERSITY OF GRETE

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This thesis, is dedicated to my beloved grandmother,

Anastasopoulou Panagiota,

Who is always next to me!

ΕΥΧΑΡΙΣΤΙΕΣ

Έφτασε η ώρα που ένα από τα πρώτα κεφάλαια τη ζωής μου, σαν φοιτήτρια, φτάνει στο τέλος του. Ένα κεφάλαιο, που με πλημμύρισε από γνώσεις και μια θάλασσα συναισθημάτων. Φοιτητικά χρόνια που θα μείνουν χαραγμένα για πάντα στη μνήμη μου θυμίζοντάς μου τις χαρές, τις στεναχώριες, τις προσπάθειες, τις επιτυχίες και τις αποτυχίες, στιγμές που συνέβαλαν στην επίτευξη του στόχου μου, να γίνω μηχανικός και να προσφέρω το λιθαράκι μου στον επιστημονικό κόσμο καθώς επίσης και στην κοινωνία.

Άνθρωποι πέρασαν όλα αυτά τα χρόνια από δίπλα μου, άλλοι ήρθαν και έφυγαν ,άλλοι ήρθαν και έμειναν. Στους τελευταίους λοιπόν, μέσα από αυτές τις λίγες γραμμές θα ήθελα να εκφράσω τις ευχαριστίες και την ευγνωμοσύνη μου για την στήριξή τους και για τις γνώσεις που αποκόμισα, τόσο σε μορφωτικό όσο και σε προσωπικό επίπεδο.

Ιδιαίτερα θα ήθελα να ευχαριστήσω την κ. Κοκκωνά, από το τμήμα της φοιτητικής μέριμνας, που μαζί με την κ. Παπαδογεωργάκη και τον κ. Μελετίου ,υπεύθυνη του Erasmus και πρώην προϊστάμενο της φοιτητικής μέριμνας αντίστοιχα, με αγκάλιασαν και με στήριξαν σαν δικό τους παιδί. Η βοήθειά τους ,τόσο σε εμένα όσο και σε πολλούς άλλους φοιτητές, ήταν πολύτιμη και αποτέλεσε βασικό θεμέλιο της υλοποίησης του στόχου μου.

Στην συνέχεια , θα ήθελα να ευχαριστήσω όλους τους φίλους μου από τα Χανιά, την Πάτρα και ακόμα πιο μακριά, Βασιλή Ανδρουλάκη σε ευχαριστώ και εύχομαι μόνο να πετυχαίνεις στη ζωή σου γιατί το αξίζεις, που με αγάπη και πίστη σε μένα , δεν σταμάτησαν λεπτό να μου υπενθυμίζουν ότι όταν θες κάτι μπορείς να το πετύχεις ,και ότι κατάφερα να σπουδάσω στο αντικείμενο που πραγματικά ήθελα, μαθαίνοντας να αντιμετωπίζω τις δυσκολίες και τα εμπόδια, σαν απλές δοκιμασίες.

Οι καθηγητές της σχολής μου, αξίζουν, εδώ, την δική τους παράγραφο. Ο κ. Βαφείδης Α. και ο κ. Παρτσινέβελος έπαιξαν σημαντικό ρόλο τόσο κατά την διάρκεια όσο και στην ολοκλήρωση των σπουδών μου. Ένα ευχαριστώ είναι λίγο, καθότι, εκτός από μένα, είχαν να συνεργαστούν με πολλούς ακόμη φοιτητές προσπαθώντας συνέχεια να ικανοποιούν τις επιθυμίες όλων μας.

Θα ήθελα, στο σημείο αυτό, να ευχαριστήσω τον κ. Σακελλαρίου απο το ΕΛΚΕΘΕ, καθώς και το ερευνητικό κέντρο Υποθαλάσσιων Ερευνών, ΕΛΚΕΘΕ στην Αθήνα, που μαζί με τον κ. Sebastian Krastel και τον κ. Felix Gross, από το πανεπιστήμιο στο Κίελο της Γερμανίας, μου μεταλαμπάδευσαν τις γνώσεις τους κατά την εκπόνηση της διπλωματικής μου εργασίας και ήταν πάντα πρόθυμοι να απαντήσουν στις απορίες και στις ερωτήσεις μου.

Τέλος, απευθύνω τις πιο θερμές μου ευχαριστίες στους δικούς μου ανθρώπους -την οικογένεια μου- Μαρία, Στάθη, Αθηνά, Δανάη και τον πολυαγαπημένο μου μικρό αδελφό Γιώργο ,τη νονά μου Ιωάννα, καθώς επίσης και τους φίλους μου ,που είναι πλέον και εκείνοι οικογένειά μου, Αλεξάνδρα, Ανδριάνα, Χρήστο, Βασίλη, γιατί ακόμα και από μακριά, πιστέψατε σε μένα και με το δικό σας ξεχωριστό τρόπο ο καθένας με γεμίσατε με δύναμη, υπομονή, πείσμα και αντοχή ,ώστε να μπορώ να γίνω αυτό που είμαι σήμερα.

Πολυαγαπημένη μου γιαγιά, η διπλωματική μου εργασία είναι αφιερωμένη σε σένα. Δεν νομίζω ότι χρειάζεται να προσθέσω κάτι περισσότερο, από την έκδηλη αγάπη και αδυναμία μου για σένα.

Απολογούμαι αν παρέλειψα κάποιον, λόγω της συναισθηματικής φόρτισης που αισθάνομαι, γράφοντας αυτές τις γραμμές. Σας ευχαριστώ όλους εκ βαθέων.

΄΄Mapping of pyroclastic flows deposits and related slopes failure phenomena NE of Santorini Island΄΄

pyroclastic flow: a fast-moving current of hot gas and volcanic matter (collectively known as tephra) that moves away from a volcano about 100 km/h average but is capable of reaching speeds up to 700 km/h .The gases can reach temperatures of about 1,000 °C

Colombo: an active submarine volcano in the Aegean Sea, about 8 km northeast of Cape Colombo, Santorini Island. The largest of a line of about twenty submarine volcanic cones extending to the northeast from Santorini, it is about 3 km in diameter with a crater 1.5 km across. It was "discovered" when it breached the sea surface in 1649-50. Thera explosion and caldera collapse, currently dated ca. 1630 BCE, with its devastating consequences for Minoan civilization. The Smithsonian Institution's Global Volcanism Program treats it as part of the Santorini volcano

Air gun: produces very low-frequency acoustic energy (2Hz-500Hz) as a result of the explosive release of high-pressure air directly into water (by generating bubbles of compressed air). The rapid release of highly compressed air (typically at pressures of ~2000 psi) from the airgun chamber creates an oscillating air bubble in the water. The expansion and oscillation of this air bubble generates a strongly peaked, high-amplitude acoustic impulse that is very effective for seismic profiling

Sedimentary arc: The sedimentary arc comprises coralline and volcanoclastic sediments underlain by volcanic rocks older than those found in the volcanic arc. This volcanic substrate may represent the initial site of volcanism as the relatively cool oceanic plate began its descent. As the 'cold' plate extended further into the asthenosphere, the position of extrusive igneous activity moved backwards to its steady state location now represented by the volcanic arc.

ΠΕΡΙΛΗΨΗ

Το υποθαλάσσιο ηφαίστειο Κολυμπώ βρίσκεται ΒΑ της Σαντορίνης και είναι ο μεγαλύτερος κρατήρας μεταξύ μιας σειράς κρατήρων οι οποίοι είναι ευθυγραμμισμένοι στη διεύθυνση ΝΑ-ΒΔ. Η κυριότερη δραστηριότητα του Κολυμπώ χρονολογείται από το 1649-1650 μ.Χ. Ο κρατήρας του έχει διάμετρο περίπου 3 χιλιομέτρων και βάθος 512 μέτρων. Σε μεγάλη έκταση γύρω από το ηφαίστειο έχουν εντοπιστεί υδροθερμικά φρέατα από τα οποία αναβλύζει καυτό νερό, έως και 220°C, με διαλυμένα μεταλλικά στοιχεία και τα οποία φιλοξενούν ένα σπάνιο οικοσύστημα από νηματοειδή βακτήρια.

Θαλάσσια σεισμική διασκόρπιση πραγματοποιήθηκε από το ΕΛΚΕΘΕ τις δεκαετίες 1986 και 1992 στην ευρύτερη περιοχή γύρω από το Κολυμπώ. Στη παρούσα διπλωματική πραγματοποιήθηκε επεξεργασία και ερμηνεία των σεισμικών δεδομένων, σε επιλεγμένες γραμμές μελέτης. Απεικονίστηκαν μια σειρά από ανακλαστήρες και ερμηνεύτηκαν τα αντίστοιχα στρώματα με βάση των σεισμικό χαρακτήρα των ανακλάσεων. Πιο συγκεκριμένα τα παρακάτω σεισμικά στρώματα αποδόθηκαν σε εναποθέσεις πυροκλαστικών ροών :

- Το στρώμα S1 το οποίο είναι οριοθετημένο προς τον κρατήρα, αποδίδεται σε πιθανή προ υπάρχουσα δομή παχύρρευστων προκλασικών αποθέσεων οι οποίες χρονολογούνται στο 1650 μ. Χ.
- Το στρώμα S2 αντιπροσωπεύει τη μινωική πυροκλαστική ροή. Εμφανίζει χαοτικές εσωτερικές ανακλάσεις, ενώ βρίσκεται στο κάτω μέρος του κρατήρα. Η πάχος του κυμαίνεται από 0,03 έως 0,06 ms.
- Το στρώμα S3 είναι το στρώμα των νεότερων πυροκλαστικών εναποθέσεων που καταλήγει στο ρηχότερο τοίχωμα του Κολούμπο που μπορεί να αποδοθεί σε ελαφρόπετρα, ηφαιστειακές εκβολές, αποθέσεις ηφαιστειακών μαζών, αλλά και σε ρεύματα λάβας και αναχώματα. Τα ρεύματα λάβας και αναχώματα μπορεί να αντιπροσωπεύουν τις ζώνες ανοίγματος των τελευταίων εκρήξεων .
- Το στρώμα Κ χαρακτηρίζεται ως μια ακολουθία πολύ στρωματοποιημένων πυροκλαστικών αποθέσεων που παρήχθησαν κατά τη διάρκεια της έκρηξης του 1650 μ .Χ.

Abstract

This thesis explores the capability of sub-bottom profiler in imaging pyroclastic flow deposits from Colombo submarine volcano. This is an active submarine volcano in the Aegean Sea, about 8 km north-east of Cape Colombo, Santorini Island. It is the largest of a line of about twenty submarine volcanic cones extending to the north-east from Santorini. It is about 3 km in diameter with a crater 1.5 km across. It was "discovered" when it breached the sea surface in 1649-50 A.D.

The seismic data was acquired during several oceanographic cruises aboard the research vessels AEGAEO and SONNE during 1986-1992. Data processing and interpretation on selected seismic lines of the area around the Colombo volcano was performed. During the interpretation of the seismic profiles, the main reflectors were identified and the basic seismic units were determined based on their seismic character. The seismic stratigraphy results were correlated with stratigraphic and lithological data of nearby areas which are available from existing studies.

That helped us to create a clear picture of the geological structure of the study area, develop a tentative chronostratigraphy of the basin and draw conclusions on the age and origin of the observed pyroclastic flows. Finally we proceeded to data interpretation that presents information about the spatial distribution of pyroclastic flows derived from Santorini volcanic field, in Colombo volcano.

The following units observed on the seismic sections are related to pyroclastic flows:

- The present Colombo volcanic edifice is mainly formed by Unit S1, which is bounded towards the crater. Unit S1 reveals a possible pre-existing structure that has been built upon by deposition of the thick 1650 AD pyroclastic deposits.
- S2 unit presents the Minoan pyroclastic flow. It shows chaotic internal reflections and is horizontally bedded. It also ends at the lower half of the crater wall. Its thicknes ranges from 0.03 to 0.06 sec.
- S3 Unit is the youngest unit which terminates at Colombo’s lower crater wall which can be described as pumice, volcanic breccias and volcanoclastic mass waste deposits, but also as lava flows and dykes. The lava flows and dykes may represent the up welling zones of the last eruptions.
- Unit K is characterized as a sequence of highly-stratified pumiceous submarine pyroclastic deposits produced during the eruption of 1650 AD. These pyroclastic flows create low reflection amplitudes due to the high porosity.

Contents

1.1Introduction

Each day, we face a growing number of rapid developments in every premise of science. Developments can play a decisive role in the evolution of both human existence and the planet. People know and discover natural phenomena which they study and explain in an optimal way how to approach their smoother treatment and the less threat for our planet. In recent years, there has been intense scientific concern about submarine explosions. These explosions verify the existence of volcanoes within the oceans. The underwater volcanoes produce 75% of our planet's magma every year. The largest number of undersea volcanoes are located near oceanic ridges where processes oceanic ridges exist.

In these areas we encounter hydrothermal wells and areas of abundant biological activity. One with a world-famous submarine volcano that is of interest both on geological and stratigraphic level is the volcano Colombo NE of Santorini. This volcano is part of the volcanic arc of the South Aegean.

For the origin of the name of the volcano, there are many opinions, the most common of which is that the name comes from the Italian Colombo which means pigeon, because during its eruption, the surface of the sea was covered with white foam, which looked like a white pigeon. Colombo is located 6.5 kilometers northeast of Santorini, marking its largest volcanic eruption in 1650. The previous year, several seismic events took place, becoming perceptible to the inhabitants of the island, although their origin is yet unknown. With the volcano eruption in 1650, the sea area around the volcano and the island was covered with the lava of the volcano giving the green hue to the water and spreading poisonous gas, and carbon dioxide in the area. Due to the spread of the lava, a small islet has been created, which has receded and collapsed into a reef. As a result within 150 kilometers from this collapse, a tsunami destroyed whatever it found in its passage.

The current state of the volcano is defined as 280 meters in height and 18 meters below sea level, its crater depth is 512 meters while its diameter is about 3 kilometers. It is important to mention that hydrothermal wells where water reaches 220ºC, are observed in the surrounding areas from the submarine volcano.

1.2 Intension

The purpose of this work is to study the seismic stratigraphy of the area around the Colombo volcano, as well as the mapping of pyroclastic and landslide structures. Any fault that characterizes the area should be recognized.

Chapter 2-Review of Bibliography

2.1 Geodynamic status of the Aegean

2.1.1 The Hellenic volcanic arc

The Hellenic volcanic arc is also known as South Aegean Arc and as mentioned above is part of the Hellenic Orogenic Arc. The active volcanoes of the South Aegean arc are located about 130-150 km above the seismically defined Benioff zone (Makropoulos, Burton, 1986) and a little deeper in the central part of the arc (Papadopoulos, 1982, 1989). The study of the Tertiary volcanic rocks in the Aegean area has shown a southward migration of the volcanism from late Eocene in the North Aegean coastal areas, to the present day active volcanoes along the southern margin of the Cycladic platform and the Cretan back arc basin (Bellon et al., 1979; Fytikas et al., 1984; Papanikolaou, 1993). The total migration of the Aegean volcanic arc is approximately 400 km within 40 Myr, which corresponds to an average rate of 10 km/Myr (Papanikolaou, 1993; Royden and Papanikolaou, 2011). Geochronological data of the Aegean volcanic rocks (Pe-Piper and Piper, 2002) indicate that the present-day volcanic arc dates back to the early Pliocene with important activity during Quaternary.

Some centers in the arc (Aegina, Crommyonia, Poros, and Milos) began their activity in the early Pliocene. Except for Milos, there was a general cessation of activity in the late Pliocene and then a renewal of activity in the Quaternary (early Pleistocene in Aegina, Santorini, mid-Pleistocene in Methana, Nisyros and the main phase of Santorini volcanism). This pattern of volcanism correlates with evidence for two phases of basin subsidence in the area of the arc (Doutsos and Piper, 1990, Perissoratis et al., 1993). Thus in addition to the evidence for subduction, the extension may have played a role in determining the timing and spatial distribution of volcanism.

Until recently, the outcrops of modern volcanic rocks are restricted to the terrestrial parts of the Aegean and the only submarine volcano known was the Colombo. Thus the volcanic centers in Greece were divided into four main groups (Nomikou et al, 2013):

- Methana-Poros-Egina group, at the western edge of the volcanic arc in Western Saronikos Gulf
- Milos group
- Nisyros-Kos group at the eastern edge near the Turkish coast and
- Santorini group in South Aegean

In the late 1980s, the Hellenic Centre for Marine Research in collaboration with the University of Athens focused on submarine neotectonic mapping, which resulted in the discovery of Paphsanias Volcano in the Western Saronikos Gulf, a few km northwest of the Methana volcanic peninsula (Papanikolaou et al., 1988, 1989; Pavlakis et al., 1990). Soon after, a number of outcrops of volcanic rocks were discovered belonging either to new, previously unknown, submarine volcanoes or to submarine prolongations of volcanic rocks of the Aegean islands in the areas of Nisyros (Nomikou and Papanikolaou, 2010a, 2010b; Papanikolaou and Nomikou, 2001; Papanikolaou et al., 1998), Milos (Alexandri et al., 2001; Camilli et al., 2007) and Santorini (Alexandri et al., 2003; Nomikou et al., 2012a; Sigurdsson et al., 2006a). The already known onshore volcanic activity in combination with the discovery of submarine hydrothermal activity in several areas indicates the continuing volcanic process both onshore and offshore. (Nomikou et al, 2013).

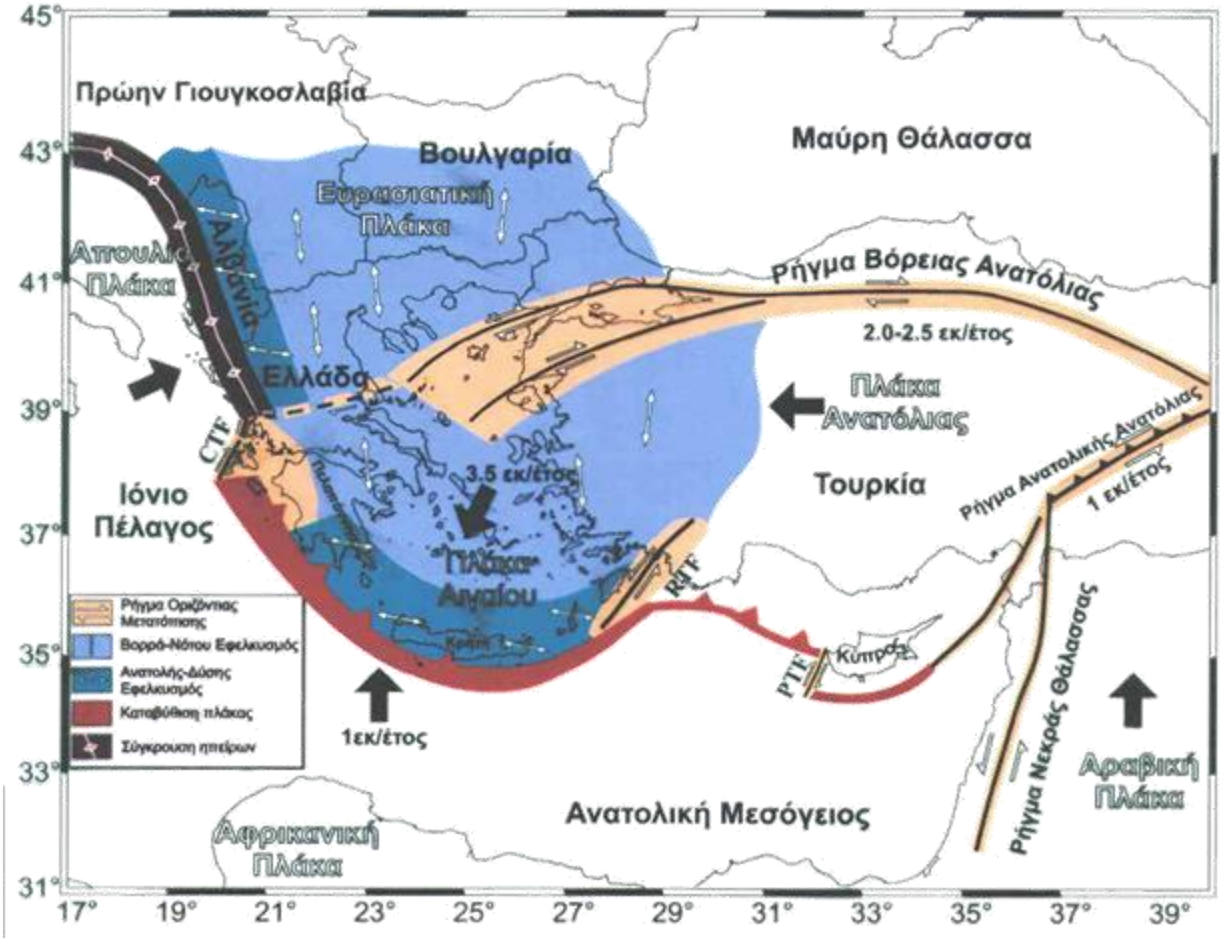


Figure 1: Map of the Eastern Mediterranean showing the active geodynamic situation, the movements of micro-plate in the region and the formation of the Greek-Aegean Arc and the Cyprus Arc (Papazachos 2001)

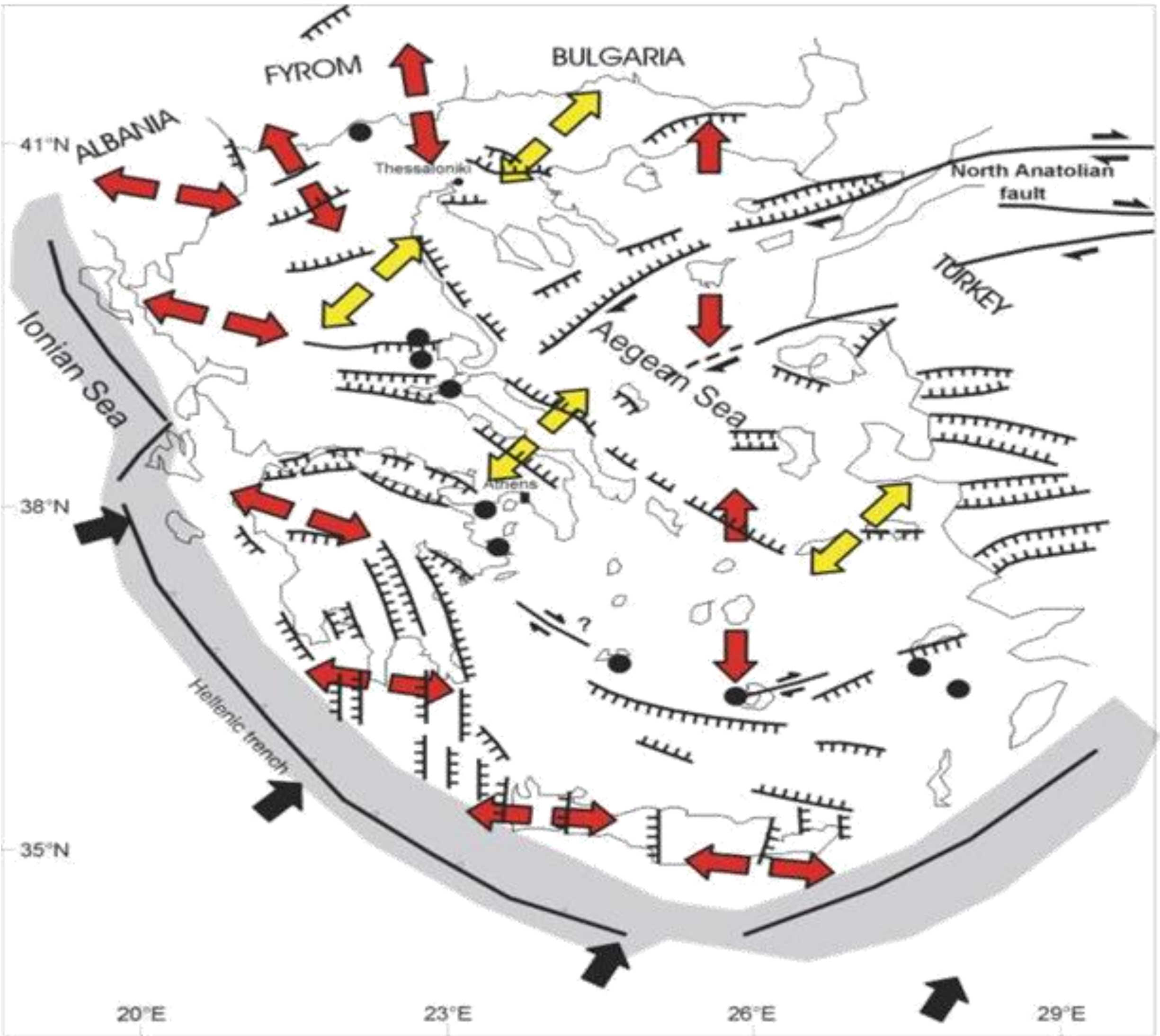


Figure 2: Simplified tectonic map showing the orienations of the extensional D4 event in the Aegean and surrounding areas. The yellow arrows show the extension in the Pliocene, the red arrows the extension in Quaternary-recent time, the black arrows the compressional direction outside the Hellenic arc, the black lines the normal and the strike-slip faults of the broader area, and the black dots the distribution of Quaternary volcanoes in the Aegean.

2.1.2 Tectonics of the Aegean region

The Aegean Sea is located in the Eastern part of Mediterranean and more specifically in the eastern Greece. It is a submarine part of the Alpine mountain chain, which, until the recent geological history, joined the Hellenizes to the west with Taurus to the east. Aegean is a region with very specific characteristics due to its position on the south margin of the European plate that collides with the African plate. The tectonic history of the region is complex, involving a long history of north-dipping subduction, an early stage of continental collision (micro-continental blocks), followed by recent (Miocene–Pliocene) extension (Jackson, 1994). The tectonics are thought to be mostly a result of a subduction-related processes. (Le Pichon and Angelier, 1979, Royden, 1993). Aegean tectonics are also thought to be intimately related to regional tectonic processes including the collision of Arabia with Eurasia, and presumed extrusion of the Anatolian plate (Sengor et al., 1984), although the relationship between these different tectonic events/processes is subject to debate (Gautier et al., 1999).

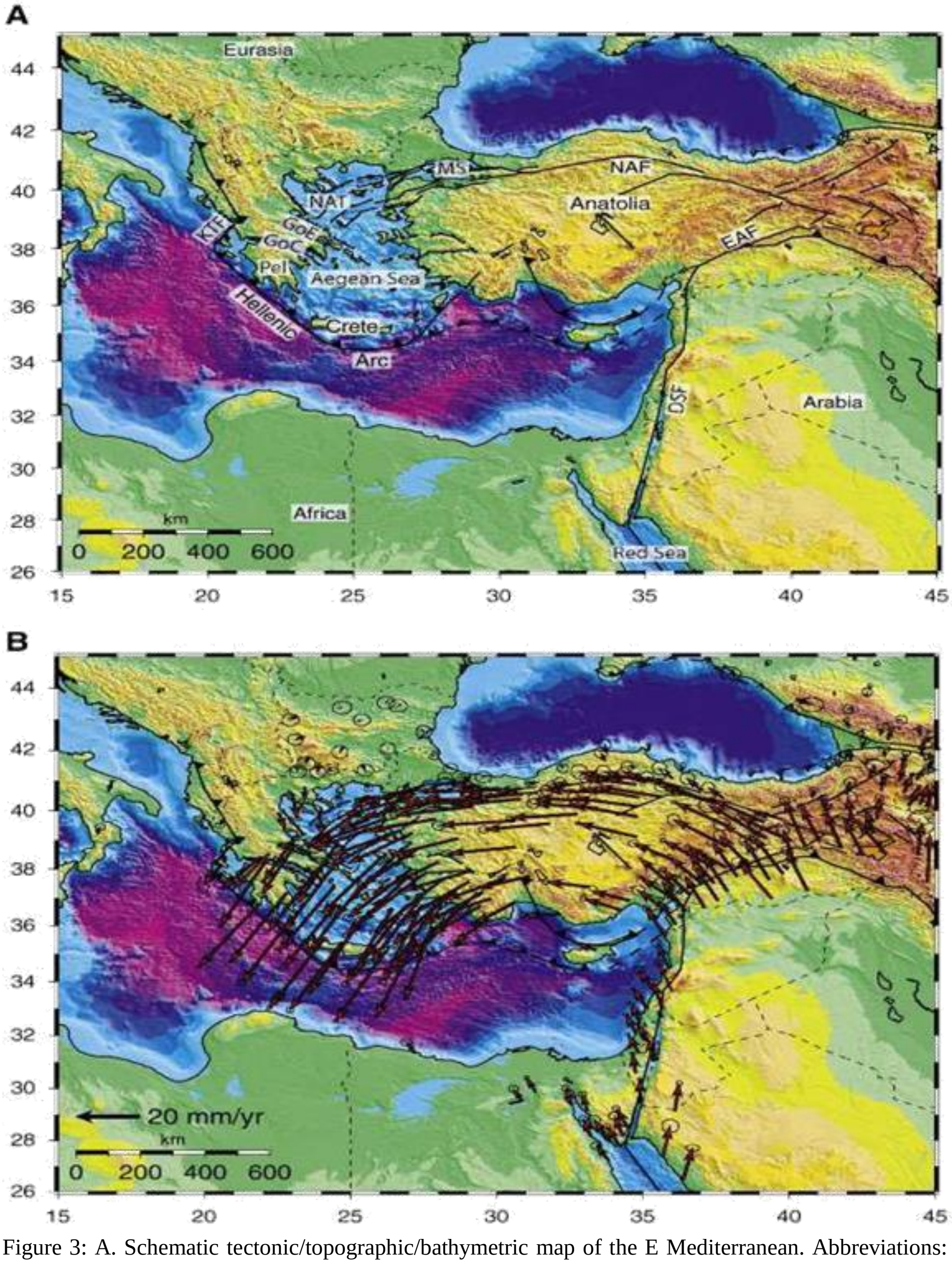


Figure 3: A. Schematic tectonic/topographic/bathymetric map of the E Mediterranean. Abbreviations: Gulf of Evia (GoE), Gulf of Corinth (GoC), Kephalonia Transform fault (KTF), North Anatolian fault (NAF), East Anatolian fault (EAF), Dead Sea fault (DSF), Marmara Sea (MS), North Aegean Trough (NAT), Peloponnisos Peninsula (Pel). B. GPS-derived velocities with respect to Eurasia (velocity field has been decimated for clarity). GPS velocity uncertainties are 95% confidence ellipses (modified from Reilinger et al., 2006).

As a result of the special geodynamic regime, the Aegean is regarded as a “deforming microplate” (Mascle and Martin, 1990). The eastern and western micro-plate boundaries of the Aegean domain are not well defined and only its southwestern corner is well expressed, particularly in the seismic and bathymetric results (McKenzie, 1978). The northern boundary of the Aegean micro-plate is the North Aegean Trough (N.A.T.), which is the westward extension of the North Anatolian Fault zone (Dewey and Sengor, 1979) and the southern boundary is formed by Levantine segment of the Hellenic subduction zone (Le Pichon and Angelier, 1979).

Mascle and Martin (1990) based on the bathymetry, divide the Aegean Sea into 3 main areas:

- The Northern Aegean Sea (N.A.S) that is characterized by a series of aligned and relatively deep
- The Central Aegean Sea (C.A.S), a wide and shallow platform which incorporates the Cyclades islands.
- The Southern Aegean Sea (S.A.S.) which like the N.A.S. is also characterized by a series of separate troughs distributed in an arc-shaped setting between the eastern Peloponnesus, Crete and southwestern Anatolia.

2.2 -Characteristics of a Greek arc

2.2.1 Morphotectonic and geotectonic features of the volcanic arc in Greece

The Greek arc, like an arc based on the sinking of an ocean plate below the mainland, consists of the following morphotectonic features. The Hellenic Trench, (tafros) formed along the contact of the two plates, surrounds the sedimentary arc externally. It is a 2000-5000 meter depth system that extends from the Ionian Sea to the south of Crete, and its maximum depth is marked southwest of the Peloponnese, in the Ionian Sea, where it is the deepest point of the Mediterranean.

The volcanic arc of the Aegean, which is located in the inner part and consists of the active and the Quaternary-Volcanic volcanoes of Santorini, Milos, Nisyros, Methane of Cromyonia, Lixades, Kos, Patmos, Antiparos and of Psathoura.These volcanoes are connected with the sinking and melting of the African plate

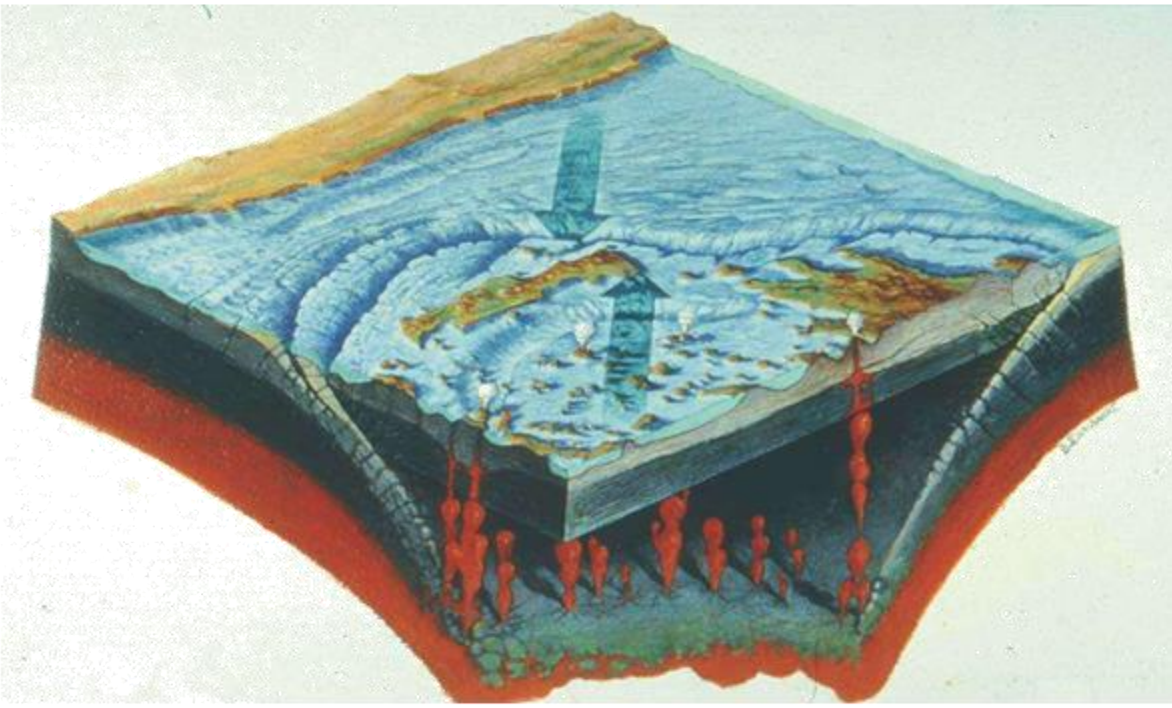


Figure 4: The stereographic features of the sinking of the African plate under the Aegean

Another Mediterranean feature is the Mediterranean ridge. The Greek outer or Mediterranean ridge that crosses the eastern Mediterranean south of the Greek Peripheral Trench, parallel to the Greek arc, is an underwater exaltation of the crust.

As far as the tectonic structure of the Greek arc is concerned, studies have shown that the effect of the strong compressive forces on the external part of the Greek arc is the deformation of sediments in the peripheral trench and in the outer curve of the sedimentary arc. These deformations are related to verse faults found in the new marine sediments south of Crete and Peloponnisos with geophysical methods and deep drilling.

The tensile forces that exert from the interior of the Greek arc are spreading across the Aegean and the continental space has a general direction from N-S and causes normal faults, with mainly general direction W-E. These trends are responsible for triggering earlier fractures, other addresses and older geological periods. This is mainly about normal NE-SW steering faults resulting from tensile tectonics

Excluding these tensile forces are the faults in the trench of the North Aegean and some other faults in the area of the central Aegean because they are an extension of the North Anatolian fault.

Finally, as far as the Northern part of the African Plate below Europe is concerned, it reaches the area of Zakynthos in Kefallinia, where the sinking phenomena are still visible, while scientists say it is continuing further north.

2.3 Volcanism and background of Santorini

2.3.1Geographic Analysis of Santorini

Santorini, Thira or Stroggili, horseshoe with its outfall facing the West, is an island located in the Southern Aegean Sea, belonging to the group of Cyclades. In the North of the island, there is Ios, in the East there is Anafi and it is about 130 miles from Piraeus.

It is a mountainous island, consisting of successive volcanic rocks which are characterized by layers of pumice and garnet. As for its morphology, Santorini is characterized as a dry and anhydrous island, lacking lakes, rivers, gorges, and streams. The island's irrigation needs are covered mostly by collecting rainwater through drilling in its subsoil. The island consists of three basic springs as well as of four healing ones. Its soil is volcanic-plain at its largest part and rocky from the side of the volcano.

The capital of the island, Thira or Fira, stands on a rock over the old port. In order to get to the capital, people had to mound a lot of steps or ride a donkey, however, nowadays there is a cable car which makes transportation much easier. The new port is in a more accessible area, called Athinios.

In the North of the island, there is preserved village Imerovigli. According to its name, it is the island Vigla with an astonishing view, the chance to see the caldera from above, and it also has an evolving tourist growth. As for the south of the island, you can see the village Akrotiri a neighboring village with mythical beaches. This village is known for the discoveries made by the archaeologist Spiros Marinatos, who exposed a whole city based on housing estate of the Minoan era, under the ashes of the volcano. It is the city whose importance is bigger than even that of the Italian Pompei's.

A characteristic resort in Santorini is Kamari, in the east coast of Thira. The reason for its fame is its huge black sandy beach and its dark sea. In the east, there are also Megalochori, Mesaria, and Monolithos where the dark beach ends. One more jewel in the North of the island is the famous IA, as well as the cosmopolitan Perissa, while the midland Pyrgos and Finikia complement the island's beauty.

Viewing the West and East Aegean, in a prominent location, with a "defensive" architecture, the midland medieval Emporio is built.

Going back 2 to 2.5 million years, before Santorini's volcanic activity, there was a small island in

Santorini's place where transformed limestones and shale were constructed, which are now strongly altered.

The volcanic activity of Santorini began from Akrotiri and the islets of Christiana Thira, where 500,000 years ago the Peristeria volcano made its appearance with the main ingredient of the Andesian lavas. As a consequence of this volcano, it took about 300,000 years to create an ash-shaped volcano that unites all the individual islands.

In the following years, 40-60,000 years ago, there was volcanic activity followed by strong volcanic eruptions, forming the volcanoes of Scaros and Thirassia, but 21,000 years ago they were destroyed by the Riva explosion. The follow-up of all these explosions was the greatest and the most significant eruption that occurred in the 17th century BC, which gave the current morphology.

This explosion is considered to be one of the most important moments of the Mediterranean. The volume of volcanic debris exceeded 50 cubic kilometers. The islands of New and Old Kameni Thira were created by the explosion.

The dipping of the African plate below Eurasian, or more precisely the undergrowth of the Aegean was the cause of the volcanic activity in the Aegean. The intense and rapid rhythms that the African Plate melts and then the rise of the melted rocks that appear on the surface form the volcanoes of Methana, Milos, Santorini and Nisyros, which constitute the volcanic Arc of the South Aegean. The Santorini complex also includes the Christian islands and the underwater volcano Colombo, which is the most active area of the arc.

2.3.2 Active tectonics of Santorini

Santorini is considered to be one of the largest quaternary volcanic centers in the world, and is the largest in the Hellenic region. It is located in the central part of the Greek volcanic arc, recording up to nine activities over the last 600 years.

The volcanic field of Santorini includes the volcanic centers of Christians, Santorini and Colombo.

The volcanic centers create a belt of crevasses that face the SW-NE direction (40º), which consists of the Kammeni line and the Colombo line, two parallel lines of cracks. The Kammeni line passes from Palaia and New Kameni, where the newest volcanic deposits of Santorini, has a thickness of 600 m and a length of 4.5 km. The Colombo line crosses the ring of the bowls of Cape Colombo and the corresponding undersea volcano from the great mountain (Soldatos, 2011).

Sakellariou et al (2010), with systematic marine geological research and mapping of the wider marine area around Santorini, showed that the Kamenis-Columbos line is a faultless zone of horizontal sliding, which has been used for the rise of magma in all volcanic centers of Santorini.

According to Papazachos et al (as reported in 2009), Santorini is located on a seismic zone (Christian -Amorgos) NE-SW direction and a length of ~ 70 km, associated with large-scale systems rifts that accommodate peripheral tension .

Its northern half is located on the Anidros tectonic ditch, where the largest volcanic activity is observed, whereas the southern part is located above the tectonic horn of Santorini-Amorgos. The first distinct line, the Kameni Line, passes from the center of the caldera includes the resources of the Kameni Islands, the mosquito ring of Asprenissi and the pores of the Upper Kisser 1 and 2 eruptions, Middle Kissaris, Upper Slavery 1 and 2 and Minoan. (Druit et al., 1999), Colombo line includes the Great Mountain Scale Powders and the Coleopte Acid Ring of the Cape.

On the two distinct NE-SW lines we meet a lot of energy resources.

2.3.3 Pre-volcanic background of Santorini

The pre-volcanic rocks belong to the Attic Cycladic zone (Fytikas et al., 1990a; 1990b;).They appear in the Mount of Prophet Elias, in the Middle Mountain, on the back of Gavrilos, the Monolithos in Pyrgos and the inner part of the caldera between Cape Plaka and Athenio (Vougioukalakis, 2005).

The limestones have the highest surface appearance compared to the other pre-volcanic rocks and appear in all the aforementioned areas except Athinios. They are pavingstones, strongly tectonic with shades of reddish, white-yellow and reddish-yellow. Their depth reaches about
600m and they are formations with high permeability.

At Athinios there is a granite of Miocene (9.5 million years ago) that is part of the extensive appearance of granite found in the Cyclades and is a source of minerals such as talc, chalcopyrite, magnetite and other minerals found in the area.

Phyllites appear in the Athenian area and the perimeter of the Prophet Elias; they are limestone with crystalline limestone and green shale lenses (Skarpelis et al., 1988)**.**

2.3.4 Volcanicity

Santorini is the most famous volcano of the volcanic arc of the South Aegean, which began when it was formed 2-2.5 million years ago by the sinking of the African Plate under the Eurasian Plate. It is a complex layered volcano with a large caldera. Then, Santorini was a small island formed by metamorphic rocks. Volcanic activity includes mainly lunar eruptions, gullies discharges, and slag cones.

2.4 The submarine Colombo volcano

2.4.1 Historical data

The first and unique historical eruption of the Colombo Volcano took place in September 1650 outside the area of Caldera in Santorini, where it caused disasters in Santorini and the surrounding islands. Intense seismic activity preceded the explosion. The slow exit Dacian-Andecian magma built an undersea volcano with a diameter of 3 Km and a height of 300 m, whose top just burst out of the sea.

Most information about the 1650 eruption comes from the inhabitants of Santorini and the neighboring islands. These records were collected by Ferdinand A. Fouque and published in his book Santorini and the Eruptions in 1879 giving valuable information about the evolution of the explosion and its consequences for people in the area at that time.

Similar references are made to the book " Ecclesiastical Horn of the Island of Thera " by priest Daniel Denaxas, who reports that since 1649 there was intense seismic activity in Santorini that continued until 1650.

The occurrence of seismic activity around the area of a volcano is the first sign of an upcoming explosion, with the intensity and frequency of seismic events increasing as the moment of explosion approaches.

Sources mention that six days before the explosion, the color of the sea was light green, due to the emergence of the magma and its mixing with seawater, and in the afternoon of September 27, the day of the first eruption, dense clouds began to emerge from the interior of the sea. Small seismic events continued to appear, and large quantities of pumice pumping out of the volcano were sitting on the surface of the sea. The explosions continued the next day, until September 29, 1650, the largest eruption took place. The sound of the explosions reached 400 km, while the seismic events were felt even in Crete (about 100km) (Nomikou et al., 2012a)

Strong winds, deposited volcanic ash, like a white layer of dust up to the west coast of Turkey.

.

Sea surface was covered with pumice stone which was washed off the coasts of the neighboring islands. The volcanic activity stopped at 23:00 on September 29 and re-started at midnight on September 30th. The weakening of activity began until it stopped after a few days. Explosive gases were very acidic, with large amounts of carbon dioxide and chlorine, many people lost their senses for several hours while a large number of people and animals, who inhaled toxic fumes, were killed along the northeast coast of Thera. Both the inhabitants of Santorini as well the neighboring islands were affected by two natural consequences of the Colombo eruption: 1) the emission of toxic gases, which traveled over long distances over the water 2) and the tsunami.

On the 4th and 5th of November, some isolated explosions with gas extinction accompanied by a small seismic activity were carried out. The depletion of the undersea hemisphere was completed after a small increase of the seismic activity and underwater disturbances (December 1650) (Nomikou. Al, 2012a)

2.4.2 The morphology of Colombo

From oceanographic surveys carried out in the underwater area of Santorini during 2001-2011, and from collaborations of the University of Rhodes (URI-USA), the Greek Marine Center (EL.KE.THE), the Institute of Geological (Nomikou, 2003; Nomikou et al., 2012b) data was collected from the Institute of Geology & Mineral Explortion (I.G.M.E) and the University of Athens (Department of Geology and Geoenvironment). Multibeam systems (multibeam system, 20 kHz, SEABEAM 2120), Air Gun 10ci single channel seismic profiling, and Box corers were used.

As a result of these surveys, the Northwest Basin of the Anydros basin (NE of the underwater area of Santorini) is a 50 km long zone with a 45º northeastern direction, called the Ios Fault Zone, (IFZ). The south-eastern boundary of the Anydros basin is of intense and large morphological and tectonic complexity, consisting of successive reactive blocks and it is called the Anydros Fault Zone (AFZ) with a general address 30º northeast (Sakellariou et al., 2010)

In the Anydros basin, more than 20 volcanic structures make their appearance, which have a planar straight line, with a general address 30º northeast. The largest of these submarine structures is Colombo, with a diameter of 3 km, width 1500 m, and depth within the crater 505 m. The distance between the western elevated zones (Anydros and Ios) is 30 km southwest of Santorini, around the Colombo area is 16 km, and southeast of the islet of Anydros, reaches 8 km.

The conclusion of the investigations is that the distinctive Colombo line is an active slip zone.

The Colombo line is an "easy" passage, from which magmatic material is exiting and is a trench and volcanic formation zone, with the largest underwater volcano Colombo (Sakellariou et al., 2010)

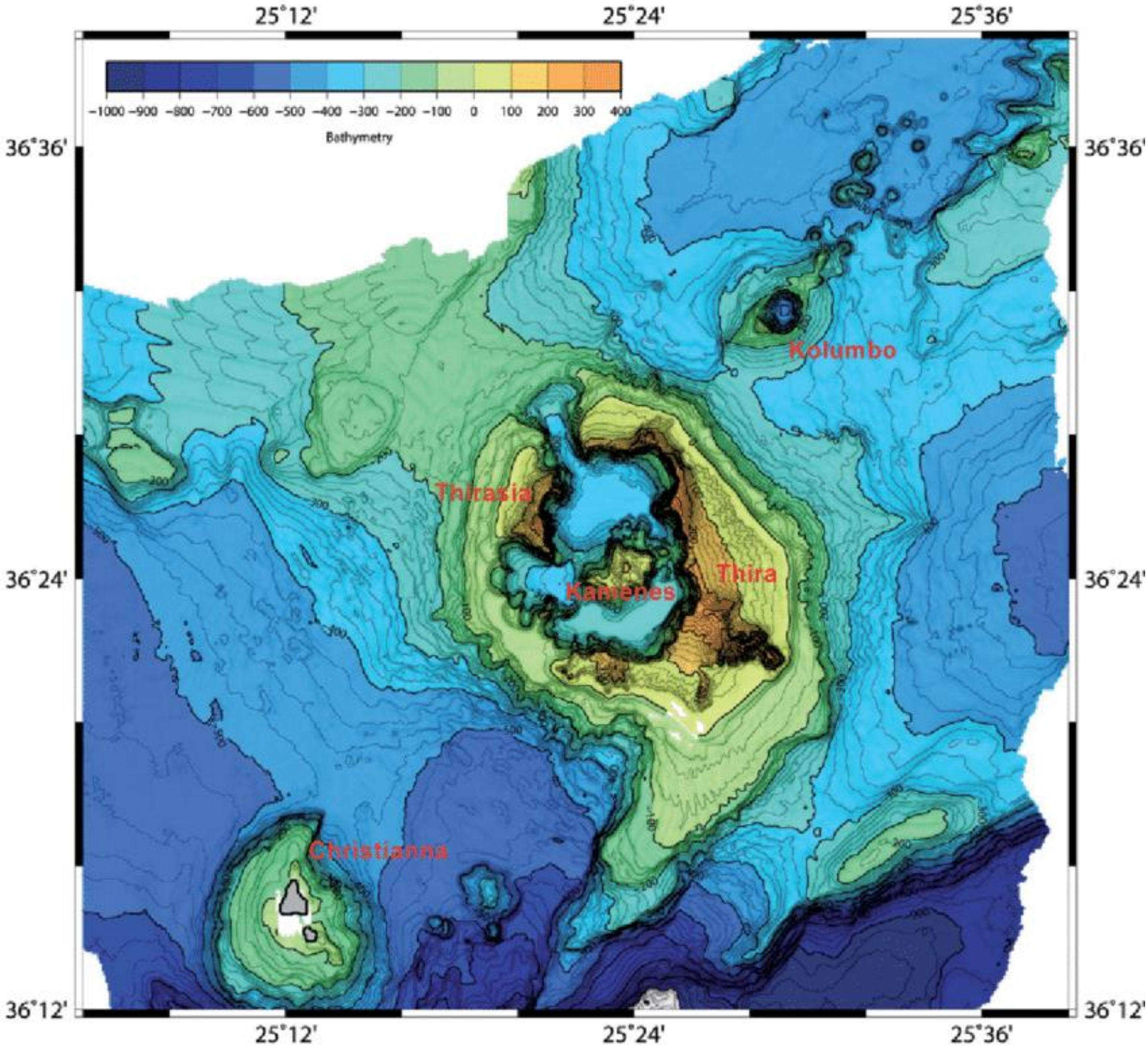


Figure 5: Combined bathymetric and topographic Map of Santorini volcanic field based on high resolution onshore and offshore data

Colombo, after surveys carried out in 2006, is considered to be one of the most important hydrothermal fields in Greece (NOAA Ocean Explorer, 2006). The hydrothermal pores, which are covered with a thick layer of bacteria, at the bottom of the caldera crater, are superheated with hydrothermal fluids of temperatures up to 224 ° C. These fluids have deposited polymetallic sulfides and sulphates and have built chimneys up to 4 m high

2.5 Pyroclastic flows

2.5.1Flow fluidization

With the simplest geological term pyroclastic flux or pyroclastic current (PDC-Pyroclastic Density Current), it is characterized as a rapidly fluidized mixture of solid and almost solid fragments of pyroclastic materials (mainly from young, primary and random volcanic wastes such as volcanic ash) moving on the surface of the volcanic field. The corresponding clouds are terribly hot with a hurricane force that can reach 700 km / h or 450 mph and a temperature of 550 ° C up to 1000 ° C. They are characterized as more devastating than all volcanic phenomena, since they are heavier than air and contain toxic gases, and they move like gasses due to their speeds. Pyroclastic streams are created by the bursting of stratigraphy and their products are acidic to intermediate.

The exceptional velocity of pyroclastic flows is due to fluidization. The floating pyroclastic flow has properties similar to those of a liquid, in spite of a moving mass of solid fragments. Thus, it can travel over long distances, characteristic of the example of a pyroclastic flow of the Koya volcano in Japan that ran a distance of 60 km, of which ten were above the water. The remaining deposits were 2 m thick but covered 60 km radius. Another example of pyroclastic flows is the Krakatau volcano eruption (Indonesia, 1883), which, having reached a distance of 40 km above the Sunda strait, retained their heat culminating in the burning of their victims on the coast.

The mobility now of the retrofitted flows is due to the lack of internal friction between the particles. A fluidized flow can be described as a dispersion of hydrocrack fragments in a medium consisting of fluidized fine fragments. The constant stream of hot, expansive gases holds the fine particles (ash and aggregates) in continuous swelling so that the larger fragments float in this solid-gas mixture. The expansion of the gases results from a combination of constant release of volcanic Irion from the overlapping pyroclastic and by entrapment, overheating and air expansion within the flow of traffic.

2.5.2 Pyroclastic activity

It is the characteristic activity of a magma with a high silicon content. During the pyroclastic activity, all kinds of volcanic suspensions are taken as the volcanic ash, which is ejected from a volcanic duct into the atmosphere. These explosions are quite intense and their speed is possible in some cases to exceed the speed of the sound, while the materials can be transported over long distances and cover hundreds or even thousands and thousands of kilometers.

Pyroclastic activity has direct effects on the environment, especially on fauna and flora, while destruction in residential areas and artefacts is also important. The most damaging cases are the explosive layers with a temperature of several hundred degrees Celsius, with more typical cases of disasters on the western coast of the USA.

2.5.3 Types of pyroclastic flows

The classification of pyroclastic flows and pyroclastic deposits is not easy. In general, there are two types of pyroclastic flows with their respective deposits. The first type of pyroclastic flows has been named Pelle. The pyroclastic flow of this kind has been named after the French geologist Alfred Lacroix, who thus called the volcanic flow of the Peele volcano. The flow was created by the explosive collapse of a developing lava dome at the top of the volcano and then swept the whole city. So explosions that create incandescent clouds are often called Pele

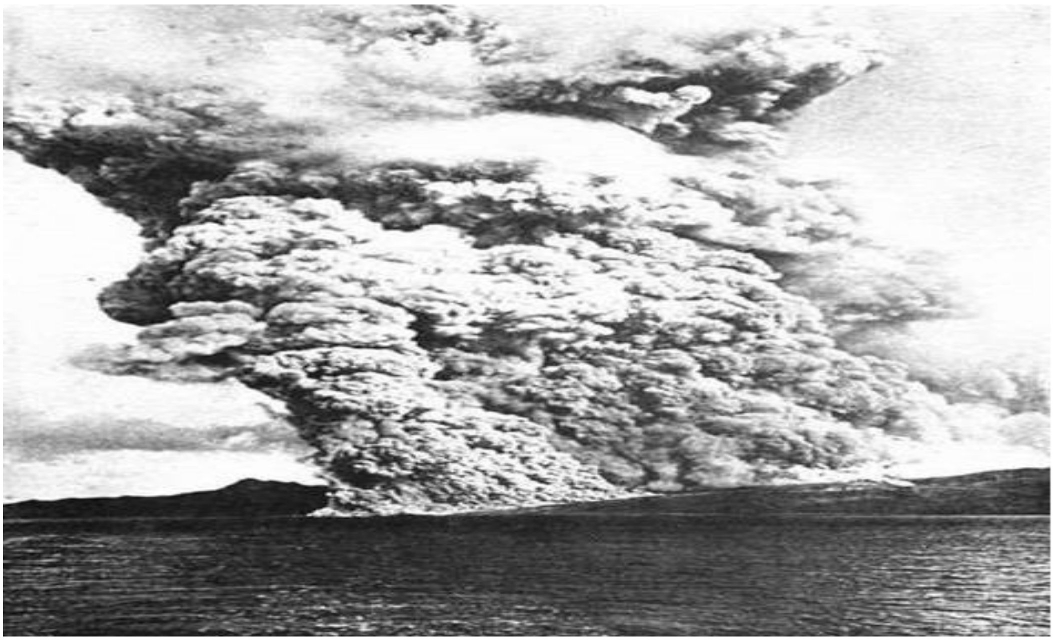


Figure 6: The volcanic cloud (nuee ardente) from the eruption of the Pele (volcano) volcano on December 16, 1902. Photo: Lacroix A.

The term "volcanic clouds" characterizes any kind of pyroclastic flow that is flowing from a dome collapse. These streams are composed of pieces and ashes, although the only visible to the human eye is the ash cloud they create which is separated during the movement of the flow. Therefore, incandescent clouds consist of two parts, an ash cloud and a pyroclastic avalanche, which is covered by the ash cloud and is not visible.

The deposits of incandescent clouds are composed of solid fragments resulting from the collapse of the lava. The deposits of incandescent clouds contain starch and ash, have a high density and extend to smaller areas on the other types of streams.

Since the collapse of an explosive column, pyroclastic fluxes are created, which are rich in bubble-filled quasars known as vortex streams. The lower part of the explosive column is called a thrust region and is characterized by a higher density than ambient air. However, the column continues to rise due to the thrust provided by the release and the sudden expansion of the gases. The column collapses because of gravity as a mass of pumice rising rapidly on the volcanic slopes. The state of incandescent clouds and pumice currents is fluidized while the latter show greater energy and mobility. The greater energy and mobility now is due to its lower density but mainly to the higher kinetic energy owing to the collapse of its converted dynamic energy, which has been attributed to the rise in the column at a height of several kilometers.

A bullet current is now composed of three parts. The main body is grounded and consists of fragments of the pumice in a mass of ash. The second part is an ash cloud covering the pyroclastic layer, similar to the case of incandescent clouds and on the front of the flow, where the ripples are promoted as loose fronts and form the third part of the vortex streams, the land masses

Figure7: Pyroclastic Flows (Sufriere Hills, 1997, Montserrat). Photo: Heard R., Cole P.

The Ignimbrites are deposits of pyroclastic streams consisting mainly of pumice and mainly of ash. They are acid magma products, they appear as compact partially glued layers that resemble lava flows and can cover vast areas of many square meters.

2.5.4 Effects of pyroclastic flows

The pyroclastic flows destroy almost everything in their path. By transporting rocks of ash-sized rock formations and traveling to the ground at speeds usually above 80 km / hr, pyroclastic flows shatter, bury or carry away almost all the objects and structures they find on their way. Large temperatures, usually 200-700ºC, burn out trees, plants, homes

Pyroclastic flows vary in size and speed, but even small flows that extend <5 km from the volcano can destroy buildings, forests, and crops. Even on the margins of the pyroclastic flow people and animals are dying of burns and inhalation of poisonous gases. Pyroclastic flows generally follow valleys or other low areas and, depending on the amount of material they carry, form loose deposits with a thickness of 1-200 m

a) Subsequent rainfall drifts loose materials and creates streams that increase drainage and corrosion.

b) The pyroclastic flows melt the snow and the ice on top and the slopes of the volcano creates a lahar.

c) The materials of the pre-flowing streams block streams and small rivers creating dams and ponds that, if broken or overflowing, create lahars.

The pyroclastic streams, are destroyed by direct impact, fill areas with volcanic debris, melt ice, snow and create lahars, burn homes and crops.

Figure 8: **Pyroclastic flow (Pinatubo, 1991, Philippines).**

Chapter 3.Equipment & Methodology

3. Methodology

3.1 Description of General Methodology

The swath bathymetry and seismic profiling data presented in this MSc Thesis was acquired during two cruises of the Hellenic Centre for Marine Research in the area on board R/V AEGAEO. Swath bathymetric data was obtained during the first cruise in 2001 by using the 20 kHz SEABEAM 2120 swath system. The second cruise took place in 2006 and included complementary swath bathymetry data and airgun 10ci single channel seismic profiling. The data sets presented here have been provided by Dr D. Sakellariou (HCMR) for the implementation of this Thesis.

The interpretation and graphical presentation of the seismic data and the line-drawing of the resolved stratigraphy was done with the use of CorelDRAW x 3 and Kingdom. During the interpretation of the seismic profiles, the main reflectors were identified and the basic acoustic units were determined through their geometrical relationship with the overlying and underlying layers and their acoustic character. After the completion of the seismic stratigraphy of the area, the results were correlated with stratigraphic and lithological data of nearby areas which are available from existing studies. Then we tried to correlate the seismic stratigraphy obtained for Colombo with the one of adjacent basins as determined by previous workers like for example Tsunami hazard risk of a future volcanic eruption of Colombo submarine volcano, NE of Santorini Caldera,Greece, D.Sakellariou, et all, July 2014 . That helped us to create a clear picture of the geological structure of the study area, develop a tentative chrono-stratigraphy of the basin and draw conclusions on the age and origin of the observed pyroclastic flows. Finally we proceeded to data interpretation and the spatial distribution of pyroclastic flows derived from Santorini volcanic field, in Colombo volcano.

3.2 Sub-Bottom Profiler

Acoustic Sub-Bottom Profiling (SBP) systems are used to determine physical properties of the sea floor and to image and characterize geological information a few metres below the sea floor. In recent years, sub-bottom profilers have been used to measure small scale sedimentary structures and processes in high temporal and spatial resolution. The systems have been widely adopted by marine researchers because of their ability to collect data rapidly and non-intrusively.

Sub-bottom profilers are usually comprised of single channel source that sends sound pulses into the shallow sub-sea floor sediments. The sound pulses bounce off the sea floor and subsequent buried sediment layers according to differences in their acoustic impedance (hardness). Acoustic impedance is related to the density of the material and the rate at which sound travels through this material. The different times taken for this signal to be returned and recorded by the sub-bottom profiler indicate how deep the layers are below the sea floor. The surface of the different rock strata beneath the sea floor are mapped over the study area.

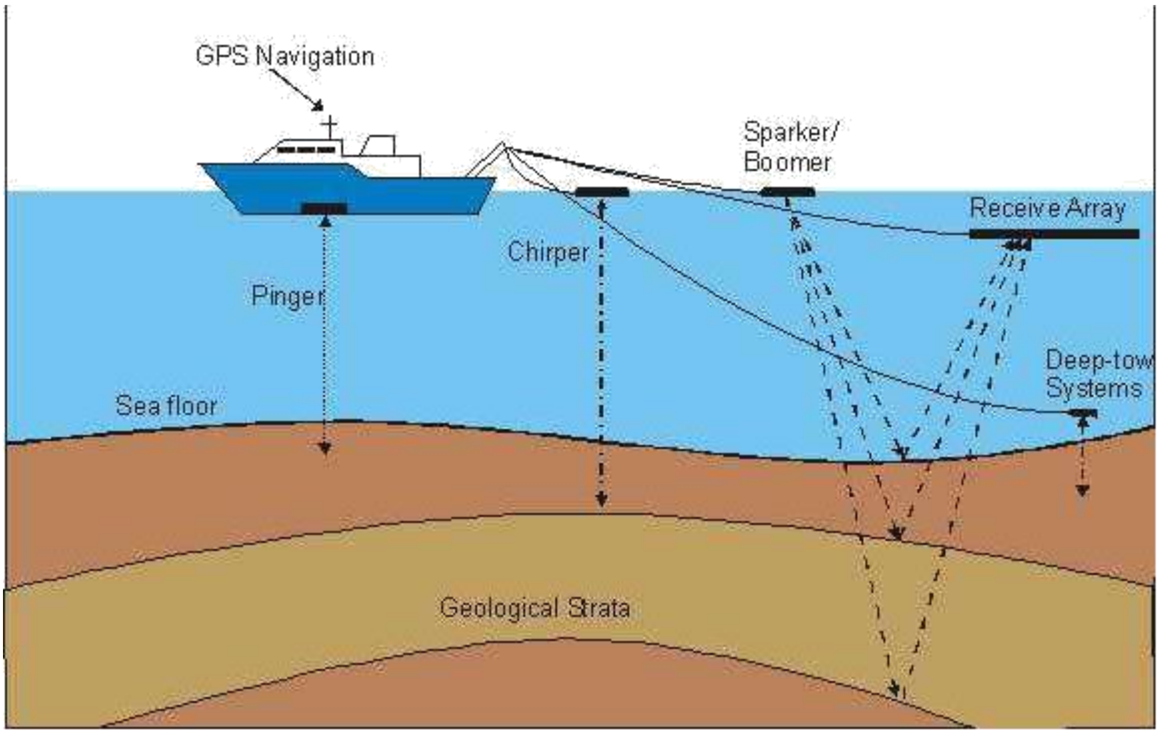


Figure 9: Deployment of various shallow-water sub-bottom profiling systems. Image from Stoker et al. (1997)

There are a number of shallow SBP systems which operate using various types of sound sources and frequencies. Different SBP systems are used depending on the objectives of the survey, water depths and prior knowledge of the rock types. The 'Pinger' is a high frequency system which operates on a range of single frequencies between 3.5 kHz and 7 kHz. Depending on various factors, such as the type of sediment and the sound source characteristics (frequency, power), SBPs can achieve sea floor penetration from just a few meters to more than 50 m and vertical resolution (layer thickness) down to approximately 0.3 m. SBPs are particularly useful for delineating shallow features such as gas accumulations and buried channels. The non-linear parametric sub-bottom profilers simultaneously transmit two signals of slightly different high frequencies (e.g. 100 and 110 kHz). Their interaction generates by interference a new low-frequency signal (with the difference frequency). They can achieve very high vertical resolution and are particularly good to use in shallow water environments.

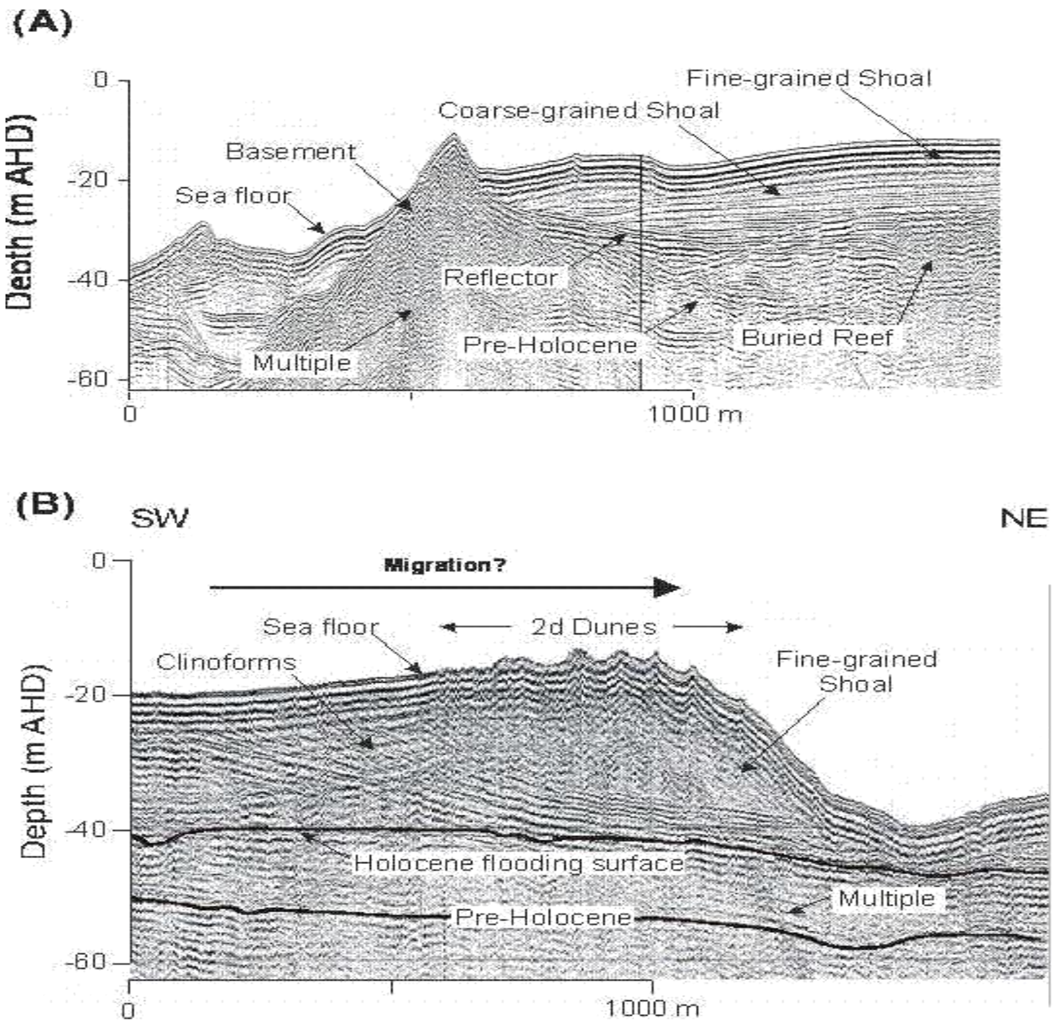


*Figure*10: Boomer sub-bottom profiles of the sea floor around the Whitsunday Islands, Great Barrier Reef platform, Australia (after Heap, 2000). The system used was an EG & G TM Uniboom sounder, triggered every 0.5 s at 200 J, and towed 0.3 m below the surface 11 m behind an 8 element hydrophone array. (A) The reflectors reveal a range of recent, Holocene, and pre-Holocene features, showing an exposure of bedrock surrounded by recent sand accumulations. (B) Steeply NE dipping bedding structures (clinoforms) and surficial dune bedforms record the accumulation and present-day movement of sand into a depocentre.

3.3 Air gun

As stated above, the data of this Master thesis was collected by using an Air gun 40 cubic inches sound source. Airguns generate very low-frequency acoustic energy (2Hz-500Hz) as a result of the explosive release of high-pressure air directly into water (by generating bubbles of compressed air). The rapid release of highly compressed air (typically at pressures of ~2000 psi) from the airgun chamber creates an oscillating air bubble in the water. The expansion and oscillation of this air bubble generates a strongly peaked, high-amplitude acoustic impulse that is very effective for seismic profiling. The pulse duration ranges from 5 to 15 msec. The penetrating ability ranges between 100 and-700 meters, depending on the nature of the sub-seafloor stratigraphy. The main features of the pressure signal generated by an airgun are the strong initial peak and the subsequent bubble pulses. As mentioned earlier, airguns are designed to generate most of their acoustic energy at low frequencies, which are most useful for seismic penetration beneath surficial seabed sediment layers. Due to their impulsive nature, airgun sources inevitably generate sound energy above centered at 100-200 Hz, although the energy output at these frequencies is substantially less than at low frequencies. In general, the frequency output of an airgun is inversely dependent on its volume: larger airguns produce lower-frequency signals. Air gun with 40 cubic inches chamber operating at 2000 psi provides an effective frequency range between 30 - 250 Hz, penetration of about 1 second two way travel time (TWT) (>750m below seafloor) in water depth of about 4000-5000 m and vertical resolution of 3-4m. In the reality the penetration may be lower depending on the nature of the substrate while the vertical resolution is compromised with depth

Figure 11: Bolt 600B air-gun with a 20 in3 firing chamber and bolted into a yellow tow fish (JIP).

Chapter 4.Interpretation of Seismic profiles

4. Tectonic Analysis -Geological Setting

The processing and interpretation of seismic data, as analyzed in the previous chapters, provide us with information on the main tectonic processes which have dominated the evolution of Colombo Volcano during Quaternary.

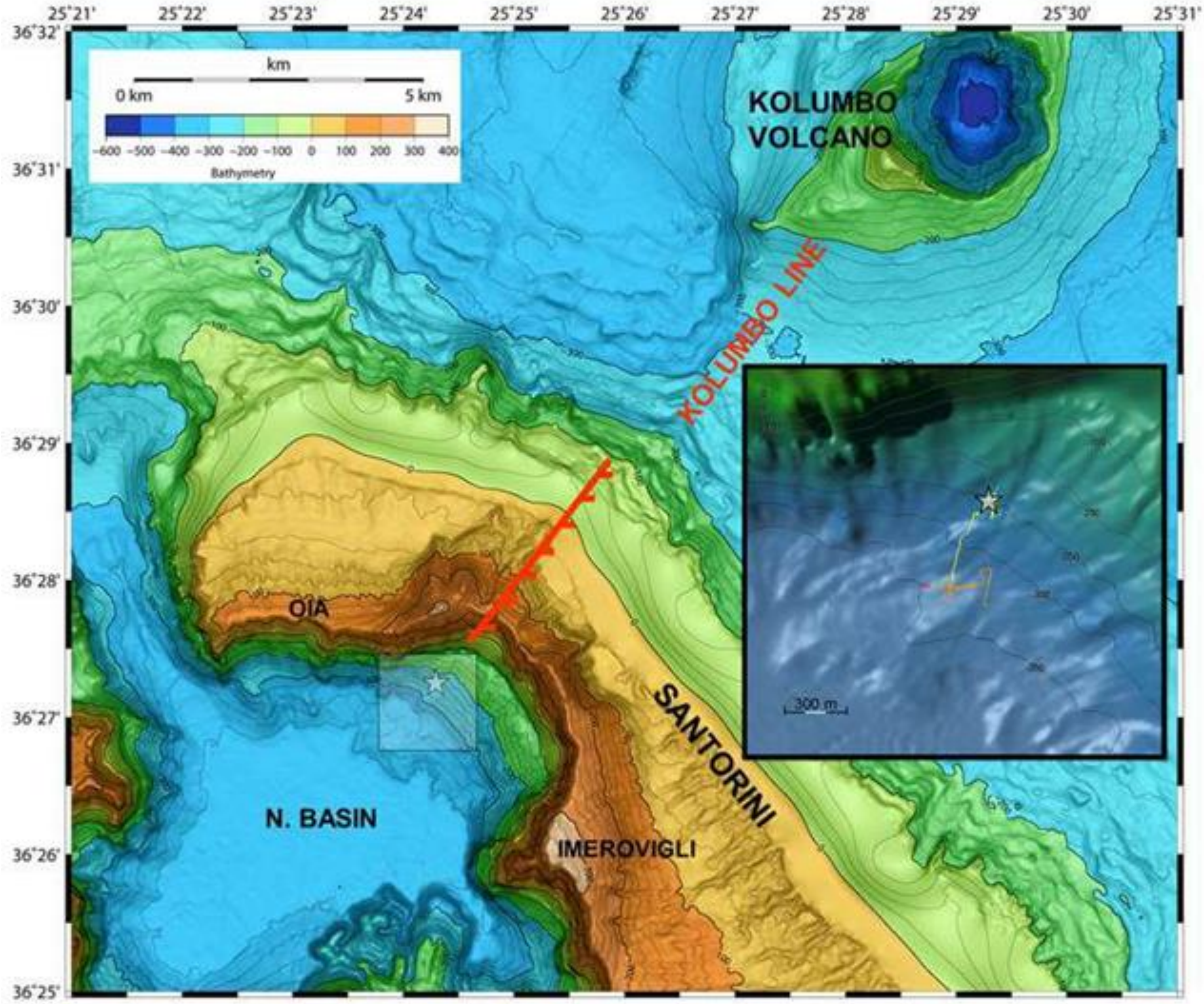


Figure 12: Topographic relief map of the northern Santorini volcanic field. The white star icon shows the location of the Kallisti Limnes CO2 pools. The onshore Colombo fault is indicated by a dashed red line, which along with the Colombo line, describes the northeast portion of the Christianna-Santorini-Colombo (CSK) tectonic line. The inset box shows a detailed view from the southwest of the caldera slope bathymetry around the study site; submersible vehicle track lines are indicated as red, orange, and yellow lines, corresponding to the first and second AUV dives, and the HOV dive, respectively. Credit: Illustration courtesy of Camilli, et al

Cycladic islands, can be characterized as metamorphics (gneiseis, schists, marbles, volcanics (tuffs, pumices, basalts) as well as Neogene-Quaternary sediments (sandstones, marls) (Bornovas and Rondoyanni, 1984,; Melidonis, 2005.).

According to Piper et al., (2007) Santorini's basement consists of metamorphic rocks belonging to the Attico-Cycladic complex, which was formed by orogenesis in Paleocene to Eocene followed by extension since Miocene.

The NE to SW directed strike-slip faults characterized the Pliocene basin in the southern Aegean which emerged in the late Pliocene to early Quaternary (Pe-Peiper et al., 2005).These faults are considered to be the consequence of the interactions between the Africa and Aegean-Anatolian plates.

The depth of the magma chamber beneath Colombo submarine volcano is between the range of 5,5km and 6, 8 km. (Colombo submarine volcano (Greece): An active window into the Aegean subduction system, Rizzo et al, 2016.)

The uppemost unit in our seismic data, (Colombo 1650 PF, Unit S3) is interpreted as pyroclastic flows or mass-transport deposits, interbedded with stratified marine sediments. Unit S2 is attributed to formations of Pliocene age, mainly consisting of terrestrial or shallow marine sediments.

Sakellariou et at al. (2010) revised the Anydros Basin and proposed that the spatial distribution of the volcanos hosted in this basin is controlled by a 40 km, long strike -slip fault zone.

Major explosive activity in Colombo area, began around 360 ka BC. Since that time 12 large explosive eruptions have occured.Repeated effusion in the northern part had changed the present day sea level. The Colombo has been capped by a 2-km^3 dyke-fed succession of dacitic lava. The dacitic lava reached a thickness of up to 200 m on the western flank of the edifice.

During the eruption of 1650 AC the upper area of Colombo, composed of over 250 m of interbedded pumice lapilli and pumice block breccias beds was formed.

The explosive eruption was driven primarily by volatile degassing, due to the high volatile content of the Colombo magma.

The 1650 Colombo tefra, formed fine grained deposits which can be traced 19 km far away from the crater.This tephra deposits surrounding Colombo represent the complement to the very fine-poor proximal pumice units exposed to the crater walls.

4.1 Colombo 1650 Pyroclastic Flow (S3)

Colombo is an active submarine volcano in the Aegean Sea, about 8 km northeast of Cape Colombo, Santorini Island. The largest of a line of about twenty submarine volcanic cones extending to the northeast from Santorini, it is about 3 km in diameter with a crater 1.5 km across.It was "discovered" when it breached the sea surface in 1649-50, but its explosion was not to be compared to the well-known Thera explosion and caldera collapse, currently dated ca. 1630 BCE, with its devastating consequences for Minoan civilization.

The 1650 explosion, which occurred when the accumulating cone reached the surface, sent pyroclastic flows across the sea surface to the shores and slopes of Santorini, where about seventy people and many animals died. A small ring of white pumice that was formed was rapidly eroded away by wave action. The volcano collapsed into its caldera, triggering a tsunami that caused damage to nearby islands up to 150 km distant.The highest parts of the crater rim are now about 10 m below sea level.

The crater floor, averaging about 505 m below the sea surface, is marked in its northeast area by a field of hydrothermal vents and covered by a thick bacterial community, (the 2006 NOAA expedition). Superheated (measured as hot as 224°C) metal-enriched water issuing from the vents has built chimneys of polymetallic sulfide/sulfates to a maximum height of 4 m, apparently accumulated since the 1650 event.

Revised, more accurate estimates of the total dense rock equivalent volume of the Minoan event(s), consisting of pyroclastic sea floor deposits, distal ash fallout and ignimbrites on the island of Santorini, is likely about 60 km^3, a greatly increased estimate, comparable to the largest historic explosion.

4.2 Minoan Pyroclastic flows (S2)

The Minoan Eruption of Santorini in the Late Bronze Age was one of the strongest experienced by humankind. Before the eruption, the shape of Santorini was similar to the one it has today: There was a ring-island: a water-filled caldera with an island in the center. The caldera had an opening to the southwest. The eruption not only changed the shape of that ring island but also buried flourishing settlements under a thick layer of pumice and ashes. All life on Santorini was destroyed. The Minoan Eruption left a synchronous layer of tephra over the eastern Mediterranean region which is an important marker of chronology.

Besides the destruction on Santorini itself the entire region was hit by earthquakes, tsunamis, floating pumice, and ash fall. Tsunamis must have devastated the coastal areas of adjacent islands, as recently evidenced on the north coast of Crete. Meanwhile, the eruption cloud might have triggered global climatic changes that resulted in the destruction of harvests in the Eastern Mediterranean. These, together with the destruction of the Minoan fleet by tsunamis, must have had severe effects on the trade network in the area – for a few generations at least.

Although the fracturing process is not yet known, the altitudinal statistical analysis indicates that the caldera had formed just before the eruption. The area of the island was smaller, and the southern and eastern coastlines appeared regressed. During the eruption, the landscape was covered by the pumice sediments. In some places, the coastline vanished under thick tuff depositions.

The eruption was of the Philian type and it resulted in an estimated 30 to 35 km high ash plume which extended into the stratosphere In addition, the magma underlying the volcano came into contact with the shallow marine embayment, resulting in a violent steam eruption.

The eruption also generated a 35 to 150 m high tsunami that devastated the north coast of Crete, 110 km away. The tsunami affected coastal towns such as Amnisos, where building walls were knocked out of alignment. On the island of Anafi, 27 km to the east, ash layers 3 m thick have been found, as well as pumice layers on slopes 250 m above the sea level

Elsewhere in the Mediterranean there are pumice deposits that could have been caused by the Thera eruption. Ash layers in cores drilled from the seabed and from lakes in Turkey however, show that the heaviest ash fall was towards the east and northeast of Santorini. The ash found on Crete is now known to have been from a precursory phase of the eruption, some weeks or months before the main eruptive phases, and it would have had little impact on the island. Santorini ash deposits were at one time claimed to have been found in the Nile delta, but this is now known to be a misidentification

The original form of the island was also altered by the eruption. It seems that much of what was lost from the central part of the ring-island was added to the outer margins. In particular, the eastern side of Thera was considerably widened by debris washed from the rim and deposited on the alluvial plain. The former island of Monolithos was joined to Thera, whereas the Pre-Kameni Island inside the caldera disappeared completely

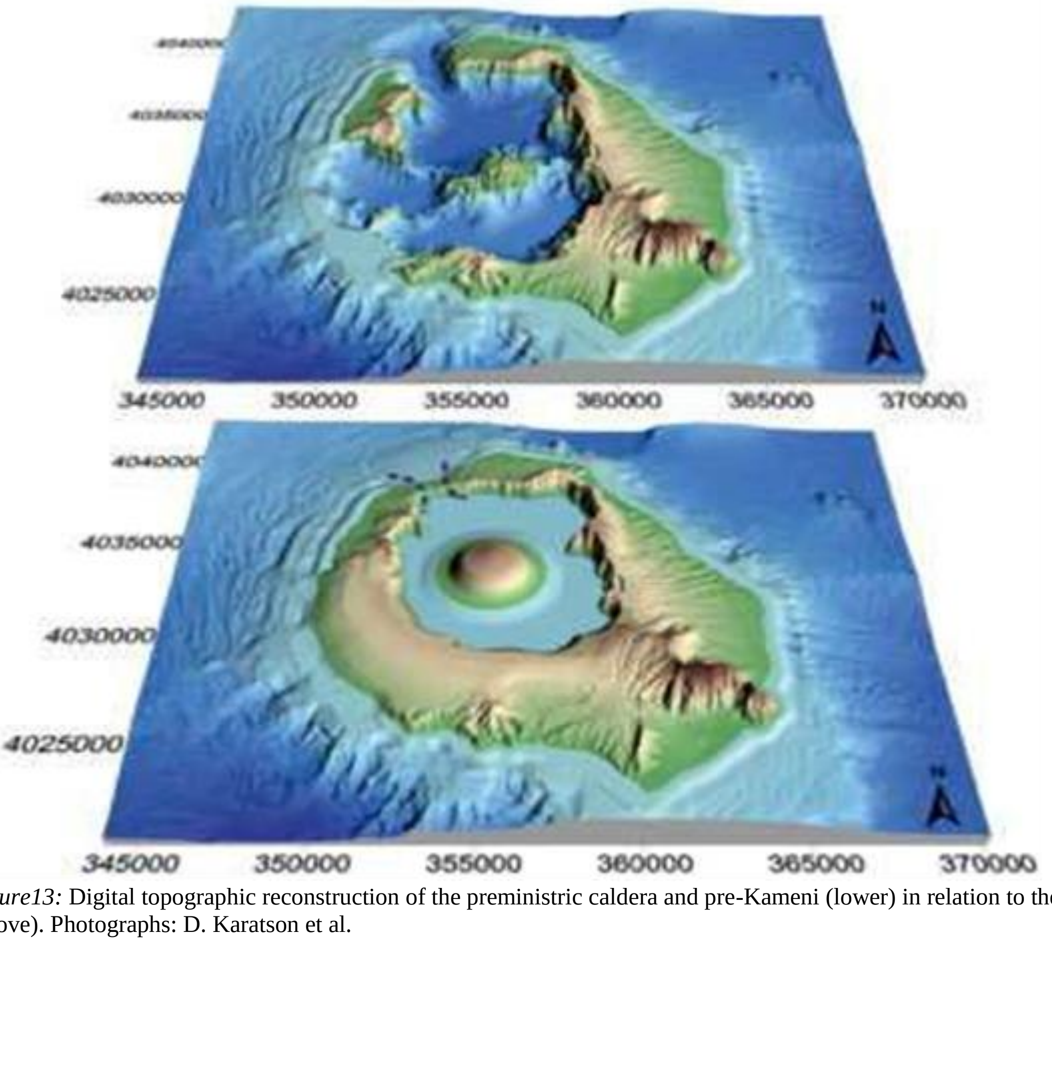


Figure13: Digital topographic reconstruction of the preministric caldera and pre-Kameni (lower) in relation to the current image (above). Photographs: D. Karatson et al.

4.3 Seismic Profile Presentation

This study based on the acquired data constructed several seismic profiles that form a dense network of NE lines in the area around the Santorini Island and the Colombo volcano. The position of these profiles can be seen in the Figure 14.

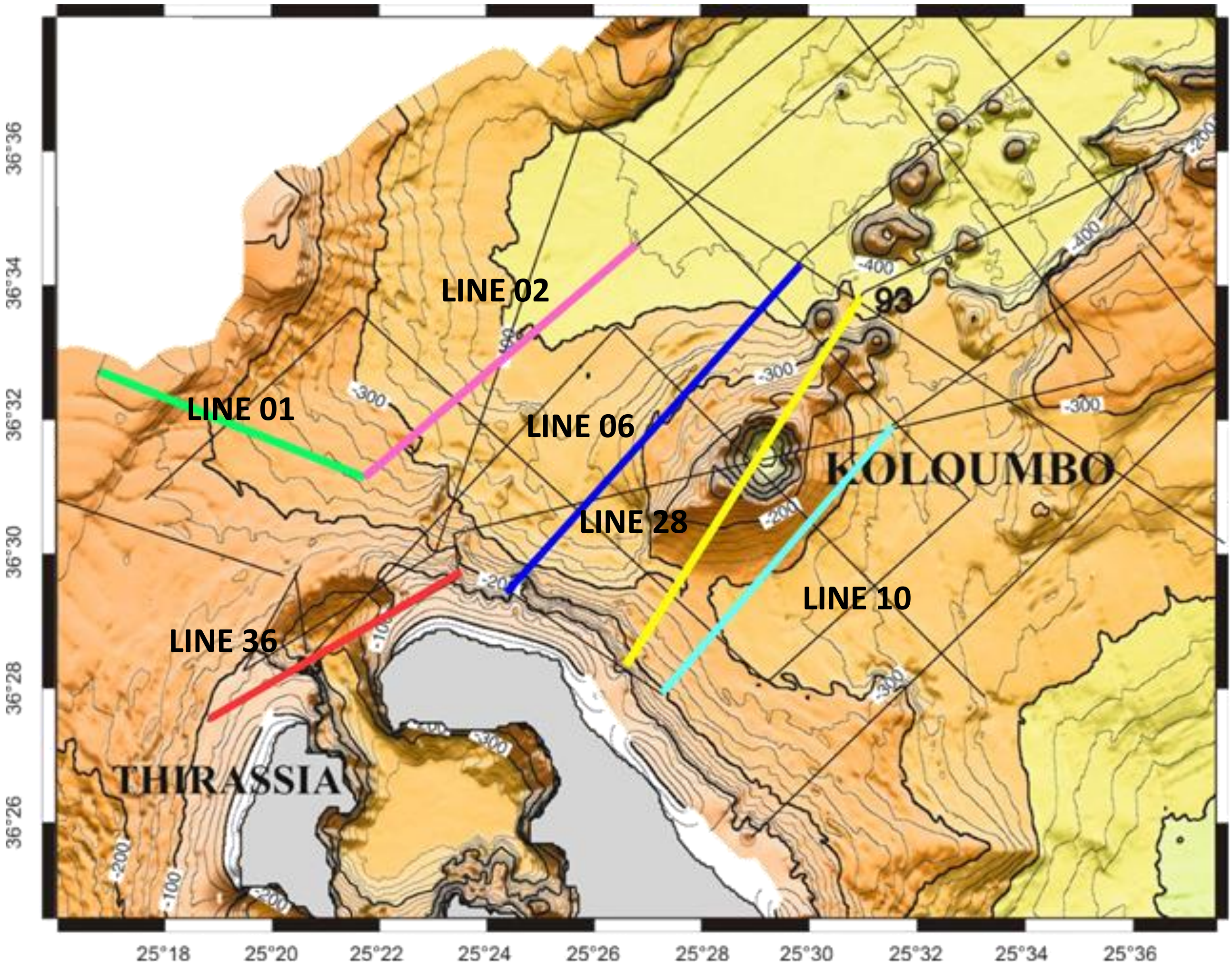


Figure 14:Map of NE area of Santorini identifying the exact position of the seismic lines studied in this Thesis, Line 01, Line 02, Line 06, Line 28, Line 10, Line 36

The seismic lines have been grouped in three categories according to their orientation:

- Line 01 and Line 02 and Line 36, which located North area of Santorini and West of Colombo
- Line 06 and Line 10, which is located in the North and South area of Colombo.
- Line 28 which crosses the Colombo

4.3.1 Seismic Stratigraphy

The processing of seismic profiles, allow us to recognize a variety of different acoustic units .The main seismic facies determined based on these seismic profiles are grouped in the following table 1.4.

Seismic facies are ''mappable, three dimensional seismic units composed of groups of reflections whose parameters differ from those of adjacent facies units''

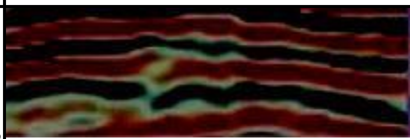
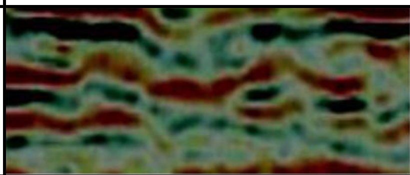
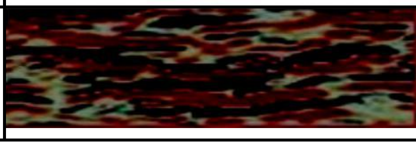
Seismic facies	Reflection configuration	Examples (vertical scale bars)
1	**Parallel ,closely spaced, continuous, high amplitude reflectors**	
2	**Semi parallel ,semitransparent, widely spaced discontinuous reflectors**	
3	**Contorted to mound shaped ,discontinuous, high frequency**	
4	**Oblique, semi continuous**	
5	**Oblique, discontinuous**	
6	**Chaotic, inherent ,undulating, discontinuous, high amplitudes reflectors**	
7	**Contorted to mound shaped**	

Table 1.4 the main seismic facies recognized on Colombo Area, Santorini, Greece

4.4 Seismic Profiles

4.4.1 Seismic Profiles No 1

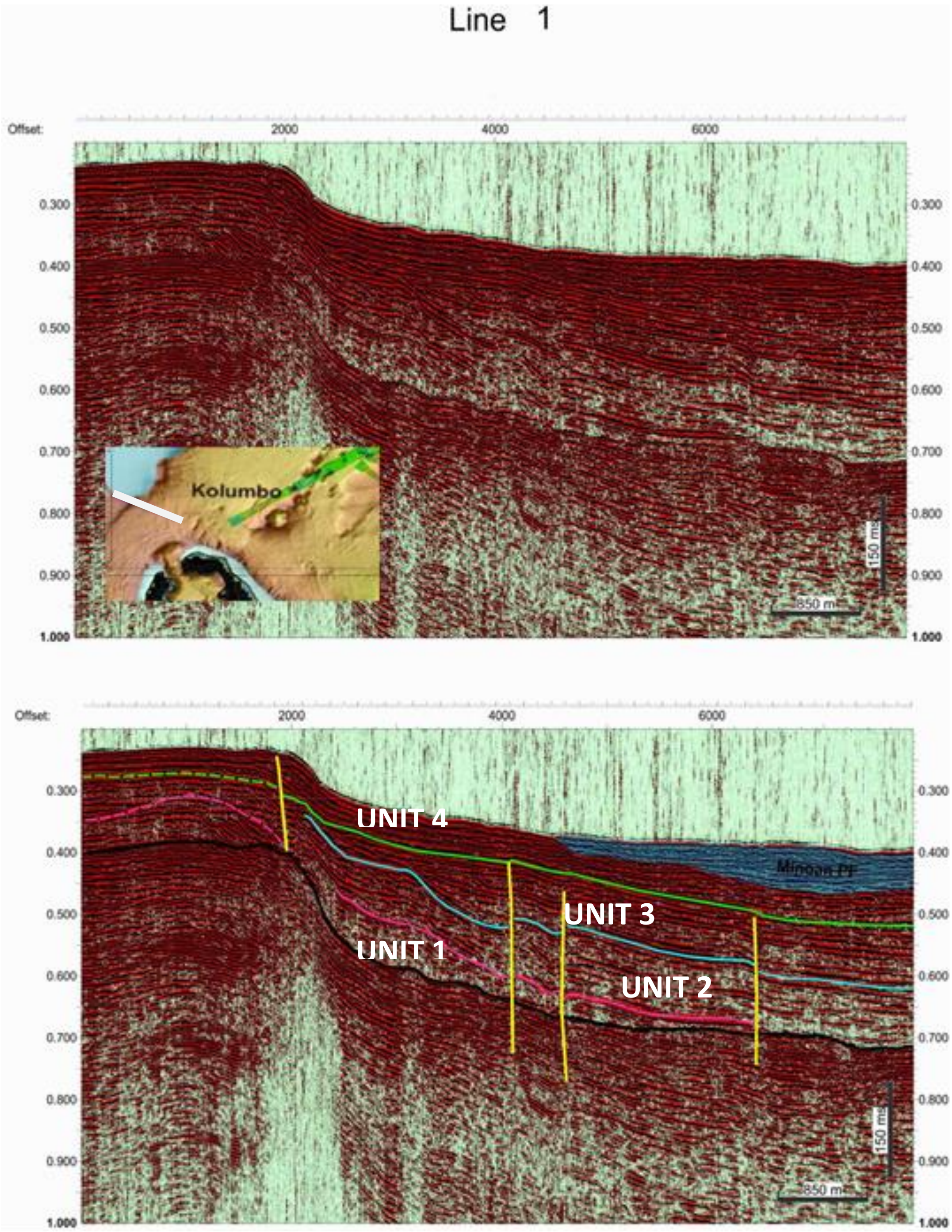


Figure 15: Seismic Profile No1, North of Santorini

The seismic profile No1 (Figure 15), which is oriented SE to NW and crosses the north part of Santorini island, northwest from the Colombo volcano, provides a characteristic stratigraphy of Santorini. The profile shows a good stratification and 4 units are identified. The units are separated from each other based on reflections and their seismic properties.

The first and oldest unit, Unit 1, has a thickness of 0,020-0,080 sec. It is characterized by low amplitude and semi-continuous to discontinuous reflectors, contorted to mount shaped. It also contains some high reflectors of low amplitudes. The west part of Unit 1 is representative of the first category of seismic facies listed in Table 1.4, since it has parallel, continuous, high amplitude reflectors. In the east part of Unit 1, continuous, low amplitude reflectors can also be recognized.
Profile No1 is a representative seismic line across the regional anticline in the western region of studied area and the basin which is located adjacent to Colombo Seamount.

Above Unit 1, there is the younger Unit 2 with 0.02-0.09 sec thickness and strong reflectors. It is characterized by parallel, continuous reflectors and exhibits high amplitudes in its west part, while its east part is characterized by semi-continuous to discontinuous reflectors with some chaotic areas.
The subsequent unit, Unit 3, has a thickness of 0.01-0.08 sec. It is characterized by closely spaced, semi-parallel, continuous, high amplitude reflectors. Unit 3 is located conformably on top of the underlying sedimentary sequence in the basin but exhibits an angular unconformity at the basin's margin. It is bound to the crest of the regional anticline shown at the western part of Figure 4.2.

Unit 3 is a representative of the second category of the seismic facies showed in Table 1.4.
The last unit, Unit 4 has an average thickness of 0.031 sec. It is characterized by oblique, continuous to semi-continuous, closely spaced reflectors and high amplitudes. It rests conformably on the underlying sedimentary sequence in the basin but with an angular unconformity (down lap relationship) at the basin's margin. Unit 4 is a representative of the fourth category of the seismic facies listed in table 4.1.

In the eastern part of the seismic profile No1 we can observe a different unit, Unit B, which is a deposit of Minoan pyroclastic flows. This unit was compared to the highest unit observed by Sakellariou et al (2012) and Hubscher et al (2015), for the northern part of Santorini's intercalant basin. After comparison, Unit B is found to be one of volcanic origin, consisting primary of submarine pyroclastic flows emplaced at high temperature or water supported flows generated by transformation of hot flows as they entered the ocean all around Santorini.

4.4.2 Seismic Profile No 2

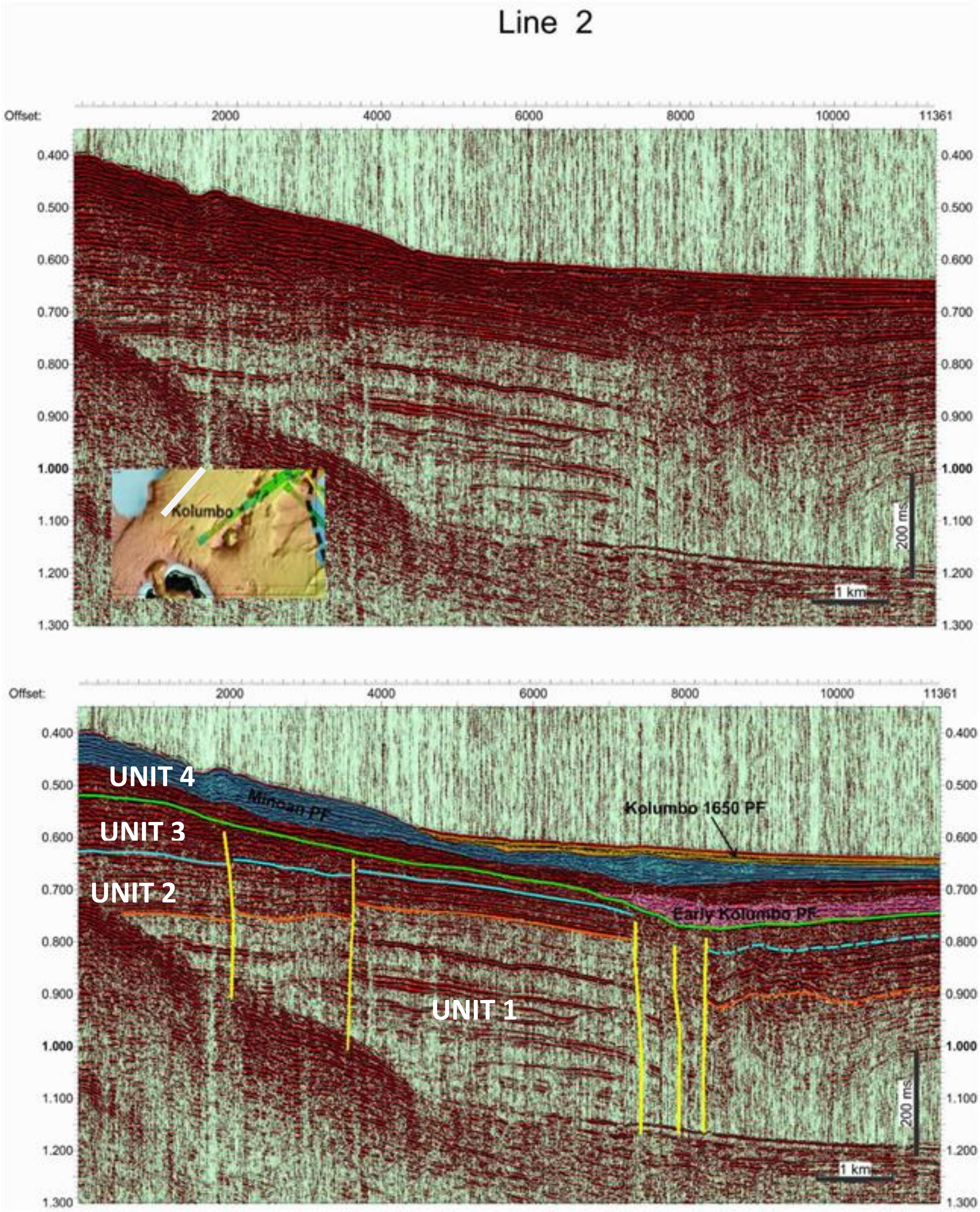


Figure16: Seismic Line No 2, North of Santorini

The seismic profile No2 (Figure 16), a SE-NW striking profile, represents a characteristic stratigraphy of the Northern region of Santorini Island. The seismic profile shows four units with normal, continuous stratification. Two parts of the seismic profile No2 are fault controlled. Between offset 554-714 and 769-783 along the seismic profile, two zones of faults can be identified. These are older faults which have been covered by the younger sedimentary units.

Unit 1 shows low amplitude and semi-continuous reflectors with some strong scattered reflectors. The thickness of the Unit 1 is between 0,040 and 0,060 sec. The NW part of this unit exhibits parallel, continuous, high amplitude reflectors, like the first category of the seismic facies in the Table 4.1. In the SE part of Unit 1, however, there are some semi-continuous reflectors with low amplitudes.

Unit 2 is a unit similar with the third category of the seismic facies of the Table 4.1. The thickness of the unit is about 0,030 sec. Discontinuous reflectors, contorted to mount shaped, with some high reflectors of low amplitude form this unit. Also, in the SE part of the seismic profile No2 down lap bounding chaotic facies can be observed.

Unit 3, with a thickness of 0,050 sec, can be characterized as a unit with strong reflectors. It consists of parallel, continuous seismic facies which exhibit high amplitudes. Unit 3 of the seismic profile No2 belongs to the first category of the Table 4.1. A continuous and draping underlying topography, as a bounding relationship appears to Unit 3. The east part of the seismic profile No2 shows blocky, semi-continuous reflectors which are separated by linear, vertical to oblique surfaces.

Finally, the youngest Unit 4 has a thickness of approximately 0,035 sec. Oblique, semi-continuous reflectors with high amplitudes characterize this unit. In the seismic profile No2, there is a slope which starts from the West and deeps towards the East. There are also some positions in the East part which exhibit semi-continuous, contorted to mount shaped reflectors.

In the top of the seismic profile No2, we can see three different deposits of pyroclastic flows, which have influenced the Santorini Island over time. The chronological deposits are analyzed in the previous chapter

4.4.3 Seismic Profile No 6

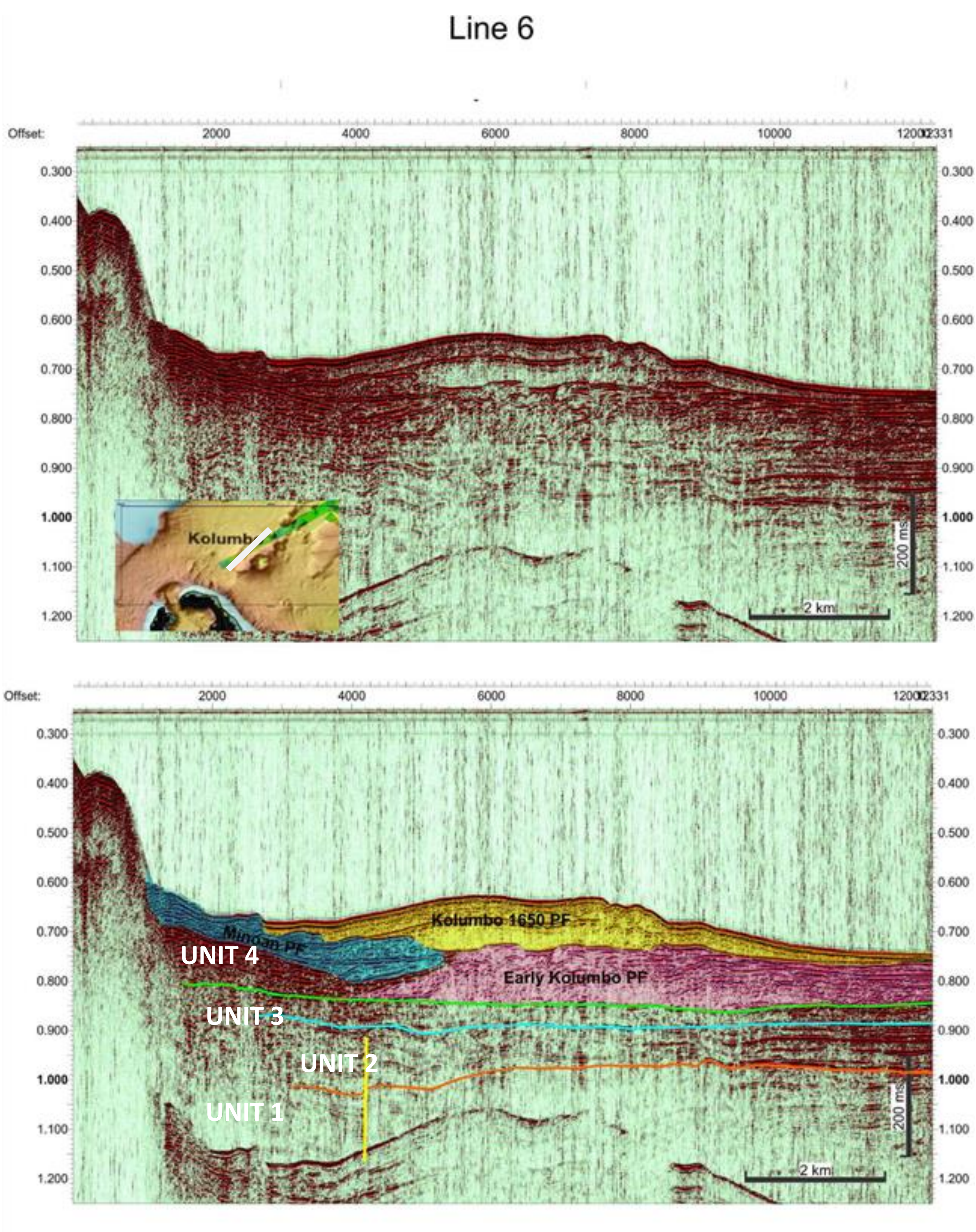


Figure 17: Seismic Line No 6, North of Colombo Volcano

The Seismic Profile No 6 (Figure 17) is located in the NW part of Colombo Volcano and its orientation is E-W.

The oldest unit of the seismic profile No6, Unit 1, is characterized by semi-parallel, continuous, low frequency reflectors. In the east part the reflectors degrade to discontinuous. This unit is a combination of the sixth and seventh categories of the seismic facies listed in Table 4.1.

Unit 2, above Unit 1, with a thickness of 0.064 sec, is characterized mainly by semi-continuous reflectors. However, some chaotic reflectors can be seen in its western part.

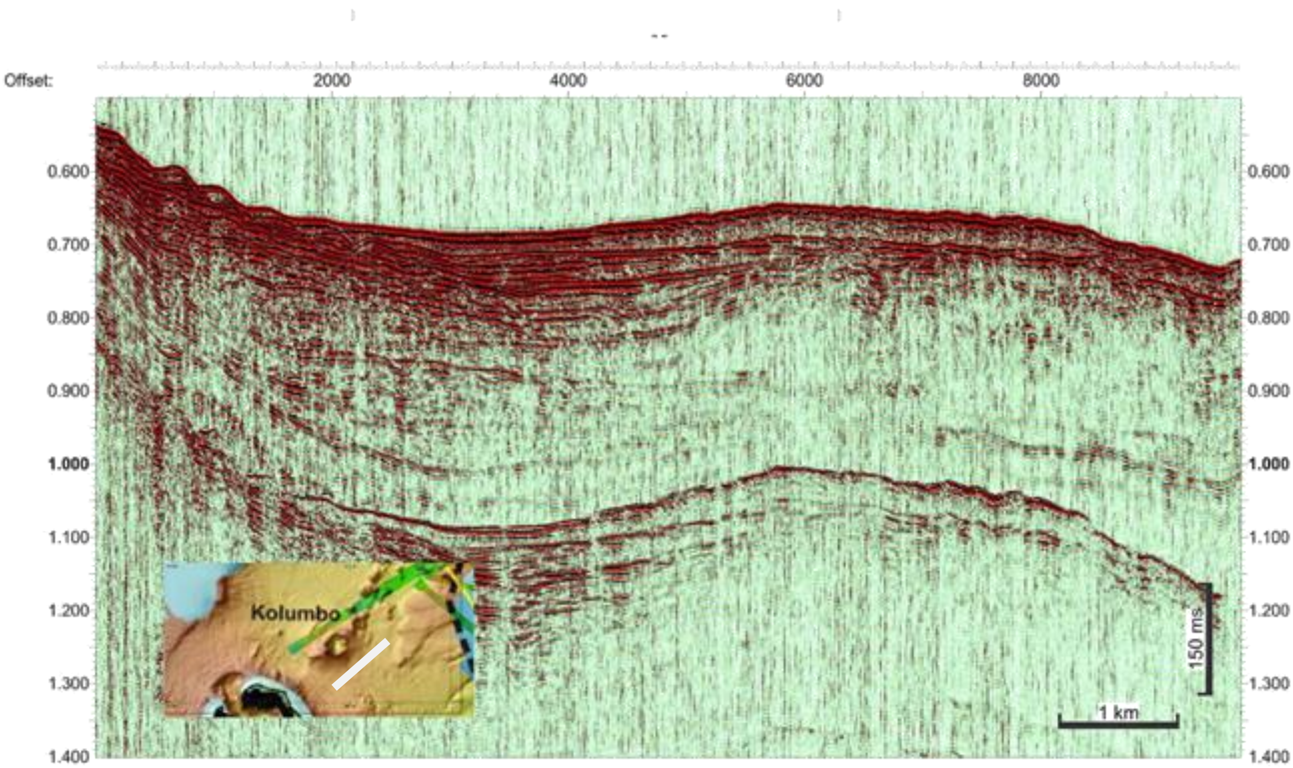
Unit 3, is characterized by semi parallel discontinuous reflectors, with high amplitude in the east part. Unit 3, is a unit, with 0,035 sec, thickness and with some strong reflectors in its west part.

The last unit, Unit 4, of seismic profile No 6 of the basin filling north of Colombo volcano, characterized by seismic reflectors having a parallel seismic facies and showing bidirectional on laps. Unit 4 is located in the west part of our seismic profile No 6.

Above Unit 4, three different chronological deposits are obvious. These deposits were formed during the eruptions which took place over the years and are analyzed in the previous chapter.

4.4.4 Seismic Profile No 10

Line 10



Line 10

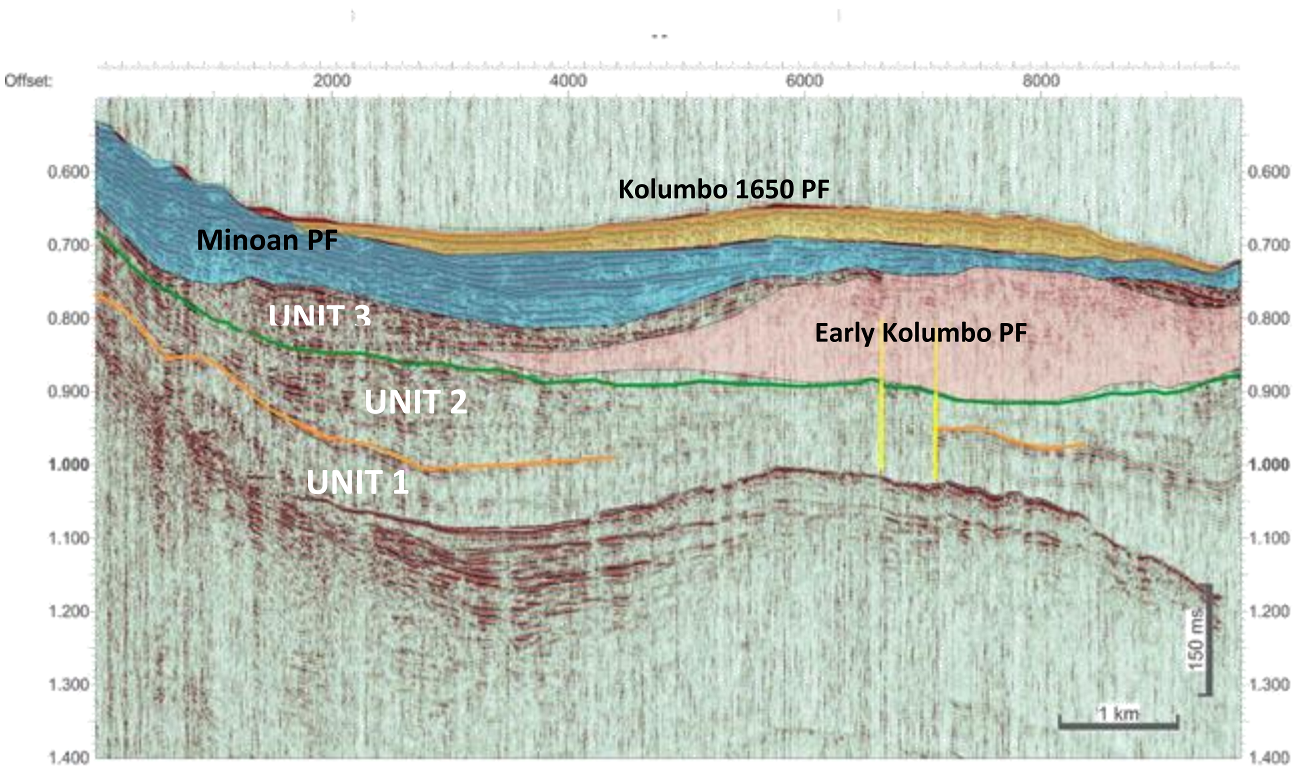


Figure18: Seismic Line No 10, South of Colombo Volcano

The seismic profile No 10, across the north part of Colombo volcano is oriented from the east to the west in the Aegean .This profile is parallel to the seismic profile No6.

The two oldest units, Unit 1 and Unit 2, consist of chaotic, incoherent undulating, discontinuous, low amplitude reflectors, with three strong reflectors which separate Unit 1 from Unit 2. The thickness of Unit 1 is 0.074 sec, and Unit 2 is between 0.050-0.032 secs.

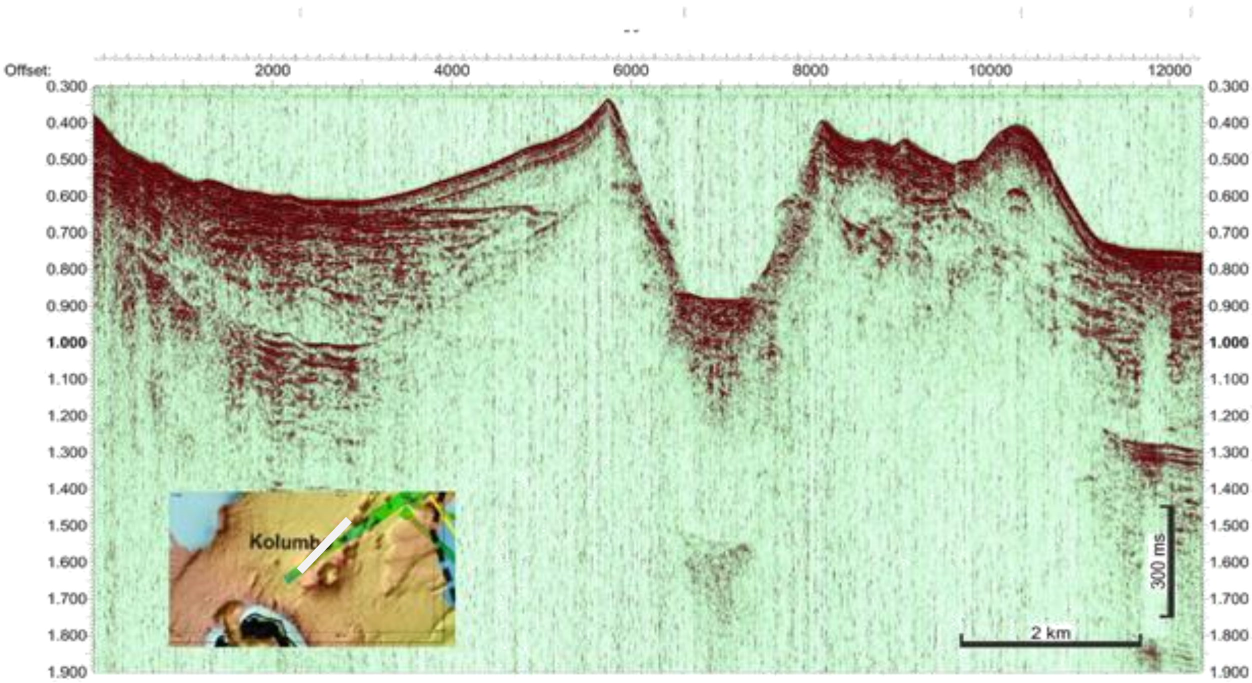
Unit 3, in seismic profile No 10 is a unit with oblique, semi continuous reflectors. In the west part of the unit, there are chaotic reflectors with low amplitudes. Unit 3, can be characterized as a combination of the fourth and sixth category of table 1.4. The thickness of the Unit 3 is between 0.030-0.086 secs. Two strong reflectors and the different stratigraphy at its east part separate it from Unit 2.

Above Unit 3 there are pyroclastic flow deposits, similarly to the seismic profile No 6. Seismic Profiles No 6 and No 10 run parallel to the northwest and the southeast slopes of Colombo Volcano. Along both the seismic sections, the upper sequence is acoustically transparent or mostly chaotic and can be interpreted as pyroclastic flows emplaced during the second phase of 1650 AD volcanic activity.

Seismic Lines No 6 and No10 run parallel to the northwest and the southwest slopes of Colombo Volcano. In both of these Seismic sections, the upper sequence is acoustically transparent or mostly chaotic and can be interpreted as pyroclastic flows emplaced during the second stage of 1650 AD volcanic activity.

4.4.5 Seismic Profil No 28

Line 28



Line 28

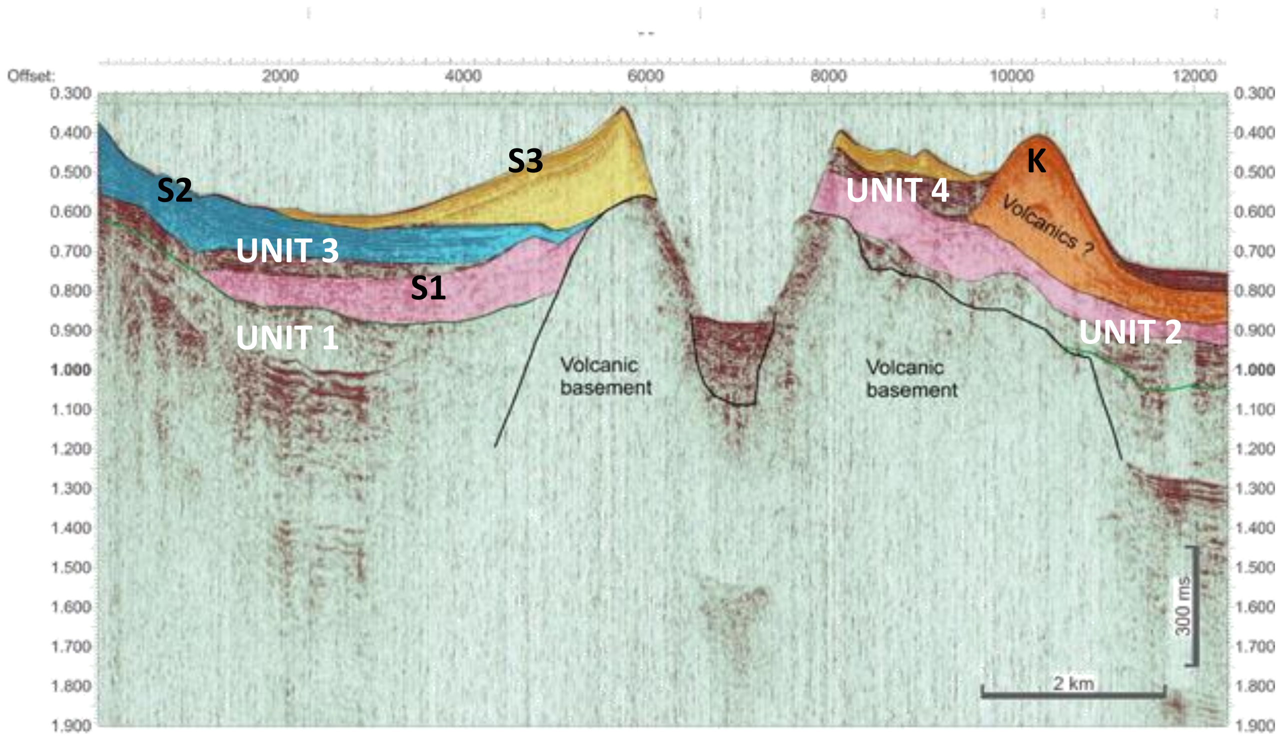


Figure 19: Seismic Line No 28, Cross Colombo Volcano

The general shape of Colombo's caldera is slightly elliptical with a main axis pointing in SW-NE direction and a maximum diameter of 2.5 km. Between Santorini's external slope and Colombo four seismic units were identified. An unconformity separates Unit 1 in an upper and a lower subunit.

In the western part, Unit 1, is rather incoherent and reveals low reflections amplitudes. The thickness of Unit 1 is 0.035-0.060 sec (seismic profile 3 Table 1.4).

The overlying Unit 2 reveals generally strong reflection amplitudes and a subparallel to incoherent reflection pattern .Its thickness is 0.03 sec. Unit 2 belongs to the second category of the table 1.4.

The Unit 3 of seismic line No 28, exhibits reflections characteristics similar to Unit 1.Its thickness is 0.03 to 0.07 sec.

Unit 4, reveals generally strong reflection amplitudes and a subparallel to incoherent reflection pattern. Its thickness is 0.015 to 0.030 sec.

Unit K comprises the inner creator wall. Based on Christian Hubscher et al, (2015), Unit K Is characterized as a sequence of highly-stratified pumiceous submarine pyroclastic deposits produced during the eruption of 1650AD. This pyroclastic flows creates low reflection amplitudes due to the high porosity.

S3 Unit is the youngest unit which terminates at Colombo's lower creator wall where Nomikou et al. (2013) also describe pumice, volcanic breccias and volcanoclastic mass waste deposits, but also lava flows and dykes.The lava flows and dykes may represent the upwelling zones of the last eruptions.

Unit S2, as S3 prograde away from crater wall. Unit S2 shows chaotic internal reflections and is horizontally bedded. It also ends at the lower half of the crater wall. Its thickness ranges from 0.03 to 0.06 sec.

The present Colombo volcanic edifice is mainly formed by Unit S1, which is bounded towards the crater. Unit S1 reveals a possible pre-existing structure that has been built upon by deposition of the thick 1650 AD pyroclastic deposits. Thus, it is possible that some partial collapse of the structure may have taken place as a result of the eruption.

Chapter 5. Conclusions

5.Conclusion

- The Minoan Eruption of Santorini was strong enough to devastate major areas in the eastern Mediterranean. Mainly the first eruption phase laid a big ash-fan over the islands east of Santorini and over a major part of Anatolia as we observed in units S1 and S2.
- The submarine pyroclastic flow deposits from the Minoan eruption are even more extensive than those of the 1883 Krakatau eruption. These results imply that the direct hazard from pyroclastic flows entering the sea and flowing over the ocean surface is likely to be much greater than previously considered for this important eruption in the Late Bronze Age. Refinement of the erupted volume of the Minoan eruption also has implications for the assessment of the potential global environmental impact that was caused by this event.
- Extensional and strike-slip faulting, has played a dominant role in the formation of the basin during Plio-Quaternary S1 and S2 units.
- Pyroclastic flows from Minoan eruption have been deposited at the sea floor of Christiana Basin covering a distance of more than 50 km(Line 1, Line 2)

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