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DIPLOMA THESIS:

The Volcanic Eruption in Prehistoric Thera: Impacts on Human and Natural Environment

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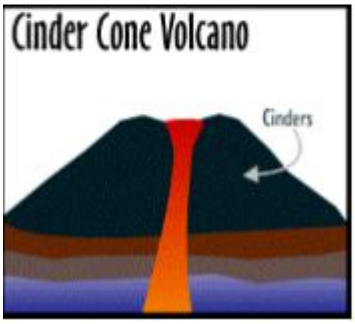
Abstract

The purpose of the thesis is to examine how the volcanic eruption in Prehistoric Thera/Santorini affected the human and natural environment through the examination of the archaeological remains and the comparison of the scientific data provided by contemporary volcanic explosions. Volcanoes are among the most hazardous of natural disasters in terms of impact scales; they can be unpredictable and often catastrophic. The Prehistoric volcanic eruption in the island of Thera (Minoan eruption) was one of the Earth's most awe inspiring, natural, cataclysmic events of all times (LaMoureaux, 1995). Dating the Minoan eruption has been a challenge for archaeologists and scientists over the years; however, after recent discoveries (2012) both seem to agree about the date of the volcanic explosion. The eruption was developed in four phases but in a short time span while the products of the explosion affected the entire Mediterranean Sea. An effort is made to estimate the amount of volcanic gases produced during the Minoan eruption by correlating contemporary measurements of volcanic gas ejectives to their volcanic explosivity index. Moreover, emphasis is given on the hazard that the volcanic gases pose to human and natural environment based on current observations concerning the interaction between volcanic emissions and the environment; the Minoan eruption itself had worldwide environmental impact on climate, vegetation, soils, and civilizations. The prehistoric explosion of Thera’s volcano caused the rapid abandonment of the flourishing settlement of the island (Akrotiri) while the explosion has been also connected with the demise of the Minoan civilisation on the island of Crete. The tremendous impact of the Minoan eruption on global scale and the continuous volcanic activity of the island, even nowadays two of the volcanoes circling the island remain active, has established the necessity of monitoring the volcanic activity, since the possibility of an eruption remains.

Introduction

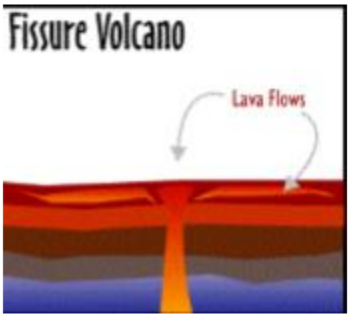
Every now and then Earth experiences tremendous explosive volcanic eruptions disturbing the life around the planet; volcanic eruptions are among the Earth's most powerful and destructive forces. A *volcanic eruption* is the escape of *magma*, i.e. molten rock, usually accompanied by steam water vapor and other gases, from beneath the surface of the Earth's crust. The surface rock may be lifted or shattered at pace of the eruption so that large quantities of solid mater are broken into various sizes and thrown up into the atmosphere, along with ash formed by solidification of the erupting magma. *Lava* is molten volcanic rock, i.e. magma, when it reaches the surface and erupts from a volcano. The composition, viscosity and gas content of lava can vary. The presence or absence of lava determines the type of the volcanic eruption; *effusive* or *explosive eruption*. Effusive is called the eruption in which lava flow predominates while an explosive eruption doesn't necessarily produce any flow liquid lava; the volcanic product in this case might all be thrown up vertically to condense as spray, solidify as ash and fall as pumice. (Lamb, 1970). Geologists generally group volcanoes into four main types:



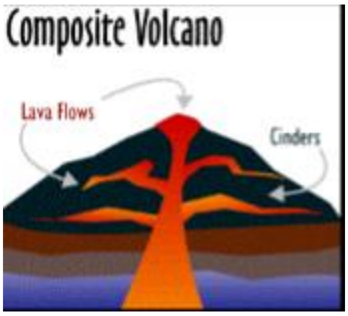
Pic. 1: *Cinder Cone Volcano*
(Dennis, 2015)

a) Volcanoes with a central, circular, vent (crater) surrounded by a built up of eruptive material; most volcanoes in and around the Pacific, in the Mediterranean and Africa, are of this type (Lamb, 1970).

b) Fissure volcanoes in which lava issues from a linear crack in the surface rock. Fissure volcanoes have no central crater at all. Instead, giant cracks open in the ground and expel vast quantities of lava. This lava spreads far and wide to form huge pools that can cover almost everything around. When these pools of lava cool and solidify, the surface remains mostly flat (Dennis, 2015).

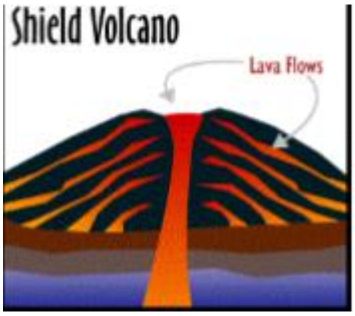


Pic. 2: *Fissure Volcano*
(Dennis, 2015)



Pic. 3: *Composite Volcano*
(Dennis, 2015)

c) The most majestic of the volcanoes are composite volcanoes, also known as stratovolcanoes. Composite volcanoes are tall, symmetrically shaped, with steep sides, sometimes rising 10,000 feet high. They are built of alternating layers of lava flows, volcanic ash, and cinders (Dennis, 2015).



Pic. 4: *Shield Volcano*
(Dennis, 2015)

d) Shield volcanoes can grow to be very big. In fact, the oldest continental regions of Earth may be the remains of ancient shield volcanoes. Shield volcanoes are tall and broad with flat, rounded shapes. They have low slopes and almost always have large craters at their summits. The Hawaiian volcanoes

> exemplify the common type of shield volcano. They are built by countless outpourings of lava that advance great distances from a central summit vent or group of vents. The outpourings of lava are typically not accompanied by pyroclastic material, which make the shield volcanoes relatively safe during eruptions (Dennis, 2015).

Volcanic activity is not randomly distributed over the Earth but is linked to the active zones of plate tectonics. In fact, more than 2/3 of the world's volcanoes are in the northern hemisphere, and in tropical regions. Establishing an accurate record of historic volcanism has long been recognized as important not only for analysis of volcanic eruption frequencies but also for the study of volcanic impacts on global scale (Textor, 2003). Volcanic eruptions have the potential to cause substantial impacts on human environment and natural ecosystems. Depending on where the volcano is located, the effects will be felt globally or at least by a whole hemisphere (Self, 2006). On the positive side, volcanoes provide fertile soils, mineral riches, hydrothermal power plus they are hypnotically attractive in terms of aesthetic beauty. Concurrently, an erupting volcano can be the cause of massive loss of lives since it can easily destroy entire communities and civilizations around the globe in a short time period while after the explosive event, the large amounts of ash blankets that cover an area can preserve its contemporary state, like Pompeii in Italy. Undoubtedly, volcanic emissions have contributed to atmospheric evolution throughout the history of the Earth since they are an important source of atmospheric gases and aerosols, both during and between eruptions (Mather, 2003; Oppenheimer, 2003). At the same time, volcanic emissions play important role in the Earth's radiation budget, in tropospheric and stratospheric chemistry and dynamics causing distress to terrestrial ecosystems and human health over local scales (Allen, 2002). The 1991 volcanic eruption of Pinatubo is such an example; the eruption produced a giant umbrella cloud in the middle to lower stratosphere that injected about 17 megatons of SO_2. The aerosol cloud spread rapidly around the globe in about 3 weeks and attained global coverage 1 year after the eruption. This large aerosol cloud caused dramatic decreases in the amount of net radiation reaching the Earth's surface. This was certainly the largest atmospheric perturbation by an aerosol cloud in this century, producing a strong climate force. The lower stratosphere also warmed immediately after the eruption and has cooled to the lowest temperatures recorded since then, causing changes in atmospheric circulation; that’s why volcanism has been implicated as a possible cause of weather and climate variations disturbing in this way the fauna and flora of the planet (Self, 1999; Robock, 2000).

Humanity has lived within the shadow of active volcanoes from the earliest periods of social and kinship organization. Eastern Mediterranean has been the cradle of many great civilizations since Prehistoric Times, but this region is also very much the cradle of volcanology. The volcanism of this broad region, stretching from Spain to the Caucasus, is largely the result of convergence between the Eurasian Plate and the northward-moving African Plate. Its geology is diverse and complex, with micro-plates defying easy tectonic generalizations. The historical and cultural richness of the Mediterranean region has led to the most robust historical record of volcanism of any region. Traditions of record-keeping go back thousands of years and generations of historians and geologists have mined those records. The lengthy historical record of this region also reflects the large numbers of people living in proximity to volcanoes. Nearly 15 million people, live within 30km of a Holocene volcano in this region. That’s why this region's eruptive record is easily the longest of any. Roughly, half of its 47 volcanoes have dated eruptions and more than half of these begin with

BCE[1] events. The large number of coastal and island volcanoes places this region at the top of the list of tsunami-producing eruptions, and the large numbers of people living in proximity to its volcanoes is reflected in the high number of eruptions causing damage to human infrastructures (Smithsonian-Institution, 2013).

The explosive eruption at Santorini in the Aegean Sea during the second millennium BCE, Middle Bronze Age (2000-1550 B.C.)[2], was the largest Holocene volcanic upheaval in the Eastern Mediterranean region (Bruins, 2008). It’s usually called the Minoan eruption since it destroyed the Minoan inhabited settlement of the island, Akrotiri, and led to the demise of cultural centers throughout the region, such as the Minoan culture on Crete and the Cycladic culture in the Cycladic Islands.

Pic.5: *The Island of Thera*
(Watts, 2012)

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[1] **BCE,** abbreviation of: Before Common Era = 1 AD, for more information: *Common Era*, American Heritage Dictionary of the English Language (3rd ed.). Boston: Houghton Mifflin. 1992

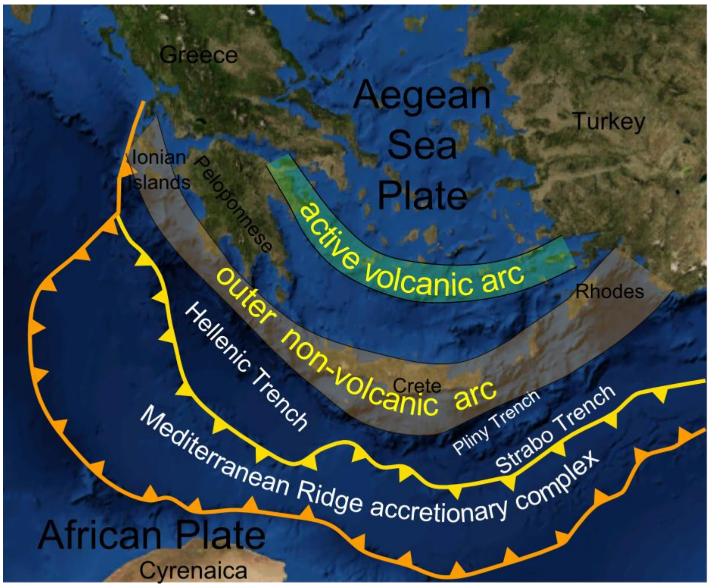
[2] For more information about the time periods of Aegean Civilizations look into: Treuil, R., Darque, P., Poursat J.Cl., Touchais, G., (1996*), Οι Πολιτισμοί του Αιγαίου κατά τη Νεολιθική και την Εποχή του Χαλκού*, pp. 119-122 in Greek// *Les Civilisations égéennes du Néolithique et de l'Âge du Bronze* (Original Title), (1989)

The eruption had profound effects in the Aegean and eastern Mediterranean region ranging from direct air-fall tephra damage in the southeast Aegean, associated seismic and especially tsunami impacts, environmental and even climate changes (Antonopoulos, 1992; McCoy, 2000).

An abundance of scientists from practically every field, ancient historians, archaeologists, volcanologists, geologists, even poets, and devoted amateurs, have concerned themselves with the volcano of Thera creating a battleground of ideological disputes for many years. Anything mysterious that occurred at about the same time has been connected, in one way or another, from time to time, with this volcanic eruption; the destruction of Minoan Crete, the myth of Atlantis, the crossing of the Red Sea by the Israelites, are just a few events which have been related to the eruption. One thing is certain; the Minoan eruption of Middle Bronze Age is the largest known Holocene eruption, which affected the eastern Mediterranean in a profound way (Friedrich, 2013).

***Chapter 1*: Dating the Minoan Eruption in Prehistoric Thera (1670 B.C.)**

Thera/Santorini is the most southerly island of the Cycladic Group in the Aegean archipelago in the eastern Mediterranean. Santorini is also part of the Hellenic Volcanic Arc. The Hellenic Arc is the surface expression of the subduction of the African plate beneath the Eurasian plate. The subduction under the Greek islands (Hellenic Arc) and southern Italy (Calabrian Arc) explains the region's volcanic centres. The arc lies 250 km behind the trench system and includes the volcanic islands of Aegina, Methana, Poros, Milos, Santorini, Kos, Yali and Nisyros. Volcanic activity began approximately 3-4 million years ago therefore the area is considered as a region of extensive Quaternary volcanism. The main explosive centres of the Upper Quaternary are Milos, Santorini, Kos and Nisyros while Santorini was developed on the northern edge of a basement horst called the Santorini–Amorgos Ridge (Dominey-Howes, 2004).



Pic. 6: *Map of the Hellenic arc showing the main tectonic elements* **(Chamot-Rooke, 2005; Mikenorton, 2010)**

Santorini nowadays is five fragments of what was once one island; a complex of five islands known as *Thera, Therasia, Aspronisi, Palaea Kameni and Nea Kameni* (Friedrich, 2013). Santorini was once about 16 km in diameter, and before it acquired the name of Thera it had be known as

Kalliste “the most beautiful island”. It was also called Stroghili, “the circular island”, with a steep sided central cone, which, judging from the present profile of the volcano rose to between 500 and 800m above sea level (Bond, 1976). The original form of the island was altered by the Bronze Age eruption. It seems that much of what was lost from the central part of the ring-island was added to the outer margins. The eastern side of Thera was considerably widened by debris washed from the rim and deposited on the alluvial plain (Friedrich, 2013). The islands of Palea Kammeni and Nea Kammeni in the middle of the caldera have been constructed by post-Minoan eruptions inside Thera’s caldera. Palea Kameni appeared above sea level in 197 B.C. After continuous volcanic activity, another island emerged from the caldera’s depths in 726 A.C. Still another island called Micro Kameni (small burnt island) arose in 1570 A.C. In 1650 A.C., in a paroxysmal phase of the submarine eruption of the Kolumbo volcano, a sea swell encircled the whole island of Santorini and the tsunami that was created swept away everything on its passage. The waves of the tsunami reached the islands of Patmos, Ios, Sikinos and north Crete (Papadopoulos, 2015). Between 1707 and 1711 A.C., it merged with the second island to form Nea Kameni. New land emerged sank and re-emerged during eruptive periods in the late nineteenth and early twentieth century. Nea Kameni has erupted seven times in the past 500 years, each involving extrusion of

Pic. 7: *Satellite image of Santorini and the surrounding sea bottom*
(Friedrich, 2013)

viscous lava forming domes and thick flows and accompanied by intermittent ash explosions over a few months or years. Santorini remains until today, the only active volcano in the Aegean Sea (Bond, 1976; Antonopoulos, 1992; Smithsonian Institution, 2013). Palaea and Nea Kameni constitute the active intra-caldera volcanic field while Mt. Kolumbo is a submarine volcanic centre located 6.5 km NE of the main island (Dominey-Howes, 2004).

Over the past 40 years, there have been prolonged discussions about when the Minoan eruption occurred, and major discrepancies have arisen in the results of scientists and archaeologists. While some archaeologists used evidence from pottery and the styles of design elements to date the eruption to around 1500–1520 B.C., a series of radiocarbon dates, ice-core dating and dendrochronological observations pointed to ages of about 100 to 150 years earlier (Friedrich, 2013).

The first attempts of dating of the eruption were in fact archaeological. Since written evidence from the Aegean Bronze Age is generally scanted, archaeologists relied on an analysis of changing pottery styles to establish a chronology of Aegean history. This method has been proven accurate in cases where the required date is more than several hundred years old (Antonopoulos, 1992). The pottery time clock indicated that the first major fall of pumice on Thera occurred at about 1550 B.C., while Professor Sp. Marinatos, Director of the Greek Archaeological Service, supported a more refined dating of the Minoan eruption, around 1400 B.C., (Marinatos, 1939; Marinatos, 1967). However, it is important to remember that this date is the beginning of the eruption activity and not of the final widespread eruption that led to the destruction of the Minoan settlement of Akrotiri. It is also the date, when Thera’s volcano became active again after a long period of quiescence and ejected the coarser pumice, which formed the lowest layer in the tephra deposits. The effects of this phase of the eruption were probably confined only to Thera. Shortly before the final Minoan eruption, volcanic activity on Santorini built-up progressively through a series of earthquakes that led to the emplacement of a thin layer of fine volcanic ash that can be found all around the Mediterranean Sea (Athanassas, 2017).

The first scientific attempt to evaluate the exact date of the eruption was after the earthquake of 9 July 1956 at Thera[3]. The earthquake disturbed the lower strata in the large tephra quarry near Phira, and the ruins of what appeared to be an ancient building were noticed under the bottom layer of pumice. Carbon-14 dating revealed two quite different dates: 1090 plus or minus 150 years and 1410 plus or minus 100 years; the first date was discounted, as the sample was believed to have been contaminated. A few years later in 2002, at the Phira quarry, a small tree was found still upright in the lowest pumice layer indicating that the tree was still alive when the eruption begun. According to the results, the first fall of pumice occurred between 1603 and 1516 B.C. The volcanic eruption and final destruction of the site was estimated to have occurred in 1622–1548 B.C. The time elapsed from the samples connected to the latest human activities could be estimated to approximately 164 years or about 135 years if one uses the median value of the date (1627–1600 B.C.), suggested from the olive tree branch wiggle matching. These time intervals (164 or 135 years) define also the duration of the Late Cycladic I phase at Akrotiri (1550-1450 B.C.)[4], during which a cosmopolitan civilisation flourished at this place before it was violently stopped by the huge volcanic eruption (Lyritzis, 2002; Maniatis, 2012). The new conclusions concerning the date of the Minoan eruption, 1670 B.C., Middle Bronze Age, allowing errors of ±30 years, is supported by both

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[3] For more information about dating the Minoan Eruption look into: Lyritzis, I., (2007), *Φυσικές Επιστήμες στην Αρχαιολογία*, Chapter 6, Second Edition, Athens, pp. 557-576 in Greek

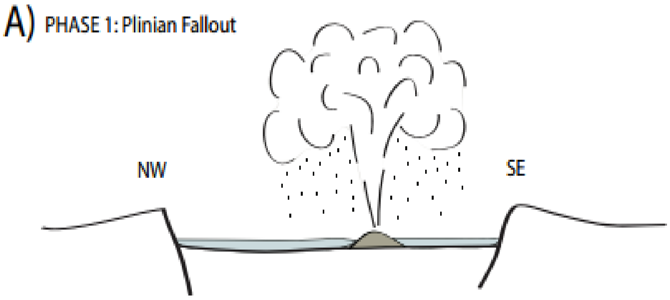
[4] For more information about the time periods of Aegean Civilizations look into: Treuil, R., Darque, P., Poursat J.Cl., Touchais, G., (1996*), Οι Πολιτισμοί του Αιγαίου κατά τη Νεολιθική και την Εποχή του Χαλκού,* pp. 119-122 in Greek// *Les Civilisations égéennes du Néolithique et de l'Âge du Bronze* (Original Title), (1989)

archaeologists and scientists nowadays (Davis, 1992; Maniatis, 2012). Although there might be disputes between different scientific fields about the exact date of the Minoan eruption, no one seems to doubt the fact that a paroxysmal eruption of extreme violence occurred on Thera during the Bronze Age changing once for all the course of life in the Mediterranean Sea (Athanassas, 2017).

Chapter 2: The Volcanic Eruption in Prehistoric Thera (1670 B.C.): Phases of the Explosion and Volcanic Products

There have been many studies on the Minoan eruption and its deposits however, there seems to be a consensus that the eruption occurred in four major phases with an initial precursory phase. The Minoan eruption was characterised by a sequence of distinctive phases like those recorded in many contemporary eruptions involving silica rich magmas. Based on scientific observations the volcanic eruption of Thera was developed in the four following phases:

i) Phase 1 - Plinian phase:



Pic. 8: *Schematic Illustration of Minoan Eruption* **(Johnston, 2014)**

The first explosive phase was very intense. As the reconstruction from the deposits shows, it began in the part of the ring-island where rising magma eventually encounter seawater. Plinian activity is the result of a continuous high intensity gas blast ejecting pyroclastic debris to a height of several tens of kilometres reaching the stratosphere, where high velocity winds spread the ejected gases over a wide area. More precisely, the first main Plinian phase of the Minoan eruption generated a sustained plume estimated at a height of 36 ± 5 km[5] and produced a reverse-graded pumice fall deposit that

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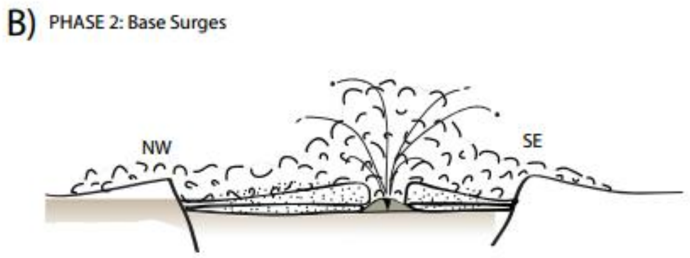
[5] For more information about smoke injection heights into the atmosphere look into: Amiridis, V., et al., *Smoke injection heights from agricultural burning in Eastern Europe as*

ranged from 6m to less than 10cm in thickness on the islands of Santorini, Therasia and Aspronisi (Bond, 1976; Johnston, 2014). As a result, the first eruption phase would have laid a big ash-fan over the islands east of Santorini and over a major part of Anatolia. The location of the eruptive vent is well established from various observations of the eruptive products. It is also visible as the deepest hole in the caldera in satellite photos (***Pic. 3, 10***) (Pyle, 1990; Friedrich, 2013).

ii) Phase 2 - Phreatomagmatic explosions:

In the second phase of the eruption, the eruptive mechanism changed completely. The feeding vent of the volcano had evidently widened, so that its surroundings broke down and cracks allowed seawater to enter. The coming together of seawater and fluid magma inside the vent led to especially violent phreatomagmatic reactions. The magma was torn into small particles, which were surrounded by a thin layer of expanding steam. Clouds of ash suspended in steam spread outward from the eruption centre in expanding rings and filed the entire caldera. They ascended the caldera walls, swept over the lower parts of the rim, and flowed down the outer slopes of the volcano, forming stratified deposits up to 12m thick (McCoy, 2000; Friedrich, 2013; Johnston, 2014).



Pic. 9: *Schematic Illustration of Minoan Eruption* **(Johnston, 2014)**

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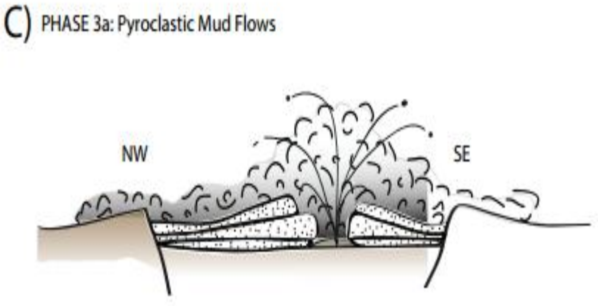
seen by CALIPSO, Available at: https://www.atmos-chem-phys.net/10/11567/2010/ (Accessed 21/11/2017)

In both the first and second eruptive phases, huge pieces of lava were torn sporadically from the walls of the feeding vent and thrown out as blocks. They are clearly visible nowadays in the ash layers forming bomb sags. Blocks more than a metre in diameter reached the Bronze Age dwellings of the Akrotiri settlement, about eight kilometres from the vent, shattering theirs stonewalls (Friedrich, 2013).

iii) *Phase 3a - Mudflows:*



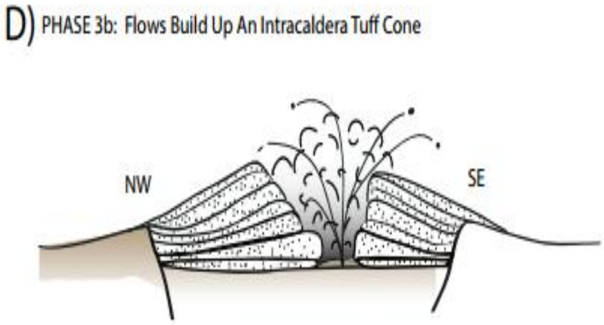
Pic. 10: *Schematic Illustration of Minoan Eruption* **(Johnston, 2014)**

A dramatic change from earlier eruption phases is evident within the third phase. Mudflows were generated, possibly due to the collapse of a tuff-ring formed around the vent, caused by the phreatomagmatic activity.

Phase 3a, increasing water, magma ratios have produced denser, partly wet, and low-temperature pumiceous pyroclastic flows transitional to mud flows. These deposits have formed a fan of numerous amalgamated single flow deposits as opposed to one giant, massive flow (Johnston, 2014). The mudflows, which contained large water-worn lava blocks with holes, can be detected in the mountain streambed on steep slopes suggesting the existence of a sizeable volcanic edifice at this stage of the eruption. The tephra of the third phase is easily recognizable in the caldera wall, even from great distances. It can be distinguished from the other layers mainly by the large numbers of dark fragments it contains; these fragments were rounded in the eruption column and got mixed with the pumice. They are different from the lithic fragments of earlier phases, consisting mostly of angular, black, glassy porphyritic lavas, like dacites of the Therasia shield located on the north-western flank of the volcanic field. Most of these well-rounded, dark, glassy blocks, measuring up to 10m in diameter, were destroyed during the widening of the vent (Bond, 1976; McCoy, 2000; Friedrich, 2013; Johnston, 2014).

iv) *Phase 3b - Pyroclastic flows:*

In Phase 3b, many pyroclastic flows were generated which flowed off the steep upper slopes and into the sea. They eventually extended to the coastal plains around the island and formed the ignimbrite. At the same time, while the vent grew wider, more of the crater wall gave way and the blocks coming from lavas of the volcano were gradually destroyed.



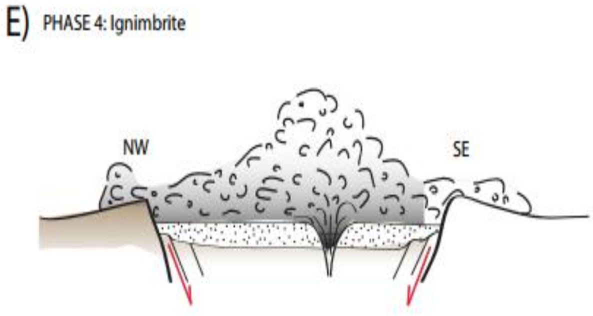
Pic. 11: *Schematic Illustration of Minoan Eruption* **(Johnston, 2014)**

The large number of non-volcanic rock fragments, that are found at this phase of the eruption, indicate the rapid evacuation of the magma chamber, which led to the collapse of large parts of the low levels of the volcanic edifice. Their collapse produced the large northern basin of the present caldera and deepened the earlier-formed southern basins. The latter were partly refilled with pyroclastic material during later eruptions (Friedrich, 2013). The total sum of the remnants of Phase 3 material seem to have plastered on the upper parts of the inner caldera wall, supporting the hypothesis of pounded, intra-caldera surge and flow deposits (Bond, 1976; Johnston, 2014). The variety of xenoliths that have been found along with the light-coloured blocks of stromatolites, indicate that the water-filled caldera existed already before the

Minoan Eruption (Bond, 1976; McCoy, 2000). It has also been deduced that in this phase the ash column did not reach the great heights attained in the first phase. Instead, turbulent clouds of ash and hot gas were directed laterally outward at low angles. Pyroclasts of different sizes, from few microns to centimetres, would have been carried aloft by the rising eruption plume and form a volcanic cloud blocking out the sun for many days (LaMoureaux, 1995). The Phase 3 deposits eventually reached 55m in thickness around the caldera rim. However, even at this stage, the collapse of the caldera had still not occurred (Friedrich, 2013).

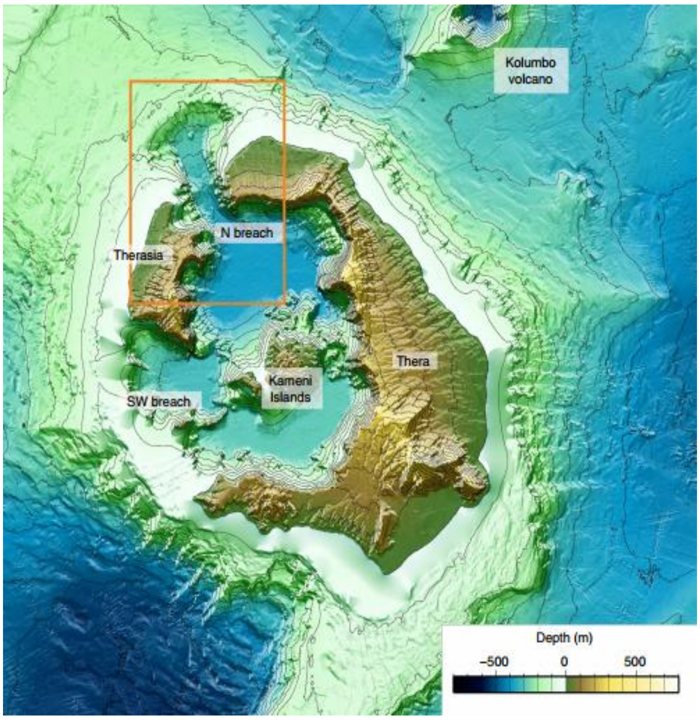
v) *Phase 4: Caldera collapse:*

There is no evidence on the exact timing, although it must have occurred after the last stages of the eruption because both the mudflows and torrent deposits require a source of material from above the level of the present caldera rim. Phase 4, saw the venting of high-temperature (300–500°C) pyroclastic flows, which produced fine-grained, non-welded ignimbrites around the caldera rim and the coastal plains. It was likely during this stage that the caldera collapse occurred with subsidence along two fault blocks to the north and west (Bond, 1976; McCoy, 2000). Caldera collapse seems to have deepened and widened the existed caldera, forming the present-day Middle Bronze Age caldera (Johnston, 2014). The caldera before the Minoan eruption that was lagoonal, became isolated from the sea and dried up before the eruptive Phase 4; that’s why the pyroclastic



Pic. 12: *Schematic Illustration of Minoan Eruption* **(Johnston, 2014)**

flows of this phase appear with no evidence for the involvement of water. Reconnection to the sea did not take place until the new caldera was flooded through the northwest strait after the eruption had ended. It is unlikely that the flood event itself would have generated major waves inside and outside the caldera; however, the effects of this event would have been limited on a regional scale (Nomikou, 2016).



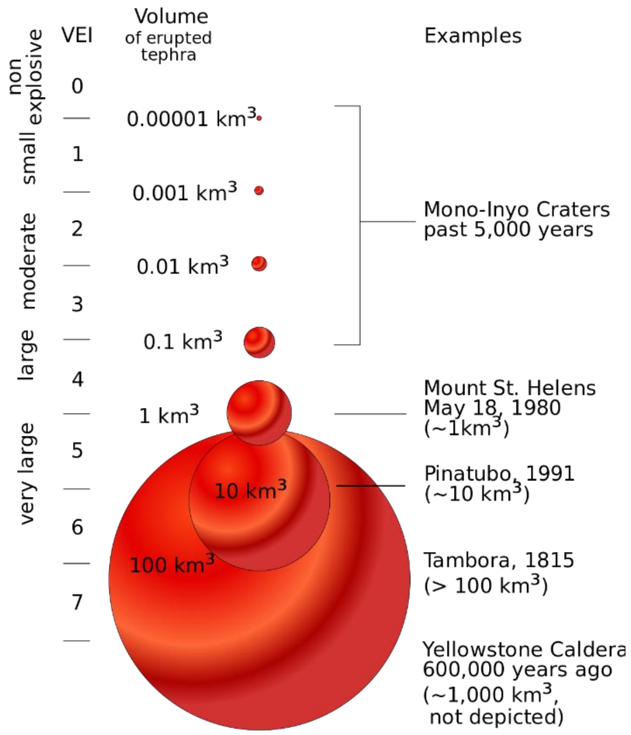
Pic. 13:

Topographic Map of Santorini-

The Northwest Breach

(Nomikou, 2016)

There have been several attempts to calculate both the volume of caldera collapse and the volume of material erupted from the Minoan eruption of Santorini. It was originally suggested that the volume of collapse was 60km^3, based on the assumption that the present caldera was entirely the result of the Minoan eruption. However, evidence demonstrate that the pre-Minoan caldera had a similar shape and areal dimensions to the present-day one from previous blasts that excavated the centre of Thera, so the volume of the eruption is estimated around 30km^3 (Druitt, 1999; Zeilinga de Boer, 2005; Johnston, 2014). Even though evidence is often insufficient and contradicted, scientists tend to catalogue the Minoan eruption as one of the top five most voluminous known Holocene eruptions in terms of bulk volume and as the most voluminous eruption in terms of Dense-rock equivalent (DRE)[6] of the past 10,000 years (Sigurdsson, 2006; Johnston, 2014).



Pic. 14: *Volume Graph of Volcanic Explosivity Index* **(Newhall & Self, 1982)**

Two important points arise from all the above. First, that the time span of the eruption was probably very short; this is deduced from the shortness of the Plinian phase and by comparison with similar historic eruptions. Second, that the volume of the Plinian phase, the phreatomagmatic phase and the flood deposits is only a small proportion of the total volume of the material apparently missing from the caldera. This also suggests that most of the material was ejected as pyroclastic flows which entered the sea (Bond,

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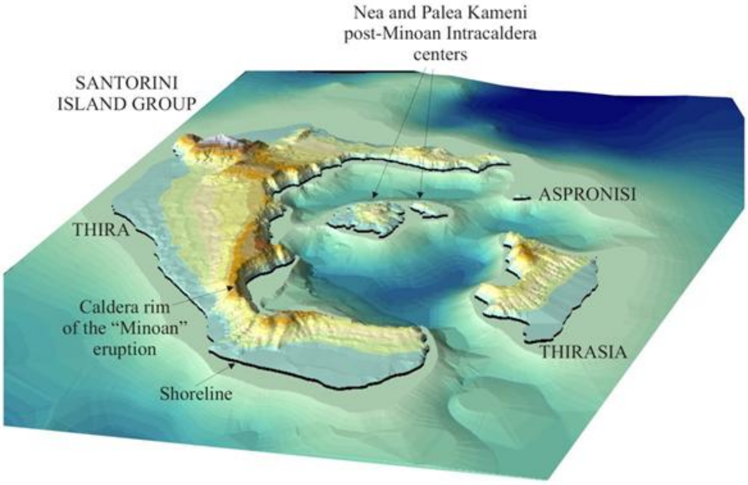
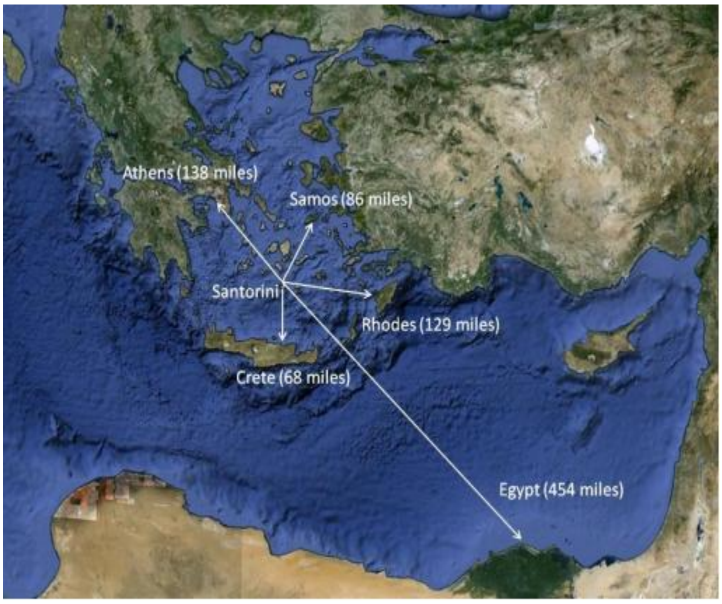
[6] **DRE,** abbreviation of: Dense-rock equivalent = is a volcanological calculation used to estimate volcanic eruption volume. Eruption volumes are commonly expressed in cubic kilometres (km^3). For more information look at: Pyle, D., M., (1989), *Thera and the Aegean World III. Volume Two: "Earth Sciences" Proceedings of the Third International Congress, Santorini, Greece, 3–9 September 1989*. The Thera Foundation. pp. 113–121

1976), creating a giant caldera in the centre, which measures about 12 by 7km and surrounded by 300m high, steep cliffs on 3 sides above sea level and another 400m below sea level (Foumelis, 2013; Johnston, 2014).



Pic. 15: *Santorini Today* **(Department of Geology, 2007)**

The power of volcanic eruptions is measured using the Volcanic Explosivity Index (VEI), a classification system developed in the 1980 that is somewhat like the magnitude scale for earthquakes. The scale goes from 1 to 8, and each succeeding VEI is 10 times greater than the last, based on quantitative criteria such as the volume of pyroclastic material ejected by the volcano that includes volcanic ash, tephra, pyroclastic flows, and other types of ejecta, the height of the eruption column and the duration of the eruption; a VEI 8 is one million times more explosive than a VEI 2 (Nasa, 2015). The explosivity of Middle Bronze Age eruption of Thera was originally estimated at 6.9 on the VEI scale and as such represents one of the largest eruptions in the past few millennia; in fact, only seven eruptions have higher VEI values (Lamb, 1970; McCoy, 2000). In historic times, only the volcanoes of Tambora (1815) and Krakatau (1883) had eruptions of similar magnitude. However according to recent investigations (Sigurdsson, 2006), there are indications that the eruption was much stronger than previously assumed. A VEI value of 7.1-7.3 is currently discussed, which, if accepted, would mean that the Minoan eruption was bigger than the Tambora eruption in 1815 and about ten times as big as the Krakatau eruption in 1883. If this is the case, the final explosion of the volcano was far greater than the atomic bomb at Hiroshima in 1945; Hiroshima atomic bomb was only about 20 kilotons (LaMoureaux, 1995).



Pic. 16: *Map depicting the distances between Santorini – Crete – Egypt*
(Anderson, 2011)

What had started as just another eruption, changed dramatically into a worldwide cataclysmic event. Santorini during the eruption would have been topped by a massive pillow-shaped cloud, while the island literally blew its top. A series of great explosions would have shaken the Earth as salt water roared into the caldera void vacated by millions of tons of lava[7]. Billowing clouds that reflected brilliant flashes of orange flame must have appeared in the sky. Thunder and lightning crackled, and static electricity in the air would have been so great that lightning would have run along the ground and over the rooftops. Crete, to the southwest, and Egypt, to the south, would have

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[7] Look in Appendices at **Pic.1,** p. 49

felt and saw this eruption. The intense volcanic activity would have created major earthquakes damaging Asia Minor and North Africa (LaMoureaux, 1995; Jorge, 2010).

The deposits of the strong Minoan eruption had a catastrophic effect not only to the island itself, but also to its surroundings; pumice and ash have covered the nearby islands as well. The islands of Anaphi, Rhodes and Crete to the south and east of Santorini have been subjected to a rain of ash, which was carried mainly in these directions; in the island of Crete, geological, archaeological and radiocarbon criteria date the geo-archaeological deposits, containing volcanic ash derived from the Minoan eruption (Bruins, 2008). Sediment cores collected from the Nile Delta include a layer with fragments of volcanic glass from Thera, proving that the ash cloud reached Egypt (Zeilinga de Boer, 2005). Ultimately, the volcanic deposits reached as far as Anatolia and the Black Sea (Friedrich, 2013). The contemporary findings of Minoan ash layers around the Mediterranean are characterised by a pink hue caused by hematite stain derived in part, from small lithic fragments that have pink halo of irregular patterns (Heiken, 1984; Bruins, 2008). Simultaneously, the volcano would have ejected so much pumice that it would covered the surface of the sea and made all navigation in the surroundings of Santorini for a long time impossible (McCoy, 2000). Pumice accumulations from all the volcanic phases, can be found in coastal deposits and archaeological sites throughout the eastern Mediterranean and Aegean, littoral suggesting extensive rafting of pumice following the Bronze Age eruption (Francaviglia, 1990); its distribution has played an important role in reconstructing the mechanism of the Minoan eruption. The huge mass of pumice covering the surface of the sea was eventually washed up at higher levels on the shores by the tsunamis, which were triggered by earthquakes and the collapse of the caldera (McCoy, 2000).

Recent volcanic activity has shown that several tsunamis often follow each other in a short time interval after an eruption. Their height and speed vary; the deeper the sea, the swifter the wave (Antonopoulos, 1992; Papadopoulos, 2015). Tsunamis may have been created during the Minoan eruption. The main tsunami would have been triggered when the roof of the magma chamber collapsed. Considering the discoveries of the fallen caldera, the sea waves that were produced could have had a height of about 50m at their starting point, Thera, to travel the distance to Crete (Antonopoulos, 1992; McCoy, 2000; Friedrich, 2013). This is also confirmed by the sedimentary deposits within the deep-sea stratigraphic succession of the eastern Mediterranean Sea, that have been identified as tsunami deposits produced by waves propagating to the west and west-southwest of Santorini[8]. Tsunami generated during the Minoan eruption has been assumed by archaeologists as one of the primary destructive effects of the eruption, although identifiable damage to human structures by tsunami remains elusive even nowadays (McCoy, 2000).

At the same time, the four major volcanic events, sent fire, and gases skyward to an elevation of at least 5km. There had to be massive loss of life from ejected gases, volcanic ash, bombs, and flows. The volcanic particles would be so thick over the eastern half of the Mediterranean that they would have blotted out the sun for days at a time. The dust and gas in the stratosphere would have changed the climatic temperatures and created spectacular sunsets around the Mediterranean Sea (LaMoureaux, 1995). So between 3500 and 3600 years ago the Aegean volcano of Thera erupted, sending out shock waves and spraying ash, pumice and a mixture of volcanic gases over the eastern Mediterranean; volcanic products that continue to unsettle the scholars who study the event even today (Runnels, 1992).

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[8] Look in Appendices at **Pic.2,** p. 51

__Chapter 3:__ *Contemporary Volcanic Eruptions*

a) Volcanic Gases

b) Risk Assessment

a) Volcanic Gases

Gases are the invisible yet often continuous products of volcanic activity; even volcanoes in a state of quiescence, not actually erupting or showing signs of unrest through seismic activity, are able to degas continuously. By studying gases, volcanologists can gain insight to a number of phenomena: they can assess whether there is magma present at shallow levels in a volcanic edifice, they can determine if the magma is comparatively rich or poor in dissolve gas, they can estimate the various sources of the gas and finally, by making repeated measurements over time scientists can use gas data to help forecast eruptive activity, particularly when this information is integrated with other types of data such as seismic activity and ground deformation (Delmelle, 2000). The amount of volcanic gases and particles arriving in the troposphere and stratosphere generally depends on both volcanological and meteorological boundary conditions such as: the chemical composition of the magma depending on the tectonic environment (e.g. subduction zone, continental rift zone), the strength and duration of an eruption, the location of the emitting volcano (altitude and latitude), plus atmospheric conditions such as temperature, humidity and wind profiles (Halmer, 2002)**.** Their composition depends on the type of volcano and its eruptive state; volcanic gas composition is controlled by volatile contents in magmas and their degassing condition (Shinohara, 2013). The most common volcanic gases produced during a volcanic eruption are the following: carbon dioxide (CO_2, 5-40 mol%), sulphur dioxide (SO_2, 5-50 mol %), hydrogen (H_2, <2 mol%), hydrogen sulphide (H_2S, <2 mol%), carbon monoxide (CO, <0.5 mol%) and in abundance water (H_2O, 30-90 mol%). Some of these, when emitted from active vents react in the atmosphere or volcanic plume to form aerosols (Williams-Jones, 2015).

An effort has been made in this chapter to estimate the volcanic gases ejected in the atmosphere during the Minoan eruption based on the data provided by contemporary volcanic gas emissions correlated with their Volcanic Explosivity Index (VEI). **Table 1** presents the volcanic gases ejected from 16 volcanic eruptions (average values from several samples taken at each volcano reported in mol%) of the 20th century along with their VEI (Halmer, 2002). The wide variation in the compositions of the volcanic gases reflects variations in the tectonic setting, magma composition, degassing state of the magma and the pressure of equilibration (Symonds, 1998).

Volcano	*Year*	*VEI*	H_2O	H_2	CO_2	*CO*	SO_2	H_2S	S_2	*HCl*	*HF*
1) Kilauea - Hawai	1918	0	37,09	0,49	48,90	1,51	11,84	0,04	0,02	0,08	0
2) Momotombo - Nicaragua	1918	1	97,4	0,45	1,45	0,006	0,41	0,23	0	2,81	0,25
3) Nyiragongo - Africa	1927	1	43,5	1,29	48,55	2,20	2,02	1,72	0,62	0	0,09
4) Showashinzan - Japan	1954	4	98,04	0,63	1,20	0,0129	0,043	0,0004	2,6	0,053	0,024
5) Surtsey - Iceland	1964	3	81,13	2,8	9,29	0,69	4,12	0,89	0,25	0	0
6) Mt. Etna - Italy	1968	2	47,26	0,51	26,06	0,54	25,18	0,20	0,21	0	0
7) Erta Ale - Africa	1974	0	77,24	1,39	11,26	0,44	8,34	0,68	0,21	0,42	0
8) Tolbachik - Kamchatka	1975	0	88,17	1,89	2,48	0	0,08	0,14	0	0,66	0
9) Ngauruhoe - New Zealand	1977	1	96	2,6	16,1	0	10,2	6,8	0	2,5	0
10) Usu - Japan	1977	3	95,8	0,273	3,02	0,00440	0,258	0,609	0,0052	0,0241	0,0116
11) G. Merapi - Indonesia	1979	2	88,87	1,54	7,07	0,16	1,15	1,12	0,08	0,59	0,04
12) Mt.St. Helens - USA	1980	5	98,6	0,39	0,89	0,0023	0,067	0,099	0,0002	0,076	0,03
13) Poas - Costa Rica	1981	1	96,29	0,524	0,78	0,0066	1,511	0,0131	0	0,784	0,091
14) Kilauea - Hawai	1983	1	81,6	0,993	3,80	0,0702	12	0,761	0,358	0,171	0,2
15) Mt. St. Augustine - Alaska	1986	4	96,83	0,54	1,49	0,0060	0,22	0,38	0	0,51	0,025
16) White Island - New Zealand	1986	3	93,2	0	4,10	0	1,1	0	0	0,9	3,7

Table 1: *Chemical composition of volcanic gases from 16 volcanic explosions of the 20th century and their VEI. Concentrations of species reported in mole%* **(Halmer, 2002; Smithsonian-Institution, 2013)**

Two bivariate plots between two different major gases compared with the VEI of the volcanic explosions were created, to cluster the volcanic eruptions according to the ejected emissions and the VEI. These biplots were used to establish a potential relationship between VEI and gas emissions which could be then applied to estimate gas activity during the Minoan eruption.

- **Fig. 1**: VEI versus H_2O illustrates differences among the volcanic gases ejected from the explosions forming 2 groups of volcanoes
- **Fig. 2**: VEI versus SO_2 detects similar groups of volcanoes

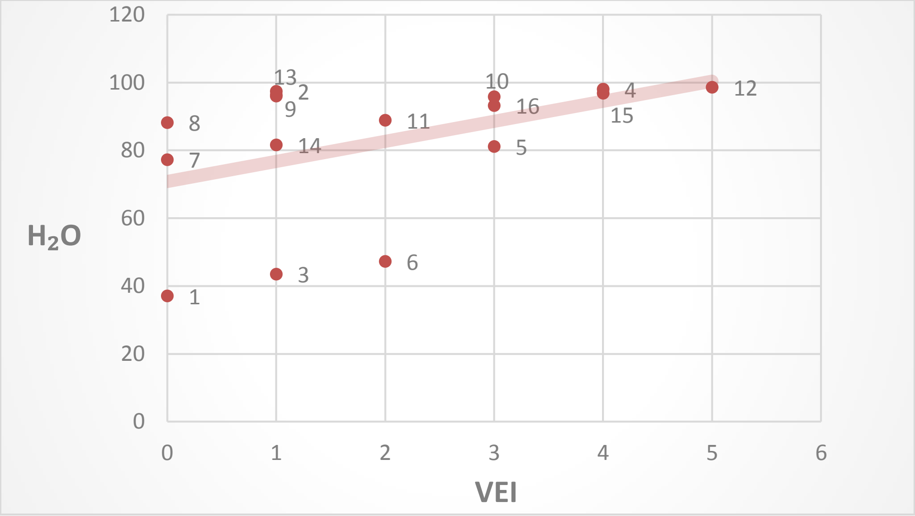


Fig. 1: *Bivariate plot of the H_2O volcanic gas, versus the VEI of the eruption. Concentrations of species reported in mole% (data presented on **Table 1**)*

On the first bivariate plot (**Fig. 1**) the volcanic eruptions:

- 1, 3, 6, form one group with a tendency of augmentation; as the VEI increases so does the amount of H_2O emissions.
- 2, 4, 5, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 form a second group where the amount of H_2O is quite similar even though the VEI of the explosion differs (VEI 0-5).

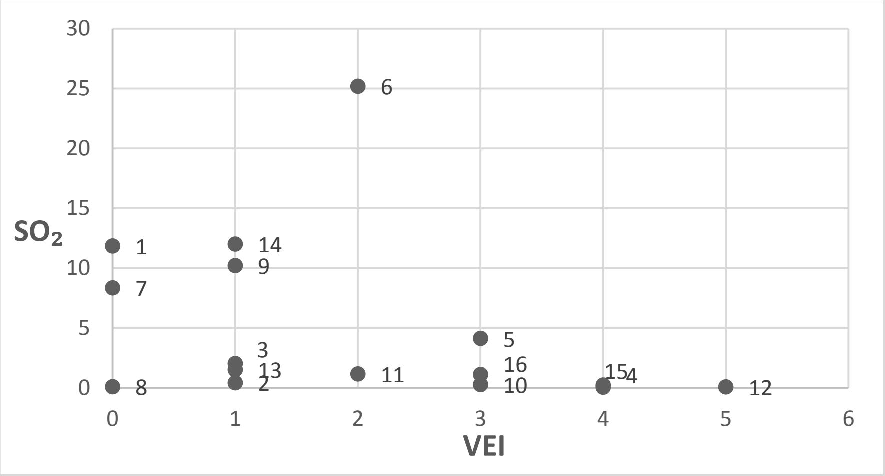


Fig. 2: *Bivariate plot of the SO_2 volcanic gas versus the VEI of the eruption. Concentrations of species reported in mole% (data presented on* **Table 1***)*

The second plot shows similar clusterings (**Fig. 2**). However, in this case the volcanic eruptions:

- 1, 7, 9, 14, form one group with relative small VEI (0-1) and similar amount of SO_2 emissions.
- 2, 3, 4, 5, 8, 10, 11, 12, 13, 15, 16, form a second group with different VEI but similar amount of volcanic ejections.
- The volcanic eruption 6 appears to be an outlier in this case.

Volcanic eruptions inject several different types of particles and gases into the atmosphere in different amounts, that vary for multiple reasons; the type volcano, the type of the explosion (effusive or explosive), the volcanic explosivity index etc. That’s why, there appear to be many differences comparing the VEI and the amount of gasses, ejected during a volcanic eruption, making it difficult to estimate the amount of volcanic gasses (%), ejected during the Minoan eruption (VEI≥6) based entirely on these calculations.

However, it could be possible to extract information about one particular volcanic gas of the Minoan eruption based on contemporary observations and the available data of volcanic explosions. Due to available technology it's easy to measure the total mass of the SO_2 emissions produced by contemporary volcanic eruptions to correlate them with the emissions produced during the Prehistoric volcanic eruption of Thera based once again on the VEI of the explosion (Robock, 2002).

Table 2 presents the VEI of 24 contemporary volcanic eruptions and the Total mass/kt of SO_2 ejected in the atmosphere during a volcanic eruption to collate it with the Minoan eruption.

Volcano	*Year*	*VEI*	*SO_2 Total mass/ kt*
1) Mt. Etna - Italy	1979	3	10
2) Mount St. Helens, USA	1980	5	875
3) Pagan, Japan	1981	4	320
4) E1 Chichon, Mexico	1982	5	8090
5) Colo, Indonesia	1983	4	200
6) Kilauea - Hawai	1983	1	36
7) Nevado del Ruiz, Colombia	1985	3	90
8) Chikurachki, Russia	1986	4	750
9) Mt. St. Augustine - Alaska	1986	4	20
10) Cerro Hudson, S. America	1991	5	4000
11) Mount Pinatubo-Philippines	1991	6	18194
12) Spurr, Alaska	1992	4	250
13) Lascar, South America	1993	4	450
14) Hekla - Iceland	2000	3	183
15) Okmok, Alaska	2008	4	150
16) Kasatochi, Alaska	2008	4	2000
17) Sarychev, Russia	2009	4	1200
18) Eyjafjallajökull, Iceland	2010	4	466
19) Grímsvötn, Iceland	2011	4	300
20) Laki, Iceland	2011	4	300
21) Nabro, Africa	2011	4	3650
22) Tolbachik, Russia	2012	4	200
23) Klyuchevskoy - Russia	2013	1	55
24) Kelut - Indonesia	2014	4	200

Table 2: *SO_2 Total Mass/kt emissions of the largest contemporary eruptions* **(Smithsonian-Institution, 2013; Zerefos, et al., 2017)**

The average value of SO_2 volcanic emissions versus the VEI were calculated and are presented on **Table 3**.

VEI	***Average value of SO_2 Total mass/kt***
1	45,5
3	94
4	697
5	4322
6	18000

Table 3: *Average values of SO_2*

Total Mass/kt emissions based on their VEI (data presented on **Table 2***)*

One final bivariate plot (**Fig. 3**) between the VEI (0-6) and the SO_2 emissions (average values also included) was created to classify the contemporary volcanic eruptions and to determine the SO_2 emissions during the Minoan eruption.

The interpretation presented here is based on the available evidence and demonstrates that SO_2 emissions show a tendency to increase exponentially as the VEI of the explosion gets higher (Average value of differentiation per VEI ≤5000 SO_2Total Mass/ kt).

The amount of SO_2 emissions during the Minoan eruption (VEI=7) can be calculated by the following equation (equation of the curve ***Fig. 3***):

$$SO_2 = 2.7927(\pm 0.71176) \cdot e^{1.46202(\pm 0.04285) \cdot VEI}$$

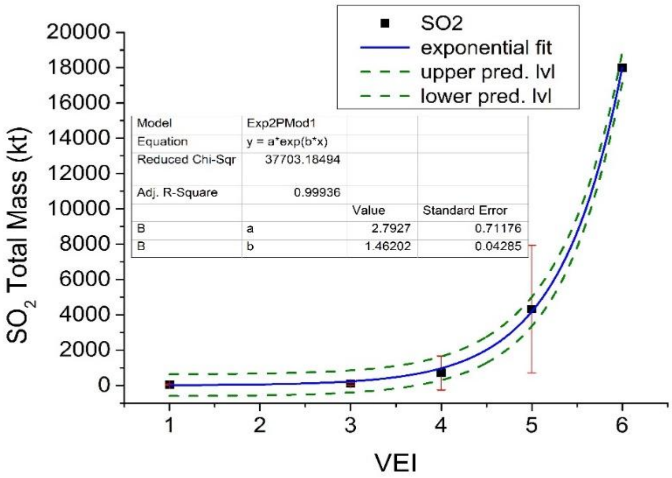


Fig. 3: *SO2 total mass as a function of VEI. The error bars (red line) represent the standard deviation of SO2 masses per VEI value. The blue line is the exponential regression line fitted to the points while the green dashed lines correspond to the 95% prediction bands.*

Based on these calculations the Minoan eruption with VEI=7 would have ejected SO_2 = 77.742 ±30.600 Total mass/kt with a range between 47.000-108.000 Total mass/kt depending on multiple factors such as the type (and rock type) of the volcano etc.; a profound amount of SO2 Total mass/kt was ejected into the atmosphere during the explosion.

Determining gas emissions from prehistoric eruptions remains a difficult task. Yet their comparison with eruptions of this century confirms that prehistoric eruptions expelled amounts volcanic gas products, stratospheric sulfur injections that caused climatic implications. Obtaining more reliable and complete data on emissions from large eruptions especially prehistoric ones, such as the Minoan eruption, that were several orders of magnitude larger than historical events remains a common objective even nowadays to assess their actual impact on the planet.

b) Risk Assessment

Although volcanic gases are only directly responsible for 1-4% of volcano-related deaths, they are nevertheless hazardous for every form of life on the planet. They have a significant effect on the regional and global environment and can contribute to the greenhouse gases of the atmosphere.

Pic. 17: *A plume of ash from the Sarychev volcano in the Kuril Islands, northeast of Japan. during the early stage of the volcano's eruption on June 12, 2009* **(Neal-Jones, 2015)**

The relative degree of hazard from volcanic gases is dependent up on the type of gas emitted and its dispersion into the atmosphere. Some gases are poisonous, while others are dangerous only if present in such high concentrations that they block oxygen respiration; emission of gases at high elevations will have less direct impact on population than low-level gas plumes. Even relatively short-lived eruptions may eject significant amounts of gases into the stratosphere with short-term global consequences. At the same time persistently, active volcanoes may present a long-term hazard. In some cases, even dormant volcanoes can pose a threat to human health and the local environment (Williams-Jones, 2015).

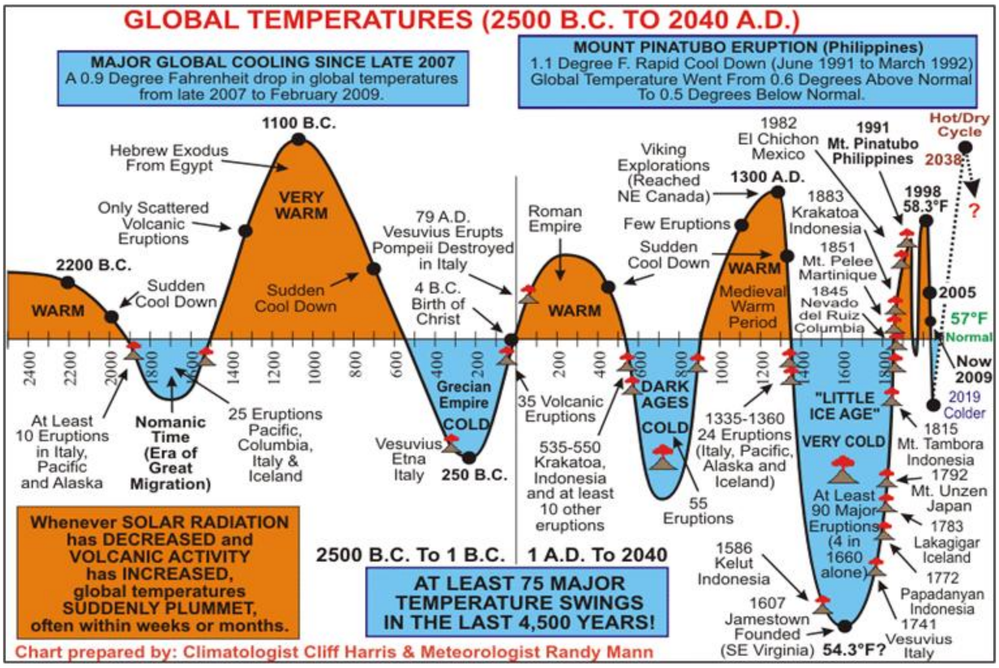
The most important and hazardous volcanic gases and aerosols are CO_2, SO_2, H_2S, HCl, HF, and H_2SO_4. Exposure to these has been the cause of most of volcanic gas-related fatalities.

- Carbon dioxide constitutes approximately 0.04% of the air in the Earth's atmosphere. In an average year, volcanoes release between about 180 and 440 million tonnes of carbon dioxide. When this colourless, odourless gas is emitted from volcanoes, it typically becomes diluted to low concentrations very quickly and is not life threatening. However, because cold carbon dioxide gas is heavier than air it can flow into in low-lying areas where it can reach much higher concentrations in certain, very stable atmospheric conditions. This can pose serious risks to people and animals. Breathing air with more than 3% CO_2 can quickly lead to headaches, dizziness, increased heart rate and difficulty breathing. At mixing ratios exceeding about 15% carbon dioxide quickly causes unconsciousness and death (Williams-Jones, 2015).
- Sulphate aerosol (H_2SO_4) is formed from sulphur dioxide (SO_2) due to chemical reactions in the atmosphere. Since gaseous H_2SO_4 has a very low saturation pressure it can easily condense in the stratosphere and form aerosols of liquid hydrated sulfuric acid. Sulphate aerosols once formed have a residence time in the stratosphere of about 3 years and can cause climate changes and affect the air quality disturbing the local environments (Zeilinga de Boer, 2005). Volcanic activity was seriously underestimated in the past regarding their climate cooling ejects caused by the injection of volcanic sulphur-rich gases directly into the stratosphere (Stolarski, 1979). Volcanic activity has in fact, a disproportionately large climatic impact despite the low total SO_2 input compared to

anthropogenic SO_2 sources, because explosive volcanism can inject sulphur directly into the stratosphere (Halmer, 2002).

- The halogens HCl and HBr volcanic ejectives destroy ozone in the stratosphere in the form of the radicals. A combined chlorine bromine interaction can be regarded as a synergetic eject of Cl and Br, which is very ejective in the polar stratosphere in destroying O_3 where oxygen atoms occur in low concentrations. The ejects of volcanic emissions on ozone destruction caused by halogen gases (HCl, HBr) was overestimated in the past (Stolarski, 1979).
- Hydrogen fluoride (HF) is the dominant fluorine species in volcanic gases. Fluorine compounds do not interact with stratospheric ozone. HF is highly soluble, and with excessive intake leads to dental and skeletal degradation and is indirectly responsible for the most lethal gas-related volcanic event. (Halmer, 2002).

To summarise the hazards posed by volcanic gas products of explosive eruptions differ from those due to all other natural disasters. Climate change is an inevitable consequence of a volcanic explosion; dominantly cooler temperatures for a few years after the eruption. In fact, the Little Ice Age (LIA=1250-1850 A.D.) has been considered the coldest interval of the Holocene experiencing significant volcanism activity and climate change. Understanding the role of volcanic and solar variations in climate change is important for understanding the LIA but also for predicting the effects of anthropogenic changes in the atmospheric composition of the 20th century and beyond (***Pic.18***), (Free, 1999; Crowley, 2008). The ozone depletion caused by stratospheric aerosols would permit higher UV-B flux to the ground in high–mid-latitude regions, effect that could last a few years after the eruption (Self, 2006).



Pic. 18: *Global Temperature Trends From 2500 B.C. To 2040 A.D.* **(Harris, 2015)**

Volcanic gases, although a relatively minor hazard in comparison with other volcanic phenomena, can have important short and long-term impacts on people and the environment. Although some attempts have been made to physically reduce gas hazards, gas monitoring and education of the public remain the most effective means of reducing the risk caused by the volcanic gases (Williams-Jones, 2015).

Chapter 4: *Impacts of the Minoan Eruption on Natural and Human Environment*

Mankind has been noticing and recording the volcanic impacts since Plutarch and others, 2000 years ago, pointed out that the eruption of Mount Etna in 44 B.C., dimmed the sun and suggested that the resulting cooling caused crops to shrivel and produced famine in Rome and Egypt (Robock, 2000). Given the size of the Minoan eruption and the associated socio-environmental upheaval, it is expected that this extraordinary event was recited in the Bronze Age Aegean scripts, or at least it should have passed down orally into the Greek mythology. However, in the Greek mythology there is no clear description of a volcanic eruption exists, except for the cataclysmic events unfolded in the Hesiod's Titanomachy (War of the Titans). Supposing that the myth was formulated in the Aegean, well before Hesiod (750 BCE) promoted a written version of it and that the Minoan eruption was an indelible memory to the indigenous people, the natural phenomena described in the Titanomachy might be a masked reference to the Minoan eruption. At the same time in Egypt, the so-called Tempest Stela (or Ahmose Stela) narrates a cataclysmic event witnessed by pharaoh Ahmose himself that could be the result of the Minoan eruption. It contains hieroglyphic text inscribed on a limestone slab that gives an account of darkened skies and colossal rainfalls, which, unlike common storms, endured for a long period and have had no parallels in the Ancient Egyptian historiography. Although their duration is lost, the Stela narrates that the rainfalls were so unprecedented in extent and intensity that turned into a widespread flood, which damaged temples, sepulchral chambers, even pyramids, as far south as Thebes. Hints of acid rain are also implied from a reference to clothing shredded right on the body of the victims. In addition, there is historic evidence that during the reign of King Chieh around 16th century B.C., climatic deterioration was registered even in China. The Minoan eruption left undoubtedly physical damage to the geology and geography in North Africa from Alexandria to the Gaza Strip and around the entire eastern Mediterranean (LaMoureaux, 1995; Athanassas, 2017).

All the phenomena mentioned above, along with storms and extreme rainfalls in the surroundings of massive volcanic eruptions, have been documented in recent analogues. The Minoan eruption would have caused stress to vegetation, chemical changes in the atmosphere, and the chemistry of the polar ice caps. Physical and atmospheric effects of the eruption may have had a modest impact on distal terrestrial and aquatic ecosystems, but a significant one in the nearby area of the volcanic activity affecting fertilization and limiting nutrients around the Aegean Sea. Research into twentieth-century volcanically induced climatic perturbations; this could be also the case in the Mediterranean Sea after the Minoan eruption (Eastwood, 2002). The Bronze Age eruption has been correlated with manifestations including darkness that blanketed the eastern Mediterranean, great pillars of fire and ash, earthquakes, electrical storms, and gas emissions that could cause boils on animals and humans and even cause death. These manifestations are all identified with present-day volcanic eruptions and confirmed by the archaeological remains of the prehistoric settlements around the Mediterranean Sea (LaMoureaux, 1995).

***Akrotiri Settlement*:** The eruption of Thera's volcano around 1670 B.C., constituted a natural catastrophe unparalleled in all of history. Akrotiri is nowadays a well-known prehistoric settlement, situated at the southern cape of the volcanic island of Santorini (Thera), that was preserved due to the Minoan eruption (Doumas, 1983; Maniatis, 2012).

***Pic. 19:** Map of Santorini - Akrotiri Settlement*
(Chemical Engineering School Computer Center, 2006)

It is known that the history of the settlement of Akrotiri had begun long before the Minoan presence on the island; it could have already begun in the Neolithic period/Early Cycladic period (3000–2000 BCE)[9].

Nevertheless, during the Middle or at the beginning of the Late Bronze Age (2000-1600 BCE) ideas and people from Crete were spread all over the Aegean; in Cyclades, Dodecanese, the west coast of Anatolia and the Greek mainland. One of the settlements most affected by Cretan presence was the Akrotiri settlement in Thera. Evidence that support this theory are the imported and imitated Minoan pottery found on the island, the architectural features of the buildings decorated with frescos similar to the Minoan ones, the prestigious goods seals that are found across the settlement along with findings of

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[9] For more information about the time periods of the Aegean Civilizations: Treuil, R., Darque, P., Poursat J.Cl., Touchais, G., (1996*), Οι Πολιτισμοί του Αιγαίου κατά τη Νεολιθική και την Εποχή του Χαλκού*, p. 119-122 // *Les Civilisations égéennes du Néolithique et de l'Âge du Bronze* (Original Title), (1989)

Linear A (Davis, 1982). In recent years, much progress has been made toward setting the site of Akrotiri within the context of the overall settlement history of the island of Thera. Additional prehistoric settlements have been located on both Thera and Therasia. It is now clear that these sites were densely settled in the centuries before the final eruption of Santorini's volcano (Davis, 1992). In fact, the Early Bronze Age (2750-2300) settlement of Akrotiri appears to have a substantial size. The full development of the settlement occurred in the Middle Cycladic period (2000-1600 or 2000-1700 B.C., depending on which chronology one adopts), period during which Akrotiri was considered as a unique cultural and cosmopolitan city in the Cyclades (Davis, 1992).

The life of the settlement was ended in the Late Cycladic I (1600-1100 B.C.) period, by a huge volcanic eruption that destroyed the biggest part of the island. The huge volcanic explosion in the middle of the island buried the city of Akrotiri under tons of pumice and volcanic ash ending abruptly its life in a manner similar to Pompeii in several metres of pyroclastic deposits effectively ending occupation on the island for generations (Doumas, 1983; Eastwood, 2002; Maniatis, 2012). The assumptions concerning the latest events which occurred at the settlement of Akrotiri before the final destruction, are based on the archaeological evidence. There are finds of a serious destruction (repaired houses, temporary settlements) at the site most probably caused by a strong earthquake before the final eruption (Doumas, 1990; Vlaxopoulos, 2007; Maniatis, 2012). The citizens of Akrotiri, apparently warned by the early phases of the eruption, were able to escape in boats to the sea, as no human artefacts have been found at the site (LaMoureaux, 1995). The volcanic material that covered Akrotiri has preserved a valuable source of information about the nature of the disaster, the mechanisms of the eruption, the sequence of events during the explosion and the population of this ancient village (McCoy, 1990; McCoy, 2000).

The settlement of Akrotiri is the perfect example of how Archaeology can be benefited from a volcanic disaster. The eruptive products have created conditions for excellent preservation of the ancient settlement creating a unique, extensive cultural landscape and providing vital information about the prehistoric site (Grattan, 2016).

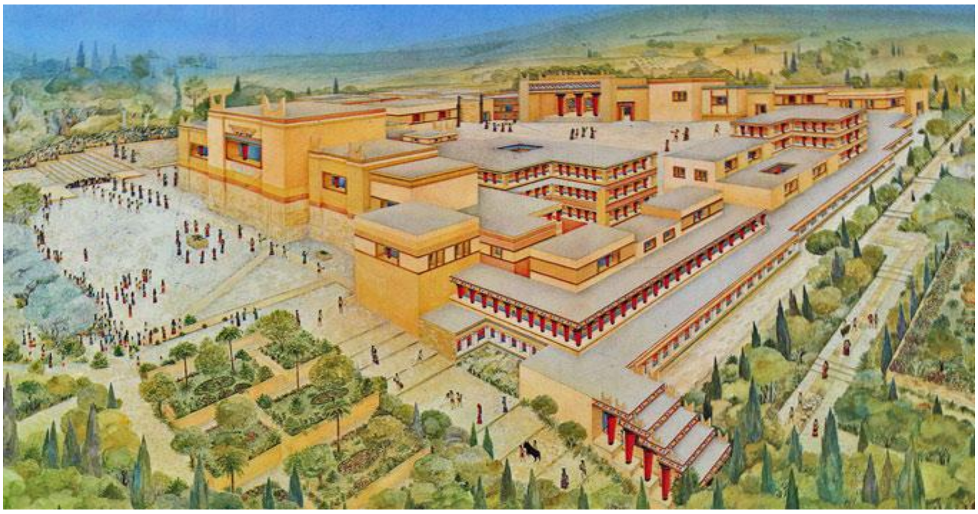
The Minoan Civilisation: The possible effects that the Santorini eruption may have had on natural and cultural environments has attracted much attention since when Sp. Marinatos (Marinatos, 1939), first hypothesized that it may have caused the destruction of the Minoan civilization based on Crete (Eastwood, 2002).

Pic. 20**:** Satellite Image of Crete **(NASA, 2011)**

The island of Crete lies approximately 70 miles to the south of Thera. During the Late Bronze Age, the Minoans, named after their legendary king Minos, inhabited Crete. The Minoans dominated the Aegean, colonizing other islands and trading with the Egyptians and the Phoenicians. The Minoan influence would have been strongest in the islands nearest Crete; that’s why it has been suggested that the settlement of Akrotiri was indeed a colonisation of the Minoans. Minoans established the first true European civilization building many towns and four major palaces, the most important of which was in Knossos.

However, during a short time period, between 1550 and 1400 B.C., the Minoan empire declined for no apparent reason tempting many scientists to connect this decline to the volcanic eruption at Thera. In 1932, Marinatos started to theorize that the destruction of the Minoan empire was an effect of Thera’s eruption and of the resulting tsunami. According to his hypothesis, the major eruption destroyed the entire Minoan power at Crete at a time when the Minoans dominated the Mediterranean world. A few years later, after his excavations in Crete Marinatos (Marinatos, 1939), claimed to have found evidence that the sudden and simultaneous destruction and abandonment of so many Minoan villas and of the three palaces (except the one in Knossos) and the general downfall of Crete was due, not to foreign invasion but to a natural catastrophe of unparalleled violence and destruction. Marinatos, implied that the source and focus of this cataclysm was the volcanic island of Thera; the tsunami generated by the eruption, literally wiped out the peace-loving Minoan civilization that inhabited the island of Crete. The eruption would have appeared at Crete as a low-lying cloud. In minutes, the giant ocean wave would have crashed into the northern shores of Crete destroying the entire seafaring fleet lying at harbour sailboats, fishing boats, and commercial vessels. Thousands of people would have died. Greek mythology includes the following statement about the Minoan demise also implying the destruction of Crete due to the volcanic eruption of Thera: “*A Bull from the sea was sent by Neptune to plague Minos*", the occurrence of a destructive tsunami which swept away the northern coastal towns of Crete; coincidentally, Neptune was the god of the sea and earthquakes (Antonopoulos, 1992). The waves destroyed Minoan naval power, halted trade activities, and the ash disrupted the island's agricultural economy. After the sea subsided, the configuration of the area was altered, and the decline of the Minoan principality on the Archipelago began (Friedrich, 2013). Minoan Crete was battered to her knees by the brute forces of nature, and never rose again (Athanassas, 2017).

Although the settlements on the northern coast of Crete could have been devastated by tsunamis triggered by the volcanic eruption, the destruction of Knossos, the greatest Minoan palace, is considered to have been caused by earthquakes rather than tsunamis, since it lies sea at a distance of 5 to 6km inland and has an elevation of about 60m above the sea level (Antonopoulos, 1992).



Pic. 21: *The Minoan Palace of Knossos* **(Amphipoli News, 2017)**

In the passage of time, there have been multiple theories about the Minoan civilisation collapse. It has been suggested that, volcanic tephra fallout from the First Phase (Plinian Phase) of the explosion, deposited or suspended in the atmosphere, travelled all the way to Crete posing threats to the environment and, hence, to human society. Volcanic tephra would mechanically injure or completely bury crops and pasture and poison water resources causing either sudden death or accentuate mortality due to famine. Such impacts may eventually have led to civil unrest and to the socio-economic breakdown of the Minoan civilization (Hölscher, 2005; Athanassas, 2017). Wave-cut cliffs and pumice found along the northern shore of Crete have been used as evidence of the magnitude of the volcanic catastrophe supporting this theory (LaMoureaux, 1995). However, according to recent studies, it is thought that Crete was spared the most severe effects of the widespread ash fall. Only the eastern tip of the island seems to have been covered with a few centimetres of pumice (Friedrich, 2013).

Climate change has been implicated in the success and downfall of several ancient civilizations. Volcanic eruptions can interrupt the usual weather pattern. Introduction of volcanic ash in the atmosphere can propagate nucleation processes, which affect the cloud properties on long time scales and spark, in turn, severe rainstorms that usually enhance surface runoff (Athanassas, 2017). While absorption and scattering of incident solar energy warms the stratosphere, it gradually leads to a net cooling effect at the surface of the Earth, that could have led to the gradual demise of the Minoan civilisation (LaMoureaux, 1995; Robock, 2000). Research into contemporary volcanically induced climatic disturbances, suggesting that temperature lowering occurs in the range 0.3-0.5 °C and lasts for a period of 3-4 years but the relationship between volcanic eruptions and climate fluctuations is complex. In climatic terms, this would indicate cooler summers, higher precipitation and increased cloudiness. Climate change could have been triggered by the volcanic eruption of Thera, cooling of the atmosphere leading to gradual Minoan demise since climate change and its associated effects have and always will influence human lives. New evidence however suggests, that the fall of the Minoan culture is no longer directly connected with the volcanic event of Santorini (Eastwood, 2002).

A more recent and complex hypothesis suggests that, a synthesis of historical, climatic, and geologic evidence that climate change instigated by an intense El Nino activity contributed to the demise and eventual disappearance of the Minoan civilization. El Nino/Southern Oscillation/ (ENSO), is called the phenomenon when a large warm spot exists over the tropical Pacific Ocean. This surface warming is large enough to interact with the atmosphere and cause significant weather changes all over the world. The North Atlantic Oscillation (NAO) in its positive phase can create dry conditions in the Mediterranean Sea that could have contributed to the Minoan destruction. This effect, however, cannot be assessed in the 2nd millennium B.C. as no proxy NAO data extend that far so it remains a hypothesis. While it is difficult for any civilization to get extinct because of climate, it is becoming clear that convergent events such as earthquakes and volcanic activity in synergy with climate anomalies may produce significant stress to contemporary populations affecting their social and economic development; which could be the case of the Minoan demise (Tsonis, 2010).

Archaeological evidence has excluded the hypothesis of a Mycenaean[10] invasion that could be responsible for the destruction of the Minoan palaces and their subsequent occupation; skeletal remains consistent with an invasion pattern have never been found. In fact, the Minoans who lived in the palaces were neatly buried in well-preserved burial sites, a pattern inconsistent with an invasion scenario. The fact that the Mycenaeans did not establish themselves in the nearby and more vulnerable Crete as they did in mainland Greece is also not consistent with their ambitious military conquest (Callender, 1999). At the same time, the archaeological data seem to confirm the theory that there was a severe economic dislocation in Crete, triggered by the Santorini eruption, and that this dislocation gradually worsened as Late Minoan I period (1600-1450 B.C.) progressed. Moreover, a combination of a general feeling of uncertainty caused by the eruption and its accompanying effects, the earlier destructions caused by earthquakes, and the need to rebuild and restablish normal economic life, may have presaged the end of the Minoan civilisation. The effects of removing a major port of call could have affected after an interval, as increased costs of

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[10] Mycenaeans: The civilisation that flourished in the mainland of Greece during and after the destruction of the Minoan civilization. For more information about the Mycenaeans: Treuil, R., Darque, P., Poursat J.Cl., Touchais, G., (1996), *Οι Πολιτισμοί του Αιγαίου κατά τη Νεολιθική και την Εποχή του Χαλκού, Γ’ Βιβλίο*, p. 403-620// *Les Civilisations égéennes du Néolithique et de l'Âge du Bronze* (Original Title), (1989)

transport gradually led to ever fewer routes and eventual economic collapse (Knappett, 2011). Problems with food production and distribution, with the existing network disintegrated, could have resulted in a decentralization of the political landscape, which went hand in hand with an increase in elitist power and competition. Probably, the latent tension between this and the demonstrable tendency to exclude those not of the group would have eventually led to conflict. The probability of internal Minoan conflict is indicated by the enormous number of conflagrations and selective destructions of houses, villas and palaces in the Late Minoan IB period (1500-1450 B.C.) (Driessen, 2000).

Volcanic eruption, earthquakes, tsunamis, climate change, Mycenaean conquest, civil war and economic crisis, or a combination of the above, are the most popular explanations of the Minoan demise; some of these theories are confirmed by archaeological findings. Certainly, the consequences of an eruption of such magnitude near the centre of two thallassocratic Bronze Age societies would have had a major impact on their future (McCoy, 2000). The combined effects along with the Minoan eruption in Late Minoan IA (1600-1500 B.C.) could have caused the eventual demise of Minoan civilization in the early Late Minoan IB period (1500-1450 B.C.), producing a snowball effect that culminated in the destruction of the Minoan palace states (Driessen, 2000). Whether this cultural change was due entirely to the eruption or to other cultural factors continues to be argued by archaeologists and historians. However, the Minoan civilisation did not collapse, and Crete was not laid waste, because of the eruption of Thera (Pyle, 1997). In the aftermath of the eruption and approximately two centuries later, both the Cycladic and the Minoan cultures were replaced by the Mycenaean culture from mainland Greece (LaMoureaux, 1995).

Chapter 5: ***Monitoring the Volcanic Activity on Thera Nowadays***

Santorini comprises the most active volcanic centre in the Aegean Sea (Greece), and is documented to have given one of the largest volcanic events known in historical time (Friedrich, 2006; Druitt, 2012). The Santorini volcanic complex is composed by two active volcanoes nowadays, Nea Kameni and Mt. Kolumbo, 6.5km offshore of Thera (Foumelis, 2013).

The last eruptive cycle of Santorini in four periods of explosive volcanic activity from 1925 to 1950 in Nea Kameni[11], was resumed by a repose period of fumarolic activity and thermal venting (Foumelis, 2013). Since then, Thera's volcano was in a dormant state, with insignificant deformation (Stiros, 2010) and seismic activity limited to a location 10km northeast of Thera (Dimitriadis, 2009). For the first time since 1950, intense geophysical activity was observed in the volcano at the beginning of 2011, when the volcano displayed signs of unrest with increased micro-seismic activity and significant ground uplift. Within the first quarter of 2012, a gradual decrease of inflation rates was confirmed from subsequent observations indicating that the volcano entered a post-unrest period.

Pic.22: *Satellite Image of Santorini today* **(NASA, 2016)**

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[11] For more information about the volcanic activity of Santorini look into*: The Historical record of volcanic activity by the National Observatory of Athens, operated station in Thira, (1893-1931*), management-commentary by Velouzos, A., reference of intense volcanic activity on the island. Look in Appendices at **Pic. 3,** p. 51

The unceasing volcanic activity of Thera along with the recent recorded and catastrophic events of volcanic eruptions around the globe has confirmed the necessity of monitoring the volcanic activity of the island (Zeilinga de Boer, 2005). There are several techniques of monitoring active volcanoes all around the world such as:

- The study of the rocks, minerals, and inclusions of the volcano by scientists can determine the amount and types of gas in a rock, in the minerals within a rock, or in the gas inclusions in minerals or glass. The methods fall into four classes: bulk extraction, energetic particle bombardment, vibrational spectroscopic techniques, and phase equilibrium studies. These methods have been used in experimental studies and for rocks from all tectonic settings, historic eruptions, and large pre-historic eruptions (Ihinger, 1994).
- Direct Sampling is the easiest, but often the most difficult way; to collect a sample by hand, placing a container directly in the gases because of the high temperatures, also involves dangers associated with being close to vents, and the possibility of contamination of the sample by the atmosphere.
- Multiple Remote Sensing techniques.

The Correlation Spectrometer (COSPEC), is a remote sensing technique designed to measure the amount of sulphur dioxide in a passing air mass, or volcanic plume. The spectrometer compares the amount of solar ultraviolet light absorbed by sulphur dioxide in the plume to an internal standard (Sutton, 1992).

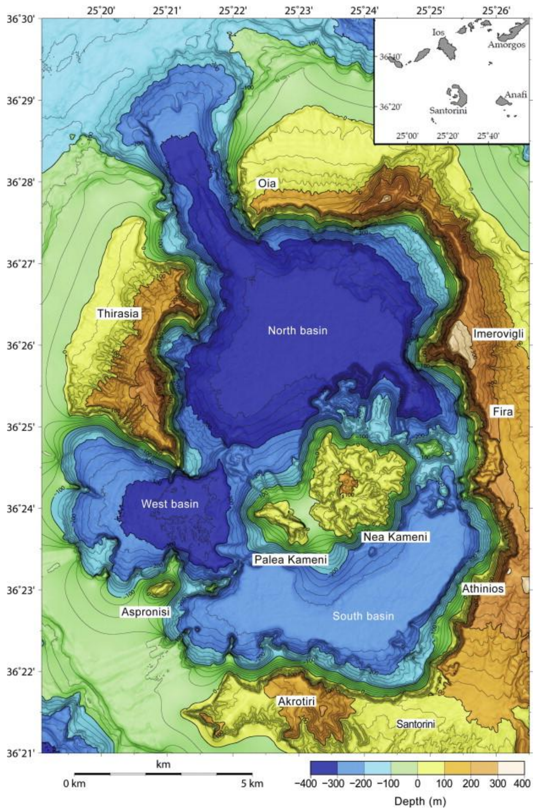
Light Detection and Ranging (LIDAR), is a surveying method that can be used to make digital 3D-representations of the target (Lyritzis, 2007). LIDAR technology can be used to analyse changes in the surface elevation of the volcano. With data derived from airborne LIDAR, scientists can accurately map, often in exquisite detail, the dimensions of the uplift and create better models to forecast volcanic hazards (Gutro, 2004).

Total Ozone Mapping Spectrometer (TOMS), is used for high-resolution mapping and measurements of the ozone layer. TOMS, also detects volcanic eruptions and measures the amount of sulphur dioxide released from them.

Advanced Very High-Resolution Radiometer (AVHRR), is a radiation-detection imager that can be used for remotely determining cloud cover and the surface temperature is used to track the aerosol layer produced by eruptions (Stowe, 1992).

Fourier transform infrared (OP-FTIR), is a field technique that is contributing significantly to the development of models for magma degassing and transport is open-path spectroscopy, in part due to its suitability for high temporal resolution measurements of gas composition. This approach is especially penetrating when combined with petrological insights and geophysical observations (Oppenheimer, 2008)

Satellite Interferometry (InSAR), is a geodetic method that uses two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or digital elevation, using differences in the phase of the waves returning to the satellite (Hanssen, 2001).



Pic. 23: *Combined bathymetric and topographic map of Santorini Caldera with 15-m grid resolution encompassing the Kameni islands* **(Nomikou, 2014)**

Some of these techniques were used successfully to monitor the volcanic activity of Santorini, in 2011. The combination of InSAR, a widely used method for surface deformation monitoring volcanic activity, with 10 Global Positioning Systems GPS (cGPS), in continuously operating sites all around the island has quantified the period of the volcanic unrest, which began in January 2011 and was diminished around the end of February 2012.

The obtained results from the joint inversion modelling of space geodetic measurements confined a deformation source at the depth of 3.5– 3.8 km. Finally, satellite data also confirmed that the islands have risen as much as 14cm since January 2011 (Foumelis, 2013; Papoutsis, 2013). After February 2012, when the rapid episode ceased, the observed displacement has declined significantly, possibly signalling a new phase of relative stability, reducing the probability of an imminent volcanic eruption, following the empirical knowledge from calderas that experienced similar inflation episodes in the past (Newman, 2012).

Pic. 24: *Palea and Nea Kameni volcanic islands,*
in the center of the Santorini caldera **(NASA, 2012)**

Since the volcano remains active the resident population of Santorini is at high risk from the hazards associated with a future eruption (Dominey-Howes, 2004). The main threats from Nea Kameni and Mt. Kolumbo volcanoes, that can put the entire community at risk include phreatic and phreatomagmatic explosions (base surges and pyroclastic flows), ballistic projectiles, tsunami, earthquakes, toxic gas/ash fall and landslides. The hazards from emissions of volcanic ash and gas are of significance due to their immediate impact on the island’s population and economy; ash and gas will be an intermittent threat to air quality, critical infrastructure and aviation. The disruption of international flights and the risk of adverse impacts for cruise ships anchoring in the southern and eastern portions of the caldera during the summer months. Possible passenger respiratory issues would have a large potential economic impact for the important tourism industry of the islands. So, tourists and the local community are at risk from a future volcanic eruption and any evacuation plan of the island, due to volcanic unrest or non-magmatic activity (e.g. phreatic eruptions) can have a significant impact upon the local economy. The combination of fine ash and gas with the local weather conditions, (dry, hot or windy weather) may also require further precautions to be undertaken, such as partial or full evacuation of the island. In addition to the health impacts of fine ash exposure, agriculture is likely to be adversely affected by fine ash and acid rain, especially in the growing seasons of spring and early summer. Volcanism should not be ignored in terms of pollution; one volcanic eruption can outgas as much carbon dioxide in one day than 250 years of anthropogenic activity (George, 2014). Building collapsing around the island is also a possibility due to ash particles (Jenkins, 2015). As the archaeological excavation at Akrotiri inevitably exposes the fragile archaeological remains of the human activity of the island, prehistoric architecture is at risk of destruction in case of strong seismic event; the probability is high, since the site is in one of the world's seismically most active volcanic regions (Chouliaras, 2012).

Holocene eruptions have generated a variety of processes, deposits and eruption mechanisms posing significant hazards of various types. Following the eruptions of Mt. St. Helens (1980), Nevado del Ruiz (1986) and Mt. Pinatubo (1991), scientists, policy makers, disaster/emergency planners, and the public have become aware of the dangers that volcanoes may pose. Hazard evaluations for all volcanoes in populated areas, regardless of their active or dormant state, and expanded monitoring could improve preparedness levels (Doocy, 2013). The Santorini volcanoes are currently experiencing a phase of quiescence that will eventually give way to a period of intense activity. In the meantime, the danger of a sudden explosion remains. All the eruption scenarios that have been made for the island of Thera assume and depend upon the premise that the volcanoes will exhibit identifiable precursory warning signs that would permit a full assessment of the impending eruption, its magnitude and effects and allow sufficient time to undertake evacuation of the islands. No evacuation or volcano emergency plan specifically exists for Santorini. Therefore, in the event of a volcanic emergency, the author cities would have to utilise the more general evacuation plan, *Xenocrates National Emergency Plan*[12], even though is too general to cover Santorini's needs. Hazard-specific mitigation strategies such as engineering projects or urban planning could be implemented to reduce potential impacts; however, their costs may be prohibitive when compared to the likelihood of an eruption in the near future. Broader-based awareness and education strategies targeted at the population at risk would likely result in more successful evacuations and may also increase

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[12] For more information look into: Homeland Security, (2008), *National Emergency Communication Plan*, https://www.dhs.gov/xlibrary/assets/national_emergency_communications_plan.pdf

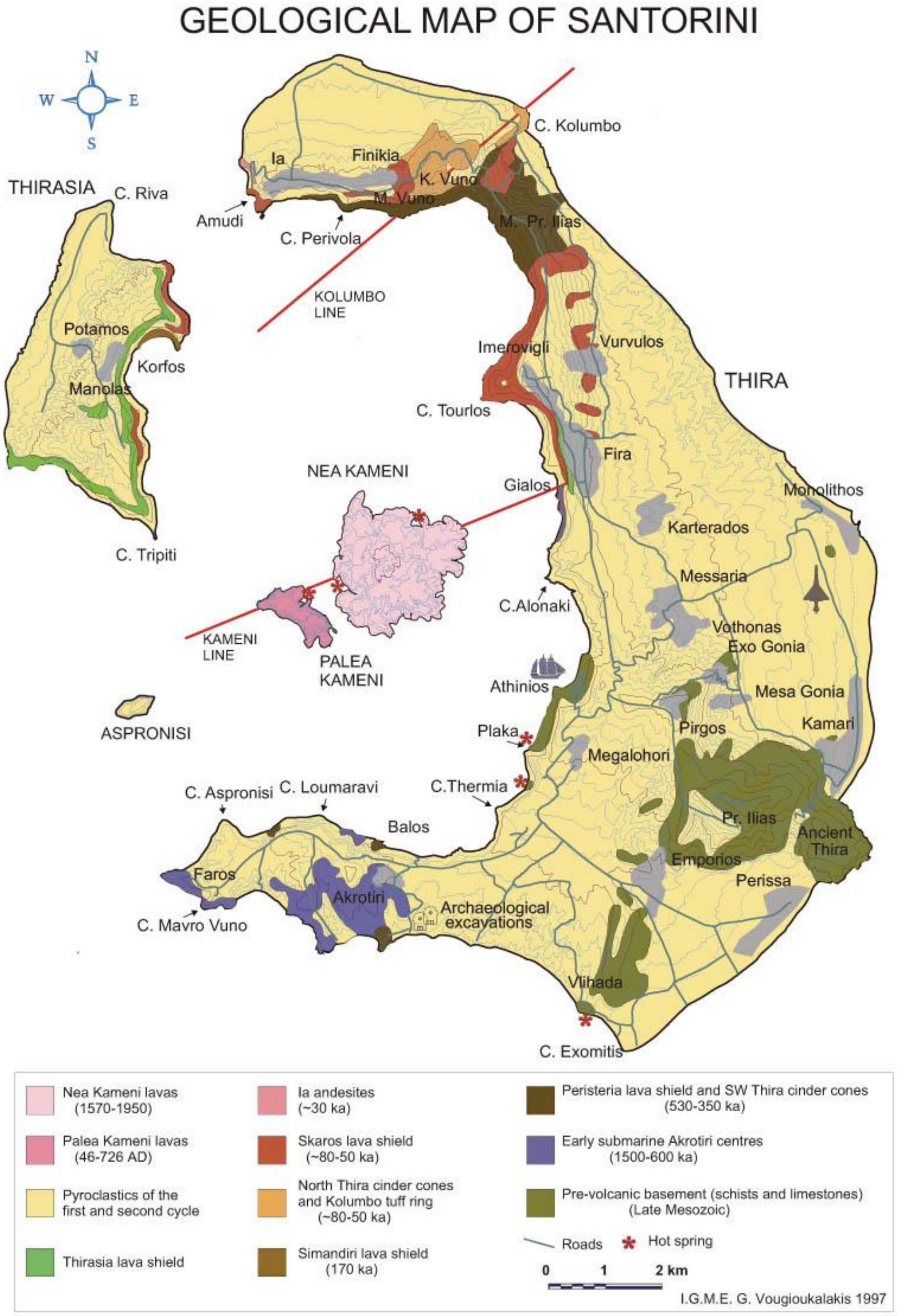
willingness of authorities to implement more costly preparedness measures (Doocy, 2013).

Santorini’s volcano is one of the most active volcanoes in Europe that has contributed at shaping the history of the planet by reforming its surface through its devastating prehistoric eruption (Minoan eruption). It’s not a matter of if but, it’s a matter of when the volcano of Santorini will erupt and how humanity will respond to this natural catastrophe. Modern technology offers a variety of desirable alternatives of monitoring the volcanic activity of the island to create a volcano emergency plan and to avoid any immediate threats of destruction.

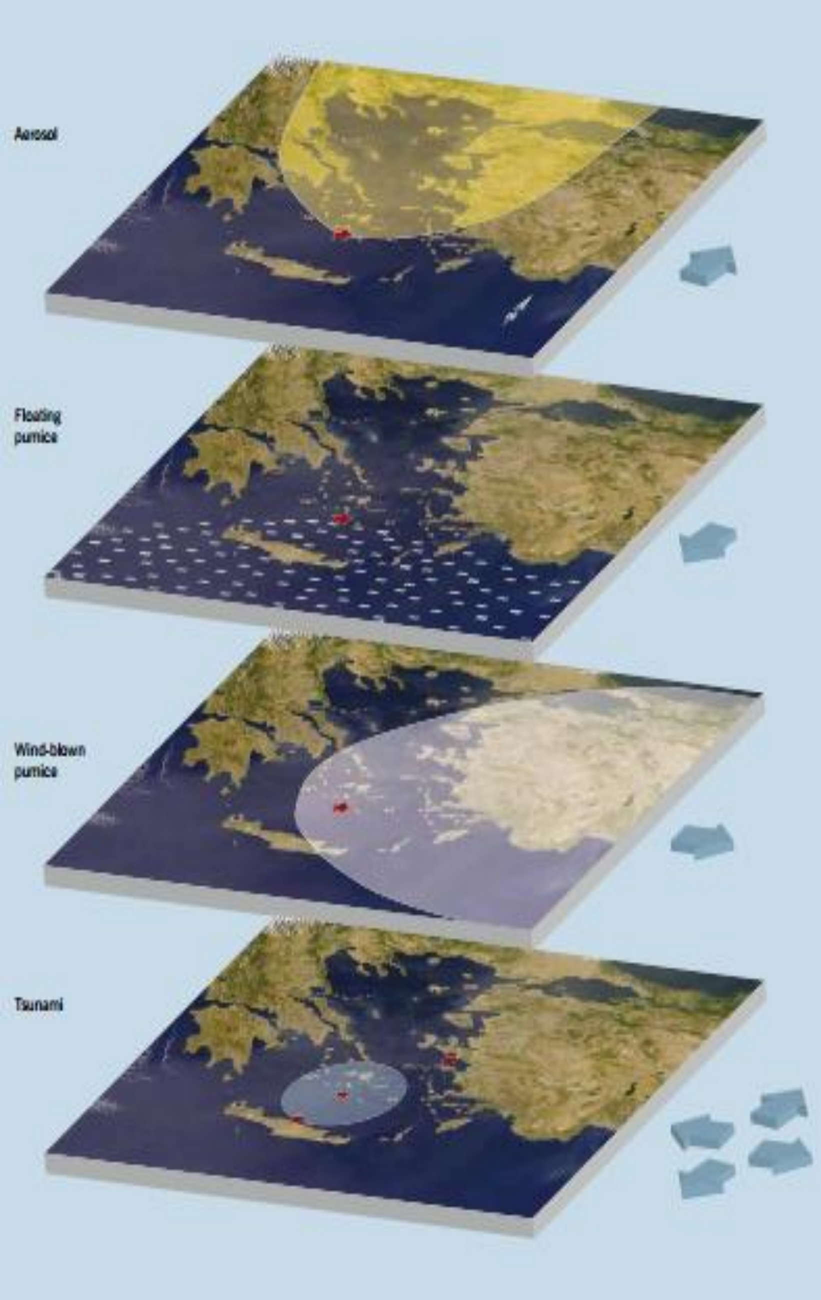
Conclusion

The attraction of the past is inescapable that's why the Minoan eruption challenges scientists even nowadays. The volcanic island of Santorini is both an ancient and a modern legend. Its history is linked with ancient maritime life of the Mediterranean Sea, the Minoan civilization on Crete and Greek mythology. The most dramatic page of Santorini's history is directly tied to the volcanic explosion of the ancient island of Thera around 1670 B.C., that changed its entire shape after one of the strongest explosions that mankind has ever witnessed; no volcanic event in human history compares with the magnitude of the Thera eruption in 17th century B.C. The eruption was developed in four stages and affected the Mediterranean region in a unique way. Through the comparison of the contemporary volcanic gases and their volcanic explosivity index it's possible to determine only the SO_2 total mass/kt 77742 ± 30600 total mass/kt with a range between 47000-108000 total mass/kt depending on multiple parameters (the type of the eruption effusive the rock type of the volcano plus the variety of the other gases ejected during the eruption). Huge explosive eruptions are one of the few natural phenomena that can produce global catastrophic effects. The Minoan Eruption of Santorini was strong enough to devastate the life on the island for decades and cause discomfort in the eastern Mediterranean affecting the atmosphere, the human/animal health, the marine ecosystems, and vegetation by its volcanic products. Historical eruptions at Krakatau, Tambora, Pinatubo, and Mount Saint Helens, have done massive environmental damage but none can compare with the sociological, religious, economic, agricultural, and political impacts from Thera (Santorini). Major natural catastrophes that have occurred over historical time illustrate the force of nature and the impact on civilizations. Extensive monitoring of the Santorini volcano with remote sensing techniques and extended geodetic measurements is necessary since the island is inhabited and highly visited by tourists while the volcanoes around it present periods of unrest even nowadays.

Appendices

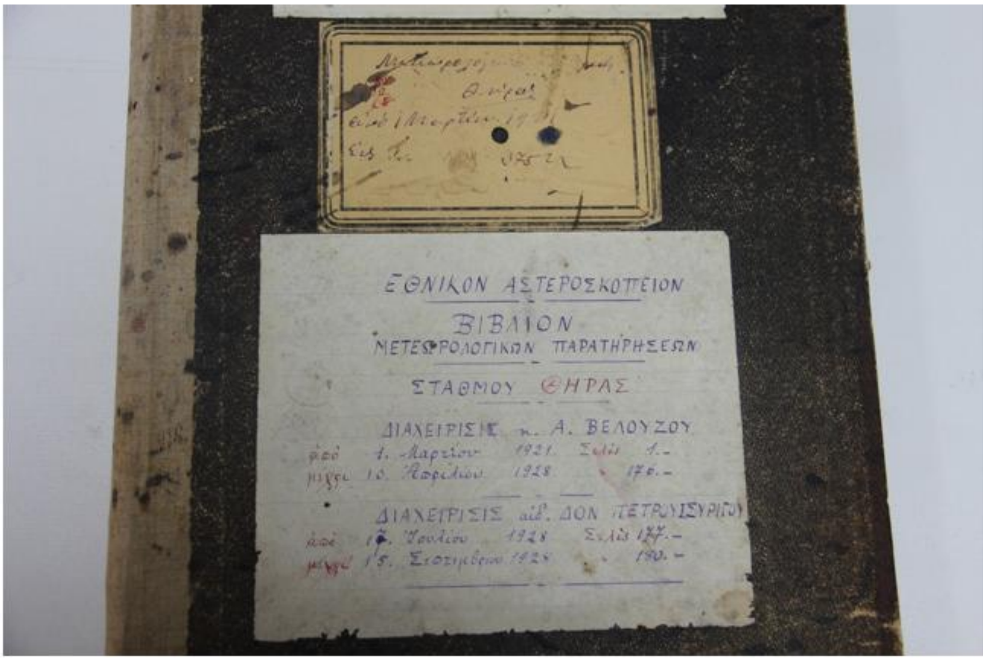


Pic. 1: *Remnant of Thera after the eruption 1670* **(Fytikas, 2017)**



Pic. 2: *The Effects and the Distribution of Products of the Minoan Eruption*

(Friedrich, 2013)



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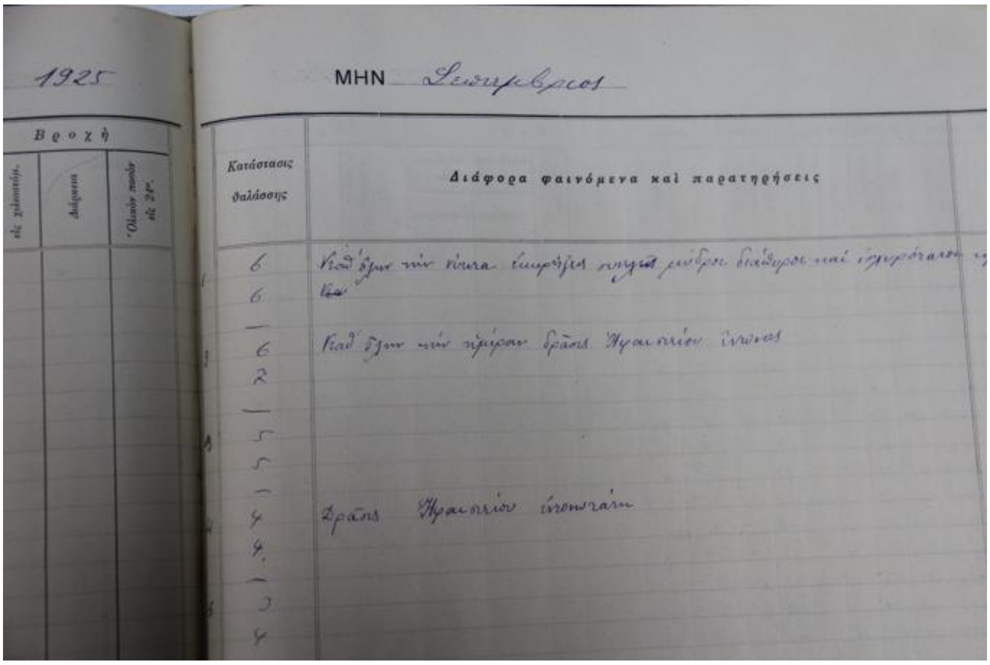

1925
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Pic. 3: *The Historical Record of National Observatory in Athens, Station in Thera (1893-1931), September 1925, Velouzos, A.*

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