Tsunami Generated by the Late Bronze Age Eruption of Thera (Santorini), Greece

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Abstract Tsunami were generated during the Late Bronze Age (LBA) eruption of the island of Thera, in the southern Aegean Sea, by both caldera collapse, and by the entry of pyroclastic surges/flows and lahars/debris flows into the sea. Tsunami generated by caldera collapse propagated to the west producing deep-sea sedimentary deposits in the eastern Mediterranean Sea known as homogenites; open-ocean wave heights of about 1.9–17 m are estimated. Tsunami generated by the entry of pyroclastic flows/surges and lahars/debris flows into the sea propagated in all directions around the island; wave heights along coastal areas were about 7–12 m as estimated from newly identified tsunami deposits on eastern Thera as well as from pumice deposits found at archaeological sites on northern and eastern Crete.

Key words: Tsunami, volcanic eruptions, tephra, pyroclastic surges, pyroclastic flows, debris flows, lahar, calderas, tsunami deposits, pumice, ash, Late Bronze Age.

1. Introduction

An explosive eruption on the island of Thera, also known as Santorini, in the Cycladic Islands, about 3600 years B.P. during the Late Bronze Age (LBA) had profound effects in the Aegean and eastern Mediterranean region. Local effects included the devastation of the island and a civilization that inhabited that island leading to the demise of cultural centers throughout the region, such as the Minoan culture on Crete (thus the eruption is often referred to as the “Minoan” eruption) and the Cycladic culture in the Cycladic Islands. Regional effects included widespread dispersal of ash, possible climate change associated with the injection of ash into high altitudes, seismic activity, dispersal of pumice rafts by oceanic surface currents, and generation of tsunami. Evidence comes from both the geological and archaeological record of the circum-Mediterranean area. Deposits of tephra are widespread throughout the Aegean and eastern Mediterranean region from the Nile

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Delta to the Black Sea (various papers in HARDY, 1990; STANLEY and SHENG, 1986; GUICHARD et al., 1993) and provide dramatic documentation of the explosivity of this Plinian-type eruption. Atmospheric temperature decrease of about 0.5°C in the Northern Hemisphere is estimated from sulphur aerosols injected into the stratosphere (SIGURDSSON et al., 1990). Seismic activity possibly associated with the eruption caused widespread damage to LBA Minoan buildings (DOUMAS, 1983; various papers in Hardy, 1990). Pumice accumulations in coastal deposits and archaeological sites throughout the eastern Mediterranean and Aegean littoral suggest extensive rafting of pumice following the LBA eruption (FRANCAVIGLIA, 1990; and others).

That tsunami were generated has been documented by the discovery of a distinctive sedimentary deposit, homogenites, interbedded in deep-sea sediments of the Mediterranean Sea (CITA et al., 1984; and others), by chaotic accumulations of tephra and other sediments at archaeological sites in the Aegean region (ASTROM, 1978; NEEV et al., 1987; FRANCAVIGLIA, 1990; and others), as well as by newly identified deposits within the LBA eruption sequence on Thera (McCoy, 1997; McCoy and HEIKEN, 1997). Geological and geophysical studies on Thera have lead to an understanding of the eruptive mechanics, vent placement and topographic changes associated with the eruption, and inferences for the generation of tsunami (BOND and SPARKS, 1976; HEIKEN and McCoy, 1984; DRUITT et al., 1989; SPARKS and WILSON, 1990; and others). Tsunami generated during the eruption has been assumed by archaeologists as one of the primary destructive effects of the eruption, although identifiable damage to man-made structures by tsunami remains elusive (MARINATOS, 1939; PLATON, 1971; DOUMAS, 1983; BARBER, 1987; various papers in HARDY, 1990; and others).

This paper reviews evidence for tsunami from the archaeological and geological record, and presents preliminary data on volcaniclastic deposits found on Thera that are possibly the result of tsunami inundation. Possible tsunamiogenic phases of the LBA eruption are discussed with inferences for wave propagation into the Aegean and eastern Mediterranean Seas; estimates for tsunami wave heights are made from sedimentary deposits considered to have originated from tsunami passage at sea and impact on land.

2. Background

2.1 Geologic and Tectonic Setting of Thera

Thera is one of several volcanic centers active during the Quaternary along the Hellenic island arc of the southern Aegean Sea (Fig. 1). Five islands surround (Thera, Therasia, Aspronisi) or occur within (Kameni Islands) two water-filled calderas to form the archipelago of Santorini (Fig. 2). Thera, Therasia, and
Aspronisi are remnants of a larger island destroyed during the LBA (Minoan) eruption. The Kameni Islands have been constructed by post-Bronze Age volcanism, the latest eruption in 1950 on Nea Kameni; these islands today have manifestations of volcanic activity with hot springs, fumaroles, and low-level seismic activity (Fytkas et al., 1990).

Volcanic activity during the past 700,000 years constructed pyroclastic cones and lava shields of dominantly dacitic composition, to form the Thera volcanic field (Pichler and Kussmaul, 1980; Seward et al., 1980; Heiken and McCoy, 1984;
Generalized geologic map of Santorini. "Basement" refers to Mesozoic metamorphic rocks; the Akrotiri volcanic complex is a sequence of pillow lavas and associated sediments of the Pliocene age. Megalo Youno volcanic complex, the Micros Profitis Elias, Therasia and Skaros volcanoes are eruption centers active over the past 900,000 years. Data from Pichler and Kussmaul (1980), Heiken and McCoy (1984), Druitt et al. (1989), and unpublished field data. The LBA eruption is often referred to as the "Minoan" eruption, after the Minoan culture that existed on Crete at the time of the eruption.

Druitt et al., 1989; Barton and Huijsmans, 1986; Friedrich, 1994; McCoy and Heiken, 2000). The latest pyroclastic eruption in this sequence was the LBA (Minoan) eruption that excavated a large caldera north of the present-day Kameni
Islands and deposited a thick tephra layer on the islands surrounding the caldera (Heiken and McCoy, 1984) (Fig. 2).

These volcanic deposits are built upon Mesozoic metamorphic rocks and Pliocene submarine pillow lavas and associated sediments (Fig. 2). The Mesozoic terrain is part of the Hellenide-Anatolide orogenic belt deformed during the early Cenozoic closure of the African and European plates (McKenzie, 1972; Pichon and Angelier, 1979; Fytikas et al., 1984). An extensional crustal regime during the Pliocene, in response to this closure, formed the Aegean basin with the islands of the Aegean basin being the subaerial portions of a series of Paleogene-Miocene nappes (Makris, 1978; Bonneau, 1984; Hall et al., 1984; Robertson and Dixon, 1984; Armijo et al., 1992). Contemporary plate-closure rates are about 10–40 mm/yr., with intra-arc extension rates of about 3–8 cm/yr. (Dewey et al., 1973; Livermore and Smith, 1985; Oral et al., 1995; Kahle and Muller, 1996). A northwesterly-dipping Benioff zone occurs beneath the arc (Fig. 1) (Agarwal et al., 1976; Bath, 1983; Spakman, 1986). Seismic activity in response to this tectonic activity, as well as to volcanism, is centered in the southern Aegean Sea in the vicinity of Thera, often with destructive tsunami (Bath, 1983; Taymaz et al., 1990).

2.2 Generation of Tsunami by Volcanism and Slumping

Tsunami created during historic volcanic eruptions have been documented, particularly those generated during the 1883 eruption of Krakatau. Accounts from this eruption come from both survivors and from later studies (see Simkin and Fiske, 1983, for an excellent compilation; see also Sigurdsson et al., 1991; Carey et al., 1996, 2000). Tsunami were produced by collapse of the caldera (Wharton, 1888), entry of pyroclastic surges and flows into the ocean (Self and Rampino, 1981; Latter, 1981; Sigurdsson et al., 1991; Carey et al., 1996, 2000), slumping of parts of the underwater volcanic edifice (Self and Rampino, 1981), in addition to the explosive interaction of magma and seawater (not considered as significant as other effects in generating tsunami by Self and Rampino, 1981). Wave heights exceeded 40 m; runup distances reached 11 miles inland over low slopes (on the order of 1–5°) of coastal benches (Simkin and Fiske, 1983).

Tsunami produced during the 1815 eruption of Tambora in Indonesia were generated by pyroclastic flows entering the ocean (Self and Rampino, 1981); coastal inundation reached up to 4 m elevations (van Padang, 1971; Walker, 1973). The 3500 yBP eruption of Aniakchak volcano in Alaska produced tsunami with runups as high as 15 m over low slopes (coastal peat bog), apparently also by entry of pyroclastic flows into the ocean (Waythomas and Neal, 1997).

Tsunami generated by sea-floor displacement due to gravity-driven slumps and slides are well documented. The collapse of volcanic edifices to produce tsunami are the focus of numerous papers in this volume and elsewhere (McGuire et al., 1996).
Massive underwater slides generating tsunami are documented, the best studied perhaps being the Storegga slides off Norway about 7000 yBP (Bugge et al., 1987; Jansen et al., 1987) leaving deposits in Scotland (Dawson et al., 1988, 1993) and Norway (Bondevik et al., 1997). Runup heights from this tsunami are estimated at up to an elevation of 11 m (Bondevik et al., 1997). An underwater slide in the Aleutian trench south of Alaska in 1946 produced devastating tsunami with runups reaching 35 m in Alaska and 17 m in Hawaii, and with estimated maximum wave-heights in Hawaii up to 15 m (Macdonald et al., 1947). Tsunamis generated by debris avalanches accompanying or following volcanic activity have produced waves of the order of 9–20 m in height (reviewed in McGuire, 1996).

In the Aegean, there are accounts describing historic volcanic eruptions and consequent tsunami. In 1650, as one example, Jesuit priests on Thera described with some awe a submarine eruption at Colombo Bank northeast of Thera (Fig. 1) “the ocean burned ..., flames leaping from the sea ... fiery clouds lowered upon us ... cast up into the heavens enormous rocks, which fell to earth again some two leagues away ... in a field we saw a boulder spewed from the bowels of the earth, of a size that 40 men could not move it ... the sea covered with pumice ... sulfurous steam” (Galanopoulos and Bacon, 1969). Tsunamis associated with this eruption were apparently generated by caldera collapse; recent bathymetric surveys of Colombo Bank indicate collapse was on the order of 400 m (Perissosratis, 1985). On Thera, waves deposited pebbles and dead fish as much as two miles inland in valleys (Galanopoulos and Bacon, 1969); tsunamis were reported to be 16 m high on the island of Ios immediately north of Thera (Luce, 1969); at Patmos, northeast of Thera “the sea rose 50 m and 30 m on the west and east coasts, respectively” (Galanopoulos and Bacon, 1969); on the northern coast of Crete, ships were torn from their moorings and sank in the harbor at Iraklion (the town was under siege by Turkish forces at the time and their ships were destroyed by the tsunami, thus ending the siege) (Galanopoulos and Bacon, 1969; Galanopoulos, 1960; Doumas, 1983).

2.3 Observations of Tsunami Wave Heights

Accounts describing tsunami often use two different observations: (1) wave height, as would be observed at the coastline with the tsunami approaching, and (2) elevation or distance onshore of runup by the wave, usually easy to distinguish by limits of damage or of displaced debris inland. Wave height is a difficult measurement, potentially dangerous to the observer, and is reliably measured by high-water levels or damage levels marked on surviving structures after inundation — such measurements are rare; good data on tsunami wave heights are correspondingly rare. Runup is not a reliable indicator of wave height, rather is a function of numerous variables: slope and topography offshore and onshore; soil/sediment and rock types offshore and onshore; roughness factors determined offshore by reefs,
bars, banks, etc., and determined onshore by rivers, hills, vegetation, buildings, etc.; in addition to wave characteristics such as wave type, height, angle of approach, onshore velocity, etc. (LOOMIS, 1976; COX, 1979). Experimental studies have found amplification factors of runup over wave height as high as 5.7 (SPIELVOGEL, 1973).

3. The LBA Eruption of Thera

3.1 Archaeological Setting

In the archaeological chronology of the southern Aegean derived from potteryshard types, the eruption occurred, and defines, the boundary between the Late Minoan IA and Late Minoan IB of the Late Bronze Age (LBA) (see various papers in HARDY, 1990). Dates center around two intervals, 1630 BC and 1500 BC (see MANNING, 1995, for discussion of the controversy concerning these dates). Archaeological evidence provides a rich account of the effects of the eruption on civilizations in the region, particularly the Cycladic culture on Santorini and the Minoan culture on Crete. On Santorini, an archaeological excavation at Akrotiri (Fig. 3) uncovered what appears to have been a prosperous small city (DOUMAS, 1983) buried within tephra of the LBA eruption.

In the aftermath of the eruption, both the Cycladic and Minoan cultures were replaced about two centuries after the volcanic disaster by the Mycenaean culture from mainland Greece. Whether this cultural change was due entirely to the eruption or to other cultural factors, such as war or economics, continues to be argued by archaeologists and historians—that widespread devastation did occur concurrently with the eruption from earthquakes, fire, and possibly tsunami, however, is clear in the archaeological record (see, for example, MARINATOS, 1939; GALANOPoulos and BACON, 1969; LUCE, 1969; HOOD, 1971; PLATON, 1971; BARBER, 1987; DOUMAS, 1983). Certainly the consequences of an eruption of such magnitude near the center of two thalassocratic LBA societies would have had a major impact on their future. One need only compare the effects of equivalently large Plinian eruptions on post-Bronze Age civilizations to see the potentially huge effect of the Thera eruption and its regional effects on these LBA societies (see, e.g., MCCOY and HEIKEN, 2000).

3.2 Explosivity, Magnitude and Tephra Volume

The explosivity index of the LBA eruption of Thera is estimated at 6.9 on the Volcanic Explosivity Index (VEI; NEWHALL and SELF, 1982) and as such represents one of the largest eruptions in the past few millennia (only seven eruptions have had higher VEI values in the past four millennia; SIMKIN and SIEBERT, 1994; DECKER, 1990; VOGEL et al., 1990).
Volcanic plume heights are estimated to have been up to 36 km (Sigurdsson et al., 1990). Injection of ash to these heights, in conjunction with estimates of a high sulfur content within the plume, suggests that global climatic cooling for a few years was a likely consequence of the eruption (Sigurdsson et al., 1990). The duration of the major part of the eruption ranged from six hours to four days with no extended interruptions in this activity, erupting at an intensity of $1.4 - 4.2 \times 10^8$ kg/sec.; accumulation rates of tephra were as high as 3 cm/min. (Pyle, 1990; Sparks and Wilson, 1990; Sigurdsson et al., 1990). Volume of caldera collapse is calculated at 18–39 km$^3$ (Heiken and McCoy, 1984; Pyle, 1990); modern depths in the caldera are 390 m (Perissoratis, 1985) indicating at least this amount of collapse during the eruption, but certainly much more, perhaps as much as 690 m depending upon reconstructions of the pre-eruption topography of the island (Pichler and Friedrich, 1980; Heiken and McCoy, 1984; Friedrich et al., 1988; Druitt and Francaviglia, 1992).

Figure 3
Map of the southern portion of Thera showing the Akrotiri region and the archaeological excavation.
3.3 Eruption Sequence and Tsunamigenic Phases

The LBA eruption occurred in four major phases, preceded by a minor precursor phase; eruption activity during three of these likely produced tsunami (Fig. 4). The discussion below is summarized from Heiken and McCoy (1984), unless otherwise noted.

A precursor eruptive phase of magmatic and phreatomagmatic activity some weeks or months prior to the major phases of the eruption deposited a thin tephra layer extending to 8 cm over southern Thera (Fig. 5a), and may have provided advance warning of the impending disaster to local inhabitants (Heiken and McCoy, 1990). Bedding structures in the precursor deposit are suggestive of air-fall deposition with local dispersal by atmospheric winds (Heiken and McCoy, 1990). Although a significant lithic component in the ash might indicate smaller collapse near the vent, there is no evidence of larger collapse structures during this precursor phase. This evidence in combination with the lack of major destruction to man-made structures (Doumas, 1983) and the inferred lower level of eruptive activity, suggest no tsunami generation during this initial eruption phase.

Intense magmatic activity of the first major phase of the eruption (BO₁/minoan A) deposited up to 7 m of pumice and ash, with a minor lithic component, to the
Depictions of vent positions (suture line) and tephra deposits (fine stippled pattern) from the precursor and major phases of the LBA eruption of Thera; also shown is the modern coastline (solid line) and the approximate LBA pre-eruption coastline (dotted line) (modified from Heiken et al., 1990).

Figure 5a. Precursor eruption phase (BO).

Southeast and east (Fig. 5b). Dispersal was by atmospheric and stratospheric winds; dispersal patterns and isopachs imply a vent north of the modern Kameni Islands, perhaps an extension and enlargement of the vent of the precursor phase. Archaeological evidence indicates burial of man-made buildings with limited damage mainly from collapsed roofs. Tephra characteristics indicate fragmentation and discharge of magma by magmatic gases in a setting where there was no water interaction at the vent. Such depositional mechanisms, in combination with the inferred vent position on land and a lack of evidence for major collapse of the volcanic edifice, are not those mechanisms and settings noted for tsunami generation during historic volcanic eruptions. Accordingly it is inferred that tsunami were not generated during this first major phase of the LBA eruption.

Pumice deposited on the sea around Thera during this first phase of the eruption may have formed enormous rafts of floating pumice that drifted on surface currents throughout the Aegean and eastern Mediterranean Seas. For
example, pumice rafts following the 1883 eruption of Krakatau, a less explosive eruption than LBA Thera (VEI = 6.0; SIMKIN and SIEBERT, 1994) were as much as 15 ft thick and floated across the Indian Ocean transporting skeletons and trees (SIMKIN and FISKE, 1983).

With the second phase (B0₂/Minoan B), however, the eruption character changed to phreatomagmatic activity with numerous thin (<1 m) pyroclastic surges and flows leaving a deposit of up to 12 m; thickest accumulations are on southern Thera (Fig. 5c). Changes in bedform characteristics indicate an increasing velocity of surges and flows as second phase activity continued, which is reflected in the complete destruction of any man-made structures not buried within first-phase or early second-phase deposits (MCCOY and HEIKEN, 2000). Flow directions and the pattern of thickness variations suggest a vent sited south of the first-phase vent in a setting where water had unlimited access into the vent.

By comparison with tsunamigenic phases of historic eruptions, such as Krakatau in 1883, it is entirely likely that tsunamis were generated during the second phase of the LBA eruption, particularly during later portions of this phase, wherever surges and flows entered the sea (assuming surge/flow bulk densities
Second major eruption phase (BO$_3$/Minoan B); also shown are pyroclastic surge and flow directions (from McCoy and Heiken 2000), with inferred sites of tsunami generation and directions of wave propagation.

greater than sea water to diminish buoyancy and allow flow into the water rather than on the sea surface). Thicker accumulations along southern Thera indicate pyroclastic activity focused in this direction and thus tsunami perhaps directed more towards the south and southeast, although tsunami would have been generated anywhere these surges and flows entered the ocean along the outer perimeter of the island. Tsunami generated within the center of the island in the southern embayment would have had limited entry into the Aegean Sea through the narrow channel in the pre-collapse landscape (Fig. 5c).

Pyroclastic flow activity continued into the third phase of the eruption (BO$_3$/Minoan C) with the initiation of caldera collapse (Fig. 5d). The deposit from this phase of the eruption is a massive unit (up to 55 m thick on central-southeastern Thera) within which individual pyroclastic-flow units are not distinguishable. A high proportion of lithic fragments, some many meters in size, and the composition of these fragments indicate major collapse of the north-central portion of the LBA.
island to form the caldera. Thickness variations and ballistic trajectories of lithic blocks indicate a vent situated approximately in the same position as that for the second-phase of the eruption. Late in this phase, lahars and debris flows were produced.

As during second-phase activity, tsunamis may have been generated wherever pyroclastic flows entered the sea around the perimeter of the island(s). Tsunamis could have been larger than those produced earlier in the eruption because the characteristics of third phase deposits on land suggest a few massive slurry-like mixtures that were thick enough to flow over caldera walls close to 400 m high (Heiken and McCoy, 1984; Sparks and Wilson, 1990)—the entry of such a pyroclastic slurry into the ocean could have produced huge tsunami propagated in all directions. In addition, large tsunamis might have been produced by sea water filling the collapsing caldera, particularly if the two peripheral fault blocks to the caldera (Fig. 2) had partially collapsed in this phase of the eruption, thus widening the ocean channels to the north and east-southeast and focusing tsunami in these directions.
Fourth eruption phase (BO₂₄/Minoin D); also depicted are areas of final caldera collapse, pyroclastic flow directions (modified from Heiken et al., 1990, and McCoy and Heiken, 2000), and inferred sites of tsunami generation. The position of the tsunami deposit at Pori is identified.

The final phase of the LBA eruption (BO₂₄/Minoin D) was marked by varied activity: lithic-rich base surge deposits, lahars, debris flows, and some co-ignimbrite ash-fall deposits (Figs. 5e and 5f). That tsunami was generated by this activity, towards the east by both a pyroclastic flow and a lahar/debris flow entering the ocean, is documented by tsunami deposits within the fourth phase deposit (described below; McCoy, 1997, 1997b). This phase also marked the completion of caldera collapse (Bond and Sparks, 1976; Heiken and McCoy, 1984; McCoy and Heiken, 2000). Vertical collapse of at least 400 m in the caldera (perhaps up to 700 m assuming about 300 m elevation to the LBA island that was collapsing into the caldera), and collapse of the two fault blocks peripheral to the caldera by 300 m, also produced tsunami (vertical displacements relative to modern sea level using bathymetric data from Perissoratis, 1985). This is documented by sedimen-
Figure 5f
Fourth eruption phase (BO$_4$/Minoan D); also depicted are flow directions of lahars, debris flows and lithic-rich base surges (modified from HEIKEN et al., 1990, and McCoy and HEIKEN, 2000), inferred sites of tsunami generation, and directions of wave propagation.

tary 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 (KASTENS and CITA, 1981; CITA et al., 1984; HIEKE, 1984).

4. Sedimentary Deposits Produced by Tsunami Generated during the LBA Eruption of Thera

4.1 Homogenites: Deep-sea Tsunami Deposits

The formation of a distinctive deep-sea sedimentary deposit found in cores from the eastern Mediterranean Sea, homogenites, has been attributed to tsunami
(Kastens and Cita, 1981; Cita et al., 1984; Hieke, 1984). A single homogenite layer can be up to 9 m thick. Homogenites are homogeneous in color (thus the name; usually a light to medium brown-grey), soupy, contain a microfossil assemblage of mixed ages, have a thin basal zone of silt or sand, show normal size grading through much of the layer, and have no sedimentary structures except for burrows in the upper few centimeters (Fig. 6). Homogenites are distinctive with their homogeneous appearance, thickness, and color that contrasts with the pelagic stratigraphic section of the eastern Mediterranean of turbidites (white to brown), sapropels (dark grey to black), volcanic ash layers (light tan to grey), burrowed pelagic muds (light green to dark brown) and oozes (white).

Homogenites are found only in cores taken of sediments from floors of enclosed basins on the sea floor. Homogenites appear in seismic reflection profiles as an acoustic transparent layer constrained to the basin floor (Fig. 7). They occur at the stratigraphic level of the ash layer from the LBA eruption; the LBA ash layer is not present in cores containing a homogenite. Cores from surrounding slopes of the basin show an unconformity/paraconformity at the stratigraphic interval of the LBA ash layer.

Figure 6
Typical sedimentological characteristics of homogenites from two cores taken southwest of Crete on the Mediterranean Ridge; thickness of both homogenite layers is close to 5 m (from Cita et al., 1984).
These factors suggest slumping of sediments onto basin floors from the surrounding walls at the time of the LBA eruption, triggered by the passage of tsunami generated during the LBA Thera eruption (KASTENS and CITTA, 1981) (Fig. 8). Tsunami would have had wavelengths adequate to provide near-bottom current velocities sufficient to erode and slump deep-sea sediments. In the intervening 3600 years since the eruption, compaction of the turbid bottom water ponded within the basin has formed the homogenites.

The occurrence of homogenites only in ocean-floor basins southwest of Crete, and the alignment of these basins with pathlines calculated for tsunami propagation to the west from Thera (Fig. 9), infer wave generation by collapse of the caldera and the fault block west of the caldera (third and fourth phases of the eruption; Figs. 5c,f). Collapse of the latter would have widened and deepened the channel into the Aegean Sea, focusing wave propagation to the west.

4.2 Tsunami Deposits on Thera

A 3.5-m thick volcanioclastic deposit intercalated between third and fourth phase deposits of the LBA eruption (see Fig. 4), near the village of Pori on the east coast of Thera (Fig. 5), has been interpreted as tephra reworked by tsunami generated during the eruption (McCoy, 1997; McCoy and Heiken, 1997). The deposit is a mixture of pumice, ash and lithic (lava) fragments, characteristic components of all phases of the eruption, in two distinct layers (Fig. 10). The lower layer has a
minimum thickness of 1.5 m and extends inland 36 m to an elevation of 6 m on a 2–16° slope. It has a lenticular shape open towards the ocean but which thins inland; internal bedding structures include planar and cross-bedded layers, some with normal size-grading, elasic tails in the lee of larger elasic particles, and layers of lithic-rich gravels, often in sharp contact with erosional features. The basal contact of the lower layer is sharp with erosional scour into the underlying tephra.

The upper layer appears to be about 2 m thick; the upper contact is gradational and indistinct. It is a chaotic mixture of particle sizes and composition with no internal bedding structures, but with a higher content of coarser lithic fragments than found in the lower layer. The contact between the lower and upper layer is distinct with some features indicative of erosion. Detailed sedimentological work on the deposit continues and will be reported elsewhere.

A tsunami origin for this deposit rather than one related to eruptive mechanisms is suggested by: (1) the lens-shaped geometry of the deposit open towards the ocean which is a unique geometry within the volcanic succession, (2) sedimentary structures in the lower layer of the deposit that are indicative of a water-laid deposit under oscillatory flow, in contrast to structures in surrounding pyroclastic and volcanioclastic deposits, and (3) the chaotic upper layer of the deposit which appears to be reworked rather than the product of deposition from pyroclastic activity, lahars or debris flows. A fluvial or debris flow origin for the deposit is discounted.

Figure 8
Diagrammatic representation of sediment disturbance and slumping into isolated basins on the Mediterranean Ridge to produce homogenite layers with passage of tsunami generated during the LBA eruption of Thera (from Cita et al., 1984).
Figure 9
Pathlines of inferred tsunami propagation. Solid arrows trace tsunami possibly generated by the collapse of the caldera and a large fault block west of the caldera (see Figs. 6e and 6f). Shaded areas in the eastern Mediterranean Sea identify basins on the deep-sea floor where cores have sampled homogenites (11 shaded areas identify 35 different basins). Dashed arrows indicate pathlines for tsunami possibly generated by the entry of pyroclastic flows and lahars/debris flows into the sea (from KASTENS and CITA, 1981).

by these observations: (1) cross-bedding structures indicate oscillatory flow rather than unidirectional flow; (2) abundant pumice is indicative of limited abrasion during flow, inferring short duration and distance of flow; and (3) the deposit does not appear constrained within a channel, rather appears to be planar in bed geometry, indicative of sheet-wash type motion.

The stratigraphic position of the tsunami deposit, in lower contact with pyroclastic flow deposits of the third (BO₄/Minoan C) phase of the eruption, and mixed along the upper contact with debris-flow deposits of the fourth (BO₄/Minoan D) eruption phase, infer tsunami origin related to the entry of pyroclastic flows and debris flows into the sea. Initial tsunami flooding is marked by the erosional basal contact. Internal packets of cross-bedded and planar beds within the lower portion of the tsunami deposit might indicate multiple inundation episodes related to repeated entry of pyroclastic flows into the sea, or seiche during maximum inundation. The upper portion of this deposit may represent tsunami generated by
the entry of a debris flow into the sea (lack of internal sedimentary structures; chaotic assemblage of pumice and lithic fragments; higher proportion of angular, pebble and cobble-sized lithic fragments; somewhat gradational upper contact into a debris flow). If the latter, this is one of few indications of tsunami generated by the entry of debris flows into the sea during a volcanic eruption.

4.3 Tsunami Deposits Elsewhere

Tsunami deposits related to the LBA eruption have been inferred from numerous coastal exposures and archaeological sites where rounded pumice has been found, often mixed with seashells and sometimes in a cultural destruction layer dated to the LBA (Fig. 11): Anaphi island east of Thera (MARINOS and MELIDONIS, 1971), Crete (at Amnissos, MARINATOS, 1939; PICHLER and SCHIERING, 1977; FRANCAVIGLIA and DI SABATINO, 1990; at Pitsidia, VALLIANOU, 1996), Cyprus (ASTROM, 1978; MESZAROS, 1978), and Israel (near Tel Aviv, PFANNENSTIEL, 1960; other coastal sites, NEEV et al., 1987).

However, the use of pumice in coastal exposures as indicators of tsunami deposition must be done with caution. The disparity between travel times for tsunami generated by the eruption and for pumice rafts drifting on surface currents

![Figure 10](image)

Sketch (from a photograph) of the tephra stratigraphy and tsunami layer near Pori, Thera. Stratigraphic identification and approximate scale on the cliff face are shown on the right. Note the lack of internal stratification in tephra layers BO₁ and the series of deposits from lahars and debris flows in BO₄, in contrast to the lenticular shape and internal stratification of the tsunami deposit. The two layers composing the tsunami deposit are shown: a lower layer characterized by numerous planar beds, cross-beds, and gravel-rich beds, most with erosional contacts including the basal contact; an upper layer characterized by the lack of internal stratification in a chaotic, poorly-sorted volcaniclastic mixture.
Figure 11
Regional ash distribution of tephra from the LBA eruption (shaded area). Symbols identify sites and sampling locations where ash (deep-sea cores, lake cores, exposures on land, archaeological sites) and pumice (exposures on land and at archaeological sites) have been found. Numbers next to the two triangles in Anatolia represent layer thicknesses in cm for ash deposits found in lake sediments; curved lines over the eastern Mediterranean Sea are isopachs of ash thickness, in cm, of the tephra layer found in the deep-sea stratigraphic sequence sampled by coring. Data are from: Ninkovich and HEEZEN (1965), NEEV et al. (1987), CADOGAN (1972), RAPP et al. (1973), VITALIANO and VITALIANO (1974), ZEIST et al. (1975), FORNASIRI et al. (1975), ASTROM (1978), WATKINS et al. (1978), HOOD (1978), DOUMAS and PAPAZOGLOU (1980), McCray (1980, 1981), SULLIVAN (1988, 1990), STANLEY and SHENG, 1986), KELLER (1980), BETANCOURT et al. (1990), MARKETOU (1990), SOLES and DAVARAS (1990), WARREN and PUCHELT (1990), FRANCAVIGLIA (1990), and GUICHARD et al. (1993).

(5–20 cm/sec., ÖZSÖY et al., 1989) constrains distances from Thera where tsunami would have arrived coincident with rafted pumice. As one example, open-ocean velocities for tsunami of the order of 1000 km/hr would have waves arriving in the Levant (approximately 1000 km, straight line distance from Thera) in about 60–100 min (Fig. 12; YOKOYAMA, 1978). Pumice rafted by surface currents of 5–20 cm/sec for 1500 km (typical surface currents in the eastern Mediterranean Sea; approximate float path following eastern Mediterranean gyres; ÖZSÖY et al., 1989) would
arrive along the Levant coastline in about 85–350 days, long after the eruption and eruption-generated tsunami (assuming a four-day duration of the LBA eruption; Sparks and Wilson, 1990; Sigurdsson et al., 1990). Accordingly, pumice found along the Levant littoral could not have been deposited by tsunami generated by the LBA eruption.

In a general case (applying assumptions noted above on surface current patterns and velocity, drift paths and rates for pumice rafts, 4-day duration of the eruption, tsunami generated during late-phase eruptive activity), rafted pumice would be at distances of only about 70–100 km or less from Thera (north-central coast of Crete, Anaphi, Melos, Amorgos) after four days of drifting and in position for tsunami arrival and deposition on land.

5. Wave Characteristics Inferred for Tsunami Generated by the LBA Eruption of Thera

Wave heights near the eruption site on Santorini (no water depth specified or distance offshore) have been estimated at 50–86 m (Yokoyama, 1978). The lower wave-height estimate was based upon two pumice deposits about 1 m thick found by Marinos and Melidonis (1971) on the island of Anaphi due east of Thera (Fig. 1) at an elevation of 40–50 m. It is not clear if the Anaphi deposit represents

![Figure 12](image)

Tsunami time-distance relationships and pathlines from Thera; contours are in minutes (from Yokoyama, 1978).
a pumice-fall accumulation or a deposit left from runup by tsunami. The upper wave-height estimate was derived by Yokoyama (1978) from the occurrence of pumice 5 m above sea level in a coastal terrace near Tel Aviv (presumed related to the Thera eruption by Pfannenstiel, 1960; see section above), assuming LBA sea-level about 2 m below present levels and a wave height of 7 m offshore of Tel Aviv, then calculating an original wave height of 86 m near Santorini. By averaging the 50–86 m wave-height estimate, then “weighting twice” the Anaphi estimate because the former “might be more reliable,” Yokoyama (1988) refined the wave-height calculation to 63 m near Santorini.

Tsunami directed towards Anaphi and the Levant, including south towards Crete, likely were generated by the entry of pyroclastic flows and lahars/debris flows in the sea (as noted previously). Tsunami deposits found near Pori on Thera suggest these estimates by Yokoyama (1978) may be too high. This deposit has an upper contact 7–8 m above modern sea level, providing a minimum indication of tsunami wave heights. Adding to this an LBA (3600 yBP) sea level perhaps as much as 2 meters lower than modern levels in the Mediterranean and southern Aegean region (van Andel and Shackleton, 1982; Flemming and Webb, 1986; Galili et al., 1988; Stanley and Warne, 1993), and evidence of perhaps up to 2 m of subsidence of Thera since the LBA (Galanopoulos and Bacon, 1969), then tsunami wave heights at coastal impact might have been as much as 11–12 m. Given uncertainties between runup and wave height, wave heights somewhere between 7 m and 12 m might be suggested. Such an estimate is close to those by Pichler and Schiering (1977) of 8–10 m wave heights along the northern and eastern coasts of Crete at various archaeological sites.

Kastens and Cita (1981) used Yokoyama’s (1978) minimum estimate of a 50 m wave near Thera, and assumed this wave amplitude at a 200 m water depth off Santorini, to calculate open-water wave heights of between 1.9 and 17 m, with wave lengths > 100 km, in the eastern Mediterranean Sea over the abyssal homogenite sites. Sea-floor current velocities of up to 49 cm/sec would result from such a wave, and would exceed critical erosional velocities needed to erode and cause slumping of fine-grained pelagic sediments off basin walls onto basin floors to form homogenite deposits (Kastens and Cita, 1981). Nearshore wave heights as open-ocean tsunami amplitudes of this magnitude entering shallow coastal waters might be considerably higher than those suggested from the tsunami deposit at Pori, Thera, a reflection of generation of the homogenite-forming tsunami by caldera collapse rather than by pyroclastic and lahars/debris flows entering the sea.

6. Summary

Tsunamis generated by the LBA eruption of Santorini were generated by (1) caldera collapse and (2) the entry of pyroclastic flows and lahars/debris flows into
the sea. Volcanogenic tsunamis produced by caldera collapse and the entry of pyroclastic flows into the sea are well documented from historic eruptions; tsunami generation by the entry of lahars and debris flows into the sea is poorly documented. Evidence for tsunami comes from deep-sea deposits left by open-ocean passage of the wave, as well as from deposits on land where inundation has left pumice accumulations, has produced destruction layers at archaeological sites, or has left distinctive volcanoclastic deposits within the tephra stratigraphy of the eruption on eastern Thera. Pumice accumulations in coastal exposures or archaeological sites at distances greater than about 100 km likely were not, however, emplaced by tsunami generated during the LBA Thera eruption considering drift rates via surface currents in the Aegean and eastern Mediterranean Seas and travel times for tsunami.

Wave propagation following caldera collapse (third and fourth phases of eruption activity) would have been to the west, considering somewhat asymmetric collapse of the volcanic edifice and the occurrence of tsunami deposits (homogenites) on the eastern Mediterranean sea-floor; open-ocean wave amplitudes are calculated to have been 1.9–17 m. Wave propagation following ocean entry of pyroclastic flows and lahars/debris flows (second through fourth phases of eruption activity) would have been in all directions around Thera, and certainly towards the east as indicated by tsunami deposits on eastern Thera; wave amplitudes are estimated at about 7–12 m along coastal Thera and Crete. The regional effects of tsunami must have been significant, considering the cataclysmic event which occurred within the core of two thalassocratic cultures, Minoan and Cycladic, and which destroyed the center of one, the Cycladic culture on Thera.

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