Discovery of Minoan tsunami deposits

K. Minoura Institute of Geology and Paleontology, Faculty of Science, Tohoku University, Sendai 980-8578, Japan
F. Imamura Disaster Control Research Center, Faculty of Technology, Tohoku University, Sendai 980-8579, Japan
U. Kuran Disaster Affairs, Earthquake Research Department, Lodumlu, Ankara, Turkey
T. Nakamura Dating and Material Research Center, Nagoya University, Nagoya 464-0814, Japan
G. A. Papadopoulos Institute of Geodynamics, National Observatory of Athens, P.O. Box 20048, Athens, Greece
T. Takahashi Research Center for Disaster Reduction System, Kyoto University, Uji 611-0011, Japan
A. C. Yalciner Coastal and Harbor Engineering Research Center, Civil Engineering Department, Middle East Technical University, 06531 Ankara, Turkey

ABSTRACT

The Hellenic arc is a terrane of extensive Quaternary volcanism. One of the main centers of explosive eruptions is located on Thera (Santorini), and the eruption of the Thera volcano in late Minoan time (1600–1300 B.C.) is considered to have been the most significant Aegean explosive volcanism during the late Holocene. The last eruptive phase of Thera resulted in an enormous submarine caldera, which is believed to have produced tsunamis on a large scale. Evidence suggesting seawater inundation was found previously at some archaeological sites on the coast of Crete; however, the cause of the tsunami and its effects on the area have not been well understood. On the Aegean Sea coast of western Turkey (Didim and Fethye) and Crete (Gouves), we have found traces of tsunami deposits related to the Thera eruption. The sedimentological consequences and the hydraulics of a Thera-caused tsunami indicate that the eruption of Thera volcano was earlier than the previous estimates and the tsunami did not have disruptive influence on Minoan civilization.

Keywords: Thera eruption, Thera tephra, Minoan tsunami, tsunami propagation, tsunami deposits.

INTRODUCTION

Geologic knowledge of the volcanic evolution of Thera on Santorini Island (Fig. 1) is indispensable for the assessment of the effect of natural hazards on the rise and fall of Minoan civilization. Of all the historical eruptions of Thera, the paroxysmal volcanic explosion of late Minoan time was the most violent and caused widespread damage. It is widely held among volcanologists that the Minoan Thera eruption, characterized by a sequence of four distinctive volcanic phases, started with strong Plinian activity and ended with collapse of the volcanic cone (Bond and Sparks, 1976; Sparks and Wilson, 1990; Keller et al., 1990). In the Plinian phase, the explosive eruption ejected huge amounts of volcanic aerosol and tephra into the atmosphere (Watkins et al., 1978; Vinci, 1985; Sullivan, 1988). Westerly to northwesterly winds spread the ejecta over the eastern Mediterranean region (Fig. 1). The phreatomagmatic eruption of the last phase led to the collapse of the Stronghyle (preeruption) volcano (Pichler and Friedrich, 1980), leading to formation of the present shape of the Santorini caldera (Eriksen et al., 1990). It has been reported that the airborne tephra accumulated over Minoan settlements on Rhodes (Doumas and Papazoglou, 1980), Kos (Keller et al., 1990), and Crete (Vallianou, 1996). Archaeological arguments (Page, 1970) that the decline of the Minoan civilization was related to agricultural and/or social disruption caused by this volcanic event are, however, doubtful because there was no significant break in the life of Minoan Rhodes (Keller et al., 1990).

At the archaeological site of Amnissos on Crete, Marinatos (1939) found the floors of Minoan ruins to be covered by a thick layer of seaborne pumice from Thera, and he hypothesized that a destructive tsunami caused by the Thera eruption invaded the Aegean Sea coast of Crete. The Marinatos theory has not been involved in archaeological debates, however, because of the lack of sufficient scientific evidence. The discovery of the Thera tephra in deep-sea sediment cores from the eastern Mediterranean (Ninkovich and Heezen, 1965) and in lacustrine sediments of western Turkey (Sullivan, 1988) has presented a new opportunity for estimating the effect of the eruption on human activities.

Explosion-collapse processes of the Stronghyle dome complex on Thera were reconstructed by Heiken and McCoy (1984), who postulated that volcanic collapse and subsequent emergence of a submarine caldera resulted in the occurrence of tsunamis.

NUMERICAL SIMULATION OF THE MINOAN TSUNAMI

Collapse of the Stronghyle dome complex was preceded by Plinian volcanism with magmatic conduits on a fault extending northeast to southwest through the center of Thera, and resulted in the formation of a large caldera (8 × 9 km wide and ~700 m deep) because of the loss of the support by magma chambers below the volcanic dome (Heiken and McCoy, 1984). Seawater rushed into the caldera, submerging it to an average depth of 380 m (Druitt and Francaviglia, 1990). Sudden collapse of the Stronghyle volcano probably generated large waves, which formed the Minoan tsunami. Inrush of seawater into the caldera and collision of water masses with the caldera wall could have oscillated sea level on a large scale, resulting in the generation of a tsunami. We carried out a numerical simulation of tsunami generation and propagation, employing TSUNAMI N2, which incorporates the shallow-water theory consisting of nonlinear long-wave equations (Shuto et al., 1990; Yalciner et al., 1995; Minoura et al., 1997). The compu-

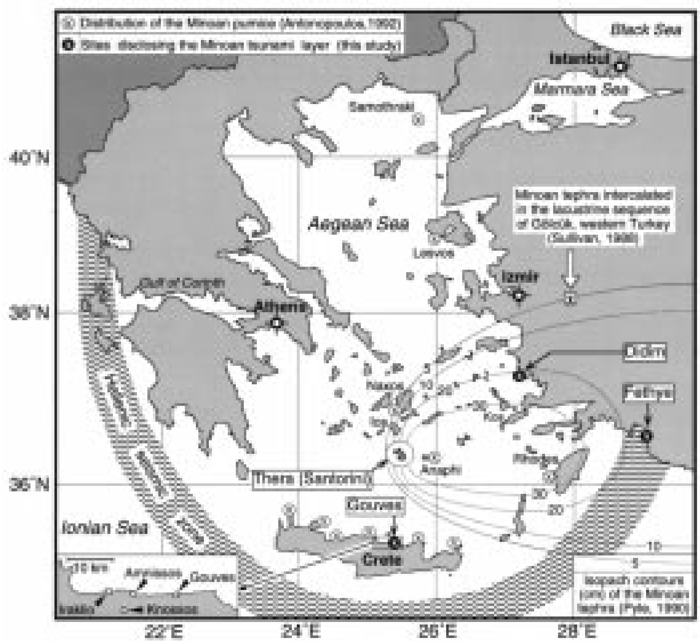

Figure 1. Map of Aegean Sea and adjacent region showing areas and sites mentioned in text. Felsic volcanic products of Minoan eruption are found on Aegean Sea coasts and in eastern Mediterranean deep-sea cores. Tsunamigenic sediment layers were discovered in Didim and Fethye (western Turkey) and Gouves (Crete).

tational region covering the south Aegean Sea and its environs was overlaid with a grid of cells, each cell being 500 m on a side. The time interval of 1.0 s was selected because it is the largest time step that maintains numerical stability. The simulation covered the tsunami propagation for 7 model hours. During the simulation, we collected computed sea levels at 3 min intervals for the entire grid mesh. Figure 2A shows our numerical results, including the seawater level 20, 40, and 60 min after the caldera collapse. A train of waves with an elevation of 5–8 m reached the Aegean Sea shore within 1–2.5 hr, and the great surf set up by the arrival of waves attacked the coast of Crete and western Turkey. The highest water level (~21 m) in the model is found to the south of Ios, and it appears that the Minoan harbor of Amnissos was attacked by waves with an elevation exceeding 10 m.

SEDIMENT LAYER OF THE MINOAN TSUNAMI

Our simulation suggests that the Aegean Sea coast of western Turkey and Crete was subjected to tsunamis with wave heights exceeding 5 m. To verify this value, we used trenching to try to detect traces of tsunami invasion on the coasts of Didim and Fethye, western Turkey (Fig. 3), where human activities have not been carried out since the Hellenic period. Sediment layers composed of fine to medium sand grains with marine fossils were found to be intercalated in the nonmarine sediments of coastal sequences. The sand layers show landward-thinning sedimentation. No structures or sediment grading were observed within the sand layers, suggesting rapid deposition of sediments from waters.

On the trench wall of Didim, it was clear that the fine sand layer composed of carbonate grains is mantled by a 10–15-cm-thick yellowish-white layer of felsic tephra (Fig. 2B). No erosional contact of the tephra with the underlying sand layer implies that the deposition of marine materials was followed subsequently by the fallout of airborne ash. Silty mud rich in fossils of shallow-marine benthic foraminifera underlies the carbonate sand layer, and grades landward into nonmarine organic mud that is ideal for the preservation of fossil plant roots and their impressions.

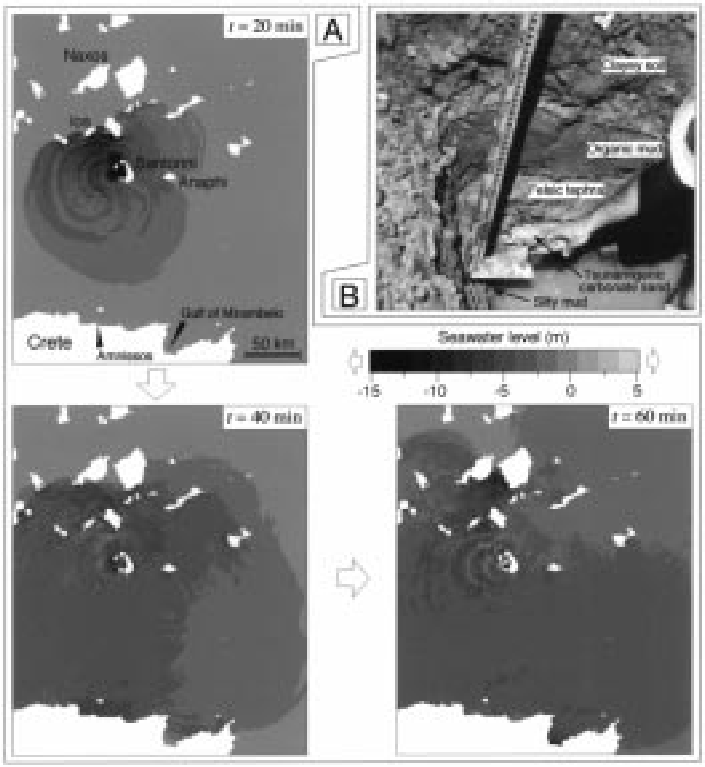

Figure 2. A: Results of numerical simulation. First wave reached Aegean Sea coast of western Turkey 2.5 hr after volcanic collapse. It is suggested that on northern coast of Crete, maximum runup height was 6–11 m and runup inundation distance was 500 m at most. B: Tsunami deposits and overlying felsic tephra layer exposed on trench wall, Didim, western Turkey.

Within the sediment sequence of the Fethye section, it was found that the sand layer consisting of siliciclastic grains is sharply covered by 5–10-cm-thick white felsic tephra. The sand layer, overlying the nonmarine sandy silt rich in plant debris, yields abundant shell fragments of shallow-marine gastropods of indeterminate genus.

At the time of the excavation in the archaeological site of Gouves (Vallianou, 1996), located about 15 km to the east of Knossos, one of us (Papadopoulos) found that the floor of the late Minoan potter's workshop is covered by a thin veneer of carbonate sand and an overlying 10–20-cm-thick pumice layer. The carbonate sand, composed of unsorted grains of skeletal fragments, is marine in origin. The excavated site is situated 30–90 m inland from the Minoan harbor installation and 2–3 m high above present sea level, and it is interpreted that the sand layer was deposited during seawater flooding in late Minoan time.

The silty mud of the Didim section is characterized by the major occurrence of euryhaline benthic foraminifera, and 43.9% of the faunal assemblage is occupied by a Miliolina group (*Peneroplis*, *Quinqueloculina*, *Spiroloculina*, *Triloculina*) that is adaptable to high-salinity conditions (~57‰: Bandy, 1960; Murray, 1970). Agglutinated foraminifera (e.g., *Ammonia beccarii*) are generally tolerant of diluted seawater (Bandy, 1960; Cooper, 1961). Considering the absence of agglutinated species in the faunal assemblages and the lateral facies change from marine to nonmarine in the same horizon, it is inferred that the silty mud was developed in an intertidal evaporative lagoon. Sediments collected from the modern shoreface (Fig. 3A) are rich in the Miliolina group, which makes up as much as 73.8% of the fossils, and lack living planktonic foraminifera. The carbonate sand layer includes abundant planktonic foraminifera and is poor in representatives of the Miliolina group (~12.7%), implying deposition in an environment far from the coast. On the basis of this paleontological evidence, we conclude that the carbonate sand originated in the offshore environment.

It is probable that waves penetrated into the coastal zone of Didim and formed fast-flowing currents associated with the rapid lateral translation of seawater and suspended sediments of offshore origin. Observation of storm surges on the coast of the Aegean Sea suggests that they are generally agents of erosion and do not produce regionally extensive deposits on land areas. Thus the unusual process of sediment transport together with the landward-tapering sedimentation of offshore materials is best explained by interpreting the carbonate sand layer to have been deposited by a tsunami (Minoura and Nakaya, 1991). Although we do not have definite paleontological evidence suggesting the silty sand of Fethye to be tsunami derived, the extensive deposition of shallow-marine sediments in the backmarsh environment shows the silty sand to have been caused by an unusual kind of sedimentation. Considering the landward thinning of the layer, we conclude it to be tsunami derived and suggest that tsunamis generated in the Aegean Sea reached the coast of western Turkey and deposited the layer.

AGE OF THE MINOAN TSUNAMI

The refractive-index values of glass shards for the Minoan Thera tephra have been reported by many authors, and most values are within the range 1.506–1.510 (Keller et al., 1990; Watkins et al., 1978; Vinci, 1985; Sullivan, 1988). The results of our refractive-index measurements on glass shards in tephra (Santorini, Didim and Fethye) and pumice (Gouves) are listed in Table 1. All indices conform to the published data, except for the sample from Fethye. The tephra in the Fethye section is poorly preserved, and microscopic observation implies that the glass-enclosed minerals are slightly altered owing to burial diagenesis. The refractive index possibly reflects this diagenetic effect, although the values are very close to those of the Thera tephra. Glass shards with a similar refractive index are found only in the Pleistocene V-1 tephra from Aegean Sea deep-sea cores (Keller et al., 1990). We conclude that the felsic layers found in the coastal sequences correspond to the Thera tephra. The major and minor element chemistry of the

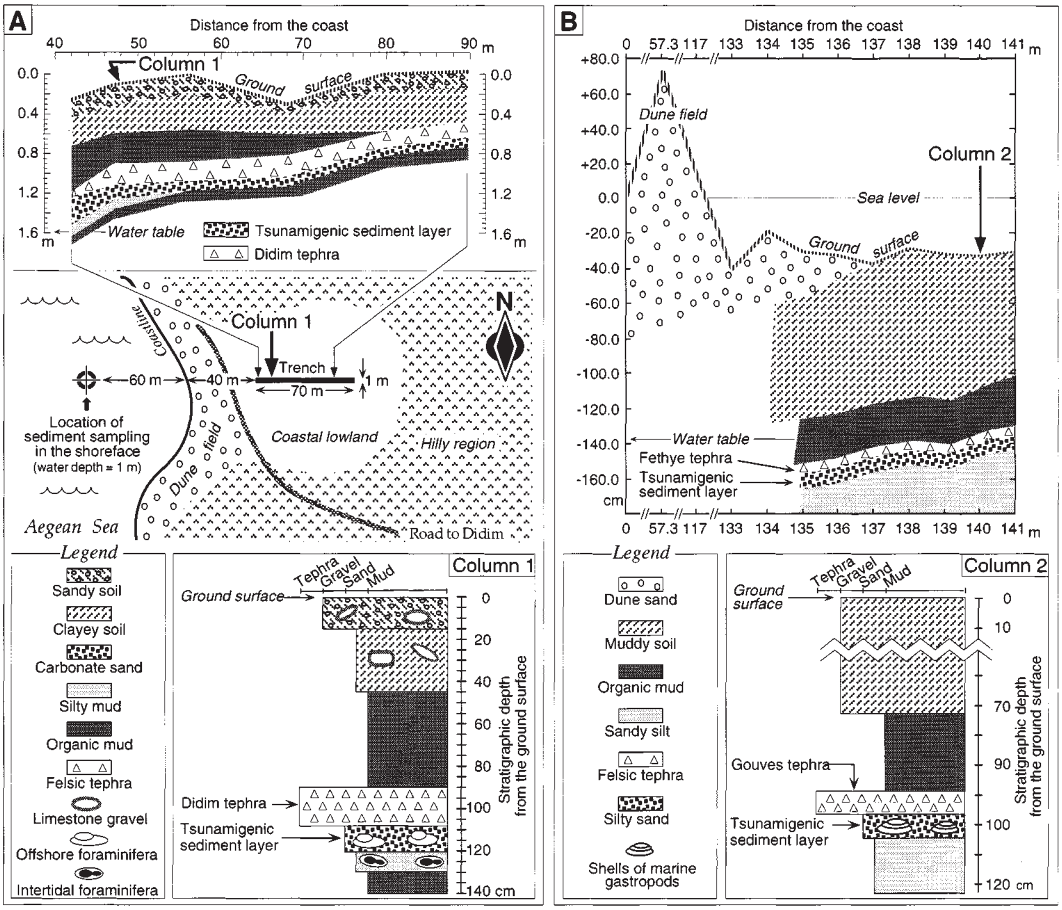

Figure 3. A: Stratigraphic section exposed on trench wall, Didim, western Turkey. Carbonate sand layer and overlying felsic tephra are found to be sharply intercalated in nonmarine organic mud. B: Stratigraphic section of coastal sequence observed on trench wall, Fethye, western Turkey. Silty sand layer including shell fragments of marine gastropods is overlain by felsic tephra.

volcanic products, determined by X-ray fluorescence (XRF) spectrometry, suggests that the origin of the Didim tephra, the Gouves pumice, and the Minoan tephra of Santorini is the same.

Radiocarbon dating of the Minoan eruption has previously been attempted on samples from the archaeological site of Akrotiri, Santorini (Michael, 1978; Meulengracht et al., 1981), and the results yield a time range around the weighted mean of calibrated ^{14}C ages corresponding to the calendar-year interval 1630–1530 B.C. (Fytikas et al., 1990). Hammer et al. (1987) detected a high annual average H^+ concentration in the acidity profile of the entire Dye 3 ice core of south Greenland, and they concluded that the high-acidity signature comes from the Thera eruption. They estimated the most accurate date to be 1645 ± 20 B.C. Sigurdsson et al. (1990) related this acidity layer to another volcanic event, and the Thera eruption was correlated with a 1626–1628 B.C. frost-ring event in the tree-ring record.

We carried out accelerator mass spectrometer (AMS) radiocarbon dating on most common and well-preserved fossil tests (*Elphidium* and *Quinqueloculina*) from the Didim section and on marine gastropod shells from the Fethye section. In accordance with Stuiver and Reimer (1993) and Stuiver and Braziunas (1993), the results were calibrated to calendar years and are listed in Table 2. The calibrated date of the carbonate sand layer (1818 ± 112 B.C.) is indistinguishable from that of the underlying silty mud (1875 ± 116 B.C.). However, the date of gastropod shells from Fethye (2457 ± 106 B.C.) is ~600 yr older than that of the carbonate sand of Didim.

We think that there are plausible mechanisms to explain these older AMS-determined ages. The calibrated date of the tsunami layer in Didim, corresponding to the time interval 1930–1706 B.C., is ~200 yr older than the date of atmospheric acidity increase that resulted from the Thera eruption. This discrepancy is probably due to the mixing of foraminifera living in the sediment at the time of the event with dead (i.e., older) foraminifera also contained within the sediment. Mollusk shells are rich in light carbon ($\delta^{13}C$ = –7.6‰), which is supposed to have been contributed from organic matter in sediments. Biochemical assimilation of old carbon from sediment organic matter is the mechanism that might produce the age that is older by ~600 yr.

The refractive-index measurements and the XRF chemistry leave little doubt that the tephra of Didim and Fethye and the Gouves pumice are from the Thera eruption. It is therefore possible to conclude that the sedimentation of marine materials in the backshore of these areas was caused by the invasion of tsunamis triggered by the volcanic event in late Minoan time.

TABLE 1. REFRACTIVE INDEX VALUES OF GLASS SHARDS IN FELSIC VOLCANIC PRODUCTS FROM GEOLOGICAL SECTIONS OF AEGEAN SEA COAST

Country	Sampling	Material	Refractive index of volcanic glass shards
Greece	Santorini	Minoan tephra	1.504 - 1.509
Greece	Gouves, Crete	Felsic pumice	1.503 - 1.510
Turkey	Didim	Felsic tephra	1.504 - 1.509
Turkey	Fethye	Felsic tephra	1.500 - 1.504

TABLE 2. AMS RADIOCARBON DATES OF CALCAREOUS SHELLS PRESERVED IN TSUNAMIGENIC SEDIMENTS OF DIDIM AND FETHYE, WESTERN TURKEY

Country	Sampling	Material	$\delta^{13}C$ PDB (‰)	^{14}C age (yr B.P.)	Error (1σ)	Calibrated age (B.C.)
Turkey	Didim	Benthic foraminifera in calcareous sand	-2.2	3837	88	1930 - 1706
Turkey	Didim	Benthic foraminifera in silty mud	+0.1	3886	86	1991 - 1759
Turkey	Fethye	Marine gastropods in silty sand	-7.6	4303	79	2562 - 2351

The age of the silty mud of Didim is obtained for autochthonous benthic foraminifera (*Quinqueloculina elongata* Natland), and is very close to that of the overlying tsunamigenic layer. This implies that the eruption of Thera volcano is slightly earlier than the previous estimates.

DISCUSSION AND CONCLUSIONS

The bending or the lateral displacement of walls of late Minoan settlements located to the south of Amnissos shows that they were destroyed in an unusual fashion (Marinatos, 1968). Antonopoulos (1992) interpreted the walls to have collapsed by the sucking action during backwash and/or rundown of the tsunami, and it was concluded that a destructive tsunami struck the harbor of Knossos. The results of archaeological study in Gouves (Vallianou, 1996) indicate that artificial objects inside the settlements were deposited and then dislocated by flooding of seawater, and it is believed that the Aegean Sea coast of Crete was invaded by destructive tsunamis in late Minoan time.

It is clear that the Thera eruption and the following tsunami are recorded in the coastal sequences of western Turkey and Crete. The fallout of tephra carried by the prevailing winds in the troposphere was preceded by the invasion of tsunamis, and the duration between the arrival of tsunamis and the ash fall was probably very short. A sequence of volcanic phases starting with the Plinian activity has been discriminated within the stratigraphic record of the Minoan eruption of Santorini, and it is estimated that the time span of the sequence was on the order of tens of hours (Bond and Sparks, 1976). The ejecta probably reached over the eastern Mediterranean within a few days. A train of tsunami waves is numerically inferred to have arrived at the Aegean Sea shore of western Turkey about 2.5 hr after the caldera collapse. Thus it follows that the time scale of the Minoan tectono-volcanic event is on the order of 24 hr.

Our numerical results and the sediment distribution show that the seawater flooding due to the tsunami invasion was restricted to the coastal zone of Crete and all along the Aegean coast. Despite its large wave height at the harbor of Amnissos and the Gulf of Mirambelo (6–11 m), it is estimated that the runup distance of waves was only several hundred meters from the coast. Although the fishing and trading economy could have been affected by the destruction of boats and harbor installation, the tsunami would have had little influence on Minoan civilization.

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