Reports

Pumice from Thera (Santorini) Identified from a Greek Mainland Archeological Excavation

Abstract. *Pumice fragments recovered from an archeological excavation on the Greek mainland have been correlated by means of index of refraction measurements with the Late Bronze Age volcanic eruption on the island of Thera (Santorini) in the Aegean Sea. Pottery from the strata containing the pumice dates from the 15th century B.C.*

The lure of the Atlantis legend and the remarkable culture Marinatos has uncovered on Thera have generated keen interest in the geological and archeological effects of the volcanic eruption on the island in the Late Bronze Age (about 1500 B.C.). Marinatos' excavation on Thera (*1*) indicates that for some months after an earthquake the inhabitants had carried out some repair work, whereupon the island was overwhelmed with up to 50 m of pumice and ash from a major volcanic eruption. Now an excavation in mainland Greece has uncovered Thera pumice from a stratum that also contains pottery which dates from the period of the Late Minoan IA style (1550 to 1475 B.C.).

Since 1939 (*2*) a lively discussion has centered on the effects of this eruption on mainland Greece, Crete, and the rest of the eastern Mediterranean (*3, 4*). Recent studies of deep-sea cores from the eastern Mediterranean (*3, 5, 6*) have detailed the nature and extent of the ash from the eruption. This ash seems to have been found principally to the southeast of Thera. However, no previous evidence of this catastrophic event has been found on mainland Greece.

Under the auspices of the Minnesota Messenia Expedition, a multidisciplinary research effort focused on the Late Bronze Age in southwestern Greece (*7*), an excavation is being conducted at Nichoria ridge about 2 km from the Messenian Gulf (see Fig. 1). McDonald (*8*) has provided a summary of the results of the excavation seasons 1969, 1970, and 1971.

Nichoria ridge was a prehistoric habitation site from the Middle Bronze Age (beginning about 2000 B.C.) through the Late Bronze Age and extending to the so-called Greek "Dark Ages" (that is, about 700 B.C.). The importance of this site in the hierarchy of local Late Bronze Age communities is shown by a number of tholos (royal) tombs already identified on the western margins of the area of habitation. Indeed, it has been suggested by Chadwick (*9*) and others that this site must be one of the towns mentioned in the Linear B tablets found in the palace of Nestor at Pylos.

One excavation trench shows what appears to be a continuous record from about 1550 B.C. through 1300 B.C. and contains, through a depth of 3 m, a stratified series of fine pottery shards. This deposit provides one of the best records of Late Bronze Age stratigraphy yet uncovered on mainland Greece.

From the lower strata in this trench we recovered several pieces of pumice (averaging 2 to 4 cm on a side), possibly waterborne to the west coast of the Messenian Gulf and carried up to the site by the Bronze Age inhabitants. However, in view of the prevailing northwest to southeast trends in the local winds, the possibility also exists that the pumice was transported in antiquity for some domestic or industrial use. The pottery with which the fragments of pumice are associated stratigraphically dates from the 15th century B.C. (mainly Late Helladic IIA style, 1500 to 1450 B.C.) (*10*). The fact that the pumice is found only in these strata suggests that the source was not available prior to about 1500 B.C. and was markedly less plentiful after about 1400 B.C.

The pumice is friable and under normal conditions would have a limited lifetime under the influence of buffeting in eastern Mediterranean storms. Bryan (*11, 12*) has studied pumice that drifted in the South Pacific for up to 7 years before being washed ashore. Pumice thrown over active beach zones during a storm and then covered with sand can still be found occasionally today in southwestern Greece as a result of the recession of coastal deposits caused

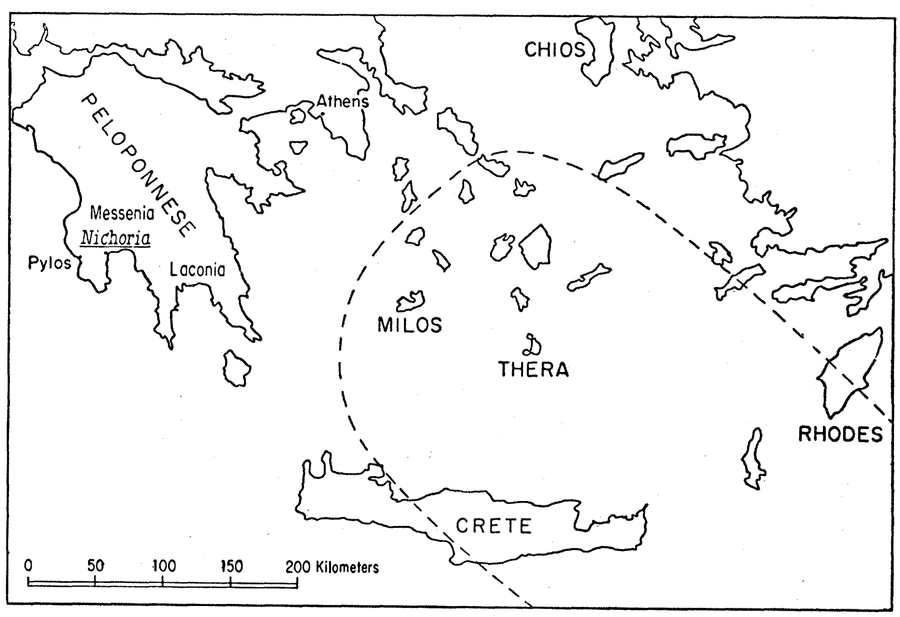

Fig. 1. Map of southern Greece. The dashed line indicates the limit of the upper Thera pumice and ash in deep-sea cores (*8*). The Nichoria archeological site is in the southwestern Peloponnese.

by erosion. However, pumice continuously subjected to wave action on the beach would be rapidly ground to fine fragments through abrasion between limestone and chert pebbles and quartz sand.

Numerous studies have been made of recent major volcanic events in the eastern Mediterranean (*3, 5, 13, 14*). Ninkovich and Heezen (*3, 5*) assigned the source of the lower pumice fragments (index of refraction of the glass $N = 1.521$) found in the Mediterranean deep-sea cores, and dated at 25,000 years before the present, to the very early lower pumice layers of Thera. Later work (*13*), however, has indicated that the island of Ischia off the harbor of Naples is the source of the lower ash found in these deep-sea cores. This leaves the lower Thera pumice and ash undated. Our optical work on the lower Thera pumice (see below) indicates that this material is not the same as the material from the cores.

To determine the source of the pumice discovered in the excavation at Nichoria, we embarked on a program of accurate determinations of the index of refraction of the Nichoria pumice and that of possible source material. Bryan (*11*) has reported that "refractive indices of pumice glass provide the best single quantitative comparison between pumice fragments." In most of the work on Mediterranean volcanic materials reported above, the indices of refraction were determined to only the second decimal place and then often with the use of only natural (polychromatic) light.

We used an essentially monochromatic light source (Na, $D_1 + D_2$ lines), and with the Becke line method we measured the indices of refraction of over 600 grains of each pumice by comparison with carefully calibrated immersion index oils. Such a large number of measurements was judged necessary since it was found that the refractive index of the glass in the individual pumices ranged from 0.004 to somewhat more than 0.008. The temperature was recorded to 0.1°C, and appropriate corrections were applied. As a running check on the effect of changes in ambient temperature on the refractive indices of the oils, simultaneous readings of the indices were made to an accuracy of $\pm$ 0.0002 with an Abbe refractometer.

The most obvious sources for any ample supply of pumice at Nichoria are as follows: (i) Thera (Thera pumice would have been transported to the Messenian Gulf at the time of the Thera explosion); and (ii) Milos, a relatively nearby island which has extensive pumice deposits and which supplied an obsidian that was widely traded in prehistoric times. These two localities were sampled areally and stratigraphically. A representative set of six samples of the upper pumice and ash at Thera, five samples of pumice from Milos, and, for additional comparison, a sample of the lower (undated) pumice that mantled Thera long before human habitation, were examined and compared with lower Nichoria pumice samples.

The results of the optical work on these samples are shown in Fig. 2. The glass fraction of the pumice found at Nichoria clearly has indices of refraction closely comparable to those of the Thera material from the Late Bronze Age eruption (upper Thera pumice). Optical examination revealed further criteria for distinguishing Milos pumice from upper Thera pumice. Nearly all Milos glass fragments have a narrow but prominent zone of birefringence rimming part or all of each grain. This birefringence, probably stemming from incipient devitrification, was totally absent from all Thera and Nichoria samples. Moreover, the pattern of gas bubbles and the nature of the early-formed crystals are closely comparable in the upper Thera and Nichoria pumice.

A separate investigation showed that the $H_2O(-)$ content of the Thera pumices ranged from 0.18 to 0.46 percent (by weight), and that of the Milos pumices ranged from 0.82 to 3.19 percent. Here, as in the earlier investigations, the Nichoria samples matched the upper Thera samples, with results ranging from 0.39 to 0.46 percent $H_2O(-)$.

An earlier (1971) study of sedimentary material from the Late Helladic IIA strata made with a petrographic microscope showed the presence of two single grains, each less than 1 mm in diameter, of ash or pumice. Although it was hoped initially that these grains were part of a more widely spread ash-fall horizon, we now believe that they

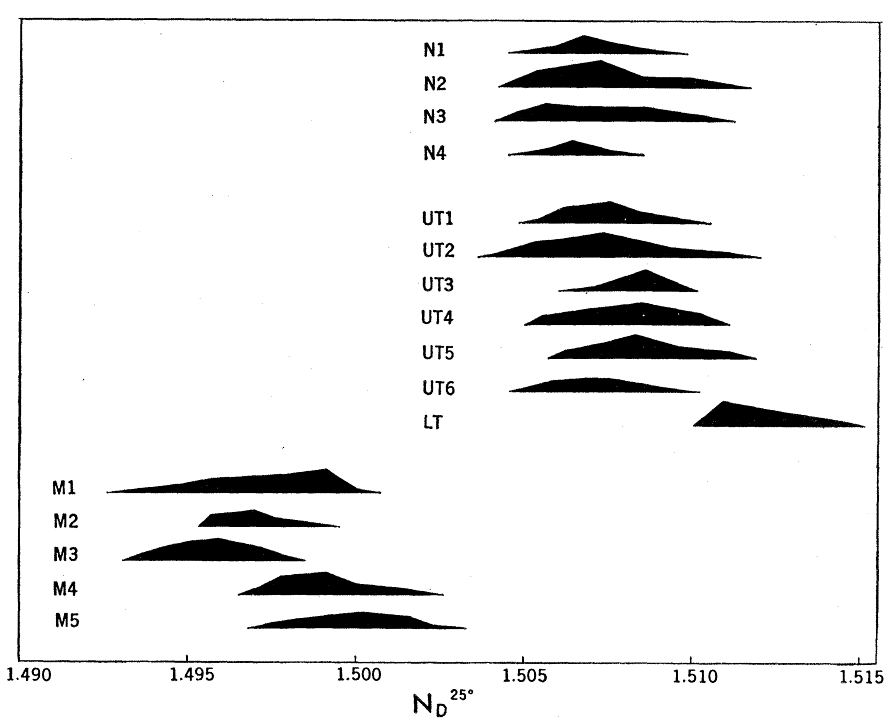

Fig. 2. Indices of refraction of the glass fraction of the pumice samples from Thera, Milos, and Nichoria. Samples N1 through N4 were uncovered at Nichoria. Locality data for the six samples of Thera upper pumice and ash are as follows: UT1, upper ash, quarry near Phira; UT2, middle ash, quarry near Phira; UT3, rose pumice, excavation site (Akrotiri); UT4, rose pumice, Phira; UT5, rose pumice, Athinion; UT6, rose pumice, Thia. The old (lower) Thera pumice and ash is labeled LT. The five Milos samples (M1 through M5) are from a section 137 m thick north of Adamas; M1 is stratigraphically the lowest, and M5 the highest in the section. The horizontal scale shows the range in refractive index of the glass in each sample of pumice. The vertical scale in each case is proportional to the relative distributions of glass shards matching the index given on the abscissa.

could have come from the disintegration of pumice that was either waterborne or deliberately brought to the mainland by ship. There is still no evidence of an ash-fall on the mainland from the Thera eruption.

Results reported here indicate that the 1400 ± 100 B.C. date from ^{14}C analyses given by Ninkovich and Heezen (*3*) as the best date for the eruption must be narrowed to $1400 + 100$ B.C to be consistent with the pottery chronology at Nichoria and at the Thera excavation (*1*). Further excavation at Nichoria may provide additional time-stratigraphic information concerning the Thera eruption, although it is to be hoped that more refinement in the dating will be realized from the archeological finds being made by Marinatos at Thera itself.

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15. We thank M. H. Reed who collected the suite of pumice samples from Thera and Milos; R. Howell whose careful excavating techniques uncovered the friable pumice intact; Prof. S. Marinatos, inspector general of the Greek Archaeological Service and director of the important excavations on Thera, who kindly provided the authorizations necessary for both the Nichoria excavation and the collection of pumice on Thera; W. B. Bryan who gave helpful counsel on the optical work on the pumices; and W. A. McDonald, director of the Minnesota Messenia Expedition, and H. E. Wright, Jr., who read the manuscript critically and provided helpful suggestions for its improvement.

15 September 1972; revised 3 November 1972

Venus: Radar Determination of Gravity Potential

Abstract. *We describe a method for the determination of the gravity potential of Venus from multiple-frequency radar measurements. The method is based on the strong frequency dependence of the absorption of radio waves in Venus' atmosphere. Comparison of the differing radar reflection intensities at several frequencies yields the height of the surface relative to a reference pressure contour; combination with measurements of round-trip echo delays allows the pressure, and hence the gravity potential contour, to be mapped relative to the mean planet radius. Since calibration data from other frequencies are unavailable, the absorption-sensitive Haystack Observatory data have been analyzed under the assumption of uniform surface reflectivity to yield a gravity equipotential contour for the equatorial region and a tentative upper bound of 6×10^{-4} on the fractional difference of Venus' principal equatorial moments of inertia. The minima in the equipotential contours appear to be associated with topographic minima.*

Present knowledge of the surface of Venus rests largely on the results of radar observations. Perhaps the most striking fact to emerge has been the retrograde direction of Venus' spin and its apparent resonance with the relative orbital motions of the earth and Venus (*1*). The earth could have captured Venus' spin in this resonance only through the action of a gravitational torque on a substantial axial asymmetry in Venus' mass distribution (*2*). Heretofore, no measurement of this asymmetry has been possible. The main purpose of this report is to demonstrate that future radar observations can be used to determine equipotential contours of Venus' gravity field and, hence, to estimate the axial asymmetry of its mass distribution. A preliminary contour for the equatorial region and a concomitant bound on the axial mass asymmetry—based on past radar observations not made explicitly for this purpose—is also included.

How can radar data be sensitive to the gravity field of Venus? A direct sensitivity seems almost unthinkable. But an indirect intermediary exists, namely, the thick, carbon-dioxide-dominated atmosphere of Venus. Because this atmosphere absorbs X-band (approximately 8000 Mhz) radio radiation strongly and, for example, S-band (approximately 2000 Mhz) radiation hardly at all, we can infer surface heights relative to a particular pressure contour from a comparison of radar cross sections measured at the two frequencies, since the intrinsic reflectivity of the surface itself should not, in general, vary sharply with frequency (*3*). The use of a third frequency would allow a more precise separation of atmospheric from surface reflectivity effects on cross section. The pressure contours can then be related to the mean planet radius with the aid of measurements of round-trip radar echo time-delays, which allow the absolute surface heights to be determined (*4*). Gravity equipotential contours will coincide with pressure contours under conditions of hydrostatic equilibrium in the atmosphere (*5*). From such a contour, the gravitational torque exerted by the earth can be estimated.

Now we develop this basic idea quantitatively. Since at present its application is restricted to the equatorial regions traversed by the subradar point of earth-based observations, we confine our analysis to that situation. The possibilities for extension to high latitudes and for the use of radars on Venus orbiters are discussed briefly in the last part of the report.

The radar cross section $\sigma(\lambda,\phi)$ per unit surface area at the subradar point can be written as

$$\sigma(\lambda,\phi) = \sigma_0(\lambda,\phi)\exp[-2\tau(\lambda,\phi)] \quad (1)$$

where

$$\tau(\lambda,\phi) = \int_{h(\phi)}^{h_{max}} \kappa(h,\lambda)\,dh \quad (2)$$

with λ being the wavelength of the radar signals, ϕ the longitude of the subradar point (we suppress θ, the latitude dependence), σ_0 the intrinsic cross