Archaeology

Absolute dating of the Bronze Age eruption of Thera (Santorini)

from Peter Warren

THE establishment of any absolute or calendrical date for a major event in Aegean prehistory would be a matter of great interest, not least because the Minoan and Mycenaean civilizations of that period exhibit many peaks of technical, social and artistic achievement. The recent, albeit tentative, dating[1] of the Bronze Age eruption of Thera to 1628–1626 BC is therefore certain to stimulate archaeologists just as the date[2] of 1390±50 BC stimulated them when it was put forward in 1980.

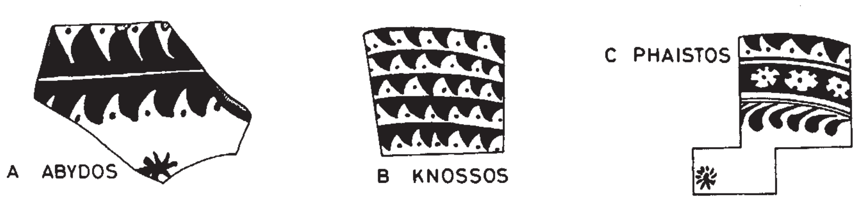
The newly suggested date is that recorded as frost damage in the bristlecone pine tree-ring sequence from Campito Mountain, eastern California; the link with the Thera eruption hinges upon the suggestion that, like some other major volcanic eruptions, it induced sufficient climatic change to leave a record of frost damage. The date of 1390±50 BC was based on a peak of acidity in the Camp Century ice core from north-west Greenland and is based on the assumption that acidity is a result of volcanic eruption. For either date to be correct it needs to be compatible with the archaeological dating of the eruption, which I shall summarize.

The Bronze Age settlement at Akrotiri on Thera, excavated from 1967 to 1974 by Sp. Marinatos[3] and since by C. Doumas[4,5], came to an end at a time when it was full of Late Minoan I A and locally equivalent pottery. It is assumed by many that it was the eruption that destroyed the settlement. Others, including the writer, hold the view that evidence of reoccupation and clearance of parts of the destroyed settlement before the pumice fall suggests an interval of time between the end of the settlement and the eruption. In that case, the eruption could have occurred in the subsequent archaeological stage, Late Minoan I B, and be correlated with the greatest destruction of the major Minoan sites of Crete, which are characterized by Late Minoan I B pottery[6].

Absolute dating of these ceramic periods from artefactual evidence is far less precise than we would like. Associations of Late Minoan I B (and its Greek mainland equivalent, Late Helladis II A) with Egyptian material sets the period at the time of Tuthmosis III (refs 7,8), the fifth pharoah of the 18th Dynasty, the highest dates for whom are 1504–1450 BC, the lowest 1479–1425 BC (ref.9). A probable correlation involving Crete, Taanach, near Megiddo in Israel, and Egypt indicates (on an accession date of 1504 BC for Tuthmosis III) a date of around 1482 BC for a point within Late Minoan I B[7,8]. May the Late Minoan I B styles have existed before the time of Tuthmosis III?

In relation to this, a pottery fragment from Abydos tomb 328 in Egypt has recently been dated to Late Minoan I B. The surviving decoration on the fragment is 'adder mark' and dot motif and star motif (Fig.1), well paralleled in Late Minoan I B, yet most of the material in the tomb is datable to the Second Intermediate or Hyksos (pre-18th Dynasty) period (although an Egyptian pottery bowl found in the tomb is also paralleled in the 18th Dynasty, at the time of Tuthmosis III). Thus, while the weight of the evidence seems to support a pre-18th Dynasty date for the fragment of Late Minoan I B pottery, a date in the time of Tuthmosis III cannot be excluded. It is also the case that Late Minoan I B has never been thought to be a long ceramic period: there is almost no evidence for a stratified sequence of Late Minoan I B deposits and the period may well have been the product of just one or two generations of vase painters. Given the other Egyptian associations of Late Minoan I B it is not easy to see how the Abydos fragment could have had a pre-18th Dynasty context.

Late Minoan I A is conventionally dated 1550–1500 BC, beginning after the inception of the 18th Dynasty[11] and followed by Late Minoan I B. A date for the beginning of Late Minoan I A pottery has not yet been firmly established, and it may be earlier than 1550 BC. A number of gypsum vessels from the Akrotiri settlement on Thera (Late Minoan I A) may well be Syro-Palestinian Middle Bronze II products, which implies a pre-18th Dynasty Second Intermediate period date in Egyptian terms[12]. This would put Theran Late Minoan I A before 1576 or 1552 BC (alternative starting dates for the 18th Dynasty[9]). An upper limit can be inferred from the famous alabaster lid from Knossos, inscribed with the cartouche of the Hyksos pharaoh Khyan, which has been dated to Middle Minoan III (ref.13, though see refs 14,15) which preceded Late Minoan I A. Khyan ruled in Egypt within about 1660–1580 BC. So Late Minoan I A could well have begun by 1600 BC though the period postdates the apparent Khyan–Middle Minoan III correlation.



Late Minoan I B pottery fragment from Abydos, Egypt, with 'adder mark' and star patterns (A) and comparable pottery fragments from Knossos (B) and Phaistos, Crete (C). Abydos fragment about 55 per cent actual size, others not to scale.

If, at first sight, the date of 1600 BC seems compatible with date of 1626 BC from the frost damage record[1], it must be remembered that 1600 BC is at the beginning of Late Minoan I A, while the Theran eruption is certainly after the beginning of Late Minoan I A (ceramics from that period are present in the buildings predating the main destruction buildings at Akrotiri) — in fact there is no known stage of pure Late Minoan I A later than the Theran destruction deposits, themselves linked by ceramics to at least six other Late Minoan I A deposits in Crete. Thus from the archaeological evidence the Theran eruption does not appear to be datable anywhere near 1626 BC or even 1600 BC. At present the balance of the archaeological evidence dates the end of Late Minoan I A no earlier than about 1500 BC. If the eruption is linked to the great Cretan destructions of Late Minoan I B, its archaeological date would be about 1450 BC, which is near the date of 1390 ± 50 BC established by Hammer *et al.*[2].

Radiocarbon dates from destruction contexts at Akrotiri[8,10,16,17] also do not offer strong support for the 1626 BC date. Of the ten short-lived samples, six, after calibration, fall in the 17th century BC, one is a little earlier, another is 1490 ± 50 BC and two are well back in the third millennium. Moreover, they may have yielded dates older than a true date[16].

Just how secure is the suggested correlation of the frost event at 1626 BC with the Theran eruption? First, according to Tables 1 and 3 in the paper by LaMarche and Hirschboeck[1], for 9 of the 19 defined volcanic events since AD 1500 there are no corresponding frost-ring events — that is, there is only about one chance in two that an eruption will induce notable frost-ring damage. Furthermore, of 17 listed frost events since AD 1500, 7 do not correspond to a listed major volcanic event.

Second, if we compare the dendrochronological sequence (from Campito Mountain, White Mountains; Table 3), which produced the 1626 BC date, with other tree-ring data from western USA (Table 1), of the 26 listed notable frost-ring events (including the one at AD 1500) since AD 595, the White Mountains sequence appears to record only 7, while it produces

6 others not present at the other locations (perhaps because smaller sample criteria were allowed for Table 3, White Mountains). Of the 13 White Mountains frost-ring events, only 5 correspond to dated volcanic eruptions. Finally, of the 11 observable joint occurrences (frost-rings and eruptions) since AD 1500 (and counting the AD 1500 events as a joint occurrence) only 3 appear in the White Mountains frost-ring sequence.

Third, with 19 major volcanic events listed since AD 1500, extrapolating back over the complete White Mountains sequence (to 3435 BC), one would expect 201 volcanic events. Even if every listed frost-ring from the White Mountains were postulated to match a notable volcanic event (and clearly more than half do not) the record of just 14 pre-AD 1500 frost-rings from that source means that it would be picking up only about 1 in 14 of the postulated 201 volcanic events.

Fourth, frost-ring events are proxy data — they could be caused by volcanic eruptions; but they could equally well be caused by other influences on climate. By contrast, high acidity peaks seem to be produced specifically by volcanic eruptions. For the period 3435 BC to AD 1963/5, of the 23 eruptions producing high acidity peaks listed by Hammer, Clausen and Dansgaard, only about 10 correlate with frost events, while no less than 26 out of 36 frost events have no matching acidity peak. The frost event of 1628–6 BC has no matching acidity peak, the nearest being in 2690 ± 80 and 1390 ± 50 BC.

On this evidence, it would seem there is little support for linking the White Mountains frost-ring event at 1626 BC specifically with the eruption of Thera. Moreover the link is not substantiated by archaeological data, nor strongly supported by radiocarbon evidence from Thera. □

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Materials science

A soft superionically conducting lower mantle?

from Robert W. Cahn

THE meagre contribution so far of materials science to the general understanding of the Earth's mantle is about to be enriched, in part by the study of ionic crystals whose properties may be a guide to those of the mantle rocks, with their capacity to undergo plastic deformation and with their large electrical conductivity.

Two lines of geophysical arguments have helped to define what needs to be explained. First, studies of post-glacial rebound, the gradual rising of the Earth's surface after the removal of overlying ice sheets, is a pointer to the viscosity of the convective mantle. Some, however, propose a uniform viscosity for the whole mantle, others, layered viscosity variations. Weertman[1] takes it as probable that the lower mantle is orders of magnitude more viscous than the mean mantle viscosity.

Second, the conductivity of the mantle, especially at its lower levels, is linked with the delays between changes in the magnetic field of the core and its manifestation at the Earth's surface — what magneticians call magnetic viscosity. Thus Anderson[2] has recently pointed out that the delay associated with a magnetic 'jerk' such as that of 1969 must be intimately linked with mantle conductivity, but has also drawn attention to the difficulties in putting a value on the mean conductivity from such observations. Nevertheless, Stacey[3] has estimated, from such data together with an analysis of the secular variation of the length of the day, an electrical conductivity at the bottom of the mantle (itself orders of magnitude higher than in the upper mantle) of 100–500 $\Omega^{-1}\,m^{-1}$.

It is widely held that the major constituent of the lower mantle is a pressure-induced polymorph of pyroxene, $(Mg,Fe)SiO_3$, with perovskite structure. The implication is that the mantle is chemically but not structurally homogeneous (though Whaler[4] has recently advanced seismic arguments for presuming chemical heterogeneity).

In assessing the compatibility of the conventional model of the lower mantle with the values of viscosity and conductivity needed to fit data on glacial rebound and magnetic delay, the difficulty arises that $(Mg,Fe)SiO_3$ of perovskite structure can be made in the laboratory only at such high pressures, and therefore minute volumes, that direct measurements of its properties are not feasible.

In any case, in spite of the large numbers of perovskite-type compounds known[5], there has been no investigation whatever of the plastic deformation of any of them. Indeed, Poirier *et al.*[6] point out that there is no direct knowledge of the phase (*pace* Whaler) presumed to occupy 40 per cent of the Earth's volume, and have accordingly undertaken a study of $KZnF_3$, a salt of perovskite structure which is stable at ambient pressure, up to its melting point of 870°C. In this they followed the lead of O'Keeffe and Bovin[7], who examined $NaMgF_3$, another perovskitic salt, and found that it becomes a solid electrolyte (alias a superionic conductor) at high temperatures.

The special importance of the work of Poirier and his colleagues is that they examined the mechanical as well as electrical behaviour of $KZnF_3$, showing both that it becomes a superionic conductor and that it acquires a low viscosity above the same critical temperature range. This remarkable finding is of importance both for geophysicists and for materials scientists.

Specifically, Poirier *et al.* have measured the creep curves of oriented crystal slices of $KZnF_3$ between 650° and 844°C and electrical conductivity between 650° and 800°C. Both primary and steady-state creep was observed. The latter has approximately newtonian characteristics, with a rate proportional to stress at a fixed temperature. At a fixed stress, the creep rate increases with temperature up to 750°C, decreases slightly between there and 800°C and then increases steeply at higher temperatures.

The conductivity rises slowly with temperature up to a value of $0.8\pm0.2\times10^{-2}$ $\Omega^{-1}\,m^{-1}$ at 700°C and then rapidly to 1.9 ± 1.8 $\Omega^{-1}\,m^{-1}$ at 800°C, with most of the increase between 700° and 750°C. The values agree well with those reported for $NaMgF_3$ by O'Keeffe and Bovin — but note the high degree of experimental scatter near 800°C.

Weertman[1] had already concluded that newtonian creep is necessary to account for observations of post-glacial rebound. Newtonian creep usually involves diffusion (Nabarro) creep in fine-grained materials, not in single crystals as in Poirier's work. Poirier *et al.* conclude that they have observed an example of Harper-Dorn creep, a mechanism reported many years ago but badly understood. They argue that the sharp increase of diffusivity of one ionic species, here F^-, associated with the advent of superionic conduction (see for example, ref. 8) should hinder creep by promoting the climb and immobilization of some dislocation segments in crystals of $KZnF_3$. Consequently, dislocations should not multiply in the familiar way during