# The Eruption of Santorini and the End of the Minoan Civilization in Crete

## AN EXAMPLE OF THE APPLICATION OF PALAEOMAGNETIC TECHNIQUES IN ARCHAEOLOGICAL TEPHRAS

*Abstract*

Determinations, by W.S. Downey, of the magnetization in samples from LMIB fired destruction levels in Central Crete showed identical directions of stable remanence (355.6°, 50.1°, $\alpha95$ = 1.1) that had been acquired in a geomagnetic field of the same intensity (65.9 ± 3.2 μT). In contrast, samples from LMIB destruction levels in Eastern Crete, although also internally consistent, showed statistically different directions of remanence (355.7°, 55.5°, $\alpha95$ = 1.1°) acquired in a somewhat weaker geomagnetic field (56.4 ± 3.9 μT). Exactly the same differences in directions were found when comparing the directions of remanence in tephra samples from the « Minoan » tephras in Santorini ; the basal Plinian ash having directions (3.7°, 59.6°, $\alpha95$ = 2.3°) identical to those of Central Crete, and the base surge and upper ashes having identical directions (358.9°, 55.4°, $\alpha95$ = 2.2°) to those in Eastern Crete. Such observations have implications for the sequence of events in the southern Aegean in LMI times and allow further consideration of the relationship between the eruption of Santorini and the destruction levels on Crete.

### *1. Introduction*

This article evaluates the evidence from studies of the magnetization made by Downey (1983) of samples from the volcanic tephra of the Minoan eruption of Santorini and from fired Minoan destruction levels on Crete (Downey and Tarling, 1984). The arguments for the age of these events, based on archaeological and other scientific dating methods, will only be briefly outlined as it is sufficient, for this example, to indicate that there is considerable uncertainty in all other dating methods for both the absolute and relative ages of these events.

The relationship between the Quaternary (Minoan) eruption of the Santorini volcano in the Aegean and the destruction of the Minoan Bronze

Age civilization on Crete has been contentious since Marinatos proposed a causal relationship between the two in 1939. Many arguments have since been proposed for both direct and indirect causative relationships between them but their validity depends fundamentally on their precise time relationship. Unfortunately, most scientific methods (thermoluminescence, radiometric, $^{14}C$, etc.) have not yet proved sufficiently precise to establish the age of either the eruption or the Minoan destruction levels to better than ± 200 years, and so the synchroneity of the two events cannot be established by most normal scientific dating methods. (See Aitken, 1988, for a recent review of $^{14}C$ dating of the eruption).

Archaeological methods have similarly not yet provided an unequivocal age relationship despite the potential precision based on Minoan pottery styles (Popham, 1967). Nevertheless, it now seems clear that the destruction of the Minoan city of Akrotiri, on Santorini, preceded that of the Minoan volcanic eruption on the same island (Doumas, 1974, 1978). The youngest Minoan pottery in Akrotiri is attributed to LMIA times (probably early - Doumas, 1978) and there is evidence that the site was completely evacuated before being largely or entirely destroyed (probably by bradyseismic — slow earthquake — activity) and was undergoing clearance and reconstruction prior to the eruption of the first volcanic ashes that were eventually to entomb the entire ruins (Doumas, 1978). However, the attribution of the limited quantity of pottery has been disputed (Luce, 1978) — although only as possibly of very late rather than early LMIA times — and the duration of the time gap between the original destruction and the later ash eruptions is uncertain (Doumas, 1978). On Rhodes, Santorini tephra overlies layers containing LMIA Minoan and Cycladic IIB pottery at Ialysos (Doumas and Papazoglou, 1980), but occupation appears to have continued, despite estimates that this ash layer may originally have been about one metre thick. On Melos, the sites of Phylakopi, minute shards of Santorini tephra may be sealed in LMIA levels, but an LMIB age cannot be excluded (Renfrew, 1978). On Crete, the major fired-destruction horizons contain pottery clearly attributable to Late Minoan IB times. It has frequently been considered that these LMIB destructions were contemporaneous, possibly within a single year, although this degree of synchroneity generally seems to reflect an *assumed* relationship with the Santorini eruption rather than having being independently established. Such an assumption is certainly open to dispute but it is clear that the LMIB Minoan cities, towns, palaces, villas, etc., on Crete appear to have suffered extensive devastation, always including intensive firing, and this event was followed by the dominance of Mycenaean influences (Hood, 1973). However, there is no clear evidence whether the destructions were natural, man-made, or a combination of the two, e.g. earthquake destruction being followed by burning which could again be a direct consequence of the earthquake or by later invaders. It is clear, however, that virtually all of the settlements, with the notable exception of Knossos, were abandoned until at least LMIII A1 times (Coldstream, 1978) and mostly for ever. Platon (1971) has reported the finding of Santorini pumice in conical cups in the LMIB destruction level at Kato Zakros in Eastern Crete. He considered these to be offerings to a deity and the pumice itself to have been erupted some 50 years earlier. If the pumice had been deliberately placed in the cups, as proposed by Platon, then the pumice had certainly already been erupted prior to the destruction, but it could have been only hours beforehand and not necessarily much earlier. However, it is also possible that the pumice was later and accidentally fell into the cups at some later time. The relative archaeological ages are therefore not absolutely clear for either the eruption or for the Cretan destruction levels, other than LMIB pottery was in use at all known sites. Their absolute (calendar) age of the LMIB destructions is even more uncertain, with most archaeologists apparently preferring a date around 1450 ± 20 B.C. (Hood, 1973 ; Furumark, 1978 ; Cadogan, 1978), although a date some 200 years earlier cannot be excluded (Warren, 1979, 1987 ; Betancourt, 1987).

The relationship between the eruption of the Santorini volcano and the Minoan destruction levels are thus of considerable archaeological interest. However, as the eruption of Santorini was one of the most devastating volcanic events of historical times, being possibly the most powerful eruption within a developed civilized area during historical times, the actual sequence of events is also of considerable importance to the understanding of such hazardous events.

## 2. *Archaeomagnetic dating*

The principles of archaeomagnetic dating are described in several standard works (Aitken, 1974 ; Tarling, 1983) and will only be described briefly. When archaeological or geological materials are heated to temperatures of some 700° C or greater, *i.e.* to a bright red heat, they will acquire a single magnetization in the direction of the Earth's magnetic field as they cool, and the intensity of this magnetization will be proportional to the strength of the geomagnetic field at that time. Such magnetization will normally be preserved for thousands or millions of years, but only by specific grains sizes, generally around 0.3 to 1.5 µm in diameter. Larger and smaller grains tend to gradually loose this original magnetization, and they gradually acquire new magnetizations aligned along later directions of the Earth's magnetic field. As these later magnetizations have a low magnetic stability, they can be removed from most archaeological samples by partial demagnetization techniques, i.e. reheating them to 100-150° C and cooling in zero magnetic field, or by placing them in alternating magnetic fields of 10-15 mT. Either demagnetization method preferentially removes the least stable magnetization, and thus isolates the magnetization acquired at the original time of cooling.

As the Earth's magnetic field is moderately uniform over large areas, a few 1,000 $km^2$, all materials heated and cooled at the same time within such an area should have an identical direction of magnetization and also an intensity of magnetization that can be related to an ambient field of the uniform strength. Conversely, materials which have acquired their magnetization at different times, i.e. after the Earth's magnetic field has changed, will have acquired different directions and also have intensities corresponding to different palaeo-field strengths. Thus comparison of the direction and intensity of the original magnetization can be used to determine whether such materials were cooled at the same time or not. If, however, there is an established record of the changes of geomagnetic direction and intensity for that or nearby areas, then absolute dating can be made by comparison of the observations with the established record. In the case of the Southern Aegean some 3,500 years ago, there is not yet an established record, although the data to construct such records are becoming established for Bulgaria (Kovacheva, 1983 ; Kovacheva and Kanarchev, 1986) and work is currently in progress in Egypt which should enable a reasonable extrapolation to determine the date of geomagnetic changes in the Aegean region. At the moment, however, archaeomagnetic dating can only be effectively used as a relative dating tool in this region for this time.

### 3. *Archaeomagnetic studies on Crete and Santorini*

The work reported here is entirely that of Downey (1983) following initial studies on volcanic bombs within the Santorini tephra (Tarling, 1978). The materials sampled were largely *in situ* fired mud-brick walls and floos, in differing orientations, although charcoal ash layers were also sampled and had similar directions and stability to the mud-brick materials at the same site. All sites were characterized by a northerly declination, but the mean inclinations from all sites in Central were distinctly steeper than those of sites from Eastern Crete at a much greater than 95 % probability level (Table 1). Similarly, sites from Central Crete had become magnetized in a lower intensity geomagnetic field than those in Eastern Crete. (These new data were also consistent with very limited studies by Thomas, 1981). It is therefore concluded that the geomagnetic field had changed in both direction and intensity between the LMIB firings in these two regions of Crete.

On Santorini, only one Minoan site could be sampled - a hearth at Akrotiri. The mean direction of remanence at this site was just over 7° different from either of the two mean directions of the destruction levels on Crete. This difference, which is statistically significant at a 95 % level, is almost entirely in declination, while the difference between the LMIB site directions on Crete were entirely in inclination. The mean palaeofield strength for the Akrotiri hearth was also distinctly weaker than the mean field strengths determined for the Cretan sites, being statistically different from Phase 2 sites (Table 1). The archaeomagnetic data therefore confirm the archaeological indications of a time gap between the occupation of Akrotiri and the destructions on Crete (and the volcanic eruptions on Santorini, *v.i.*).

TABLE 1. — MEAN DIRECTIONS OF REMANENCE AND PALAEO-INTENSITIES

| | B | N | Decl. | Incl. | $\alpha_{95}$ | B | N | M(μT) | ± |
|---|---|---|---|---|---|---|---|---|---|
| Phase 2 Events | | | | | | | | | |
| Archaeological[1] | 3 | 120 | 355.6 | 60.1 | 1.1 | 5 | 29 | 65.9 | 3.2 |
| Paroxysmal Phase | | 32 | 3.7 | 59.6 | 2.3 | | | | |
| Combined | | 152 | 357.3 | 60.0 | 1.0 | | | | |
| Phase 1 Events | | | | | | | | | |
| Archaeological[2] | 6 | 106 | 355.7 | 55.5 | 1.1 | 3 | 20 | 56.4 | 3.9 |
| Plinian Phase | | 101 | 358.9 | 55.4 | 2.2 | | | | |
| Combined | | 207 | 357.2 | 55.5 | 1.2 | | | | |
| Earlier Phases | | | | | | | | | |
| Akrotiri | 1 | 17 | 10.6 | 57.3 | 3.5 | 1 | 6 | 51.0 | 4.9 |

N = number of samples ; B = number of sites ; $\alpha_{95}$ = radius of circle of 95 % confidence.
M = ancient geomagnetic field strength.
The mean field direction is calculated giving equal weight to each sample (N), but the mean field intensity is calculated giving equal weight to each site (B).
[1] Kato Zakros, Palaikastro.
[2] Slavokambos, Gournia, Hagia Triada, Phaistos, Malia town, Malia palace.

## *4. Palaeomagnetic studies on Santorini*

The tephra deposits on this island are particularly difficult to sample as the ashes are small and unwelded so that they tend to move during orientation by standard methods. The original study (Tarling, 1978) was therefore confined to the volcanic bombs and large tephra within the upper ashes. It was found that each of the volcanic bombs had a distinctly different direction of magnetization although each bomb had a clearly identifiable remanence. It was concluded that the volcanic bombs had therefore been cooled elsewhere, where they obtained their stable remanence, and then had later been ejected into their present position without subsequent reheating. However, the few larger tephra samples showed directions of remanence which were in the general direction of the present Earth's magnetic field, but these were too few for interpretation. It was on the basis that the tephra appeared to have acquired some magnetization after emplacement that further studies were planned using the disk technique of sampling that had then been developed mainly for sampling small, fragile archaeological materials (Tarling, 1983).

Subsequent collection and study of the tephra deposits were entirely by Downey (1983). These were mostly from the main quarry at Thera, but extended to other parts of the island, e.g. Oia and Akrotiri. Thermal demagnetization showed that these tephra had been emplaced at temperatures around 320° C at Thera quarry, but some 100° C cooler at Akrotiri, some 10 kms further away from the caldera. The difficulty of sampling, and the small range of temperature over which the remanence could be defined, meant that the precision of the remanent directions was much less than that of the archaeological materials (Table 1). Nonetheless, samples from the Plinian (lower) ash had a uniform direction of remanence identical to that of the Central Crete archaeological sites, while the overlying base surge and higher tephra were characterized by a direction — best defined within the ignimbrites — which was identical to that of the archaeological sites of Eastern Crete. The magnetic directions of the two tephra sequences in only just statistically different at a 95 % level of confidence, but the agreement with the directions of the archaeological sites is extremely well defined. It is concluded, therefore, that the differences between the basal Plinian and the overlying tephra, are real. Unfortunately, the small temperature range over which the original remanence was acquired inhibits the determination of palaeointensities.

## 5. *Interpretation and conclusions*

It is not appropriate to discuss here the archaeological or volcanological implications of the archaeomagnetic dating exemplified here. It is, however, relevant to assess the precision of technique in this instance as an illustration of the potential of this form of dating. In this example, only relative dating is currently available, *i.e.* it provides no information or test of the absolute dates of either the eruption or of the Late Minoan destruction levels. However, for the assessment of the temporal relationship between the eruption and the destruction, the extant data appear to be clear.

1. The Akrotiri hearth on Santorini was last used some time before both the eruptions of the volcano and the destructions on Crete.
2. On Crete, two distinct times of destruction are involved ; the settlements on Central Crete being destroyed at a different time to those in Eastern Crete.
3. The eruptions of the Santorini volcano was contemporaneous with the destructions on Crete. The lower Plinian ashes were erupted at a similar time to the destructions on Central Crete and the upper volcanics were synchronous with the destructions on Eastern Crete.

Clearly such a conclusion can only be made within the temporal accuracy of the technique itself and this requires a knowledge of the rate of geomagnetic field change at this time which is not yet available. However, an estimate can be made from the average rate of geomagnetic directional change now determined for Britain during the last 2,000 years (Tarling, 1988). The modal average rate of change was 0.05° (solid angle) per year. This means that the radius of a circle of 95 % confidence ($\alpha_{95}$) of 1° would correspond, on average, to a 95 % probability error or 20 years. Assuming that the field in the Aegean in Late Minoan times was changing at this average rate for Britain, then the angular difference between the mean directions of the phase 1 and 2 destruction levels (4.6°) corresponds to 92 years, while the angular difference between the two error circles (2.4°) corresponds to 48 years. Clearly, both faster and slower rates of change are possible, with corresponding smaller or larger age differences.

Such « errors » are thus still large in the context of archaeological interpretations, i.e. they do not rule out the possibility of destructive invasions over a decade or so in each area, although there was a distinct time gap between the firings in the two regions. Nonetheless, the *simplest* hypothesis is that the destructions in Central Crete were synchronous in very early LMIB times, and those in Eastern Crete were all in very late LMIB times. There is no clear indication of systematic trend in the firings from one area to another, although vastly more detailed work is required to substantiate this evaluation. The earthquake destruction of Akrotiri, in early LMIA times, was thus followed by the Plinian eruption in early LMIB times, when the Central Cretan sites were destroyed, apparently followed by the paroxysmal eruption in late LMIB times when the Eastern Cretan sites were destroyed.

In terms of comparison with other scientific dating techniques, this relative archaeomagnetic dating method has been shown to have a effective precision of $<0.6$ % - vastly more precise than any other scientific method. Furthermore, it seems probable that archaeomagnetic dating in Egypt (and other areas of Greece) may shortly enable an extrapolation of calendar dated geomagnetic secular variation to allow absolute dating within the Aegean region. In a wider context, it is also evident that similar chronological problems in other areas and times, involving either volcanic materials or fired archaeological materials, could be tackled similarly. The synchroneity, or not, of fired destruction levels at different locations within a region can clearly be established by such methods. In the case of tephra, such dating can also be combined with a magnetic evaluation of the temperature of emplacement and, using magnetic fabrics, the nature and flow direction of during the deposition of the tephra (Incoronato *et al.*, 1983).

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