Mediterranean Archaeology and Archaeometry, Vol. 11, No. 2, pp. 151-168

PALAEOMAGNETIC RESULTS FROM MINOAN ASH DEPOSITS IN (RV VEMA) CORES V10-50 AND V10-58, SOUTH AEGEAN SEA

W.S. Downey

Department of Geosciences, University Brunei DarussalamTungku Link Gadong, Bandar Seri Begawan, Brunei Darussalam

Received: 05/04/2011
Accepted: 30/09/2011
Corresponding author: billdowney49@yahoo.com

ABSTRACT

Palaeomagnetic and anisotropy measurements were carried out on Minoan ash deposits obtained from the deep-sea cores, (V10-50 and V10-58), South Aegean Sea. Three distinct layers have been reported within the ash deposit in core (V10-50). Based primarily on grain-size differences, a link to three separate eruptive phases of Santorini has been suggested. Magnetic results were unable to resolve any differences between these layers which suggests that the eruption may have been a 'single event'. Some magnetic parameters indicate that the final ignimbrite phase of the eruption of Santorini is most likely to have been responsible for the bulk of the deep-sea ash deposits, although a contribution from the first phase (phreatomagmatic and/or Plinian air-fall) cannot be excluded. Anisotropy of magnetic susceptibility measurements indicate a primary sedimentary fabric and quiet depositional conditions for V10-50 ash sediment. A more disturbed petrofabric is observed for V10-58 suggesting, bottom current activity and/or slumping. The mean palaeomagnetic inclination calculated from appropriate V10-50 results is:- 60.2° ± 4.3° (corrected for anisotropy and geographical location differences of sites). This is statistically identical to values obtained for burnt mud brick from destruction sites in eastern Crete but different to the mean palaeomagnetic inclination obtained for central Cretan sites. A comparison with the secular variation (inclination) data for the Balkan region and for Greece, suggests that the eruption/s of Santorini occurred in the period between ~1540 and 1500 BC.

KEYWORDS: Deep-sea cores, ash deposits, magnetic remanence, inclination, secular variation, anisotropy, Santorini, dating

INTRODUCTION

Palaeomagnetic measurements on deep-sea ash from cores V10-50 and V10-58 are compared to results from the sub-aerial pumice deposits on Santorini in order to ascertain whether any similarities or differences exist between the deposits. Deep-sea tephra layers have been used as time-stratigraphic marker beds to establish numerical or relative ages (Lowe et al., 2002). Recovery of deep-sea cores that contain volcanic ashes is important to archaeologists and Earth scientists for determining events that may relate to eruptions including the Minoan eruption of Santorini. The first marine tephra deposit related to the Minoan eruption was recognized by Mellis (1954) in piston cores recovered by the Albatross (1947-48). Later studies by Olausson (1960, 1961), Ninkovich and Heezen (1965, 1967), Keller et al., (1978) and Watkins et al., (1978) delineated the spatial distribution of Santorini ash. The characteristics of the land tephra have been described by Bond and Sparks (1976), Friedrick and Pichler (1976), Pichler and Schiering (1977), Vitaliano et al., (1978) and Keller (1980). Palaeomagnetic analyses were carried out by Opdyke et al., (1972) mostly on carbonate and sapropelic mud deposits from the V10-50 and V10-58 cores with 15 and 4 measurements respectively of remanence intensity and specific susceptibility.

GEOLOGICAL SETTINGS

Lithology, Dating and Correlation

Correlations between cores and identification of Santorini Minoan ash deposits from other volcanic ash horizons have been made using petrographic (glass refractive index) and geochemical analyses (Vasilatos et al., 2010; Francaviglia and Di Sabatino, 1990; Vitaliano et al., 1990; Huijsmans et al., 1988; Federman and Carey, 1980; Keller, 1980 and Vitaliano and Vitaliano, 1978). The cores containing tephra (ash) are largely composed of pelagic carbonate sediments with thinner inter-stratified beds of sapropelic mud (Ninkovich and Heezen, 1965).The stratigraphic position of the deep-sea deposited ashes has been based on their relationships to sapropels and to micropalaeontological criteria, in addition to numerous ^{14}C dates (McCoy, 1980). Ninkovich and Heezen (1965) used refractive indices of Minoan volcanic ash in the Vema cores and proposed a correlation with ash found in the Albatross cores.

Ash Distribution and Source

The grain size and thickness of the tephra layers are a function of distance from source and direction of the prevailing wind (Ninkovich, 1978; Ninkovich and Heezen, 1965). Isopach maps (Thorarinsson, 1954, 1958; Watkins et al., 1978 and Pyle, 1990) are the principal tools for studying ash distribution. Although the direction and velocity of high-altitude winds can suggest the general pattern of distribution from the volcanic source, bottom currents and sea floor topography may significantly influence the local distribution (Ninkovich and Heezen, 1965). Isopachs of the Minoan ash based on ash layer thicknesses illustrate the magnitude of redeposition. Variations in present-day thicknesses of the Minoan tephra downwind, along the presumed primary dispersal axis can vary between 1 cm only 40 km from source to nearly 200 cm within the Cretan Trough (McCoy, 1980). Volcanic eruptions, in which ignimbrites are generated, often have a specific sequence of events (Sparks et al., 1973). A distinctive type of fine-grained ash is produced with crystal to glass ratios that are systematically lower than artificially crushed pumice from the same ignimbrites. These ashes complement ignimbrite eruptions and have been referred to as 'co-ignimbrite' ashes with large volumes comparable to those of sub-aerial ignimbrites. They produce large ash fall accumulations in deep-sea environments rather than 'fall-out' from preceding Plinian phases (Sparks and Walker, 1977). The characteristics of such co-ignimbrite ash fall deposits are observed in the Mediterranean Minoan ash units in proximal cores and have striking bimodal grain-size distributions in distal cores. These features are interpreted in terms of a model for ignimbrite formation by eruption column collapse (Sparks and Huang, 1980).

Coring and Sedimentological Disruptions

An important factor in interpreting deep-sea sedimentological data is an understanding of the coring process (McCoy, 1980). Piston coring can present some difficulties with up to a meter of the uppermost sediment disturbed or not sampled at all due to the impact of the heavy piston cores (McCoy and Von Herzen, 1971). The Santorini tephra partly occurs within this uppermost interval but the degree of compaction is unknown. Indications are that cored intervals are not compressed by more than 10% of their in situ value, but this depends on the physical properties of the sediment (McCoy, 1980).

Skinner and McCave (2003) report the effects of piston-corers on the dimensional accuracy of marine sediments and show that discrepancies are attributed to effects of 'over-sampling' in the upper portions of piston cores. Knowledge of the dimensional accuracy of such cores is essential to an evaluation of past sedimentation rates, lest coring artifacts be interpreted as sedimentary signals. In addition, ash thickness variations may indicate post-depositional mixing during the past 3500 years, which may be due to benthic bioturbation (McCoy, 1980). Present-day thickness variations of tephra often mimic the bathymetry ie., they follow depth contours which implies slumping (Olausson, 1961 and McCoy, 1980) and re-sedimentation of tephra from steep surrounding slopes into troughs. Accumulations can also be due to dispersal of ash by currents and re-deposition (McCoy, 1980). Even in cores where mixing processes appear to have been at a minimum and where layer thicknesses approximate well to in situ thicknesses, there are still noticeable amounts of shards mixed into the surrounding host sediments.

MAGNETIC MEASUREMENTS ON DEEP-SEA CORES

The first detailed study of magnetization of deep-sea sediments was made by Keen (1963), in which, three important observations were made:- 1. magnetic inclination value recorded within the sediment is similar to that of the ambient geomagnetic field. 2. bioturbation destroys any depositional remanent magnetization. 3. slumped or deformed material can acquire a post-disturbance magnetization. Opdyke and Henry (1969) from a comprehensive study on fifty two deep-sea cores, from all oceans, concluded that there were no inclination errors. The fundamental nature of the physical processes which give rise to the inclination error, coupled with its apparent absence in deep-sea sediments implies that, such sediments are re-magnetized after deposition but the post depositional remanent magnetization (PDRM) processes do not lead to errors in the recorded magnetic inclination (Verosub, 1977). Post-depositional remanent magnetization, may arise due to the action of bioturbation on the sea floor, (Laughton, 1963; Ruddiman and Glover, 1972). However, Katari et al., (2000) do not support this hypothesis, reporting that PDRM reorientation occurs in natural undisturbed sediments below the sediment-water interface.

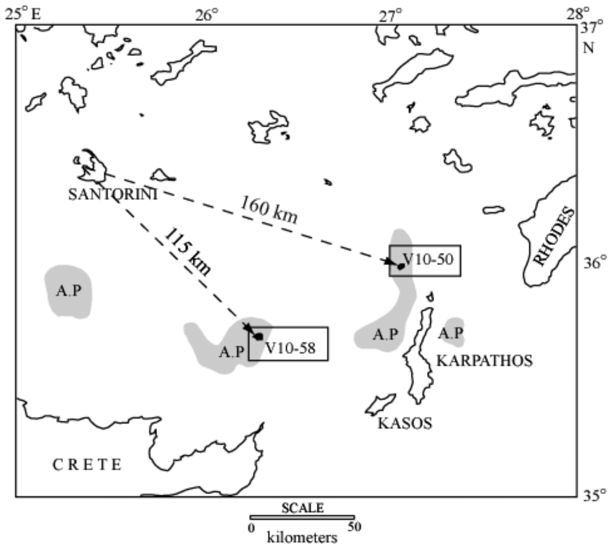

Figure 1. Map (after Opdyke et al., p.146, 1972) showing locations of Vema cores V10-50 and V10-58 in Abyssal Plains (AP), Southeast Aegean Sea. Approximate distances from source (Santorini) of core locations are also given.

Description of Core Sections from (V10-50, V10-58) as used for Magnetic Measurements

Two deep-sea cores with high rates of deposition (Opdyke et al., 1972) were recovered from the South Aegean Sea during cruise 10 of the R.V. Vema (Fig.1). Both cores were recovered from abyssal plains: Core V10-50, (35° 57.47′ N, 27° 04.45′ E (NNW of Karpathos) was recovered from a depth of 2547 m (~160 km SSE of Santorini) and core V10-58, (35° 40.30′ N, 26° 18.00′ E) (north of eastern Crete) was recovered from a depth of 2283 m (~115 km from Santorini)

(Opdyke et al., 1972). Core V10-50 is 480 cm in length and the upper 274 cm is composed of calcareous sediment. A thick volcanic ash layer occurs between 274 cm and 470 cm in core V10-50 and has been correlated by Ninkovich and Heezen (1965) with the Minoan ash from core V10-58.

Core V10-58 is 603 cm in length and is composed of calcareous lutite, sapropelic mud interspersed by three layers of windblown volcanic ash, the upper of which occurs between 55 cm and 114 cm depth. This layer has been correlated on the basis of physical properties and chemical composition of volcanic glass shards with the Minoan tephra on Santorini (Keller, 1971).

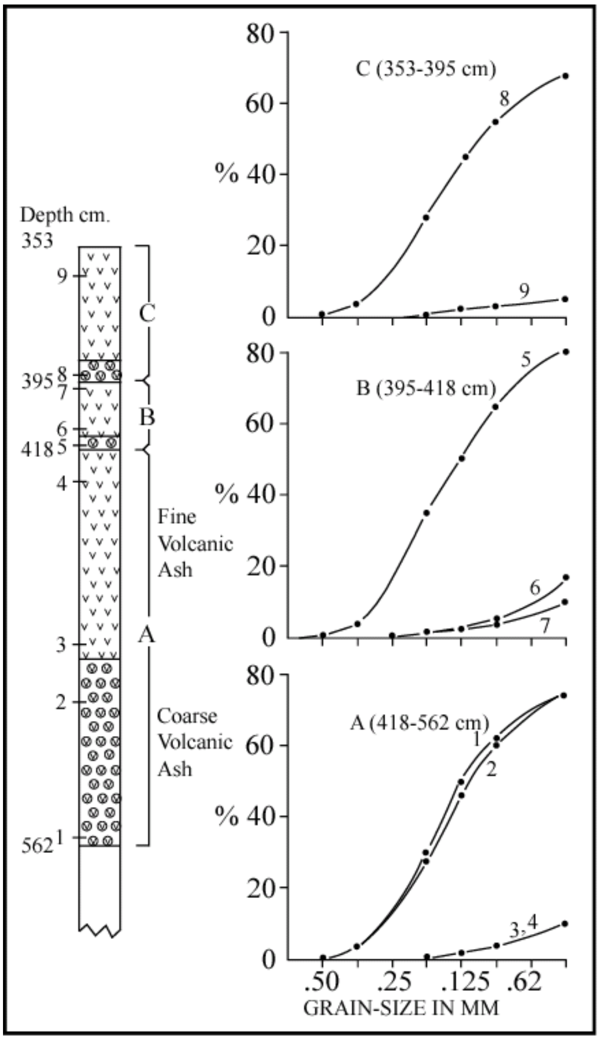

Figure 2. Granular analyses diagrams of the Minoan ash layers in core V10-50. (after Ninkovich and Heezen, p. 426, 1965).

Sedimentation rate over the past 27000 years indicates fairly tranquil abyssal conditions. Ninkovich and Heezen (1965) recognized three graded deposits in the ash of core V10-50, which they claimed to be related to three distinct eruptions of Santorini (Fig. 2).

However, it is possible that these deposits represent, at least in part, re-worked accumulations due to currents and/or slumping. Ninkovich and Heezen (1965) divided the V10-50 ash layer into 'A' (lower), 'B' (middle) and 'C' (upper) sections. This designation is retained in this study for convenience and to evaluate whether magnetic evidence justifies this sub-division.

The Minoan ash layers in both cores V10-50 and V10-58 are a light grey rhyodacite vitric ash which are often indistinguishable from the surrounding similarly coloured muds and biogenic oozes (McCoy, 1980).The mineralogy indicates derivation from the calc-alkaline Santorini volcanics (Nicholls, 1971; Keller et al.,1978). Further extensive descriptions of the Santorini rhyodacite products can be found in Sparks and Wilson (1990) and Pyle (1990).

PREVIOUS PALAEOMAGNETIC STUDIES ON CORES V10-50 AND V10-58

Magnetic analyses, including measurements to obtain palaeomagnetic inclinations were carried out by Opdyke et al., (1972) mostly on carbonate and sapropelic mud horizons in cores V10-50 and V10-58. They identified the magnetic carrier in the Minoan ashes as 'magnetite' from X-ray diffraction (XRD) analysis with a grain size of ~5 μm. Opdyke et al., (1972) found the average palaeomagnetic inclination values for carbonate lutite in cores V10-58 and V10-50 to be 55° ± 14° (1σ) and 46° ± 13° (1σ), respectively, stating that they were consistent with those of the geomagnetic field.

No correction for potential inclination error (King, 1955) was applied because they concluded that 'magnetite' grains were deposited in a water-logged slurry and that the palaeomagnetic inclinations represented a true depositional remanent magnetization (DRM). No consideration, at the time that these palaeomagnetic measurements were made, was given to the possible presence of authigenic (ferri-magnetic) greigite (Fe_3S_4), (Roberts, 1995 and Roberts et al., 2011).

NEW MAGNETIC MEASUREMENTS ON CORES V10-50 AND V10-58

Methods

A magnetic study was carried out on volcanic ash from cores V10-50 and V10-58 to determine AMS, palaeomagnetic inclinations (NRM), volume susceptibilities, stabilities of remanences (to AF demagnetization) and to ascertain if any magnetic differences within, or between cores, existed. Samples were measured for magnetic remanence using a fluxgate magnetometer (Molyneux, 1971) and low field susceptibility, (Collinson et al.,1963). Repeat measurements were made at each step and assessed for accuracy using the α_{95} and the k precision parameters (Fisher, 1953). Step-wise alternating field (AF) demagnetization was carried out at room temperature on forty four V10-50 and V10-58 ash samples from a peak field (PF) of 2.5 mT to a maximum PF of 30 mT or 40 mT, [sufficient to establish the median destructive field of the natural remanent magnetization (MDF_{NRM}) range], at intervals of 2.5 mT (PF). A low PF between 2.5 mT and 5 mT was generally required to remove 'soft' viscous remanent magnetization (VRM). The (NRM)s were measured prior to anisotropy of magnetic susceptibility (AMS) measurements, which was measured using a three axis anisotropy delineator attached to the fluxgate magnetometer (Molyneux, 1971; Noltimier, 1967). Essentially the method is similar to that used for measurement of remanent magnetization but with the addition of a known applied field acting on the sample which produces an induced magnetization. Samples were rotated at 7 Hz in an applied field of 0.35mT. Measurements were taken over 2^5 cycles i.e., 3840 readings which were processed by Fourier analysis.Previously unmeasured dry core cuboid ash samples of sides ~ 1 to 2 cm across at ~ 5 cm stratigraphic intervals were supplied by the Lamont Doherty Earth Observatory; for core V10-50 (39 samples) from depths of 273-471 cm and for core V10-58 (5 samples) from depths of 58 -102 cm. For core V10-50, only the upper section of Ninkovich and Heezen (1965), subsection (A, lower), (53 cm thick) was available for measurement ie., the lower part of this deposit, described as 'coarse volcanic ash" and possibly representing the first Plinian basal pumice air-fall phase, was not available for measurement.

Depositional and Post-depositional Remanent Magnetization

The magnetic polarity of recent sediments was first investigated by McNish and Johnson (1938) and Ising (1942) who considered the magnetization to arise from a preferential alignment with the geomagnetic field of magnetic minerals which develops whilst the particle settles through water. Depositional remanent magnetization is well understood theoretically and experimentally but its applicability to natural sediments may be limited (Verosub, 1977). Particles become aligned with the ambient geomagnetic field but inclination may be systematically reduced by the 'rolling' of particles on contact with the sediment surface, thus producing an inclination error. Many sediments do not record such errors and any deviation introduced during deposition is often lost in the water-logged slurry even if bioturbation is present. Studies on many deep-sea sediments indicate that inclination error is not as common as in sediments from shallower water environments, as reported by Steele (1981). Post depositional remanent magnetization arises as a result of the mobility of magnetic carriers within fluid-filled voids in the sediment and may be the dominant process by which sediments acquire their magnetization. The nature and composition of the magnetic carriers and the sediment as well as the pore-water content, influence the balance between DRM and PDRM which makes it difficult to identify which mechanism is responsible for acquisition of the magnetic remanence (Verosub, 1977).

Inclination Error

King (1955) applied a correction based on the relationship $\tan I_0 = f \tan I_f$, where I_0 is the measured uncorrected inclination and I_f is the corrected inclination. A value of 'f' (flattening factor) = 0.4 is chosen (King, 1955) because sediment is assumed as consisting of a mixture of spherical and disc-shaped particles whose magnetic moment is in the plane of the disc. The spherical particles remain aligned with the geomagnetic field when they come to rest on the sediment surface but the disc-shaped particles rotate so that they lie horizontally. If both sets of particles have equal magnetic moments, then 'f' can be identified as the fraction of spherical particles. Ninkovich and Heezen (1965) reported that the grain size range for the ash A, B and C layers (V10-50) is from ~ 0 - 500 μm. For clastic sediments, this range clay size to coarse silt (Wentworth scale, Wentworth, 1922) but there appears to be no significant differences in grain size or their distribution between the A, B and C layers (Fig. 2). Vitric pumice particles from Santorini have been described as irregular, not spherical or discoid (Bond and Sparks,1976), however, Vitaliano et al., (1978) describe the deposits from the Fira quarry section (Santorini) as containing glass shards of uniform shape and occasionally crescentric. Riley et al., (2003) describe the volcanic particles as being generally quite angular and/or irregular with equant mineral grains and subrounded vesicular pumice clasts. In view of these differing grain shape observations and assuming that similarly shaped particles were deposited in the deep-sea environment, the question arises, as to the value of 'f ' that would be appropriate to use in any 'inclination error' calculation. The 'King' inclination correction was not applied.

Parameters of Magnetic Anisotropy and Anisotropy Inclination Correction

Anisotropy in sediments generally arises as a consequence of the preferred orientations, or fabric of constituent magnetic mineral grains which are them selves anisotropic. Measurements form the basis for quantitative characterization of petrofabric which in turn provides information on the conditions of deposition. The usual way of representing magnetic anisotropy is in terms of the principal susceptibilities ($K_1 \geq K_2 \geq K_3$), which may be visualized by the approximate geometric representation using a triaxial ellipsoid (Hrouda, 1982). Using simple geometrical analogies, oblate spheroids correspond to disc-like (flat) grains, and prolate spheroids correspond to rod-like (elongated) grains. To distinguish petrofabrics, anisotropy parameters have been defined which attempt to emphasise one or other useful features; 'q' factor, E (eccentricity), L (lineation), F (foliation), P (degree of anisotropy) , anisotropy %, ellipsoidal shape:- prolateness, oblateness, etc., (Hrouda, 1982). The 'q' parameter, (Rees, 1965) is a measure of the relative strengths of foliar and linear elements in AMS. It is derived from the magnitudes of the principal magnetic anisotropy susceptibility axes and has a theoretical distribution from 0 to 2. In undisturbed sediments it usually lies in the range 0.06 to 0.67 (Hamilton and Rees, 1970). If 'q' falls outside this range, then sediment deformation might be expected to have taken place (Rees and Frederick, 1974). However, values within the range do not necessarily exclude a deformational fabric because similar values of 'q' can result from deposition in running water on a horizontal bed or from deposition in still water on a sloping bed. A tabulation of 'q' values and the corresponding physical conditions of deposition are given by Hamilton and Rees (1970). The 'q' factors for V10-50 and V10-58 samples are given in Table (1, 2). Jackson et al., (1991) determined inclinations of experimental DRM acquired by synthetic sediments composed of magnetite, silica and kaolin. The clay produces inclination errors by heterocoagulation with magnetites (Lu et al., 1990). An inclination correction based on anisotropy of magnetic remanence (AMR) largely removes the dependence of inclination due to the clay content and gives the correct inclination mean (Collombat et al., 1993). Anson and Kodama (1987), Lu et al., (1990), Deamer and Kodama, (1990) have shown that clay can cause inclination errors by adhering to magnetite particles due to electrostatic and van der Waal's forces. Fine clay-sized particles are present (~20% – 90%) in the V10-50 ash core (Ninkovich and Heezen, 1965), (Fig. 2).

RESULTS

Palaeomagnetic Directions and Remanence Intensities

Natural remanent magnetization directions were obtained for ash in both cores and show a scattered distribution (Fig. 3a, c). The declination scatter may be due errors in the cores' 'downhole' orientation marking ie., the marks are not confined to the same face of the sample but on occasion, marked on a face rotated horizontally through 90º or 180º. Negative (anomalous, presumed up-side-down) NRM inclination values were also observed and excluded from any mean palaeomagnetic inclination calculations.

Measurements from the ash in core V10-50 (whole rock N = 39) from depths of 273 – 471 cm recorded a NRM range of ~ 4 – 472 mAm^{-1} (mean 202 ± 123 mAm^{-1}) (Fig. 4a, Table 1). Specifically, for the sub-divisions in the V10-50 ash below this layer, the mean values obtained are :- [(A), 194 ± 95 mAm^{-1}, (B), 264 ± 136 mAm^{-1} and (C), 242 ± 99 mAm^{-1}]. Within error (1σ) layers A, B and C are statistically identical and to the overlying ash layer (273 – 351 cm depth). The question remains, as to the source material for this ash deposit i.e., which layers represent the initial phases, (air-fall phreatomagmatic and Plinian) and which are attributable to the other most likely source, (the co-ignimbrite air-fall, final phase). From eruptive mode considerations, it is unlikely that the base-surge or chaotic ash flows made any significant contribution to airborne tephra. Core V10-58 (5 ash samples, 58 – 102 cm) recorded an NRM range of ~ 31 – 160 mAm^{-1} (mean 85 mAm^{-1}), somewhat lower than V10-50 ash (Fig. 5a, Table 2). Figure (6) shows a comparison between the NRM intensities of pumices from the Plinian and ignimbrite eruptions and the ash from the two cores.

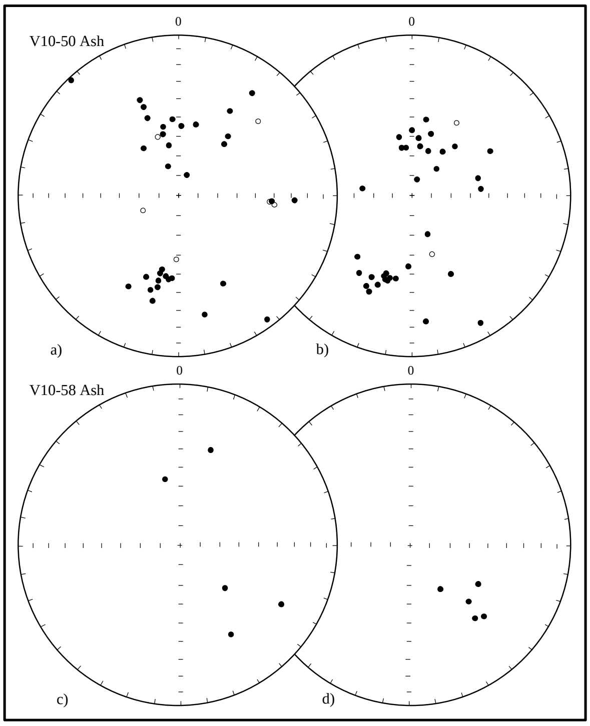

Figure 3. Lower hemisphere stereographic projections showing palaeomagnetic directions for V10-50 ash:- (a) NRMs. (b) 'Cleaned' means after step-wise AF demagnetization. For V10-58 ash:- (c) NRMs. (d) 'Cleaned' means after step-wise AF demagnetization. Solid dots and open circles indicate, +ve. and -ve. inclinations, respectively.

Table 1. V10-50 Ash

V 10-50 Ash N.R.M.					**Stable Mean**						**Anisotropy Parameters (AMS)**				
Sample Depth cm	**Vol. (cm³)**	**Dec. (deg)**	**Inc. (deg)**	**Int. mAm⁻¹**	**Dec. (deg)**	**Inc.**	**Inc. (deg) corr.**	**S.I.**	**Vol. χ (SI)**	**MDF (mT)**	**'q'**	**PA**	**KMIN (deg)**	**KINT (deg)**	**KMAX (deg)**
273-275	4.86	173.9	48.6	129	162.8	54.5		2.57	0.77	20	0.91*				
279-281	6.46	170.9	-57.8*	245	158.8	-59.3*		5.99	1.27	27	0.28				
283-285	3.72	273.8	-42.2*	463	155.3	-69.3*		2.60	1.40	27.5	0.81*				
285-287	5.47	160.1	-58.9*	430	156.8	-58.3*		3.99	1.24	23	0.33				
294-296	8.28	213.3	38.2	137	215.5	42.6*		11.15	1.11	21	0.48				
295-297	6.10	272.4	27.5	343	222.1	48.5		2.66	1.57	12	0.31		67.2*	22.5	2.9
302-304	9.20	208.7	36.8	127	207.5	39.4*		5.66	1.27	23.5	0.09				
309-311	7.71	338.1	47.7	44	59.5	42.8		1.42*	0.86	20	0.03*				
314-316	**13.80**	**191.0**	**52.0**	**202**	**198.9**	**49.3**	**53.6**	**16.01**	1.46	**23.5**	**0.14**	**1.0523**	**82.0**	**5.9**	**5.1**
318-320	9.35	46.9	-32.1*	4	30.7	-44.7*		5.47	0.82	20	0.08				
323-325	8.83	186.1	47.9	141	198.4	46.3		3.58	1.12	18.5	0.45		6.6*	12.1	6.0
329-331	**8.58**	**323.5**	**78.8**	**72**	**83.4**	**54.3**	**58.0**	**3.75**	0.77	**16**	**0.11**	**1.0476**	**84.3**	**5.4**	**1.3**
332-334	6.46	167.0	26.0	169	173.6	24.2*		1.79*	1.39	4	0.21				
338-340	9.94	323.9	60.1	286	347.8	58.5		5.78	1.81	26	0.18		72.6*	8.5	14.9
344-346	7.88	192.9	45.6	307	200.9	41.2		7.21	1.34	24.5	0.01*				
349-351	9.49	341.5	74.5	201	41.4	70.3*		6.57	1.69	21.5	0.75*				
353-355	8.36	193.5	48.3	257	199.5	45.5		9.17	1.37	25	0.22		76.6*	11.7	6.1
358-360	8.75	344.1	58.3	85	76.1	54.6		3.20	1.46	26	0.74*				

363-365	10.12	201.1	44.3	168	206.7	42.4		8.69	1.43	22	0.10		76.8*	12.6	3.7
369-371	**6.95**	**93.5**	**40.4**	**326**	**42.0**	**57.0**	**60.0**	**8.59**	1.95	**9**	**0.10**	**1.0390**	**87.8**	**0.4**	**2.1**
373-375	10.58	189.2	48.0	238	195.8	45.9		24.20	1.76	23.5	0.31		79.1*	7.6	7.6
379-381	9.94	14.6	53.1	240	10.1	65.6*		11.64	1.86	23	0.23		75.9*	3.5	13.5*
383-385	6.00	194.0	33.1	240	204.8	34.7*		4.35	1.38	22	0.33				
388-390	8.74	41.0	50.7	378	11.0	60.1		4.75	1.03	20.5	0.08		71.4*	8.8	16.1
393-395	**8.71**	**196.5**	**38.2**	**244**	**196.1**	**44.4**	**50.5**	**5.75**	1.63	**23.5**	**0.22**	**1.0736**	**86.4**	**2.3**	**2.6**
399-401	7.86	42.8	55.0	229	348.7	68.5*		4.28	1.76	8.5	0.25				
404-406	**11.50**	**192.6**	**41.6**	**198**	**191.9**	**46.0**	**52.9**	**12.88**	1.70	**22**	**0.16**	**1.0852**	**85.0**	**4.9**	**0.0**
409-411	5.19	337.6	37.8	350	21.9	67.3*		2.56	1.46	12	0.27				
414-416	5.04	95.2	-39.3*	472	-	-		-	1.27	-	-				
≈418	13.50	349.7	64.4	72	352.7	65.3*		6.05	1.50	12	0.05*		70.1*	12.8	14.9
425-427	11.29	316.3	2.4*	121	-	-		-	1.48	-	-				
429-431	8.80	354.8	51.1	256	18.4	57.8		7.00	1.95	20	0.19		71.2*	10.3	15.4
434-436	**8.97**	**151.9**	**38.2**	**215**	**152.9**	**44.5**	**55.2**	**6.55**	2.80	**13**	**0.22**	**1.1354**	**85.3**	**3.2**	**3.3**
439-441	9.13	346.9	54.2	186	21.1	81.1*		7.39	1.99	20.5	0.37				
≈449	14.40	2.9	55.2	125	7.7	60.2		14.31	1.40	25	0.13		71.3*	1.9	18.5
453-455	3.24	245.2	-70.4*	163	275.9	-75.5*		3.46	1.05	21	0.76*				
459-461	5.08	36.5	22.5	362	36.4	62.6		3.68	2.05	19	0.22		66.9*	23.0	1.3
464-466	8.32	144.0	6.9*	28	150.9	11.2*		3.79	0.69	11	1.54*				
469-471	**11.20**	**337.5**	**41.2**	**294**	**1.1**	**56.8**	**61.4**	**11.87**	2.18	**17**	**0.13**	**1.0623**	**80.4**	**8.7**	**3.7**

Palaeomagnetic results (N = 39) are shown for :- upper ash (273 – 351cm.), ash sub-divisions (Ninkovich and Heezen,1965), C (353-395cm.), B (399-418cm.) and A (lower, 425-471cm.). Inc.(corr.) is Inclination corrected for anisotropy using, $\tan(I_{CORRECTED}) = P_A^3 \tan(I_{DRM})$. MDF_{NRM} are means of Median Destructive Field to AF demagnetization of NRM. Vol.χ is Volume susceptibility. The 'q' factor is an anisotropy parameter, (see text). Anisotropy paramerter $P_A = TRM_{HORIZONTAL}/TRM_{VERTICAL}$. where TRM is used as a proxy for ARM. Principal susceptibility axes K_{MIN} (minimum), K_{INT} (intermediate), K_{MAX} (maximum). Highlighted 'bold' indicates samples which meet strict selection criteria for mean palaeomagnetic inclination calculation. * (symbol) indicates rejected inclination values because of either: 1) Anomalously high/low inclinations. 2) Amonalous negative inclination values. 3) Low (< 2.5), S.I. (Stability Indices), ie.(unstable to AF demagnetization). 4) 'q' factor values outside range (0.06 - 0.67). 5) K_{MIN} < 80° or K_{INT} or K_{MIN} > 10°.

The measurements made by Opdyke et al., (1972) in cores V10-50 and V10-58 (excluding the Minoan ash horizon), also show directional scatter. They report that, errors may have resulted from collection (coring procedures), with reduction in palaeomagnetic inclination values due to compaction by overburden or drying out of the sediment after extraction and storage. This may also be the case for ash samples as used in this study.

Table 2. V10-58 Ash. Palaeomagnetic results (N = 5), are shown for V10-58 ash. * (symbol) indicates rejection of all values for mean inclination calculation. All titled abbreviations are the same as described in Table 1).

V 10-58 Ash N.R.M.					**Stable Mean**					**Anisotropy Parameters (AMS)**			
Sample Depth cm	**Vol. cm³**	**Dec. (deg)**	**Inc. (deg)**	**Int. (mAm^{-1})**	**Dec. (deg)**	**Inc. (deg)**	**S.I.**	**Vol. χ (SI)**	**MDF (mT)**	**'q'**	**K_{MIN}**	**K_{INT}**	**K_{MAX}**
58	10.6	134.2	59.5	31	139.4	57.0	5.88	0.52	23	0.61	1.2*	18.0*	71.8*
68-70	5.17	121.0	29.6	160	139.2	30.9*	4.24	0.65	13	0.05*	20.3*	58.8*	22.4*
78-80	5.38	150.5	38.1	96	134.8	37.7*	1.96*	0.75	11.8	0.06	38.5*	41.8*	24.1*
89-91	7.52	346.6	53.4	50	147.8	63.3*	1.98*	0.67	7.9	0.05*	0.9*	19.3*	70.6*
100-102	5.88	16.2	36.7	85	119.5	50.5	1.51*	0.65	17.8	0.03*	0.7*	55.8*	34.1*

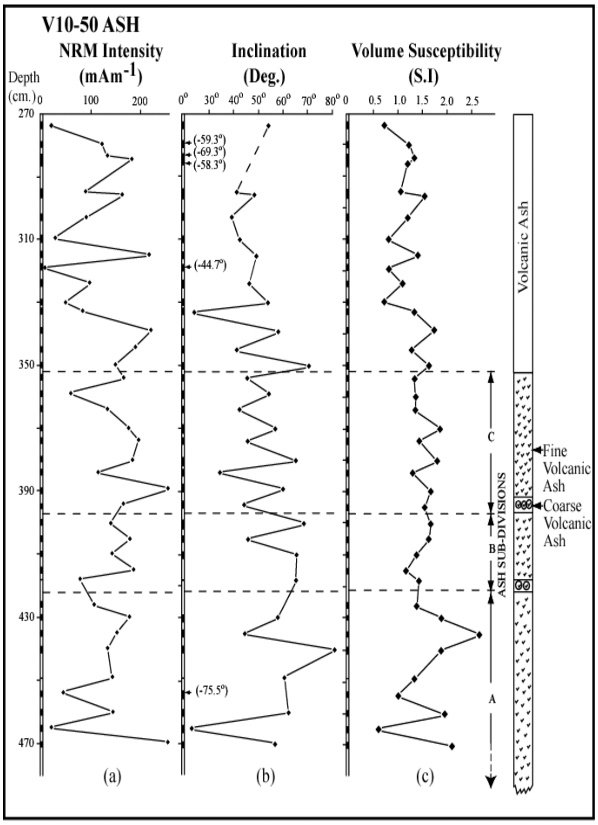

Figure 4. V10-50 ash. Variations with depth of :- (a) NRM Intensity. (b) Inclination mean values (after AF demagnetization). (c) Volume Susceptibility. Right-hand column shows the sub-divisions according to Ninkovich and Heezen, (1965).

Volume Susceptibility

The values obtained are 1.25, 1.63, 1.53 and 1.73 for ash layer (273 – 351 cm), C, B and A respectively (Fig. 4c, Table 1).

There are no statistical differences (1σ) between these mean values so, no sub-division is believed to be justified. V10-58 ash, volume susceptibilities range from (~0.42 – 0.60) with the mean of (~ 0.52 ± 0.06) significantly lower than those obtained for core V10-50 ash, probably because of depleted abundances of magnetic carriers (Fig. 5c, Table 2). Opdyke et al., (1972) obtained similar susceptibilities ranges of (1.78 – 2.46) and (1.05 – 1.35) for V10-50 and V10-58, respectively. [Conversion of Opdyke's specific (mass) susceptibility measurements was made assuming an average density of 1.3 gcm^{-3}].

Greigite, if present would have a volume susceptibility range of ~0.18 – 0.52 (Roberts, 1995) lower than that observed for V10-50 ash but partially within the range of V10-58 ash. This does not necessarily imply that greigite is present in V10-58 ash.

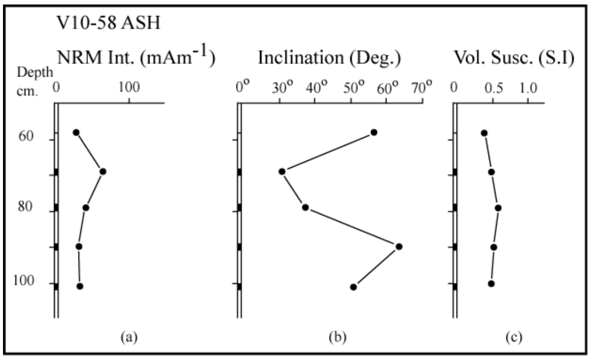

Figure 5. V10-58 ash. Variations with depth of :- (a) NRM Intensity. (b) Inclination mean values (after AF demagnetization). (c) Volume Susceptibility.

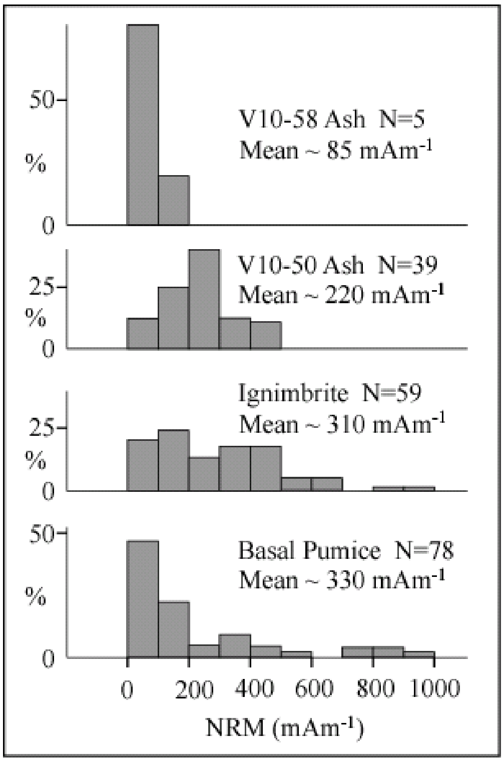

Figure 6. Histograms showing comparisons between the percentages of NRM ranges, for V10-50, V10-58 ashes and Santorini sub-aerial Plinian (air-fall, basal) and Ignimbrite, final stage pumices.

AF Demagnetization and Coercivity Spectra

Figure (3b,d) and Table (1, 2) show the stable mean palaeomagnetic directions obtained after AF demagnetization (principal component analyses) for V10-50 and V10-58. Circles of remagnetization were observed in seven ash samples in V10-50 (Fig. 7a,c). Re-magnetization may result from mechanical re-orientation of magnetic grains ie., regarded as a PDRM in the conventional sense or, due to the movements of moments and domains in magnetically soft, low-coercivity grains. A test for PDRM verses DRM was proposed by Stober and Thompson (1979) which showed that the effect of PDRM was small and rare in natural sediments. It is likely that a 'soft' VRM of comparatively low stability has been imposed 'recently' by the Geomagnetic field on more stable DRM components. Secondary components due to weathering, may be of high stability (Robertson and Hastie, 1962) but no 'hard' magnetizations of chemical remanent magnetization (CRM) origin were identified, (Downey, 1983). Greigite can grow in sediment in the early and late stages of diagenesis leading to unwanted re-magnetization. Multiple mechanisms for the late diagenetic re-magnetizations have been documented by Roberts and Weaver (2005). This can therefore be a problemic mineral in palaeomagnetic studies and deciphering evidence for the timing of its growth is crucial to avoid misinterpretation of palaeomagnetic records, (Florindo and Sagnotti, 1995, Rowan et al, 2009).

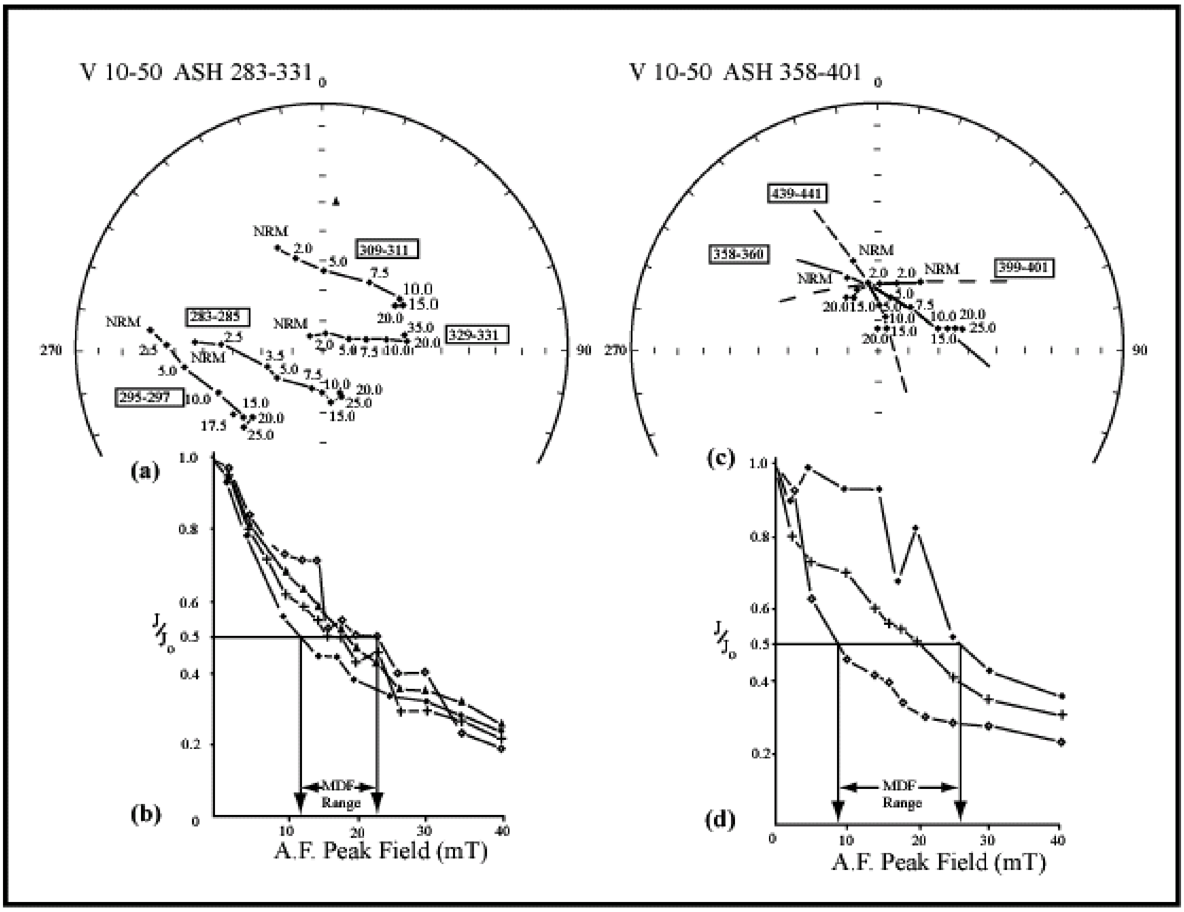

Figure 7. V10-50 ash. Lower hemisphere stereographic projections showing 'circles of remagnetization' and corresponding decay of normalized remanence against AF peak field, (coercivity spectra). Solid dots, +ve. inclination, open circles, -ve. inclination.

The directional changes in NRM and associated AF demagnetization decay curves for the re-magnetized samples from the V10-50 ash are shown in Figures (7 a,b,c,d). The decay of NRM to AF demagnetization (coercivity spectra) for V10-50 ash layers (upper 273 – 353 cm A, B and C) are shown in Figure (8), with rates of decay and MDF_{NRM} values similar for each of the ash sub-divisions. The V10-50 ash MDF_{NRM} mean is ~18 mT (range 8 – 28 mT) which is comparable to the MDF_{NRM} mean of 19 mT (range 8 – 23 mT) for V10-58 ash (Table 1,2). Figure (9) shows a comparison between the AF demagnetization characteristics, (coercivity spectra) and MDF_{NRM} ranges for Plinian and ignimbrite pumices.

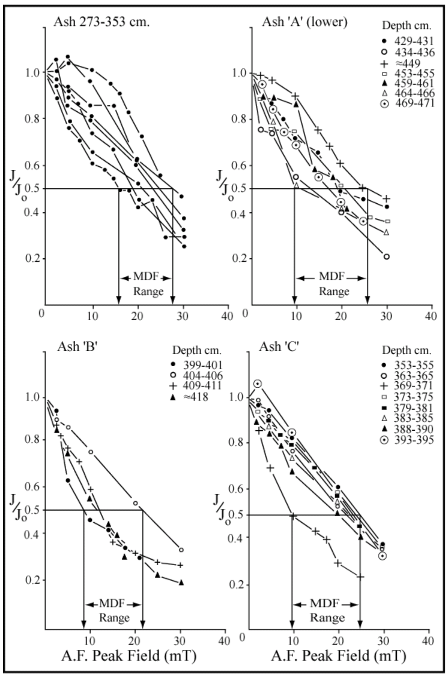

Figure 8. V10-50 ash. Normalized NRM intensity against AF peak field (coercivity spectra) for ash layers:- [(upper 273-353cm.), subdivisions A (lower), B and C). MDFNRM ranges are also indicated.

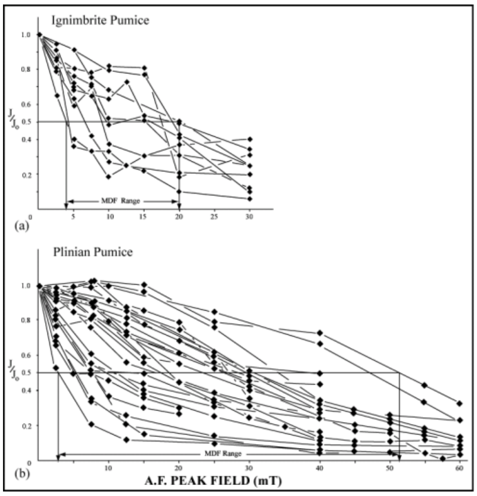

Figure 9. Normalized NRM intensity against AF peak field (coercivity spectra) for Santorini sub-aerial pumice clasts for:- (a) Ignimbrite. (b) Plinian. MDFNRM ranges are also indicated.

Figure (10) shows the MDFNRM ranges for all of the sub-aerial pumice (overall range, 2 – 55 mT) deposits :- Plinian (3 – 55 mT), basesurge (2 – 18 mT), ashflow (2 – 27 mT) and ignimbrite (3 – 20mT). The MDFNRM range for the Plinian pumices is greater than that for both cores (range 8 – 28 mT). This shows that ~ 65% MDFNRM values (Plinian pumice) are not represented in the core ashes. Ignimbrite MDFNRM ranges from 3 – 20 mT , in this case with ~65% of values corresponding to those in the cores' ash (range of 8 – 28 mT). This may suggest that the magnetic mineralogy of the core ashes reflects that of an ignimbrite source, however Plinian pumice air-fall cannot be excluded as a contributor.

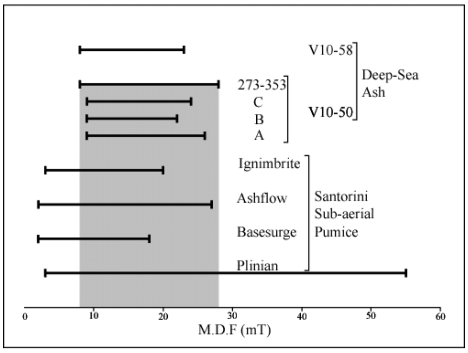

Figure 10. MDFNRM ranges for V10-50, V10-58 ash and pumices from all Santorini sub-aerial eruptive phases. The shaded area indicates the range limit for the V10-50/58 ash and its corresponding (overlap) with the sub-aerial pumice ranges.

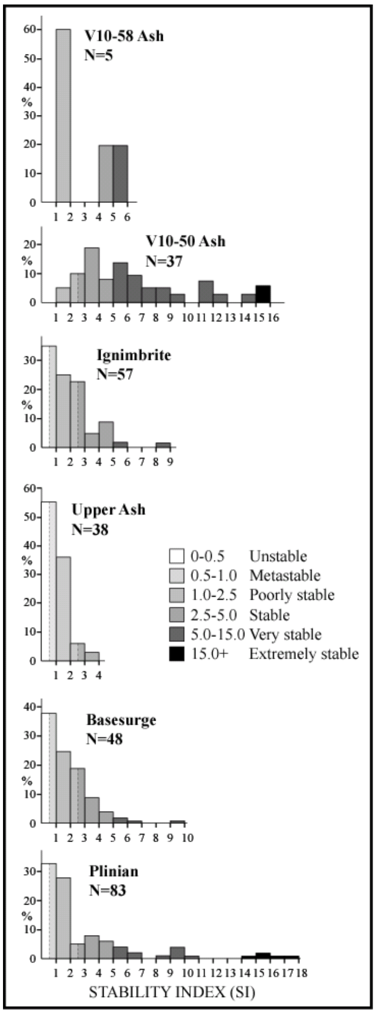

Figure 11. Histograms showing the percentage of samples against Stability Index (SI) ranges for V10-50, V10-58 and sub-aerial pumice samples from all Santorini eruptive phases.

Stability of Remanence

Stability indices S.I. (Tarling and Symons, 1967) were determined from AF demagnetization analyses and although the 'index' is a subjective classification of remanence stability in terms of the circular standard deviation, it has proved useful in the identification of metastable and unstable samples. The stabilities of the V10-50 and V10-58 ash samples are tabulated in Table (1, 2). Figure (11) shows a comparison of the stability indicies for V10-50 and V10-58 ash sediments with the sub-aerial pumice igneous deposits.

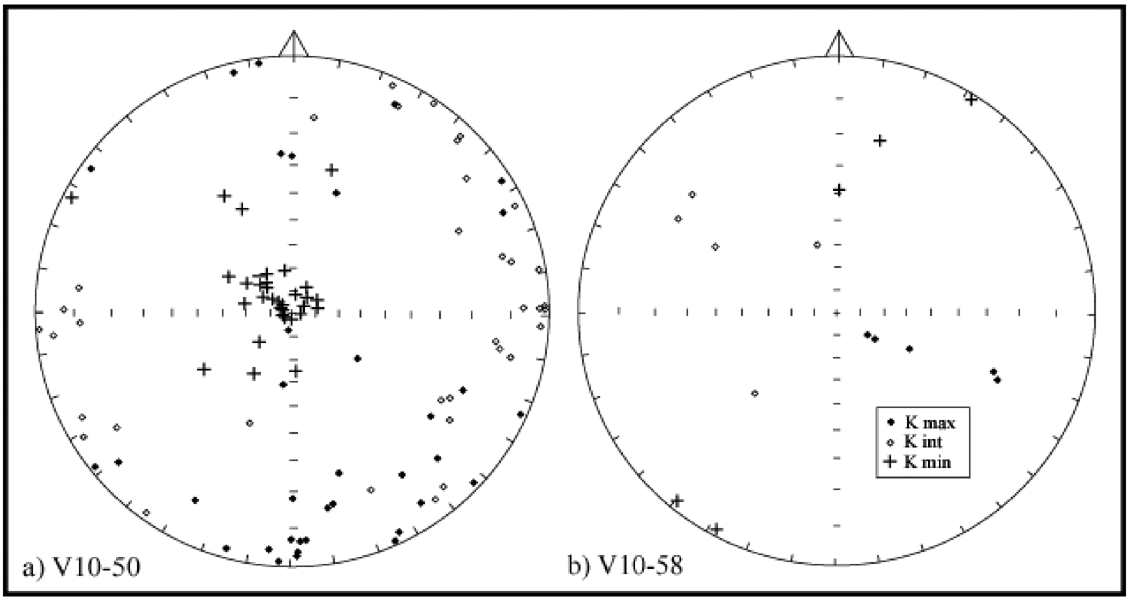

Figure 12. Lower hemisphere stereographic projections showing AMS principal susceptibility axes directions for cores:- (a) V10-50. (b) V10-58.

Platy clay-sized particles, flattened volcanic glasses and titanomagnetite grains, tend to lie horizontally on deposition, resulting in anomalously shallow inclinations. Corrected field inclinations can be derived using anhysteretic remananent magnetization (ARM).

Collombat et al., (1993) showed that there is an empirical dependence of I_{NRM} (in this case DRM)(P_A) where P_A = ARM $_{HORIZONTAL}$ / ARM$_{VERTICAL}$ given by:- $\tan(I_{CORRECTED}) = P_A^3 \tan(I_{DRM})$. Here, low field TRM, is used as a proxy for ARM for the calculation of P_A (Table 1).

Its acquisition is mathematically similar but relies on variations in applied field as opposed to temperature as a blocking mechanism. Figure (13) and Table (1) show the stable mean uncorrected (I_{DRM}) and the corrected inclinations ($I_{CORR.}$). The error calculated for the corrected mean inclination is reduced by 17% as compared to the uncorrected mean error (Fig. 13).

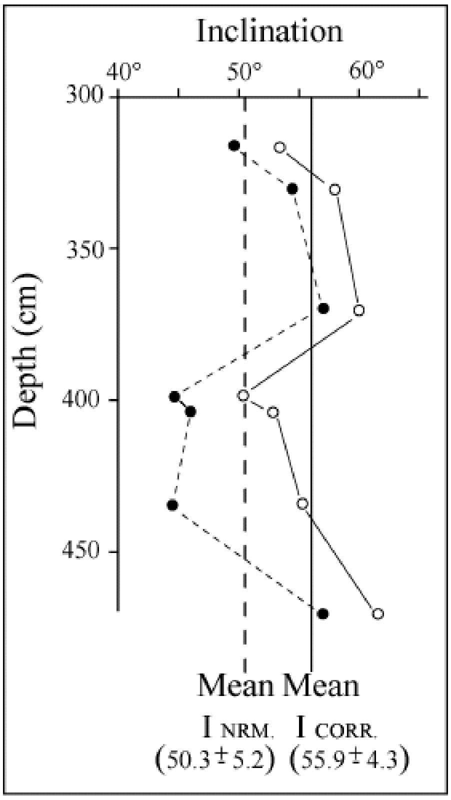

Figure 13. Comparison of stable mean DRM inclinations and their corresponding anisotropy corrected inclinations, with calculated means for each set.

V10-50 ash Palaeomagnetic Inclination Calculation.

Stringent criteria have been applied to palaeomagnetic inclination results (Fig. 4b,5b. Table. 1,2) to determine which are appropriate for inclusion in the calculation of the mean. Values are excluded on the bases of the following:- 1. anomalously high or low values [outside of the maximum recorded range of ~ 40^0 to ~ 67^0 from the secular variation (SV), inclination curve], (Tema and Kondopoulou, 2011; Evans, 2006; Kovacheva et al., 1998). 2. negative (anomalous inclinations). 3. unstable stability indices, < 2.5 (to AF demagnetization), 4. AMS, K_{MIN} < 80° with corresponding K_{INT} and K_{MAX} values >10° and 5. a 'q' factor outside the range 0.06 – 0.67.

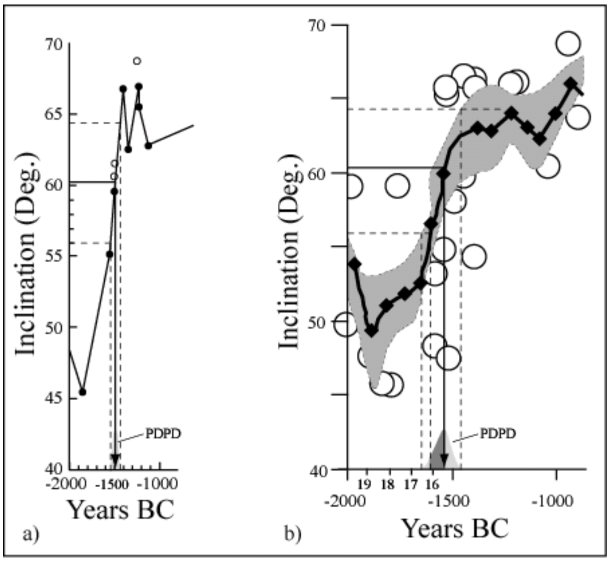

Figure 14. Selected portions of the inclination magnetograms for:- (a) Greece, (after Evans, p.94, 2006) reset to the geographical location at Thessalonika. No error bars are presented by Evans. (b) Balkan region, (after Tema and Kondopoulou, p. 609, 2011). Grey shading indicates the error in inclination. Solid 'arrowed' vertical lines indicate the inclination means obtained from the intersection with the SV curves. The dotted horizontal and vertical lines indicate the error limitations. PDPD is (Probability Density Possible Date, at 95% confidence level)

Seven samples from the V10-50 ash deposits from a total of forty four measured from both cores, meet the above selection criteria and give a DRM mean of 50.3° ± 5.2°. The anisotropy corrected, mean is 55.9° ± 4.3°. In addition, to allow for the geographic spread of the sampling sites, this value is re-calculated at Thessaloniki (40.60 N, 23.00 E) by means of the CVP (Conversion via Pole) method (Noel and Batt, 1990). The 're-set' mean then becomes, 60.2° ± 4.3° . This mean value (at 95% confidence level), when compared to the SV curves for inclination for Greece (Evans, 2006) (corrected) and the Balkan region (Tema and Kondopoulou, 2011) gives possible dates at ~1500 and ~1540 BC respectively, (Fig. 14a,b).

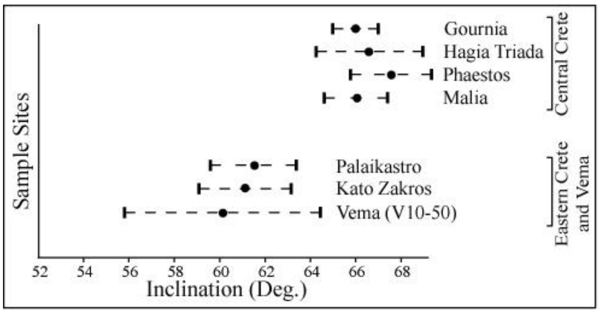

Figure 15. Palaeomagnetic inclinations for V10-50 and the two eastern Cretan sites. Four central Cretan sites are shown for comparison. All values are corrected for geographical location differences 'at Thessalonika'. The dotted lines indicate the error range (1σ).

The rapid increase in inclination at this time, confines the error range (time axis) using Evans Greek curve to ± 50 yrs but the error for the Balkan data is greater (Fig.14b).

The corrected V10-50 mean palaeomagnetic inclination is statistically identical (1σ) to values obtained from burnt mud-bricks from the Minoan sites at Katro Zakros (61.1° ± 1.9°) and Palaikaistro (61.6° ± 1.8°) in eastern Crete. The fire-destroyed central Cretan Minoan sites show inclinations that appear to be significantly steeper :- Malia (66.1° ± 1.4°), Gournia, (66.0° ± 1.0°), Hagia Triada, (66.6° ± 2.3°) and (Phaestos, 67.6° ± 1.7°), (Fig. 15).

All inclinations have been 'adjusted' to the geographical location at Thessalonika to facilitate comparison. The archaeomagnetic directions obtained for Cretan sites are given by Downey (2011) and Downey and Tarling (1984).

DISCUSSION AND CONCLUSION

The range of NRM intensities and susceptibilities observed in core V10-50 ash probably reflect the inhomogeneous distribution in the magnetic mineral concentration. Anisotropy of magnetic susceptibility results indicate an essentially, primary sedimentary fabric and hence a stable depositional environment for this deposit. The NRMs of pumice samples from Santorini also show a considerable range, epecially in the first phase Plinian air-fall pumices, however this range is much greater than that observed in the V10-50 ash deposits whose values appear to correlate more closely with those of Santorini sub-aerial ignimbrite. The NRM intensities and volume susceptibilities obtained for core V10-58 ash are lower than for V10-50, suggesting that the magnetic mineral concentration is probably lower. The diminished thickness of the V10-58 ash deposit, suggests a periodically erosional environment with transportation of some sediment which may have included magnetic detritus. The AMS results for V10-58 reflect a disturbance in the petrofabric suggesting a more active depositional environment, perhaps involving current activity and/or slumping. The decay of NRM to progressive AF demagnetization is similar for the ash in both cores, indicating that the coercivity spectra and MDF_{NRM} values are the result of a similar range in grains sizes and composition of the constituent titanomagnetites. No meaningful comparison between palaeomagnetic inclination values for ash layers A, B and C in core V10-50 could be made, as the number of suitable values which met the selection criteria ie., 'good' results, within each sub-division, is too low. In addition, volume susceptibility values are not definitive in separating the layers. From some magnetic results, it is likely that, the V10-50 and V10-58 deep-sea ash deposits originate from the Santorini 'final-phase' ignimbrite eruption from which co-ignimbrite (air-fall) ash was produced in large volume. However, the first phase air-fall (phreatomagmatic/ Plinian) eruption/s cannot, however be excluded as contributors to the ash layers in the cores on the basis of this palaeomagnetic evidence. The corrected mean palaeomagnetic inclination of 60.2° ± 4.3° is calculated assuming a 'single eruptive' event (or eruptions within short intervals of time). This value, when compared to the SV curves (inclination) for the Balkan region and for Greece, suggests that, the deep-sea ash in V10-50 and possibly V10-58, were deposited at ~1540 to 1500 BC. The V10-50 palaeomagnetic inclination is statistically identical to those obtained from archaeomagnetic results from the fire destruction sites at Katro Zakros and Palaikastro in eastern Crete. This suggests that the deep-sea ash deposits and fire destructions may have been contemporaneous or separated by a short interval of time.

ACKNOWLEDGEMENTS

The author thanks the Lamont-Doherty Earth Observatory (in particular Floyd McCoy) for supplying and allowing magnetic measurements on the Vema Minoan ash samples. Thanks also to the anonymous referees and to Phua Eng Siong, Nur Farah Tuah and Mdm Lim Yeely (University Brunei Darussalam) for technical assistance. The project was originally funded by the former Science and Engineering Research Council (UK).

REFERENCES

Anson, G.L. and Kodama, K,P. (1987). Compaction-induced Inclination Shallowing of the Post-depositional Remanent Magnetization in a Synthetic Sediment. *Geophys. J. R. Astr. Soc.* 88, 673-692.

Bond, A. and Sparks, R.S.J. (1976). The Minoan Eruption of Santorini, Greece. *J. Geol. Soc.*, 132, issue 1, 1-16.

Collinson, D.W., Molyneux, L. and Stone, D. (1963). A total and anisotropic magnetic susceptibility meter. *J. Sci. Inst.*, 49, 310-312.

Collombat, H., Rochette, P. and Kent, D.V. (1993). Detection and Correction of Inclination Errors in Deep-sea Sediments using the Anisotropy of Anhysteretic Remanence. *Geologique de France*, 164, 103-111.

Deamer, G.A. and Kodama, K.P. (1990). Compaction-induced Inclination Shallowing in Synthetic and Natural Clay-rich Sediments. *J. Geophys. Res.* 95, 4511-4530.

Downey, W.S. (2011). Archaeomagnetic Directional Determinations on Various Archaeological Materials from the Late Minoan Destruction Site at Malia, Crete. *Mediterranean Archaeology and Archaeometry*, Vol, 11, No. 1, 21-31.

Downey, W.S. and Tarling, D.H. (1984). Archaeomagnetic Dating of Santorini Volcanic Eruptions and Fired Destruction Levels of Late Minoan Civilization. *Nature*, Vol. 309, 519-523.

Downey, W.S. (1983). Magnetic Studies of Santorini Minoan Tephra and Cretan Archaeological Materials. *Ph.D Thesis, University of Newcastle upon Tyne, (Unpublished).*

Evans, M.E. (2006). Archaeomagnetic investigations in Greece and their bearing on geomagnetic secular variation. *Phy. Earth and Planet. Int.* 159, 90-95.

Federman, A.N. and Carey, S.N. (1980). Electron microprobe correlation of tephra layers from Eastern Mediterranean abyssal sediments and the island of Santorini. *Quaternary Research*, 13, 160-171.

Fisher, R.A. (1953). Dispersion on a sphere. *Proc. Roy. Soc. London. Ser. A*., 217, 295-305.

Florindo, F. and Sagnotti, L. (1995). Palaeomagnetism and rock magnetism at the upper Pliocene Valle Ricca (Rome, Italy) : Palaeomagnetic data. *Ann. Geofis*., 38, 177-178.

Francaviglia, V. and Di Sabatino, B. (1990). Statistical study on Santorini pumice falls.In: DA Hardy, J Keller, VP Galanopoulos, NC Flemming and TH Druitt (Eds), *Thera and the Aegean World* III, V.2, (Earth Sciences), The Thera Foundation, London, 29-52.

Friedrick, W.L. and Pichler, H. (1976). Radiocarbon dates of Santorini Volcanics. *Nature*, 262, 373-374.

Hamilton, N. and Rees, A.I. (1970). The use of magnetic fabric in palaeo-current estimations. In: *Palaeogeophysics* (Ed. S.K.Runcorn.), 445-464.

Huijsmans, J.P.P., Barton, M. and Salters, V.J.M. (1988). Geochemistry and evolution of the calc-alkaline volcanic complex of Santorini, Aegean sea Greece. *J. Volc. Geoth. Res*., 34, 283-306.

Hrouda, F. (1982). Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophysical Surveys*, 5, 37-82.

Ising, G. (1942). On the magnetic properties of varved clays. *Ark. Mat. Astr. Phys*., 29A, No.5, 1-37.

Jackson, M., Banerjee, S.K., Marvin, J., Lu, R. and Gruber, W. (1991). Detrital Remanence, Inclination Errors and Anisotropy of Anhysteretic Remanence: Quantitative Model and Experimental Results, *Geophys. J. Interat*. 104, 95-103.

Katiri, K., Tauxe, L. and King, J. (2000). A re-assessment of post-depositional remanent magnetism: preliminary experiments with natural sediments. *Earth Planet. Sci. Lett*., 183, 147-160.

Keen, M.J. (1963). The magnetization of sediment cores from the eastern basin of the North Atlantic ocean. *Deep sea Res*., 10, 607-622.

Keller, J. (1971). The major volcanic events in recent Eastern Mediterranean volcanism and their bearing on the problem of Santorini ash layers. *Acta. Int. Sci. Congress on the Volcano of Thera, Greece,* 152-167.

Keller, J. (1980). Prehistoric Pumice tephra in Aegean islands. *Thera and the Aegean World* II. (Ed. C. Doumas),The Thera Foundation, London, 49-56.

Keller, J., Ryan, W.B.F., Ninkovich, D. and Altherr, R. (1978). Explosive volcanic activity in the Mediterranean over the past 200,000 yr. as recorded in deep-sea sediments. *Geol. Soc. Am. Bull*., 89, 591-604.

King, R.F. (1955). Remanent magnetism of artificially deposited sediments. *Mon. Not. Roy. Astron. Soc*.,7, *Geophys. Suppl*., 115-134.

Kovacheva, M., Jordanova, N. and Karloukovski, V. (1998). Geomagnetic Field Variations as Determined from Bulgarian Archaeomagnetic Data. Part II: The Last 8000 years. *Surveys in Geophysics*, 19, 431-460.

Laughton, A.S. (1963). Microtopography in the Sea. Vol 3, (Ed. M.N. Hill) 437-472. Interscience, NY.

Lu, R., Banerjee, S.K. and Marvin, J. (1990). Effects of clay mineralogy and the electrical conductivity of water on the acquisition of depositional remanent magnetization in sediments. *J. Geophys. Res*. 95B, 4531-4538.

Lowe, D.J., Newnham, R.M. and McCraw, J.D. (2002). Volcanism and early Maori society in New Zealand. In: Natural Disasters and Cultural Change; Torrence, R. and Grattan, J. (eds.), Routledge, 126-16.

McCoy, F.W. (1980). The upper Thera (Minoan) ash in deep-sea sediments: Distribution and comparison with other ash layers. *Thera and the Aegean World* II, The Thera Foundation, London, 57-78.

McCoy, F.W. and Von Herzen, R.P. (1971). Deep-sea core-head camera photography and piston coring. *Deep-sea Res.* 18, 361-373.

McNish, A.G. and Johnson, E.A. (1938). Magnetization of unmetamorphosed varves and marine sediments. *Terr. Magn. Atmos. Elec*., 43, 401-407.

Mellis, O. (1954). Volcanic ash-horizons in deepsea sediments from the Eastern Mediterranean. *Deep Sea Res*, 2, 89-92

Molyneux, L. (1971). A complete result magnetometer for measuring the remanent magnetization of rocks. *Geophys. J.R. Astr. Soc*. 24, 429-434.

Nicolls, I.A. (1971). Petrology of Santorini Volcano, Cyclades, Greece. *Journal of Petrology,* 12, 67-119.

Ninkovich, D. (1978). Volume and extent of the Minoan tephra from Santorini Volcano: new evidence from deep-sea sediment cores. *Nature*, 271, 122-126.

Ninkovich, D. and Heezen, B.C. (1965). Santorini tephra. *Proceedings of the 17th symposium of the Colston Res. Soc.* Butterworth Scientific Publications. London: 413-453.

Ninkovich, D. and Heezen, B.C. (1967). Physical and chemical properties of volcanic glass shards and Pozzoulana ash, Thera. *Nature*, 213, 582-584.

Noel, M. and Batt, C.M. (1990). A method for correcting geographically separated remanence directions for the purpose of archaeomagnetic dating. *Geophys. J. Int.* 102, 753-756.

Noltimier, H. C. (1967). Use of the spinner magnetometer for anisotropy measurements. In: D.W.Collinson, K.M. Creer and S.K. Runcorn, (eds), Methods in Palaeomagnetism. Elsevier, Amsterdam, (1971), 309-402.

Olausson, E. (1960). Descriptions of sediment cores from the Mediterranean and Red sea. *Rep. Swed. Deep Sea Exped*., 8, 286-334.

Olausson, E. (1961). Studies of deep sea cores. *Rep. Swed. Deep Sea Exped*. 8, 335.

Opdyke, N.D. and Henry, K.W. (1969). A test of the dipole hypothesis. *Earth. Planet. Sci. Lett*., 6, 139-151.

Opdyke, N.D., Ninkovich, D ., Lowrie, W. and Hayes, J.D. (1972). The palaeomagnetism of two Aegean deep sea cores. *Earth Planet. Sci. Lett.,* 14, 145-159.

Pichler, H. and Schiering, W. (1977). The Thera eruption and Late Minoan-IB destructions on Crete. *Nature*, 267, 818-822.

Pyle, D.M. (1990). New estimates for the volume of the Minoan eruption. *Thera and the Aegean World III,* V. 2 (Ed Hardy DA) The Thera Foundation, London, 113-121.

Rees, A.I. (1965). The use of anisotropy of magnetic susceptibility in the estimation of sedimentary fabric. *Sedimentology*, 4, 257-271.

Rees, A.I. and Frederick, D. (1974). The magnetic fabric of samples from the deep-sea drilling project, leg 1-6. J. *Sedim. Petr*., 44, 655-662.

Riley, C.M., Rose., W.I. and Bluth, G.J.S. (2003). Quantitative shape measurements of distal volcanic ash. *J. Geophys. Res.,* Vol. 108, No. B10, 2504 -2519.

Roberts, A.P. (1995). Magnetic characteristics of sedimentary greigite (Fe_3S_4). *Earth Planet. Sci. Lett*., 134, 227-236.

Roberts, A.P. and Weaver, R. (2005). Multiple mechanisims of remagnetization involving sedimentary greigite (Fe_3S_4). *Earth Planet. Sci. Lett*., 231, 263-277.

Roberts, A.P., Chang, L., Rowan, C.J., Horng, C-S. and Florindo, F. (2011). Magnetic Properties of Sedimentary Greigite (Fe_3S_4): An Update. *Reviews In Geophysics*, 49, Issue 1. RG1002.

Robertson, P.H. and Hastie, L. (1962). A palaeomagnetic study of the Cygnet Alhalmi complex of Tasmania. *J. Geol. Soc. Australia*, 8, 259-268.

Rowan, C.J., Roberts, A.P. and Broadbent, T. (2009). Palaeomagnetic smoothing and magnetic enhancement in marine sediments due to prolonged early diagenetic growth of greigite. *Earth Planet. Sci. Lett*., 277, 223-235.

Ruddiman, W.F. and Glover, L.K. (1972). Vertical mixing of ice-rafted volcanic ash in North Atlantic sediments. *Geol. Soc. Amer. Bull.*, 83, 2817-2

Skinner, L.C. and McCave, I.N. (2003). Analysis and modeling of gravity and piston coring based on soil mechanics. *Marine Geology*, v.199, 181-204.

Sparks, R.S.J. and Huang, T.C. (1980). The volcanological significance of deep-sea ash layers associated with ignimbrites. *Geol. Mag*., 117, 425-436.

Sparks, R.S.J. and Wilson, C.J.N. (1990). The Minoan deposits: a review of their characteristics and interpretation. In: Hardy, D., Keller, J., Galanopoulos V.P., Flemming, N.C., Druitt T.H.(Eds). *Thera and the Aegean World* III, V.2. The Thera Foundation, London, 89-99.

Sparks, R.S.J., Self, S. and Walker, G.P.L. (1973). Products of Ignimbrite Eruptions. *Geology* 1, 115-118.

Sparks, R.S.J. and Walker, G.P.L. (1977). Significance of vitric-enriched air-fal ashes associated with crystal-enriched ignimbrites. *J. Volc. Geoth. Res*., 2, 329-341.

Steele, W.K. (1981). Remanent magnetization of ash from the 18 May 1980 eruption of Mount St.Helens. *Geophysical Research Letters*, 8, No.3, 213-216.

Stober, J and Thompson, R. (1979). Magnetic remanence acquisition in Finnish lake sediments, *Geophys. J.R.Astr. Soc.* 57 727-739.

Tarling, D.H. and Symons, D.T.A. (1967). A stability index of remanence in palaeomagnetism. *Geophys. J. Roy. Astron. Soc.* 12, 443-448.

Tema, E. and Kondopoulou, D. (2011). Secular variation of the Earth's magnetic field in the Balkan region during the last eight millennia based on archaeomagnetic data. *Geophys. J. Int.* 186, 603-614.

Thorarinsson, S. (1954). The tephra fall from Heckla on March 29, 1947. The Eruption of Heckla, S*oc. Sci. Islandica*, 11, 3-71.

Thorarinsson, S. (1958). The Oreafajokull eruption of 1362. *Acta nat.Islandica*, 2, 1-100.

Vasilatos, Ch., Vlachou-Tsipoura, M. and Stamatikis, M.G. (2010). On the Occurrence of a Volcanic ash layer in the Xylokastro area, North Peloponnesus, Greece: *Mineralogy and Geochemistry. Bull. Geol. Soc. Greece*. XLIII, No.5, 2773-2784.

Verosub, K.L. (1977). Depositional and post depositional processes in the magnetization of sediments. *Rev. Geophys. Space Phys*.15, 129

Vitaliano, C.J., Fout, J.S. and Vitaliano, D.B. (1978). Petrochemical Study of the Tephra Sequence Exposed in the Phira Quarry.*Thera and the Aegean World* II, (Ed.), C. Doumas The Thera Foundation, London, 203-215.

Vitaliano, D.B. and Vitaliano, C.J. (1978). Tephrochronological Evidence for the Time of the Bronze Age Eruption of Thera. *Thera and the Aegean World* II, (Ed.), C. Doumas. The Thera Foundation, London, 217-219.

Vitaliano, C.J., Taylor, S.R., Norman, M.D., McCullogh, M.T. and Nicholls, I.A. (1990). Ash layers of the Thera volcanic series: stratigraphy, petrology and geochemistry. In: D.A Hardy., J. Keller., V.P. Galanopoulos., N.C.

Flemming. and T.H. Druitt. (Eds) , *Thera and the Aegean World* III, V.2, (Earth Sciences), The Thera Foundation, London, 53-78.

Watkins, N.D., Sparks., R.S.J., Sigurdsson, H., Huang, T.C., Federman, A., Carey, S. and Ninkovich, D. (1978). Volume and extent of the Minoan tephra from Santorini Volcano: new evidence from deep-sea sediment cores. *Nature*, 271,122-126.

Wentworth, C,K. (1922). A scale of grade and class terms for clastic sediments. *Jour. Geol.* 30, 377-392.