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The efficacy of travertine as a palaeoenvironmental indicator: palaeomagnetic study of neotectonic examples from Denizli, Turkey

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Abstract: This study has aimed to evaluate whether a discernible environmental signature is recorded in tectonic travertine by applying palaeomagnetic study to examples from the Denizli region in western Turkey. Palaeomagnetic sampling in 7 quarry exposures through short stratigraphic intervals of bedded travertine has determined variations in magnetic susceptibility and palaeofield direction; the former is a potential proxy of climatically-controlled atmospheric dust input and the latter is a possible indicator of directional changes resulting from geomagnetic secular variation of the ancient magnetic field and hence a measure of the rate of travertine accretion. Most sites record normal polarity as predicted from emplacement during the Brunhes Chron, although one had reversed polarity evidently imparted during the Matuyama Chron and confirming longer-term preservation of remanence. A few sites with coherent directions widely different from the recent field axis appear to have slumped or tectonically rotated since emplacement. Within-section groupings of palaeomagnetic directions are tight with lack of dispersion indicating that secular variation has been averaged over protracted periods of time. Magnetic remanence is therefore a diagenetic phenomenon, as expected from prolonged infiltration through porous bedded travertine. Magnetic susceptibilities are mostly very weak and dominated by the diamagnetic host, but some positive values record paramagnetic and ferromagnetic constituents. We find that environmental signatures may be revealed in bedded travertine by magnetic susceptibility. Palaeomagnetic directions provide no reliable constraint on incremental growth although fissure emplacements, including an additional example reported in this study, can record a short-term record of secular variation and yield estimates for the duration of fissure activity. In contrast the tufa-like deposits laid down by geothermal waters spilling out at the surface are highly porous and susceptible to later fluid seepage and only atmospheric dust landing on the surface can potentially record environmental effects. Isotopic and palaeomagnetic systems are homogenised over long intervals of time and unable to record short-term near-surface changes.

Key Words: Travertine, Denizli, Pamukkale, Palaeomagnetism, Magnetic susceptibility, Environmental signature

1. Introduction

Environmental changes caused by mankind and natural climatic cycles have been a major focus of academic study in recent years. Evaluating and explaining these changes, and then forecasting how they might change in the future are key to planning for the future. An evaluation on times scales longer than historic relies primarily on the products of continuous sedimentation, and the search continues for sediments containing a record of environmental change accumulated during time intervals of hundreds to thousands of years. Travertine, the product of quasi-continuous carbonate deposition from groundwater, is recognised as a potential recorder. This is most favourably the case when deposition has been promoted by regional tectonic and magmatic activity. The latter examples are a consequence of 'travitonics' as defined by Hancock *et al.* (1999) and are the specific focus of the present study.

Although there are many definitions of travertine in the literature, the differences between them are small. Thus, according to Guo *et al.* (1998), *"Travertines are limestone formed where hot ground waters, rich in calcium and bicarbonate, emerge at springs. Carbon dioxide outgassing results in rapid precipitation and the resulting deposits are both locally restricted and internally complex."* Chafetz and Folk (1984) defined travertine as *"a form of "freshwater" carbonate deposited by inorganic and organic processes from spring waters."'* According to the definition by Julia (1983) travertine is an *"accumulation of calcium carbonate in springs (karstic, hydrothermal), small rivers, and swamps, formed mainly by incrustation (cement precipitation and/or biochemical precipitation)."*

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Altunel and Hancock (1993) concluded that morphology is the most suitable criterion for classifying travertine. Following their investigations of the Pamukkale (Denizli) travertine, they added three new types to the morphological classification of Chafetz and Folk (1984). When travertine deposition is tectonically controlled (fissure-ridge type) the axial crack direction, length, and width yield key data linking formation of the travertine to the tectonic regime impacting the region. Fissure-ridge type travertines occur in two settings (Figure 1). The material deposited within the feeding fissure or orifice (usually episodically pulsed in the case of tectonic travertine) is fissure travertine and it accumulates layer by layer, typically as a compact deposit with little or no porosity. In contrast, waters which reach the surface disperse by seeping over a usually rough substrate that is typically a site of active organic activity. This bedded precipitate has a complex porous texture, often friable enough to be classed as tufa, and it may incorporate falling atmospheric debris including wind-blown dust from seasonal winds and products of volcanic fallout. Such material usually contains a fraction of ferromagnetic minerals, usually magnetite, hematite or goethite, which can potentially provide a magnetic signature amenable to laboratory study.

The efficacy of fissure travertine as a recorder of temporal changes in magnetic susceptibility and remanence has been demonstrated in the Sıcak Çermik geothermal field in central Turkey (Piper *et al.* 2007). However, this material was not open to the surface at the time of precipitation and, although variations are present which are likely to record fluctuations in meteoric water flow, and hence pluvial input, the link is an indirect one and cannot be effectively dated. The main objective of the present study has therefore been to evaluate the potential of the magnetic record in bedded travertine which would formerly have had direct access to the atmosphere. We have conducted the study primarily at seven clean quarry exposures within the classic travertine of the Pamukkale region at Denizli in western Turkey.

2. Geological Framework

Şengor (1980) classified Turkey into three main neo-tectonic regions, comprising the Aegean graben extensional regime in the west, a plain ('ova') region in the centre, and an Anatolian compressive regime in the east (Figure 2a). The Denizli Basin is located within the former and near to the triple rift arm intersection where two wings of the Great Menderes Graben connect with the Gediz Graben (Figure 3). The basin, 50 km long and 20 km wide, is surrounded by active normal faults along the northeast and southern margins (Figure 2b).

The rocks within the rifted basin and its margins fall into two broad divisions: pre-Neogene basement rocks and post-Neogene cover units (Özkul et al. 2002, Altunel 1996, Kaymakçı 2006). Metamorphic rocks comprising the basement were first defined by Hamilton and Strickland (1840) and the term 'Menderes Massif' was applied by Paréjas (1940) to include Palaeozoic schists and marbles exposed in the Denizli Basin. Rocks post-dating the metamorphic massif comprise Mesozoic limestone, dolomite, evaporites, ophiolites and Palaeogene limestone.

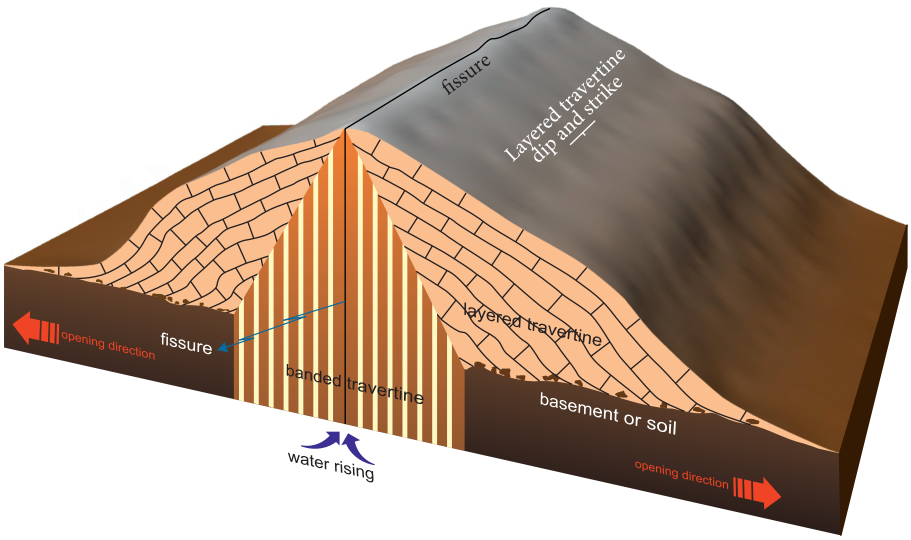

Figure 1. The mode of formation of a travertine mound above an extensional fissure (modified after Mesci 2004).

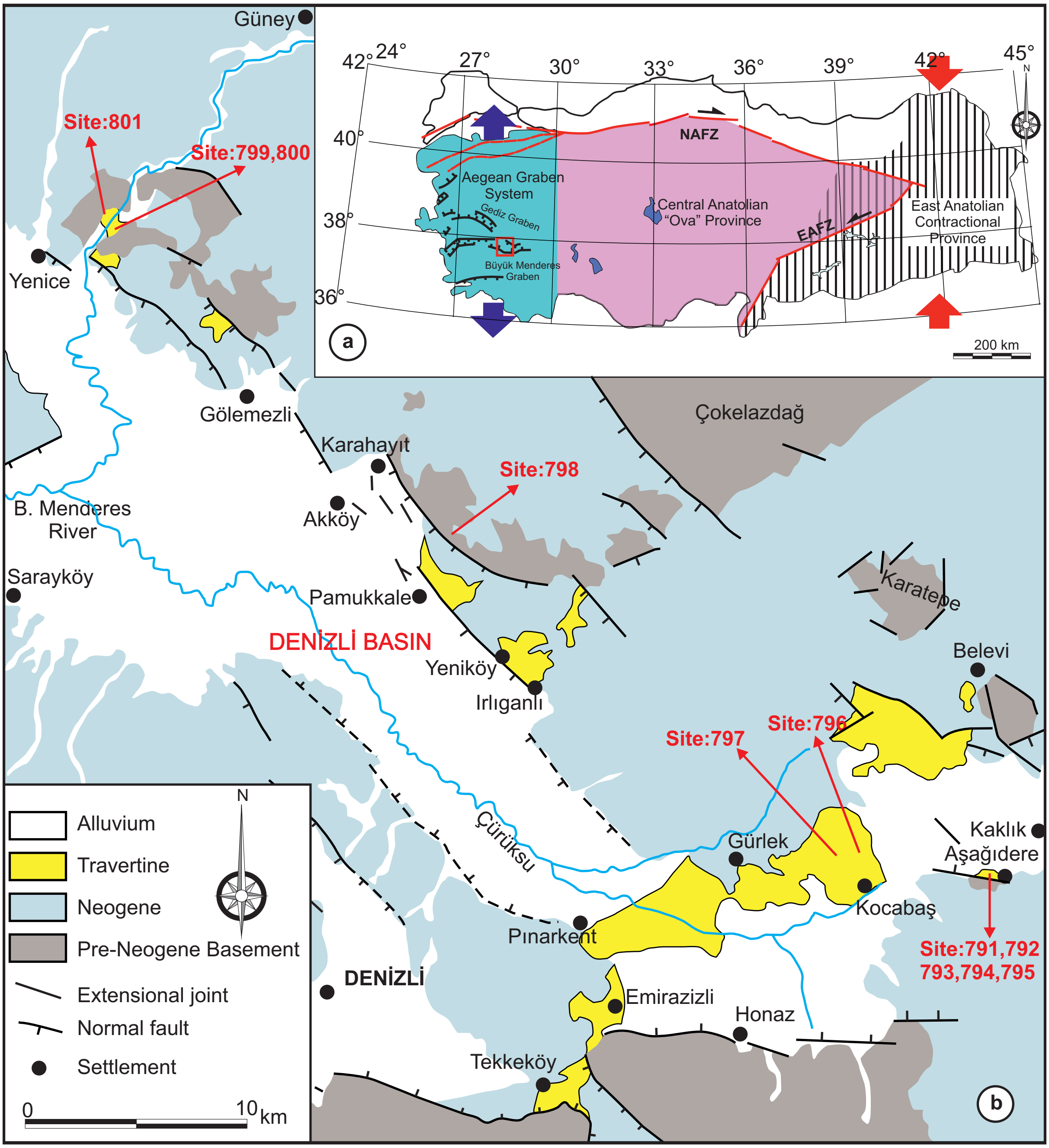

Figure 2. Outline neotectonic features of western Turkey after Şengör *et al.* (1985). **(a)** Major elements of the Aegean graben system and **(b)** location of the Denizli basin and palaeomagnetic sampling locations in travertine from the Denizli region (modified after Sun, 1990).

Post-Neogene cover rocks comprise conglomerates, sandstones, and limestone on which are deposited Quaternary alluvium and travertine (Figure 2b). The location of the Denizli Basin within the Aegean graben system (Figure 2a) and the fault surface system indicate that this region is currently under north-south directed tension (McKenzie, 1972) and up to 50% extension is identified from fault edge geometries and listric graben sections (Şengör 1980).

Koçyiğit (2005) showed that the Denizli Basin developed on metamorphic rocks of the Menderes Massif, the Lycian nappes and an Oligocene-Lower Miocene cover sequence. He concluded that the basin evolved episodically rather than continuously, as indicated by: (1) the inclusion

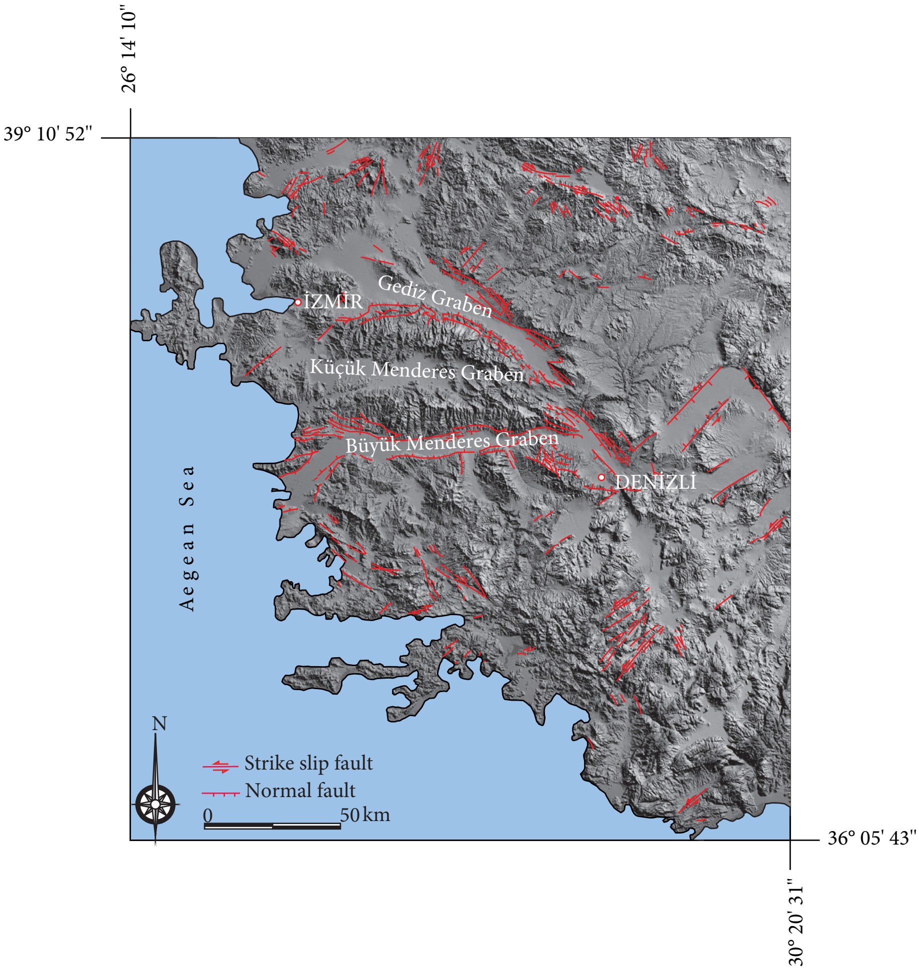

Figure 3. Active fault map of western Turkey superimposed on to a SRTM image (modified after Şaroğlu *et al.* 1992).

of two graben infills with an ancient infill separated from the modern infill by angular unconformity; (2) the ancient graben infill comprising two Middle Miocene-Middle Pliocene sequences 660m thick accumulated in a fluvio-lacustrine depositional setting controlled firstly by NNW-SSE- and latterly by NNE-SSW-directed extension (first-stage extension). It was then deformed by folding and strike-slip deformation resulting from NNE-SSW to ENE-WSW-directed compression in late Middle Pliocene times. In contrast, the modern graben infill consists of a 350-m thick, undeformed (except for locally against the margin-bounding active faults) succession of nearly flat-lying fan apron deposits and travertines of Plio-Quaternary age; (3) the ancient graben infill is confined not only to the interior of the graben, but is also exposed well outside whereas the modern graben infill is restricted to the interior. Both the southern and northern margin-bounding faults of the graben horst system are oblique-slip normal faults with minor right- and/or left-lateral strike-slip components. The faults bounding the Denizli Basin are still active and have a potential seismicity with magnitudes 6 or higher.

Denizli travertine has been the subject of numerous investigations. Important contributions include studies of their cement value (Özkuzey 1969) and their geothermal potential in the Dereköy region (Erişen 1971). Canik (1978) investigated the relationship between hot waters and travertine formation and Özkul *et al.* (2002) studied petrographic aspects. Koçyiğit (1984) and Okay (1989) focused attention on their tectonic significance within the framework of graben rifting in southwest Turkey. Specific neotectonic implications of the Pamukkale travertines were reported by Altunel and Hancock (1993, see also Altunel 1996 and Çakır 1999). According to Çakır (1999) fissures supplying the carbonate-rich waters to produce the travertines develop preferentially at the ends of fault segments or in extensional step-over zones where offset between fault strands is 1 km or more. The deposition of travertines in such structural settings is probably a consequence of the supply of carbonate-rich waters from highly interconnected networks of fissures within zones of complex extensional strain (Altunel and Hancock 1993, Hancock *et al.* 1999). The primary tectonic focus of these studies was complemented by Kaymakçı (2006) who used kinematic and palaeostress data to interpret the tectonic evolution of the Denizli Basin. Further to these investigations, Kappelman *et al.* (2008) have described a *Homo erectus* fossil discovered in 2002 by workers in one of the travertine quarries.

2.Palaeomagnetic study

2.1. The field sample

Altunel (1996) classified travertines in the Denizli region using morphological criteria comprising terrace-type, fissure-ridge type, eroded-sheet travertines, range-front travertines, and self-build channel types. Travertine localities of terrace-type excavated by quarrying occur inside the Denizli Basin and distributed from northeast of Yenice towards Pamukkale, Yeniköy and Kocabaş in a southwest direction (Figure 2b). Within these travertine formations 12 sites in 5 regions (Yenice, Pamukkale, Yeniköy, Kocabaş, and Aşağıdere) were investigated; 183 cores approximately 10 cm in length and 2.4 cm in diameter were obtained by coring using motorised hand-held drills and oriented by Sun and magnetic compasses (Table 1, Figure 2b); this collection was supplemented by a number of oriented hand samples. Field numbers of the sites are 791-801 with numbers 791-799 referring to sites in layered travertine and sites 800 and 801 to travertine fissures.

2.2. Palaeomagnetic results

Magnetic susceptibilities in the bedded travertine are mostly dominated by the diamagnetic host (section 3.3) and remanent magnetisations are very weak. Furthermore the carbonate comprising the cores is poorly cemented and seldom remains coherent at temperatures above 300°C. Accordingly alternating field (a.f.) demagnetisation was the primary method used for standard demagnetisation to resolve magnetic component structures and a total of 198 cores from sites 791-800 were treated in this way. Site 801 is in a young travertine fissure characterised by precipitation of silica and hematite, and this more lithified material was amenable to heating, with 44 samples treated by thermal demagnetisation; 22 of these samples were taken perpendicular to the fissure axis to evaluate the magnetic effects of incremental growth. Magnetisations in most of these samples were weak and measured by a nitrogen SQUID (FIT) magnetometer. Representative results from the layered travertine are shown in Figure 4, with progressive results plotted as conventional orthogonal projections and progressive loss of remanence also illustrated as graphs of magnetisation against applied alternating field.

The demagnetisation results show stable behaviours in a dominance of low coercivity components at sites 791-795 from quarries in the Asağıdere region. These converge to the origin of the orthogonal projections following the first step or two of a.f. treatment. Components of magnetisation were resolved from visual inspection of orthogonal projections and directions calculated by Principal Component Analysis (PCA). Site mean results are summarised in Table 2.

The sampling region is located at 28.7°E, 37.8°N where the geocentric axial dipole source predicts a mean geomagnetic dipole field axial direction of D/I =0/+57° and 180/-57°. Sites 791-794 have directions close to the present field and magnetisations are assigned to the Brunhes Normal Chron. Site 797 is of uniform reversed polarity and was presumably magnetised in the preceding Matuyama Reversed Chron consistent with the age inferred from field evidence (Table 1). Site 795 yields some normal polarity directions (Figure 4) but components are mostly dispersed and no mean direction is calculated for this travertine. The sites 796, 798, 799 and adjoining fissure 800 typically yield tight groupings of directions but the means are not readily related to the present geomagnetic field direction. In view of consistent within-site behaviours it seems likely that these sites have been rotated away from the present geomagnetic field axis although the specific causes could not be confirmed at outcrop. In the case of sites 799/800 hill slump is likely because these are sited in an old quarry located on a slope; fault block rotation may be applicable to the other examples. Whilst within 95% confidence bounds, magnetic inclinations at all localities except the reverse polarity site 797 are shallower than the predicted dipole field inclination (57°) at this latitude. This inclination-shallowing effect is ubiquitous in bedded materials and its presence here is predictable.

To evaluate whether the bedded travertine at Denizli is a faithful recorder of the secular variation of the geomagnetic field we need to compare the dispersion of recorded directions with those expected from progressive sampling of the geomagnetic field. The dispersions are summarised in Table 3 in terms of the angular standard deviations of the directional distributions (S_{63}). The lower and upper limits (S_L and S_u) on these deviations are after Cox (1969). We observe that the directional distributions in the layered travertine are significantly less than values expected from the short term sampling of secular variation in Late Tertiary times (McFadden *et al.* 1991); only site 792 shows marginal statistical overlap with values expected. This implies that these bedded travertines have been subjected to pervasive diagenesis as they became cemented and lithified; as a result their magnetisations have been integrated over protracted periods of time and therefore fail to adequately record the ancient secular variation.

Table 1. Sampling locations of Travertine Deposits in the Denizli region.

Region	Site No.	Latitude (UTM)	Longitude (UTM)	L/N	Age	Bedding Tilt (Dip/Direction °E)
Aşağıdere	791	4187646 N	35 710255 E	8/18	Quaternary	14/6
	792	4187646 N	35 710255 E	5/11	Quaternary	14/6
	793	4187646 N	35 710255 E	6/12	Quaternary	14/6
	794	4187646 N	35 710255 E	3/6	Quaternary	14/6
	795	4187601 N	35 710147 E	10/20	Quaternary	14/6
NNW of Kocabaş, Kaklık Quarry	796	4192499 N	35 706869 E	10/23	Mio-Pliocene*	~9/145
	797	4193521 N	35 705205 E	14/34	Mio-Pliocene*	Horizontal
West of Pamukkale	798	4201172 N	35 687662 E	16	223-185 Ka (Altunel, 1994)	64/220
NE of Yenice	799	4213789 N	35 673200 E	14/35	Quaternary	12/270
	800	4213789 N	35 673200 E	8	Quaternary	12/270
	801	4213962N	35672964 E	5/44	Quaternary	76/110

Footnote: *L/N – Number of layers/Number of separately-drilled cores. *These sites are intercalated with fine grained siltstones, sandstones and marls of probable lacustrine origin and are referred to an Upper Miocene-Pliocene age on the MTA geological map of the Denizli sheet; other general ages are inferred from geological setting.*

Magnetic properties of the travertine fissure at 801 have been studied away from the axis of the fissure to evaluate possible temporal changes reflecting progressive incrementation following the procedure adopted by Piper *et al.* (2007). Two long cores drilled in large oriented block samples perpendicular to the axis permit a comparison (Figure 5). The magnetisations in these cores have low temperature spectra largely unblocked by 400°C (Figure 5) with northerly positive-directed components. The directional dispersion here is compatible with that expected from a record of secular variation unlike the remaining sites of this study (Table 3). Hence it is likely that that progressive deposition of travertine on either side of the fissure has recorded a successive record of the geomagnetic field direction. There proves to be a sympathetic, albeit imperfect, record of directional and intensity change away from the axis of the fissure with decline in intensity of magnetisation and some mirroring of changes in inclination and declination of the magnetisation (Figure 5).

3. Variability of Magnetic Susceptibility

Measurements of magnetic susceptibility were performed on the samples using a Kappabridge. Magnetic susceptibility measures the response to an applied magnetic field and is negative for the diamagnetic minerals (lacking transition elements) and positive for paramagnetic and ferromagnetic minerals; positive values are thus applicable to the iron-bearing silicates, iron oxides and sulphides with ferromagnetic grains including magnetite and hematite yielding much higher positive values. Figures 6 and 7 display the results of magnetic susceptibility measurements obtained from the Denizli layered travertines (together with field photographs) as a function of distance above the base of the short sampled sections. Whilst susceptibility values frequently display negative values dominated by the diamagnetic carbonate, some samples show positive values evidently caused by accumulation of ferromagnetic and paramagnetic dust, and suggesting a potential environmental signature. The susceptibility of the weak ferromagnetic component detected by magnetometer is evidently suppressed in the bulk samples by the dominant diamagnetic host.

4. Discussion

We find that a weak stable palaeomagnetic record of the ambient field is recorded in most of the layered travertine from the Denizli Basin and the evidence from the single reversed polarity site shows that this remanence is able to survive with minimal overprinting for hundreds of

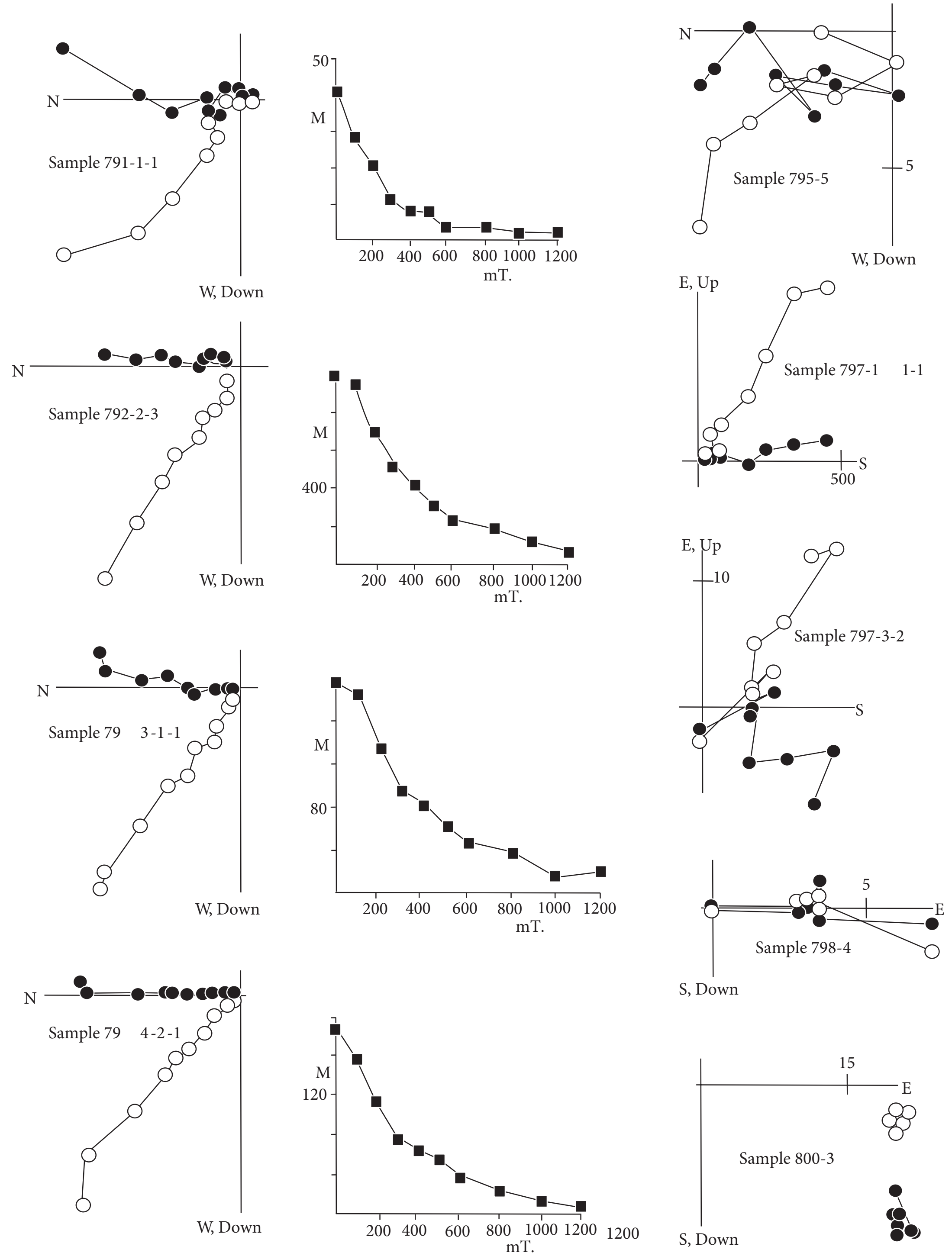

Figure 4. Examples of progressive demagnetisation behaviours of the Denizli travertine shown as intensity plots and orthogonal vector plots with magnetisations projected onto horizontal (closed symbols) and vertical planes (open symbols). Magnetisations are $x10^{-5}$ $A.m^2/kg$ and demagnetisation steps are in 5mT (milliTesla) steps to 50mT followed by 10 mT steps to variable peak fields up to 140mT. Note that most samples demagnetise effectively with a.f. treatment although 800-3 is an example of high coercivity remanence residing in hematite or goethite where this method is unable to significantly subtract the magnetism.

Table 2. Group Mean Palaeomagnetic results from Denizli Travertine Sites.

Site No.	D	I	D’	I’	N	R	a_{95}	k
791	346.9	53.6	351.3	40.2	16	15.77	4.6	65.5
792	4.5	50.0	4.8	36.0	11	10.46	10.9	18.5
793	6.3	54.9	6.2	40.9	11	10.85	5.6	67.9
794	7.9	50.3	7.5	36.3	19	18.65	4.7	51.8
795	No coherent groupings recognised							
796	178.8	12.4	178.1	4.9	11	10.90	4.6	98.7
797	165.3	-60.1	165.3	-60.1	30	29.59	3.1	70.8
798	87.4	1.5	109.6	38.3	11	10.66	8.6	29.1
799	73.3	17.8	29.3	71.7	31	30.84	1.9	190.9
800**	112.2	14.2	113.8	25.3	7	6.915	7.2	70.5
801**	5.6	37.1	5.6	37.1	31	29.02	6.9	15.2

Footnote: *D(D’) and I(I’) are the mean declination and inclination derived from N sample components before (after) tilt adjustment. The length of resultant vector is R, the cone of 95% confidence about the mean direction is* $a_{95;}$ *k is the Fisher precision parameter (=(N-1)/(N-R)). **Fissure travertine.*

thousands of years. However, when stable remanence has been imparted it typically exhibits tight clustering of magnetic components to produce dispersions that have not faithfully recorded secular changes in the geomagnetic field. Where bedded travertines are accumulating on the surface at the present day the textures are typically highly porous with the characteristics of tufa. The geothermal waters flowing out from the feeder fissures wash over these surfaces and progressively sink away into the underlying material. Hence bedded travertine is exposed to diagenesis linked to prolonged infiltration, cementation and compaction which has evidently imparted magnetism over prolonged periods of time. Since the travertine deposit retains degrees of porosity at depth, the magnetic remanence recorded in centimetre-size cores is therefore an integrated effect recording at least hundreds of years of seepage and is not amenable to recording a short-term environmental signature.

The source of the magnetic remanence is not readily discerned. In the case of bedded travertine it is expected to be primarily atmospheric dust, although this will be flushed by the water seepage and, since the fissure travertine also contains some ferromagnetism, magnetic material must be carried up in the geothermal waters. The magnetic susceptibility measurements identify the influence of the dominant diamagnetic carbonate in the travertine. Although this diamagnetism is very weak, it is the primary control on bulk susceptibility because the carbonate host completely dominates the tiny fraction of ferromagnetic constituent. Local positive values are presumably the record of significant inputs of magnetic dust and a further example of this from the Sıcak Çermik field is illustrated in Piper *et al.* (2007). In fissure travertines the secondary micritic calcite is essentially confined to single layers on a millimetre scale and suggests that diagenetic alteration is confined to single layers and is of short duration. It may be for this reason that the fissure travertines preserve a record of palaeomagnetic direction changes analogous to secular variation (Piper *et al.* 2007) whereas the bedded travertines of this study from Denizli do not. The single fissure from Denizli (801), where progressive change in magnetic properties could be evaluated away from the feeder axis as in the Sıcak Çermik examples, shows lateral changes in direction and dispersion of these directions compatible with secular variation: the sympathetic directional changes on either side of this fissure axis appear to record between one and two variation cycles (Figure 5). Studies on other Holocene materials, notably lake sediments, suggest that such cycles typically last between one and two thousand years (e.g. Butler 1992).

An implication of petrographic study of these travertines is the recognition of widespread (bedded travertine) or much more restriceted (fissure travertine) diagenesis. The prominent variegated colour banding in the

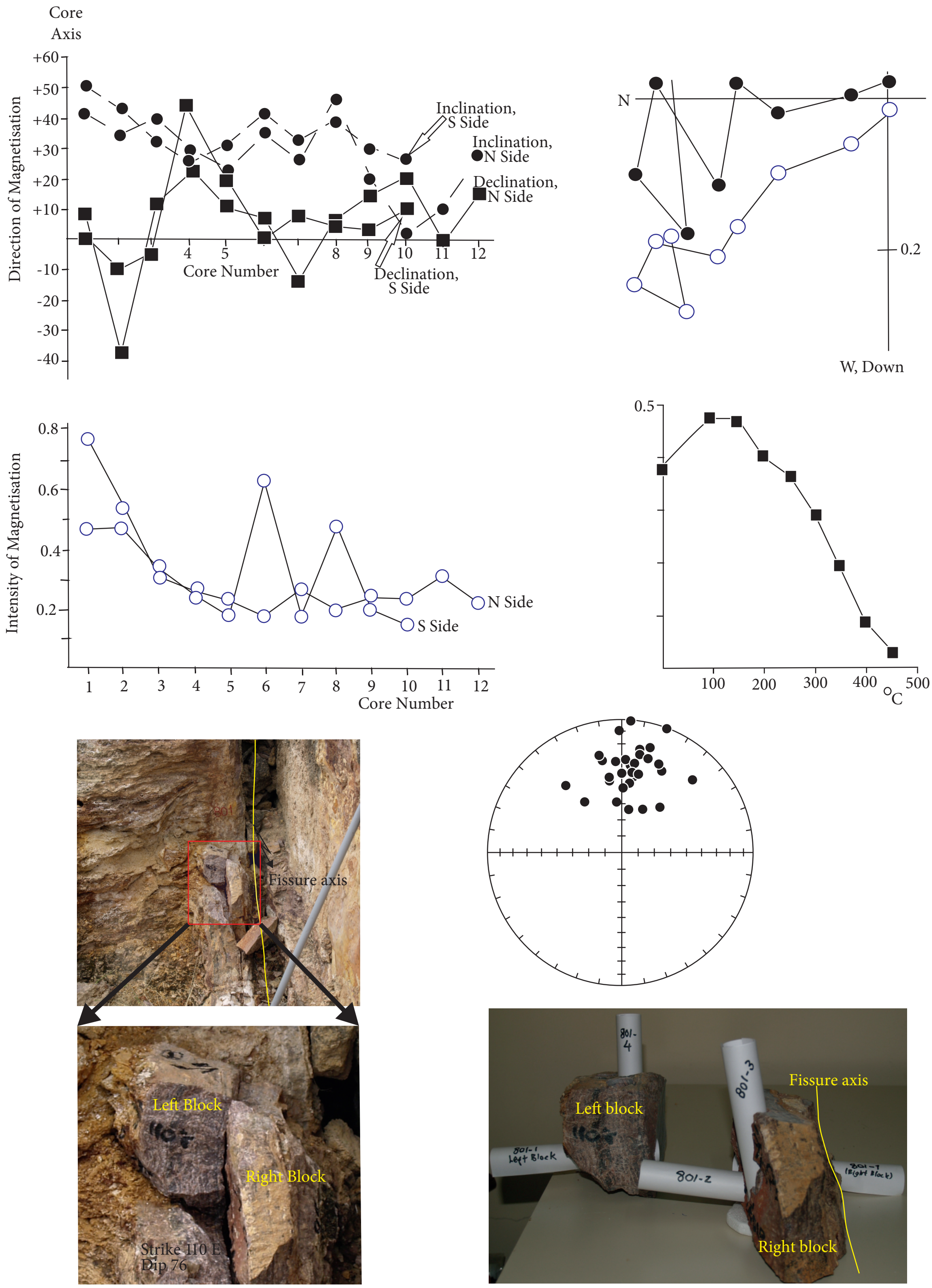

Figure 5. Magnetic intensity, declination and inclination change away from the axis of the travertine fissure at site 801; left block is north side and right block is south side. A typical orthogonal plot and intensity change with progressive thermal demagnetisation are also shown together with the distribution of component directions (the latter including results from cores drilled parallel to the fissure axis). The photograph shows the block samples with cores drilled from them. Magnetisation intensities are x10^{-5} A.m^2/kg and symbols on the orthogonal plot are as for Figure 4.

Table 3. VGP Dispersion for palaeomagnetic results from the Denizli Travertine sites expressed in terms of 95% confidence limits on the angular standard deviations.

Site No.	N	Pole Position (°E, °N)		S_{63}	S_L	S_U
791	16	238	74	10.00	7.99	13.38
792	11	196	72	18.83	14.71	26.20
793	11	186	75	9.83	7.68	13.67
794	19	186	71	11.25	8.07	14.41
796	11	32	-50	8.15	6.37	11.34
797	30	320	78	9.63	8.17	11.72
798	11	90	-1	15.02	11.73	20.89
799	31	65	63	5.86	4.98	7.13
800	7	12	-1	9.64	7.19	14.68
801	31	191	73	20.77	17.64	25.28
Reference Field 5-22.5 Ma, 40-50° latitude				21.2	20.0	22.6
Reference Field 22.5-45 Ma, 30-40° latitude				14.7	12.9	17.0

Footnote: *Upper and lower limits to* S_{63} *are calculated from the table in Cox (1969). The reference field values from McFadden* et al. *(1991) show the expected dispersions as determined from selected palaeomagnetic data within the time limits indicated. Sites 800 and 801 are in fissure travertine.*

latter examples, often on a sub-millimetre scale, is found to comprise alternating metastable aragonite, presumably of primary origin and calcite of presumed secondary diagenetic origin. This discovery implies that U-Th series dating conducted on this material up to the present time is unlikely to be reliable and is specifically doubtful in highly homogenised bedded travertine. This is highlighted by the conflicting duration estimates of travertine fissure emplacement in the Sıcak Çermik fissures from central Turkey (Piper *et al.* 2007, Mesci *et al.* 2008): U-Th dating of internal and external parts of fissures here suggests that activity from single fissures could have lasted for tens of thousands of years (Mesci *et al.* 2008); in contrast the apparent record of just 1-2 secular variation cycles at Sıcak Çermik (Piper *et al.* 2007) in the same fissures (and at site 801 from Denizli) indicates that single fissures are never active for more than a few thousand years. In the case of the fissure travertine, dating should therefore in future be conducted on material carefully extracted from aragonite bands since the calcite bands are products of the diagenesis and also contain impurities reflected in the colour signature. Only by controlled selection of material from individual bands will it be possible to constrain the duration of active fissure deposition from U-Th dating of the interior and outer parts of travertine fissures.

5. Conclusions

Examination of magnetic susceptibility in 7 short stratigraphic sections through bedded tectonically-forced travertine from the Denizli basin in SW Turkey shows small variations dominated by the diagenetic carbonate host. However, weak but stable ferromagnetism is also present in most samples and the local preservation of reversed magnetism from the Matuyama Chron is evidence for long-term stability. The stable components of magnetisation resolved from stepwise a.f. demagnetisation are tightly-grouped and do not show dispersions anticipated from a record of secular variation. The magnetism in these travertines is therefore interpreted as a long-term diagenetic phenomenon. Two travertine fissures from this area have been investigated, with one yielding stable results showing systematic variation in properties away from the fissure axis, apparently recording the signature of between one and two cycles of secular variation. This supports palaeomagnetic studies of similar fissures in central Turkey implying that individual travertine fissures are active for no more than a few thousand years. The ferromagnetic constituents in bedded travertine may result predominantly from atmospheric dust although the presence of ferromagnetism in most samples from the fissures shows that ferromagnetic material is also brought up in the geothermal waters.

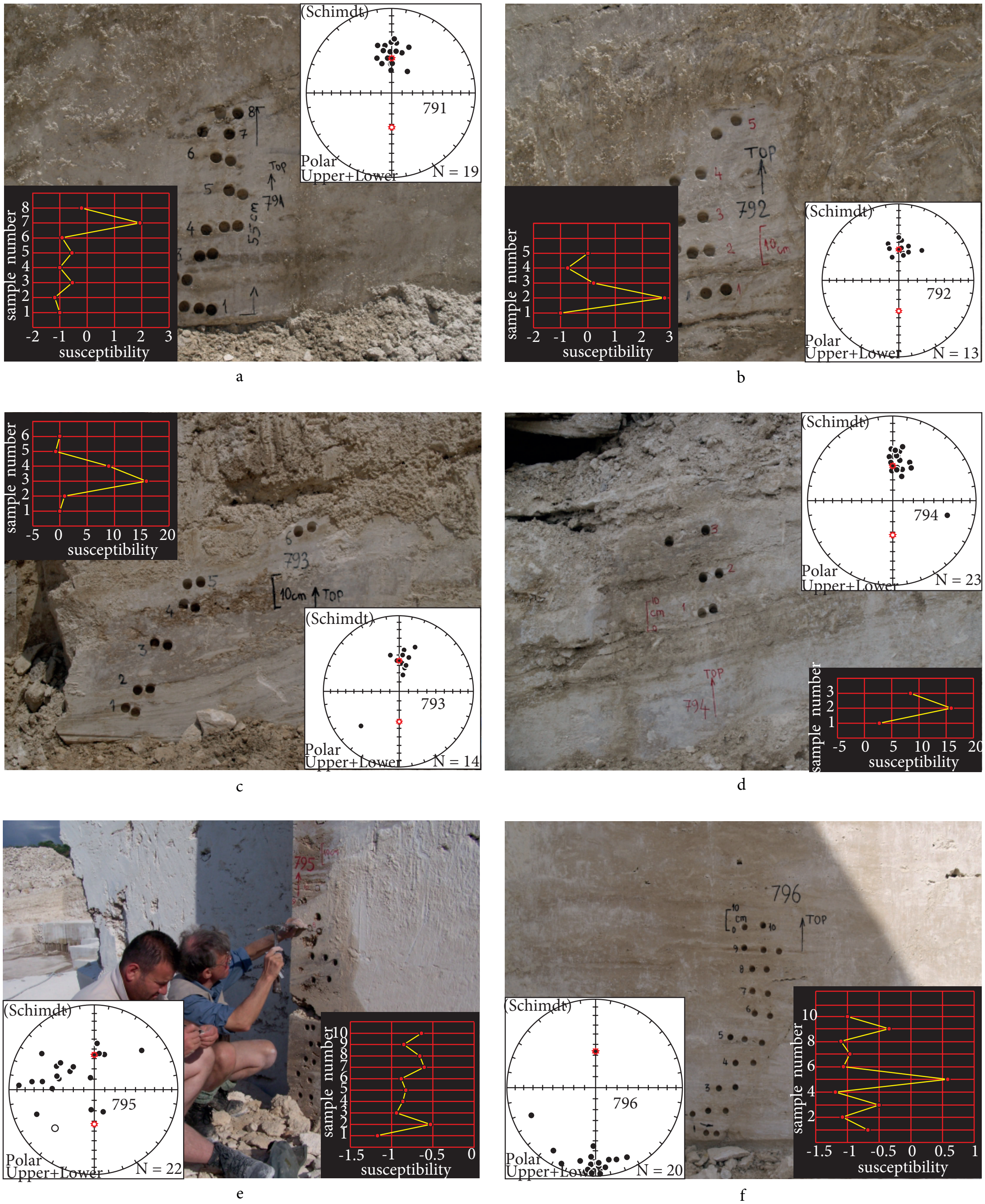

Figure 6. Field photographs of sites in bedded travertines showing variation of average magnetic susceptibility (red dots). The stereonets show components of magnetisation resolved by alternating field cleaning of samples sites at 791 **(a)**, 792 **(b)**, 793 **(c)**, 794 **(d)**, 795 **(e)** and 796 **(f)** with the red dots defining the directions of the (normal and reversed polarity) mean field axis.

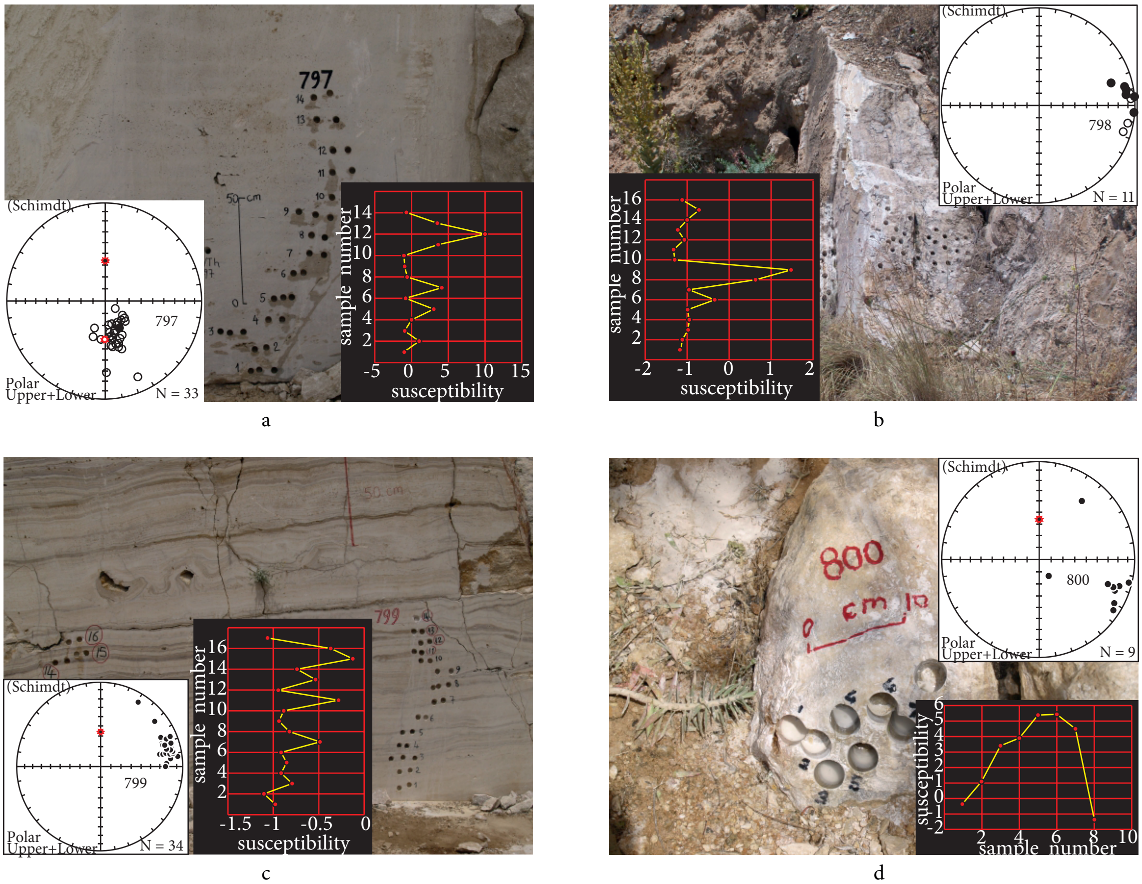

Figure 7. Field photographs of sites in bedded travertines showing variation of average magnetic susceptibility (red dots). The stereonets show components of magnetisation resolved by cleaning at sites 797 **(a)**, 798 **(b)**, 799 **(c)** and 800 **(d)** with the red dots defining the directions of the (normal and reversed polarity) mean field axis. Note that Site 800 is in a feeder fissure emplaced into layered travertine close to sites 799.

Although the results of this study are essentially negative in showing that palaeomagnetic, and by inference isotopic, signatures of layered travertine are profoundly influenced by diagenesis, it remains possible that magnetic susceptibility can recognise profound events from magnetic dust input. Judicious selection of primary aragonite for U-Th dating may also provide a key for dating material older than the Holocene.

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