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SUMMARY

The construction of a secular variation (SV) reference curve for a region for which little or no archaeomagnetic directions are available is presented here. A SV curve is illustrated for Austria, centred on Radstadt (47.38°N, 13.45°E) and based on data from sites in other countries less than 500 km away. The published data were selected on site characteristics of $N \geq 3$ and $k \geq 50$, and dated within 400 yr. This yielded 170 directions from which a SV curve was derived using Bayesian techniques. The obtained reference curve represents the past 2300 yr. New data, mainly from Austria, substantiate this curve and confirm the validity of the techniques employed which can, therefore, be applied for similar situations. Another test has been made using the German reference curve for dating the Austrian archaeological sites, here a systematic shift to older times in the order 30–110 yr occurs.

Key words: archaeomagnetic dating, Austria, Bayesian statistics, Germany, secular variation.

INTRODUCTION

Archaeomagnetic secular variation (SV) curves are used as a dating tool in archaeology as, for an archaeological structure of unknown age, its magnetic direction can be compared with the local curve and the time at which such magnetization was acquired to be determined. However, the regional variation of SV means that local curves must be calculated. While certain countries France, the UK, or Bulgaria (Gallet *et al.* 2002; Batt 1997; Kovacheva 1997) have well-established records from each country, the global coverage is poor. Accordingly, these reference curves are often transferred to other regions. The new approach proposed here is to obtain a local curve with the data sets from neighbouring regions. This study illustrates the situation for Austria, for which only one archaeomagnetically analysed site is available. However, large data sets exist for neighbouring countries as Germany (Schnepp & Lanos 2005; Schnepp *et al.* 2004) and Hungary (Márton 2003), and a surprisingly large database could be gathered. The data selection criteria will be outlined first and the resultant data will be used to construct a first SV curve for Austria. The validity of this curve will then be tested using new Austrian data.

THE DATA SET

The geographical distribution of archaeomagnetic data in Europe shown in Fig. 1 taken from Schnepp & Lanos (2005). Most of this data set is available from the archaeomagnetic data base managed by Don Tarling (Tarling 1999). For the Austrian SV curve a circular area with a radius of 500 km was chosen around Radstadt (47.38°N, 13.45°E), which lies close to the geographic centre of Austria. The archaeological sites in this area provide 184 archaeodirections (taken from Hedley & Wagner 1981; Hedley *et al.* 1983; Bucur 1994; Moutmir 1995; Kovacheva 1997; Márton 2003; Kovacheva *et al.* 2004; Schnepp *et al.* 2004; Schnepp & Lanos 2005) which are obtained from sites in the neighbouring countries of Austria: Bosnia, France, Germany, Hungary, and Switzerland. Only one direction from a site in Austria could be found. Unfortunately, no data from Czechia, Italy, Slovakia or Slovenia have been published.

For selection criteria similar limits as by Schnepp & Lanos (2005) have been applied to the data set, e.g. all those directions have been discarded for which the number of samples was less than 3, the precision parameter k less than 50 and the age interval longer than 400 yr, or the age was before 1000 BC. The compiled data set consists of 170 directions (see Table 1) for which the geographic distribution is seen in Fig. 1. All these directions have been corrected for their geographic variation to the centre of the area (Radstadt) by using the virtual geomagnetic pole correction introduced by Le Goff *et al.* (1992).

The temporal distribution of these data is plotted in Fig. 2 as diagrams of declination and inclination versus time, respectively. The archaeomagnetic directions show a considerable dispersion but also a clear variation with time. Furthermore, the archaeomagnetic directions from the NW part of the area (open symbols) are in certain agreement with those from the SE part (solid symbols). The time interval before 300 BC is only poorly covered and further gaps appear during the time intervals from 450 to 650 AD and 750 to 900 AD.

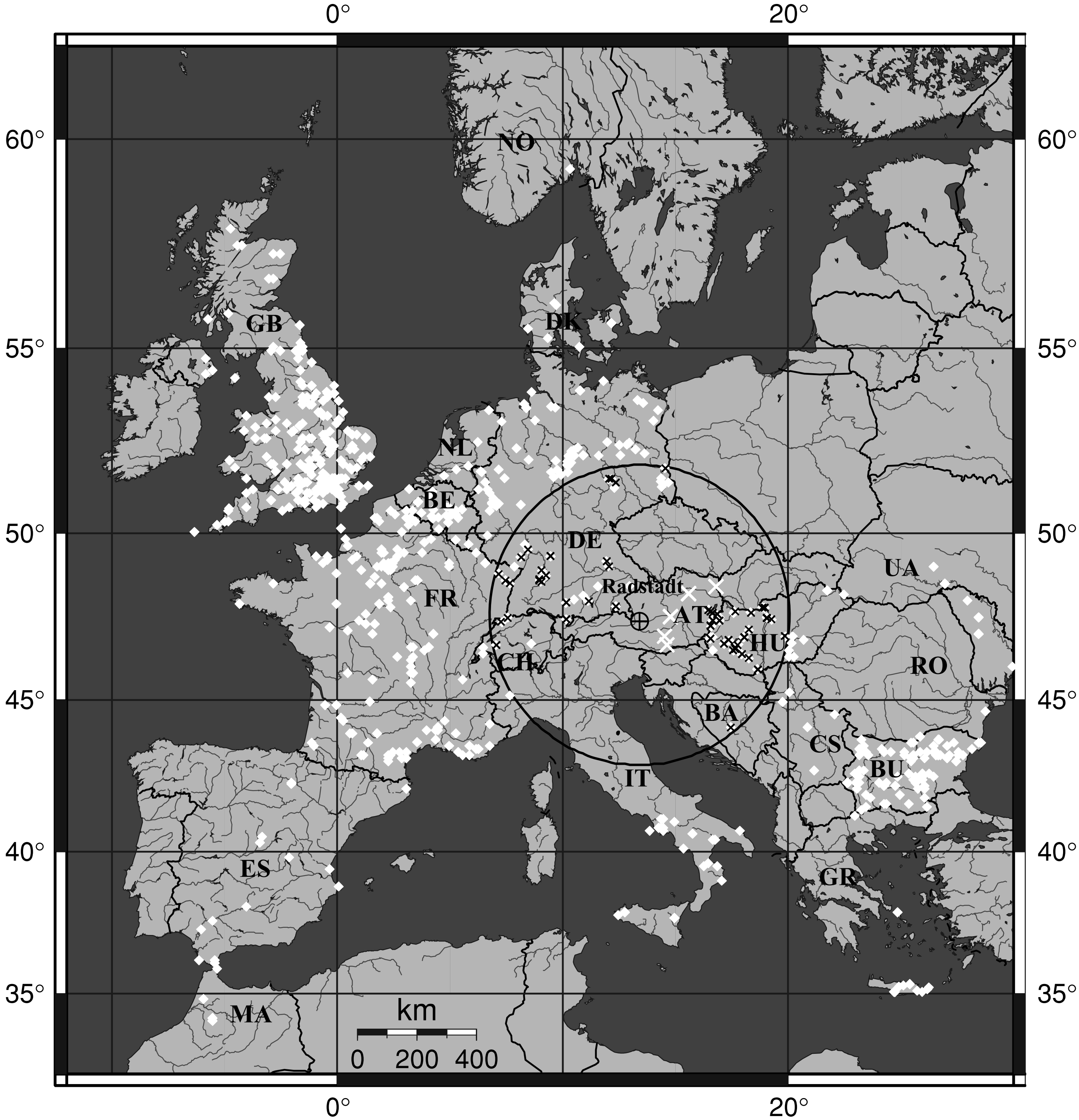

Figure 1. Map (Mercator projection) showing locations (white diamonds) of archaeomagnetic sites in Europe taken from the archaeomagnetic database and further references (see Schnepp & Lanos 2005). As reference site for Austria the town of Radstadt (47.38°N, 13.45°E) has been chosen and a circle of 500 km radius is the reference area. The data taken finally for the SV reference curve are marked by black crosses. The investigated Austrian sites are shown by white crosses.

This corresponds well to the fact that much more archaeological sites are known for the Roman epoch as well as for Mediaeval times.

SPLINE SMOOTHING WITH BAYESIAN MODELLING

In order to use this scattered data set for obtaining a SV reference curve smoothing has to be applied, which should provide bivariate spherical curves of declination and inclination versus time together with a 95 per cent confidence limit. In archaeomagnetism this is usually done with a sliding window technique in a univariate way (i.e. Márton 2003), but this technique has the disadvantage that the choice of the window size is not obvious and difficult for unevenly distributed data. An alternative was developed by Lanos (2001; Lanos *et al.* 1999) and discussed by Lanos *et al.* (2005) in comparison with moving window techniques. In the present study, the further developed method is used, as described by Lanos (2004).

Table 1. Data set which was used for the calculation of the reference curves for Austria. Country, Reference, number of structures, description of selected structure, number of data rejected for reasons see text. The data file can be requested from the corresponding author.

Country	Reference	*N*	Description	*n*	Rejected
Austria	Márton (2003)	1	Site Drassburg	1	–
Hungary	Márton (2003)	137	Data from all sites with Geographical longitude <20°E	137	–
France	Bucur (1994)	2	Site no. 9 and 144	3	–
	Moutmir (1995)	1	Site Marlenheim		–
Switzerland	Hedley & Wagner (1981)	1	All sites	3	–
	Hedley *et al.* (1983)	1	All sites		Site Disentis
	Kovacheva *et al.* (2004)	2	All sites		–
Bosnia	Kovacheva (1997)	1	Site Bugojno	1	–
Germany	(Schnepp & Lanos 2005; Schnepp *et al.* 2004, and references therein)	39	Site nos. 10–14, 43, 90, 92–102, 114–125, 135, 141, 146, 151–153, 156,	25	Same sites for same reasons as in references
	Bucur (1994)	1	site 334		–

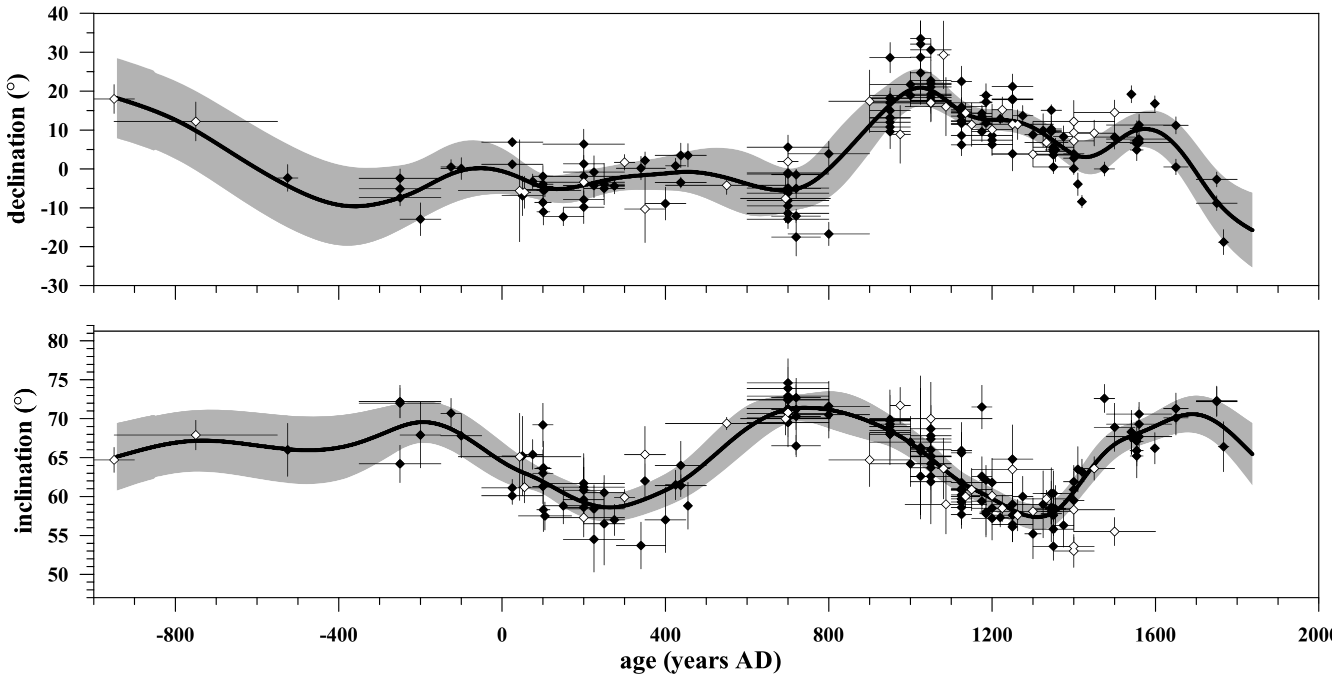

Figure 2. Declination and inclination values are plotted versus time scale together with error bars (2σ or archaeological estimate for age, 95 per cent confidence limit for declination/inclination) for the selected data set (open symbol: France, Germany, Switzerland; closed symbol: Austria, Bosnia, Hungary). The two bold black lines represent marginal curves of declination and inclination of the obtained secular variation reference curve for Austria surrounded by their 95 per cent error envelope (grey area).

The aim of this approach is to determine as best as possible SV curves in the past together with an estimation of precision on the curves for both, inclination and declination. The implemented Bayesian hierarchy allows to model stratification of all experimental errors (Lanos *et al.* 2005) and to fit a spherical spline function based on roughness penalty to the data with bivariate statistics, which means declination and inclination are treated simultaneously with time. Assuming smooth SV changes, modelling of measurement errors according to multivariate normal distributions (the Fisher distribution can be locally approximated by a bivariate normal distribution, *cf.* Love & Constable 2003), and of age uncertainties according to given prior densities (uniform or Gaussian) constrained by stratigraphy, is done in the frame of the Bayesian statistics. This allows a posterior mean curve to be estimated and a functional envelope (error band) at 95 per cent confidence level to be obtained. This means that the 'true' curve will lie somewhere inside the derived error band.

THE ARCHAEOMAGNETIC SV REFERENCE CURVE FOR AUSTRIA

The obtained reference curve is shown in Fig. 2 as marginal curve of declination and inclination. Similar to France (Gallet *et al.* 2002) or Hungary (Márton 2003) the inclination shows a more or less sinusoidal variation with minima near the end of the Roman epoch as well as at the beginning of the 14th century and maxima at the beginning of the middle age and around 1700, while declination was close to N during the first millennium and westerly until the 18th century. A direct comparison with the Hungarian or French curve is avoided here as these curves have been calculated with a moving window average techniques with a fixed window size. As the aim is to present a SV reference curve for Austria, the spatial distribution of SV in Europe will not be discussed. According to Fig. 2 this curve is well defined during the time interval from 300 BC to 1750 AD, which an α_{95}-error envelope in the range of 1.1° to 3.0°. For this

Table 2. Archaeomagnetic directions from new Austrian sites: number, structure name; age as calendar date with a 95 per cent confidence interval and method of dating (archaeological age estimate or dendrochronological dating), number of samples, declination, inclination, precision parameter and 95 per cent confidence limit of characteristic remanent magnetization (ChRM), site name, kind of structure, geographic latitude (°N) and longitude (°E), laboratory treatment (AF: alternating field demagnetization, Th: thermal demagnetization, Tv: Thellier viscosity test), determination of ChRM (PCA: principal component analysis or VT: Thellier viscosity test cleaned NRM).

No.	Name	Age (yrs A.D.)	Method	N	D (°)	I (°)	k	α_{95}(°)	Site	Structure	Lat (°N)	Long (°E)	Treatment	ChRM
2	ST1	1270–1600	arch.	8	14.9	73.8	408	2.7	Stillfried	bread-oven	48.415	16.841	Th,AF	PCA
3	ST2	1270–1600	arch.	12	1.8	65.6	903	1.4	Stillfried	bread-oven	48.415	16.841	Th,AF	PCA
4	SE1	315– 327	dendro.	7	357.0	53.5	152	4.9	Semlach1	iron-kiln1	46.928	14.557	Th,Tv,AF	PCA,VT
5	HB	575–625	arch.	15	3.0	65.7	165	3.0	Hemmaberg	hypocaust	46.667	14.667	Th,AF	PCA
6	RSM	1350–1400	dendro.	11	4.2	61.5	366	2.4	Eisenerz/Ramsau	charcoal-pit	47.519	14.826	Th,AF	PCA
7	SP1	300–400	arch.	11	357.9	59.0	227	3.0	St.Pölten	hypocaust	48.206	15.626	Th,AF	PCA
8	SP2	325–425	arch.	16	358.0	60.2	218	2.5	St.Pölten	hypocaust	48.206	15.626	Th,AF	PCA

Table 3. Results of archaeomagnetic dating (95 per cent probability) obtained from the Austrian and German calibration curves in comparison with independent dating as in Table 2. Age intervals that are in agreement with the archaeological age estimates are in bold.

No.	Name	Age (yrs A.D.)	Dating obtained from Austrian curve (yrs A.D.)	Dating obtained from German curve (yrs A.D.)
2	ST1	1270–1600	[−900; −663] [796; 969] **[1575; 1692]**	[−501; −436] [669; 958] **[1636; 1681]**
3	ST2	1270–1600	[−763; −427] [−107; 62] [434; 580] **[1419; 1504]**	[−495; −265] [26; 142] [332; 512] **[1533; 1559]** [1858; 1921]
4	SE1	315–327	**[138; 410]**	**[133; 353]** [1336; 1450] [1874; 1930]
5	HB	575–625	[−882; −291] [−189; 56] **[446; 626]** [1422; 1633]	[−501; −251] [−3; 128] **[344; 636]** [879; 944] [1511; 1686] [1845; 1916]
6	RSM	1350–1400	[−676; −517] [−35; 78] [293; 526] **[1347; 1474]**	[−410; −328] [66; 423] **[1233; 1368]** [1422; 1552] [1891; 1930]
7	SP1	300–400	**[133; 422]**	**[113; 369]** [1880; 1930]
8	SP2	325–425	**[103; 451]**	**[98; 378]** [1887; 1930]

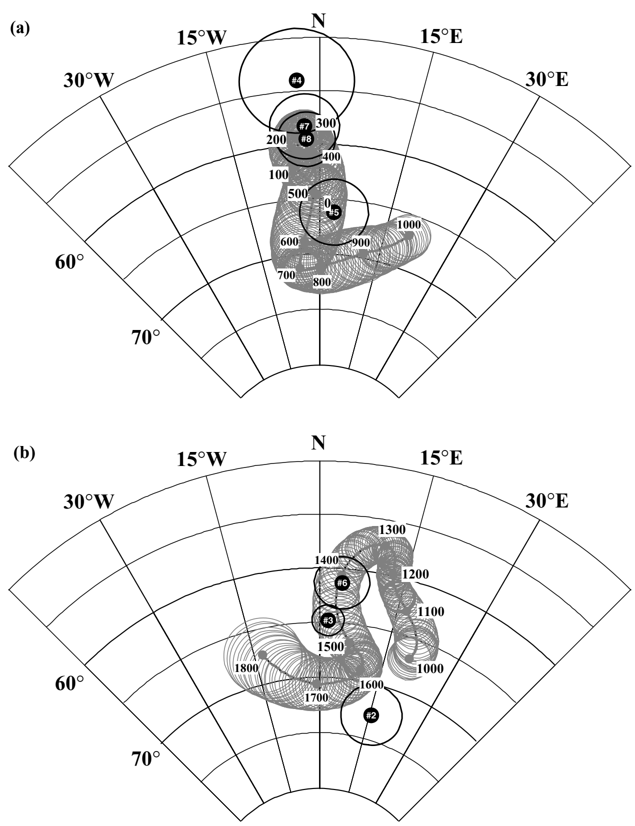

Figure 3. The Austrian archaeomagnetic reference curve with its 95 per cent error band is shown in a clipped stereographic equal-area net in comparison with the archaeomagnetic directions with α_{95}-circles. Structure numbers refer to Table 2, numbers indicate years AD. All data are reduced to Radstadt using the virtual geomagnetic pole. (a) first millennium AD and (b) second millennium AD.

interval of time the Austrian reference curve presented here is now ready to be used as a dating tool.

NEW RESULTS FROM AUSTRIA

In summer 2004 systematic field work with archaeologists was started in order to obtain samples from sites in Austria, which could be dated archaeomagnetically or, if well dated, could contribute to the SV reference curve for Austria. Most samples are still under investigation. Nevertheless, preliminary results of seven structures are presented here, which can be dated with the new reference curve (Tables 2 and 3).

The palaeomagnetic sampling and investigation was done in the same way as described in Schnepp & Lanos (2005). Oriented, drill cores or block samples have been taken from the archaeological structures and were subdivided in cylindrical or cubic specimens. Thermal as well as alternating field (AF) demagnetization of the specimens yielded well-defined characteristic remanent magnetization directions, obtained from principal component analysis. The preliminary mean directions given in Table 2 are well defined as the precision parameter k ranges between 150 and 900 while the radii of the α_{95} confidence circles are small (1.4° to 4.9°).

Fig. 3 shows the new archaeomagnetic data points from Austria together with the reference curve for Austria in stereographic plots for the first and second millennium AD, respectively. Five of the α_{95}-circles are close to the reference curve and there is a large overlap with the error-band of the curve. For the results of two structures (#2 and #4) this overlap is only small but both structures date in time intervals where the curve shows a cusp. Here, it has to be kept in mind that the reference curve is a smoothed curve, and especially maximum and minimum values of inclination are under or over estimated (see Schnepp & Lanos 2005).

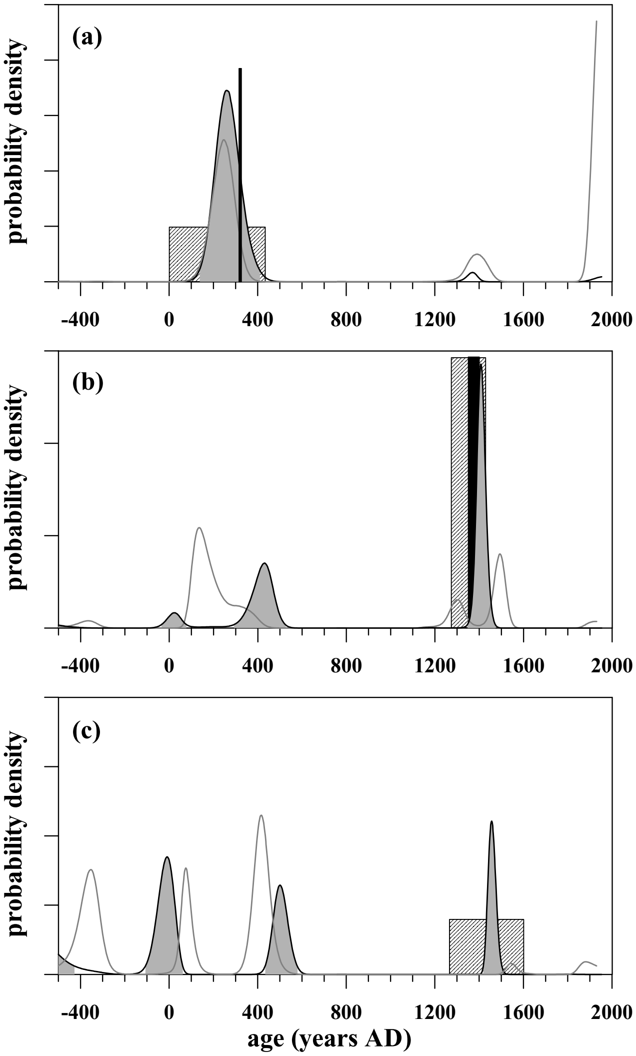

Figure 4. Probability densities for dating of the structures #4 (a), #6 (b), and #3 (c) (*cf.* Tables 2 and 3) obtained from the reference curve for Austria at 95 per cent confidence (black line and grey area). The grey line is the probability density obtained from the German reference curve, while the hatched area indicates the archaeological age estimate and the black area gives dating obtained from dendrochronology (see text).

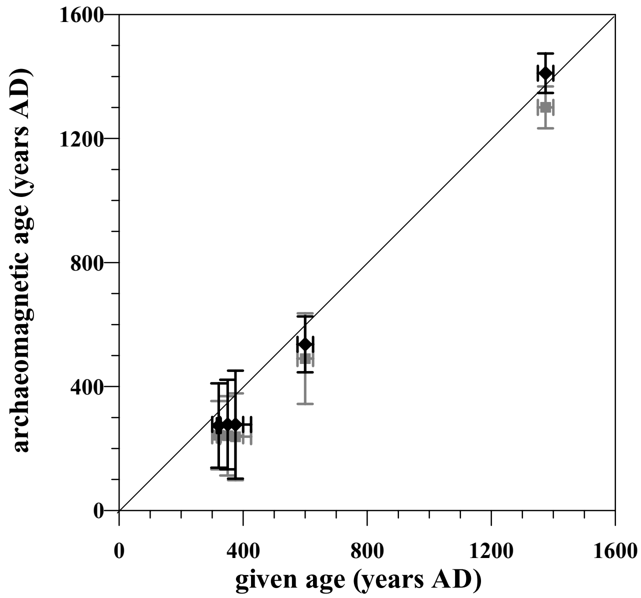

Figure 5. The result of archaeomagnetic dating obtained from the Austrian (black) and the German (grey) reference curves is plotted versus independent age estimates based on potsherds or dendrochronology. A line of slope one is indicated.

DATING

Archaeomagnetic dating was performed for all seven structures using the reference curve for Austria (this study). For this purpose all directions (Table 2) have been reduced to Radstadt. Fig. 4 shows three examples of the probability density curves (combined for inclination and declination) in comparison with dating from archaeological evidence. In these three cases the archaeological age estimate can be refined by archaeomagnetic dating. This is not true for the Roman structures #5, #7 and #8 (see Table 3), for which a very precise dating based on Roman potsherds is available. Nevertheless in all cases the archaeomagnetic date is in good agreement with the dating from archaeological evidence. For two structures also dating from dendrochronology was obtained using large pieces of charcoal. For structure #4, a Roman iron kiln, only one piece of charcoal gave a very narrow date, which perhaps underestimated the possible time interval. Although slightly younger, the archaeomagnetic age is in very good agreement with it. The same is true for the Medieval charcoal pit #6, (Klemm 2004) for which a lot of charcoal pieces have been dated. The dendrochronological age distribution shows a maximum in the second half of the 14th century at the end of which the charcoal pit was abandoned (Klemm, private communication, 2005). Here the maximum of the probability density obtained from archaeomagnetic dating appears ten years later and shows a precise coincidence with the independent dating method. For the third structure (#3) archaeological dating could only be based on potsherds which occur over a long interval in Mediaeval times. In this case, the archaeomagnetic dating is able to refine the age considerably and to distinguish it from oven #2 which was found a few metres away in the same horizon, but is dated about 170 yr younger according to the obtained archaeomagnetic direction (*cf.* Table 3).

Five of the structures in Table 3 (#4 to #8) are precisely dated and allow, therefore, to investigate the validity of the reference curve for Austria, which does not include these Austrian data. In Fig. 5 the ages obtained from archaeomagnetic dating are plotted versus the independent age estimates obtained either from the well-elaborated chronology of Roman potsherds or from dendrochronology. The data points close to the line with slope one indicate that both age estimates are in good agreement within their 95 per cent error limits. Note, that the three structures with differing archaeological ages in the 4th century AD are confined to more or less the same age by the archaeomagnetic dating. This seems to be a consequence of the dating process. If there is a cusp in the curve, here a loop with a minimum in inclination (*cf.* Figs 2 and 3), and the α_{95}-error circle overlaps it, the obtained age will always be centred to the extremal value, which is here 280 AD. Nevertheless, the mean results follow very well the reference curve, but it has to be kept in mind that archaeomagnetic dating can shift the age in the order of 100 yr in periods where cusps in the reference curve occur.

Some publications (e.g. Gallet *et al.* 2003) claim that reference curves can also be used outside the region from which the archaeomagnetic calibration data set comes. In order to test this assumption, all the new Austrian sites also have tentatively been dated using the reference curve for Germany (Schnepp & Lanos 2005), of which the reference area includes also the NW part of Austria but none of the sites presented here. They have distances between 550 and 640 km to the German reference point Göttingen. The obtained probability densities are also plotted in Fig. 4, and these examples show considerable shifts between the two dating approaches. All possible age intervals are also listed in Table 3 and it can be seen that apart from these shifts also more possible dating intervals are obtained from the German curve. Fig. 5 demonstrates that the shift in age is systematic resulting in to older ages in the Roman epochs as well as in Mediaeval times. Fig. 5 allows us to estimate that the shift is in the order of 30–110 yr and, therefore, not negligible.

CONCLUSION

A surprisingly large set of archaeomagnetic directions could be compiled for a circular area around Radstadt, which is situated close to the geographic centre of Austria. From this data set, a well-defined SV reference curve could be obtained for the time interval 300 BC to 1800 AD. It was demonstrated that this curve is valid in Austria and that the existence of a national data set is not a prerequisite to start with archaeomagnetic dating in a country as long as there is a rich archaeomagnetic data set in the surrounding area. If this is the case a valid curve can be obtained from a reference area, which must also include, preferably surround, the area for which dating is desired. However, it is of cause much more preferable to have a data set which covers the reference area more or less evenly. By testing the archaeomagnetic reference curve for Germany with Austrian structures it can be demonstrated that transferring archaeomagnetic data to a reference which is to far away (>550 km) leads to systematic shifts in age in the order of 30 to 110 yr.

Comparing the reference areas for Germany (Schnepp & Lanos 2005) and Austria the question may arise which curve may be the better one for application of archaeomagnetic dating in Bavaria for example. To the authors opinion none of both curves would be the best as the optimal curve lies somewhere in between. Therefore, we would like to emphasize that the growing European archaeomagnetic data set will soon allow to step away from 'national' archaeomagnetic curves for dating. They should be replaced either by a regular geographic net work of reference curves or preferably, by a curve which is always calculated especially for the site to be dated from an appropriate surrounding area.

Nevertheless, the archaeomagnetic calibration curve for Austria allows now to apply archaeomagnetic dating during the past 2300 yr in Austria as well as in Czechia, Northern Italy, Slovenia or Switzerland.

Files of the data used for curve calculation as well as for the presented curves can be requested via e-mail from the authors.

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