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Posterior archaeomagnetic dating: An example from the Early Medieval site Thunau am Kamp, Austria

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ABSTRACT

The Early Medieval valley settlement of Thunau am Kamp in Lower Austria has been under archaeological excavation for 10 years. The site was occupied during the 9th and 10th centuries AD according to potsherds, which seem to indicate two phases of activity: in the older phase ovens were placed in the corners of houses while during the younger phase they are found in the middle of the wall. The present study has been conducted in order to increase the archaeomagnetic database and fill the temporal gap around 900 AD. For this purpose 14 ovens have been sampled for their paleomagnetic signals. Laboratory treatment generally confirmed that the baked clay has preserved stable directions. Apart from one exception, all the mean characteristic remanent magnetisation directions are concentrated on the Early Medieval part of the directional archaeomagnetic reference curve of Austria at about 900 AD. Using this curve archaeomagnetic dating provides ages between 800 and 1100 AD, which are in agreement with the archaeological dating. Together with the archaeological age estimates and stratigraphic information the new data have been included into the database of the Austrian curve and it has been recalculated using a new version of RenCurve. The new data confine the curve and its error band considerably in the time interval 800 to 1100 AD. This calibration process also provides probability density distributions for each included structure, which allows for posterior dating and refines temporal errors considerably. Because such dating includes archaeological information it is not an independent age estimate but is a combination of all available dating methods.

1. Introduction

The Early Medieval period in Central Europe is sparsely represented by historical documents and additionally it has a low number of extensively investigated, published archaeological sites, especially in eastern Austria. Accordingly, refined archaeological dating of Early Medieval finds and other material especially in eastern Austria and parts of its adjacent regions is still a major problem of the "Slavic archaeology". Indeed, research since the early second half of the 19th century has traditionally focused on the archaeology of graveyards. Here scientists found materials where dating seemed to be possible, due to the fact that the graves yielded grave goods, which could be easily compared with other regions and sites. In comparison, the investigations of "normal" Early Medieval settlements played a minor role. They seemed to have little potential for precise dating. The artefacts in these settlement sites, mostly ceramics, were regarded as chronologically insensitive and were most commonly dated only to the 9th century or even up the 11th century (Friesinger, 1965a, 1965b, 1974).

In the last few decades the situation has changed, though slowly. More and more settlements have been entirely or partly investigated (Wawruschka, 1999), often as part of large scale rescue excavations. Although not all of these studies are published (i. e. Kühtreiber et al., 2008), they are the first step towards a broader understanding of material culture, which will provide the possibility for comparison, and in turn develop a better understanding of Early Medieval settlement activities, especially in north-eastern Austria (see for example Nowotny, 2014). Nevertheless, dating can be difficult through analogy to other sites. This problem is further aggravated by the limited use of radiocarbon dating on such sites, since the calibration curve is characterised by three plateaus in the time interval between 650 and 950 AD (Reimer et al., 2004). Hence, radiocarbon dating is very imprecise in this time interval. In comparison, the archaeomagnetic calibration curve for

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Austria shows a strong movement of the geomagnetic field direction from 500 to 1000 AD (Schnepp and Lanos, 2006). Unfortunately, due to the limited dataset the error envelope is large and accordingly the calibration curve also produces relatively large errors in calendar dates when used for archaeomagnetic dating of this time period.

The archaeological site of Thunau am Kamp is situated in the middle Kamp-region in the north-western part of Lower Austria (Waldviertel, 48.59°N, 15.65°E). This central settlement agglomeration has been known since the second half of the 19th century. It consists of two main parts — the hillfort on the 'Schanzberg' and a settlement in the valley near Kamp River. Since 1965 excavations have mainly taken place in the hillfort. Occupation of the site started in the Late Neolithic period and later phases have been identified in the periods of Urnfield, Hallstatt, Late Iron Age, Late Roman, and finally Early Medieval the time period, which was predominately investigated (Friesinger and Friesinger, 1991). New excavations started in the valley in 2004, in an area situated in a basin developed from a former meander bend of the River Kamp. Its ancient erosion bank is formed by two hills: "Schanzberg" in the north and "Goldberg" in the west. According to the excavations the area can be divided into three parts, each with different functions: a large graveyard from the 9th and 10th centuries is situated on the steeper slopes of "Goldberg" and has been known about since 1872. Then, in the south a settlement area is situated on a flatter alluvial terrace. The third area has an "industrial" character, lying close to the banks of the River Kamp. The high density of houses also used for habitation purposes suggests that the settlement area was one of the outer baileys of the administration centre of the hillfort.

The predominant kind of residential buildings in the settlement area were pit houses dug up to 1.5 m into the *in-situ* loess loam or weathered layers of gneiss bedrock. All of them were furnished with one or two ovens. In the current stage of analysis it is possible to distinguish two forms of houses, which seem to have chronological relevance. The presumed older houses are less frequently recorded and they do not normally contain finds contemporary with their period of use. A common attribute is that they all have an oven with cupola in one corner, made of rock, loam or both materials (Figs. 1 and 2). The presumed younger houses (of 10th century date) still contain many finds including potsherds, mill stones and abundant loom weights. However, the oven constructions were completely different. They were dug from one inner flank of the house into the *in situ loam* (Fig. 1). Frequently the remnants of the cupola were preserved, in some cases even the entire oven. Another feature was a trench used as a working pit for a battery of similar ovens in its latest phase (Fig. 3). After their use the trench was continuously infilled and compacted with "municipal waste" dating to the 10th century. The majority of ovens may have been used for bread production. In addition to these ovens some oval or round hearths or fireplaces were also found, either outside or on the floor of the houses. Furthermore a few other pyrotechnic features such as a pottery kiln have been found (Obenaus et al., 2005; Obenaus, 2011). However, evidence for metal processing is only indirectly documented by the discovery of fragments of furnace wall covered with slag and by tuyeres.

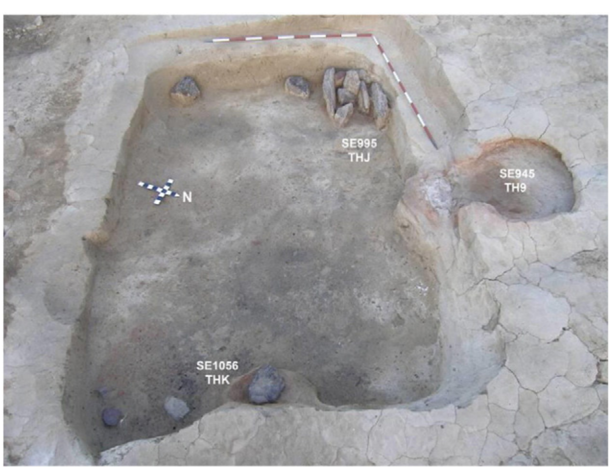

Fig. 1. View into a pit house with two phases and three heated features (*cf.* Table 1). The older oven in the NW corner was rectangular with walls made of boulders, the round oven was dug into the loess of the northern wall, and a round fireplace (partly covered by a boulder) was situated in the middle of the eastern wall.

The settlement in the valley had the function of a productive area, which supplied in cooperation with the hinterland the whole centre to the east and north of it. According to the archaeological investigation of potsherds and other finds the settlement in the valley lasted from the 9th century up to the beginning of the 11th century AD.

In 2009 14 of the fired structures were sampled for an archaeomagnetic investigation. These structures could be dated in two ways: on the one hand by using the existing curve (Schnepp and Lanos, 2006) taking into account stratigraphic constraints and some evidences for contemporaneity; or on the other hand, by constructing a new curve, which would incorporate the data provided by the 14 new structures with some *a priori* dating information. Bayesian modelling as part of the new curve construction process could then provide both posterior curves and posterior dating for each structure. The purpose of this paper is to compare the dating results from using both these approaches.

2. Archaeological dating

The dating of finds and other settlement activity at the Early Medieval site of Thunau am Kamp is primarily based on stratigraphic observations and is still in progress. The intense settlement activity on the valley for at least 150 years has left a complex stratigraphy, which can be used to develop a relative chronology of site development (older–younger). The higher resolution dating control is based on information provided by small finds and other artefacts, which can be compared with other contemporary sites and graveyards, most of them located in the Czech Republic (see for example, Vignatiová, 1992; Dostál, 1966; Sláma, 1977).

However, a major problem is that ceramics, which represent the largest number of artefacts in the working area, develop very slowly from a typological perspective and hence they can only show general tendencies (Cech, 1991, 2001; Staňa, 1994; Macháček, 2001; Pokorná, 2011). The main type of ceramic in Slavic settlements is the pot, which shows very little change in the 9th and 10th centuries AD. As a chronological indicator the use of graphite in pottery vessels starts to increase strongly from the second half of the 9th century and lasts up to High Medieval times (Szameit, 1998). Also the use of locally produced bottles increases from the second half of 9th century.

The small finds (mostly metal) in combination with ceramics allow for a more precise dating. The best dateable metal finds in the settlement area are represented by personal jewellery and dress attributes which have been lost: earrings, rings, dress pins and enamelled circular *fibulae*, mostly made of bronze (sometimes gilded). These jewellery artefacts illustrate the accessories of the local inhabitants who seemed to have been well dressed and relatively wealthy, but did not belong to the "upper classes". Most of the jewellery shows influences which are well known from Moravian sites as well as from the Danubian basin and are dateable from the second half of the 9th up to the 10th centuries (Felgenhauer-Schmiedt, 2006; Herold, 2007; Wawruschka, 2008, 2009; Sedlmayer, 2013; Obenaus, 2013; Nowotny, 2014). A change in this tradition starts during the 10th century: more and more different jewellery appears in the stratigraphically younger layers that shows a clear influence from the late Carolingian and the following Ottonian Empire and its adherent regions. Circular *fibulae*, lunular-shaped earrings and earrings with knot-ends represent the latest phase of the so called "Köttlach-culture" (Giesler, 1980, 1997, 2002; Eichert, 2010). These items are already missing in the material recovered from the fortified hilltop settlement on the "Schanzberg" which

Fig. 2. (a) View into another pit house whose floor is not yet excavated. Hence the fireplace (*cf.* Table 1) in the right corner is not seen. The sketch (b) explains the stratigraphy of TH7 and TH4 (see chapter 5.0). The stratigraphic model for all features is shown in the box (c): lower and upper levels represent the older and younger phases; arrows indicate constraints seen in the field. A hatched frame indicates contemporary use.

seems to have been abandoned around the middle of the 10th century (Szameit, 1995, 1998; Herold, 2008, 2012). In comparison with the finds from the latest part of the cemetery north of the valley settlement these finds clearly point out that the agglomeration of Thunau survived up until the end of 10th and the beginning of the 11th centuries, following the end of the hillfort — maybe under a new political influence (Obenaus, 2008, 2011, 2014).

Beside these mentioned items the riding equipment (mostly prick spurs) and rests of belt gears as well as remnants of weaponry clearly point out that the main chronological focus of settlement activity was during the 10th century AD. Other, more common metal finds like knives and parts of tools in most cases show no chronological sense.

Nevertheless, a major problem is the dating of the beginning of settlement activity at Thunau am Kamp near the river. At the moment it is assumed that the first structures were built at a time when the hillfort was already in use and had started to expand. This phase of expansion is tightly connected with the erection of the large scale rampart and it is well constrained by dendrochronological dating of its wooden remains. The oldest construction timbers date back to the first half of the 9th century (834 AD and younger) while the mass

Fig. 3. Two ovens which were situated along the trench. The picture on the right shows an earlier stage of the excavation when the second oven (SE 724) on the left is only visible in some traces of baked clay and charcoal.

of samples shows a clear peak in the advanced second half of it (Cichocki, 1999). In the same period of time (mid of 9th up to the first half of 10th centuries) the manor farm, the seat of a local elite on the so called "Holzwiese", also reaches its height (Herold, 2008).

From its beginnings and its upturn in the second half of the 9th century, the valley settlement was tightly connected with the fortified hilltop settlement. It served as a junction between the fortresses itself and the agriculturally structured hinterland in the "Horn basin" and was strongly orientated towards production and crafts. This intense coexistence lasted for a time period of approximately 100 years, until the hillfort settlement as a centre of local power was abandoned around or shortly after the mid of the 10th century. After that severe cut, the settlement in the valley did not cease to exist. It survived without any sign of local rule until the transition from the 10th to the 11th centuries AD. The same chronological pattern is recorded by the large adjacent, graveyard north of the settlement (only partly excavated) with its start in the second half of the 9th century and its end around 1000 AD (Friesinger, 1965a; Obenaus et al., 2005; Obenaus, 2011). However, as analysis of the finds and other material is still in progress for the Early Medieval valley settlement of Thunau am Kamp, the dating and the chronological framework for the site must still be considered preliminary.

3. Material and methods

In the valley settlement of Thunau am Kamp the palaeomagnetically sampled, archaeological features were distributed over distances of several tens of metres. The sampled ovens were mostly situated in houses and in three cases the excavation provided stratigraphic constraints. In two cases layers containing the ovens were superimposed (Figs. 1 and 2) while another two were found side by side along a trench (Fig. 3) which served as a working pit in one of its latest phases. The stratigraphic model is shown in Fig. 2c.

The sampled material of most features was baked loess loam with a gradient in colour from grey-brown around the inner surface of the oven, to increasingly redder after a few to several centimetres. Table 1 lists the 14 pyrotechnic features, mainly ovens with cupolas, which have been sampled by means of 6 to 16 soft cores (Schnepp et al., 2008). Sometimes the inner part of the ovens had a well burnt, very hard layer about 1 cm thick, which was removed prior to sampling to aid penetration of the sampling tubes.

After consolidation in the laboratory the soft cores were cut into cylinders of 22 mm length. Then natural remanent magnetisation (NRM), bulk susceptibility (2G-Cryogenic magnetometer and Agico Minikappabridge) and mass were measured and the Koenigsberger ratio was calculated. For characterisation of the magnetic carrier and its stability high temperature magnetic susceptibility was measured in air using an Agico Kappabridge CS3.

157 specimens were subjected to alternating field (AF, 2G in line) and 48 to thermal (TH) demagnetisation using a MMTD80A furnace (Magnetic Measurements). The AF demagnetisations were carried out with 9 to 13 steps ranging from 3 to 120 mT, while TH steps were performed from 150 °C up to 600 °C with a 50 °C increment. Change in susceptibility was checked after 200 °C with a 100 °C increment. The characteristic remanent magnetisation (ChRM) direction was evaluated using principal component analysis (PCA, Kirschvink, 1980). For each feature a hierarchical mean direction was calculated by averaging at first specimens of each core and then all independently orientated samples (cores). The statistical methodology of Fisher (1953) was used for these purposes. In order to test significant agreement or disagreement of directions, the F-test proposed by McFadden and Lowes (1981) was calculated.

4. Curve and reference dating estimation using Bayesian modelling

The archaeomagnetic dating procedure requires two steps: firstly, a dataset of archaeomagnetic directions obtained from well-dated features for a region of 500 to 1000 km radius. From this dataset an archaeomagnetic reference curve is calculated. Secondly, as soon as such a calibration curve is constructed it can be used for dating other archaeological structures from the same region. A calibration reference curve for Austria has been published by Schnepp and Lanos (2006).

The model used for creating such archaeomagnetic reference curves is based on a formal Bayesian framework for constructing chronologies. A first description of the algorithm was published by Lanos (2004). All prior information on the observations that includes experimental errors on direction and uncertainty on age as well as stratigraphic information is translated into prior probabilities. The Bayesian inversion gives back posterior dating probabilities for the reference data and posterior probabilities of the temporal evolution of the magnetic components, which can be used later for dating new structures. The inversion process minimises the misfit of each data point with respect to the curve by exploring the multi-dimensional space of probability densities using Monte Carlo Markov chains.

Here an updated algorithm (Lanos et al., in preparation) is used for which new features regarding the prior probabilities have been implemented in Bayesian calculations. Prior time is given by diverse methods which are natural science dating (*e.g.* radiocarbon after applying a calibration process), archaeological age estimation using finds and/or historical information. Uncertainties on age have to be translated into probability density functions. While Lanos (2004) used uniform prior probabilities, the new algorithm takes the "true" probability distribution into account, which is uniform for archaeological and/or historical dates, Gaussian for thermoluminescence dates, or irregular for calibrated radiocarbon ages resulting from the radiocarbon calibration process (see *i.e.* Reimer et al., 2004). Each measurement (observation: inclination, declination, intensity) also has an experimental error calculated by the laboratory. In addition, over-dispersions are put on the measurements and on the date in a hierarchical Bayesian framework in order to

Table 1
Archaeomagnetically sampled features (2009) at the site Thunau am Kamp, Grundstück Nro 98/1 (48.59°N, 15.65°E).

Feature no.	Kind of feature	Phase (position in house)	Archaeological age (century AD)	Name (archaeomagnetic)	Stratigraphic constraint
SE669	Round oven	Older (corner)	2nd half of 9th	TH1	–
SE612	Oval oven	Younger (flank of trench)	2nd half of 10th	TH2	Coeval to TH3
SE724	Oval oven	Younger (flank of trench)	2nd half of 10th	TH3	Coeval to TH2
SE768	Oval/round oven	Unknown (outside)	2nd half of 9th–1st half of 10th	TH4	After TH7
SE526	Oval oven	Younger (flank)	2nd half of 10th	TH5	–
SE524	Round oven pit	Unknown (outside)	9th–10th	TH6	–
SE888/SE887	Oval oven and fireplace	Older (corner)	No finds	TH7	Before TH4
SE847	Rectangular oven	Older (corner)	No finds	TH8	–
SE945	Oval oven	Younger (flank)	Middle–2nd half of 10th	TH9	Coeval to THK, after THJ
SE995	Rectangular oven	Older (corner)	2nd half of 9th–1st half of 10th	THJ	Before TH9 and TH K
SE1056	Fireplace	Younger (flank)	Middle–2nd half of 10th	THK	Coeval to TH9, after THJ
SE1023	Oval oven	Younger (flank)	Middle–2nd half of 10th	THL	–
SE876	Round oven	Unknown (not inside)	9th–10th	THM	–
SE803	Round oven	Unknown (not inside)	9th–10th	THN	–

take into account unknown errors, which are not included in experimental and dating errors provided by the laboratory or by the archaeology. Moreover, a "shrinkage" prior probability (Congdon, 2010) is put on the smoothing parameter, which controls the degree of smoothing/fitting of the cubic spline function used to estimate the curve. This prior probability replaces the cross-validation technique previously used (Lanos, 2004). As a consequence, this more comprehensive modelling provides an efficient automatic penalization of outliers and leads to a more adapted curve estimate.

The archaeomagnetic reference curves are then displayed as smooth continuous curves represented by a mixing of cubic splines. Finally, reference chronology and reference curves can be products of the same global statistical approach. This kind of modelling offers an advanced dating process: the dating of each *a priori* dated reference structure used for construction of the reference curve is *a posteriori* improved along with Bayesian curve calculation.

5. Results and discussion

For about 80% of the specimens the Koenigsberger ratios (Q) are above 2 (Fig. 4a) suggesting that most of them carry at least a partial thermal remanent magnetisation. The ovens THM and THN stand out with many low Q-values. They were found in the steeper part of the plateau in a layer of decomposed gneiss, which is a sandier material than the loess loam of the terrace. For A-specimens of the cores, which were closer to the ancient fire, Q-values are systematically higher than for B-specimens. Variability of Q, NRM and susceptibility can be explained by the variability of thermal alteration due to the heating of the loess loam in the past. This is seen by thermomagnetic curves of susceptibility (Fig. 4b) which were all irreversible. Specimens with very low bulk susceptibility (TH2-12, TH4-01) show strong formation of magnetite after 400 °C and a strong increase of susceptibility during cooling. A weaker to moderate alteration is still seen for specimens (TH6-08, THL-11) with (factor 10 to 100) higher susceptibility and Q-values. A similar alteration was also seen during thermal demagnetisation, although the change rarely exceeded 200% after 500 °C. According to the Curie temperature of about 580 °C, the newly formed magnetic mineral is magnetite, which may be maghemised or contain impurities. Because this mineral is formed during heating of the loess loam the magnetic carrier of the archaeomagnetic direction is also close to magnetite.

With the exception of ovens THM and THN most NRM directions cluster above 60° inclination with declinations mostly between 0° and 30° (Fig. 5). These clusters do not coincide with the present field direction. Some ovens show a considerably larger dispersion than others, *i.e.* oven THL (l) has much less dispersion compared to oven THN (n), which was more eroded and situated in a sandier material.

According to the demagnetisation experiments the majority of the specimens carried a stable magnetisation with no or only weak viscous overprints. Examples of AF and thermal demagnetisations are shown for one of the older ovens (Fig. 6a, TH7) one of the younger ovens (b, TH3) and for those with relatively scattered NRM directions (c and d). No general difference in quality of the demagnetisations is observed apart from the fact that thermal demagnetisation (red) was generally a bit more scattered as AF demagnetisation (black). For all examples the data points in the orthogonal component projection diagrams form well defined straight lines to its origin. Each diagram shows two pairs of almost parallel lines. This demonstrates that both demagnetisation techniques (red and black) led to the same directions, because the data points show parallel lines for west *versus* north (closed symbols) and vertical *versus* horizontal (open symbols) components, respectively. Great circle or completely unstable behaviour was only observed in three cases. Secondary components have been removed for the majority of the specimens at 5 mT or 150 °C and after that straight lines to the origin have been obtained. In most cases the characteristic remanent magnetisation direction has been calculated from five or more steps. For 88% of the specimens PCA yielded maximum angular deviation (MAD) angles of less than 2° underlining that very stable and well defined directions have been observed. MAD exceeded in only two cases 6°, which is much lower than the value of 15° given by Butler (1992). Nevertheless, such results were rejected. Further eleven results have been rejected, in three cases because of great circle behaviour and eight aberrant directions, which have been obtained from very short soft cores presumably caused by imprecise orientation.

Fig. 5 also shows the results of the first step of hierarchical averaging: the statistically independent ChRM directions of the core samples. Compared to the NRM directions in all cases a concentration of the ChRM directions is observed. This confirms that secondary components have been removed efficiently. The same data are shown in Fig. 7 together with the mean direction and α_{95} error circle of each feature. In most cases error circle radii are small (<3°) and range from 1.4 to 5.9° (*cf*. Table 2). Apart from THM and THN the obtained mean directions are significantly different from the present field. Therefore these stable mean directions are considered as measures of the ancient field during the last cooling of the ovens. Fig. 8 shows the obtained archaeomagnetic directions together with the Austrian reference curve (Schnepp and Lanos, 2006). All of them lie within the 95% error envelope of the curve or overlap with it. Except for TH8 and THM the directions are concentrated between 800 and 1000 AD in agreement with the archaeological dating. Three results are outstanding. THN is characterised by a very large error but it does not exceed the limit of 9° proposed by Tarling and Dobson (1995). THM plots in the Roman epoch. It has to be kept in mind that the error circle includes for both structures the direction of the present day field (Fig. 7m and n).

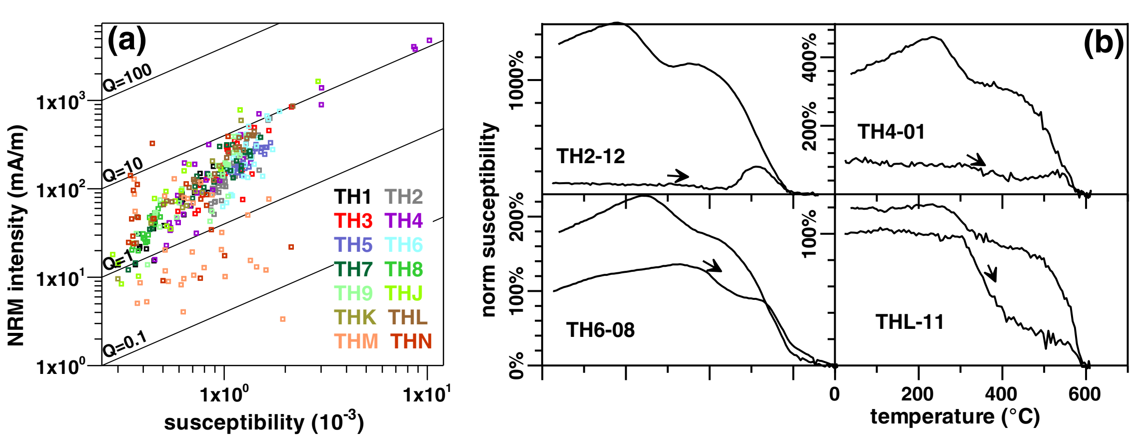

Fig. 4. (a) Intensity of natural remanent magnetisation (NRM) is plotted *versus* bulk susceptibility; isolines of Koenigsberger ratio Q are shown. (b) Diagrams of susceptibility *versus* temperature normalised to the initial value at room temperature.

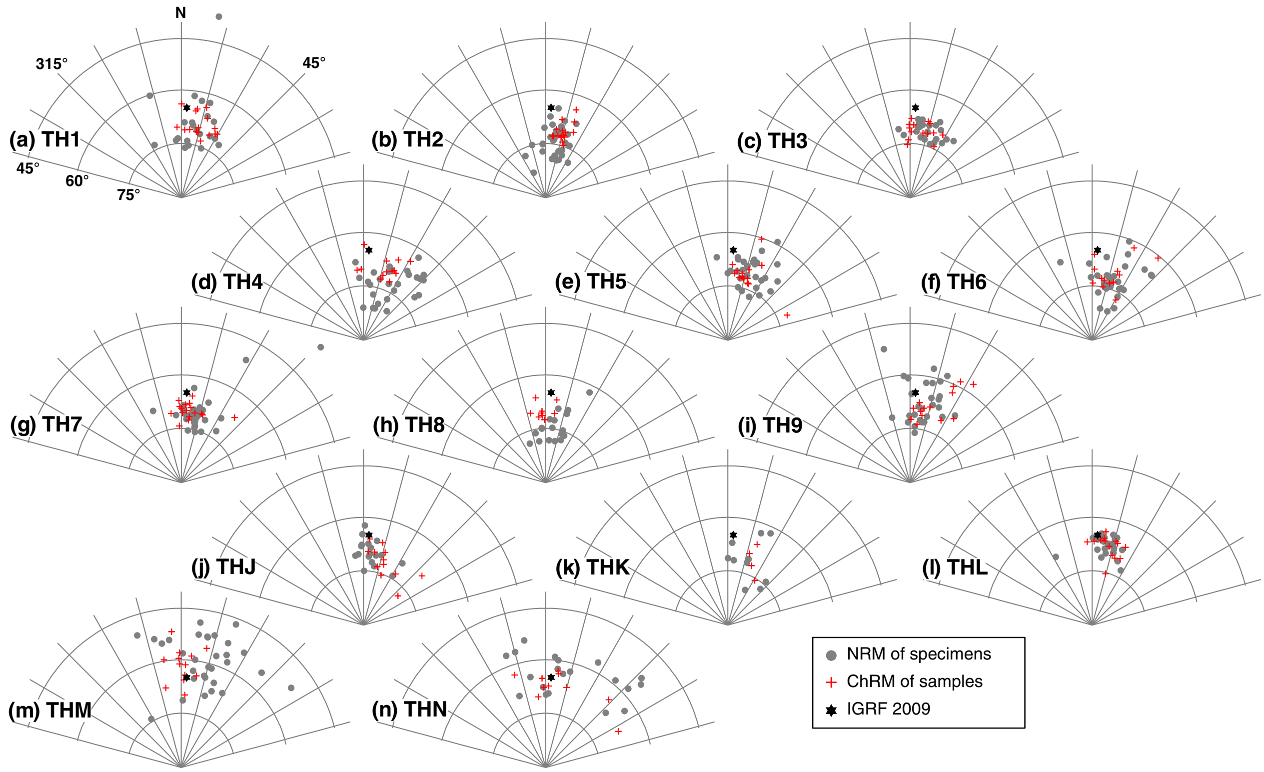

Fig. 5. Natural remanent magnetisation (NRM) directions are shown in equal area projection together with the mean characteristic remanent magnetisation (ChRM) directions obtained after demagnetisation.

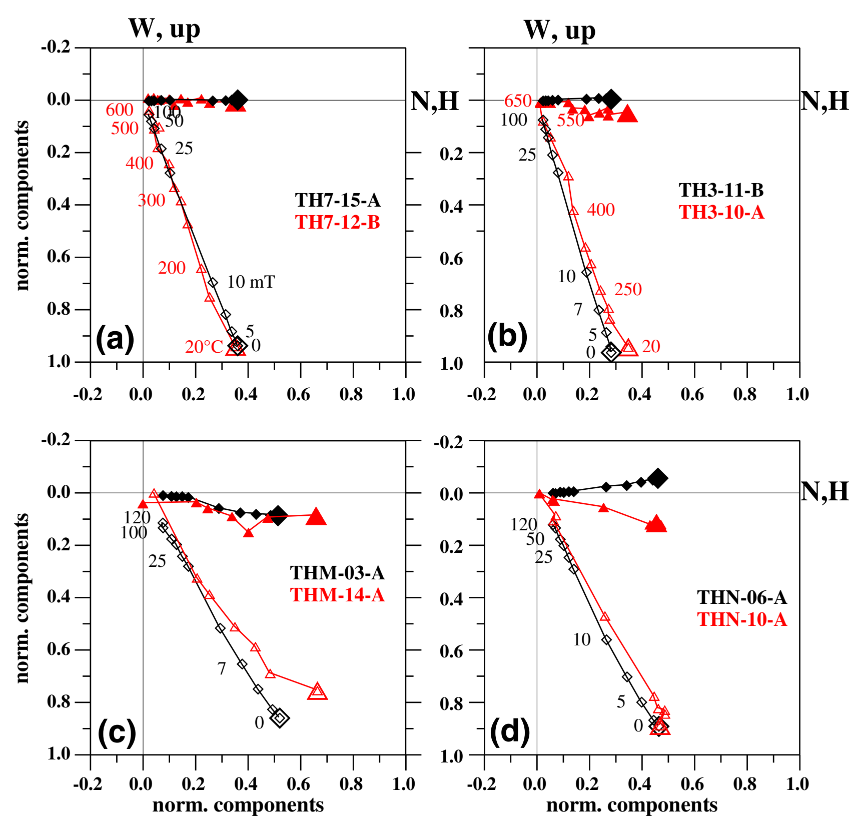

Fig. 6. Diagrams of orthogonal vector components (Zijderveld diagram, see *i.e.* Butler, 1992) of progressive demagnetisation. All values are normalised to maximum intensity. Red triangles show thermal, black diamonds show AF demagnetisation, and numbers give demagnetisation steps in °C or mT. Closed symbols are West component (W) *versus* North component (N, angle with horizontal diagram axis corresponds to declination), and open symbols are vertical component (up) *versus* horizontal component (H, angle with horizontal axis corresponds to inclination). Examples from four of the ovens are presented, and the first three characters of the specimen names correspond to the names given in Table 1.

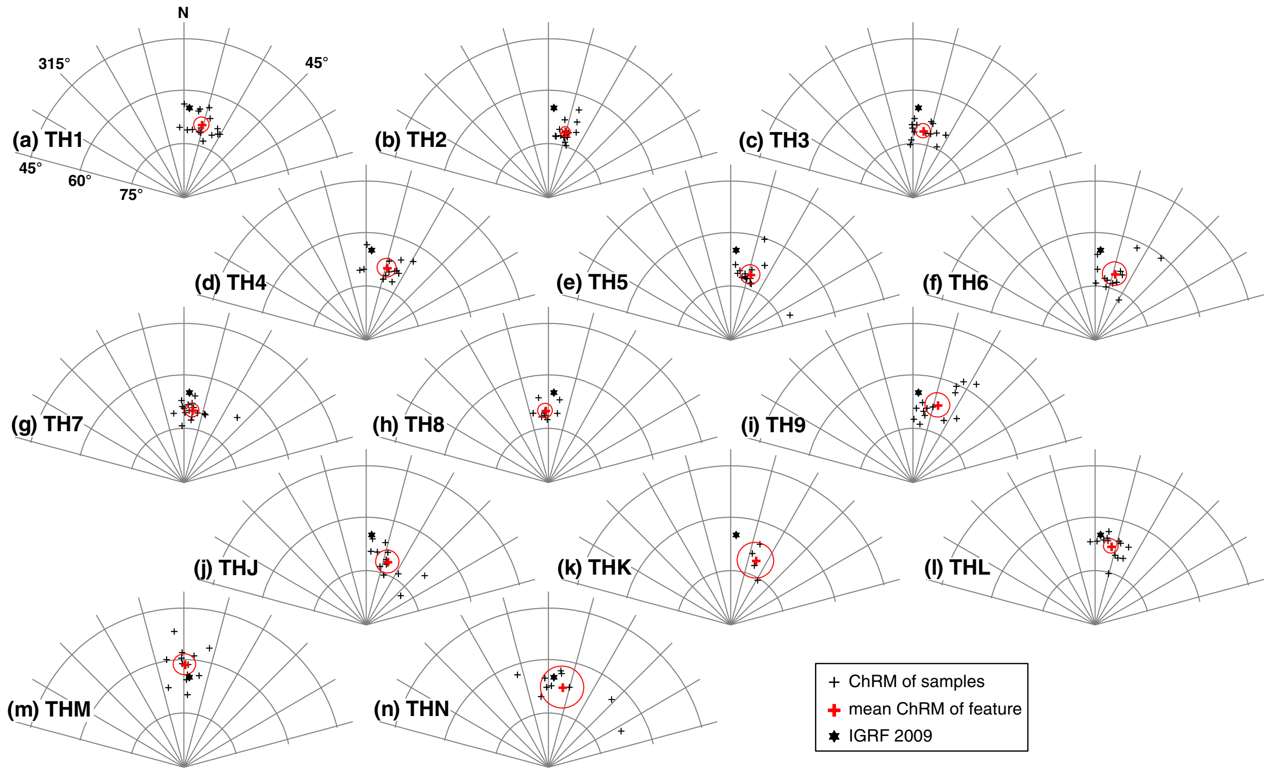

Fig. 7. Sample mean characteristic remanent magnetisation (ChRM) directions (Fig. 5) are shown in equal area projection together with the feature mean ChRM direction with α_{95} error circle (*cf.* Table 2).

Furthermore the material was sandy and low Q-ratios were observed. Accordingly unresolved overprints or remagnetisations after excavation cannot be excluded and the direction of THM seems to be unreliable in combination with the archaeological dating based on potsherds from the filling. On the contrary TH8 whose error circle includes 800 AD has a reliable direction and may represent the oldest structure investigated. This rectangular oven was situated in the corner of a house which did not contain any finds. According to the archaeological investigation it belongs to the older phase of occupation.

The archaeological investigations provided stratigraphic constrains for one pair and two triples of features (*cf.* Table 1 and Fig. 2). Ovens TH2 and TH3 were found side by side along a trench, which served as working pit (Fig. 3). Both directions are similar and their error circles overlap. According to the F-test the directions are statistically the same. This supports the hypothesis that the oven battery was used in the same period. The features TH9, THJ and THK come from two superposed houses (Fig. 1). THJ was found in the older one. According to the F-test the three mean directions cannot be distinguished. The same is

Table 2
Archaeomagnetic directions and dating of the site Thunau am Kamp (48.59°N, 15.65°E): feature number; name; archaeological age estimate as calendar date; number of soft cores; number of independent characteristic remanent magnetisation (ChRM) directions; declination; inclination; precision parameter; 95% confidence limit; results of archaeomagnetic dating performed with confidence (95%), between 0 and 1953 AD, obtained from Austrian calibration curve (Schnepp and Lanos, 2006), age intervals which contradict the archaeologically observed age range are printed in italic; same dating approach, but using stratigraphic information or 'same event model' as stratigraphic constraints; and posterior dating obtained from new reference curve modelling (see text) which combines archaeological and archaeomagnetic dating.

No.	Name	Age (years AD)	n	N	D (°)	I (°)	k	α_{95} (°)	Archaeomagnetic dating (years AD, c = 95%)	Posterior archaeo-magnetic dating using constraints (years AD, c = 95%)	Posterior dating obtained from curve modelling (years AD, c = 95%)
SE669	TH1	850–900	16	16	13.4	69.1	315	2.1	[861; 1001]	–	[849; 923]
SE612	TH2	950–1000	16	16	14.3	71.1	681	1.4	[853; 968]	[826; 962]	[924; 993]
SE724	TH3	950–1000	16	14	8.5	71.2	406	2.0	[796; 942]	[826; 962]	[857; 1000]
SE768	TH4	850–950	16	13	15.8	69.1	258	1.9	[877; 1031]	[832; 1113]	[858; 962]
SE526	TH5	950–1000	16	15	16.5	71.0	203	2.7	[857; 999]	–	[937; 1003]
SE524	TH6	800–1000	16	13	16.3	70.8	160	3.3	[849; 1010]	–	[845; 1002]
SE888/SE887	TH7	850–950	18	17	6.3	69.8	344	2.6	[545; 620] at 8.2% [786; 942] at 86.8%	[505; 984]	[800; 901]
SE847	TH8	800–900	10	9	−2.7	70.0	689	2.0	[539; 845]	–	[745; 896]
SE945	TH9	930–1000	15	14	17.5	67.4	139	3.4	[915; 1098]	[904; 1082]	[926; 1028]
SE995	THJ	850–950	13	12	18.4	71.5	183	3.2	[855; 1006]	[772; 1020]	[854; 956]
SE1056	THK	930–1000	7	4	21.0	70.8	336	5.0	[855; 1053]	[904; 1082]	[929; 1007]
SE1023	THL	930–1000	15	14	11.3	67.7	384	2.0	[839; 1050]	–	[885; 1006]
SE876	THM	800–1000	15	13	0.3	61.3	194	3.0	*[400; 490] at 77.3%* *[1369; 1399] at 16.8%*	–	not used
SE803	THN	800–1000	10	10	9.7	67.4	67	5.9	[421; 635] at 23.9% [785; 1185] at 70.9%	–	[808; 996]

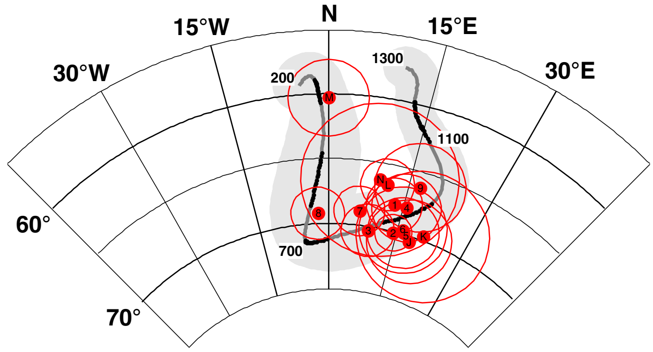

Fig. 8. Mean directions (reduced to Radstadt) of the ovens with α_{95} error circle (red, *cf.* Table 2) are shown in equal area projection. For comparison the secular variation reference curve of Austria (Schnepp and Lanos, 2006) with 95% error band (grey) for the time interval from 200 AD to 1300 AD is plotted.

true for a combined mean of TH9 and THK with respect to THJ. Accordingly the temporal gap between the two houses seems to be small but the direction of THJ obviously overlaps with the slightly older part of the calibration curve. On the contrary for features TH4 and TH7 stratigraphy was not so evident. The photograph (Fig. 2a) seems to imply that the oven TH4 was cut by the house containing TH7, but a more careful inspection shows that this was not the case. TH7 consists of an oven with a cupola built with stones and a fireplace, both situated in opposite corners of this house at the same stratigraphic level (which was the floor of this house). No finds were recovered from this house, so it is likely that it belongs to the older phase. TH4 was found on a higher stratigraphic level and was originally a round or oval structure. TH4 contained finds dating it from between the 2nd half of 9th century and the 1st half of the 10th century, corresponding to the younger phase of occupation. As shown in Fig. 2b, after abandonment oven TH4 was disturbed by another pit with a border more or less parallel to the wall of the older house which contained oven TH7. The archaeomagnetic directions of both older features (TH7) form a statistical universe according to the F-test and the mean direction is significantly different from that of TH4 at the 95% confidence level. TH4 obviously plots on the younger part of the calibration curve (Fig. 8) following the stratigraphy. The time interval of the corresponding archaeomagnetic direction agrees well with the age of the potsherds found in its fill.

The investigated archaeological features mostly yield well-defined archaeomagnetic directions, which allow for refinement of the Austrian calibration curve (Schnepp and Lanos, 2006) for the Early Medieval period. Although archaeological fine dating of the site is not yet complete, there is good agreement with the reference curve, which underlines its reliability. With age intervals between 20 and 100 years (*cf.* Table 2 column 3), the dating precision is sufficient to include the new data into the database of the Austrian curve. By doing this, the number of directions in the database has increased from 16 to 29 for the interval between 800 and 1000 AD. The reference curve has been recalculated using the new version of RenCurve as described above. The results of declination and inclination are shown together with the whole dataset in Fig. 9. In particular, it shows that the 9th century is much better represented by data now. The published marginal curves of declination and inclination (Schnepp and Lanos, 2006) are drawn in comparison with the recalculated curves. This shows that the old and new curves are in very good agreement and the error bands become narrower along the whole curves. Apart from this, the effect is stronger in the 9th and 10th century because of the additional data and accordingly dating of this time interval will become more precise.

The high accordance between the Thunau data and the archaeomagnetic reference curve underlines that the archaeological dating is reliable and in agreement with other sites in the region, especially from Hungary, which provided most of the archaeomagnetic data for the reference curve (see Schnepp and Lanos, 2006 and references therein). The new data have also been used to perform archaeomagnetic dating. This was undertaken using the RenDateModel software in two ways: (1.) every oven was dated independently and (2.) stratigraphic constraints according to Fig. 2 and Table 1 were used. The results of the dating procedure are listed in Table 2 and the probability densities are shown in Fig. 10 (a and b). Except for structure THM the archaeomagnetic dating confirms the archaeological age estimates, but only for TH6 that dating was confined (*cf.* Table 2). As pointed out already, the archaeological analysis of finds is in progress and not finished yet. So the absolute chronological data, as given in Table 2 column 3, display only the state of research to date, and sampling of features in 2009 should be regarded as a coarse chronological aid for the archaeomagnetic research.

Generally, the age intervals obtained from archaeomagnetic dating are longer than those obtained from archaeological dating. It has to be kept in mind that archaeological dating is on the basis of potsherds and other finds which provide a maximum age while archaeomagnetic dating gives the age of abandonment of an oven. Accordingly, only those archaeomagnetic dates need further discussion that give an age interval earlier in time. Such discrepancies occur for four of the features (*i.e.* TH3, TH7, TH8 and THM). For TH3, the archaeomagnetic age interval ends 8 years before that obtained by the approximate archaeological dating. By using 99% probability for the dating, the interval would end in

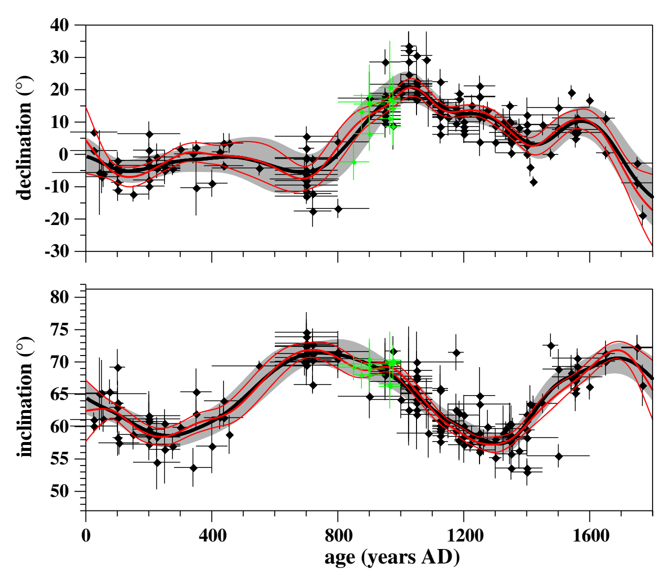

Fig. 9. Mean directions of the ovens (green) are plotted together with the data (black) and marginal curves of declination and inclination obtained from Bayesian modelling for the secular variation for Austria (black/grey Schnepp and Lanos, 2006). New curves (red) of an advanced algorism including the new data are shown. All data are reduced to Radstadt.

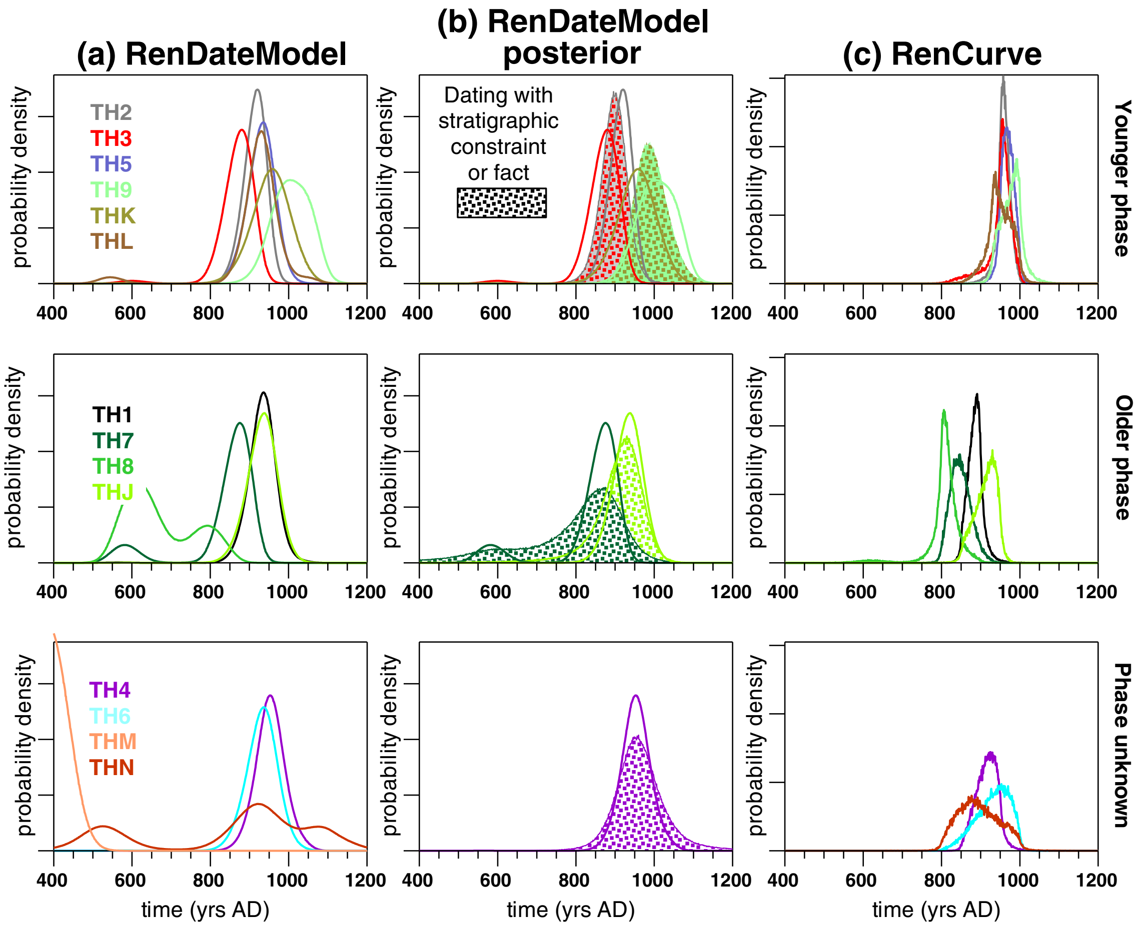

Fig. 10. Dating of the Thunau ovens: probability distributions (arbitrary scale) *versus* calendar time are plotted. They were obtained from dating approaches calculated with RenDateModel software using overlap with 95% confidence of archaeomagnetic direction with secular variation curve (Fig. 8). (a) Each feature independently dated, (b) stratigraphic model and facts were used (Fig. 2c), and (c) posterior probability distributions obtained from Bayesian secular variation curve modelling using the new version of RenCurve software.

965 AD in agreement with TH2, which also seems to be older than that suggested by the archaeology. Therefore, structures TH2 and TH3 situated along the trench may be somewhat older than expected from archaeological finds and may belong to the older phase. Ovens TH7 and TH8 have archaeomagnetic directions which lie close to the cusp of the reference curve at about 700 AD (Fig. 8). Here, the error circle of the direction overlaps strongly with the error band of the part of the reference curve from the 6th and 7th century. Hence, dating is ambiguous and this is seen in the fact that the probability distributions are bimodal (Fig. 10a). Thus, dating intervals become rather long (TH8) or split into two intervals (TH7). In agreement with archaeological dating archaeomagnetic dating provides evidence that the ovens were abandoned during the 9th century AD and confirm the chronological relevance of the ovens' position in the house. Because the archaeomagnetic direction of oven THM is not considered as reliable, the dating approach was only tentatively made and is also not reliable. Structures TH4 and TH6, which were not attributed to a house, seem more likely to have been abandoned during the younger phase.

Using stratigraphic constraints or in the fact the 'same event' (Fig. 10b) moves and/or confines the dating intervals (95% probability) slightly, but no significant change is observed (Table 2).

As another approach, posterior dating with RenCurve is shown for comparison (Fig. 10c). The calculation process for obtaining the calibration curves provides a posterior probability distribution for each feature, which represents the best fit on the curve together with all other data and other constrains (*i.e.* stratigraphy). Here the prior temporal errors are considerably refined with respect to usual archaeomagnetic dating. In this approach the features presumably dating from the younger period are much better confined with respect to their dating interval than those of the older period. This may be explained by the fact that the older houses had been flattened after they had been abandoned with almost all of the household removed. This demolition included most of the cupolas as seen *i.e.* in Fig. 1 for feature THJ and may also have slightly deformed or tilted the oven floors which have been sampled. Generally the archaeological dating interval is confirmed (*cf.* columns 3 and 12 in Table 2) within the order of about 25 years, but the posterior dating interval of four features (TH3, TH7, TH8, THL) tends to be older, while in one case (TH6) the dating interval is refined.

The alternative approaches of archaeomagnetic dating presented here raise the question as to which kind of approach is most appropriate as a tool for archaeologists and their sites. It seems that it is not possible to give a simple answer. It depends on the archaeological context in which the dating is applied. If the archaeological study requires a completely independent dating method, the only choice is to apply archaeomagnetic dating by using the characteristic remanent magnetization and the archaeomagnetic calibration reference curve. Although such dating can provide ambiguous results because of cups and loops of the calibration curve, it can support or reject the presumed archaeological age. For this purpose it has to be kept in mind that archaeomagnetic dating estimates directly the time of activity of our ancestors, *i.e.* the last use of an oven for example. Archaeomagnetic data which were not obtained from already dated archaeological features cannot be used for reference curve building. If the archaeological context provides good chronological information, based for example on comparison of finds and results from other sites, such data can be used for curve building. For this purpose approximate archaeological dating is sufficient with a precision of about 200 years (Tarling and Dobson, 1995). In this case, archaeological dating could also be refined by a posterior dating using the calibration curve building process. But in this case the dating is not independent of the archaeological age estimate. For both alternative dating approaches information on stratigraphy can be used as additional source by the Bayesian framework.

6. Conclusions

New reliable archaeomagnetic directions have been obtained from 13 ovens found in an Early Medieval settlement situated in Lower Austria. The new results fill a gap that exists in the archaeomagnetic database of Austria around 900 AD. These directions agree well with the archaeomagnetic reference curve and contribute to its further refinement between 800 and 1000 AD. Independent of the archaeological age estimates for the site, the archaeomagnetic dating provides an age interval of about 200 years from the late 8th up to the beginning of the 11th century AD for the occupation of the lower part of the settlements at Thunau am Kamp.

Generally archaeological age estimates and chronological relevance of different placement of ovens in the houses are supported by the archaeomagnetic directions. No indication of a break is present for the two subsequent phases. Archaeomagnetic dating is not able to refine archaeological age estimates and is not improved by the use of stratigraphic information, except for the 'same event model'. Recalculation of the archaeomagnetic reference curve provided posterior dating information which combines the archaeological age estimate with archaeomagnetic information. Here a considerable refinement of the age interval is possible. Because such dating includes archaeological information it is not an independent age estimate but is a combination of all available dating methods.

Although archaeomagnetic dating can provide independent age confirmation in support of archaeological dating through comparison with finds, in many cases it is not yet able to constrain dating across other sites. This would need much more new data in order to improve the archaeomagnetic reference curve considerably. This will be possible by including additional new data which will be obtained from Thunau where 12 additional ovens have now been sampled. Furthermore new data from Hungary (Márton and Ferencz, 2006; Márton, 2010) and other Austrian sites under investigation will be used to advance the reference curve for Austria in the coming few years.

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