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Archaeomagnetic dating of seven archaeological fireplaces in the Netherlands

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Abstract

The palaeomagnetic directions of seven Dutch fireplaces are compared with the archaeological age estimates which range from the first to the 17^{th} century AD. A comparison with the British master curve of secular variation for archaeomagnetic dating results in a refinement of the archaeological age estimates in two cases, while four other archaeological age estimates can be confirmed. For one fireplace only one sample is reliable, resulting in a very poorly defined archaeomagnetic age of 2 to 3 centuries younger than the expected age (i.e. late Middle Ages). On the other hand, accepting the archaeological age estimates, the palaeomagnetic directions can contribute to the database that is used to construct the British secular-variation master curve. We applied the classification grades proposed by Tarling & Dobson (1995) which range from unreliable (grade 1) to reliable (grade 5). Three fireplaces have grades 5, one has grade 4, one grade 3, one grade 1 and for one case no grade was assigned.

Introduction

Archaeomagnetic dating is based on the directional change of approximately 0.3°/year of the geomagnetic field (called secular variation) and the study of the characteristic remanent magnetisation (ChRM) of archaeological baked structures like fireplaces. Under ideal conditions, a ChRM is acquired when the fireplace cools down after heating. Every time a fireplace is heated above the Curie point of the minerals that carry the remanence, the previous magnetisation is lost and the magnetic minerals acquire a new magnetisation during subsequent cooling to ambient temperature. In homogeneous isotropic samples, this magnetisation is then parallel to the ambient geomagnetic field. The direction of the ChRM thus represents the direction of the magnetic field at the moment of final cooling. The secular variation can be reconstructed by evaluating the palaeomagnetic directions of archaeological fireplaces of which the ages are known by archaeological studies. For the last 21 centuries these reconstructions have been established for large areas like France (Bucur 1994) and the United Kingdom (Malin & Bullard 1981; Clarke et al. 1988; Tarling & Dobson 1995). Once these reconstructions are established, fireplaces of which the ages are poorly known can be dated by correlating their ChRM directions with the master curve of secular variation valid for that area (cf. Parés et al. 1992; Schnepp & Pucher 1996).

Seven fireplaces found during excavations in different localities in the Netherlands (Figure 1) have archaeological age estimates ranging from the 1^{st} to the 17^{th} century AD. An archaeomagnetic study of these fireplaces may be expected to improve the archaeological age estimates by comparing their ChRM directions with the most recent British master curve of secular variation (Tarling & Dobson 1995). Conversely, this curve was established by using ChRM directions from

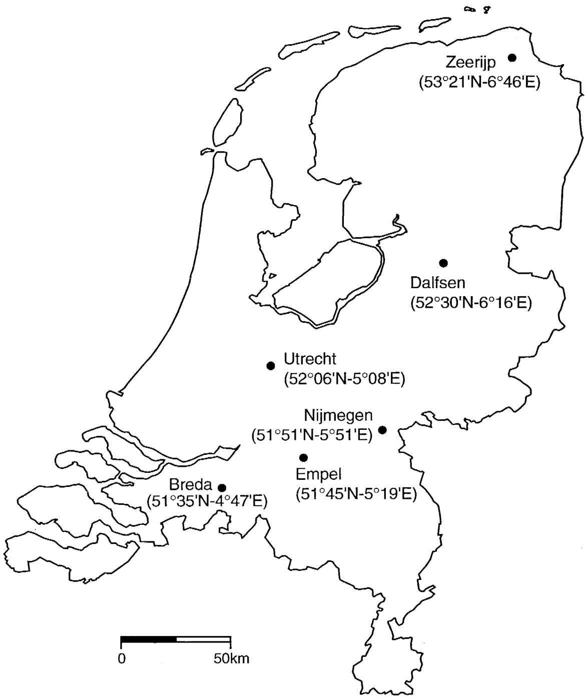

Figure 1. Locations of the seven investigated fireplaces in the Netherlands (Table 2). Two fireplaces were studied from each of the cities of Breda and Nijmegen.

Table 1. Classification grades used for the evaluation of archaeomagnetic data, after Tarling & Dobson (1995). Age error in years, α_{95} in degrees, N: number of samples.

Grade	Age error	α_{95}	N
1	$\geq$ 100	$>$ 15	$>$ 1
2	$\geq$ 75	$>$ 9	$>$ 1
3	$\geq$ 50	$>$ 5	$\geq$ 2
4	$\geq$ 25	$>$ 3	$\geq$ 5
5	$<$ 25	$\leq$ 3	$\geq$ 7

fireplaces located within the area between latitudes 48 and 57° N and longitudes 6° W and 9.5° E. Because the fireplaces in the Netherlands are within this area, their archaeological age estimates and palaeomagnetic directions may provide additional data for the refinement of the British master curve. For the evaluation of the Dutch data we use the criteria that were proposed by Tarling & Dobson (1995) who divided data into five grades (Table 1). The grades are primarily based on the precision of the ChRM direction, i.e. the α_{95} cone of confidence at the 95% level (Fisher 1953), and secondly on the number of the individual directions that make up the average direction. In defining the secular-variation curve, fired structures with grades 1 or 2 are excluded as being too imprecise; they are only used to assist in the evaluation of more precise data.

Secular variation in the Netherlands

Only since the year 1862 the secular variation of the geomagnetic field has been measured directly in the Netherlands. Data before this date are very scarce. Since a few decades, however, scientists have been working on a secular-variation master curve for the United Kingdom for the last two millennia based on archaeological ages of numerous fireplaces (cf. Malin & Bullard 1981; Clarke et al. 1988). Recently, a revised version of the British master curve has been published (Tarling & Dobson 1995). This curve can also be used in the Netherlands after a transposition of the declination and inclination (D, I) values at the reference location (Meriden, 52°26' N, 1°37' E) to the corresponding D and I values at the reference location in the centre of the Netherlands (Utrecht, 52°06' N, 5°08' E). For this procedure, we use the virtual geomagnetic pole (VGP) correction proposed by Irving (1964). This assumes that the D and I values are caused by a purely dipolar geomagnetic field. In reality, it appears that the directions since 1862 are approximately 3° east from those of the transposed British master curve while the difference in inclination is negligible ($<$ 0.5°; cf. Figure 4). If this eastern offset of approximately 3° is constant, the (unknown) true Dutch master curve should be depicted some 3° to the east relative to the transposed British master curve.

Geographical and archaeological settings of the furnaces

Nijmegen. The city of Nijmegen has been the subject of intensive archaeological research for many years, because it has been a place of importance since the Romans founded it a few decades BC. In this city, two kilns have been sampled: a pottery kiln at the Maasplein location and a limestone kiln in the centre of the city. Based on pottery shards of a pile of misfires near the furnace, the age estimate for the pottery kiln is the second part of the first century. The limestone kiln must be of Roman Age (approximately 12 BC to 400 AD). Under the increasing threat of Frankish invaders after 300 AD the Romans were forced to build fortifications even though consolidated rocks were absent in the area. Civilian buildings, constructed of limestones from northeastern France (Kars & Broekman 1981) were therefore destroyed to produce the lime (mortar) for fortress building. The most probable age is hence between 300 and 400 AD. The first archaeomagnetic results of this limestone kiln were published by Langereis & Kars (1990), based on the master curve by Clarke et al. (1988).

Dalfsen. In the province of Overijssel, near the village of Dalfsen, the remnants of several slagpit furnaces dating from the 3^{th} to 4^{th} century AD were excavated. This dating is based on a few pottery shards. The furnaces are an indication of early historical iron production. During the production process, the ironhydroxide in the bog iron ore is reduced into (metallic) iron and the gangue material (mainly quartz) has to be separated from the iron. The silica reacts with divalent iron oxide to form a fayalitic melt (the slag) which runs into a pit underneath the furnace and forms a slag block. The furnaces were situated on a cover-sand ridge in the eastern periphery of a small village. After its occupation, the fireplace was covered with up to 60 cm of wind-blown sand which still protects it fairly well. The slag block was found in situ, enabling palaeomagnetic dating.

Empel. Close to the relicts of the 13^{th} century castle of the Lords of Meerwijk, near the village of Empel north-east of the city of ‘s-Hertogenbosch, a brick furnace was found. This furnace was probably used for the production of bricks during the renovation of the castle. Based on the few pottery shards found in the vicinity, we have estimated that the fireplace belongs to the first quarter of the 15^{th} century AD.

Breda. Two fireplaces have been sampled in the city of Breda. One furnace is at the terrain of the Royal Military Academy (KMA), the other is a pipe furnace located in the city centre, used for the manufacturing of tobacco pipes of baked clay. The KMA furnace belonged to a castle of Jan II van Polanen which was built between 1350 and 1362 AD. As is mentioned in the archives from 1462, a renovation of the Polanen castle took place during the reign of Jan IV van Nassau (1442–1475). Since this renovation, the furnace was not used any more because a new and larger hearth was built. It is therefore likely that the furnace was last used in the third quarter of the 15^{th} century.

The pipe furnace and its backgrounds are extensively described in an archaeological study by Carmiggelt & Van den Eynde (1993). The discovery of this 17^{th} century furnace is unique in the Netherlands; comparable furnaces are only found in the United Kingdom. The historical date (1658 $\pm$ 1 AD) of the final use of the oven is known very precisely because it is related to the death of the pipe maker. The archaeomagnetic dating of this furnace, which is also described by Carmiggelt & Van den Eynde (1993), is re-evaluated here, using the latest version of the master curve.

Zeerijp. The furnace investigated in the province of Groningen near the village of Zeerijp is most probably a kiln in which sea shells were burnt for lime production. Because the bricks of the kiln are similar to the bricks of the local church which was built in the 13^{th} or 14^{th} century AD, it is assumed that the kiln also stems from this period.

Sampling and laboratory treatment

In most cases oriented cores were taken with an electric drill. If this was not possible because of the fragility of the baked material, we took oriented hand samples that were cored in the laboratory. The cores were oriented by measuring their dip and azimuth, or the strike and dip of a plane on the hand samples. A magnetic compass was used to obtain the azimuth, which was corrected for its (space and time-dependent) local deflection of true North. In the Netherlands, this deflection is between 2.9 and 3.6° to the west (IGRF 1995).

The magnetic remanence was measured using a modified Jelinek JR3 or a Jelinek JR5 spinner magnetometer. The specimens were stepwise demagnetised thermally (TH) or by alternating fields (AF). The ChRM direction was determined by least-square fitting (Kirschvink 1980) of the demagnetisation steps at which the ChRM is isolated.

Single-domain (SD) and/or pseudo-single-domain (PSD) (titano)magnetites are generally considered as stable magnetic minerals for palaeomagnetic purposes. Rock-magnetic experiments to test whether these minerals are present are described in the next section.

Rock magnetism

Apart from the primary remanence induced by the geomagnetic field at the last time of cooling, a secondary remanence may occur. Such a secondary remanence is often caused by magnetically viscous behaviour or by alterations of the magnetic minerals, such as may be caused by oxidation (weathering) which may take

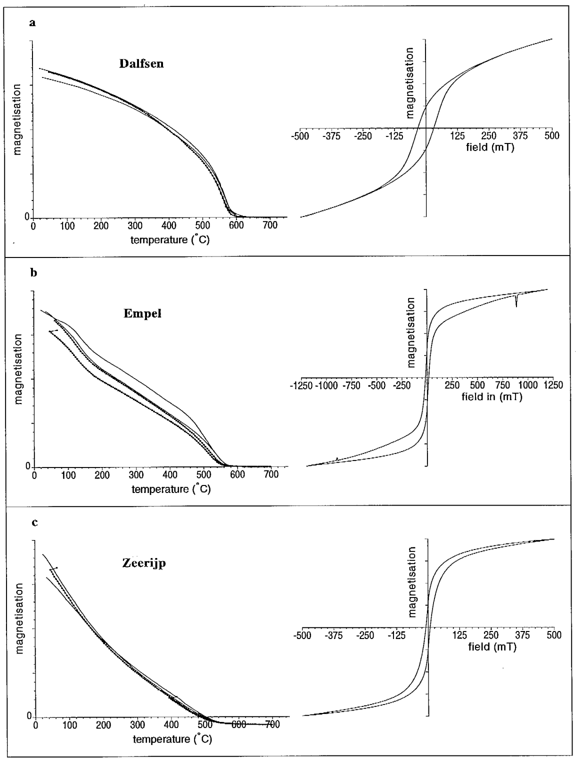

Figure 2. Curie-balance curves (left) and hysteresis loops (right). Vertical axes are in arbitrary units. The hysteresis loop and Curie-balance curve of the Dalfsen slag (a) show only magnetite. The 'wasp-waisted' hysteresis loops of the baked materials from Empel (b) and Zeerijp (c) indicate that two types of magnetic material are present. The decay at temperatures > 500° C in the Curie-balance curves points to the presence of (titano)magnetites as one of the two magnetic minerals.

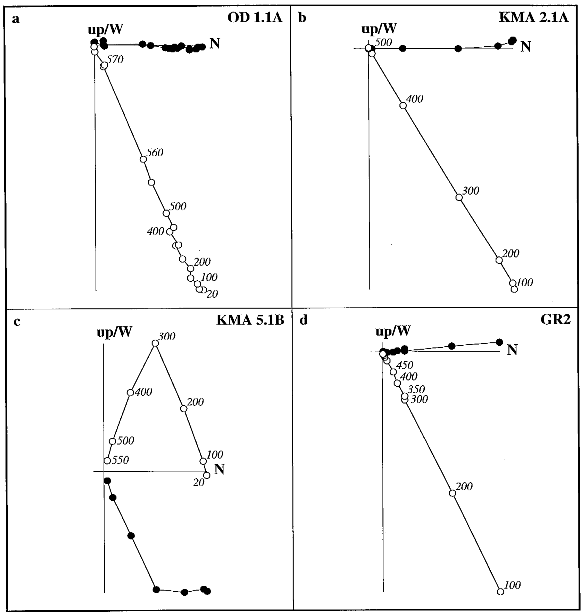

Figure 3. Typical thermal demagnetisation diagrams of specimens from Dalfsen (a), Breda KMA (b, c) and Zeerijp (d). Temperature steps of thermal demagnetisations (°C) are indicated. The Dalfsen demagnetisation shows a strong decay between 560 and 580 °C while the other specimens are demagnetised at approximately 500 °C. Specimen KMA 2.1A is from the kiln centre and its ChRM is demagnetised at 500 °C. Specimen KMA 5.1B is from an outer part of the kiln, and shows a ChRM component with maximum unblocking temperatures up to 300 °C; the north-east/up component unblocking at > 550 °C is induced during its manufacturing. Open (closed) symbols: projections onto horizontal (vertical, N–S) plane.

place centuries after the final heating. The direction of the secondary remanence may be mistaken for the geomagnetic field direction acquired during the final cooling. The stability of the magnetic minerals that carry a secondary remanence is generally different from that of the minerals that carry the primary remanence. Therefore, rock-magnetic experiments are carried out to control wether the magnetic remanence is indeed primary. The rock-magnetic experiments used in this study are hysteresis-loop experiments, performed on a MicroMag M2900, while thermomagnetic experiments were made in a modified Curie balance (Mullender et al. 1993). To obtain information on alterations of the magnetomineralogy during heating, each thermomagnetic experiment consisted of four successive heating/cooling cycles of 200, 400, 600 and 700 °C, respectively. For the rock-magnetic experiments we used sample fragments of a few tens of milligrams. Hysteresis loops with relatively low saturation fields of approximately 200 mT (Figure 2a) show that the slag specimens from Dalfsen are dominated by only one magnetic mineral. Because the hysteresis-loops of the baked materials are 'wasp-waisted' with high saturation fields of 500 mT or more (Figures 2b, c), these samples are dominated by two magnetic minerals (Roberts et al. 1995; Tauxe et al. 1996). Both observations are confirmed by the Curie balance experiments: the Dalfsen material only shows one Curie point at 580 °C. The Empel sample fragments show two Curie points: between 500° and 600 °C, and at approximately 150°C. The Curie-balance loops show that the Zeerijp material is mainly paramagnetic. However, it has also a magnetic fraction with a Curie point between 500 and 600 °C. The presence of (titano)magnetites is indicated by the decrease in intensity between 500 and 600 °C which is observed in all Curie-balance experiments. We therefore conclude that the remanences in all fireplaces are of primary origin.

Results of demagnetisations and average directions

The demagnetisation diagrams of all fireplaces are of high quality (examples in Figure 3), and the determination of the ChRM directions is straightforward. The demagnetisations of the Dalfsen specimens show characteristic maximum unblocking temperatures close to the Curie point of magnetite of 580 °C (Figure 3a) while in all other fireplaces the maximum unblocking temperatures are 550° or less (Figures 3b–d). Hence, the maximum heating temperatures of the furnaces must have been higher than 500 °C. The temperature reached in the Dalfsen furnace must have exceeded 1000 °C, as is confirmed by the slag found in this furnace. Apparently, magnetites prevail as can be seen from the highest unblocking temperatures and from the Curie-balance experiments (Figure 2). Sometimes lower blocking temperatures occur, which can be illustrated by the demagnetisations of specimens from bricks taken from the KMA furnace in Breda. Here, most of the samples were taken in the central part of the furnace except for two which were taken at the outer parts. The ChRM of a specimen from the centre is removed at 500 °C (Figure 3b) while in a specimen from the outer part the ChRM is removed between 20 and 300 °C. At higher temperatures up to 550 °C a second component is observed (Figure 3c). The north-east/up direction of this second component is not consistent with any expected geomagnetic field direction at this latitude. It must have been introduced during the manufacturing of the brick and thus is not relevant for the archaeomagnetic directions. The demagnetisation of the ChRM component at temperatures between 20 and 300 °C indicates that temperatures higher than 300 °C were never reached in the outer part of the KMA furnace.

Using Fisher (1953) statistics, the average ChRM directions for each independently orientated core or hand sample have been calculated. These average directions were then used to calculate the overall mean ChRM direction of each fireplace (Table 2). The α_{95} circles of confidence are poorly defined for two fireplaces (KMA furnace in Breda and Nijmegen limestone kiln) because the number of ChRM directions that make up the average direction is less than seven. Nevertheless, these circles are used to estimate the error in the archaeomagnetic age determinations in all fireplaces with the exception of the Zeerijp fireplace which yielded only one independent direction. Magnetic refraction, i.e. a shallowing of the inclination in floor samples and a deviation to the east (west) in the western (eastern) side of the structure, has been observed in several archaeomagnetic studies (Aitken & Hawley 1971). Such refraction is very difficult to observe if the number of samples is small and the sampling limited to a small part of the kiln (Hus & Geeraerts 1995). It is generally not more than a few degrees or non-existent, although Soffel & Schurr (1990) and Hus & Geeraerts (1995) show that occasionally the refraction may be much larger. We have not corrected for refraction because its amount is unknown. Moreover, for the construction of the British master curve this correction was not applied either.

The average directions and the α_{95} circles of confidence are compared with the secular-variation master curve to determine the archaeomagnetic ages. In addition, we also estimated the ages after a 3° westward translation of the average directions because the (unknown) Dutch master curve may be $\sim$3° east of the British curve.

New data for the archaeomagnetic database

Because Tarling & Dobson (1995) used only grades 3 to 5 for their archaeomagnetic database, all our results can be used for the definition of the reference curve (Table 2), except for those from Dalfsen and Zeerijp. The grades 1 and 2 are used only to assist in the evaluation of the higher grades. The archaeological age of the Zeerijp kiln (no grade assigned) is expected to be the 13^{th} or 14^{th} century. The ChRM direction of one of the Zeerijp samples strongly deviates from the direction expected for its archaeological age (Figure 4). The ChRM inclination of this sample is close to the inclination known from the secular-variation curve for this age and also close to the inclination of the other sample taken during the second sampling, but the declination is at least 15° too far west. A deflection in the declination can be explained by an error in azimuthal orientation during sampling. Hence, the archaeomagnetic age determination is based on only one sample. This implies that for the construction of the archaeo- magnetic master curve the ChRM direction of the Zeerijp fireplace cannot be used.

Comparison of the ChRM with the British master curve

This study aims to date the fireplaces by correlating their average archaeomagnetic directions to the British master curve (Tarling & Dobson 1995). For clarity,

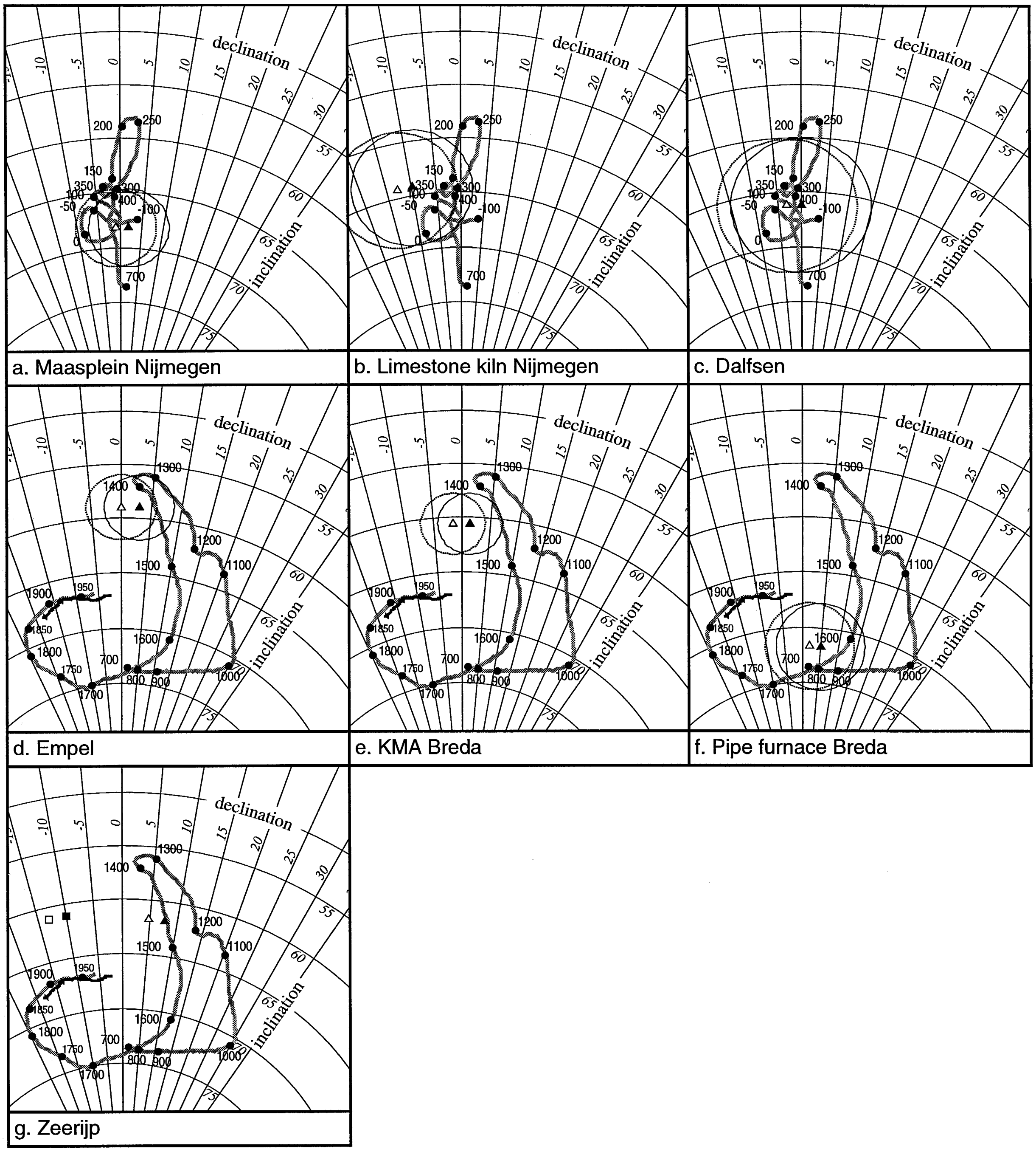

Figure 4. Results from the seven investigated fireplaces (a-g) plotted against the revised British master curve of secular variation, redrawn from Tarling & Dobson (1995) and transferred to the city of Utrecht in the centre of the Netherlands. For clarity, the curve is split into two parts: 100 BC to 700 AD (a–c) and 700 AD to present (d–g). The black line in d–g represents the measured secular variation in the Netherlands since 1862. It is approximately 3° east of the British master curve. ▲: average ChRM direction together with its α_{95} circle. △: average ChRM direction after a 3° westward correction. Squares in Zeerijp diagram represent the average direction (with (□) and without (■) westward correction) of a hand sample with an azimuthal orientation error; triangles represent the direction of the sample, taken during a second sampling.

Table 2. Results of the archaeomagnetic study of the seven fireplaces; for locations see Figure 1. Archaeological ages (in years AD) are given as lower and upper age limits. The average ChRM based on N samples and transposed to Utrecht via VGP correction is given as declination (dec) and inclination (inc), together with the cone of confidence (α_{95}). Archaeomagnetic ages are given with their error which is based on the α_{95}. The estimates of the Empel fireplace and Breda pipe furnace are respectively 1400 and 1640, after a 3° westward correction (see text for further explanation). Grades are assigned according to the classification scheme in Table 1. For the Zeerijp fireplace no grade is assigned: no error could be given because the age estimate is based on only one sample. N: number of samples.

Site	Archaeological age		ChRM direction				Archaeomagnetic	
	from	to	dec	inc	α_{95}	N	age	grade
Nijmegen Maasplein	50	100	2.0	68.2	3.5	9	60 ± 80	4
Nijmegen limestone kiln	300	400	350.1	64.2	5.3	6	350 ± 100	3
Dalfsen	200	400	359.9	66.2	6.1	7	440 ± 160	1
Empel	1400	1450	3.0	59.0	3.0	11	1420 ± 40	5
Breda KMA	1450	1475	1.4	60.6	2.8	5	1440 ± 50	5
Breda pipe furnace	1657	1659	5.0	71.7	3.9	11	1630 ± 50	5
Zeeprijp	1200	1400	7.7	61.8		1	1475 ??	–

we have split this curve into an older part from 100 BC to 700 AD and a younger part from 700 AD to present. Based on archaeological evidence we used for each kiln either the younger or the older part of the curve (Figure 4). The best archaeomagnetic age estimate of each fireplace is the point of the curve that is closest to the average ChRM direction, provided that this estimate does not contradict the archaeological age estimate.

The results of the archaeomagnetic age determinations are summarised in Table 2. The average directions of six out of seven fireplaces do not contradict the archaeological data. The archaeomagnetic age of the Zeerijp fireplace has not been determined because the direction of the remanence strongly deviates from any expected direction.

Discussion

The reliability of the archaeomagnetic age determination (Figure 4) of both Nijmegen kilns and the Dalfsen furnace, using the first part (100 BC–700 AD) of the master curve may be questioned. Firstly because it is still not clear whether the early Roman part of the secular variation curve is east or west of the late Roman part of the curve (Tarling & Dobson 1995). Secondly and more importantly, because the variation in direction of the geomagnetic field during this part of the master curve is very small. The α_{95} circles should be extremely small ($< 1°$) to be able to refine the archaeological age estimates. The α_{95} circles of the three fireplaces are between 3.5° and 6.0°, and they cover the major part of the 100 BC–700 AD master curve. This results in uncertain archaeomagnetic age determinations and large error estimates. Increasing the number of independently sampled cores will generally decrease the α_{95}. To arrive at $\alpha_{95} = 1°$, many cores should be taken, but the numbers of cores are generally limited by the brittleness of the baked materials or by the fact that the fireplaces are to be conserved: archaeomagnetic sampling inevitably leads to damage of the kilns.

Nijmegen. The average ChRM directions of the Maasplein fireplace are close to a junction of three parts of the master curve (100 to 50 BC, 0 to 100 AD, or 400 to 600 AD) of which archaeological data provided by misfires exclude the first and the third parts. Consequently, the best archaeomagnetic age estimate is 50 AD ± 50.

The archaeomagnetic age of the Nijmegen limestone kiln is late Roman (300 to 400 AD). The nearest point of the curve (100 AD), however, cannot be the most appropriate archaeomagnetic age: the observation that the kiln was built against a wall built of volcanic tuff excludes that it was constructed before 200 AD since tuff was only imported after this time (Willems 1986). Further, there is no indication that raw limestone was used in the Netherlands before 300 AD. Therefore, 350 AD ± 100 is the best archaeomagnetic age estimate. An alternative option is that the remanence was induced recently because the average direction is also quite close to the present-day field direction. One of the limestone kiln samples, however, shows a two-component demagnetisation (see Figure 3 in Langereis & Kars 1990), similar to the two-component demagnetisations of one of the Breda KMA samples (Figure 3c). This indicates that the remanence is primary (acquired during heating), rather than secondary (induced recently).

Dalfsen. The average direction of the Dalfsen furnace, both before and after the 3° westward correction, is in the cluster of the 100 BC–700 AD part of the master curve, while the error is so large that α_{95} encloses this part almost entirely. At best, it can be said that the estimated archaeological age of the 3^{th} to 4^{th} century is not in contradiction with the average ChRM direction.

Empel. The archaeomagnetic age of the Empel kiln is 1420 AD ± 40, or 1400 AD ± 40 after the 3° westward correction. This age fits very well with the first quarter of the 15^{th} century based on the archaeological data.

Breda. The average directions of the Breda KMA furnace indicate that the date of final heating is 1440 AD ± 50. This archaeomagnetic age fits very well with the final use of the furnace in the third quarter of the 15^{th} century. The average direction of the tobacco pipe kiln from Breda indicates an archaeomagnetic age of 1630 AD ± 50 or 1640 AD ± 50 after a 3° westward correction. This in good agreement with the archaeological age of 1658 AD ± 1.

Zeerijp. The determined age of the Zeerijp kiln is approximately 1475 AD, which is 75 to 275 years younger than the archaeologically expected 13^{th} to 14^{th} century. This discrepancy can be explained by a re-use of the bricks for the construction of the kiln after the building of the church. Such a re-use is observed quite often. In the near future, ^{14}C dating on tree remains found in the ashes, will be performed to solve this problem. As stated before, the archaeomagnetic age determination is based on only one sample and is therefore very poorly defined while no error can be calculated.

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