The magnitude of the palaeomagnetic field: a new non-thermal, non-detrital method using Sun-dried bricks

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Summary. A new method for determining the magnitude of the palaeomagnetic field is described. The material used is adobe Sun-dried mud brick, and some of the magnetic properties of these bricks are described. The magnetization acquired by the mud in the higher coercive force region seems to be caused by shear strain (squeezing) alone. This magnetization is called an SRM. The method is tested on a modern adobe brick from Lima, and it is shown to be accurate and repeatable. The method may also be used to determine values of \( D \) and \( I \), if the adobe brick is found in situ. Three results from old adobe bricks — two from Peru and one from Egypt — are presented and are compared with the world-wide average of published ancient VDM's.

1 Introduction

Several established methods already exist for determining the magnitude of the Earth's magnetic field. Some of these (Koenigsberger 1938; Momose 1963; Thellier & Thellier 1959; Wilson 1961; Coe 1967; Kono 1974; Shaw 1974; Tanguy 1973; Domen 1974) are based on the use of thermal remanent magnetization (TRM). McElhinny & Evans (1968) and Van Zijl (1961) used alternating field techniques. Markert & Heller (1972), and Banerjee & Mellema (1974) used anhysteretic remanent magnetization (ARM) methods. Johnson, Murphy & Torreson (1948) used a method involving detrital remanent magnetization of sediments.

The new method described in this paper is one that uses adobe bricks as the material, and relies upon the fact that mud can acquire a magnetization which seems to be caused by shear action while flowing. The value of this technique lies in its reliability, and in the availability of material. It is important because it gives us a technique for determining the variation of the magnitude of the Earth's magnetic field during archaeological time which is independent of the use of thermoremanent magnetization (TRM), and so it can serve as a check on the values obtained from materials such as ceramics and kilns. We are studying this time variation of the Earth's magnetic field so that we will gain more knowledge about the mechanism of the production of the field, since any knowledge of its variation with time will necessarily place constraints on models of how the field is generated.
The method of making adobe bricks, both in Peru and in Egypt (where our samples come from) has remained largely unaltered through many millenia. For example, a picture of men at work making mud bricks is preserved on an ancient Egyptian frieze from Thebes, and written accounts are also preserved. The brick is made by flinging the mud into a wooden former, which is then removed, leaving the brick to dry in the sun. Typical drying time for such a brick in Peru is about three days to a week, depending on weather, as we learnt from a modern brick-maker in Peru in the summer of 1975. A lot of the original work on the magnetic properties of the adobe bricks was carried out on a brick which was made in Lima in 1975 August. The first problem was to determine the cause of magnetization.

**Mechanism of magnetization**

A sample of a mud brick was left in a known field (50 $\mu$T) in the laboratory for 15 days, and was kept wet by adding water at regular intervals so that the sample was wetter than normal ground conditions, but was not stirred or mixed. No change in magnetization was observed, other than a small amount along the direction of the applied field compatible with the acquisition of a viscous remanent magnetization (VRM) over the given time, when compared with the viscous magnetization acquired by other dry samples. We conclude that wetting alone does not magnetize this adobe brick. Also, since we are not dealing with a sediment, then post-depositional detrital remanent magnetization (Irving & Major 1964; Løvlie 1976) cannot be the mechanism of magnetization.

When a sample of mud is either thrown into a container or stirred inside a container, the sample is always magnetized along the direction of the applied field. This is demonstrated in Figs 1 and 2. To prove that it was the throwing or stirring only which caused the magnetization, the following experiment was carried out. A plastic cubic container was aligned with its $X$-axis parallel to the applied field. After the mud was stirred in the container, the cube...
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was turned through 90° and left to dry with its Y-axis now along the applied field. The result was that the percentage of magnetization along Y was only 15 per cent which is compatible with a VRM acquired over the same time, and all of this was removed by af demagnetization to 10 mT maximum field. Hence the magnetization acquired after the stirring was only in the low-coercive-force region, and in the method to be described, this part of the coercive force spectrum is not used to determine the magnitude of the magnetic field. In another experiment, the cube was again rotated through 90° after the sample had been mixed, but it was then vibrated 20 times using an adapted vibrating engraver, each application lasting about 2 s. The vibrator was operating at 50 Hz direct from the mains supply. Even with this vigorous treatment, only 20 per cent of the magnetization was along Y, and this was reduced to about 10 per cent by af demagnetization to 20 mT.

In another experiment, a small adobe brick (10 × 10 × 5 cm) was made in the laboratory by flinging the mud into a wooden box, with its X-axis along the direction of the applied field. The box was then rotated through 90°, and the mud brick was removed by tipping the box upside down. It was then left to dry in this position with its Y-axis along the direction of the applied field. The result was that 8 per cent of the total magnetization was along the Y-axis, and this was removed by af demagnetization to 60 mT.

We conclude from these experiments that the magnetization acquired by the mud in the higher coercive force region seems to be caused by shear strain (squeezing) alone. The magnetization acquired by an adobe sample after it has been formed in the laboratory will be called a shear remanent magnetization (SRM) because we believe it may be due to the shear during the flow deformation necessary to conform to the shape of the container it is moulded in. But whatever the internal mechanism may be, the magnetization of adobe bricks is certainly created during the entry of the mud into the mould.

3 A test using a modern adobe brick (Code P1)

The method used for producing the SRM in the laboratory involves the use of a piston and cylinder arrangement shown in Fig. 5. The mud is crushed and mixed with water, and then packed into the cylinder. The assembly is then placed on top of another plastic cylinder which fits into the cubic plastic container. There is a small hole in the base of the second cylinder to allow air to escape. By depressing the piston forcibly, the mud can be ‘squeezed’ or thrown into the second cylinder in a way which necessarily involves shear deformation. It is then left to dry.
Figure 3. A summary of all of the NRM–SRM results quoted in the paper. Sample P1m was rejected because the SRM was totally unstable on demagnetizing. Sample P34b was rejected because the direction of the NRM was unstable on demagnetizing. The numbers next to the dots refer to the alternating field strength (Tesla).
In Fig. 3, the top four graphs show the final results of the experiments on four specimens from a modern brick from Lima. The NRM is plotted against the SRM using the demagnetizing alternating field as parameter. The slope of the NRM/SRM graph should give the ratio of the original field in which the brick was made ($B_{anc}$) to the field in which the SRM was given ($B_{lab}$), as is the case for TRM's. So the ancient field is calculated from $B_{anc} = B_{lab} \times$ gradient. These four results give an average value for the magnitude of the field of

$$B_{anc} = 29 \pm 2 \mu T$$

where the error is the rms deviation from the mean. (The magnitude of the Earth's field was 28 $\mu T$ in 1966 as recorded at the Huancayo Observatory which is 312 km from Lima. The IGRF field value for Lima in 1975 was 28 $\mu T$.)

An earlier set of six results on the modern bricks, however, had yielded straight line plots on the NRM/SRM graph which did not go through the origin. This implied that the SRM given to the sample had a different coercive force spectrum to the NRM. An example of this is shown in Fig. 4. Assuming the straight line was the correct part of the graph to use, even though it did not pass through the origin, the average value of the magnitude of the field for these six samples would be $30 \pm 2 \mu T$. But the problem of the NRM/SRM plot not going through the origin led to certain changes in the method of producing the SRM. It was clear that although the slope of the NRM/SRM graph seemed to be giving the correct value for the magnitude of the field, the sample was acquiring too much magnetization in the high-coercive-force region.

Figure 4. An example of a plot of NRM–SRM which produced a straight line but which did not go through the origin. The SRM was produced by stirring. Some values of the alternating field are indicated on the diagram.
Figure 5. The piston and cylinder arrangement used to produce an SRM. The piston is 4 cm long and 2.0 cm in diameter. (Inset) This sketch shows how the mud was packed into the cylinder at different angles: (i) Perpendicular to the sides of the cylinder, (ii) at a steep angle to the sides, and (iii) at a shallow angle.

One possible reason for this could have been that the samples had not been left long enough to dry completely before being measured. We studied the effect of drying time on the magnitude of the SRM, and found that the magnitude did decrease until the sample had been left for about 75 hr, and remained unaltered from then on. From this, we concluded that the samples must be left to dry for at least four days before being measured. However, proper drying still did not make the NRM/SRM slope go through the origin. Another possible cause could have been that there was not a linear relationship between the applied field and the magnetization of the SRM throughout the whole of the coercive force spectrum. Since the original sample was set in a field near to 30 $\mu$T, an SRM was given in this field in the laboratory, rather than in the 50 $\mu$T previously used. However, the line still did not go through the origin (sample P1J), although the slope of the linear portion still led to an apparent value for $B_{\text{anc}}$ of 29 $\mu$T. Another way of trying to solve this problem was by only demagnetizing the NRM and SRM to 100 mT instead of 150 mT. This did not solve the problem, and so we decided to check if it was the mixing process that was making our NRM/SRM curves non-linear.

Originally, the SRM was given stirring the mud with a glass rod. It turns out, experimentally, that the 'stirring' is too efficient in the high-coercive-force region (meaning presumably 'for very fine grains'), compared to the original 'throwing' of the mud. So we devised a method of reproducing this 'throwing' action used by the original brick-maker. This is the method described at the beginning of this Section. Fig. 2 shows that using this method, the mud is magnetized along the direction of the applied field. Four results involving this
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method are shown in Fig. 3 (P1l, P1n, P1o, P1p). All lines go through the origin, and give the previously quoted ancient field value of $B_{\text{anc}} = 29 \pm 2 \mu T$ where the error is the rms deviation from the mean.

We therefore conclude that: (a) the piston method is good because it yields straight line plots which go through the origin, and therefore we are presumably reproducing well the original mechanism of magnetization, and (b) the modern brick tests the method, since we can compare the result we obtain with the known field value.

3.1 UNIFORMITY OF MAGNETIZATION

Six specimens from the modern brick were oriented and the NRM was demagnetized, so as to check that the direction of magnetization in the brick was uniform. In all six cases the direction became steady above alternating fields of 50–60 mT. The values for declination and inclination were

\[
D = 224^\circ \pm 2^\circ \quad \text{(arbitrary azimuthal orientation)}
\]

\[
I = -7^\circ \pm 2^\circ \quad \text{(relative to the horizontal in Peru)}
\]

where the error is the rms deviation from the mean. This shows that the brick is very uniformly magnetized throughout. A sample taken from a corner of the brick, however, showed a variation in direction from the above of 16°, so it seems to be important to try to avoid using the corners of bricks if possible. Presumably the extreme deformation necessary for the mud to conform to sharp corners can rotate the magnetization away from the applied field direction.

3.2 THE LOWER-COERCIVE-FORCE REGION

In Fig. 6, a plot of NRM against SRM is given using all the values of the demagnetizing alternating field as parameter, including the lower-coercive-force region. It can be seen that there is a 'secondary' component of magnetization present. This secondary magnetization has so far been removed by between 30 and 60 mT maximum alternating field. It accounts for between 25 per cent (for the 1975 adobe) and 60 per cent (some 3000-yr old Egyptian bricks) of the NRM. This secondary component is possibly explained in terms of VRM. Several experiments on VRM’s were performed. In one case, the acquisition of a VRM over short time intervals was studied, after the NRM of a sample had been demagnetized in 20 mT. This was repeated after demagnetization in fields of 40, 60, 80, 100 and 150 mT. The result of this experiment was that in each case no measurable VRM was acquired within 2 min after demagnetization. This ensured that in future experiments the samples could be measured after demagnetization before they acquired a VRM, as it takes about a minute to measure a sample. In two other experiments, the VRM acquired by two samples after 16 hr was removed by af demagnetization in a maximum field of 20 and 15 mT. It follows that a VRM acquired by these samples lies in the lower-coercive-force region, and may be responsible for the secondary component of magnetization present in the NRM.

3.3 REJECTION CRITERIA

For the purpose of calculating the ancient field strength, the lower-coercive-force region of the NRM/SRM graph is rejected on the basis of the stability of the NRM direction. Sometimes the secondary component has quite a stable direction itself, usually in the case of older samples. But when this is all removed, the stable direction remaining is taken to be that due to the Earth’s field at the time the brick was made. Some data also have to be rejected when
Figure 6. The plot of NRM–SRM using the demagnetizing field as parameter. The points labelled R were rejected for the reasons explained in the Section 'Rejection criteria'. (Inset) A plot of the accepted data for sample P1n.
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The magnetic moment of the material becomes so weak that it is of the same order of magnitude as instrumental error. When this does occur it is usually in the very high-coercive-force region, where the alternating field is greater than 120 mT.

3.4 Linear relationship of the SRM to \( B \)

Two experiments were performed to check whether the SRM was linearly proportional to the applied field. Firstly, three successive SRM’s were given to a sample from an Egyptian brick. The first two were given in a 50-\( \mu \)T field, and a plot of SRM (1) against SRM (2) gave a gradient of 0.98 instead of 1.00, thus showing a 2 per cent variation from the theoretical value, since the two SRM’s should of course be identical. The third SRM was set in a 30-\( \mu \)T field, and a plot of SRM (2) against SRM (3) which should in theory give a gradient = 1.67, gave 1.75, which is a 5 per cent variation from the theoretical value. The slightly large value of 5 per cent could be due to a loss of material between the successive SRM’s.

Secondly, values for the modern field in Lima were obtained from different samples from the modern brick by giving the SRM in different applied fields. The fields used were 20, 30, 40 and 50 \( \mu \)T. The results of these experiments are shown in Table 1. Both of these experiments indicate that within experimental error, the magnetizations of the samples are linearly proportional to the applied field within the range 20–50 \( \mu \)T.

### Table 1.

A table showing the ancient field values obtained by using laboratory fields in the range 20–50 \( \mu \)T.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( B_{\text{lab}} (\mu \text{T}) )</th>
<th>( B_{\text{anc}} (\mu \text{T}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIJ</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>PIJ</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>PIQ</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>PIN</td>
<td>50</td>
<td>29</td>
</tr>
</tbody>
</table>

3.5 Dependence of the SRM on how the mud is packed into the cylinder

A series of experiments was performed to see if the angle at which the mud was packed into the cylinder affected the magnetization acquired by the SRM (see inset in Fig. 5).

In three separate experiments, samples of the modern adobe brick from Lima were packed into the cylinder at different angles, \( \alpha \). The angles used were 20°, 70° and 90°.

The values obtained for \( B_{\text{anc}} \) were 30, 32 and 31 \( \mu \)T respectively. So we conclude that the SRM is independent of the angle at which the mud is packed into the piston, and also that very little shear deformation seems to be needed to produce the SRM, if indeed that is the mechanism.

3.6 Declination and inclination from adobe bricks

This technique, using adobe bricks, also provides possibilities for determining values of declination \( D \) and inclination \( I \). After the removal of any secondary component of magnetization the stable direction of the NRM may be used to determine \( D \) and \( I \) for the magnetic field. If the brick was made in situ and found in situ, then these values of \( D \) and \( I \) will be
those of the archaeomagnetic field. If the brick was not made in situ, then assuming that the brick was made in a horizontal position, one can still derive within certain errors the value of $I$ but not of $D$.

In the case of the 1975 adobe from Lima, we know only the horizontal position of the brick. As previously described, six samples from this brick gave a value for $I = -7 \pm 2^\circ$. The IGRF value for the inclination of the field in Lima in 1975 is $0^\circ$, so the value obtained from the adobe brick is in reasonable agreement with this, allowing for local variations in the magnetic field, and for the possibility that the brick may not have been made in an exactly horizontal position.

The results discussed in this section demonstrate that using the piston injection method, we can simulate the original process by which the brick-maker unwittingly provided a magnetization which records the archaeomagnetic field. It is also clear that this magnetization is not easily altered by wetting or vibration, and that secondary magnetizations, at least of the bricks here studied, may be successfully removed by af demagnetization. The magnetization, called an SRM, is linear with applied steady field. Armed with this knowledge we evolved the following method of retrieving the ancient field strength.

4 Method of retrieving the ancient field strength

A core 2 cm in diameter and 1 cm long is taken from the dry adobe brick using a hole saw in a low-speed drill. The NRM of the core is measured, and it is then af demagnetized and remeasured in 5 mT intervals up to a maximum alternating field of 75 mT, and then in 10 mT intervals up to 150 mT. The sample is then, following a technique due to Shaw (1974), given an ARM — called ARM(1) — in a maximum af of 150 mT using a known constant field of 0.66 mT. This ARM is then af demagnetized in the same way as the NRM. The dry sample is then crushed, and a known amount of water is added. This is usually about five drops per gram, depending on the material being used. The correct amount of water for a particular brick has to be found, experimentally, so that the mud has the right consistency when mixed, and so that when it dries out no cracking occurs in the mud. The thoroughly mixed sample is put into the piston arrangement shown in Fig. 5. All this is carried out in a set of Rubens coils (Rubens 1945) which have a uniform field in the inner 1 m$^3$ of the coils. The field used for these experiments is 50 $\mu$T, and is along one axis of the coils. The sample is then thrown into the cylindrical container inside a plastic cube by depressing the piston forcibly.

Sufficient force must be used to ensure the mud is ejected by the piston into the cylinder. This ensures that the mud does not stick to the piston, and also reproduces the original throwing of the mud into its container. The sample is then left to dry for four days in the Rubens coils. The SRM is then af demagnetized in the same way as the NRM. Finally, a second ARM — ARM(2) — is given under the same conditions as ARM(1), and this is also af demagnetized and remeasured in the same intervals as the NRM.

A plot of NRM against SRM using the alternating field as parameter is then drawn (see Fig. 6). Then after rejection of data at low and high alternating fields as described in the previous section, the remaining part of the NRM/SRM graph is redrawn using a least-squares fit programme (see inset, Fig. 6). This line is forced through the origin, and it can be seen from the results themselves (Fig. 3) that this is justifiable. From this straight line we derive the magnitude of the ancient field $B_{anc}$, from

$$B_{anc} = B_{lab} \times \text{gradient}.$$
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As a check that the magnetic properties of the sample have not changed ARM(1) is then plotted against ARM(2) — see Fig. 7. This should give a straight line of gradient = 1.00. Any variation from unity is a measure of the degree of alteration undergone by the sample during the resetting of the SRM. If the gradient differs from unity by more than 5 per cent, the sample is rejected. Only two results out of 14 from the 1975 adobe brick from Lima had to be rejected, with ARM slopes of 1.07 and 0.92. Subsequent improvements in technique, including re-weighing of the samples at each stage of the procedure, have reduced even these errors, and it is expected that the 5 per cent rejection limit — which was purely an arbitrary choice — may in future be reduced to perhaps as little as 2 or 3 per cent. Fig. 8 shows a histogram of all ARM(1)—ARM(2) slopes so far obtained, which demonstrates the stability of the magnetic material to resetting. It is far more stable than are pottery and igneous rocks to reheating.

It must be emphasized that the ARM's are not used in any way to calculate $B_{anc}$. 

Figure 7. An example of a plot of ARM(1)—ARM(2). The sample is rejected if the gradient differs from unity by more than ±5 per cent. With improved technique, it is expected that this value can be lowered to 2 or 3 per cent.
5 Application of the method

This method can be applied to adobe bricks from anywhere in the world and of any age. We have some results which are derived from ancient adobe bricks from Peru, and one result from an Egyptian brick (see Table 2).

5.1 A BRICK FROM THE VIRU VALLEY, PERU

This brick (Code P34 — see Fig. 3) came from an adobe rectangular enclosure, dated archaeologically as 1450 ± 100 AD. The sample was collected by Dr J. Shaw with the help of Dr M. West and the members of the Viru Valley Project (Los Angeles County Museum of Natural History).

Table 2. Results and data.

<table>
<thead>
<tr>
<th>Code</th>
<th>Site</th>
<th>Lat</th>
<th>Long</th>
<th>Cores</th>
<th>$B_{anc}$ ($\mu T$)</th>
<th>VADM ($\times 10^{21}$ Am$^{-3}$)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Lima</td>
<td>-12.0</td>
<td>283</td>
<td>4</td>
<td>29 ± 2</td>
<td>7.2 ± 0.5</td>
<td>1975 AD</td>
</tr>
<tr>
<td>P34</td>
<td>Viru</td>
<td>-8.5</td>
<td>281</td>
<td>4</td>
<td>44 ± 1</td>
<td>10.9 ± 0.2</td>
<td>1450 ± 100 AD</td>
</tr>
<tr>
<td>P17</td>
<td>Moche</td>
<td>-8.0</td>
<td>281</td>
<td>2</td>
<td>49 ± 2</td>
<td>12.3 ± 0.5</td>
<td>700 ± 100 AD</td>
</tr>
<tr>
<td>E9</td>
<td>——</td>
<td>25</td>
<td>35</td>
<td>2</td>
<td>43 ± 1</td>
<td>8.9 ± 0.3</td>
<td>1440 ± 120 BC</td>
</tr>
</tbody>
</table>

Notes:

(1) The code numbers from Peru are based on site numbers used by the joint Liverpool/Oxford expedition to Peru in 1975.
(2) The code number for the Egyptian sample is just to distinguish the brick from other samples of Egyptian brick we have for our use.
(3) The site of the Egyptian brick is not precisely known, so to obtain a VADM value, the latitude and longitude shown were used.
Figure 9. A comparison of the adobe results with the data published by Cox (1969). The adobe results are shown by the numbered crosses: No. 1 is the modern adobe from Lima; No. 2 is P34; No. 3 is P17; No. 4 is E9. Each dot represents the average value of data over a 500-yr period, and over many longitudes and latitudes of sites, of the dipole moment of the magnetic field. Since we do not know the values of $D$ and $I$ for each of our samples, they have all been expressed as virtual axial dipole moments, which may be up to 10 per cent different from the virtual dipole moment values.
5.2 A Brick from the Moche Valley, Peru

This brick (Code p17 — see Fig. 3) came from a large adobe pyramid at Huaca del Sol, and is dated archaeologically as 700 ± 100 AD. It was collected by Dr J. Shaw with the help of Dr M. Mosely (Peabody Museum, Harvard University).

5.3 An Egyptian Brick

This brick (Code E9 — Fig. 3) has been dated by means of an inscription on the brick and comes from the 18th Dynasty (1440 ± 120 BC). A sample of this brick was given to us by Dr D. Downs of the Merseyside County Museum.

Fig. 9 shows how these results compare with the world-wide average of published ancient VDM’s, all derived from fired material. The graph is the one published by Cox (1969) which is based on the values collated by Smith (1968). Cox’s values are shown in the diagram as dots. It is important to note that each dot represents an average value of data over a 500-yr period, and over many longitudes and latitudes of sites, of the dipole moment of the magnetic field. Since we do not know the values of \( D \) and \( I \) for each of our samples, they have all been expressed as virtual axial dipole moments (VADM’s). These may be up to 10 per cent different from the virtual dipole moment values, and this is indicated clearly in the case of the modern brick.

It can be seen that our local results are in acceptable agreement with the world average of the dipole moment, but until many more such results exist, no further geomagnetic conclusions can be reached.

The present paper establishes the feasibility of this new method, and provides the first few ancient field magnitudes. The method is simple, and it avoids the great difficulty always inherent in reheating fired material, that the magnetic properties are changed by heating. A moderately sensitive magnetometer has so far been sufficient, but a good af demagnetizer is very necessary, capable of coherently demagnetizing most samples up to 150 mT.

We feel that the method will be inherently capable of producing ancient geomagnetic field magnitudes with better than 5 per cent accuracy. It may become useful as an archaeomagnetic dating tool, once a sufficient number of firmly dated samples have been measured from any one locality.

Acknowledgments

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