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Archaeomagnetic Analyses of Six Glozelian Ceramic Artifacts

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An attempt has been made to measure the strength of the geomagnetic field at the time of manufacture of six ceramic artifacts from the controversial archaeological site at Glozel, in the Massif Central of France. A bisexual figurine appears to have been fabricated from clay without firing, while three other objects have been fired at high temperatures, but do not yield precise estimates of the original field strength. Measurements on specimens from two tablets bearing inscriptions in the apparently unique and undeciphered Glozelian form of writing show that they were last heated and allowed to cool in a magnetic field similar to the present-day geomagnetic field at Glozel. It is suggested that dates between 1500 BC and 1500 AD are unlikely for these tablets.

Introduction

Fifty-two years have elapsed since the discovery of the controversial site at Glozel and a majority of archaeologists have long regarded as fakes the strange assemblage of finds; particularly the pottery and terracotta objects, and bone fragments and pebbles with animal engravings, many of which carry inscriptions in an undeciphered writing found only at Glozel. Recently, however, a new era of open discussion has begun about the possible antiquity of the finds, following the publication of a preliminary report by McKerrell *et al.* (1974) of a comprehensive thermoluminescence investigation of ceramics from Glozel. Their report was illustrated with sets of glow curves from 19 Glozelian objects, all of which showed natural thermoluminescence levels at least an order of magnitude greater than those which could, they argued, have accumulated in about 50 years. This finding was clearly inconsistent with the archaeological view that the Glozel ceramics were fired in the early part of this century and the authors tentatively suggested thermoluminescence age limits of 700 BC–100 AD for the objects sampled.

In addition to the conflicting eyewitness and police accounts of incidents in the 1920s (summarized by McKerrell *et al.*, 1974, and discussed in the accompanying editorial in *Antiquity*), there are strong archaeological objections to the Glozel finds. Renfrew (1975) drew attention to the bone objects and pebbles bearing animal engravings (in the style of palaeolithic engravings older than 10 000 year bp) together with Glozelian inscriptions (similar to those on the ceramics for which McKerrell *et al.* (1974) suggested thermoluminescence age limits of 700 BC–100AD), and pointed out that it is difficult to reconcile such chronological inconsistencies with the authenticity of all the finds. Renfrew and many others have also stated that the uniqueness of the Glozelian finds as

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an assemblage (and the majority of them individually), as well as the complete absence of any object typical of the well-documented cultures of that region for the dates suggested by McKerrell *et al.* (1974), are strong arguments against their authenticity.

It is worth considering some of the ways in which a fabricator of ceramics might, in principle, either by accident or by design, confuse the results of a subsequent thermoluminescence analysis. When ceramics are fired or reheated to a temperature in excess of $\sim$450 °C, all previously-stored thermoluminescence of the type normally measured is erased. After cooling, the constituent minerals slowly accumulate new thermoluminescence because of the small amount of natural radioactivity in the ceramic and its surroundings. Given that there are no abnormal measurement difficulties, then the only known way in which a ceramic could possess thermoluminescence in excess of that appropriate to the combination of natural radiation levels and time elapsed since the last heating would be through *artificial irradiation* of one kind or another. There are, however, no reported cases in the literature of such an attempt, and McKerrell *et al.* (1975) and Aitken & Huxtable (1975) have already described details of experiments indicating that clandestine irradiation is an unlikely origin for the observed thermoluminiscence levels of *some* Glozelian ceramics.

But there are other possibilities which may have some bearing on the Glozel problem. A wide range of artifacts, which may superficially look like ceramics, can be made without firing and would therefore give misleading thermoluminescence results if they were not recognized. Shaped but unfired pottery (*clay ware*) changes colour and hardens as interstitial water is lost during drying; such material would exhibit essentially the same thermoluminescence as the raw material, without modification due to the manufacturing process. Artificial binding agents, such as plaster, lime, mortar, cement, glue, plastic, or even egg-white, can be used to increase the mechanical strength and genuine ceramic materials could be pulverized and substituted for some or all of the clay body; unfired artifacts containing older ceramic materials are here termed *pseudo-ceramics*. This possibility has been mentioned by Hall (1975). Provided that the binding does not give a large amount of spurious thermoluminescence (and arouse suspicion), a pseudo-ceramic could be fabricated with virtually any desired "instant thermoluminescence age".

Another technique, which might be used with the intention of misleading a wide variety of physical and chemical authenticity tests (and not just thermoluminescence analyses), is the *renovation of ancient ceramics*. New features and even shapes can be carved out of old objects, and if they are not refired at that time a subsequent thermoluminescence analysis would relate to the original firing of the sub-stratum rather than the date of renovation. In the case of terracotta material originally fired at temperatures not much above 500 °C, the clay may regain some of its plasticity when wet; it has been suggested that this might permit reshaping of the material (Warren, 1975).

If drying or curing of clay wares, pseudo- or renovated ceramics is carried out at a slightly elevated temperature, thermoluminescence normally released below that temperature would be erased; an appreciation of this effect can be gained by looking at the partial annealing of geological thermoluminescence in samples of Glozel clay at temperatures between 200 and 300 °C, as described by McKerrell *et al.* (1974). Artifacts would acquire additional thermoluminescence between fabrication and laboratory examination and any annealing effects would become less obvious with the passage of time.

In a situation where the results of a thermoluminescence investigation could conceivably be misleading, an independent method of analysis is obviously of value. Archaeomagnetic techniques are well-established for determining the strength of the magnetic field in which ceramics were allowed to cool after firing and, since the geomagnetic field strength at any given location has generally varied in the past, the method is capable of being used in a limited way for authentification. The same method can also be used to estimate firing temperatures below about 600 °C, and to discriminate between fired material and clay wares or pseudo-ceramics. Archaeomagnetic field strength analyses of small specimens, one from each of six Glozelian ceramic artifacts, are reported and discussed here.

Remanent Magnetization and the Thellier Method

The clay deposits which are used in the manufacture of pottery usually contain a few per cent by weight of various iron oxides and oxyhydroxides which carry only a weak remanent magnetization. These minerals are progressively dehydrated and oxidized if the material is heated and with prolonged baking at more than 700 °C in air all the iron minerals are converted to haematite. If the temperature is raised above about 1000 °C in air, or the material is fired in a reducing atmosphere, fine-grained magnetite may be produced instead of haematite. As the material cools, it acquires a relatively strong and stable *thermoremanent magnetization* (t.r.m.) which is both proportional and parallel to the external magnetic field.

The acquisition of thermoremanence is a continuous process with cooling between the Curie or Néel temperature (675 °C for haematite; 580 °C for magnetite) and the final ambient temperature (about 20 °C). This is because the magnetic minerals generally have a broad distribution in grain size and shape and therefore in *blocking temperature*, which is the temperature below which the small remanent magnetization of a particular grain is locked or frozen in direction. Provided the grains are single-domained (that is, small enough for the internal magnetic ordering to be in the same direction throughout the grain) and are dispersed so that there are no strong interactions between grains, the *partial t.r.m.* (or p.t.r.m.) *element* acquired in any given temperature interval will be uniquely associated with that interval and completely independent of the state of magnetization of grains with blocking temperatures outside that interval. This leads to the *law of additivity of p.t.r.m.* (Thellier, 1951), which states that the observed total t.r.m. is equal to the vector sum of all the discrete p.t.r.m. elements acquired separately over consecutive arbitrary temperature intervals.

Archaeomagnetic field strength measurements can be made on baked material using the Thellier & Thellier (1959) method, with the minor modification that the first heating and cooling at each temperature is performed in zero magnetic field (a procedure described by Nagata *et al.*, 1963 and Coe, 1967*a*). The original magnetization in the specimen, termed the *natural remanent magnetization* (n.r.m.) is partially destroyed (*demagnetized*) during the first heating and the remaining *partial n.r.m.* (p.n.r.m.) is measured. The specimen is then reheated to exactly the same temperature, cooled in a measured laboratory magnetic field to give it a *partial t.r.m.* (p.t.r.m.) in addition to the remaining p.n.r.m., and remeasured. The p.t.r.m. value is obtained by vector subtraction of the first measurement from the second, and the double-heating process is repeated at successively higher temperatures. If the n.r.m. is a t.r.m., the specimen's t.r.m.-bearing capacity remains unchanged at all temperatures and the law of additivity is obeyed, then the points on a graph of remaining p.n.r.m. against acquired p.t.r.m. for each temperature will define a straight line with negative slope equal to the ratio of original to laboratory magnetic fields. The plots are usually referred to as *n.r.m.–t.r.m. diagrams*.

If a Thellier measurement is attempted on a specimen of unbaked material, the soft magnetization characteristic of such material can easily be identified in comparison with the laboratory thermoremanence, since it is relatively much weaker and less stable and is usually distributed differently over the blocking temperature spectrum. For a pseudo-ceramic, the effect of pulverizing previously-baked material would be to mechanically randomize the orientation of the particles and reduce the resultant magnetization of the material; the contrast between its n.r.m. demagnetization and laboratory remagnetization behaviour would be similar to that of unbaked material.

Specimens of baked material which are magnetically well-behaved during the double-heating experiments yield n.r.m.–t.r.m. diagrams in which the points are always slightly scattered about the ideal straight line because of experimental error, and the Maximum Likelihood method (Kendall & Stuart, 1973: Chapter 29) can be used to obtain an estimate of the true slope. Linearity of the points, which corresponds to a constant ratio of the p.n.r.m. and p.t.r.m. elements associated with each temperature interval, is a powerful argument for the absence of physical or chemical changes since the original cooling and hence for the validity of the overall result.

Not infrequently, however, deviations from linearity are evident at low or high temperatures, and it is usual to exclude these points and derive an estimate of the slope from the linear portion of the n.r.m.–t.r.m. diagram. This procedure is justifiable when linearity exists over a considerable temperature range so that the consistency argument can still be invoked, and a plausible explanation can be given for any non-linear region. Examples of the latter are the effects of secondary *components* of magnetization at low temperatures, such as a superimposed *viscous remanent magnetization* (or v.r.m., which arises from the time-dependent relaxation of magnetization in grains with blocking temperatures just above the storage temperature) or a p.t.r.m. acquired from some intermediate temperature after the original firing (Thellier & Thellier, 1959; Coe, 1967*b*; Barbetti & McElhinny, 1976). Non-linear effects at high temperatures may arise if the material was originally baked below the Curie temperature (Bucha, 1971; Schwarz & Christie, 1967), or if physico-chemical changes affecting the t.r.m.-bearing minerals (such as grain size alteration or oxidation) occur during laboratory reheating (Nagata *et al.*, 1963; Coe, 1967*b*; Bucha, 1971). Non-linearity may be evident over most of the temperature range if the material has undergone weathering since the original firing, and is therefore contaminated with hydrated iron minerals which are unstable to laboratory reheating (Barbetti *et al.*, 1976). All the above forms of non-ideal behaviour are now well-documented.

The particular method used later in this article for interpreting results from specimens with large secondary p.t.r.m. has not been described previously; it is, however, a minor variation using the law of additivity, and does not involve any new assumptions.

Artifacts Sampled

The following specimens for archaeomagnetic analysis were provided by H. McKerrell of the National Museum of Antiquities of Scotland, Edinburgh.

Glozel Clay

Formed into tablet and dried at about 100 °C at Edinburgh. Specimen 2 cm × 1 cm × 1 cm.

744004

Bisexual figurine, poorly fired, illustrated in Plate XXX*c* of McKerrell *et al.* (1974). The archaeomagnetic specimen was a 7 mm thick cross-sectional slice through the phallus.

744105

Round hollow lamp, apparently well-fired light red pottery (Munsell colour 2.5YR 6/8) with white flecks. Specimen 2 cm × 1·5 cm × 1 cm thick from the side of vessel, extending from the rim to the base.

744106

Face urn, colour and texture identical to 744105. Plate XXX*b* of McKerrell *et al.* (1974). Specimen 2·5 cm × 2·5 cm × 1 cm deep from the inside surface, behind the inscription.

744109

Inscribed fragment of a tablet with vitrified surface, Plate XXXI*b* of McKerrell *et al.* (1974). Specimen 1·5 cm × 1 cm × 8 mm thick from the underside; about three-quarters of the specimen has a vesicular texture and appears glassy as though fused.

744112

Lamp fragment, colour and texture identical to 744105. Specimen 2·5 cm × 2 cm × 1 cm thick.

A specimen (198b1) was also obtained from the fragment of inscribed tablet for which a thermoluminescence analysis was reported by Aitken & Huxtable (1975) as follows.

198b1

Friable and apparently poorly-fired, reddish yellow (Munsell colour 5YR 6/8). Specimen 2 cm × 2 cm × 2 cm from the edge and through the full thickness of the tablet.

Results

Measurements of remanent magnetization were made using a Digico slow-speed computerized magnetometer (Molyneux, 1971) and the double-heatings performed with a furnace of the type described by Barbetti (1973). The first heatings at each temperature were made in zero magnetic field, achieved by surrounding the furnace with the Rubens coil system described by Weaver (1966). Specimens were replaced in exactly the same positions within the furnace for the second heatings and allowed to cool in the ambient laboratory magnetic field (48·3 μT).

The observed directions of stable n.r.m. components have been transferred to the artifacts by reassembling the specimens, and some inferences made about their orientation during the original firing, assuming that this occurred near Glozel and that limits for the value of geomagnetic inclination at the time of firing are +50° to +70° (inferred from the data of Thellier, 1966).

Magnetization curves and n.r.m.–t.r.m. diagrams are also presented for each specimen in turn. The implications of the results are discussed in the next section.

Glozel Clay

The small but measurable n.r.m. was found to disappear rapidly with demagnetization up to 200 °C (Figure 1), as would be expected if the n.r.m. is composed entirely of v.r.m. Above 200 °C, the very small values for partial n.r.m. are upper limits for the specimen magnetization, because a significant contribution to the measured value came from the combined noise levels of the magnetometer and slight inhomogeneities in the zero-field coil system. In contrast to the low values of p.n.r.m., the p.t.r.m. acquired by cooling in the laboratory magnetic field was very large for temperatures above about 300 °C.

Specimen 744004

The curves for p.n.r.m. and p.t.r.m. (1) for this specimen [Figure 2 (a)] are almost identical to those of unbaked Glozel clay (Figure 1). This does not necessarily mean, however, that the specimen was not mildly heated in antiquity, because any presumed ancient p.t.r.m. residing in grains with blocking temperatures below 100 °C might have been replaced by a v.r.m. in a matter of months, and that between 100 and 200 °C in a matter of a few thousand years. Assuming that the maximum possible v.r.m. would be no larger than the observed laboratory p.t.r.m. from 200 °C, and noting that this v.r.m. component could be in the opposite direction to a supposed ancient p.t.r.m., then, according to the p.t.r.m. (1) curve, v.r.m. could possibly have masked an ancient p.t.r.m. from 250 °C but not one from 300 °C. This specimen therefore cannot have been heated above 300 °C at any time in the past.

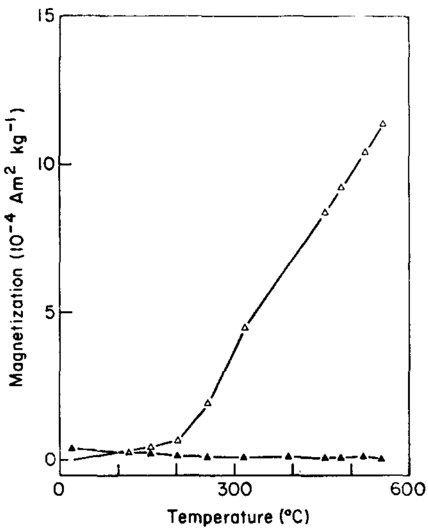

Figure 1. Specific magnetizations for a sample of unbaked Glozel clay measured after laboratory heating to and cooling from a series of discrete temperatures. The n.r.m. was progressively demagnetized by heating cycles in zero magnetic field, and values for the remaining partial n.r.m. (▲) are shown. Immediately after each demagnetization step, the specimen was remagnetized by repeating the heating cycle in a laboratory magnetic field of known strength; values for the acquired partial t.r.m. (△) are also shown.

After the pair of heatings at 471 °C, a new series of double-heatings was performed. The first p.t.r.m. from 471 °C was gradually demagnetized and the second set of acquired p.t.r.m. values was found to agree well with the first set [Figure 2 (a)], indicating that there had been no significant changes in the magnetic minerals during either the first or second series of laboratory heatings.

Figure 2 (b) illustrates the method of determining the original magnetic field strength and firing temperature; in this case the "original" specimen magnetization was a p.t.r.m. acquired during cooling from 471 °C in the laboratory magnetic field. A plot of partially demagnetized p.t.r.m. against the second set of acquired p.t.r.m. values yields, as expected, a straight line up to 452 °C with slope close to —1. An obvious change of slope occurs between 452 and 481 °C, indicating the temperature from which the initial magnetization was acquired.

Specimens 744105, 744106 and 744112

These were found to have magnetizations with stable directions up to at least 600 °C, after the first demagnetization step (155 °C) had removed the v.r.m. components. Artifact 744105 was probably fired either resting on its side or upside down, while artifact 744106 was probably fired with the "face" upside down.

N.r.m.–t.r.m. curves are illustrated in Figure 3 and considerable departures from linearity are evident. This could be interpreted as arising from small irreversible changes in the magnetic minerals during heating, but the changes do not closely resemble any of the well-documented types of behaviour (mentioned earlier). On closer inspection, another somewhat unusual possibility is evident. All three specimens acquire a relatively large p.t.r.m. on cooling from 155 °C to room temperature and the p.t.r.m. values for higher temperatures are generally less than twice this first value. Small changes in room

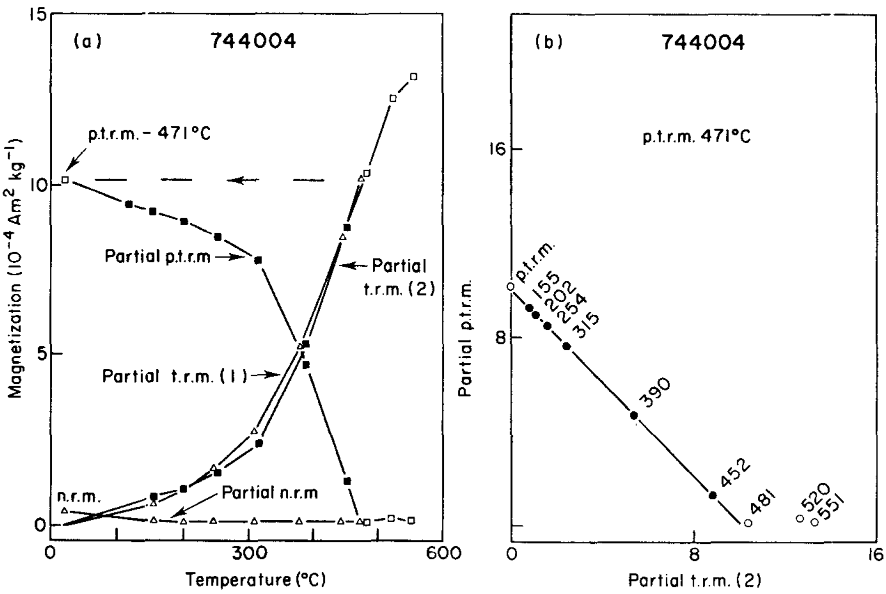

Figure 2. (a) Demagnetization and remagnetization curves for specimen 744004. The first series of double-heatings yielded the partial n.r.m. and partial t.r.m. (1) curves (triangles) which are similar to those shown for unbaked Glozel clay in Figure 1 (note the same vertical scales). After 471 °C, a new series of double-heatings was performed on the first p.t.r.m. from 471 °C, yielding the partial p.t.r.m. and partial t.r.m. (2) curves (solid squares); this time the heatings were continued beyond 471 °C (open squares). In (b), the remaining partial p.t.r.m. is plotted against acquired partial t.r.m. (2), with the double-heating temperature indicated in °C near the points. A straight line fitted through the points between 155 and 452 °C (solid symbols) has a slope of $-1{\cdot}00 \pm 0{\cdot}01$ (95 % confidence). At 481 °C and above, all the first p.t.r.m. from 471 °C had been entirely removed, but values of partial p.t.r.m. (2) continued to increase (open symbols).

temperature during the two weeks when the heatings and measurements were performed could therefore have caused the observed scatter of the points. This interpretation seems more likely, particularly if one notes the similar shapes of the diagrams for 744106 and 744122, with the relatively greater scatter of the former diagram; a second series of measurements with specimen 744105, performed at the same time but not illustrated here, exhibited the same trends. If this is correct and the presumed room temperature variations were short rather than long term, then the Maximum Likelihood slopes (Table 1, next section) should be unbiased estimates (albeit with large uncertainties) of the true slopes.

Specimen 744109

The directions of p.n.r.m. for this specimen were found to change gradually with demagnetization and were distributed in a plane [Figure 4 (a)]. A vector diagram of the p.n.r.m. in that plane indicates that the total n.r.m. is comprised of two components with directions differing by about 34°. The direction of the component residing in grains with blocking temperatures above about 400 °C is only approximately located, but the direction of the secondary (later) component is well-defined by the line fitted through the vector endpoints representing the p.n.r.m. measurements up to 315 °C. These results indicate that the tablet had originally cooled from above 481 °C to about 400 °C in one position (probably with the tablet lying flat and the inscription uppermost), and subsequently from 400 to 100 °C or below in another position (probably standing vertically). It is not possible to say whether the tablet was originally baked just once (and moved during the single cooling), or baked on two separate occasions (with the second heating to a temperature of about 400 °C).

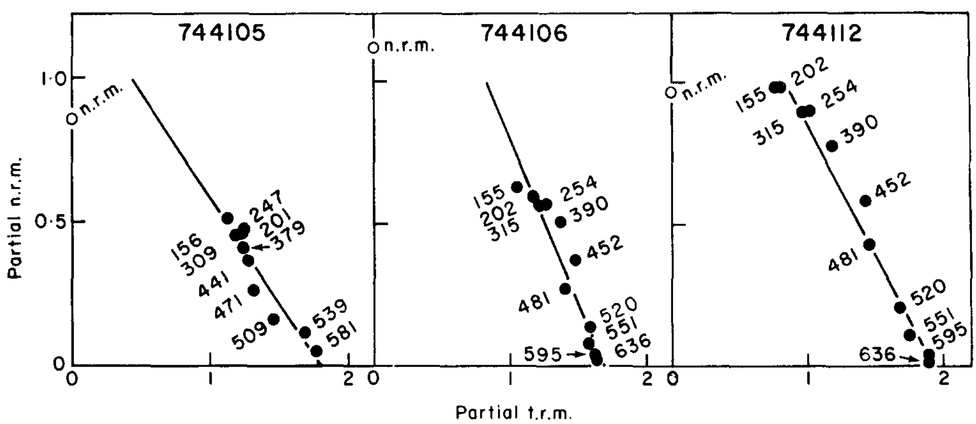

Figure 3. N.r.m.–t.r.m. diagrams for specimens from the three artifacts of apparently well-fired, light red pottery. Partial n.r.m. and t.r.m. values are in units of 10^{-4} Am^2 kg^{-1} and numbers near the points indicate heating temperatures in °C. Maximum Likelihood straight lines have been fitted, using all points except the initial n.r.m. which contains a large viscous component of magnetization.

The observed values of p.n.r.m. are vector resultants of elements in two different directions, but the method of finding the slope from an n.r.m.–t.r.m. diagram requires all p.n.r.m. and p.t.r.m. values to be represented effectively as scalar quantities. It is therefore necessaiy to find the magnitude of the p.n.r.m. element resident in each temperature interval (by vector subtraction of the successive measured p.n.r.m.) and to replace the measured p.n.r.m. for each temperature in the n.r.m.–t.r.m. diagram by the calculated scalai sum of all discrete elements of magnetization *above* that temperature. The changes for specimen 744109 [Figure 4(5)] are small, because the angle between the components of magnetization is small.

The points between 155 and 481 °C [Figure 4 (b)] are a good fit to a single straight line (correlation coefficient 0·9988) and there is no evidence for a change of slope between 390 and 452 °C. This suggests that the two components of magnetization were acquired by cooling in magnetic fields with the same strengths.

The change in slope between 481 and 520 °C is interesting, since it might be interpreted as suggesting that the specimen may not have been originally heated above 500 °C. This cannot be true of the vitrified portion (which showed no signs of melting during laboratory reheating to over 600 °C) so it would be necessary to infer the existence of

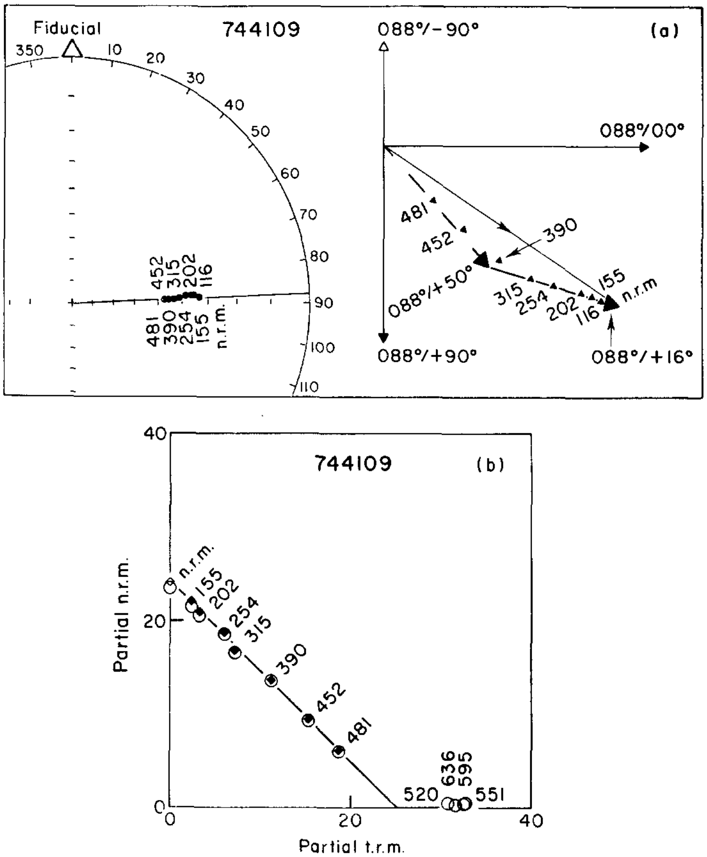

Figure 4. (a) An equal-angle stereographic projection of directions of partial n.r.m. is shown on the left. Solid symbols are used to indicate positive (downwards) inclinations. The directions are relative to an (arbitrary) fiducial mark on the specimen, and numbers near the points give the demagnetization temperatures in °C. The line through the points indicates the plane (oriented at 088°, dipping vertically) in which they are distributed. On the right, the magnitude and direction of the measured partial n.r.m. values are plotted as vectors in that plane, with the vector end-points indicated by the small triangles. The total n.r.m. vector (thin line) is seen to be the resultant of two components of magnetization, represented by the thick lines terminated with large triangles. During demagnetization, a component of magnetization in the direction 088°/+16° was being preferentially removed at temperatures below 390 °C, leaving a higher temperature component in a direction of approximately 088°/+50° which was removed at temperatures above 400 °C.
(b) N.r.m.–t.r.m. diagram for specimen 744109; values are in units of 10^{-4} $Am^2\ kg^{-1}$ and numbers near the points indicate heating temperatures in °C. The partial n.r.m. values actually measured (circles) are the vector resultants of two components of magnetization, and the scalar sums required for the n.r.m.–t.r.m. diagrams have been calculated and plotted (diamonds). A Maximum line has been fitted to the points marked by solid diamonds.

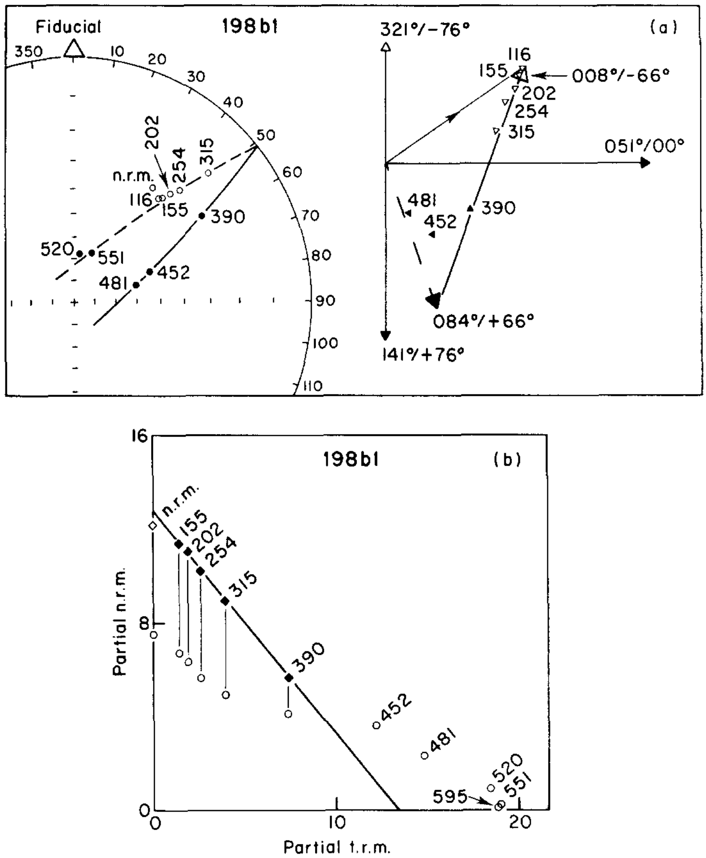

Figure 5. (a) An equal-angle stereographic projection of directions of partial n.r.m. for specimen 198b1 is shown on the left. Solid (open) symbols are used to indicate positive (negative, i.e. upwards) inclinations, numbers near the points give the demagnetization temperatures in °C, and the directions are relative to a fiducial arrow on the inscribed surface of the tablet. The presence of four components with different directions of magnetization is revealed; a primary component approximately in the direction 008°/+66° (isolated at 520 and 551 °C) on which are superimposed secondary and tertiary components and a small v.r.m. below 116 °C. The solid (dashed) curves indicate the trace of a plane in the lower (upper) hemisphere in which the directions between 116 and 481 °C lie. On the right, a diagram of the partial n.r.m. vectors in that plane illustrates how the directions of the secondary and tertiary components (thick lines) are resolved as 084°/+66° (approximately, therefore dashed) and 008°/−66°, respectively. The tertiary component was being selectively demagnetized at temperatures between 116 and 390 °C. Between 390 and 481 °C, the last of the tertiary component as well as some of the secondary component was being removed, and the vector endpoint for 452 °C does not lie on either of the thick lines.

(b) N.r.m.–t.r.m. diagram for specimen 198b1; symbols are the same as in Figure 4 (b).

a very large temperature gradient across the specimen during the first original heating, if this interpretation were found to be correct. However, there are other possible explanations for the change of slope. The p.n.r.m. remaining above 481 °C was completely erased between that temperature and 520 °C, so there are no measurements to confirm or deny the possible existence of yet another component of magnetization in a very different direction which might explain the results. Mineralogical changes, enabling the specimen to carry enhanced p.t.r.m., are also possible. There are, unfortunately, virtually no magnetic grains with blocking temperatures above 520 °C which might help to determine which explanation is the correct one.

Specimen 198b1

The directions of p.n.r.m. of this specimen were distributed in a plane and the magnetization comprised a small primary component, isolated above about 500 °C, on which were superimposed large secondary and tertiary components with directions differing by about 140° [Figure 5 (a)]. The direction of the secondary component, residing in grains with blocking temperatures between 500 and about 400 °C, is only approximately located but the direction of the tertiary (latest) component is well-defined by the line fitted through the vector endpoints between 116 and 390 °C. The results indicate that the tablet originally cooled from above 550 to about 500 °C with the inscribed surface uppermost, that it cooled from 500 to about 400 °C with the inscribed surface still uppermost but probably rotated anticlockwise by about 75° and that the final cooling from about 400 to 150 °C or below occurred with the tablet inverted. It is not possible to say whether these three positions are associated with movement during cooling or later reheating.

The n.r.m.–t.r.m. diagram is illustrated in Figure 5 (b) and, as with specimen 744109, it has been necessary to calculate scalar p.n.r.m. values. The changes in this case are rather large, because of the large difference in direction between the secondary and tertiary components. Even after recalculation, however, the points at 452 °C and above are not co-linear with those at lower temperatures; the reason is that the heating cycle at 452 °C demagnetized part of the secondary component even though not all of the tertiary component had yet been erased. This happens because there is a temperature gradient of about 30 °C between the centre and surface of a large specimen during the laboratory heatings; all temperatures quoted refer to the surface of the specimen. Analysis of the directions of the elements of magnetization removed in each temperature interval (calculated but not illustrated) showed that those for the intervals 390–452 °C and 452–481 °C were in fact combinations of parts of the secondary and tertiary components, and that a second-order resolution of those elements would be sufficient to make co-linear all the points up to 481 °C. A similar second-order resolution for the interval 481–520 °C could then make all the points up to 551 °C co-linear, but this technique could not be used to give a more precise estimate of the slope because of the possible errors arising from the uncertainty on the direction of the secondary component. Temperature gradients across the specimen during the *original* heatings could also have produced the same effect, but for this specimen the results can be satisfactorily explained in terms of the laboratory temperature gradients alone. The Maximum Likelihood slope (Table 1, next section) is therefore derived from the tertiary component of magnetization.

Discussion

One of the artifacts sampled, the bisexual figurine 744004, has been fabricated without being heated as high as 300 °C and must therefore be classed as a clay ware or as a pseudo-ceramic. In either case it is most unlikely that any apparent thermoluminescence age could be related to the date of fabrication of the finished artifact.

Each of the archaeomagnetic specimens from the other five artifacts has been heated to 500 °C or more at some time in the past and has not been pulverized and reconstituted since then. Therefore, once the possibility of artificial irradiation has been specifically excluded for a particular artifact, the thermoluminescence age should give the date of firing of its substratum. At the moment, full information on both types of measurement has been published for only one specific artifact, namely the tablet fragment 198b1, and it has a medieval age (Aitken & Huxtable, 1975).

Table 1. Summary of original firing temperatures and magnetic field strengths

Specimen	Estimated original firing temperature (°C)	Slope ± 95% confidence limits (*n* points)	Original magnetic field strength (μT)	95% confidence intervals on original magnetic field strength (μT)
744004	<300	no estimate possible		
744105	⩾600	$-0{\cdot}77\mp^{0\cdot24}_{0\cdot20}$ (10)	37·0	27–49
744106	⩾600	$-1{\cdot}23\mp^{0\cdot38}_{0\cdot28}$ (11)	59·2	46–78
744112	⩾600	$-0{\cdot}91\mp^{0\cdot12}_{0\cdot10}$ (11)	44·1	39–50
744109	⩾500	$-0{\cdot}97\mp0{\cdot}06$ (7)	46·7	44–49
198b1	⩾550	$-0{\cdot}95\mp0{\cdot}04$ (5)	46·0	44–48

The firing temperature estimates are derived from a comparison of the partial n.r.m. and partial r.t.m. at various temperatures. Negative slopes (column 3) are the Maximum Likelihood estimates of the ratio of original to laboratory magnetic field strengths, derived from the specimen n.r.m.–t.r.m. diagrams. The 95% confidence intervals are placed on the true slopes using the *t* distribution (Kendall & Stuart, 1973, p. 405). The present-day magnetic field at Glozel is 46 μT (D. Lemercier, private communication).

The measurements of original magnetic field strength (Table 1) provide independent information on the date of firing of the substrata of the artifacts. In Figure 6, the stippled band delineates the original magnetic fields for artifacts 744109 and 198b1 at the 95% confidence level. When, and where, in the past was the *geomagnetic* field strength within these limits? Figure 6 illustrates predicted values for the neighbourhood of Glozel; obtained by using the available published data for locations within about 1000 km and making a small adjustment (⩽8%) for differences in geographic latitude (but not archaeomagnetic inclination, so that regional features are preserved). The data between 1500 BC and 1500 AD all fall outside the stippled band. Therefore, if the last heatings of these two artifacts took place within 1000 km of Glozel, they must have been accomplished either *before* about 1500 BC or at some time between about 1500 AD and the present-day. It is also interesting to note that the data for artifacts 744105, 744106 and 744112 (Table 1) do not preclude the possibility that they also were fired during the same period, but a precise estimate of their ages is not possible because of the pronounced non-linearity (of uncertain origin) in their n.r.m.–t.r.m. diagrams.

There are two possible loopholes in the archaeomagnetic dating for artifacts 744109 and 198b1. The first is that the artifacts might have been fired at some more distant locality where the geomagnetic field strength variation was different in the past; this possibility could probably be discounted if it were demonstrated that these artifacts have trace element patterns identical to that of Glozel clay. The second loophole concerns the predicted geomagnetic behaviour for the Glozel region: is there any possibility that the field might have plunged briefly below 49 μT between 1500 BC and 1500 AD? Relative decreases in local geomagnetic strength at around 600 AD and 1350 AD for the Ukraine, and at 200 AD for Bulgaria, are evident in other published data (Rusakov & Zagniy, 1973; Kovacheva, 1973), but these decreases might have been due to non-dipole geomagnetic sources which may have had considerably less effect on the local geomagnetic field 2000 km away at Glozel. Meanwhile, all nearby observations give predicted values for Glozel which are well separated from the values for artifacts 744109 and 198b1 at the 95% confidence level (Figure 6), so the probability that these objects were fired near Glozel at the time of an undetected local decrease in geomagnetic strength must be quite small.

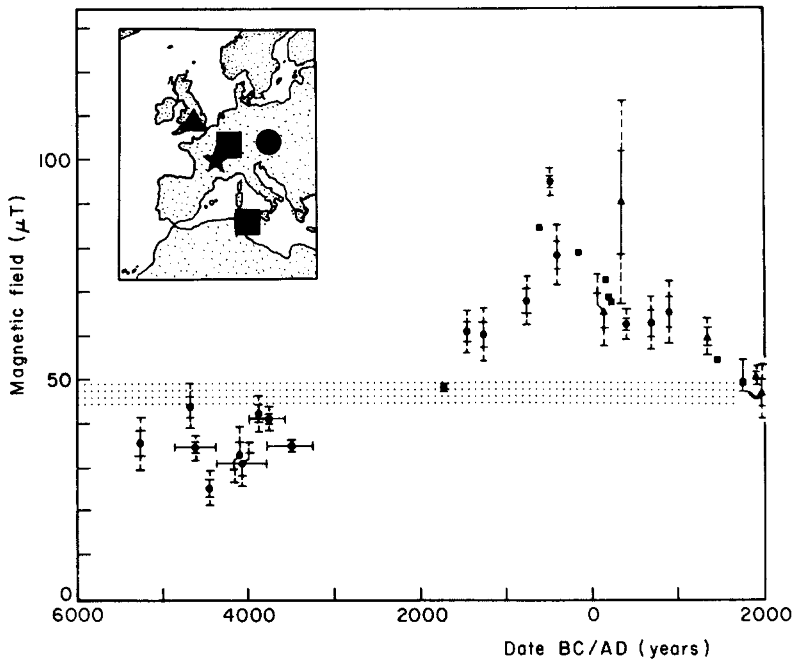

Figure 6. Geomagnetic field strength values (microtesla) predicted for Glozel by adjusting observed ancient field strengths to a common latitude of 46°N, without correcting for variation in archaeomagnetic inclination. Data taken from: Thellier & Thellier (1959) (squares); direct measurements quoted by the Thelliers (solid line for the last century); Bucha (1967) (circles) and Shaw (1974) (triangles). Symbols on the inset map indicate the approximate locations for which the original data were obtained. Vertical solid (dashed) bars indicate one (two) standard error limits when this information was given by the original author. The bc dates given by Bucha (1967) have been converted to BC dates using the calibration of Clark (1975); the horizontal bars for certain data correspond only to the possible age range quoted by Bucha. The broad stippled band indicates the 95% confidence interval placed on the strength of the magnetic fields in which artifacts 744109 and 198b1 last cooled.

The archaeomagnetic and thermoluminescence estimates of age for artifact 198b1 are in reasonable (but not excellent) agreement and the latter suggests a slightly earlier date of firing. McKerrell *et al.* (1974) did not specifically quote an age or rule out artificial irradiation for artifact 744109 but a date between 1500 BC and 1500 AD would conflict with the archaeomagnetic evidence.

The ages discussed so far relate to the firing of the artifacts, and therefore do not, by themselves, preclude the possibility of subsequent renovation. For artifact 198b1, there is at the moment no other evidence to indicate whether the inscriptions were added before or after firing, but the inscription on tablet 744109 was in place before vitrification occurred (McKerrell *et al.*, 1974) and publication of the details of its thermoluminescence analysis must therefore be awaited with interest.

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