Appendix 1
Estimating the VRM contribution to the specimens NRM

A1.1 A model for the specimen remanent magnetisation at Catholme

The magnetisation of any specimen is likely to be composed of a number of magnetisations from separate origins, contributing to the total *in situ* magnetisation NRM_0. Where NRM_0 is:

$$\mathbf{NRM_0 = VRM_A + pRM + Noise} \qquad 1)$$

Where:

- VRM_A is the VRM acquired by the sample since its time of deposition in antiquity (or perhaps sometimes its last heating episode), in the direction of Earth's magnetic field at Catholme.
- pRM is any primary stable magnetisation, such as DRM, CRM or TRM (See appendix 4) acquired by the specimen, whilst *in situ* or being deposited at the site. Such magnetisations will be along the magnetic field direction at the site.
- Noise is any magnetisation components not along the magnetic field direction at the Catholme site. These may be due to sampling, measurement induced noise, or to any residual magnetisations of the clastic particles which are relict from their origin prior to their deposition at the site.

The relationship between NRM_0 and the first laboratory measurement of the NRM (NRM_1) can be expressed as:

$$\mathbf{NRM_0 = VRM_1 + NRM_1} \qquad 2)$$

Where VRM_1 is the total VRM lost by the specimen between the time of sample collection and the first measurement in the laboratory. What is outlined here is a methodology to estimate VRM_A and estimate the value of NRM_0, using a determination of VRM_1.

A1.2. Calculating the amount of specimen viscosity

The Catholme specimens were collected during five trips to the site, the first one on August 12th and the last one on October 13th 2004. Their NRM was measured one day after collection and is referred to as the NRM_1. In most specimens the direction of the NRM_1 was close to the modern field direction (Fig. 14 in the main text). After this measurement the specimens were then placed into a position within the laboratory, such that the Earth's magnetic field was opposite in direction (as closely as feasible) relative to the specimen, in comparison to their positions at Catholme. Hence in this new position, two things would happen to the specimens magnetisation:

a) a new viscous remanent magnetisation (VRM) would then start building-up opposite in direction to any acquired at Catholme,
b) the VRM acquired by the specimen at the Catholme site would slowly decay (through viscous processes), progressively removing larger proportions of the VRM acquired during their stay in the magnetic field at Catholme.

In order to evaluate this process the remanent magnetisation of the specimens were measured at approximately 15, 30, 45, 60, and 90 days later, producing measurements of remanent magnetisation $\mathbf{RM}_{15}$, $\mathbf{RM}_{30}$, …., etc.

The net apparent **VRM** acquired on consecutive days was calculated as the vector 'semi-difference' between the $\mathbf{NRM}_{1}$ and the subsequent $\mathbf{RM}_{15}$, $\mathbf{RM}_{30}$, and so on for example,

$$\mathbf{VRM_{15} = 0.5 * (NRM_1 - RM_{15}),} \qquad \mathbf{(3)}$$
$$\mathbf{VRM_{30} = 0.5 * (NRM_1 - RM_{30}), \ldots}$$

The **residual** portions of the original magnetisations remaining after 15 days, 30 days etc would be r$\mathbf{NRM}_{15}$, r$\mathbf{NRM}_{30}$, and are given by the vector 'semi-sums':

$$\mathbf{rNRM_{15} = 0.5 * (NRM_1 + RM_{15}),} \qquad \mathbf{(4)}$$
$$\mathbf{rNRM_{30} = 0.5 * (NRM_1 + RM_{30}), \ldots}$$

Fig. A1.1 shows the typical logarithmical build-up in the VRM intensity (Dunlop&Özdemir, 1997).

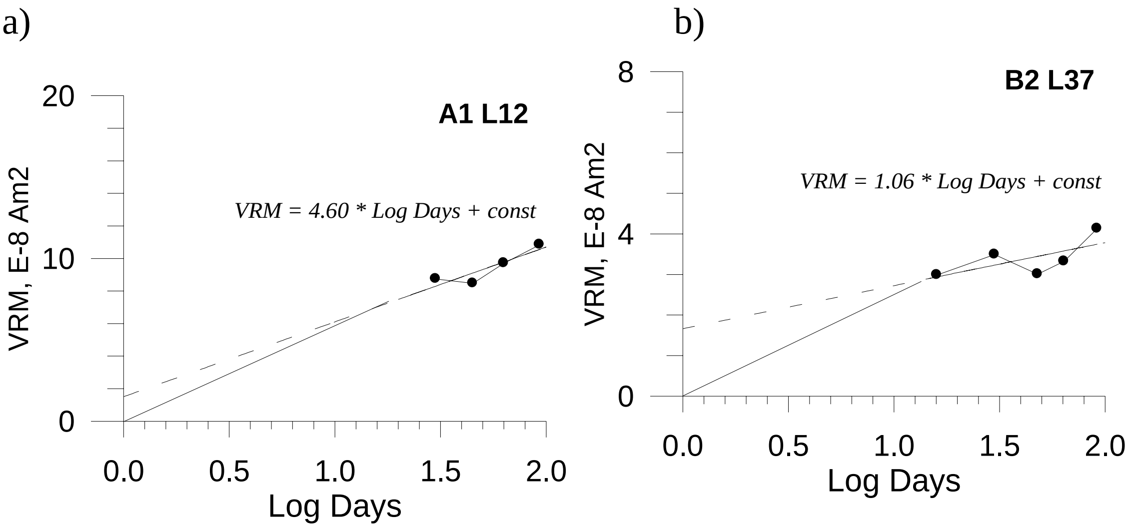

Fig. A1.1. Acquisition of VRM in specimens A1 L12 and B2 L37 between 15, 30, 45, 60, and 90 days. Zero Log days on this plot corresponds to the day one measurement (NRM_1).

The four or five data points following the NRM_1 measurement allow the estimation of the viscosity coefficient S, which is the gradient of a straight line through the VRM versus log(time) plots (Fig. A1.1), for example:

$$\mathbf{S = \delta\, VRM / \delta\, (log\ time)} \qquad \mathbf{(5)}$$

Not all specimens produced realistic estimates of the viscosity coefficient. In some specimens, especially those from the sands and gravels the changes in the NRM intensity were below the measurement accuracy and no meaningful, linear plots of VRM versus Log time could be produced. All successful determinations of the values of S are listed in the tables in Appendix 2.

Apart from this VRM build-up between 15 and 90 days, most specimens experienced an initial, faster build-up in the period between 1 to 15 days (Fig. A1.1b). Specimen

A1-L12 in Fig. A1.1a is representative of a small set of specimens, in which the initial VRM acquisition rate is similar to the longer period rate of VRM growth. We assume that the VRM build-up between 1 and 15 days is also representative of that between time of specimen collection (day zero) and the day one measurement. The reasons for the initial faster build-up to ~day 15 are not entirely clear, but reasons could include:

- The specimens may have two populations of magnetic particles, which give rise to a faster initial VRM acquisition, followed by a magnetic particle population with slower VRM acquisition (measured by S) after about 15 days.
- It is known that the acquisition of short-term VRM, and loss of VRM occur at different rates, with the acquisition some 30% of the loss (Dunlop and Ozdemir, 1997). Hence the apparent two step behaviour may be reflection of these two different rates interacting.
- There may be some moisture loss in the specimens, during the initial two weeks, which causes physical realignment of some of the magnetic particles in the laboratory magnetic field. This physical realignment may stabilise after about two weeks in the laboratory.

With the current data we are not able to distinguish these possibilities.

A1.3. Determination of NRM_0 for the specimens

The *in situ* remanent magnetisation (NRM_0) of the specimens is given by equation 2, where VRM_1 is the unknown. VRM_1 can be estimated as the rate (in log time) of the VRM loss between day 1 and the day of the first VRM determination, which is shown as day 15 in Fig. A1.2. This rate of loss can then be projected back for the period between 24 and 1 hours, using the log of time in hours as the appropriate scaling factor. For specimen B2-L37 from Fig. A1.1b, for example, it would mean using the value of VRM_{15}, the viscous loss between 1 and 15 days:

$$\mathbf{VRM_1 = \log (24) * [VRM_{15} / \log(15+1)]= 1.38* [VRM_{15} /1.20]}$$

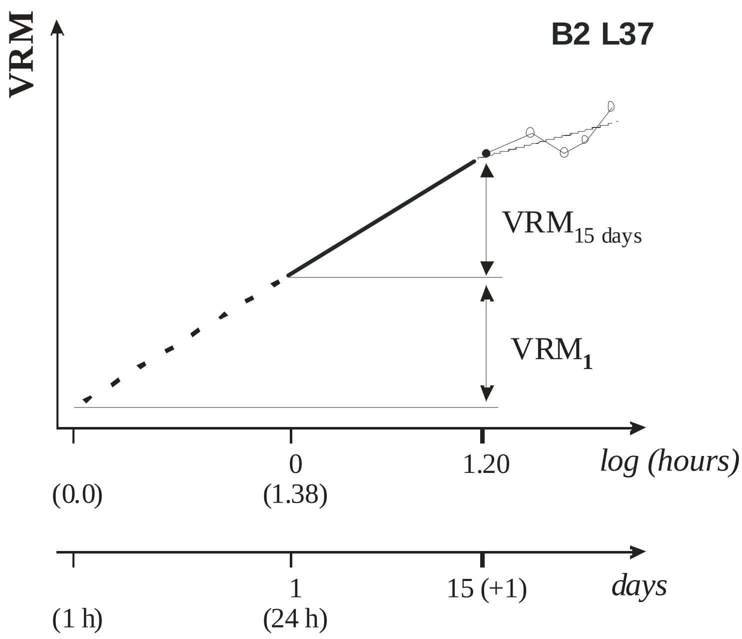

Fig. A1.2. The acquisition of VRM in specimen B2 L37 between 1 and 15 days (VRM_{15}, solid line) and between 1 and 24 hours (VRM_1, dotted line).

This is an estimate of VRM_1 in the sense that, the NRM_1 measurement was not necessarily determined exactly 24 hours after the initial collection. But taken over the whole specimen data set this is a reasonable assumption, considering that each specimen has its own determination.

A1.4. The direction of the true viscosity component

The NRM_1 directions are close to the present field direction at the Catholme site (Fig. A1.3a; giving a Fisher mean direction: $D_m = 355.8^o$, $I_m = 64.4^o$). The measured $\mathbf{RM}_{30}$ and $\mathbf{RM}_{90}$ magnetisations directions become increasingly reversed as the specimens acquire the new laboratory VRM (Fig. A1.3b, d), with more than half of the specimens having negative inclinations by 93 days (indicated by the open circles in Fig. A1.3). The large acquisition of VRM by 93 days in the laboratory time indicates the high contribution of the viscous remanence to the specimens original NRM.

For the specimens collected during the Catholme II trip, the directions of the VRM_{30} and VRM_{93} (Fig. A1.3c, e) are close to the laboratory field ($D = 0^o$, $I = 60.3^o$), with a mean inclinations of $I_m = 60.4^o$ and 61.5^o respectively (and mean declinations of $D_m = 3.1^o$ and $D_m = 6.3^o$, respectively). The closeness of these directions to the laboratory field indicates that the specimens were indeed subjected to a new magnetic field nearly opposite in direction to that of Catholme.

However, for other specimens from Catholme this degree of opposite realignment of the specimens was not possible. This was due to the fact that specimens other than the 'Catholme II' specimens, were collected from vertical cuts into the archaeological features, with a variety of orientations. We were unable to accurately re-orient the specimens in the laboratory field because of this. This is indicated in Fig. A1.4 which shows the direction of VRM_{16} and VRM_{48} in the specimens collected during the third sampling trip ('Catholme III', specimens B2 L28-L50). This comes about because equation 1 is only valid for oppositely directed VRM loss and VRM gain. If not opposite then the VRM calculated from equation 1) is a vector resultant of the lost VRM and the new VRM acquired.

In order to try to allow for these deficiencies in some specimens, all the specimens were treated to the following procedure:

- The VRM magnitude from equation 1 was **forced** to lie along the expected magnetic field direction of the Catholme site. The geomagnetic field direction corresponding to a geoaxial dipole field ($D = 0^o$, $I = 69.2^o$ for Catholme) is the best choice, as it averages the magnetic field changes over thousands of years. This procedure will provide a lower estimate of the magnitude of VRM and S, with the true value of these parameters being somewhat larger. The specimens from the Catholme II sampling are likely to provide the best estimates of the VRM.

The assignment of forced direction to the VRM_{15}, VRM_{30}, .., VRM_{90}, also necessitated a re-calculation of the residual magnetisation $rNRM_{15}$, $rNRM_{30}$, .. $rNRM_{90}$, through equation 4.

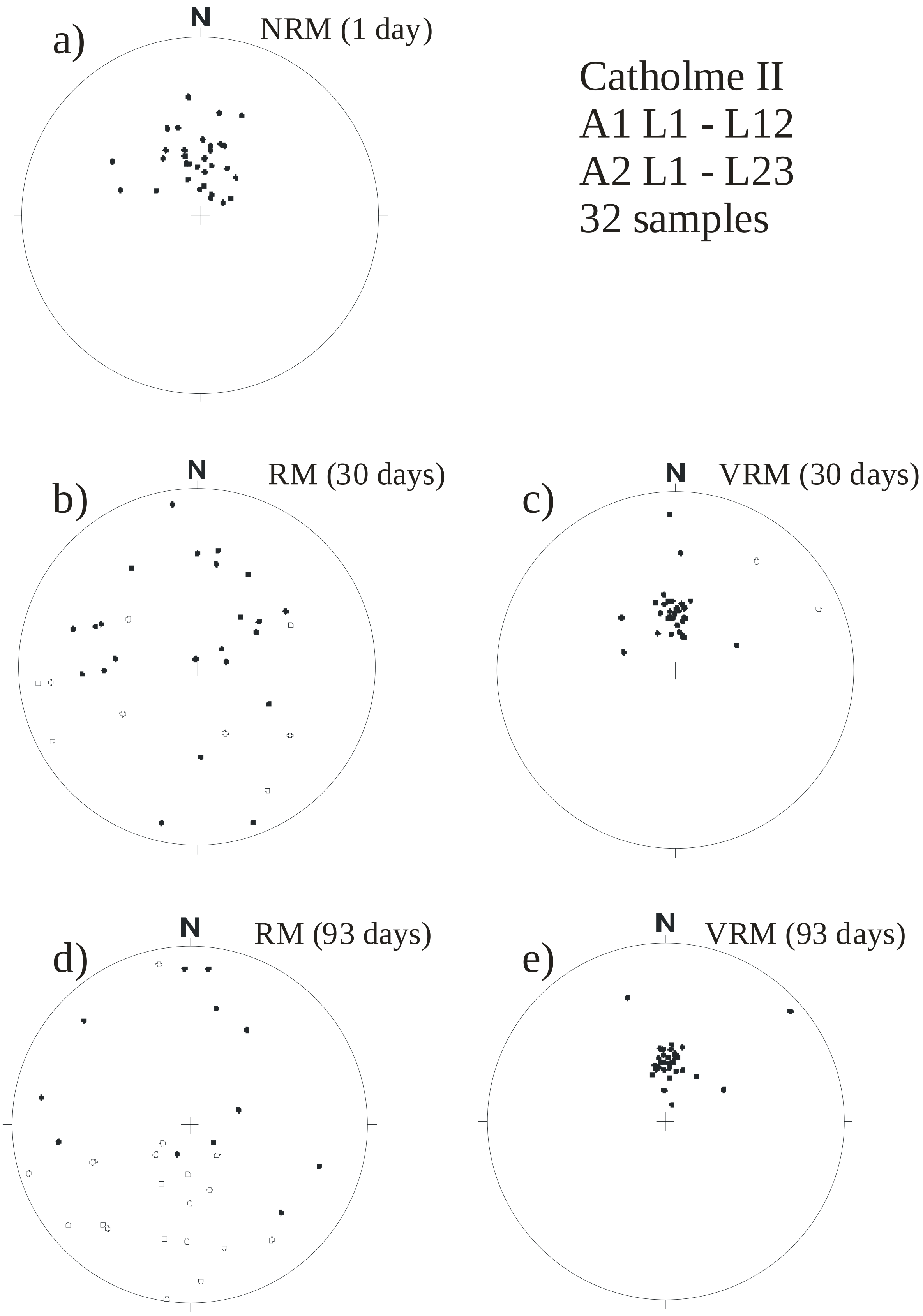

Fig. A1.3. a) Specimen NRM_1 (day 1) directions. b, d) Specimen's magnetisations directions after 30 and 93 days in the opposite laboratory magnetic field. c, e) the site-VRM directions removed during the stay in the laboratory magnetic field for 30 and 93 days. Specimens collected during the second trip to Catholme ('Catholme II').

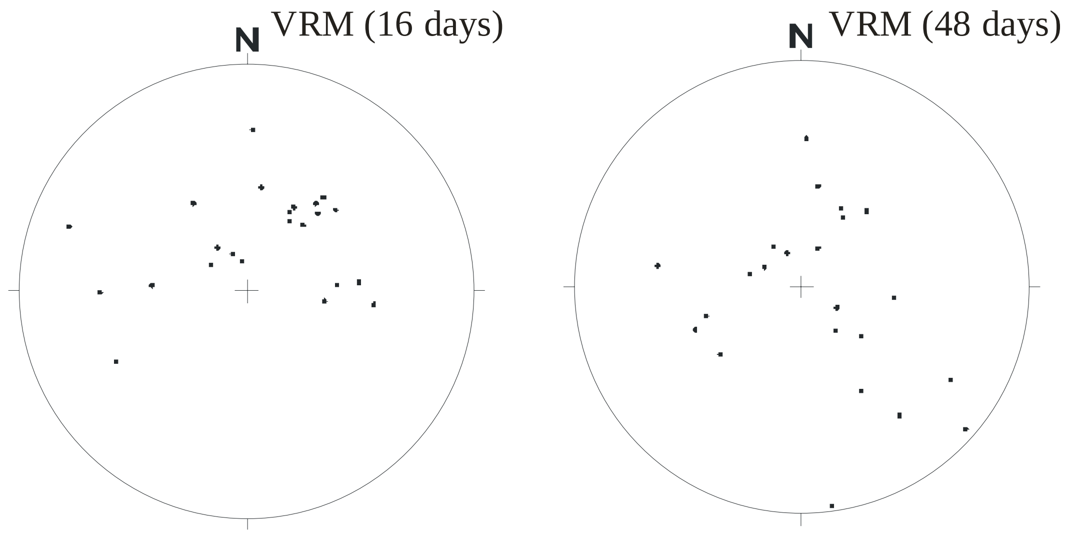

Fig. A1.4. Stereoplots of the directions of the VRM_{16} and VRM_{48} components in the specimens for the 'Catholme III' sampling episode.

A1.4. Estimating the total viscosity component (VRM_A), from antiquity in one population of specimen NRM directions

We also tried to estimate the likely total contribution of VRM to the NRM_1 remanent magnetisation of the specimens, assuming that the specimens had not been chemically and physically unaltered since the Bronze Age. This value we have referred to as VRM_T, signifying the VRM acquired from antiquity, until day 1 after collection ($VRM_A = VRM_1 + VRM_T$). This total viscous component can be modelled using the values of:

1) the observed initial steep rise, VRM_{15}, and
2) the viscosity coefficient S, estimated from the VRM build-up between 15 and 90 days. As this build-up is logarithmic with time, S represents the gain in the VRM intensity over one decadal increase in the log of time (in days).

VRM_T, will be the sum of the observed initial steep rise, VRM_{15}, and a certain number of decadal gains, N_d, of magnitude S, all approximately in the direction of the geocentric axial dipole field for the Catholme site for example:

$$\mathbf{VRM_T} = \mathbf{VRM}_{15} + N_d * \mathbf{S} \qquad (4)$$

The directional distribution of the residual portions of the original NRM i.e. $rNRM_{15}$, $rNRM_{30}$, can be used in estimating the value of N_d. Fig. A1.5 compares the original distribution of NRM_1 directions in the 32 'Catholme II' specimens with the $rNRM_{30}$ directions. 31 out of the 32 'Catholme II' specimens yielded reliable estimates of the viscosity coefficient S.

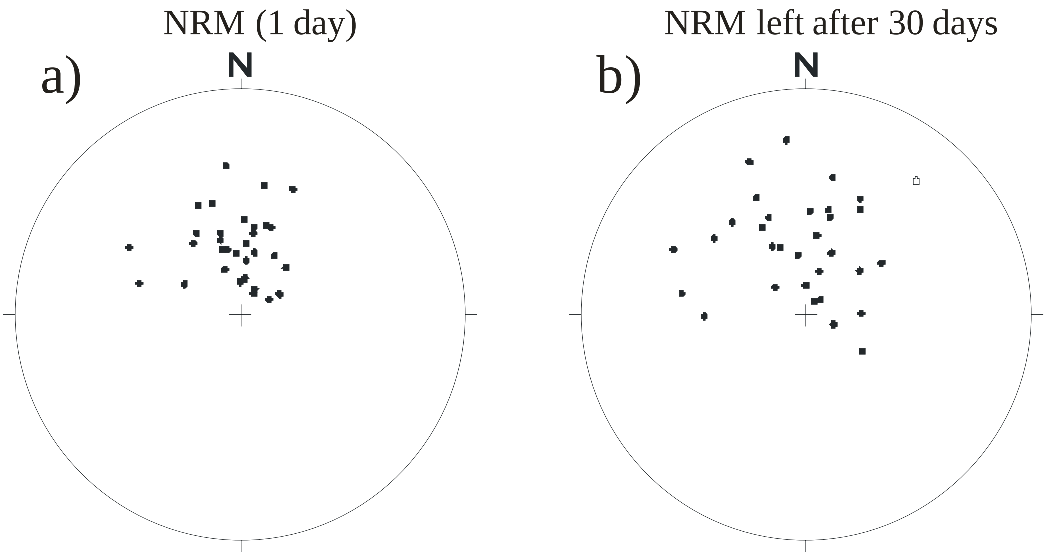

Fig. A1.5. Stereoplots of (a) the directions of NRM_1 , and (b) $rNRM_{30}$ (re-calculated after the directions of VRM_{30} were forced to coincide with the direction of the geoaxial dipole field for Catholme).

It can be seen in Figure A1.5b that compared to the NRM_1 values the $rNRM_{30}$ directions are more scattered. A modified version of the R parameter of the Fisher statistics (parameter R') was used to estimate the degree of directional scatter of the specimen populations, where R':

$$R' = \sqrt{\left(\sum_i X_i\right)^2 + \left(\sum_i Y_i\right)^2 + \left(\sum_i Z_i\right)^2}, \qquad (5)$$

where X_i, Y_i, and Z_i are the Cartesian coordinates of the rNRM vectors. It is different from conventional Fisher R, in that it uses the vectors scaled to their magnitude, rather than unit vectors. R' is a measure of the vector-summed remanence of the specimen population, and will be larger for larger degrees of directional consistency between rNRM values of specimens (for a mixed number of specimens).

If the R' value of the NRM_1 population (Fig. A1.5) is normalised to a value of 100 %, the R' value of the $rNRM_{30}$ population (i.e. Fig. A1.5b) would be 62 %.

The R' value for $rNRM_{300}$, i.e. after one decadal gain ($rNRM_{300} = NRM_{30} - 1 * S$) is 49%. The R' value after two decadal gains (~3000 days), for $rNRM_{3000}$ ($NRM_{3000} = NRM_{30} - 2 * S$) is 36.8 %. This shows:

1) there is an increased scatter in the rNRM directions, which remain after removing the viscous components acquired from 30 to 3000 days'
2) the diminishing contribution of the rNRM values to the NRM_1 values of these specimens.

Table 1 lists the values of R' (as a percentage of the R' value of the $\mathbf{NRM_1}$ population) for decadal gains (N_d) between 0 and 9. A fuller picture of this behaviour is shown in Fig. A1.6.

Table 1.

N_d	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
%R'	62.1	49.3	36.8	25.3	16.9	17.0	25.4	37.1	49.5	62.4	75.4

The maximum in the directional scatter of the rNRM values for the 'Catholme II' specimens is achieved when N_d = 4.5 (Fig. A1.6).

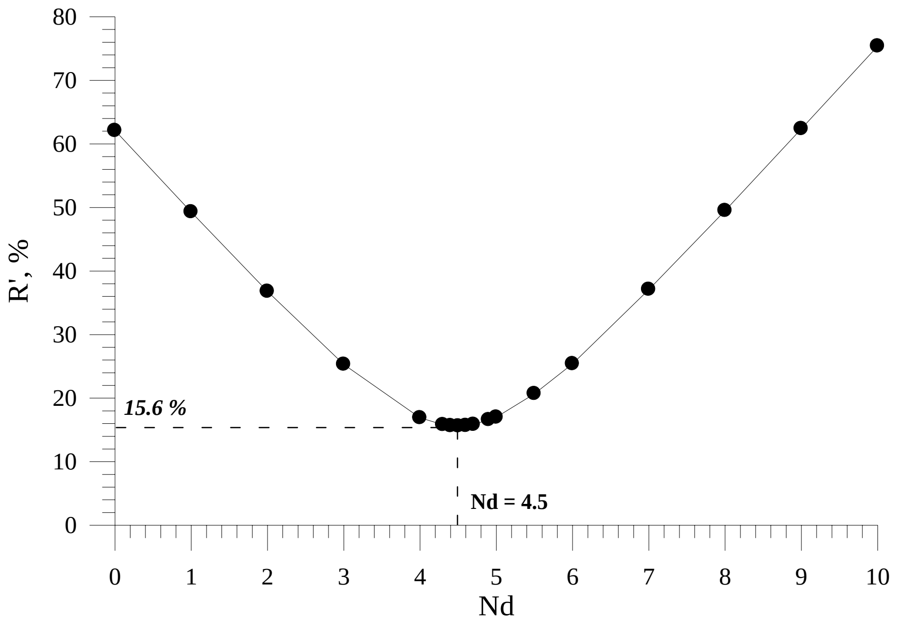

Fig. A1.6. The normalised R' (%R') versus N_d behaviour for the 'Catholme II' specimens. %R' increases beyond a minimum value due to the reversal of the resultant direction by addition of VRM artificially beyond the minimum limit.

At this number of decadal gains, the rNRM values account for some 16 % of the total NRM_1 signal of the specimen population. In a general sense the minimum in the R' values corresponds to a point, when the specimens as whole approach their values of 'noise' in equation 1. Hence we can say that as a whole, these specimens have values of 'noise' which are some 16% of the NRM_1 signal. The remaining part of NRM_1 is composed of pRM, and part of the VRM_A signal. Factors which contribute to the 'noise' signal are:

1) The stable remanent magnetisation of the clastic grains (pebbles/ sand) present in the individual specimens. This is widely scattered because it is clear from the measurements on the gravel clasts (Section A1.4.3) that these retain a stable magnetisation inherited from their location in their original rocks.
2) Spurious magnetisations produced by deformation in the specimens during sample preparation at the site (Jordanova *et al*., 1996).

Starting from the first point in the logarithmic rise of VRM at 30 days (Fig. A1.1a), one decadal gain of S in VRM would require 30 to 300 days, two decadal gains would require 300 to 3000 days, i.e. approximately 8.2 years after specimens' collection, and so on. Hence, an N_d value of 4.5 corresponds to ~2600 years (Figs. A1.8, A1.7). This time represents a maximum age for the VRM. It is maximum because it is not possible to estimate the pRM value using this approach, which is included within the VRM_T value. The values, of course, are very approximate as there are a number of large uncertainties and assumptions.

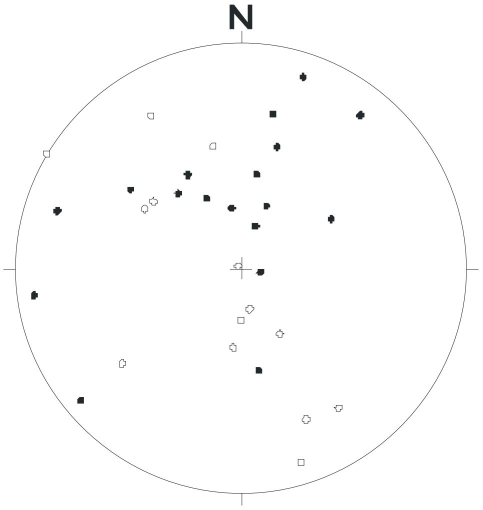

Fig. A1.7. The scatter in the rNRM values of the ‘Catholme II’ specimens, achieved at 4.5 decadal gains in magnetic viscosity.

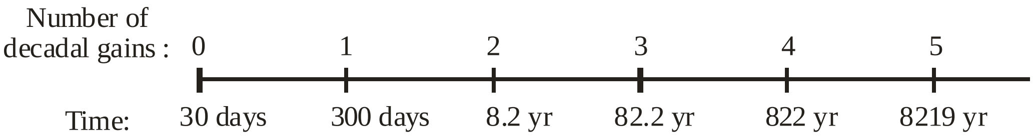

Fig. A1.8. Approximate time values of the N_d gains for the ‘Catholme II’ specimens.

Thus, for the ‘Catholme II’ specimens up to ~85 % of the **NRM**$_1$ can be explained as a viscous magnetisation which is up to ~2600 years old (with direction of D = 0^o , I = 69.2^o) built-up in the specimens during their prolonged stay at the site.

Out of the 186 Catholme specimens in the collection, 99 yielded reliable estimates of their viscosity coefficients. These were divided into three groups 1) archaeological material, 2) sands and 3) gravels. The total viscosity contribution to their NRM’s was modelled separately using the previous method.

A1.4.1. The archaeological materials

This group included 71 specimens from archaeological features dominated by siltier archaeological fills from ditches and pits.

At N_d = 5.1 decadal increases, the remaining portions of the **NRM** account for only 9 % of the initial NRM_1 (Fig. A1.9). We can conclude that up to 90 % of the remanence in the archaeological specimens is a viscous remanence.

In this case the meaning of the N_d parameter is not so clear and this population combines specimens from four trips and four separate VRM experiments, with decadal gains counted after either 30 or 13, 16, or 26 days. If a starting point of 13 days is used (as in the case of approximately 55 % of the specimens), N_d of 5 corresponds to ~3560 years. This clearly overestimates the extent of any viscous remanence by not accounting for the pRM component which may form a significant part of the VRM_T.

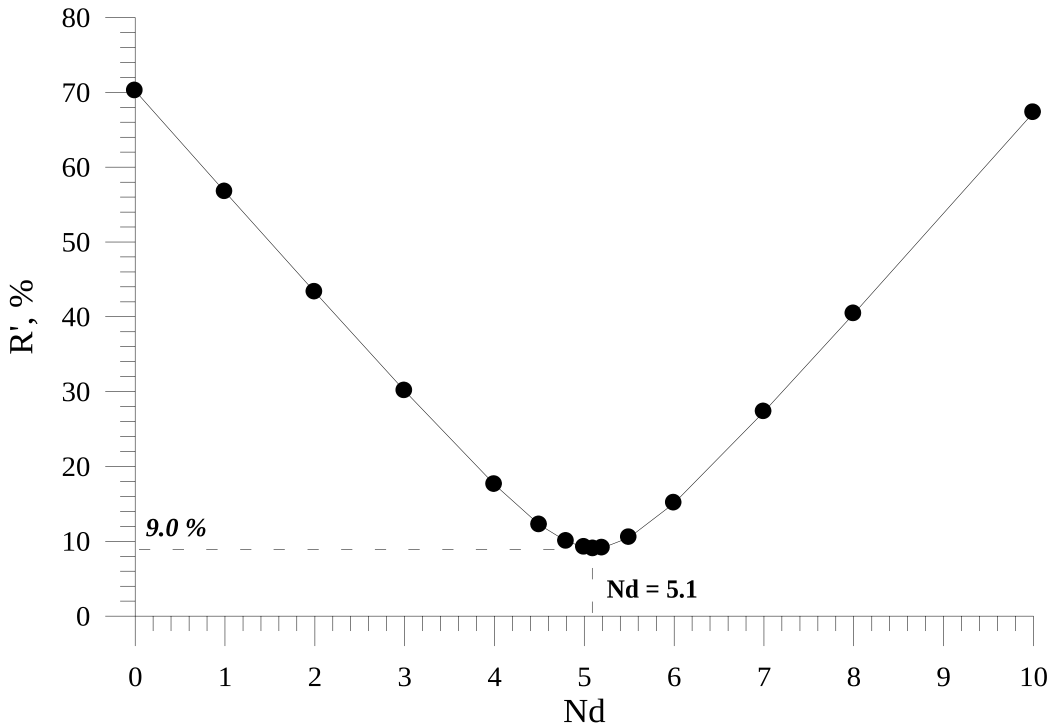

Fig. A1.9. The R’ (as a percentage of their **NRM**$_1$) versus N_d behaviour in the archaeological material (pits, ditches etc).

A1.4.2. The Devensian sand specimens

Twenty-eight specimens from the Devensian sands yielded reliable estimates of their viscosity coefficients.

The much flatter shape of the curve indicates the lesser contribution of VRM to the NRM_1 of the Devensian sands. The higher value of R’ of 29.8 % suggests the lesser importance of the prolonged exposure to viscous build-up to the NRM of these specimens and, conversely, the greater importance of the remanence of rock fragments and pebbles. The maximum scatter in the remaining portions of the NRM is again at N_d = 5.0 (Fig. A1.10). This probably suggests that the NRM_1 is dominantly carried by silt and clay-sized particles derived from water-percolation through the archaeological fills (or overlying soil) as a main carrier of the viscosity. This is consistent with the unexpectedly large value of $\%\chi_{FD}$ of some of these Devensian sand specimens.

A1.4.3. The gravel clasts

The gravels (twenty specimens from seven samples), form a separate group from the sands as none of them allowed a secure determination of their viscosity. The stereoplots (Fig. A1.11) of the directions of their **NRM**$_1$ and of their remanent magnetisation measured 13, 33, 48, and 66 days later, show no significant changes. Occasional small directional changes of 1-2^o are most certainly measurement inaccuracies. The observed changes in the NRM intensity were < 1 % of the total signal and do not signifying any trend- probably reflecting changes below instrument sensitivity.

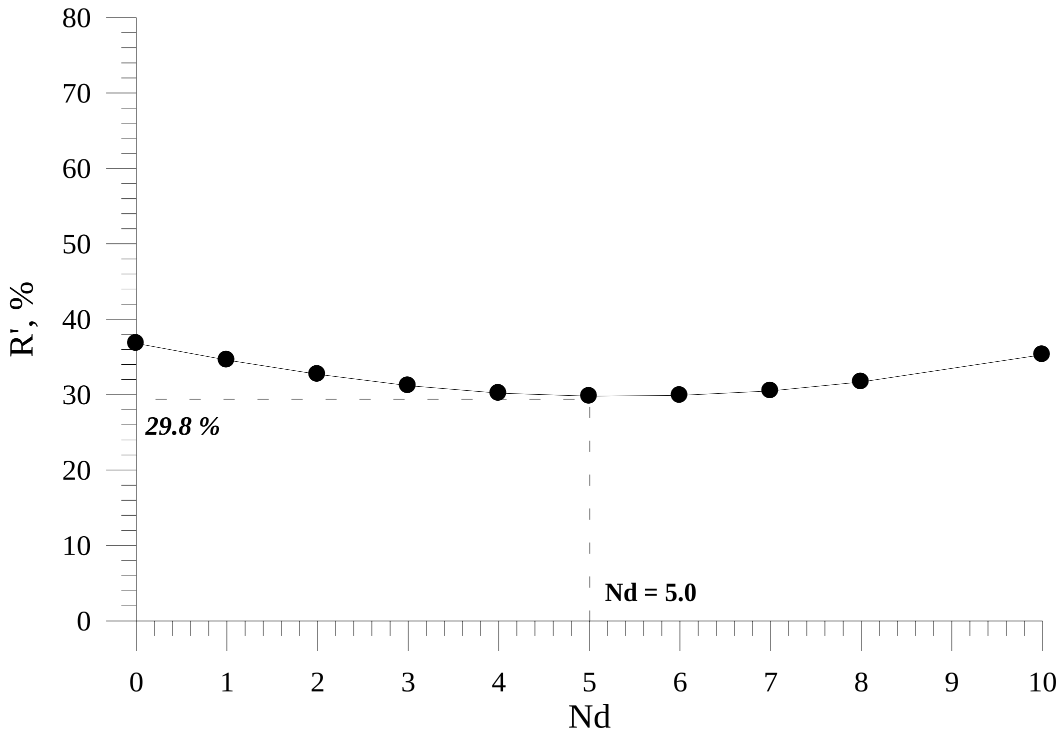

Fig. A1.10. The R’ (as a percentage of their **NRM$_1$**) versus N_d behaviour in the natural sands.

A1.5. Assessment

An assessment of the long term versus the short term behaviour of the VRM acquisition can be obtained by examining the relationship between VRM$_1$, which is acquired over 24 hours, versus the longer term behaviour exemplified by VRM$_T$. For the archaeological fills the VRM$_T$ has a wide variety of relations ranging from slightly more than 1x VRM$_1$ to more than 10x VRM$_1$ (Fig. A1.12). To some extent these relationships are related to types of archaeological feature functions, since post-pits and pit-alignments fall close to the 1:1 line in Figure A1.12. These features also have the on average larger VRM$_1$ acquisition rates compared to the NRM$_1$ values (Table 7 in main text).

Shallow pits and huge pit features fall mostly between the x1 to x5 lines in Fig. A1.12 and are in this sense are similar to most of the Devensian sands (Fig. A1.13). Burnt features fall mostly beyond the x5 line, like most soils and the material from plough furrows (Fig. A1.13). We can only speculate as to the reasons for this partitioning into separate - VRM behaviour fields - it is probably related in some way to the magnetic mineralogy.

For the burnt features the estimate of total VRM is probably a gross overestimate, since these have relatively low value of %VRM$_1$/ VRM$_T$ of about 19% (Table 7 in main text). Hence in these materials the pRM part of the remanence exemplified by equation 1 is probably relatively large. This may also be the case for other materials, although its not possible to say which with the current data.

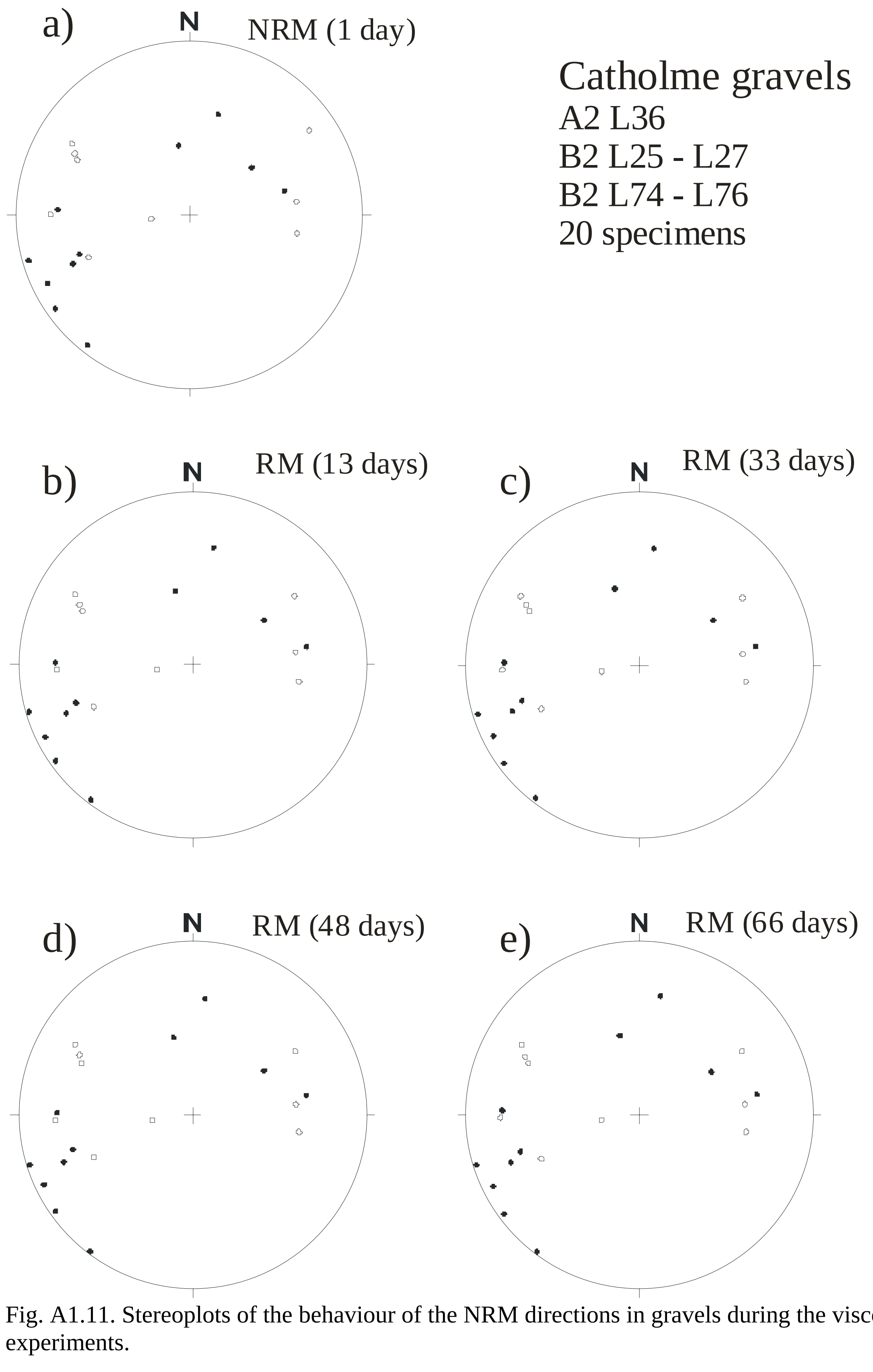

Fig. A1.11. Stereoplots of the behaviour of the NRM directions in gravels during the viscosity experiments.

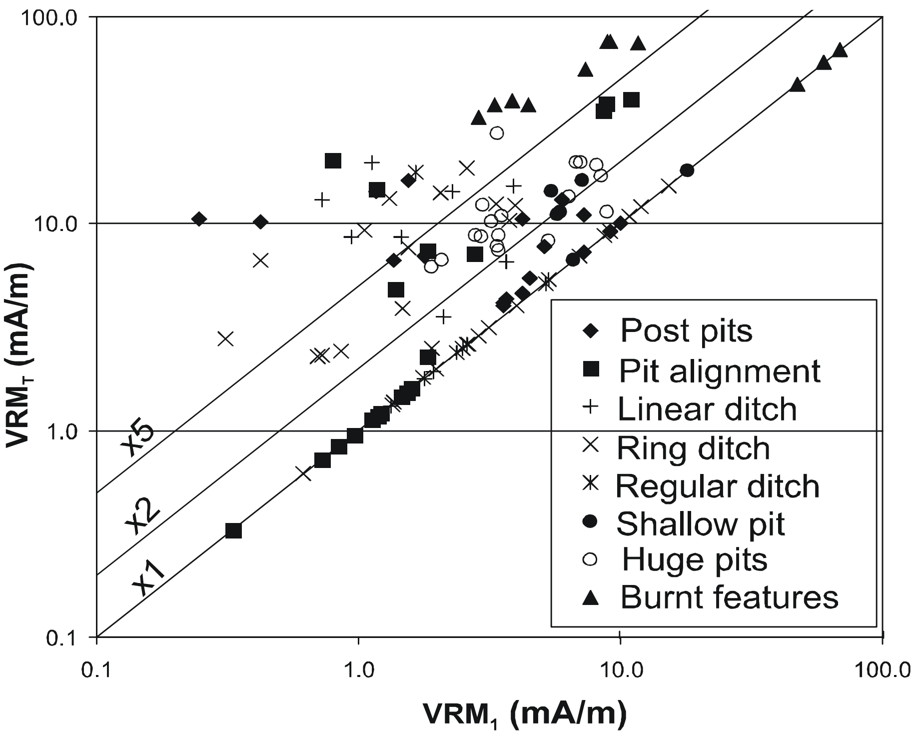

Figure A1.12. Relationship between the VRM acquired over the first 24 hours, since sampling (VRM_1), and the longer term VRM estimated from the first time of measurement into antiquity (VRM_T). The lines are when VRM_T is 1x, 2x and 5x the magnitude of VRM_1.

There are clearly a number of interesting relationships between the mineral magnetic behaviour, the type of archaeological feature, the nature of the fills, and its affect on the *in situ* remanence of these materials. These factors may be important in dictating the type and form of anomaly detected on the Catholme site.

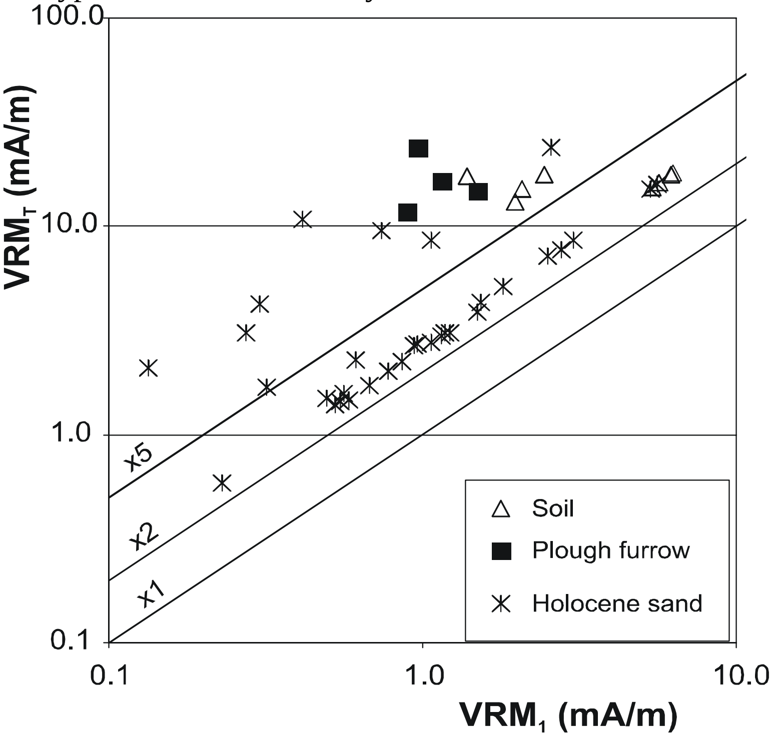

Figure A1.13. Relationship between the VRM acquired over the first 24 hours, since sampling (VRM_1), and the longer term VRM estimated from the first time of measurement into antiquity (VRM_T). The lines are when VRM_T is 1x, 2x and 5x the magnitude of VRM_1.