Remagnetization Dating of Roman and Mediaeval Masonry

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(Received 5 March 1996, revised manuscript accepted 31 May 1996)

The Earth's magnetic field may partially remagnetize rocks, often by the process of viscous remanent magnetization (VRM). Thus, when masonry is turned and placed in a monument it magnetizes parallel to the Earth's field, partly overprinting any older geological magnetizations. The intensity of this new overprint will increase with time, if the masonry is undisturbed. Older magnetizations require higher demagnetization temperatures. Thus, the unblocking temperature ($T_{UB}$) relates directly to the age of the remanence and, therefore, the age of stabilization of the masonry. For suitable rocks, we can calibrate the remagnetization time scale for the rock using historically dated structures. The scale then permits us to estimate the age of more enigmatic structures by interpolation, or modest extrapolation. Some samples reveal multiple episodes of remagnetization, showing that masonry was recycled, acquiring a differently oriented remanence each time that it stabilized in a new architectural configuration. Masonry from the Bishop's Palace (Lincoln, U.K.) includes Roman (c. AD 300), mediaeval (1160–1450), post-Civil War (1650–1720) and Victorian phases that have characteristic $T_{UB}$, consistent with their ages. Some mediaeval masonry recycled Roman building materials.

Keywords: REMAGNETIZATION DATING, VRM, VRM DATING, DATING MASONRY, RECYCLING OF MASONRY.

Introduction

We can measure the paleomagnetism of most rocks. Normally, an ancient geological event, such as volcanic or metamorphic activity, provides sufficient thermal or chemical energy to trigger the magnetization of the rock in the paleofield direction. Discrepancies between the rock's ancient "internal compass" direction and the present Earth's field (PEF) reveal rotations that postdate primary magnetization. The internal "magnets" remember the declination and inclination of the magnetizing field with respect to the rock sample. In this way, geophysicists detect the rotation of geological units from the size of continents to pebbles. Magnetizations of paleomagnetic significance are "hard" remanences. Normally, we can only erase them by high temperatures (unblocking temperature = $T_{UB}$), or strong alternating magnetic fields.

However, the magnetization of many rocks changes, partly due to the kinetic energy of random thermal fluctuations at the ambient temperature. This partial remagnetization is logarithmically time dependent so that initial large changes in "soft" magnetization occur quickly and smaller changes in "hard" remanences occur slowly. Geologists are normally uninterested in viscous remanent magnetization (VRM) components because they represent magnetization by the PEF. The Earth's field reverses every few million years and the present, north-seeking or normal polarity field has only existed for the last 0.7 Ma (Brunhes' epoch). Therefore, the age of most VRM is <0.7 Ma. Paleomagnetists regard this "soft" VRM, parallel to the PEF, as a nuisance that they erase easily in the laboratory by thermal demagnetization (<200°C) or alternating field demagnetization (<20 mT), within a field-free space. This soft magnetization is of archaeological value because it may yield evidence of human interference. The remaining magnetization components are then geologically significant.

Raman magnetism of natural rock outcrops is normally of ancient geological significance, if the outcrop was not heated, struck by lightning or severely weathered. However, VRM dominates the bedrock source of our masonry because it is magnetized solely parallel to the PEF (Borradaile, 1994). Thus, it may be entirely of Brunhes' epoch origin (<0.7 Ma). This direction is difficult to distinguish from the Jurassic-Lower Cretaceous (160 Ma) paleomagnetization expected in outcrops. However, for our purposes, it is unimportant whether the oldest geological remanence in the samples is 0.7 Ma or 160 Ma. In either case,
those remanences cannot be confused with partial VRM due to cultural disturbances in the last 2000 years. We refer to the oldest, pre-cultural magnetizations as outcrop magnetization.

Usually, the acquisition or decay of VRM may be completed in minutes or thousands of years, depending on the magnetic properties of the rock. Thus, it has the potential to track and record historical and prehistorical cultural activities that reoriented the rock. The VRM component will date from the last placement in a fixed orientation in a building. On the other hand, the “hardest” geological remanence will serve as a more permanent reference direction locked in the sample. Ideally, the source rock should have only one geological magnetization direction. Then, multiple geological magnetizations cannot be confused with possible, multiple partial VRMs acquired due to repeated reorientation by humans.

Néel (1949, 1955) explained the theoretical basis by which materials may become progressively, partially magnetized in a weak magnetic field, like the Earth’s magnetic field. His formulation for VRM is only strictly valid for grains comprising a single magnetic domain. It defines the relaxation time (t), required for a remanence to reduce to 1/e of its initial value. t depends on grain volume (v), coercivity (Hc), saturation magnetization (Ms), the absolute temperature (T), Boltzmann’s constant (k) and a frequency-factor constant (f);

\[ t = f \cdot e^{\frac{Hc \cdot Ms}{kT}} \]

Thus, VRM develops with the passage of time, without changes in environmental conditions, and dates changes in orientation of rock samples with respect to the Earth’s field (Dunlop, 1989). In practice, nomograms based on the above formula allow us to estimate crude dates from progressive thermal magnetization temperatures of the sample’s remanence (Pullaiah et al., 1975; Middleton & Schmidt, 1982; Kent, 1985). Imprecision is caused by:

(a) variation of domain structure of magnetic grains from single-domain size;
(b) variation in Hc, Ms and v between and within samples;
(c) the limit to the number of thermal demagnetization steps before the sample is destroyed or its magnetic mineralogy changed;
(d) a suitable history of sample rotations, with stationary intervals that permitted different characteristic magnetization directions.

The application of a generalized theoretical formula is unlikely to be successful, because it is difficult to determine suitable values that represent the actual frequency distributions of (a) and (b) for a specific sample. VRM will normally be a poor tool for absolute dating. However, Heller & Markert (1973) used three samples from Hadrian’s Wall (AD 100–400) to provide absolute ages that concur with the historical and archaeological evidence within ± 100 years. Their experimental approach was quite indirect; it did not involve heating to relax the VRM overprint.

VRM dates relative, recent ages of rock rotation more successfully, e.g. prehistorical rock movements by glaciation (Kent, 1985) or post-glacial landslides (Borradaile, in press), younger than 20 ka. The technique is increasingly less precise for older events (e.g. see Dunlop, 1989). In fact, dating older geomorphological and geological processes is useless because the isothermal VRMs of most rocks saturate within a few thousand years.

Similarly, in archaeology, the relative dating of masonry with VRM is probably more valuable than attempts at absolute dating. For example, multiple, poorly documented building episodes using the same source rock may be distinguishable from analysis of VRM. Also, we may detect the ancient recycling of building material, rarely identifiable by other means. We need a uniform bedrock source with a simple, usually single, geological paleomagnetic vector. The latter avoids confusion of multiple masonry orientations with geological sample orientations. With sufficient samples and documented ages of masonry, we can develop an empirical nomogram of age versus magnetization for that particular site. These are far superior to theoretically derived nomograms that are based on assumptions of rock magnetic properties.

Figure 1 illustrates the technique for a hypothetical rock with ideal magnetic properties that record both
geological and successive historical sample orientations, with respect to the Earth’s field. We neglect secular variation in declination and inclination of the Earth’s field as they are smaller than the changes in sample orientation due to human interference.

Figure 1(a) shows the basis of the stereographic projection used to present orientation data in geology (q.v. Tarling, 1983; Butler, 1992). The single vector represents the magnetization in the present Earth’s field direction (down and to the north). Many rock samples show this orientation of magnetization vector. The vector lengths represent the intensity of magnetization and orientation of the net remanence vector. Thus, changes in the slope of the intensity graph (Figure 1(d)) correspond to changes in orientation (q.v. Stupavsky et al., 1982 for a geological example). Normally, intensities decay rapidly with temperature, vanishing to zero at the Curie point of the mineral that carries the remanence (=573°C in this study). The primary geological magnetization is stable remanence direction that persists until the last stages of demagnetization. Rarely, the intensity plot may show a small remanence increase over a few temperature intervals. This is due to the unblocking of an older remanence that is nearly antiparallel to the one isolated in previous demagnetization steps (e.g. Figures 2, 3(b), 4(b)).

Remagnetization Dating of Roman and Mediaeval Masonry

The first firm evidence of the establishment of the Bishop’s Palace, Lincoln

The Bishop’s Palace, Lincoln

The first firm evidence of the establishment of the Bishop’s Palace at this site, immediately south of Lincoln Cathedral, dates from the episcopate of Robert de Chesney (1148–1167). The greatest period of construction was initiated by Bishop Hugh of Avalon (later St Hugh) in the late 12th century and completed by Bishop Hugh of Wells in the early 13th century. This period saw the erection of the East Hall and West
ranges that constitute most of the surviving mediaeval ruins. Bishop A. Inwick made the last major additions in the 15th century, updating the buildings to contemporary standards of style and comfort.

Deterioration set in during the 16th century when the bishops of L. c. 300); Bishop R. de Chesney (1155–1167); Bishop Hugh of W. 1290–1325); Bishop William A. Inwick (1436–1448); Civil War to early 18th century (1650–1720); early Victorian (1838–1850); and modern site rubble, stable since 1990. We took a few samples directly from walls under repair. However, most samples were from fallen masonry, accumulated due to frost action in recent years. Found directly below the source masonry, we refitted them into the monument to determine their original orientation in the monuments. The floor plans of Figures 5 & 7 show the sample sites. These yielded 109 cores of which 78 provided magnetizations large enough to demagnetize incrementally and measure with the J.R.5a automatic spinner magnetometer (sensitivity ≤ 0.01 mA/m).

All samples show multiple remagnetizations, including a resistive, “hard” remanence with high $T_{UB} (>400^\circ C)$ that originated in outcrop. All samples show also a young, spurious magnetization component, unblocked by thermal demagnetization ≤100°C, attributed to recent remagnetization, probably by VRM (<20 years). This young remanence is very soft and is considerably disturbed by the stress of freeze–thaw action (Borradaile, 1994). These feeble, young remagnetizations provide no useful archaeological information. Well-defined magnetization directions appear only for remanences with $T_{UB} >100^\circ C$. Since most samples were frost shards collected from the ground, the youngest component is mostly random in orientation with respect to sample coordinates.

For samples removed directly from the buildings, the youngest component is subparallel to the PEF. The oldest remanence is of outcrop origins. Intermediate magnetizations date from historical times since the masonry stabilized in the monument.

Demagnetization Data from the Site

We thermally demagnetized each sample in nine to 12 steps from 50 to 550°C. Naturally, one could bracket the turning points in the demagnetization path more precisely with smaller temperature increments. Unfortunately, limestones do not survive many heating cycles. Moreover, thermal demagnetization invariably involves some mineralogical change that can interfere with the magnetic record. We monitored magnetic susceptibility to ensure that the metamorphism was negligible. However, with too many heating cycles oxidation will always be a problem, even if one heated samples in an evacuated chamber. Thus, we
were limited to ≤13 heating steps per drill-core subsample. The specific temperatures were not reproduced precisely in each batch of thermal analysis. Each batch used overlapping sequences of thermal demagnetization, e.g., 50, 100, 150°C ... in one batch and, e.g., 75, 125, 175°C in another. This adds a little more precision to the study, since almost every sample yielded more than two cores that were then heated incrementally in different overlapping temperature sequences. The unblocking temperatures are plotted in histograms. We binned the actual TUBs in 25°C intervals, causing unavoidable imprecision in estimating the characteristic value. The true unblocking temperature is best estimated from the mean value of the distribution, rather than the mode. Finally, we note that mean TUB estimated in this way are subject to an error of ≤9°C (s.d.).

The youngest component of magnetic remanence
Every sample contains a remanence component removed by heating to between 60 and 120°C in a field-free space. For the few in situ fragments, this direction is close to the PEF, confirming the recent VRM origin. For the frost-liberated fragments picked from the ground, the direction of this component is random, in specimen coordinates. To confirm the young age, we sampled a pile of limestone rubble known to have lain undisturbed since 1990.

Four fragments of a large sample are shown in vector plots (q.v. Tarling, 1983; Butler, 1992) in Figure 6. The youngest component of magnetic remanence
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Figure 5. Ground floor plan of the Bishop’s Palace compound.

Figure 6. Vector plots of the successive steps of demagnetization in a rubble fragment, stable since 1990. All show a small northward, downwards magnetization parallel to the present earth’s field that was erased by heating to 66°C. However, some older magnetization components are present indicating stabilization in mediaeval monuments (demagnetized at 204°C) and in the source outcrop (stable from 204 to 410°C). •: Plan view; ◆: vertical section.
vector plot is a simplified form of presentation that suffices for the simple pattern of demagnetization in this sample. The very young component of magnetization is unblocked by heating to 66°C. This is due to 5 years of incomplete VRM acquisition in the PEF. The youngest VRM component is generally northward (black dots=plan view) and downward (open circles=North–South cross-section), close to the PEF. Two older demagnetization components are shown by differently oriented linear portions of the graph (Figure 6(a), perhaps Figure 6(c)).

The oldest component of magnetic remanence

Normally, the oldest component of remanence is that remaining just before complete demagnetization. To confirm this we sampled bedrock from the site. Bedrock crops out in the undercroft of the East Hall at two sites (Figure 7). However, at least one of the massive (>500 kg) blocks sounds loose when struck with a hammer. Its direct contact with solid bedrock cannot be confirmed more reliably without damaging the building.

The loose block shows a single remanence component indicating magnetization subparallel to the PEF for all components up to 250°C (Figure 8(a)). The oldest magnetization is isolated between 250 and 410°C and the younger component is due to remagnetization since quarrying. This large block may have been displaced slightly during quarrying of the hillside, into which the undercroft was built. The bedding direction of the block is horizontal, as in outcrop. Thus, any disturbance would have been restricted to rotation in the horizontal plane, about a vertical axis.

A second block, which may be firmly connected to outcrop, yields a weak remanence component in the PEF direction. This is retained at least until a blocking temperature of 450°C (Figure 8(b)–(d)). It appears that this block has not been rotated and it provides the simplest single-component, outcrop remanence without any cultural disturbance.

**Structural Features**

(1) Bishop Alnwick’s Audience Chamber (1436–1448)

This room is situated on the ground floor of the chapel range, known to have been built by William of Alnwick, Bishop of Lincoln from 1436 to 1448. Originally below the chapel, but now open to the sky, this room had a large bay window looking south onto the chapel courtyard (Figures 7(a) & 9). Figure 10 shows demagnetization of two samples from the foot of the bay window. The rock possesses two turning points in its demagnetization path. One is between 150 and 200°C, corresponding to the removal of the youngest
remanence component (Figure 10). The next $T_{UB}$ is shown by the turning point at 260°C. It corresponds to the most recent stabilization of the sample in the wall, in 1436–1448. Only heating to near 305°C can erase that remanence component. This turning point isolates the last detectable magnetic vector through to 400°C.

We will see later that the 305°C turning point is probably due to previous stabilization in a Roman structure.

(2) The West Hall of the Bishop’s Palace (1209–1235) Documentary and architectural evidence show that construction of the West Hall range started in under Bishop Hugh of Avalon (later St Hugh) in the late 12th century. Bishop Hugh of Wells completed it during 1209–1235. It has been a roofless shell since the Civil War (1642–1649).

We collected all samples from frost-shattered fragments lying on the edge of the lawn. We repositioned fragments into the walls to fix their original orientations. Figure 11 shows the demagnetization paths for three fragments. In each case, one sees a turning point between 75 and 125°C. This corresponds to the youngest remagnetization, imposed while the fragments lay on the ground. We believe the next significant turning point ($T_{UB} \approx 250°C$) characterizes the age of stabilization. Averages from many samples from the West Hall yield $T_{UB} \approx 260°C$ (Table 1; Figure 13). These
three samples also show a turning point near 300°C due to stabilization in an earlier building. We will later argue that it was derived from Roman masonry. Above 300°C the last, stable component of remanence vanishing at 440°C is the outcrop remanence.

(3) The east wall of the Chapel courtyard
The east wall of the palace precinct (Figures 5, 7, 9) aligns with the eastern defences of the lower Roman colonia that were strengthened in c. AD 300 (Jones, 1996). In 1995, repairs to the east wall of the Chapel courtyard allowed us to sample in situ masonry, and frost debris from the ground. This 1 m-thick wall displays several phases of construction (Figure 14). We chose this wall for concentrated sampling because it offers the most comprehensive test of relative dating by remagnetization. Also, we hoped to confirm or refine the relative ages of certain elements. We outline the main features of the wall in Figure 14 and discuss them in chronological order below.

Table 1. Correlation of blocking temperatures (TUB °C) with chronology

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<td>Courtyard east wall</td>
<td>40</td>
<td>93</td>
<td>171</td>
<td>225</td>
<td>275</td>
<td>350</td>
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<td>West Hall</td>
<td>10</td>
<td>118</td>
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<td>250</td>
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<td>Alnwick’s Chamber</td>
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<td>85</td>
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<td>Disturbed bedrock</td>
<td>7</td>
<td>77</td>
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<td>7300</td>
<td>&gt;403</td>
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<td>Bedrock Undercroft (Quarry)</td>
<td>6</td>
<td>66</td>
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<td>360</td>
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<tr>
<td>Rubble</td>
<td>6</td>
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Boldface blocking temperatures are from materials dated from historical, architectural or archaeological sources. The boldface temperatures in the second column are modern because they are commonly from remanences parallel to the geomagnetic field. Their VRM was imposed while they lay on the ground in recent years as frost shards, or as rubble static since 1990. In the rightmost column, the TUBs correspond to geological age remanences from their similarity to bedrock magnetic signatures. Boldface dates in the column header are confident on archaeological, architectural and historical grounds. The other two dates are inferred from a combination of relative VRM dating and reasonable supposition based on the available historical and archaeological evidence. The blocking temperatures in fainter type suggest ages solely from rock magnetic information, and comparisons with the rock magnetic information of dated material. N represents the number of critical turning points obtained from the demagnetization curves. The s.e.s of the mean blocking temperatures are <9°C, calculated from the dispersion of data about the mean in the histograms of Figures 13 & 16–18. Individual blocking temperatures for individual samples, e.g. quoted in text figures, may differ slightly from these mean values. Figure 12 shows the empirical dating curve.

Figure 12. Empirical remagnetization dating curve for Lincoln Limestone at the Bishop’s Palace, Lincoln, England.

Figure 13. Histograms of turning points (TUB °C) on the demagnetization diagrams for the West Hall of the Bishop’s Palace (1220).

(3a) 1838–c. 1850. The upper 0.7–1.1 m of the wall is capped by multiple, thin courses of a shelly, grey ragstone and Yorkshire Flagstone. Five phases of construction appear below the wall capping. The latest, probably contemporary with the capping, is the large area at the north end. It comprises horizontally cours ed, relatively unweathered blocks, up to 50 x 30 cm. This work is attributed to documented restoration work, started in 1838. A single sample, from a fallen frost shard, reveals a simple demagnetization history with a young remanence unblocked by heating to a temperature between 125 and 175°C (Figure 10). This represents remagnetization while the sample lay on the ground (probably
<10 years). The next turning point, below 225°C, isolates remagnetization since installation in the wall in the mid-19th century. Above 250°C, the last component is of outcrop origins. One would normally prefer to recognize the same component to much higher temperatures (cf. Figures 8, 10, 11). However, the sample demagnetized before such temperatures could be achieved.

(3b) 1650–1720. To the south of the 19th century refacing, the wall was refaced or rebuilt from the level of a former, raised courtyard (Chapman et al., 1975). The horizontally coursed rubble of this phase was of more weathered, roughly rectangular blocks up to 55 × 25 cm. Five in situ samples were collected with the assistance of the stonemasons during restoration work. These included fragments of three broken facing blocks and two fragments from the packed rubble in the core of the wall. All drill cores sampled from this material showed a two-component remanence, the younger component being unblocked near 225°C. The older remanence is univectorial, showing that the sample was freshly quarried for construction.

(3c) 1436–1448. We believe that the northernmost 1·75 m of the wall, including the recessed water trough, belongs to the building programme of Bishop William Alnwick (1436–1448). It abuts the mouldings of Alnwick’s chapel range and represents reinstatement of the boundary wall, following the erection of the chapel. We could take no samples from this phase of construction.

(3d) 1155–1167 or 1285–c. 1300. We observe horizontally coursed limestone rubble south of the water trough and immediately below the work of the 17th–18th century and Victorian era. It is smaller and more uniform in size than the overlying refacing blocks. Nine or 10 courses survive to a height of 1·3 m along the length of the wall (Figure 14). Inconclusive evidence from the courtyard excavations of 1968–1970 and its relationship to other structural elements allow us to assign a “mediaeval” age. It may be the remnants of a refurbished east precinct wall, dating from the founding of the palace on the site by Bishop Robert de Chesney (1155–1167), or date from late in the 13th century when the Vicar’s Court was founded immediately to the east, during a documented expansion of the cathedral close. We consider the late 13th century date most likely. Most samples from this section were sampled from the ground, as Figure 3(b). They show a soft remagnetization component, removed by heating to between 100 and 150°C. This remanence was acquired as the fragments lay on the ground since frost action spalled them off the wall. The next harder component is always unblocked by a temperature close to 250°C. This temperature characterizes the date of construction of this section of wall. Further demagnetization reveals a turning point near 330°C, after which the vector components veer off toward the vanishing point of the magnetization near 400°C. The magnetization isolated between 330 and 400°C was acquired in outcrop because no harder magnetization is found. Thus, the component fixed between TUB of 250 and 330°C must be intermediate between the age of the geological magnetization and the mediaeval construction. For this, we propose a Roman age.

Figure 3(a) shows a sample found in situ in the wall. Thus, we see a smooth demagnetization path to 305°C without any young overprint due to disorientation in the last decade. This single remanence
component was acquired since construction in the 12th or 13th centuries. The samples of Figure 3(a) & (b) bracket the $T_{UB}$ associated with the age of construction, between 250 and 305°C. The spread in critical $T_{UB}$ is due to mineralogical variation between samples and the coarseness of demagnetization intervals (25 or 50°C) in individual experiments. Later, we will show the frequency distribution of $T_{UB}$ from all the samples. They refine estimates of the mean $T_{UB}$ that characterize construction phases.

Figure 15 shows results obtained from frost shards. All possess a soft remagnetization component acquired in the last decade as they lay scattered on the ground. The first archaeologically significant $T_{UB}$ is near 250°C, dating from the mediaeval construction. A higher $T_{UB}$ close to 330°C represents the unblocking of post-Roman remagnetization. The remaining remanence decays to zero near 400°C and originated in outcrop.

(3e) Roman (c. AD 300). The lowest walling is slightly offset, built of roughly rectangular rubble, and bonded with a lime mortar that contains fragments of crushed brick or tile. It is not horizontally coursed like the overlying masonry but follows the south-sloping hillside. Excavations revealed that this section continues 1.6–1.8 m below the present courtyard (Chapman et al., 1975). The lowest course was further offset and bedded on limestone rubble foundation on bedrock. The excavations did not provide conclusive evidence for the age of this lower element of the wall. However, the east wall is on the line of the eastern defensive wall of the lower Roman colonia, dating to c. AD 300. Jones (1980, 1996) observed walling of similar appearance and construction elsewhere in the Roman circuit at Lincoln, with coursing following the topography and an offset bottom course.

We present the demagnetization of two of several fragments. The first was removed from the wall and smoothly demagnetizes to 330°C (Figure 4(a)). This represents the remagnetization since this section of wall was completed. By comparison with data from the West Hall (1209–1235), this masonry is considerably earlier and the only reasonable archaeological alternative is that it is Roman. Above 330°C, the single vector remanence decaying to the origin indicates an outcrop remanence.

We harvested the remaining samples from frost shards on the ground. Thus, all show a recent remagnetization, acquired while the samples lay at the foot of the wall. This remagnetization component is erased by thermal demagnetization to 50 or 100°C. All samples then demagnetize smoothly along one vector, until a significant $T_{UB}$ near 330°C, associated with the age of construction. Further demagnetization removes the remaining outcrop remanence.

**Summary**

Critical $T_{UB}$s, at turning points of the demagnetization paths, flag the thermal energy required to erase so many years of remagnetization. One could calculate the age from the $T_{UB}$ of an ideal crystalline substance (Dunlop, 1989; equation 1). However, this is impossible for most rocks that contain a spectrum of grain sizes, mineral compositions and crystal-defect densities. Thus, we adopt a less elegant, pragmatic approach.

The histogram of Figure 16 reveals the frequency distribution of $T_{UB}$ for the demolition rubble stable since 1990. Four main modes are apparent. The lowest $T_{UB}$ at 75°C represents the removal of very young remanence acquired in the last 5 years since the rubble remagnetized where it lay. All other material harvested from frost shards on the ground shows a similar feeble magnetization with $T_{UB}$=75°C, corresponding to 5-10 years worth of remagnetization.

Rubble samples, undisturbed since 1990, provided fragments that show an old $T_{UB}$=250°C. This suggests derivation from a mediaeval building. Two samples also possess a $T_{UB}$=350°C. By analogy with the samples from the sloping masonry at the base of the east wall, this could represent stabilization also in the Roman period. This suggests the possible reuse of
Roman masonry in a mediaeval structure, the subsequent collapse or demolition of that structure, and its eventual recovery for use in the repair of ancient monuments. Finally, many rubble samples show remanence remaining until >450°C that is clearly of outcrop origin.

Bishop Alnwick's audience chamber (1436–1448) yielded TUBs in a broad range from 200 to 250°C that correspond to its construction (Figure 17). Frost shards from the West Hall of the Bishop's Palace were analysed (Figure 13). Most possess recent magnetization in the PEF as they lay in random directions on the ground; this is erased by TUB ≈ 100°C. A significant peak of TUB = 250°C corresponds to the next oldest remanence that developed since inclusion in the building in 1209–1235. A smeared peak of TUB from 325 to 400°C includes outcrop magnetization and some TUBs due to magnetizations of the same age as the suspected Roman element of the East Courtyard Wall. Thus, Roman building materials may have been recycled in the erection of the West Hall.

The east wall of the Chapel Courtyard provided most samples, mainly as frost shards. Figure 18 shows a broad range of young overprints, centred on TUB = 75°C. These remagnetizations developed by VRM in the last decade, with numerous disturbances due to gardening. The next oldest peak of six samples from the Victorian repair work yields TUB = 200°C. Eight samples from the reconstruction in the late 17th–early 18th centuries have TUB near 225°C. Samples from the horizontally coursed mediaeval element have TUB = 275°C. Comparison with results from the West Hall (1209–1238), suggests this course was remagnetized in a stable orientation since 1155–1167 (Figure 18). This is the earlier of the two previously conjectured dates for this phase of construction.

Finally, the sloping masonry at the base of the Courtyard East Wall provided 15 samples in which TUB = 350°C removes the post-construction remagnetization. The high unblocking temperature indicates remagnetization since the Roman period, confirming that it was part of the Roman colonia wall, c. AD 300.

Conclusions
Well-defined TUBs from several elements of the ruins isolated remanences of different antiquity. On demagnetization plots, turning points characterize the maturity of the remanence component. Older remanence components are removed by higher temperatures. The sequence of partial remagnetizations agrees with the historical and archaeological data (Table 1). Thus, we may use the characteristic TUB for each remagnetization to identify or bracket the ages of unknown parts of the site.

We propose the following specific, new conclusions:
(a) The sloping masonry at the base of the Chapel Courtyard east wall is of Roman age;
(b) The immediately overlying horizontal masonry dates from 1155–1167, rather than the other possible date of 1285–c. 1300;
(c) Mediaeval builders used stone that had been remagnetized previously, since the Roman period. Roman masonry may have been directly recycled or disoriented blocks may have been reclaimed from the abandoned Roman quarries. This masonry was evidently stable between AD 300 and the mediaeval period because we find no evidence of intervening TUB between the Roman TUB = 350°C and the mediaeval TUB.

Our general conclusion is that remagnetization dating in masonry can be a sound tool for relative dating and correlation. It is imprecise for absolute dating. Our TUB-chronology scale must not be taken as universal. Different rocks remagnetize at different rates and some acquire none at all (Borradaile, 1996), although many limestones are potentially suitable (Borradaile et al., 1993). If the remagnetization is due to VRM it should follow a mathematically predictable form, permitting
extrapolation. Where weathering causes some chemical remagnetization, relative remagnetization dating is still possible. However, the appearance of the samples, the similar demagnetization behaviour of samples from interior and exposed surfaces, and hysteresis studies (Borradaile, 1996) do not favour significant chemical remagnetization. Thus, we believe that this study deals with remagnetization largely due to VRM. However, whether the remagnetization is viscous, chemical or both would not alter the interpretation and application of remanence dating at this site.

Usually, remagnetization dating works best for lithologies of uniform magnetic mineralogy. Applying it is easier if the masonry derives from outcrops with a previous simple, univectorial magnetization. Therefore, we should avoid bedrock with a complex geological history of rapid plate-tectonic motion, tectonic deformation or metamorphism.

Acknowledgements

We thank Mike Sutherill of English Heritage for permission to undertake sampling of the site. Ann Hammond prepared core samples, Sam Spivak drafted some diagrams, and Cora Borradaile aided in sampling. The laboratory portion of this research was funded by a grant from the Natural Sciences and Engineering Research Council of Canada to Graham Borradaile.

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