Paleomagnetism and paleothermometry of the Sydney Basin
2. Origin of anomalously high unblocking temperatures

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Abstract. The Milton Monzonite of southeastern Australia was thermoviscously remagnetized as a result of Cretaceous burial and uplift. Thermal demagnetization separates the low unblocking temperature (LT) overprint from the high unblocking temperature (HT) primary remanence, with a relatively sharp junction between LT and HT components in vector projections. For single-domain grains, the junction temperature $T_J$ between two such vectors corresponds to the maximum blocking temperature $T_B$ reactivated in nature, apart from a correction for the difference between natural and laboratory timescales. However, measured $T_J$ values are distributed over an implausibly wide range (>250°C) for burial remagnetization of an untilted intrusion like the Milton Monzonite. Furthermore, many $T_J$ values are anomalously high compared to the predictions of single-domain theory. Multidomain grains are the cause of these anomalies. Samples pretreated before thermal demagnetization by zero-field cycling to liquid nitrogen temperature, so as to erase multidomain remanence and isolate single-domain remanence, do have the theoretically expected $T_J$ values. In these samples, realistic remagnetization time and temperature ($t$, $T$) conditions in nature are predicted using the $t$-$T$ contours of Pullaiah et al. [1975]. The anomalously high $T_J$ values before low-temperature treatment are due to multidomain grains, which carry $>50\%$ of the LT overprint. The LT thermal demagnetization curve in samples dominated by multidomain grains is quasi exponential in shape with a high temperature tail extending almost to the Curie point, as predicted by multidomain theory. These high LT unblocking temperatures, which are much greater than plausible remagnetization temperatures reached in nature, overlap and mask the lower part of the HT unblocking temperature spectrum, driving up $T_J$ values and leading to inflated estimates of $T_B$. Although multidomain remanence is a sufficient explanation of anomalously high unblocking temperatures of thermoviscous overprints in the Milton Monzonite, chemical overprinting may be a factor in other lithologies and tectonic settings.

1. Paleomagnetism of the Milton Monzonite

Dunlop et al. [this issue] (hereinafter referred to as paper 1) showed that the Milton Monzonite, an Early Triassic intrusion into flat-lying sediments of the Sydney Basin of southeastern Australia, has a natural remanent magnetization (NRM) with four distinct components. (1) The high unblocking temperature (HT) component, carried by magnetite or occasionally pyrrhotite, is interpreted to be the primary NRM. (2) the low unblocking temperature (LT) component, carried by magnetite or pyrrhotite, is believed to be a thermoviscous overprint of HT acquired during Cretaceous uplift and cooling. (3) a chemical remanent magnetization (CRM) carried by magnetite (CRM1) has higher unblocking temperatures than either LT or HT; CRM1 and LT have similar directions and ages but widely separated unblocking temperature ranges, and (4) a second CRM (CRM2), carried by hematite, has the highest unblocking temperatures of all. CRM2 and HT have similar directions and ages.

The widely separated LT and CRM1 unblocking temperatures (100-150°C of nonoverlap, flanking JHT below and above) make it unlikely that LT is a chemical overprint. It is difficult to imagine chemical processes that would generate two types of magnetite with no overlap in grain size and unblocking temperatures. However, there are two problems in the interpretation of LT as a purely thermoviscous overprint. First, junctions between LT and HT on vector diagrams are somewhat rounded, not perfectly sharp as they should be for a partial thermoremanent magnetization (TRM) carried by single-domain grains overprinting another remanence. Second, maximum laboratory unblocking temperatures $T_u$ of the LT overprint, measured as junction temperatures between the LT and HT vectors in orthogonal vector diagrams (e.g., paper 1, Figures 4 and 5), are often unexpectedly high in view of the known limits on remagnetization temperatures $T_R$ in the Sydney Basin [Middleton and Schmidt, 1982].

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2. Time-Temperature Relations

Anomalously high unblocking temperatures of magnetic overprints are well documented elsewhere. Chamalaun [1964] was the first to study thermoviscous remagnetization and construct time-temperature (t-T) contours to correct laboratory \( T_u \) data for the effect of slow cooling in nature. With the differing timescales of cooling taken into account, \( T_u \) values for remagnetized British red beds matched plausible geological remagnetization temperatures \( T_r \). However, in calculating this \( t-T \) contours, Chamalaun omitted the key factor \( \beta(T) = M_s(T)/M_u \), where \( M_s \) is spontaneous magnetization and subscript zero indicates room temperature value. If we use contours calculated with \( \beta(T) \) included [Pulliaah et al., 1975], Chamalaun's \( T_u \) data predict \( T_r \) values that are higher than expected on geological grounds.

Pulliaah et al. [1975] based their calculations on the classic Néel [1949] theory of thermoviscous magnetization in single-domain grains. Néel had shown that the blocking temperature \( T_B \) of a partial 1Km during cooling or its unblocking temperature \( T_{un} \) during heating are governed by the thermal variation of the magnetic relaxation time \( \tau \):

\[
1/\tau(T) = C \exp[-\mu_s V M_u H_K \beta(T)/2k],
\]

where \( C = 10^8 \text{ s}^{-1}, \mu_s = 4\pi \times 10^{-7} \text{ H/m}, V \) and \( H_K \) are grain volume and micro coercive force, and \( k \) is Boltzmann's constant. For shape anisotropy, \( n = 2 \). Omitting \( \beta(T) \) from (1) gives \( \tau \) values that are too high at all temperatures and orders of magnitude too high near the Curie point \( T_C \).

Because \( \tau \) depends exponentially on \( V(T)/T \), temperature changes of a few degrees Celsius have a large effect on \( \tau \). At \( T_B \), a slight cooling will render the magnetization relaxation sluggish or blocked, while at \( T_{un} \) (which is equal to \( T_B \) for a particular single-domain assembly in weak fields like that of the Earth), a slight heating will cause instantaneous relaxation, i.e., within a time shorter than the observation time \( t \).

\( T_u \) or \( T_{un} \) mark a sharp boundary between blocked and unblocked magnetization states. Partial TRM acquired by a single-domain ensemble at \( T_B \) during cooling should demagnetize completely during zero-field reheating at \( T_{un} = T_B \). For this reason, the unblocking temperature spectrum of a partial 1Km should be sharply separated from that of the NRM in overprints, giving sharp junctions on vector diagrams rather than rounded ones.

Using as a blocking/unblocking condition \( \tau = t \) (relaxation time equal to observation time), (1) gives the following relation between the maximum laboratory unblocking temperature \( T_u \) of overprinting partial TRM, measured in thermal demagnetization over a relatively short time \( t_u \), and the original blocking temperature or remagnetization temperature \( T_r \) of the partial TRM during long exposure for time \( t \), in nature:

\[
T_u \beta_r^{-1} \ln(C_r) = T_r \beta_r^{-1} \ln(C_r) = \mu_s V M_u H_K / 2k. \tag{2}
\]

This is the Pulliaah et al. [1975] time-temperature relation.

3. Remagnetization Diagrams and Results

Contours calculated from (2) are plotted as solid curves in Figure 1. The value of \( \mu_s V M_u H_K / 2k \) determines the contour value of the quantity \( T \beta^{-1}(T) \ln(C) \) for a particular single-domain grain ensemble. Larger or more coercive grains have higher blocking/unblocking temperatures. Since \( t_u \) is typically a few minutes (residence time at peak temperature in a heating step), while \( t \) can be millions of years for deep burial and slow uplift, \( T_u \) can be as much as 100°C higher than the remagnetization temperature \( T_r \) the rock experienced in nature.

The results of our work and several previous studies are plotted in Figure 1. The two sets of points labeled SD come from thermal demagnetization of laboratory viscous remanent magnetizations in single-domain magnetite [Dunlop and Ozdemir, 1993]. The data parallel the contours, verifying the Pulliaah-Néel equations over the longest timescales available in the laboratory. Other single-domain data (not shown) which follow the Pulliaah et al. contours over more extended timescales include remagnetized Appalachian red beds containing single-domain hematite [Kent and Miller, 1987] and blocks of fine-grained Columbia River basalt tumbled in a landslide [Tysen Smith and Verosub, 1994].

However, the results of other studies are in serious disagreement with the Pulliaah et al. [1975] contours. The points marked A and B in Figure 1 are from Kent's [1985] study of Appalachian limestones. A denotes boulders from a till which have acquired postglacial viscous overprints. B denotes bedrock material that has been regionally remagnetized during mild heating. In both cases, the lines joining laboratory and natural \( (t, T) \) points have much lower slopes than predicted. That is, laboratory heating to much higher temperatures \( T_u \) than predicted is required to completely erase the thermoviscous overprint.

Middleton and Schmidt's [1982] report of similarly elevated laboratory unblocking temperatures \( T_u \) in the Milton Monzonite was the incentive for the present study. Our \( T_u \) data, from much more detailed thermal demagnetization of Milton Monzonite samples (see paper 1), are plotted in Figure 1 as groups 1, 2, and 3. Group 1 includes samples from site 1 and samples from other sites that were pretreated by zero-field cycling to liquid nitrogen temperature to isolate single-domain remanence. Group 2 includes results (without low-temperature pretreatment) from sites 1, 3, 4, 5, 6, and 9 and agrees quite well with Middleton and Schmidt's result. Group 3 includes results from sites 10 and 11, where multidomain magnetite carries the remanence.

During burial, samples from all sites experienced a maximum temperature \( T_{max} \approx 200^\circ \text{C} \) for \( t_u \approx 3 \text{ Myr} \) (Middleton and Schmidt [1982]; based on coal grade, regional metamorphism, and fission track data). When this point is joined to each of the three groups, we can see that group 1 results are consistent with the Pulliaah et al. [1975] contours, group 2 results have higher \( T_u \) values which are compatible (coincidentally, we believe) with a different set of dashed contours proposed by Middleton and Schmidt on the basis of a single-domain remagnetization theory by Walton [1980], while group 3 results have still higher \( T_u \) values that are incompatible with either set of contours.

Samples from site 10 contain large, truly multidomain grains of magnetite, whereas the magnetite at other sites is smaller in size (moderate to large pseudo-single-domain, \( \geq 10 \mu\text{m} \) approximately) (see paper 1, Figure 3 and Table 1). Partial TRMs and viscous remanences carried by multidomain magnetite have long thermal demagnetization tails, extending essentially to the Curie temperature \( T_C \) [Bol'shakov and Shcherbakova, 1979; Worm et al., 1988; Xu and Dunlop, 1994; Dunlop and Ozdemir, 1997, Figures 10.11, 10.13, 16.11]. Thus the elevated maximum unblocking temperatures of the LT component in group 3 samples could be due to multidomain magnetite. The compatibility of group 1 results with the Pulliaah et al. [1975] contours is not surprising since low-temperature pretreatment was intended to isolate single-
domain magnetite. Group 2 results may represent a mixture of single-domain-like and multidomain carriers, or it may be characteristic of pseudo-single-domain carriers of a certain grain size. We shall test these ideas in the remainder of this paper.

4. Thermal Demagnetization Results

Figure 2 shows the results of 194 determinations of $T_d$, the maximum unblocking temperature of the LT component, from sharp or slightly rounded junctions between LT and HT vectors on orthogonal vector diagrams (e.g., Figures 4, 6, and 7 or Figures 4 and 5 of paper 1). The $T_d$ values fall into four groups. Many samples from sites 7 and 8 have $T_d$ between 200 and 230°C. This peak is probably due to pyrrhotite ($T_c$ = 320°C), which is known to carry the LT and HT remanences in some of these samples (see paper 1, Figure 5), and not to magnetite. These data have therefore not been included in Figure 1.

The second $T_d$ peak is between 280 and 330°C. Most of these values are for samples that were pretreated by zero-field cycling through the magnetite isotropic temperature ($T_c = -150°C$) to unpin domain walls and demagnetize multidomain remanence. This process of low-temperature demagnetization (LTD) is a standard method of isolating single-domain remanence in magnetite [Ozima et al., 1964; Kohayashi and Fuller, 1968; Merrill, 1970]: the memory ratio R of remanence after LTD to remanence before LTD decreases rapidly as grain size increases [Heid et al., 1992; Halgedahl and Jarrard, 1995]. The other $T_d$ determinations in this group are for samples from site 2, which did not have single-domain-like hysteresis properties (paper 1, Table 1 and Figure 3). However, these samples do have unusually small LT components relative to the HT component (Figures 4, 5, and 6) and we will argue later that this circumstance brings the single-domain fraction in both HT and LT into prominence. Thus initial indications are that the second $T_d$ peak, corresponding to group 1 in Figure 1, is due to single-domain remanence.

The third and largest peak in $T_d$ values is between 350 and 460°C, especially between 400 and 440°C. These results, from sites 1, 3, 4, 5, 6, and 9, constitute group 2 in Figure 1.

The fourth and highest grouping of $T_d$ values is between 500 and 550°C. These results are from sites 10 and 11 and comprise group 3 in Figure 1. These unblocking temperatures are crucial because they are too high to be explained by either the Pullaith et al. [1975] or the Middleton-Schmidt [1992]-Walton [1980] (MSW) $r$-$T$ contours unless totally unrealistic geological temperatures are assumed. In any case, the very wide spread between groups of unblocking temperatures in
5. Thermal Demagnetization of Multidomain Grains

We now return to the fourth cluster of $T_L$ values, for samples from sites 10 and 11. These samples are special in two ways. First, Table 1 and Figure 3 of paper 1 show that site 10 samples contain large magnetite grains ($\geq 100 \mu m$ approximately) with truly multidomain hysteresis properties (no unheated site 11 material remained for hysteresis measurements). Second, all 12 samples from sites 10 and 11 have very small HT components compared to samples from other sites; an estimate of the HT direction was only possible for 2 samples (paper 1, Table 3).

6. Correlation Between $T_L$ and the HT/LT Ratio

The idea that a large HT component masks the full tail of the LT demagnetization curve while a small or vanishing HT component reveals the entire tail is borne out by the data for groups 1, 2, and 3. Figure 4 and Table 1 show that site 10 and 11 samples, with HT/LT = 0, have LT unblocking temperatures extending to 500°C and above, as already illustrated in Figure 3. Samples from site 6 and other group 2 sites, with HT/LT in the range 0.2-0.5, have LT unblocking spectra that.
7. Effects of Low Temperature Demagnetization

7.1 Rounded and Sharp Junctions

Any overlap between the unblocking temperature spectra of two remanence vectors, e.g., between LT and HT as discussed in section 6, will result in rounded junctions between their vector trajectories during thermal demagnetization. Such overlap and rounding are not necessarily proof of multidomain grains: a CRM overprint would have the same effect. However, if rounded vector junctions become sharp when the composite NRM is pretreated by LTD, we can be sure that the LTD-treated overprint is a partial TRM in single-domain-like grains and that the original rounding/overlap was due to multidomain grains.

This is the case in our samples. Specimen 2a2 has rounded junctions between LT and HT vectors in its demagnetization trajectories (Figure 6). Its companion, 2a3, was pretreated before thermal demagnetization by LTD to erase multidomain remanence. As a result, the LT vector lost about one-half its intensity (the segment between the NRM and 20°C steps). The remaining LT vector, the low-temperature memory, now has a sharp demagnetization junction with HT.

Sharp junctions are a feature of single-domain partial TRM or viscous overprints. As discussed earlier, they result from the fact that a single-domain grain with blocking temperature \( T_B \) has a unique unblocking temperature, \( T_{UB} = T_B \). Multidomain partial TRM behaves quite differently. A particular blocking temperature \( T_B \) does not have a single corresponding unblocking temperature \( T_{UB} \) but rather a broad distribution of \( T_{UB} \) extending from room temperature essentially to \( T_C \) [Dunlop and Xu, 1994]. LT-HT junctions which become sharp after LTD show that the original rounding was a result of distributed \( T_{UB} \) in multidomain grains.

A multidomain fraction carrying either LT or HT would result in \( T_{UB} \) overlap and rounding. If LT contains the major multidomain fraction and HT is single-domain-like, the main effect will be to push junction temperatures up, because LT will continue to demagnetize above its original maximum blocking temperature. If LT were concentrated in single-domain grains and HT in multidomain grains, the junction
temperature would tend to be pushed down as a result of HT demagnetizing below its original minimum blocking temperature. These trends are in addition to those due to the relative intensities of LT and HT.

The experimental evidence is that a large proportion of LT (one-half to two-thirds) is carried by multidomain grains and is destroyed by LTD. The HT vectors, on the other hand, do not decrease significantly as a result of LTD (e.g., Figures 6 and 7). HT is single-domain-like. Therefore we anticipate that junction temperatures in most samples have been pushed up, i.e., are anomalously high, and will tend to be lowered by LTD. This hypothesis is tested in section 7.2.

### Table 1. Component Ratios and LT Unblocking Temperatures

<table>
<thead>
<tr>
<th>Site</th>
<th>HT/LT</th>
<th>( R = \text{LT(LTD)}/\text{LT} )</th>
<th>( T_L ) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.184 ± 0.057</td>
<td>0.486 ± 0.027</td>
<td>401 ± 35</td>
</tr>
<tr>
<td>2 (a-d)</td>
<td>1.90 ± 0.36</td>
<td>0.268 ± 0.010</td>
<td>333 ± 15</td>
</tr>
<tr>
<td>3 (b-g)</td>
<td>0.109 ± 0.035</td>
<td>0.427 ± 0.028</td>
<td>393 ± 18</td>
</tr>
<tr>
<td>4</td>
<td>0.280 ± 0.090</td>
<td>0.408 ± 0.019</td>
<td>428 ± 22</td>
</tr>
<tr>
<td>5</td>
<td>0.504 ± 0.054</td>
<td>0.577 ± 0.105</td>
<td>440 ± 15</td>
</tr>
<tr>
<td>6</td>
<td>0.289 ± 0.070</td>
<td>0.564 ± 0.055</td>
<td>394 ± 27</td>
</tr>
<tr>
<td>7</td>
<td>0.220 ± 0.12</td>
<td>0.267 ± 0.61</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.080 ± 0.002</td>
<td>0.484 ± 0.06</td>
<td>427 ± 6</td>
</tr>
<tr>
<td>9 (c)</td>
<td>0.259 ± 0.043</td>
<td>0.459 ± 0.073</td>
<td>427 ± 6</td>
</tr>
<tr>
<td>9 (d-f)</td>
<td>0.259 ± 0.043</td>
<td>0.459 ± 0.073</td>
<td>427 ± 6</td>
</tr>
<tr>
<td>10</td>
<td>0.388 ± 0.076</td>
<td>0.516 ± 14</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.477 ± 0.072</td>
<td>0.538 ± 8</td>
<td></td>
</tr>
</tbody>
</table>

HT and LT are the magnitudes of the high-temperature and low-temperature NRM vectors, respectively. LT(LTD) is the magnitude of the LT vector after low-temperature demagnetization. \( T_L \) is apparent remagnetization temperature as determined in the laboratory as the junction temperature between the LT and HT vectors.

#### 7.2 Reduction of \( T_L \)

LTD reduces the LT-HT junction temperature \( T_L \) in specimens of sample 2a from about 314°C to 302°C (Figure 6). The reduction is much larger in other samples, particularly from sites other than 2. Figure 7 gives two examples. Sample 2e has a much lower HT/LT ratio than samples 2a-2d and therefore more elevated junction temperatures before LTD. LTD lowers the \( T_L \) from 352°C to 288°C. Sample 6b, from group 2, has a still smaller HT/LT ratio. Its \( T_L \) value, originally 420°C, is reduced to 294°C by LTD. Notice that LTD does not affect the IIT-CRM1 junction temperature, which was 518°C without LTD and 510°C with LTD.

The preponderant effect of LTD is to reduce \( T_L \) values, which were originally elevated relative to the predictions of Pullahah et al. [1975] and widely spread (over a range of 250°C; groups 1, 2, and 3 in Figure 1), to a narrow concentration around 300°C (second \( T_L \) peak in Figure 2). This value of \( T_L \) is as predicted by Pullahah et al. We have thus verified that single-domain or single-domain-like carriers of thermoviscous magnetization do obey the predictions of conventional single-domain remagnetization theory on geological time-
Figure 5. Correlation between $T_1$ and the HT/LT ratio. Values shown are site or subsite averages with standard deviations (Table 1). The masking effect of multidomain grains produces a >250°C spread in $T_1$ values from purely single-domain values ($<300°C$, including LTD-treated samples) to purely multidomain values ($500-550°C$).

Sample:2a2 (without LTD)

Sample:2a3 (with LTD)

Figure 6. A demonstration that rounded junctions between LT and HT vectors, indicating overlap in their unblocking temperature ranges, become sharp (single-domain-like: $T_{un} = T_a$) as a result of LTD pretreatment.
scales. The Middleton-Schmidt-Walton contours are not necessary to explain single-domain remagnetization. Elevated unblocking temperatures are a consequence of varying admixtures of multidomain remanence carriers, which are particularly prominent in the Milton Monzonite because of the coarse average grain size.

This picture is of course an oversimplification. Figure 8 documents sample-by-sample changes in $T_r$ values as a result of LTD. Although there is a strong tendency for $T_r$ to decrease as a result of LTD, there are examples of no significant change or even increases (1a, 1f, 3g). These increases could be due to variability in HT/LT between specimens of the same sample, to unusual mixtures of multidomain and single-domain carriers (e.g., multidomain carriers of HT), or possibly to some degree of chemical overprinting in these samples. For example, specimen 1a5 has HT/LT = 0.240 while its companion 1a5, pretreated by LTD, has HT/LT = 0.133. The lower HT/LT ratio will tend to increase $T_r$ (see Figure 5). Furthermore, more than one-third of HT in both specimens is carried by multidomain magnetite. The ratio of HT vector intensities in 1a5 (after LTD) and 1a3 (no LTD) gives a memory ratio $R = 0.637$, an unusually low $R$ value for the HT component in the Milton samples.

8. Discussion

It was previously thought [Schmidt and Embleton, 1981] that maximum unblocking temperatures of thermoviscous overprints in the Milton Monzonite were anomalously high, on the basis of existing single-domain remagnetization theory [Néel, 1949; Pullaiah et al., 1975]. A new set of time-temperature contours, proposed by Middleton and Schmidt [1982] on the basis of a theory by Walton [1980], explained the data more satisfactorily. Walton's analysis also used single-domain relaxation theory but his criterion for remagnetization was that the overprinting NRM should have the same intensity as the overprinted NRM. In reality, thermoviscous overprinting of single-domain grains occurs by replacement of the overprinted NRM, whatever its intensity or direction, by the overprinting NRM up to $T_s = T_{LM} = T_r$ (for a laboratory timescale). This is the criterion used by Pullaiah et al., and it is the correct picture of remagnetization in a geological context (see discussion by Enkin and Dunlop [1988]).

Our restudy of the Milton Monzonite, with broader sampling and more exhaustive thermal demagnetization than in Schmidt and Embleton’s [1981] study, has shown that the apparent success of the Middleton Schmidt-Walton (MSW) remagnetization contours was coincidental. Although 6 of our 11 sites give $T_r$ values similar to those of Schmidt and Embleton (the third $T_r$ grouping in Figure 2) which are compatible with MSW contours (group 2 in Figure 1), samples from other sites give very different results.

Samples from sites 10 and 11 yield $T_r$ values between 500 and 550°C (highest grouping in Figure 2, group 3 in Figure 1), much too high to explain by the MSW contours. On the basis of hysteresis data and low-temperature memories, these
samples have multidomain magnetite as their principal magnetic constituent. Furthermore, thermal demagnetization curves of their LT overprints, unobscured by the considerable underlying HT remanence that survives at other sites, extend almost to T_C with tails of the form predicted by multidomain partial TRM theory [Dunlop and Xu, 1994; Xu and Dunlop, 1994]. If LT were a CRM, it would likely have "thermally discrete" unblocking temperatures, concentrated just below T_C, rather than the observed "thermally distributed" unblocking temperatures with a quasi-exponential spectrum characteristic of multidomain partial TRM. A thermally discrete chemical overprint, CRM1, with the same direction as LT, does exist at most sites but the LT and CRM1 unblocking ranges are cleanly separated, with 100-150°C of nonoverlap (paper 1, Figure 6).

At the other extreme, samples from site 2 and many from other sites which have been low-temperature cycled to demagnetize multidomain magnetite, have much lower T_C values, around 300°C (second peak in Figure 2, group 1 in Figure 1). Most site 2 samples have HT >> LT, unlike samples from any other site. With few exceptions, HT does not lose significant intensity as a result of LTD: it is single-domain-like. Because LT is of low intensity at site 2, its thermal demagnetization tail does not significantly cloud the single-domain-like demagnetization of HT. For this reason, site 2 samples (as well as many LTD-treated samples) give T_C values that are close to true single-domain values. The agreement of group 1 results with the Pulliiah et al. contours (Figure 1) confirms that the Pulliiah-Néel theory is a correct description of single-domain thermoviscous remagnetization.

Figure 8. A sample-by-sample comparison of T_C values without LTD (left-hand points in each pair, usually two specimens) and with LTD (right-hand point, one specimen), as indicated by the symbol at top. In all but three instances, T_C decreases as a result of LTD, and in many cases (every sample for sites 2 and 6), the T_C value following LTD is in the range expected for single-domain grains (~300°C).
9. Conclusions

1. In the case of single-domain NRM, thermoviscous remagnetization is accurately described by the theory of Néel [1949] and Pulaiah et al. [1975]. Geological conditions during remagnetization, \((t, T)\), are correctly predicted from short-term laboratory observations, \((t, T)\), by using the Pulaiah et al. contours, and not the Middleton-Schmidt-Walton contours (Figure 1).

2. In the case of multidomain NRM, unblocking temperature spectra of overprinting and overprinted NRMs overlap, leading to rounded rather than sharp junctions between vector demagnetization trajectories of the two NRM components. The junction temperature \(T_j\) between the vector projections of the two components may be pushed either up or down compared to the single-domain case by the overlap of unblocking temperatures. In the Milton Monzonite, where the overprinted HT primary NRM is single-domain-like and the thermoviscous LT overprint is at least 50% multidomain, \(T_j\) values are pushed up in general (Figure 2).

3. When HT is very small, LT exhibits a quasi-exponential thermal demagnetization curve with a high-temperature tail extending almost to \(T_C\) (Figure 3). The thermally distributed unblocking temperatures and the shape of the demagnetization tail are in accord with predictions of multidomain partial TRM theory [Dunlop and Xu, 1994].

4. When LT is larger than HT, the LT demagnetization tail masks the lower part of the HT unblocking temperature spectrum, pushing the junction temperature \(T_j\) up. The amount by which \(T_j\) exceeds the expected single-domain value correlates with the HT/LT ratio (Figure 5).

5. When LT is less than HT, the masking effect is small and laboratory \(T_j\) values are close to expected single-domain values (Figure 1, group 1).

6. When the multidomain fraction of LT is removed by prior low-temperature demagnetization, the observed \(T_j\) values are generally reduced (Figures 7 and 8), often close to expected single-domain values (Figure 2, second \(T_j\) grouping).

7. Multidomain remanence explains the "anomalously" high unblocking temperatures of LT in the Milton Monzonite, but chemical overprinting may be a factor in other lithologies and tectonic settings.

8. Most of the Milton Monzonite samples have hysteresis properties characteristic of moderate to large pseudo-single-domain grains of magnetic (10-100 µm approximately). Only a few approach truly multidomain sizes (>100 µm). The multidomain and single-domain-like fractions of NRM are therefore likely a property of pseudo-single-domain grains, rather than of separate multidomain and single-domain grains.

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References


Heider, F., D. J. Dunlop, and H. C. Soffel, Low-temperature and alternating field demagnetization of saturation remanence and thermoremanence in magnetite grains (0.037 μm to 5 mm), *J. Geophys. Res.*, 97, 9371-9381, 1992.


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