JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. B12, PAGES 27,285–27,295, DECEMBER 10, 1997

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

D. J. Dunlop and Ö. Özdemir
Geophysics Laboratory, Department of Physics, University of Toronto, Toronto, Canada

P. W. Schmidt
Division of Exploration and Mining, CSIRO, North Ryde, New South Wales, Australia

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_L between two such vectors corresponds to the maximum blocking temperature T_r reactivated in nature, apart from a correction for the difference between natural and laboratory timescales. However, measured T_L values are distributed over an implausibly wide range (>250°C) for burial remagnetization of an untilted intrusion like the Milton Monzonite. Furthermore, many T_L 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_L values. In these samples, realistic remagnetization time and temperature (t_r, T_r) conditions in nature are predicted using the *t-T* contours of *Pullaiah et al.* [1975]. The anomalously high T_L 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_L values and leading to inflated estimates of T_r. 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 HT 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_L 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].

Copyright 1997 by the American Geophysical Union.

Paper number 97JB02478.
0148-0227/97/97JB-02478$09.00

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_L data for the effect of slow cooling in nature. With the differing timescales of cooling taken into account, T_L values for remagnetized British red beds matched plausible geological remagnetization temperatures T_r. However, in calculating his t-T contours, Chamalaun omitted the key factor $\beta(T) = M_s(T)/M_{s0}$, where M_s is spontaneous magnetization and subscript zero indicates room temperature value. If we use contours calculated with $\beta(T)$ included [*Pullaiah et al.*, 1975], Chamalaun's T_L data predict T_r values that are higher than expected on geological grounds.

Pullaiah 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 TRM during cooling or its unblocking temperature T_{UB} during heating are governed by the thermal variation of the magnetic relaxation time τ:

$$1/\tau(T) = C \exp[-\mu_0 V M_{s0} H_{K0} \beta^n(T)/2kT], \tag{1}$$

where $C \approx 10^9\ \mathrm{s}^{-1}$, $\mu_0 = 4\pi \times 10^{-7}$ H/m, V and H_K are grain volume and microcoercive force, and k is Boltzmann's constant. For shape anisotropy, $n = 2$. Omitting $\beta(T)$ from (1) gives τ values that are too high at all temperatures and orders of magnitude too high near the Curie point T_C.

Because τ depends exponentially on $\beta^n(T)/T$, temperature changes of a few degrees Celsius have a large effect on τ. At T_B, a slight cooling will render the magnetization relaxation sluggish or blocked, while at T_{UB} (which is equal to T_B for a particular single-domain assemblage 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_B or T_{UB} 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 $T_{UB} = T_B$. For this reason, the unblocking temperature spectrum of a partial TRM should be sharply separated from that of the NRM it 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_L of overprinting partial TRM, measured in thermal demagnetization over a relatively short time t_L, and the original blocking temperature or remagnetization temperature T_r of the partial TRM during long exposure for time t_r in nature:

$$T_L\, \beta_L^{-n} \ln(Ct_L) = T_r\, \beta_r^{-n} \ln(Ct_r) = \mu_0 V M_{s0} H_{K0}/2k. \tag{2}$$

This is the *Pullaiah 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 $\mu_0 V M_{s0} H_{K0}/2k$ determines the contour value of the quantity $T\, \beta^{-n}(T) \ln(Ct)$ for a particular single-domain grain ensemble. Larger or more coercive grains have higher blocking/unblocking temperatures. Since t_L is typically a few minutes (residence time at peak temperature in a heating step), while t_r can be millions of years for deep burial and slow uplift, T_L 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 Özdemir*, 1993]. The data parallel the contours, verifying the Pullaiah-Néel equations over the longest timescales available in the laboratory. Other single-domain data (not shown) which follow the Pullaiah 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 [*Tyson Smith and Verosub*, 1994].

However, the results of other studies are in serious disagreement with the *Pullaiah 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_L than predicted is required to completely erase the thermoviscous overprint.

Middleton and Schmidt's [1982] report of similarly elevated laboratory unblocking temperatures T_L in the Milton Monzonite was the incentive for the present study. Our T_L 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 2 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 $T_r \approx 200$°C for $t_r \approx 3$ 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 *Pullaiah et al.* [1975] contours, group 2 results have higher T_L 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_L 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, ≥ 10 µm 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 Özdemir*, 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 *Pullaiah et al.* [1975] contours is not surprising since low-temperature pretreatment was intended to isolate single-

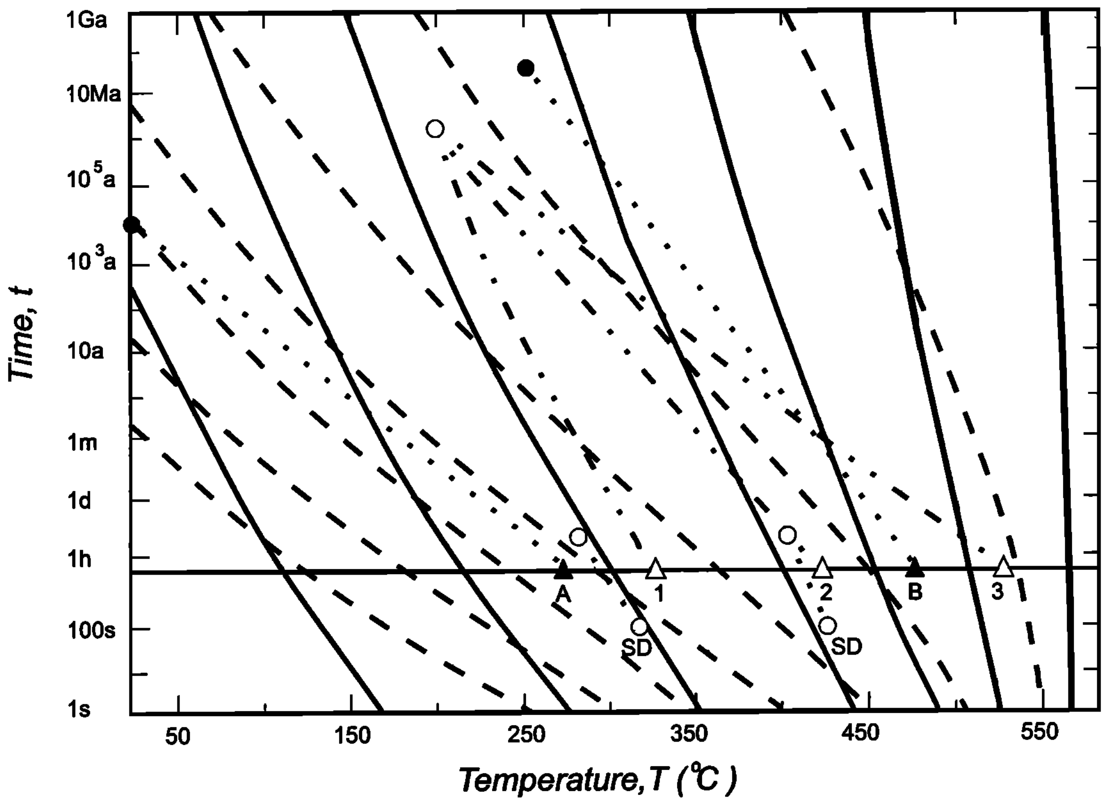

Figure 1. Thermoviscous remagnetization contours predicted by *Pullaiah et al.* [1975] on the basis of *Néel* [1949] single-domain blocking theory (solid curves) and by *Middleton and Schmidt* [1982] on the basis of the single-domain relaxation theory of *Walton* [1980] (dashed curves). Data shown are short-term and longer-term (t, T) pairs for single-domain magnetites (SD, *Dunlop and Özdemir* [1993]), Appalachian limestones (A, B, *Kent* [1985]), and the Milton Monzonite (1, 2, 3 and open circle at top, this paper). Only SD and our group 1 data agree with Pullaiah et al.'s predictions. A, B, and our group 2 data agree with the MSW contours. Group 3 has laboratory unblocking temperatures too high to be explained by either set of contours. We believe group 1 is due to single-domain remanence, group 3 is due to multidomain remanence, and group 2 is due to a mixture of single-domain and multidomain remanence or to pseudo-single-domain grains whose remanence has both single-domain-like and multidomain-like aspects.

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_L, 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_L values fall into four groups. Many samples from sites 7 and 8 have T_L 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_L 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 ($T_I \approx -150$°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; *Kobayashi and Fuller*, 1968; *Merrill*, 1970]; the memory ratio R of remanence after LTD to remanence before LTD decreases rapidly as grain size increases [*Heider et al.*, 1992; *Halgedahl and Jarrard*, 1995]. The other T_L 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_L peak, corresponding to group 1 in Figure 1, is due to single-domain remanence.

The third and largest peak in T_L 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_L 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 *Pullaiah et al.* [1975] or the Middleton-Schmidt [1982]-Walton [1980] (MSW) t-T contours unless totally unrealistic geological temperatures are assumed. In any case, the very wide spread between groups of unblocking temperatures in

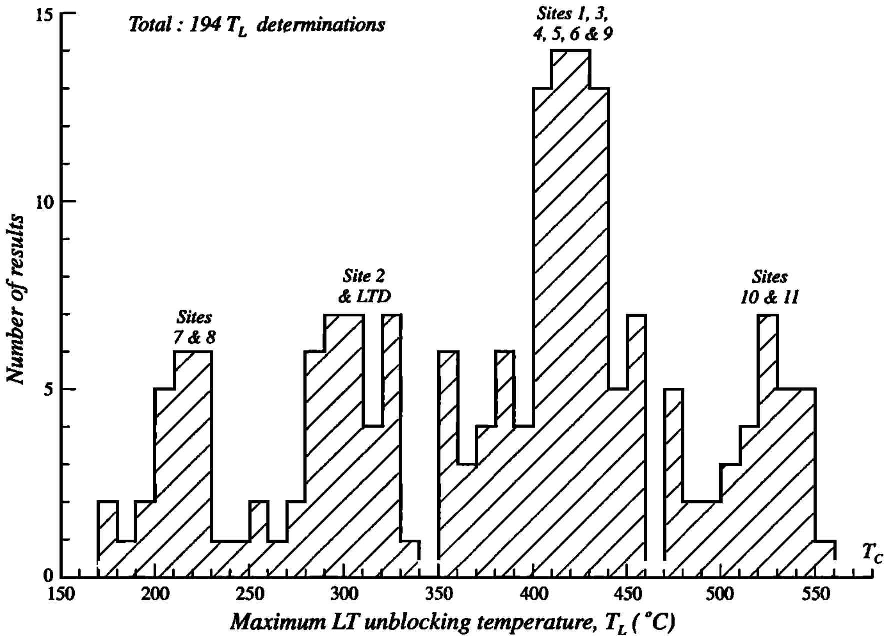

Figure 2. Histogram of 194 values of the maximum laboratory unblocking temperature T_L of the LT overprint, determined from junctions between vector trajectories of LT and HT thermal demagnetization data. The four T_L groupings correspond to samples containing pyrrhotite (sites 7 and 8); samples dominated by single-domain remanence (LTD treated samples) or with unusually small LT components (site 2); samples with mixed single-domain-like and multidomain carriers of LT (sites 1, 3, 4, 5, 6, and 9); and samples with predominantly multidomain carriers of LT (sites 10 and 11).

Figure 1 or 2 shows that something is amiss in our understanding of thermoviscous remagnetization.

Two other possible explanations of anomalously high unblocking temperatures were considered in paper 1. First, long-term average geological reheating temperatures determined from vitrinite reflectance (a measure of coalification) might be lower than thermal pulses which could cause remagnetization. However, different sites in an untilted body the size of the Milton Monzonite ($\approx$50 km^2 in cross-section) could not have reached peak temperatures differing by several hundred °C. Second, possibly the LT overprint is not wholly thermoviscous but is partly chemical. The 100-150°C window between unblocking temperatures of LT and CRM1, which is definitely a chemical overprint, is then inexplicable.

We therefore believe that LT is indeed a thermoviscous overprint. Its anomalously high average value of T_L (anomalous according to conventional theories) is not the only, or even the main, problem. The wide spread of T_L values shows that thermoviscous remagnetization is not explicable in terms of single-domain grains only, whether the *Pullaiah et al.* [1975] or the MSW model is used.

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 μm 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).

This fortunate circumstance allows us to examine the thermal demagnetization of an almost single-component multidomain remanence. The results shown in Figure 3 for 10d1 and 10e2 are typical. The LT component demagnetizes slowly in almost exponential fashion up to ~500°C, above which the very small HT component demagnetizes. The tail of the LT demagnetization curve is in good agreement with multidomain partial TRM theory [*Xu and Dunlop*, 1994] and with measured thermal demagnetization tails for 135 μm magnetite grains [*Dunlop and Özdemir*, 1997, Figures 10.11, 16.11].

The results in Figure 3 show that when LT is carried by multidomain grains and its thermal demagnetization is not obscured by underlying HT magnetization, the LT unblocking temperatures extend up nearly to the Curie point. It may be that the two conditions are related: HT may well be localized in single-domain or small pseudo-single-domain grains which are rare at sites 10 and 11 because of the large average grain size. However, whether or not HT is single-domain-like, a large HT component demagnetizing over the same range as LT would mask the LT tail (since LT and HT are almost antiparallel vectors) and would result in a lower junction temperature T_L between LT and HT. That is, T_L should decrease as the HT/LT ratio increases. We will test this idea in section 6.

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 $\approx$ 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

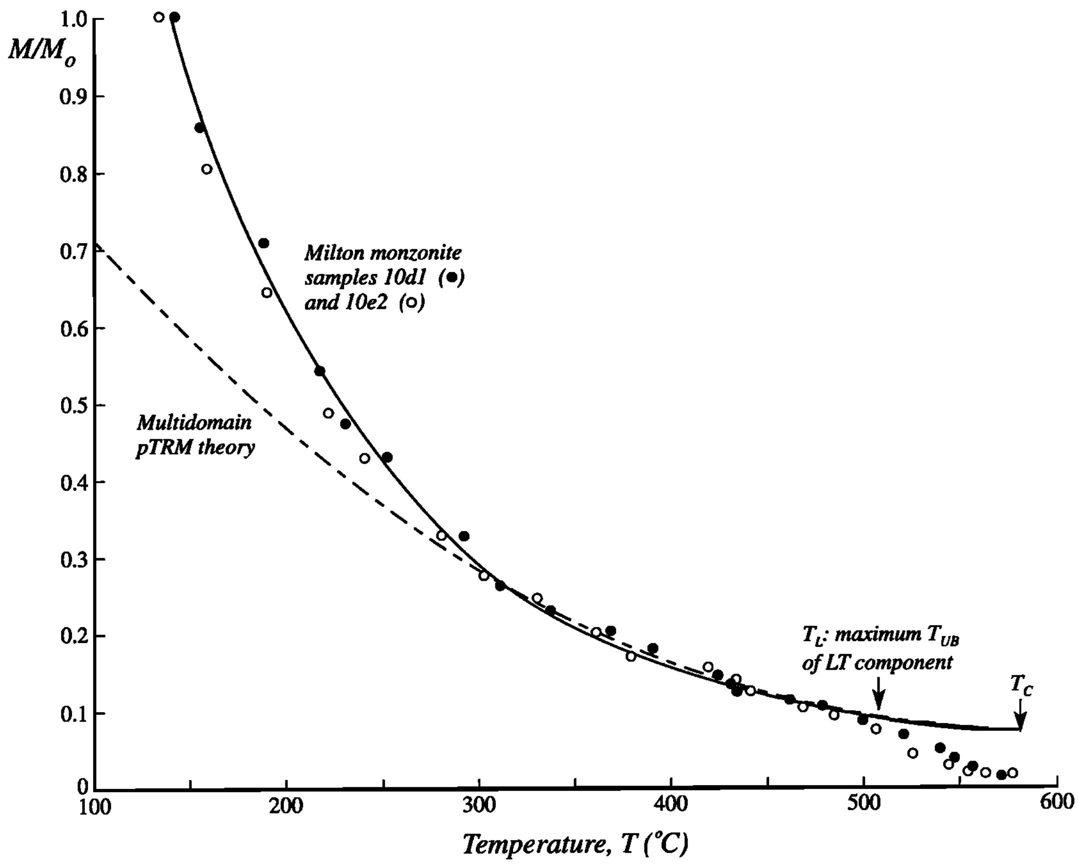

Figure 3. Thermal demagnetization of two samples from site 10, where LT is carried by truly multidomain grains and HT is very small compared to LT. The demagnetization tails off exponentially and agrees with predictions of multidomain partial TRM theory [*Dunlop and Xu*, 1994]. The final decrease in magnetization just below T_C is due to demagnetization of the small HT vector.

are truncated or masked above T_L = 400-450°C by demagnetization of HT. Samples from site 2 (group 1) have HT/LT ≈ 2 and HT unblocking outweighs LT unblocking above T_L ≈ 330°C.

The correlation is clear in a plot of T_L versus HT/LT (Figure 5). As HT/LT changes over the full range 0 → 2, average T_L values decrease by about 200°C.

At the same time, low-temperature memory ratios R for the LT component (i.e., LT intensity after LTD divided by LT intensity initially) are in the range 0.3-0.55 and are uncorrelated with T_L or HT/LT (Table 1). Multidomain remanence forms a similar fraction of LT (one-half to two-thirds) at all sites where magnetite carries LT. Sites 2 and 10 have the lowest R values, in accord with their overall more multidomain hysteresis (paper 1, Figure 3). In section 7, we will see that the HT vector is less affected by LTD and is therefore more single-domain-like.

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

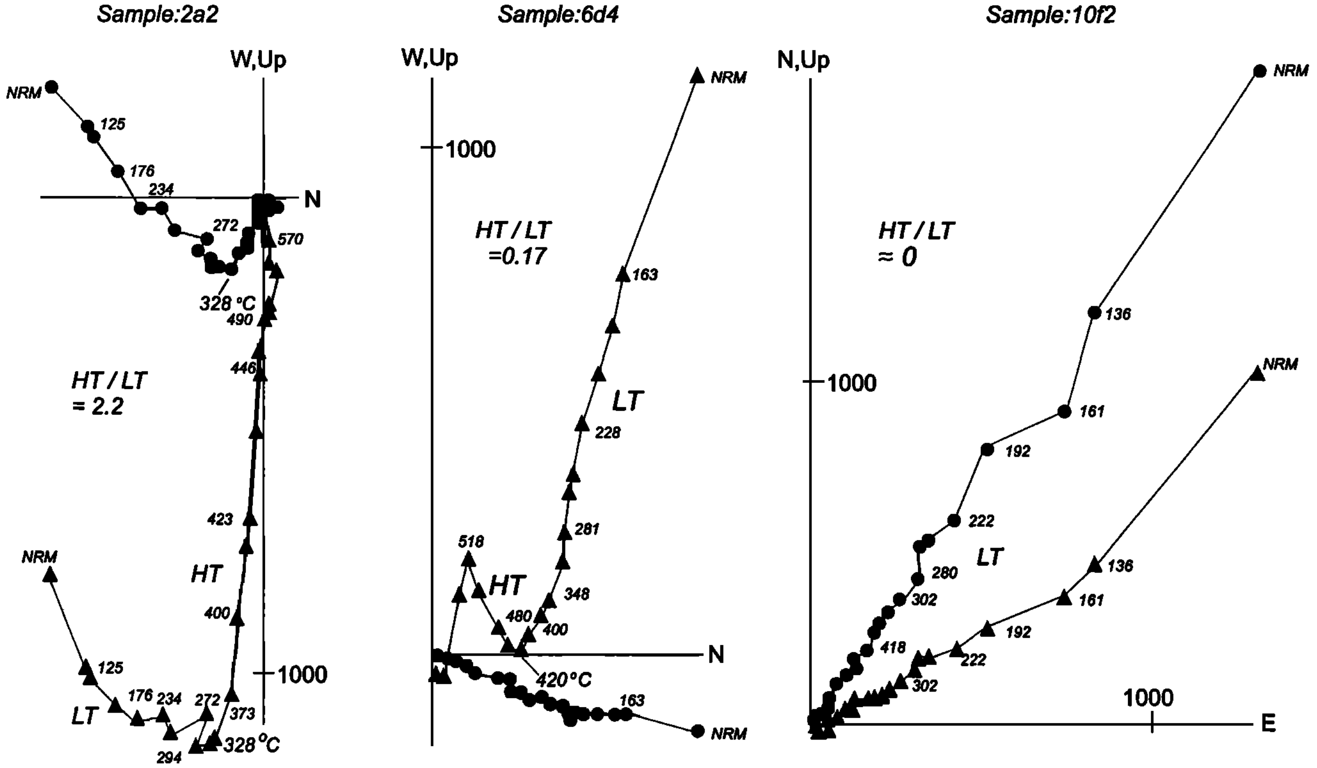

Figure 4. A demonstration that the relative magnitude of the HT and LT vectors influences the junction temperature T_L between their demagnetization trajectories. The larger LT becomes relative to the single-domain-like HT component, the higher is T_L: 328°C for 2a2 with HT/LT = 2.2; 420°C for 6d4 with HT/LT = 0.17; and >500°C for 10f2 with HT/LT ≈ 0. The effect is due to masking of part of the HT unblocking spectrum by LT unblocking temperatures spilling over above their original blocking temperature. Sample 10f2 and samples 10d1 and 10e2 in Figure 3 are extreme examples of the masking effect, in which demagnetization of a very small HT vector is hidden until close to T_C.

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

Site	HT/LT	R = LT(LTD)/LT	T_L, °C
1	0.184 ± 0.057	0.486 ± 0.027	401 ± 35
2 (a-d)	1.90 ± 0.36	0.268 ± 0.020	333 ± 15
3 (b-g)	0.169 ± 0.035	0.427 ± 0.028	395 ± 18
4	0.280 ± 0.090	0.408 ± 0.019	428 ± 22
5	0.504 ± 0.054	0.577 ± 0.105	440 ± 15
6	0.289 ± 0.070	0.564 ± 0.055	394 ± 27
7			220 ± 12
8			267 ± 61
9 (c)	0.080 ± 0.002		484 ± 6
9 (d-f)	0.259 ± 0.045	0.459 ± 0.075	427 ± 6
10	≈0	0.388 ± 0.076	516 ± 14
11	≈0	0.477 ± 0.072	538 ± 8

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 HT-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 *Pullaiah 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 Pullaiah 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-

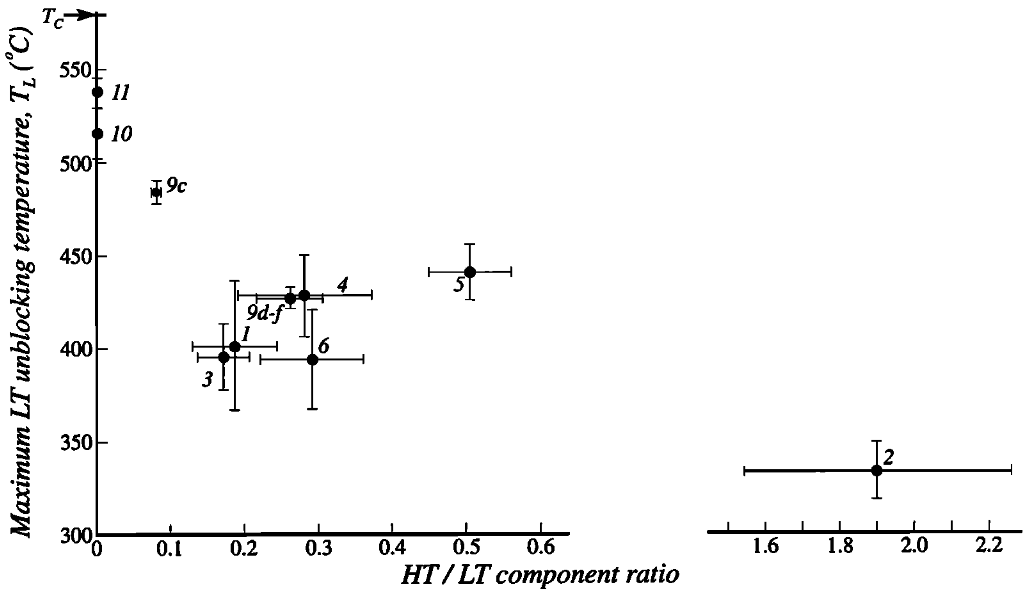

Figure 5. Correlation between T_L and the HT/LT ratio. Values shown are site or subsite averages with standard deviations (Table 1). The masking effect of multidomain grains produces a >250°C spread in T_L values from purely single-domain values (≤300°C, including LTD-treated samples) to purely multidomain values (500-550°C).

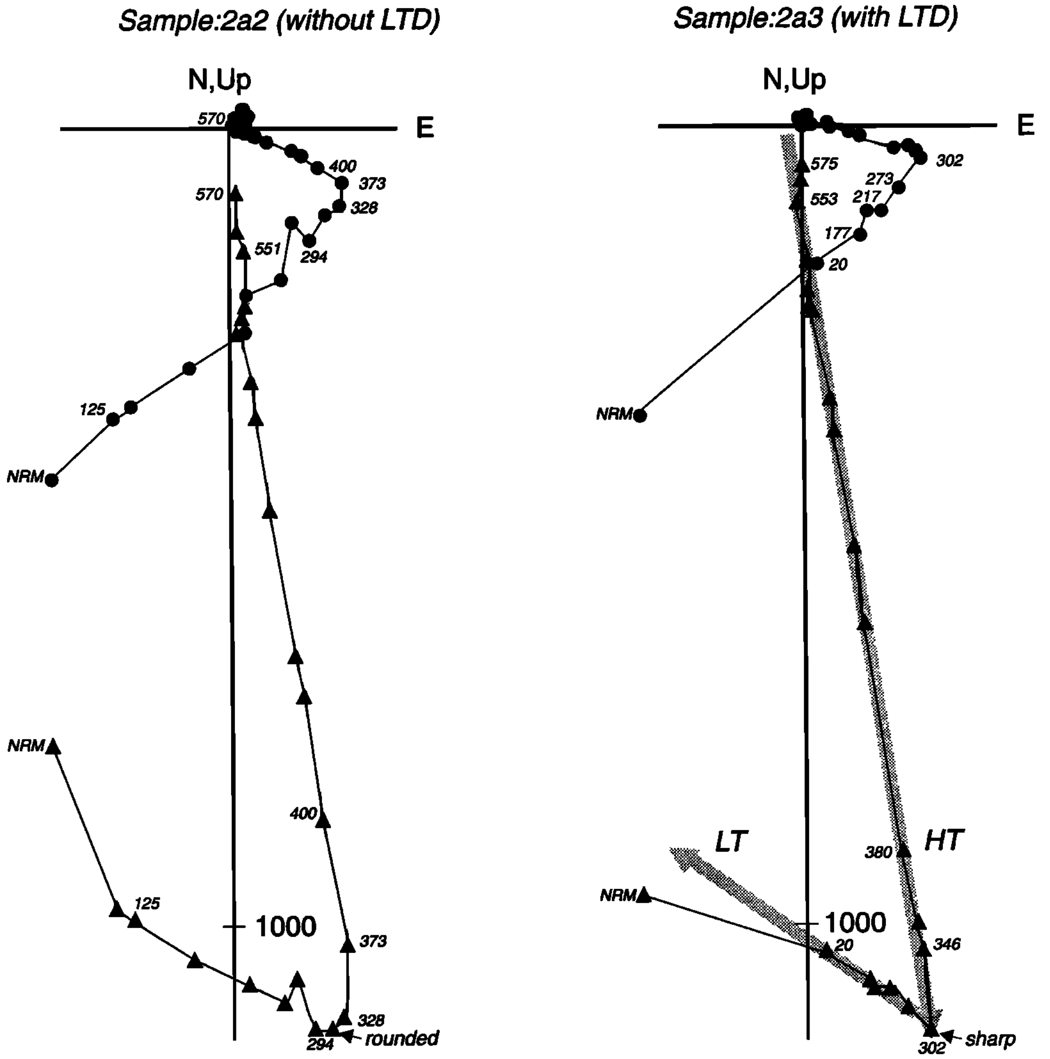

Figure 6. A demonstration that rounded junctions between LT and HT vectors, indicating overlap in their unblocking temperature ranges, become sharp (single-domain-like: $T_{UB} = T_B$) as a result of LTD pretreatment.

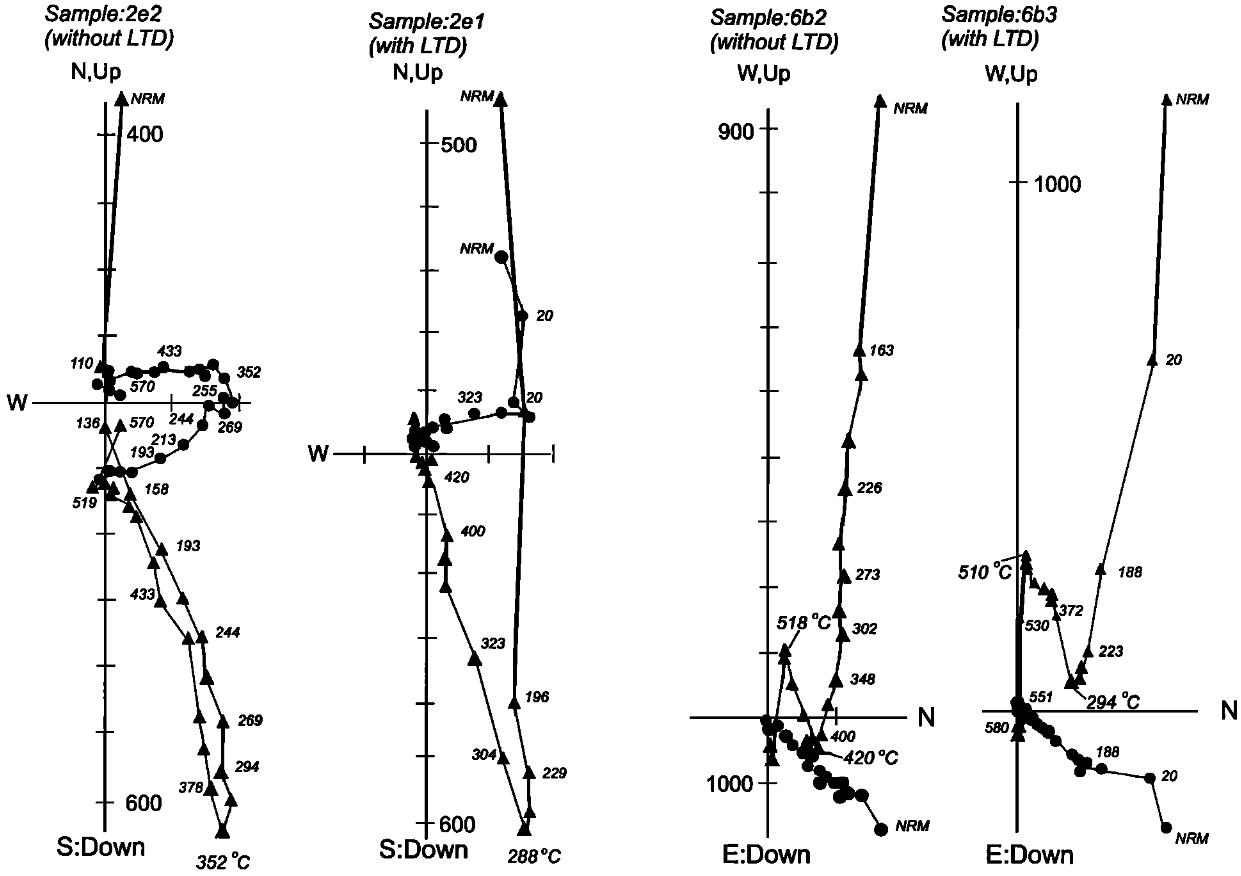

Figure 7. Two examples of decreases in T_{L} as a result of LTD pre-treatment. The T_{L} value after LTD is ~300°C in both cases. The reduction in T_{L} is greater for 6b than for 2e because the larger LT vector (relative to HT) in 6b had a greater masking effect and pushed the original T_{L} higher than in 2e. Notice that the HT-CRM1 junction temperature in 6b is unaffected by LTD (518°C before LTD, 510°C after LTD). The intensity of the HT vector is similarly unchanged by LTD in either 2e or 6b. Both observations demonstrate the single-domain-like nature of HT.

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_{L} values as a result of LTD. Although there is a strong tendency for T_{L} 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 1a3 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_{L} (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 $T_{\mathrm{B}} = T_{\mathrm{UB}} = T_r$ (T_{L} on 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_{L} values similar to those of Schmidt and Embleton (the third T_{L} 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 $\mathrm{T_L}$ 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

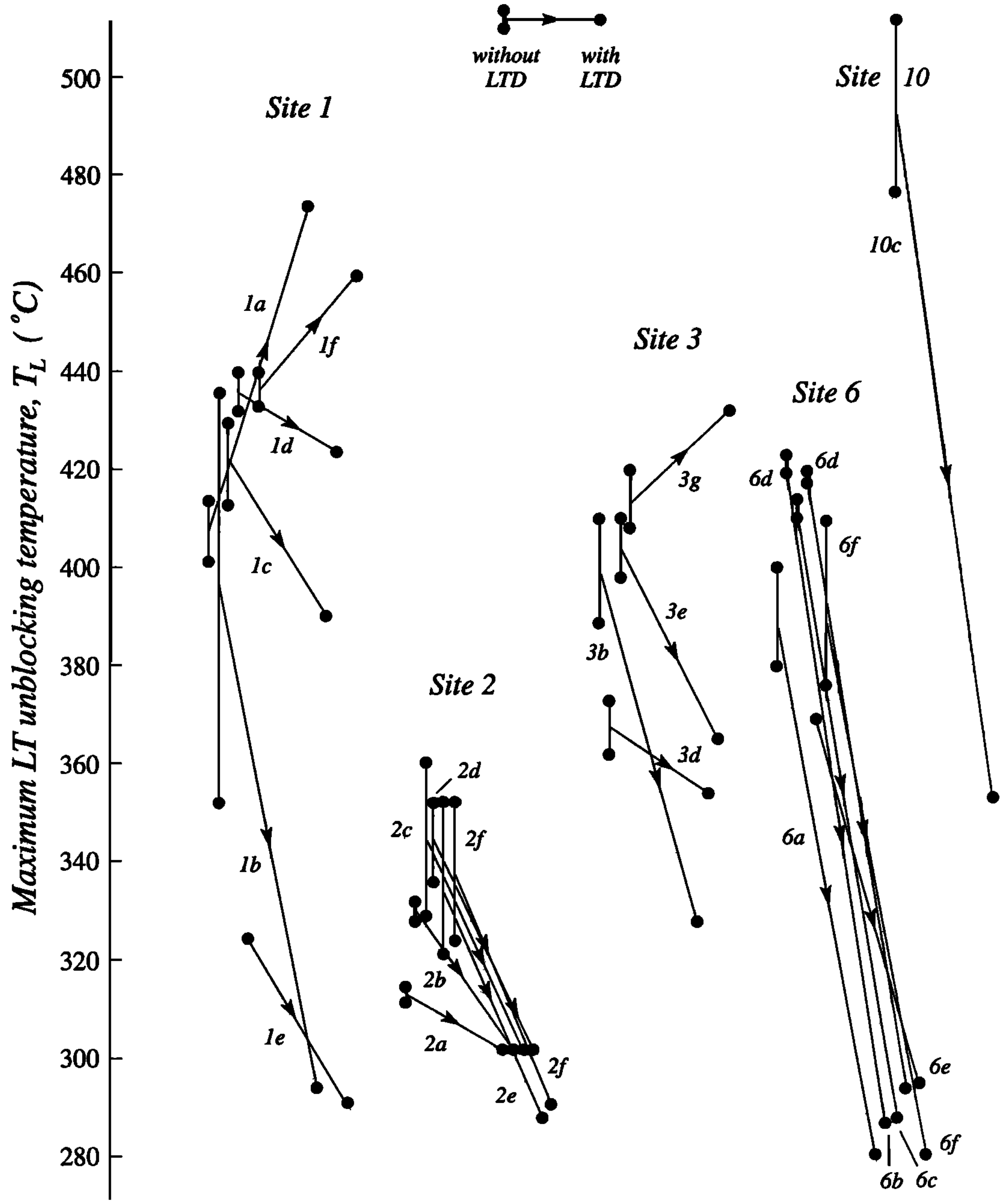

Figure 8. A sample-by-sample comparison of T_L values without LTD (left-hand points in each pair, usually two specimens) and with LTD (right-hand point, one specimen), as indicated by the model at top. In all but three instances, T_L decreases as a result of LTD, and in many cases (every sample for sites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

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_L 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_L values that are close to true single-domain values. The agreement of group 1 results with the Pullaiah et al. contours (Figure 1) confirms that the Pullaiah-Néel theory is a correct description of single-domain thermoviscous remagnetization.

At other sites, LT >> HT. The low-temperature memory ratio between LT after and before LTD ranges from ~0.3 to ~0.55. Thus about one-half to two-thirds of LT is carried by multidomain magnetite. Because LT is of high intensity compared to HT, the multidomain demagnetization tail of LT outweighs the intensity decrease of the almost antiparallel HT vector in the lower part of the HT demagnetization range, with the result that HT appears to begin demagnetizing at higher temperatures than it actually does. This masking effect, in which LT unblocking overwhelms HT unblocking and artificially inflates the measured LT-HT junction temperature T_L, grows as LT/HT increases (Figure 5). We believe this is the explanation of anomalously high unblocking temperatures in the Milton Monzonite (Figure 1, groups 2 and 3).

The tremendous spread in laboratory T_L values in Figures 1 and 2, for a single value of T_r (and of t_r) in nature, demonstrates that either the overprinting is not purely thermoviscous or it is not purely single-domain. We have argued above that LT is very different in character from the known Cretaceous chemical overprint CRM1 and has all the earmarks of a partial TRM overprint. Therefore multidomain carriers of NRM must be the key factor.

If this idea is correct, demagnetizing as much of the multidomain remanence as possible before beginning thermal demagnetization should yield more single-domain-like, i.e,. lower, T_L values. This is what happens in the great majority of cases when the NRM is treated initially by low-temperature demagnetization (Figures 7 and 8). This simple procedure requires no more than 30 min and can be carried out in blanket fashion on large numbers of cores. It is recommended as a standard pretreatment. If LTD is observed to sharpen junctions between NRM components in vector projections, compared to rounded junctions in untreated specimens (compare Figure 6), one has independent evidence that single-domain-like remanence has been isolated.

Is multidomain remanence a general explanation of anomalously high unblocking temperatures? The Milton Monzonite is an ideal test case because (1) the grain size is coarse, favoring large pseudo-single-domain to multidomain grains, (2) variable amounts of the older HT remanence survive, and (3) at most sites there is a chemical overprint of the same age as LT which is clearly distinct from LT in its properties, specifically its range of unblocking temperatures. Other published case histories are not so clearcut.

For example, in *Kent*'s [1985] study of Appalachian limestone samples, the A overprint (Figure 1) is certainly a viscous remanence because the glacial boulders that carry A must have remained near room temperature in nature and could not have been chemically altered except surficially. Multidomain magnetite is the likely culprit in this case. The B overprint resulted from mild burial reheating (≤250°C according to conodont alteration data) in a tectonic setting where chemical remagnetization is known to have been widespread [*McCabe and Elmore*, 1989]. However, there is no high-T_{UB} magnetite CRM, and primary NRM, if present at all, is carried by hematite which unblocks above the magnetite Curie point. The unblocking temperature spectrum of the B overprint is peculiar in this and some other eastern North American carbonate studies. Unblocking does not continue to 580°C, but tails off around 400-450°C and certainly below 500°C. These thermal demagnetization tails resemble our site 10 results (Figure 3) and are very suggestive of multidomain remanence.

9. Conclusions

1. In the case of single-domain NRM, thermoviscous remagnetization is accurately described by the theory of *Néel* [1949] and *Pullaiah et al.* [1975]. Geological conditions during remagnetization, (t_r, T_r), are correctly predicted from short-term laboratory observations, (t_L, T_L), by using the Pullaiah 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_L 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_L 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_L up. The amount by which T_L exceeds the expected single-domain value correlates with the LT/HT ratio (Figure 5).

5. When LT is less than HT, the masking effect is small and laboratory T_L 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_L values are generally reduced (Figures 7 and 8), often close to expected single-domain values (Figure 2, second T_L 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 magnetite (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.

Acknowledgments. D.J.D. and Ö.Ö. are grateful to CSIRO for covering the expenses of their research visit. Most of the measurements were made at CSIRO; most of the analysis was done at Toronto with support from NSERC research grant A7709 to D.J.D. We thank Gillian Turner, Bob Butler, and an anonymous referee for their helpful reviews and editorial suggestions, and David Clark, Randy Enkin, and Dennis Kent for useful discussions about remagnetization.

References

Bol'shakov, A. S., and V. V. Shcherbakova, A thermomagnetic criterion for determining the domain structure of ferrimagnetics, (transl. from Russian), *Izv. Phys. Solid Earth, Engl. Transl.*, *15*, 111-117, 1979.

Chamalaun, F. H., Origin of the secondary magnetization of the Old Red Sandstone of the Anglo-Welsh cuvette, *J. Geophys. Res.*, *69*, 4327-4337, 1964.

Dunlop, D. J., and Ö. Özdemir, Thermal demagnetization of VRM and pTRM of single domain magnetite: No evidence for anomalously high unblocking temperatures, *Geophys. Res. Lett.*, *20*, 1939-1942, 1993.

Dunlop, D. J., and Ö. Özdemir, *Rock Magnetism: Fundamentals and Frontiers*, 573 pp., Cambridge Univ. Press, New York, 1997.

Dunlop, D. J., and S. Xu, Theory of partial thermoremanent magnetization in multidomain grains, 1. Repeated identical barriers to wall motion (single microcoercivity), *J. Geophys. Res.*, *99*, 9005-9023, 1994.

Dunlop, D. J., P. W. Schmidt, Ö. Özdemir, and D. A. Clark, Paleomagnetism and paleothermometry of the Sydney Basin, 1, Thermoviscous and chemical overprinting of the Milton Monzonite, *J. Geophys. Res.*, this issue.

Enkin, R. J., and D. J. Dunlop, The demagnetization temperature necessary to remove viscous remanent magnetization, *Geophys. Res. Lett.*, *15*, 514-517, 1988.

Halgedahl, S. L., and R. D. Jarrard, Low temperature behavior of single-domain through multidomain magnetite, *Earth Planet. Sci. Lett.*, *130*, 127-139, 1995.

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.

Kent, D. V., Thermoviscous remagnetization in some Appalachian limestones, *Geophys. Res. Lett.*, *12*, 805-808, 1985.

Kent, D. V., and J. D. Miller, Redbeds and thermoviscous remagnetization theory for hematite, *Geophys. Res. Lett.*, *14*, 327-330, 1987.

Kobayashi, K., and M. Fuller, Stable remanence and memory of multi-domain materials with special reference to magnetite, *Philos. Mag.*, *18*, 601-624, 1968.

McCabe, C., and R. D. Elmore, The occurrence and origin of Late Paleozoic remagnetization in the sedimentary rocks of North America, *Rev. Geophys.*, *27*, 471-494, 1989.

Merrill, R. T., Low-temperature treatment of magnetite and magnetite-bearing rocks, *J. Geophys. Res.*, *75*, 3343-3349, 1970.

Middleton, M. F., and P. W. Schmidt, Paleothermometry of the Sydney Basin, *J. Geophys. Res.*, *87*, 5351-5359, 1982.

Néel, L., Théorie du traînage magnétique des ferromagnétiques en grain fins avec applications aux terres cuites, *Ann. Géophys.*, *5*, 99-136, 1949.

Ozima, M., M. Ozima, and S. Akimoto, Low temperature characteristics of remanent magnetization of magnetite: Self-reversal and recovery phenomena of remanent magnetization, *J. Geomagn. Geoelectr.*, *16*, 165-177, 1964.

Pullaiah, G., E. Irving, K. L. Buchan, and D. J. Dunlop, Magnetization changes caused by burial and uplift, *Earth Planet. Sci. Lett.*, *28*, 133-143, 1975.

Schmidt, P. W., and B. J. J. Embleton, Magnetic overprinting in southeastern Australia and the thermal history of its rifted margin, *J. Geophys. Res.*, *86*, 3998-4008, 1981.

Tyson Smith, R., and K. L. Verosub, Thermoviscous remanent magnetism of Columbia River basalt blocks in the Cascade landslide, *Geophys. Res. Lett.*, *21*, 2661-2664, 1994.

Walton, D., Time-temperature relations in the magnetization of assemblies of single domain grains, *Nature*, *286*, 245-247, 1980.

Worm, H.-U., M. Jackson, P. Kelso, and S. K. Banerjee, Thermal demagnetization of partial thermoremanent magnetization, *J. Geophys. Res.*, *93*, 12,196-12,204, 1988.

Xu, S., and D. J. Dunlop, Theory of partial thermoremanent magnetization in multidomain grains, 2, Effect of microcoercivity distribution and comparison with experiment, *J. Geophys. Res.*, *99*, 9025-9033, 1994.

D. J. Dunlop and Ö. Özdemir, Department of Physics, Erindale College, University of Toronto, 3359 Mississauga Road North, Mississauga, Ontario, Canada L5L 1C6. (e-mail: dunlop@physics.utoronto.ca)

P. W. Schmidt, Division of Exploration and Mining, CSIRO, North Ryde, New South Wales 2113, Australia. (e-mail: phils@syd.deg.csiro.au)

(Received January 16, 1997; revised July 7, 1997;
accepted August 27, 1997.)