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# Unblocking Temperatures of Viscous Remanent Magnetism in Displaced Granitic Boulders, Icicle Creek Glacial Moraines (Washington, USA)

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Key Points:

- pVRM of large boulders was measured in four glacial moraines ranging 13–105 ka
- The unblocking temperature of pVRM1 gives relative age of last displacement
- Average unblocking temperature gives estimate of displacement age for boulders in younger moraines

Supporting Information:

- Text S1, Figures S1–S3, and Tables S1 and S2

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# Unblocking temperatures of viscous remanent magnetism in displaced granitic boulders, Icicle Creek glacial moraines (Washington, USA)

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**Abstract** Viscous remanent magnetization (VRM) may partially overprint original magnetization in rocks displaced by geomorphic events. An established theoretical relationship between the time and temperature of acquisition of VRM and the time and temperature of demagnetization suggests that laboratory demagnetization (unblocking) of VRM can be used to estimate the displacement age of rocks. We test this hypothesis at four nested glacial moraines in the Icicle Creek drainage of central Washington, the ages of which were previously determined by cosmogenic surface exposure dating. The moraines are composed primarily of granodiorite boulders, and magnetic remanence is carried dominantly by magnetite. Both the maximum and average pVRM demagnetization temperatures ( $T_D$ ) increase with relative age of the moraines. For the three younger moraines, the average  $T_D$  yields an age comparable to the cosmogenic age, within uncertainty of pVRM acquisition temperature. Uncertainty in the acquisition and demagnetization temperatures can limit the utility of pVRM for absolute dating.

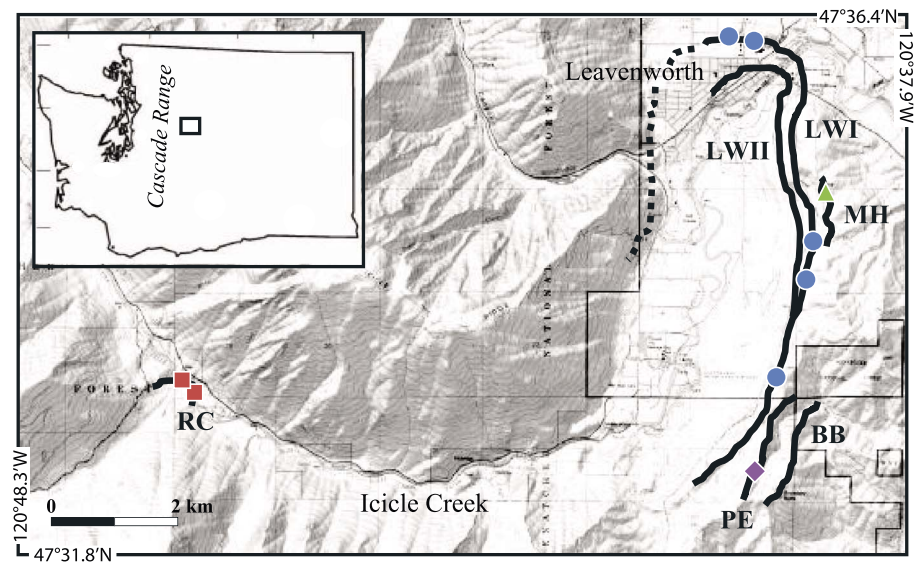
## 1. Introduction

Most rocks contain an assemblage of ferrimagnetic particles that record the ambient magnetic field present at the time of the rock's formation. In the best characterized process of magnetic remanence acquisition, thermal remanent magnetism (TRM) is acquired as the rock cools through the blocking temperatures of the magnetic minerals it contains. These blocking temperatures are a function of both intrinsic properties of the remanence carriers (mineral species, composition, shape, and particle size distribution) and the thermal history (duration and temperature of thermal events) the rock has experienced. Some of the magnetic grains in an assemblage of remanence-carrying particles may have low blocking temperatures, and, given time, their magnetization can change with changes in the magnetic field. The result is a "viscous" remanent magnetization (VRM) acquired by that subset of particles. If the rock rotates after initial magnetization such that its magnetic moment is no longer parallel to the ambient magnetic field, a VRM component can grow in the new field direction. The VRM is recognized as a magnetic component that has partially overprinted the original remanence: a partial VRM (or pVRM, also known as partial thermal VRM or pTVRM). The relationship between the duration ( $t_A$ ) and temperature ( $T_A$ ) of acquisition of the overprint and the duration ( $t_D$ ) and temperature ( $T_D$ ) of thermal demagnetization required to remove (or "unblock") the overprint in the lab [Enkin and Dunlop, 1988] was established theoretically for single-domain (SD) particles [Néel, 1949, 1955] and has been evaluated in a variety of rocks [Heller and Markert, 1973; Pullaiah et al., 1975; Middleton and Schmidt, 1982; Kent, 1985; Tyson Smith and Verosub, 1994; Borradaile, 1996; Dunlop et al., 1997]. For magnetite, the relationship can be expressed as [Pullaiah et al., 1975]

$$\frac{T_D \ln C t_D}{M_{S(T_D)}^2} = \frac{T_A \ln C t_A}{M_{S(T_A)}^2}, \quad (1)$$

where the frequency factor  $C = 10^{-10} \text{ s}^{-1}$  and  $M_S$  is the saturation magnetization, which varies with temperature. We use  $M_{S(T)} = M_{S(T_{293K})} [(T_C - T)/(T_C - T_{293K})]^\gamma$ , where  $T_C$  is the Curie temperature for magnetite in degrees Kelvin,  $M_{S(T_{293K})} = 4.8 \times 10^5 \text{ A/m}$  [Dunlop et al., 1997], and  $\gamma = 0.38$  [Tauxe et al., 2014, equation (3.11)]. This formulation assumes that grain volumes are small (single domain) and the microcoercivity of magnetite is dominated by shape anisotropy and is equivalent to  $M_S$ .

The relationship between time and temperature in acquisition and demagnetization of pVRM suggests potential use as a geochronometer by estimating  $t_A$  of the pVRM overprint. Age estimation of pVRM acquired



**Figure 1.** Icicle Creek drainage near the town of Leavenworth, WA. Bold lines trace the crests of glacial moraines, as mapped by Porter and Swanson [2008]. Colored symbols show approximate sampling locations; each symbol represents several boulders. Moraines are labeled: RC = Rat Creek; LWI, LWII = Leavenworth I and II; MH = Mountain Home; PE = Peshastin; and BB = Boundary Butte. Inset shows the location of the study area in Washington State.

in rock over archaeological or geological timescales has seen mixed success, with a few studies reporting correspondence to Néel theory [e.g., Tyson Smith and Verosub, 1994], while others suggest an alternative relationship [e.g., Walton, 1980; Middleton and Schmidt, 1982] or an empirical approach to using pVRM for age estimation [e.g., Borradaile and Almqvist, 2006]. Tyson Smith and Verosub [1994] showed first-order agreement between the  $T_D$  of pVRM in basalt boulders of a several-hundred-year-old landslide deposit and age predicted by Néel SD theory and the related Pullaiah *et al.* [1975] nomograms. Sato *et al.* [2014] use pVRM to distinguish emplacement ages of two magnetite-bearing coral boulders moved by tsunamis but do not replicate the radiocarbon ages. Here we report on pVRM from granitic boulders in nested alpine glacial moraines of known age and assess the utility of pVRM to estimate rock displacement ages in this setting.

## 2. Geologic Setting

The study area is in the Icicle Creek drainage in central Washington State, on the east side of the Cascade Range (Figure 1). The valley experienced multiple pulses of Pleistocene glaciation, recorded in a series of nested moraines [Page, 1939; Porter, 1969]. The moraines are composed almost entirely of granodiorite boulders from the southeastern part of the Cretaceous Mount Stuart Batholith (MSB). Grain size of the silicate minerals in the granodiorite is ~2–4 mm, and the composition is 20%–40% mafic minerals. Most boulders are texturally isotropic, but some have visible foliation, defined by weak segregation and alignment of mafic minerals. On the basis of thermal demagnetization temperatures of natural remanent magnetization (NRM) and on multicomponent isothermal remanent magnetization experiments on rocks from the MSB, Housen *et al.* [2003] identified magnetite as the magnetic remanence carrier for rocks in the source area of the Icicle Creek moraines. This finding is consistent with other observations that in felsic and intermediate plutonic rocks, original and well-defined remanence is typically carried by very small inclusions of magnetite within feldspars and Fe silicates [Dunlop and Özdemir, 1997].

The age of deposition of the moraines has been determined by  $^{36}\text{Cl}$  cosmogenic nuclide surface exposure dating [Porter and Swanson, 2008]. Mean cosmogenic ages for the moraines are: Rat Creek I and II,  $12.5 \pm 0.5$  and  $13.5 \pm 0.8$  ka; Leavenworth I and II,  $16.1 \pm 1.1$  and  $19.1 \pm 3.0$  ka; Mountain Home,  $71.9 \pm 1.5$  ka; and Peshastin,  $105.4 \pm 2.2$  ka. Boulders in the younger moraines appeared fresh or slightly weathered with some discoloration, while boulders in the older two sampled moraines were slightly to moderately weathered, showing some physical decomposition of the rock. A fifth, older moraine (Boundary Butte) is present, but boulders were too disaggregated to sample.

In an ideal test of pVRM to estimate the emplacement age of boulders in the moraines, a number of conditions would be met: The boulders would be transported only once and would not rotate after deposition; postdeposition pVRM would be the only process that overprints the original TRM; and all boulders would acquire a distinct pVRM overprint carried exclusively by SD magnetite. In natural geological settings, however, these conditions are unlikely. At Iclicle Creek, a number of processes could potentially complicate identification and interpretation of postdepositional pVRM. Moraine degradation is evident in the older moraines and may have led to postdepositional rotation of the boulders [Porter and Swanson, 2008]. We sampled only the largest boulders from the crest of each moraine to reduce the possibility that sampled boulders had rotated since deposition. Natural forest fires are not uncommon and may have occurred repeatedly in interglacial periods [Porter and Swanson, 2008]; heating by fire could reset pVRM, potentially introducing a young, high-temperature magnetization. A major fire burned much of the study area in 1993, and there is evidence of fire-related spalling of outer surfaces of some boulders on the Leavenworth moraines. We endeavored to collect cores that were not visibly affected by the fires. Lightning also regularly occurs in the field area. Lightning strikes and related ground current could wholly remagnetize a rock or partially overprint the NRM. We therefore evaluated specimens for the possibility of lightning contamination (supporting information). Additionally, boulders in younger moraines may have been recycled from older glaciations. In such cases, there could be two or more pVRM components: we identified the lowest-temperature component (pVRM1). It is also possible that a boulder could be deposited with its NRM nearly parallel or antiparallel to the ambient magnetic field. Approximating a boulder as a cube, we estimate a two-in-six chance for this to occur. In such cases, a postdeposition pVRM may be more difficult to recognize, as there is no change in direction with demagnetization; however, it can be possible to recognize a change in the intensity of magnetization. Further, it is possible that some rocks do not acquire a stable pVRM, despite magnetic moment misalignment after deposition, because of the particular distribution of grain size, shape, or composition of the magnetic carriers. Finally, it is rare that SD magnetite is the exclusive remanence carrier in natural rocks; therefore, we assessed the magnetic mineralogy and magnetic grain size distribution of the Iclicle Creek boulders.

### 3. Sample Collection and Laboratory Methods

We collected samples from 34 granodiorite boulders greater than 2 m in diameter [Globokar, 2014]. We combined samples from composite moraines (Rat Creek I and II and Leavenworth I and II), to evaluate four depositional events: Rat Creek, Leavenworth, Mountain Home, and Peshastin. For the mean age of the composite moraines, we assign the grand mean of the mean cosmogenic age of each moraine and use the larger uncertainty: Rat Creek composite mean age =  $13.0 \pm 0.8$  ka and Leavenworth mean age =  $17.6 \pm 1.1$  ka. Sampling of the older moraines was limited by the lower abundance of intact boulders: The Leavenworth moraines have a surface boulder density of nearly 100 per 100 m<sup>2</sup>, while Peshastin has a surface boulder density less than 1 per 100 m<sup>2</sup> [Porter and Swanson, 2008]. We used a gas-powered drill to obtain oriented, 2.4 cm diameter core samples. At more than half the boulders, we drilled a core on two or more different faces of the boulder; at the others only one core was drilled. Samples were stored in a cool dark place until lab preparation to minimize further VRM acquisition and were processed within 2 weeks of collection. A nonmagnetic rock saw was used to cut samples into 2.2 cm specimens, and subsamples were created from any core longer than 4.4 cm, yielding 95 specimens from 62 core samples. After sample preparation, the specimens were stored and analyzed in a room temperature ( $\sim 22^\circ\text{C}$ ), field-free room.

The NRM of all samples was measured at room temperature using a 2-G 755 DC-SQUID magnetometer. After initial measurement, samples were treated with liquid nitrogen in 20 min low-temperature demagnetization (LTD) cycles and measured after warming to room temperature, until no significant changes were observed in remanence. LTD cycling is designed to preferentially erase the remanence carried by multidomain (MD) magnetite grains and leave SD remanence unaffected [Dunlop et al., 1997; Housen et al., 2003]. The samples were then progressively demagnetized by heating, in temperature steps of 5°C to 20°C from 70°C to 250°C and in larger steps from 250°C to 450°C. At each step, the temperature was held constant for 30 min after which samples were allowed to cool for 10–15 min, and then remanent magnetization was measured. Oven temperature was monitored by digital displays connected to thermocouples at two locations within the oven and by three to five, irreversible, self-adhesive temperature labels spread across the 46 cm (18 inches) sample tray. With these observations, we modeled a 1-D temperature gradient in the oven,

interpolating linearly between observations. We assigned the interpolated temperature to each sample at each step with respect to its position in the oven.

To understand magnetic mineralogy, we measured hysteresis and backfield demagnetization of selected samples with a Princeton Instruments vibrating sample magnetometer. Because hysteresis loops for most whole rock chips were dominated by paramagnetic susceptibility of the mafic minerals (Figure S1a), we manually separated felsic components from four crushed chips and evaluated them separately (Figure S1b). Ratios of saturation remanence ( $M_r$ ) to saturation magnetization ( $M_s$ ) and coercivity of remanence ( $H_{cr}$ ) to coercivity ( $H_c$ ) on a Day plot [Dunlop, 2002] reveal a range of apparent magnetite grain sizes within and between boulders from different moraines (Figure S2). In general, felsic concentrates tended to yield more SD-like results, but all samples tested show evidence that the primary magnetic carrier is pseudosingle domain (PSD) magnetite or SD-MD admixtures [Dunlop, 2002].

We also reanalyzed data of 53 specimens from six sites of in situ Mount Stuart granodiorite along Icicle Creek, originally reported in Housen *et al.* [2003]. These specimens were demagnetized at  $\sim 50^\circ\text{C}$  steps from 20 to  $500^\circ\text{C}$  and subsequently at  $10^\circ\text{C}$  steps through  $600^\circ\text{C}$ .

## 4. Data Analysis

### 4.1. In Situ Rocks

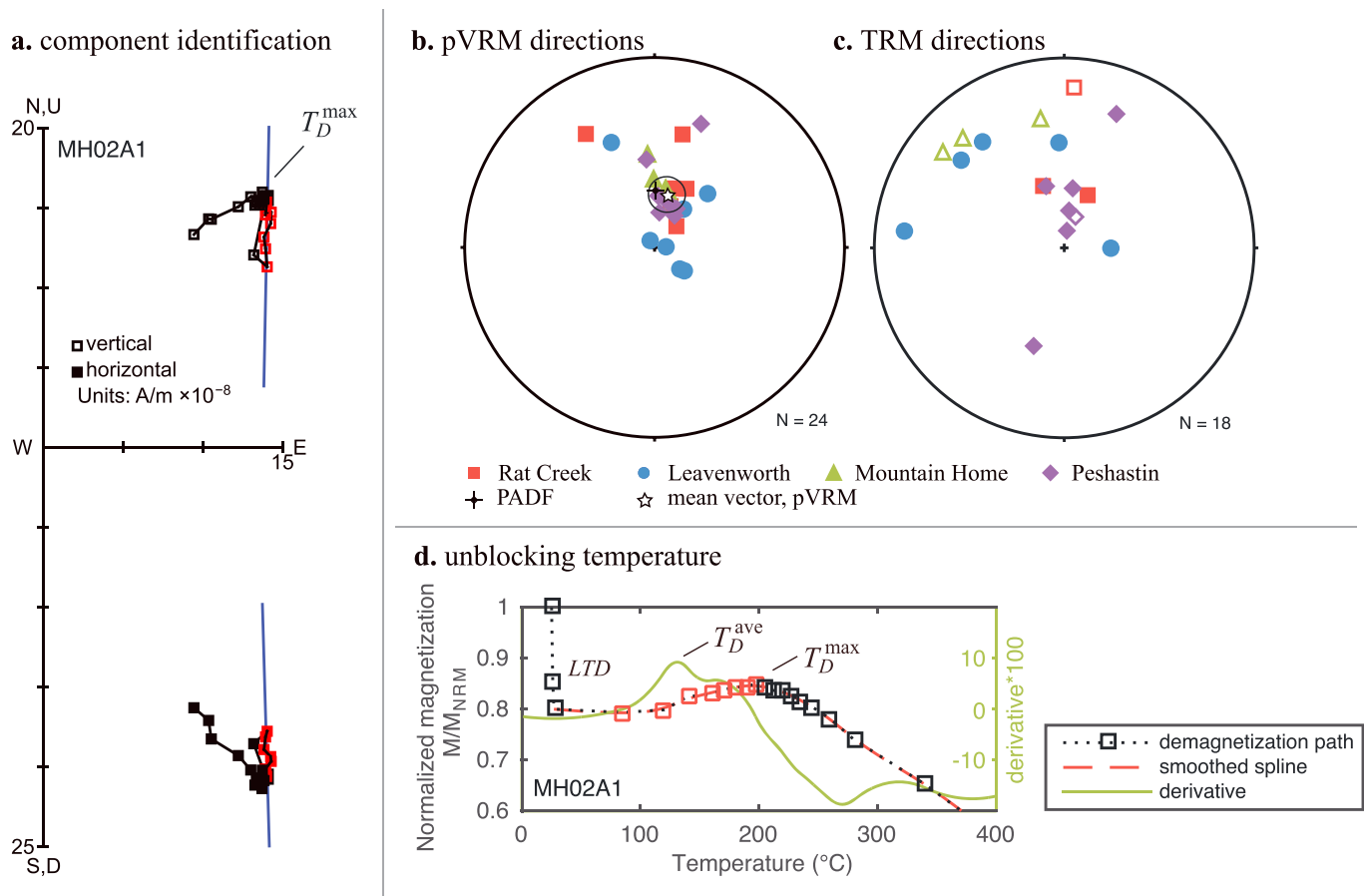
We reexamined earlier data from in situ Mount Stuart granodiorites near the Icicle creek moraines to evaluate the magnetic response of nontransported rocks to other environmental factors. Most show a high-temperature component that unblocked over the range  $500\text{--}575^\circ\text{C}$ , interpreted to be the direction of initial TRM. Line fits through moderate-temperature ( $270\text{--}400^\circ\text{C}$ ) demagnetization paths for half the sites give scattered directions but for the other three sites show means in the direction of the present axial dipole field. We interpret this to suggest that some in situ rocks have acquired a pVRM, and this pVRM may extend to moderate temperatures.

### 4.2. Moraine Boulders

Half of all specimens collected from the Icicle Creek moraines responded to thermal demagnetization. We identified specimens that retain more than one direction of magnetization, as defined by linear segments on orthogonal demagnetization diagrams [Zijderveld, 1967, Figure 2a]. Assuming that the boulders have not rotated since deposition, we expect that the first component removed during thermal demagnetization is the most recent component acquired and that this component is the magnetic overprint accumulated since deposition in the moraines (pVRM1). For this analysis we accept an estimate of the pVRM1 direction as valid if the line fit to the linear segment using principal component analysis has a maximum angular deviation (MAD) [Kirschvink, 1980] of  $15^\circ$  or less. We further expect that pVRM acquired since final emplacement in the moraines will be in the direction of the average magnetic field since deposition, which we estimate to be approximately the present axial dipole field (PADF). For this analysis, we accept as valid all pVRM1 directions within  $40^\circ$  of the PADF at the study site (declination =  $000^\circ$ , inclination =  $65.5^\circ$ ). We use this large radius to account for the expected magnitude of Pleistocene and Holocene paleosecular variation [e.g., Hagstrum and Champion, 2002; Korte *et al.*, 2005], as well as uncertainties in vector direction and sample orientation.

Twenty-four specimens meet these criteria. Figure 2b shows the directions of the accepted pVRM1 components. The mean direction for these pVRM1 components is declination =  $013^\circ$ , inclination =  $67^\circ$ , with  $8^\circ$  semi-angle of 95% cone of confidence, and concentration factor  $k = 15.5$ . This is indistinguishable from the present field direction (declination =  $016^\circ$ , inclination =  $69^\circ$ ). Higher-temperature components for specimens from this set that have line fits with  $\text{MAD} < 15^\circ$  are scattered ( $k = 1.6$ ; Figure 2c).

To test the hypothesis that  $T_D$  correlates with time elapsed since the boulders were moved, we identify the demagnetization (or unblocking) temperature of pVRM1. Experiments on magnetite separates have shown that PSD grains do not have a single  $T_D$  but unblock over a range of temperatures [Dunlop and Özdemir, 2000, 2001]. We evaluate two approaches to select a value for  $T_D$ : In the first approach we select the lowest temperature at which there is an abrupt change in the direction or intensity of magnetization. This is the temperature at which pVRM1 has been erased and thus is the maximum  $T_D$  for the suite of particles in the specimen ( $T_D^{\text{max}}$ ). Second, we evaluate the distribution of temperatures for demagnetization of pVRM1,



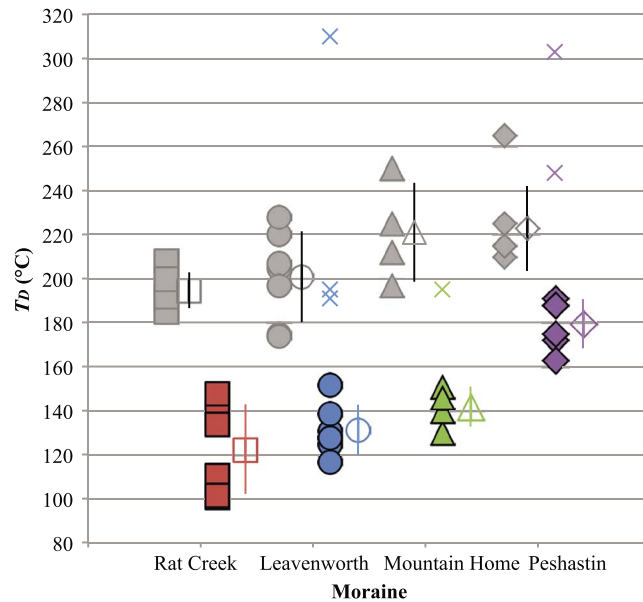
**Figure 2.** (a) Representative output of thermal demagnetization experiments: Specimen MH02A1 from the Mountain Home moraine. Zijderveld diagram shows changes in direction between lower temperature component (red, the pVRM1) and higher-temperature component, with blue showing line fit to pVRM1. LTD = liquid nitrogen treatment (low-temperature demagnetization). N,U = North, Up. S,D = South, Down. (b) Lower hemisphere equal area projections of directions of pVRM1 recorded in boulders of the Icicle Creek moraines. Filled color symbols represent pVRM directions within  $40^\circ$  of present axial dipole field direction (PADF, dec. =  $000^\circ$ , inc. =  $65.5^\circ$ ) and line fit MAD  $< 15^\circ$ . Small circle shows cone of 95% confidence around the mean of those directions (star);  $k = 15.5$ . (c) Higher-temperature ( $>300^\circ\text{C}$ ) components excluding those with MAD  $> 15^\circ$ ;  $k = 1.6$  (upper and lower hemisphere). (d) Magnetization versus temperature for specimen MH02A1.  $T_D^{\text{max}}$  is the temperature at the change in direction and demagnetization rate.  $T_D^{\text{ave}}$  is the temperature at the maxima in the derivative of the smoothed demagnetization path (see also Figure S3).

$f(T_D)$  [Dunlop and Özdemir, 2001]. We fit a smoothed spline to the demagnetization data and numerically differentiate the resulting model  $f(T_D)$ . We take the extreme value in that derivative to represent the average  $T_D$  of pVRM1 of the population of remanence-carrying grains in that specimen (Figure 2d). Dunlop and Özdemir [2001] suggest that identification of  $T_D^{\text{ave}}$  permits application of Néel SD theory to PSD magnetite.

### 5. Interpretation

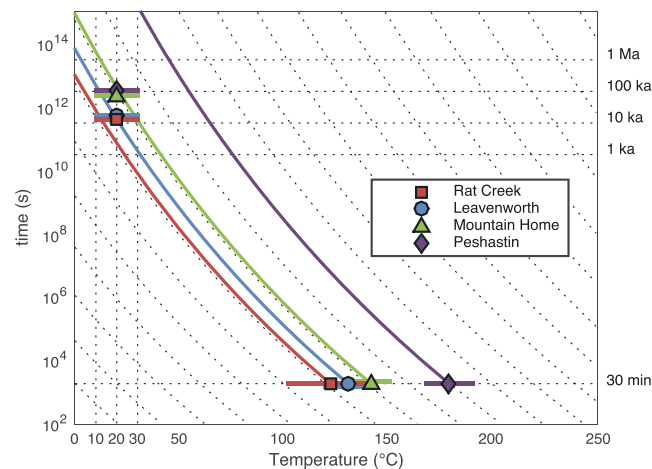
There is an increase in  $T_D^{\text{max}}$  of pVRM1 as a function of moraine position (Figure 3, grey symbols), corresponding to the relative age of the moraine. The geomorphically youngest moraine (farthest upvalley) has the lowest mean  $T_D^{\text{max}}$ . The geomorphically oldest moraine has the highest mean  $T_D^{\text{max}}$  and contains the boulder with the highest absolute  $T_D^{\text{max}}$ . Assuming that  $T_D^{\text{max}}$  increases with time of acquisition as predicted by Néel SD theory, then this technique has correctly identified the relative ages of the moraines. The sample size is small, and the variance is large; we cannot confidently reject the null hypothesis that pVRM1 from all the moraines has the same  $T_D^{\text{max}}$ . However, probability is only 1 in 12 (or 0.083) that the correct order of all four moraines would be predicted by chance.

The average demagnetization temperature ( $T_D^{\text{ave}}$ ) from the derivative of  $f(T_D)$  also reproduces the known relative ages of the moraines (Figure 3, colored symbols). The geomorphically youngest moraine has the



**Figure 3.** Unblocking temperatures ( $T_D$ ) of pVRM1 in boulders from the Icicle Creek moraines. Symbols as in Figure 2b. Smaller grey symbols show  $T_D^{\max}$  versus moraine; color symbols show  $T_D^{\text{ave}}$  versus moraine. Filled symbols are  $T_D$  for individual samples; open symbols give mean  $T_D$ , with error bar showing one standard deviation (Table S1). Outliers in  $T_D^{\text{ave}}$  indicated by crosses are not used in subsequent analyses.

geologically reasonable ages (Figure 4). The specific age estimates are sensitive to the choice of acquisition temperature ( $T_A$ ), which is not well constrained. If we assign  $T_A = 20^\circ\text{C}$ , pVRM age estimates for three younger moraines are Rat Creek, 2 ka; Leavenworth, 13 ka; and Mountain Home, 134 ka. These are within  $\pm 90\%$  of the cosmogenic surface exposure ages (Table S2). The same approach yields an unreasonable age estimate



**Figure 4.** Time-temperature nomograph for thermal demagnetization of magnetite (equation (1)) [Pullaiah et al., 1975]. Time and temperature for acquisition (upper left) and demagnetization (lower right) for Icicle Creek moraines are shown in solid symbols; bars show uncertainty in  $T_A$  and standard deviation in mean  $T_D^{\text{ave}}$ . Cosmogenic surface exposure ages [Porter and Swanson, 2008] are taken as the acquisition time ( $t_A$ ). Color curves trace the nomographs for the mean  $T_D^{\text{ave}}$  of each moraine; the curves predict the cosmogenic age within the uncertainty in acquisition temperature for the three younger moraines (Table S2).

lowest mean  $T_D^{\text{ave}}$  and contains the boulder with the lowest absolute  $T_D^{\text{ave}}$ . The geomorphically oldest moraine has the highest mean  $T_D^{\text{ave}}$  and contains the boulder with the highest absolute  $T_D^{\text{ave}}$ . The absolute value of demagnetization temperature determined this way is  $75^\circ\text{C}$ – $100^\circ\text{C}$  lower than the  $T_D^{\max}$  for each moraine. Furthermore, the statistics are somewhat improved: the standard deviation of the mean  $T_D^{\text{ave}}$  is half that of the mean  $T_D^{\max}$  for three of the four moraines (Table S1).

We assess the potential to determine absolute age of displacement from pVRM comparing moraine ages estimated using equation (1) to those determined by cosmogenic isotopes. As expected for specimens containing PSD or MD magnetite [e.g., Dunlop and Özdemir, 2000], using  $T_D^{\max}$  yields unrealistically old ages for all moraines ( $10^{10}$  years and older). Using  $T_D^{\text{ave}}$  in equation (1), the pVRM age estimates for the three younger moraines give geologically reasonable ages (Figure 4). The specific age estimates are sensitive to the choice of acquisition temperature ( $T_A$ ), which is not well constrained. If we assign  $T_A = 20^\circ\text{C}$ , pVRM age estimates for three younger moraines are Rat Creek, 2 ka; Leavenworth, 13 ka; and Mountain Home, 134 ka. These are within  $\pm 90\%$  of the cosmogenic surface exposure ages (Table S2). The same approach yields an unreasonable age estimate of 80 Ma for the Peshastin moraine; the age of the oldest moraine is not predicted from  $T_D^{\text{ave}}$  with any reasonable  $T_A$ .

## 6. Discussion

Extracting the demagnetization temperature of pVRM from these rocks is a challenge. A small fraction of the analyzed specimens yielded relevant information. Most of the rest of the samples either did not demagnetize in the temperature range applied or displayed only single-component decay. This success rate is similar to that achieved in paleointensity studies [e.g., Tauxe et al., 2013]. We note that granodiorite is not the most natural choice of lithology in which to test age estimation with pVRM, as this rock type does not typically have remanence carried exclusively by SD particles. Given this extra complexity, our first-order success in relative age determination suggests

further promise for pVRM age estimation for displaced rocks with finer-grained magnetite. Even in more ideal rocks, however, the challenges of identifying  $T_D$  suggest that many samples are required to confidently distinguish geomorphic features of unknown relative age. For the observed distribution of mean  $T_D^{\text{ave}}$ , to distinguish among the four moraines at 90% confidence, it would be necessary to triple the number of successful measurements and reduce the standard deviation of the means by two thirds.

Modeling the distribution of unblocking temperatures  $f(T_D)$  of pVRM1 to determine  $T_D^{\text{ave}}$  of the population of magnetic grains improved resolution of relative age compared to using  $T_D^{\text{max}}$ . Furthermore, for the three younger moraines  $T_D^{\text{ave}}$  gave reasonable estimates of displacement ages using equation (1). Our analysis thus suggests that rocks with PSD magnetite remagnetized over geologic timescales may have similar behavior to the PSD magnetite separates remagnetized at laboratory timescales reported by Dunlop and Özdemir [2001].

Calculating an absolute age relies on making an educated estimate of ambient temperature over the period of acquisition ( $T_A$ ). Many studies assume acquisition temperatures of 20°C [e.g., Tyson Smith and Verosub, 1994; Borradaile and Almqvist, 2006]; others have used modern mean annual temperatures [e.g., Sato et al., 2014]. In the Icicle Creek study area, modern mean annual temperature is about 10°C. It is possible, however, that pVRM is acquired during the warmer summer months when the diurnal heating is also longer each day. Mean summer temperature in the study area is close to 30°C. Furthermore, modern temperatures may not be good  $T_A$  estimates for glacial-aged events. Age estimates from pVRM are sensitive to these choices: uncertainty in  $T_A$  of 10°C leads to an order-of-magnitude uncertainty in age (Figure 4).

Even after accounting for  $f(T_D)$ , the average demagnetization temperature for the oldest moraine in this study remains anomalously high compared to expected values if equation (1) applies. The high  $T_D$  persists even after repeated LTD treatment, consistent with dislocation pinning of domain walls in non-SD grains. Further progress could be made with additional alternating-field pretreatment of specimens prior to thermal demagnetization [e.g., Dunlop and Özdemir, 2001]. The failure of  $T_D^{\text{ave}}$  to yield a reasonable age for the oldest moraine also suggests that approximation of PSD behavior with  $T_D^{\text{ave}}$  does not fully describe the magnetic process in these specimens. This problem of age estimation for older events is further compounded because time resolution decreases logarithmically with increased  $t_A$  (equation (1)), so loss of precision in input leads to large uncertainties. Moreover, older deposits also are exposed to more geologic processes that complicate the magnetic overprints, including weathering, multiple displacements, or lightning and fires.

In summary, our data from the nested Icicle Creek glacial moraines illustrate that measurements of  $T_D$  of pVRM can determine the relative ages of rock displacement, even in the case where remanence is carried by non-SD magnetite. This approach could be valuable where geomorphic evidence for relative age is absent or ambiguous, for example, in evaluating the relative ages of moraines in separate valleys, nonoverlapping landslide deposits, boulders displaced by tsunami [e.g., Sato et al., 2014], and rock fall or toppled rocks related to earthquakes. In addition, using the average demagnetization temperature from a modeled distribution of  $T_D$  gives an estimate of the absolute age of rock displacement, within better than an order of magnitude for the Holocene and latest Pleistocene moraines. Our findings bolster the possibility that pVRM could be a useful alternative or complement to other Quaternary dating tools for determining the age of geomorphic events.

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