GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 24, PAGES 2661-2664, DECEMBER 1, 1994

Thermoviscous Remanent Magnetism of Columbia River Basalt Blocks in the Cascade Landslide

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Abstract: We studied sixteen basalt samples from a landslide in the Columbia River Gorge to determine if they had acquired a thermoviscous remanent magnetism (TVRM) since the slide was emplaced about 800 years ago. All samples were thermally demagnetized at 20 heating steps until 360°C, where a large change in susceptibility was noted. Analysis of the directional changes during demagnetization indicates that the samples contain up to four TVRM components, in addition to an NRM component. The TVRM components with the lowest blocking temperatures are tightly clustered around the present field direction while the NRM directions are consistent with a random distribution, as expected for a landslide deposit. Measurements of hysteresis parameters and thermomagnetic analyses of the samples demonstrate that the dominant magnetic mineral in the basalt is single-domain magnetite. The temperature at which the first TVRM component was removed ranges from 70°C to 100°C. This result can be compared to nomographs that relate the time and temperature used to demagnetize a TVRM with the time and temperature at which the TVRM was acquired. Our results are more consistent with the nomograph of *Pullaiah et al.* [1975] than with the nomograph of *Middleton & Schmidt* [1982].

Introduction

Thermoviscous remanent magnetism (TVRM) is a secondary magnetization acquired by all rocks as a result of exposure to an external magnetic field, including that of the Earth. The duration of the exposure and the temperatures at which it takes place determine the degree to which the rocks acquire a TVRM. In principle, a TVRM can be removed by thermal demagnetization at a time-temperature combination that is equivalent to that at which the rock acquired the TVRM *[Neel,* 1949]. Nomographs of equivalent time-temperature curves for pure magnetite and hematite have been published by *Pullaiah et al.* [1975] and *Middleton & Schmidt* [1982]. Both sets of authors derived their nomographs from theoretical calculations using the single domain theory of *Neel* [1949], supplemented by laboratory experiments in the case of *Pullaiah et al.* and by field observations in the case of *Middleton and Schmidt.* Unfortunately the two sets of nomographs are quite different. One way to determine which set of nomographs is correct is to study the thermal demagnetization of TVRMs acquired during geologically significant time scales. Such a study requires an accurate estimate of the duration of the exposure to the Earth's magnetic field and the temperature at which the exposure took place. There are very few situations where these estimates can be made with any certainty. However, a collection of randomly-oriented rocks at the Earth's surface, such as a landslide deposit or a glacial till, can be used to study TVRM if the date of emplacement is known. For a suite of oriented samples from such a deposit, the TVRM would manifest itself as a secondary magnetization component that was parallel to the Earth's magnetic field. In contrast, the primary components of magnetization of the samples would have a random distribution.

This approach has been used previously by *Kent* [1985] who analyzed TVRM in blocks of Appalachian limestone deposited as glacial till. Kent's results were more consistent with the time-temperature curves of *Middleton & Schmidt* [1982] than with those of *Pullaiah et al.* [1975]. Similar results were found by *Jackson and Van der Voo* [1986] who analyzed Brunhes-age remagnetizations in magnetite- and hematite-bearing dolomites. *Kent and Miller* [1987] analyzed thermal overprinting of hematite in a red bed adjacent to a dike, and *McClellan Brown* [1981] examined overprinting of both hematite and a mixture of hematite-magnetite by the same mechanism. In both cases, better agreement was found with the curves of *Pullaiah et al.* [1975]. *Kent* [1985], *Jackson and Van der Voo* [1986] and *Kent and Miller* [1987] all acknowledged that their results could have been affected by the presence of pseudo-single domain and multidomain magnetite and hematite grains while *McClellan Brown* [1981] did not specifically address the question of grain size. We have studied the TVRM acquired by landslide-emplaced basalt

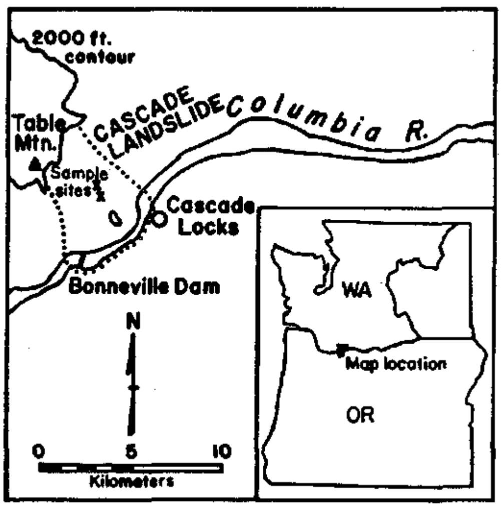

Figure 1. Map showing the location of the sampling sites on the Cascade Landslide.

Paper number 94GL02669
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blocks whose magnetic carrier is predominantly, if not solely, single-domain magnetite. This approach allows us to make an unambiguous evaluation of the two nomographs for magnetite.

Geologic Setting

The Cascade Landslide sits at the base of Table Mountain, which overlooks the Columbia River Gorge northeast of Cascade Locks, Oregon, on the Washington State side of the river (Figure 1). Table Mountain consists of 500 meters of Columbia River Basalt that is underlain by the Eagle Creek Formation, an easily eroded river-deposit conglomerate. The basalt at Table Mountain belongs primarily to the Sentinel Bluffs Unit and Winter Water Unit of the Grande Ronde Basalt *[Reidel et al.,* 1989]. Both units are within the N2 magnetic polarity interval of the Grande Ronde Basalt and were erupted between 15.9 and 15.6 Ma *[Baksi,* 1989]. Petrographic analysis of the Grande Ronde Basalt indicates that the primary magnetic mineral is magnetite or titanomagnetite *[Reidel et al.,* 1989].

The slope failure that created the Cascade Landslide was caused by erosion of the Eagle Creek Formation and collapse of the undercut basalt. The landslide occurred between 700 and 850 years ago and dammed the Columbia River for a number of years. The age of the landslide was determined by radiocarbon dating of wood collected from a forest that became submerged when the landslide blocked the river *[Smith,* 1992]. Government Locks and the Bonneville Dam now cover the lower portion of the Cascade Landslide; however, the upper portion is accessible on the north shore of the Columbia River near Stevenson, Washington.

Sample Collection and Laboratory Methods

We collected four fully-oriented samples hand samples at each of four localities on the field of basalt cobbles (Figure 1). Magnetic orientations were checked by siting to landmarks in the field. In the laboratory, samples were cast in plaster in their field position and then subsampled using a 2.5 cm diameter diamond core drill.

The remanent magnetism of one subsample from each of the 16 blocks was first measured at room temperature (20°C) using a 2-G Enterprises cryogenic magnetometer. The subsamples were then thermally demagnetized in 10°C increments from 50°C to 180°C, and then at 200°C, 220°C, 260°C, 300"C, and 360°C. At each demagnetization level, the temperature was maintained for 30 minutes. The magnetic susceptibility was measured after each step, and no changes in this parameter were noted until 360°C where there was a dramatic increase in magnetic susceptibility. Also at this temperature, some of the samples fractured. We took these observations as evidence for significant thermal alteration of the samples, and the thermal demagnetization was stopped. By 360°C, however, all of the samples had lost most of their original magnetization.

In order to determine the domain state of the magnetic carriers, we used a Princeton Measurements Corp. alternating gradient magnetometer to measure the hysteresis parameters of small chips from unheated subsamples. The homogeneity of the samples was tested by measuring several chips from the same sample. We also checked the mineralogy of the magnetic component by measuring the susceptibility of the samples as a function of temperature using a Geofizyka KLY-2 Kappabridge equipped with a CS-2 furnace.

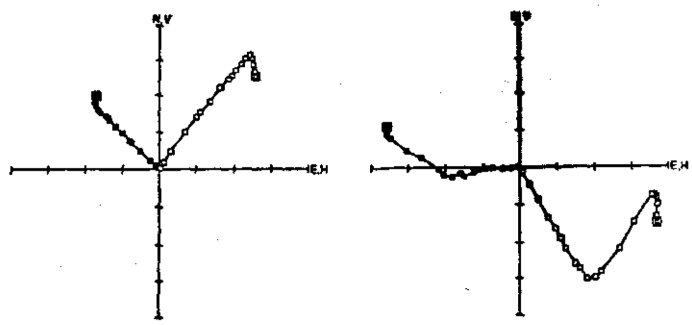

Figure 2. Zijderveld plots. Left and right plots correspond to samples that contain 1 and 2 TVRM components, respectively. Closed symbol refer to north and east axes.

Data Analysis

Zijderveld plots for the sixteen samples were analyzed using the least squares method developed by *Kirschvink* [1980]. Because each sample had been demagnetized at 20 different levels, we were able to resolve with confidence up to five separate components of magnetization. The component with the lowest unblocking temperature was designated as TVRM1, the next lowest, if present, was assumed to be a thermoviscous remanent magnetization, and was designated as TVRM2, and so on. The highest temperature component was designated as the NRM. In every case, the NRM component decayed univectorially toward the origin. Five of the samples contained only a single TVRM component in addition to the NRM component. Of the remaining samples, 5 contained two TVRM components, 3 contained three components, and 3 contained four TVRM components. Typical Zijderveld plots for samples containing one and two TVRM components are shown in Figure 2.

The paleomagnetic directions for the NRM and TVRM1 are shown in Figure 3. As noted above, for a landslide deposit, the NRM components should be randomly-oriented and the TVRM1 component should be parallel to the present field direction. With the exception of one outlier, the TVRM1 components are tightly clustered. On the other hand the NRM components are widely scattered. We can test for random orientation by comparing the values of R for TVRM1 and NRM with values given by *Watson* [1955]. For a set of 16

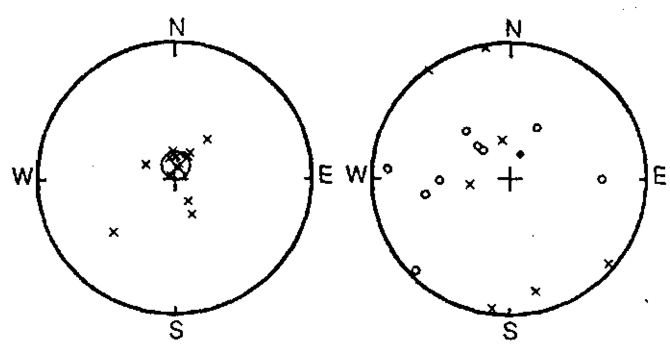

Figure 3. Equal angle stereographic projections of NRM and TVRM1 components. The plots represent TVRM1 (left) and NRM (right) components for the full suite of 16 samples. The x represents a direction in the northern hemisphere, the open circle represents a direction in the southern hemisphere, and the diamond is the direction of the present field.

vectors, there is a 5% chance that the vectors are randomly oriented when the value of R exceeds 6.40. There is only a 1% chance of random orientation when the value of R exceeds 7.60. For 15 vectors, the 5% and 1% threshold are 6.19 and 7.36, respectively. The other TVRM components were also widely scattered.

In Table 1, we give the paleomagnetic parameters for the full suite of sixteen samples and for a reduced suite with the outlier removed. For both suites, the NRM components are consistent with the hypothesis of random orientation and the TVRM1 components are not. All other combinations of TVRM components had values of R that were consistent with random orientations. Furthermore, at the sampling site, the present field direction has an inclination of 68.5° and a declination of 19.8°. This direction falls within the cone of 95% confidence of the mean TVRM1 direction of both suites.

The unblocking temperature of the TVRM1 component in different samples ranged from 70°C to 160°C. The other TVRM components had unblocking temperatures that ranged as high as 220°C. The unblocking temperature of the TVRM1 component of the outlier sample in Figure 3 is 160°C, and all of the other TVRM1 components fall in the narrower range of 70° to 100°C. We believe that the anomalous direction and higher TVRM1 unblocking temperature of the outlier justify its exclusion from the data set.

The hysteresis measurements from different chips from the same sample yielded almost identical results. With the exception of one sample, all of the samples (including the outlier) plot in the single-domain field of *Day el al.* [1977]. The exception plots in the pseudo-single domain field. The other usual feature of this sample is that its magnetic susceptibility is about 3 time higher than the other samples. We do not feel that there is sufficient evidence to exclude this sample from the dataset although whether or not it is included makes no difference to our conclusion.

The thermomagnetic curves of susceptibility as a function of temperature had well-defined Hopkinson peaks that correspond to Curie temperatures in the range of 520-550°C. These values are close to the Curie temperature of pure magnetite and indicate that there has been relatively little cation substitution in the magnetite.

Interpretation

The presence in some samples of more than one TVRM component raises an interesting problem. One possible explanation is that the samples with multiple TVRM components moved one or more times after emplacement of the Cascade Landslide. Two possible mechanism that could produce these movements are frost heaving and seismic activity. However, the unblocking temperature of the TVRM of a sample that had not moved at all after emplacement should be higher than the unblocking temperature of any TVRM component of a sample that had moved one or more times after emplacement. According to this model, the unblocking temperatures of samples with only one TVRM component should be higher than the highest unblocking temperatures of samples with more than one TVRM component, whereas in our study the opposite is observed. An alternate hypothesis is that rocks with multiple TVRM components had previously been part of older landslides that pre-dated the Cascade slide. Given the geologic conditions at the Cascade Landslide, it is quite reasonable to postulate that slides have occurred there before and that subsequent slides incorporated material from older slides. If an older slide had remained undisturbed for more than 800 years, the rocks that had been incorporated in it would have TVRM components with higher unblocking temperatures than those of the fresh material in the Cascade slide. Furthermore, the Cascade slide would have randomized the directions of these older TVRM components, which is what we observe.

We conclude that the TVRM1 component is the appropriate one to associate with the Cascade Landslide. The unblocking temperatures for this component falls in the range between 70°C and 100°C. The time used to demagnetize the sample was 30 minutes. This component was acquired as a result of exposure to the Earth's magnetic field over a period of 700 to 850 years. We estimate that temperatures at the sampling site range from 0°C in winter to 40°C in summer. These inferences provide us with two equivalent time-temperature points (700-850 years at 0-40°C and 30 minutes at 70-100°C).

In Figure 4, these points are plotted on the nomographs for magnetite of *Pullaiah el al.* [1975] and *Middleton and Schmidt* [1982]. If a nomograph is correct, the two points should fall on a line that is parallel to the time-temperature curves shown

Table 1. Paleomagnetic Parameters of TVRM1 and NRM

	N	D	I	a_{95}	R	R* (5%)	R* (1%)
TVRM1	16	4.5°	79.4°	12.2°	14.5	6.40	7.60
TVRM1	15	15.1°	76.3°	9.5°	14.2	6.19	7.36
NRM	16	282.2°	-32.1°	60.7°	4.8	6.40	7.60
NRM	15	284.5°	-38.3°	70.4°	4.0	6.19	7.36

R* is the value of R which must be exceeded if there is less than a 5% or 1% chance that the vectors have a random distribution.

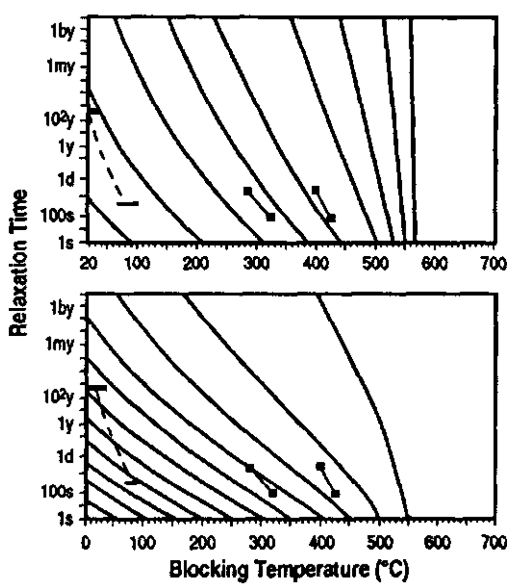

Figure 4. Time-temperature nomographs for thermal demagnetization of magnetite according to *Pullaiah et a/.*[1975] (top) and *Middleton and Schmidt* [1982] (bottom). Results of present study shown on the left as dashed line connecting horizontal bars. Results of *Dunlop and Ozdemir* [1993] shown in the center as solid lines connecting squares.

on the nomograph. Clearly this is the case for the nomograph of *Pullaiah et al.*[1975] while on the nomograph of *Middleton and Schmidt* [1982], several equivalence lines must be crossed in order to connect the two data points. Thus, in contrast to the magnetite data of *Kent* [1985] and of *Jackson and Van der Voo* [1986], our data support the (magnetite) nomograph of *Pullaiah et al.* rather than that of *Middleton and Schmidt.* However, both *Kent* [1985] and *Jackson and Van der Voo* [1986] felt their results could have been influenced by the presence of pseudo-single domain and multidomain grains. Our rock magnetic studies demonstrate that we are only dealing with single domain magnetite grains.

The validity of the nomograph of *Pullaiah et al.* is also supported by the work of *Dunlop and Ozdemir* [1993] on the thermal demagnetization of the TVRM acquired by pure single-domain magnetite under laboratory conditions. In that study, TVRM components acquired as a result of heating at 283°C and 404°C for 3.5 hours demagnetized at temperatures of 322°C and 425°C, respectively, with a heating time of 100 sec. These two time-temperature pairs are plotted on the nomograph of *Pullaiah et al.* in Figure 4.

Because of the conflicts between the nomographs of *Pullaiah et al.* [1975] and those of *Middleton and Schmidt* [1982], several authors have questioned the appropriateness of the single-domain theory of *Neel* [1949], on which the nomographs are based. For example, *Enkin and Dunlop* [1988] argued that the "low-field approximation" used in the calculations was not applicable to magnetite assemblages in the Earth's magnetic field. Earlier *Walton* [1980] suggested that the size distribution of the magnetic grains could influence the time-temperature equivalence lines, and *Moon and Merrill* [1986] proposed a different mechanism for the acquisition of a TVRM. Our work and that of *Dunlop and Ozdemir* [1993] raises the question of whether there is a need for these alternative theoretical formulations. However, many questions still remain about the acquisition of TVRM and consequently about the appropriate procedures for removing it by thermal demagnetization.

Conclusion

Thermal demagnetization of basalt cobbles from the Cascade Landslide have provided new data about the acquisition and removal of a thermal viscous remanent magnetization (TVRM). These data imply that that the theory *Neel* [1949], as applied by *Pullaiah et al.* [1975], may provide a suitable model for TVRM in single domain grains. Our results and those of *Kent* [1985] demonstrate the feasibility of studying TVRM by conducting paleomagnetic investigations of randomly-oriented rocks that have been exposed to the Earth's magnetic field for geologically significant periods of time. They also emphasize the need for careful characterization of the domain state of the magnetic carriers.

Acknowledgment. This work was supported by NSF grants EAR-8 03925 andEAR-91-15962.

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(Received July 27, 1994; accepted September 13, 1994.)