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Cooling rate effects on the magnetization of volcanic rocks: Some implications for paleointensity determination

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RESUMEN

Se analizan los efectos de la variación del ritmo de enfriamiento en la adquisición de la magnetización termoremanente (TRM, por sus siglas en inglés) en un conjunto de rocas volcánicas. Se empleó un procedimiento experimental en tres etapas aplicado a tres temperaturas diferentes de adquisición de TRM. Se aplicó una TRM parcial (pTRM @ 300°C) a una selección de dieciséis muestras, estables térmicamente, de flujos de lava del Cuaternario Tardío, empleando un ritmo de enfriamiento lento. Las intensidades adquiridas se midieron a temperatura ambiente. Una segunda pTRM fue aplicada a los mismos especímenes usando un ritmo de enfriamiento rápido, determinándose las intensidades adquiridas a temperatura ambiente. Finalmente se aplicó una tercera pTRM, como en el primer paso, usando un ritmo de enfriamiento lento. El procedimiento se repitió para crear pTRM's a temperaturas mayores de 450° y 550°C. Se calculó la variación porcentual correspondiente entre la intensidad de las magnetización adquirida a ritmos de enfriamiento lento-rápido y lento-lento para investigar la influencia del ritmo de enfriamiento sobre la intensidad de adquisición de la TRM, así como los cambios en la capacidad de adquisición de la TRM, respectivamente. Se observan variaciones tan altas como 300% en el primer caso (300°C). La intensidad del campo magnético antiguo, obtenida de rocas volcánicas, podría estar sobreestimada al menos 15% debido a la diferencia entre los ritmos de enfriamiento empleados comúnmente en el laboratorio y los ritmos de enfriamiento, más lentos, encontrados en la naturaleza.

PALABRAS CLAVE: Ritmo de enfriamiento, paleointensidad, rocas volcánicas, magnetismo de rocas.

ABSTRACT

Effects of variation of cooling rate in the acquisition of thermoremanent magnetization (TRM) are analyzed on a suite of volcanic rocks. We use a three-step cooling rate experimental procedure applied at three distinct temperatures of TRM acquisition. Sixteen selected, thermally stable samples from Late Quaternary lava flows were given a pTRM (300°C) at a slow cooling rate. The acquired intensities were measured at room temperature. A second pTRM was applied to the same specimens using a fast cooling rate, and the acquired intensities were measured at room temperature. Finally a third pTRM was induced as in the first step, using a slow cooling rate. The procedure was repeated to create pTRM's at higher temperatures of 450° and 550°C. Corresponding percent variations between magnetization intensities acquired at slow-fast and at slow-slow cooling rates were calculated to investigate the influence of cooling rate on TRM intensity acquisition, and on TRM acquisition capacity. We observe values as high as 300 % in the former case (300 °C). Intensity of the ancient geomagnetic field obtained from volcanic rocks could be overestimated by at least 15% due to a variation in cooling rate normally employed in the laboratory, as compared to slower rates found in nature.

KEY WORDS: Cooling rate, paleointensity, volcanic rocks, rock magnetism.

INTRODUCTION

The effect of cooling rate on thermoremanent magnetization (TRM) was first considered by Neel [1955], and later by Pullaiah *et al.*, [1975] and York [1978]. Since the early 80's, numerous theoretical and experimental studies have been devoted to investigate the influence of cooling rate upon the intensity of TRM acquisition [e.g., Walton, 1980; Fox and Aitken, 1980; Halgedhal *et al.*, 1980; Dodson and McClelland Brown, 1980; McClelland Brown, 1984; Walton and Williams, 1988; Chauvin *et al.*, 1991; Biquand, 1994]. Most of these authors provide analytical or numerical solutions of magnetization for assemblies of single-domain grains, whereas experimental studies are mainly devoted to synthetic magnetite and titanomagnetites of varying sizes, or to archaeomagnetic materials. Dodson and McClelland-Brown [1980] predicted a 7% increase in TRM intensity for an order of magnitude decrease in cooling rate. This effect may have important implications for paleointensity determinations, yet few studies take into account the cooling rate effects [e.g., Pick and Tauxe, 1993; Chauvin *et al.*, 2000; Carlut and Kent, 2002; Genevey and Gallet, 2002].

In this study, we report new experimental data to evaluate the effect of cooling rate on the intensity of TRM and we examine some implications on paleointensity determinations for magnetically and chemically well-characterized and thermally stable volcanic rock samples.

SAMPLES AND LABORATORY PROCEDURES

Samples used in this study come from Late Quaternary lava flows of Chichinautzin volcanic field in Central Mexico. These samples previously provided high technical quality Thellier paleointensity results. The rock-magnetic and paleodirectional properties of these flows have been previously investigated in detail [Morales *et al*., 2001 and 2003]. The remanence is dominated by a stable, single component magnetization as attested by alternating field and thermal cleanings. The main magnetic carriers are low-Ti titanomagnetites as evidenced by reasonably reversible susceptibility versus temperature curves. The ratios of hysteresis parameters indicate that all samples fall in the pseudo-single domain grain size region, probably indicating a mixture of multidomain and a significant amount of single domain grains [Morales *et al*., 2003]. Characteristic concave-up Arai plots for MD samples [Shcherbakova *et al*., 2000] are not observed, suggesting no major influence of MD grains.

Samples were heated to 600°C and maintained at this temperature for 20 minutes in zero magnetic field. After this time they were allowed to cool inside the free field furnace chamber down to 300 °C. A magnetic field intensity of 30 μT was induced at this point by the coil of an MMTD (*Magnetic Measurements LtD*) oven. Samples were then allowed to cool naturally at a slow cooling rate (~10 hours) down to room temperature. Intensity of the partial TRM (TRM1) so obtained was measured using a JR5 (*Agico LtD*) spinner magnetometer. In a similar way, a second pTRM (TRM_2) was created at a faster cooling rate (for about 30 to 45 min). The intensity of TRM_2 was measured. The last step of this procedure consisted of inducing a third partial TRM (TRM_3) in the same conditions as those employed to create TRM_1, that is, using the same cooling conditions. Acquired TRM intensities obtained in this three-step procedure were plotted in bar graphs as shown in Figure 1 (a).

The entire procedure was repeated to create pTRM's at two higher temperatures of 450 and 550°C. The corresponding histogram plots are shown in Figure 1 (b) and (c), respectively.

The anisotropy of magnetic susceptibility (AMS) was measured on all samples to further investigate any possible mineralogical effects on remanence acquisition. AMS determinations were carried out on each specimen using a *Kappabridge* KL-2 instrument.

RESULTS

The effect of cooling rate upon TRM intensity was estimated from percent variation between the intensity acquired during a long and a short cooling time (Table 1). Changes in TRM acquisition capacity was estimated by means of the percent variation between the intensity acquired during same inconsecutive cooling time (first and third pTRMs).

Most samples experienced an increase in TRM (300°C) acquisition capacity (slow-slow cooling rates, first and third heatings) of 14 %, on average, occasionally increasing to 30% and up to 100%, in some extreme cases. Samples with a lower variation index show changes due to differences in cooling rates (slow-fast rates, first and second heatings) of 35 %, on average, extending up to 100 and 300 %, in a few cases, Table 1.

In the two remaining cases, [TRM (450 °C) and TRM (550 °C)] the variation in TRM acquisition capacity was below 5% in most of the samples, with only two exceptions. In contrast, variations due to differences in cooling rates yield raised values higher than 30%, on average, and above 100% in some cases for TRM (450 °C). Corresponding values for TRM (550 °C) did not exceed 20% in most of the samples, with only two exceptions (25.5 and 37.9 %) (Table 1).

A higher intensity of pTRM, gained during quick cooling (central bar) for all the samples, is attested in Figure 1 (b), in accordance to McClelland-Brown's observations [1984] for PSD or MD titanomagnetites. The same effect is observed in half of the samples for a temperature of 300 °C, Figure 1 (a), though it is more evident at a temperature of 450 °C, which is within the Curie temperature range of the titanomagnetite matrix.

No anisotropy correction was needed since AMS was low (less than 1%) in all the samples. Thus, anisotropy effects may be discarded as responsible of the observed TRM behavior.

DISCUSSION

The effect of cooling rate upon acquisition of pTRMs in volcanic rocks appears to be more complex than found in archaeomagnetic investigations. Even samples with near to zero variations in TRM acquisition capacity can show strong dependence on cooling rate (row 6, column 4 of Table 1). In the best case (row 14, column 6 of Table 1), a difference in cooling rates of just one order of magnitude may produce a difference of more than 10% in magnetization. It should be noted that the effect of cooling rate upon acquisition of pTRMs (TRM_1 vs TRM_2, Table 1) is generally greater than the variation in TRM acquisition capacity (TRM_1 vs TRM_3, Table 1).

Carlut and Kent [2002] observed a somewhat similar behavior on four glassy and non-glassy sub-samples from

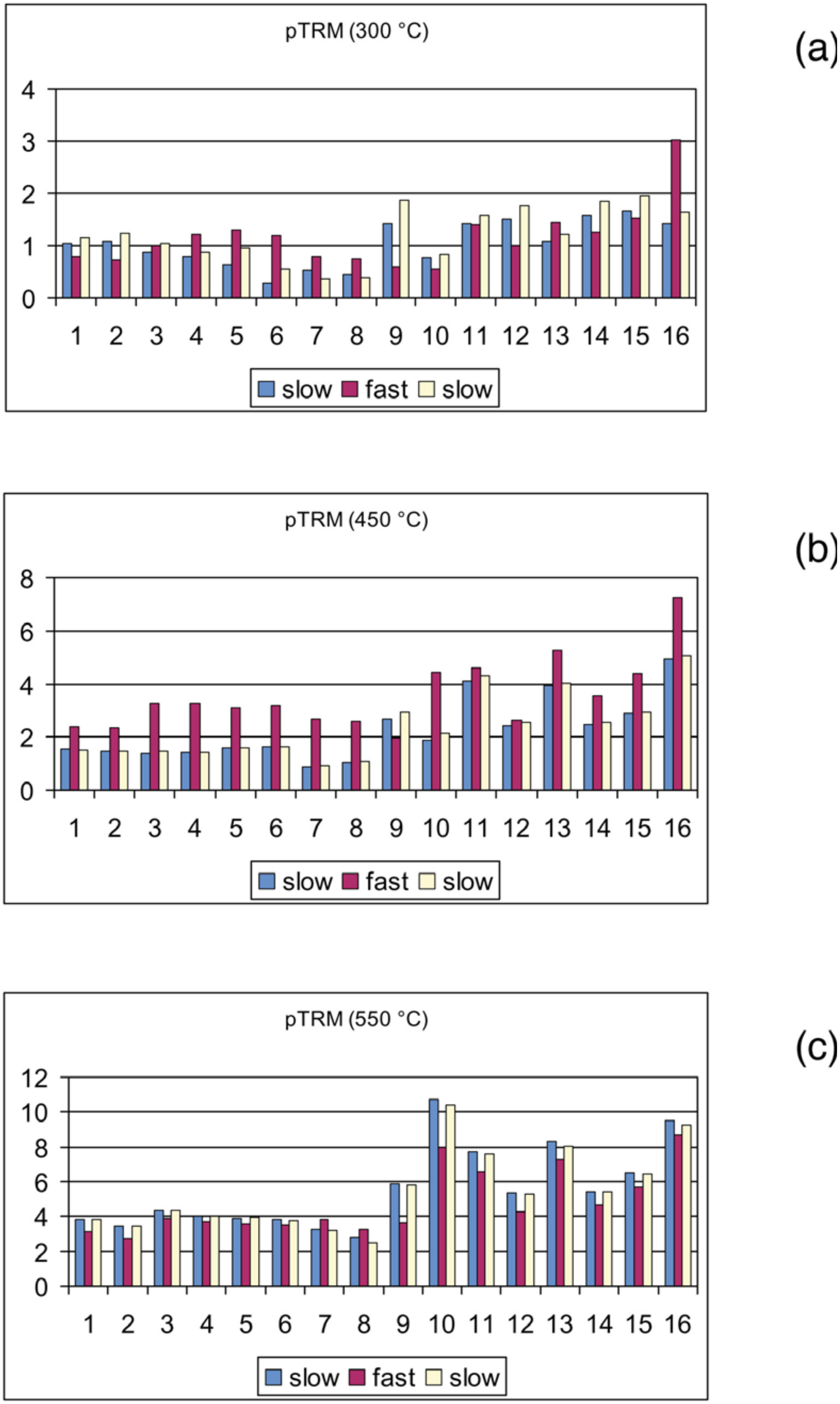

Fig. 1. Bar graphs showing absolute TRM intensities gained during slow, fast and slow cooling rates. (a), (b) and (c) pTRM 300, 450 and 550 °C, respectively (see text for additional details).

Table 1

Percent variation of TRM intensities between slow-fast and slow-slow cooling rates for pTRM (300 °C), (450 °C) and (550°C), respectively (see also text for further details)

	pTRM [300 °C]		pTRM [450 °C]		pTRM [550 °C]	
sample	TRM1-2	TRM1-3	TRM1-2	TRM1-3	TRM1-2	TRM1-3
92H010A	23.9	-10.1	-51.6	2.4	18.2	0.9
92H010B	33.2	-14.0	-61.6	-0.4	19.4	0.3
92H011A	-17.1	-21.8	-134.3	-4.0	11.2	0.2
92H011B	-56.5	-12.7	-127.0	-0.8	7.6	-0.2
92H012A	-104.8	-51.8	-94.8	0.8	8.5	-1.4
92H014A	-323.7	-101.4	-96.9	0.0	8.9	2.5
92H015A	-48.7	30.5	-205.4	-6.2	-19.1	1.8
92H017A	-71.9	12.8	-148.8	-3.4	-14.7	12.7
92J002A	58.7	-30.8	25.4	-10.5	37.9	1.4
92J008A	27.6	-8.9	-136.6	-13.5	25.5	3.2
92J010A	1.1	-10.7	-11.7	-4.9	15.2	1.4
92J011A	33.8	-16.6	-8.2	-4.5	20.5	1.3
92J011B	-33.0	-11.2	-34.9	-2.3	12.3	3.1
92J011C	19.7	-18.4	-43.3	-4.0	13.6	0.1
92J011D	7.7	-16.8	-52.1	-2.1	12.6	1.0
92J012A	-112.7	-14.8	-46.2	-2.3	8.9	2.3

submarine basalts. They reported differences of up to 15% between partial remanences acquired using different (one order of magnitude) cooling rates. The cooling in these experiments, however, was performed from relatively low temperatures (340°C maximum), faraway from the higher Curie temperature (T_c) estimated for these submarine basalts. As suggested by McClelland-Brown, [1984] no intensity changes occur below the Curie temperature of the titanomagnetite matrix. Above T_c, however, the intensity of the acquired TRM increases drastically.

Paleomagnetic sampling is usually done on artificially exposed outcrops on roads cuts and sampling is distributed horizontally and vertically to minimize block tilting effects. Sampling along several meters of a single lava flow along a profile is also common practice in paleointensity studies. In either case, core samples come from different cooled volumes within the flow.

Calculations made by a simple extension of the model outlined by Pick and Tauxe [1993] led us to estimate the time that it takes for a volcanic rock to cool down from 560° to 100 °C as a function of depth. From Figure 2, it takes a lava flow around 2 days to cool between these limits for a depth of 10 cm. This corresponds to a difference of two orders of magnitude in cooling rate with respect to ordinary laboratory cooling times. For a volcanic unit in the same cooling conditions it will take around 7 and 17 days for a thickness of 20 and 30 cm, respectively. Even within a specific outcrop, differences of several orders in cooling rates between nature and laboratory should be expected.

An estimate of the cooling rate effect on the intensity of TRM for paleointensity (PI) determinations can be straightforward estimated by means of Koenigsberger's 'single-heating' method [1938]. It is not necessary to use the more reliable stepwise Thellier method [Thellier and

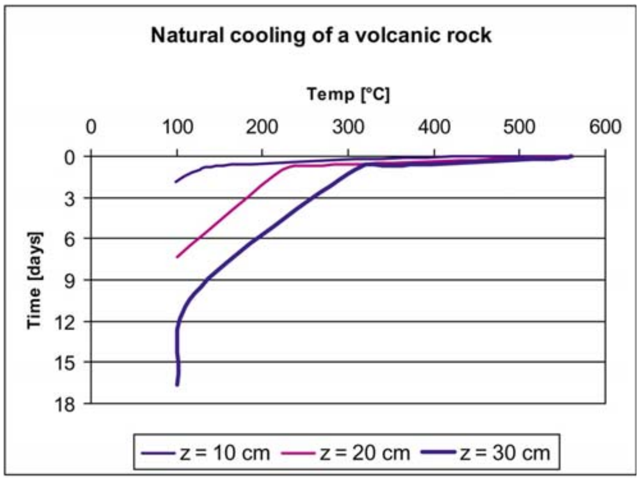

Fig. 2. Time in days needed for a volcanic rock to cool from 560 °C to 100 °C for depths (z) of 10, 20 and 30 cm, respectively (calculations performed following method outlined by Pick and Tauxe, [1993]).

Thellier, 1959], since the remanences are characterized by stable, single components. Intensity of 'ancient' geomagnetic field would be overestimated by at least 15% for cooling rates normally employed in the laboratory, as shown in the second column of Table 2. On the contrary, when similar cooling rates are used, the''PI' is accurately reproduced within 1% error (column 3, Table 2), as reported in earlier studies.

In conclusion, we show that the effect of cooling rate may play an important role in paleointensity determinations. This effect should always be considered when samples are collected at different depths.

Table 2

Estimation of cooling rate influence on paleointensity determinations by the Koenigsberger [1938], single-heating method. TRM_1, TRM_2 and TRM_3 are absolute intensities of pTRMs (550 °C) produced at a slow, fast and slow cooling rate, respectively. TRM_1/TRM_2 (TRM_1/TRM_3) represents the ratio of pTRMs created with dissimilar (similar) cooling rates

sample	TRM1/TRM2	TRM1/TRM3
92H010A	1.223	1.009
92H010B	1.241	1.003
92H011A	1.127	1.002
92H011B	1.082	0.998
92H012A	1.093	0.986
92H014A	1.098	1.026
92H015A	0.840	1.018
92H017A	0.872	1.146
92J002A	1.610	1.014
92J008A	1.342	1.033
92J010A	1.179	1.014
92J011A	1.258	1.013
92J011B	1.140	1.032
92J011C	1.158	1.001
92J011D	1.145	1.010
92J012A	1.097	1.024
mean =	**1.156**	**1.021**
s.d. =	**0.175**	**0.036**

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