A selective procedure for absolute paleointensity in lava flows

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[1] We present a compilation of experiments of absolute paleointensity using double heating protocols on very recent lava flows from Hawaii, La Réunion, the Canary islands and Santorini. The existence of a sharp distribution of grain sizes carried by a single mineralogical phase always yielded successful determinations of paleointensity that deviate by less than 10% from the actual field value. Thus, a rapid decrease of at least 70% of the initial magnetization over a narrow range of temperatures prior to the Curie point combined with a unique mineralogical phase define an optimal situation for obtaining reliable estimates of absolute paleointensity. Consequently, we suggest that stepwise standard thermal demagnetization of companion specimens should be routinely performed prior to paleointensity experiments. Not only do these measurements provide important information about the characteristic magnetization, but they indicate which samples are appropriate for paleointensity experiments, which increases the success rate to almost 100%. **Citation:** Valet, J. P., E. Herrero-Bervera, J. Carlut, and D. Kondopoulou (2010), A selective procedure for absolute paleointensity in lava flows, *Geophys. Res. Lett.*, *37*, L16308, doi:10.1029/2010GL044100.

1. Introduction

[2] When cooling down lava flows acquire a thermoremanent magnetization that records the direction and the intensity of the geomagnetic field. In principle, the direction of the field can be isolated properly after thermal demagnetization, but it is much more delicate to determine the field intensity. The classical approach for paleointensity studies [*Thellier and Thellier*, 1959; *Coe*, 1967] relies on the amount of original magnetization lost after zero-field heating versus the one imparted after in-field heating at the same temperature. This comparison requires partial remagnetization of the samples by heating them in presence of a known laboratory field. Since the protocol is repeated at incremental temperature steps it is very time-consuming, but the most limiting parameter is the low success rate (10–20%) of the experiments due to mineralogical changes produced during heating. Various techniques have been proposed including the use of plagioclase [*Cottrell and Tarduno*, 1999] extracted from basaltic samples, but they do not convincingly reduce the duration of the experiment. The use of basaltic glass [*Pick and Tauxe*, 1993] can be seen as an alternative to the whole rock basaltic samples, but it is not completely exempt of problems and sampling locations are not readily available. So far, there is no suitable criterion to select the samples that would be appropriate for paleointensity experiments. It is usually considered that reversible thermomagnetic curves are a favorable situation [*Valet*, 2003] but this condition is not sufficient and does not always yield acceptable determinations. This reinforces the importance of investigating what basic properties could be used to discard inappropriate specimens. In the meantime, it is also critical to estimate the degree of fidelity of the determinations, which can only be achieved by studying historical or contemporaneous flows.

[3] With these objectives in mind, we recently performed an exhaustive study of the 1955 and 1960 flows in Hawaii [*Herrero-Bervera and Valet*, 2009]. We noticed a link between the unblocking temperature spectra derived from the resistance of the natural remanent magnetization (NRM) to heating in zero field and the accuracy of the value of paleofield. This points out the origin of difficulties in presence of a wide distribution of grain sizes and/or the existence of several magnetic phases. These conclusions, being restricted to two Hawaiian flows, must be validated for other volcanic provinces. In order to achieve this goal we have followed the same philosophy as for the 1955 and 1960 Hawaiian flows by restricting the experiments to historical flows. We have selected lava flows from Sicily (Mount Etna), Canary, Réunion, and Santorini (Greece) islands to which we have added the 1859 lava flow from the Big Island of Hawaii.

2. Experiments and Results

2.1. Thermomagnetic Experiments

[4] We carried out thermomagnetic experiments in strong fields of 720 mT up to 700°C using a Variable Field Translation Balance instrument. In Figure 1 are plotted the thermomagnetic heating and cooling curves along with the evolution of TRM intensity during thermal demagnetization in zero field for companion specimens. For comparison we also show typical results obtained from the 1955 and 1960 neighbored flows [*Herrero-Bervera and Valet*, 2009]. The pattern of the decreasing TRM is either linear at almost all temperatures or roughly exhibits two slopes with a faster decrease at high temperatures and a Curie point of 570–580°C due to almost pure magnetite. Thermomagnetic curves are rightfully frequently considered as a good technique to select samples for paleointensity experiments. It is thus interesting to scrutinize their characteristics with respect to the success of the paleointensity experiments. For this reason we have indicated when no determination of absolute paleointensity has been obtained for the companion samples shown in Figure 1. Keeping in mind that there may be some differences between the two samples we can draw a few conclusions. The first one is that reversible thermomagnetic

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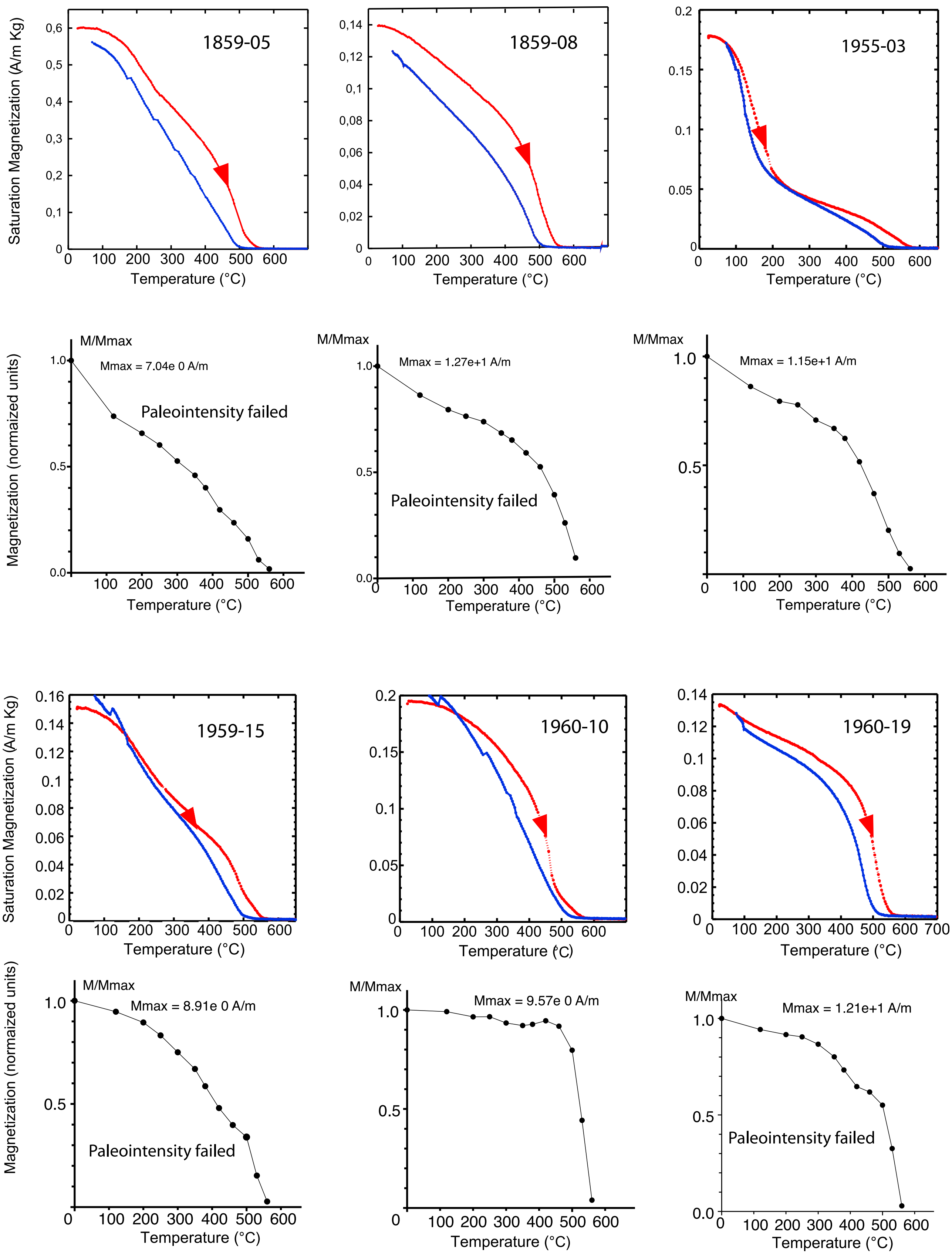

Figure 1. Typical thermomagnetic curves for samples from the 1859, 1955 and 1960 Hawaiian flows. For each sample is shown the evolution of the initial NRM of a companion sample taken from the same core as a function of temperature. The changes in NRM have been derived from the experiments of absolute paleointensity. Samples that did not yield any suitable result are mentioned as failed, while all others have been successful.

curves do not guarantee the absence of mineralogical changes during heating and thus not also the success of the experiments. We also note that similar thermomagnetic patterns (e.g., 1960-10 and 1960-19) can be associated with either successful or failed paleointensity experiments (a failed experiment being defined when the paleointensity deviates by more than 10% from the expected field intensity). The second one is that the thermomagnetic curves (especially the heating curves) can be quite different from the evolution of the NRM upon thermal demagnetization (e.g., 1955-03 and 1960-10), which partly explains the first point. Thus thermomagnetic curves can certainly be used as a first-order selection procedure, but they do not provide any definite indication about the success and the reliability of the future experiments. For this reason we prefer to investigate the characteristics of the initial NRM.

2.2. Hawaiian 1859, 1955 and 1960 Lava Flows

[5] Paleointensity experiments were carried out using the Coe version [*Coe*, 1967] of the Thellier experiments but we measured the TRM prior to the NRM [*Valet et al.*, 1998]. We routinely performed pTRM checks mostly after each new temperature step. The quality of the pTRM checks was defined from the mean of the deviations between each initial pTRM and the corresponding check over the NRM-TRM segment presumably selected for the calculation of the slope. The deviation has been expressed in percentage (DEV) after normalizing the DEV value, defined as DEV = Σ (pTRM-pTRMcheck), with respect to the length of the TRM segment. Similarly, we also considered the largest deviation (maxDEV) obtained at all steps. Note that in contrast to the calculation of the DRAT [*Selkin and Tauxe*, 2000] we did not incorporate any value of the NRM in the calculation of DEV because they are decoupled from the pTRM checks.

[6] Only one sample (08A) out of 13 from the 1859 basaltic Hawaiian flow could have been tentatively used for field determination. Such low success has been caused by the presence of negative pTRM checks and/or the absence of a well identified linear segment of the NRM-TRM plot. In Figures 2a–2c we show three typical Arai plots with the evolution of their NRM upon demagnetization. The NRM of sample 05B linearly decreased with temperature so that less than 25% of its initial intensity remained at 450°C. The Arai plot with a slightly concave shape and negative pTRM checks has been rejected as indicated (Figure 2a). The second sample (03B in Figure 2b) has preserved 40% of its magnetization beyond 450°C and shows a better Arai plot with negative pTRM checks beyond 350°C. However the curve shows no segment with positive checks that can be used to calculate a paleointensity. In these two cases the characteristic concave shape of the NRM-TRM graphic indicates the existence of multidomain grains which is also depicted by a large distribution of unblocking temperatures [*Kissel and Laj*, 2004; *Herrero-Bervera and Valet*, 2005, 2009]. The hysteresis parameters indicate grain sizes in the pseudo-single domain ranges for all specimens and are thus not diagnostic. Lastly, sample (08A, Figure 2c) has a low-temperature segment and very low DEV values that make it appropriate for calculation of paleointensity. It is striking that the slope gives a field value which is 23% higher than the expected field intensity. Note that the fraction f of the NRM incorporated in the NRM-TRM segment used to calculate this slope [*Coe*, 1967] is only 26%, thus below some criteria of acceptance [*Kissel and Laj*, 2004; *Herrero-Bervera and Valet*, 2009]. Thus, despite a larger proportion of grains with high unblocking temperatures (52% of the NRM magnetization at 450°C) the grain size distribution remains too wide for providing a correct estimate, similarly to many unsuccessful samples from the neighbored 1955 and 1960 flows (Table 1). In Figures 2d and 2e are shown two interesting results from these last two flows. Despite its linear Arai plot and positive checks, it is striking that the paleofield derived from the first sample is 27% off the expected field intensity and that only 39% from the initial magnetization remained at 450°C in this case. In contrast 91% remained at the same step in the second sample (Figure 2e) which provided a suitable field value. These results point out the importance of the unblocking temperatures distribution for successful experiments of absolute paleointensity.

2.3. Etna and Réunion

[7] We have conducted paleointensity experiments from three recent basaltic flows (1971, 1986, 1992) of the Etna volcano but the overall quality of the diagrams was not suitable to calculate a paleofield determination. One characteristic sample from each flow is shown in Figures 2f–2h. Sample E71E2 (flow1971) has kept 50% of its initial magnetization after heating at 450°C and displays a low temperature segment characterized by a mean DEV of 10% which is not really acceptable. It is thus not completely surprising that the paleointensity deviates by almost 40% from the expected value. The sample from the 1986 flow (Figure 2g) shows two mineralogical phases the first one being characterized by a decrease of the magnetization between 20°C and 300°C. This is likely caused by titanomagnetite and a smaller amount of magnetite. There is a unique low temperature segment associated with the first phase that gives a value 35% higher than expected. Lastly, the sample from 1992 (Figure 2h) is characterized by a large distribution of grain sizes but a relatively small mean DEV of 5%. Sixty percent of its initial magnetization has been lost after 450°C and the pTRM checks at 350°C and 400°C are negative. The value of 25μT derived from the lower unblocking temperatures only represents 43% from the expected field intensity. Thus, even samples with appropriate Arai diagrams can indicate erroneous paleointensity. It is also noticeable that none of them displays a sharp distribution of high unblocking temperatures (Table 1).

[8] Measurements have been made from four blocks taken from the 1984 recent basaltic flow at the Réunion island. Sample R1984 26A (Figure 2i) has positive pTRM checks and a concave down shape with one low and one high temperature segment with a very different slope. This situation is linked to the existence of multidomain grains which prevents from any rigorous interpretation. The following sample (Figure 2j) is characterized by a linear and thus again an acceptable Arai plot with a unique slope but a paleointensity value which is 13% too low, thus not successful. If we refer to the evolution of its magnetic moment we notice that 60% of the magnetization has been retained at 450°C. This result suggests that the limit of 60% residual magnetization at 450°C is not stringent enough to obtain an accurate determination of paleointensity, which confirms the conclusions obtained for the 1955 and 1960 flows [*Herrero-Bervera and Valet*, 2009] setting up the limit above 70%. In fact, none of the 19 studied samples kept more than 60% of

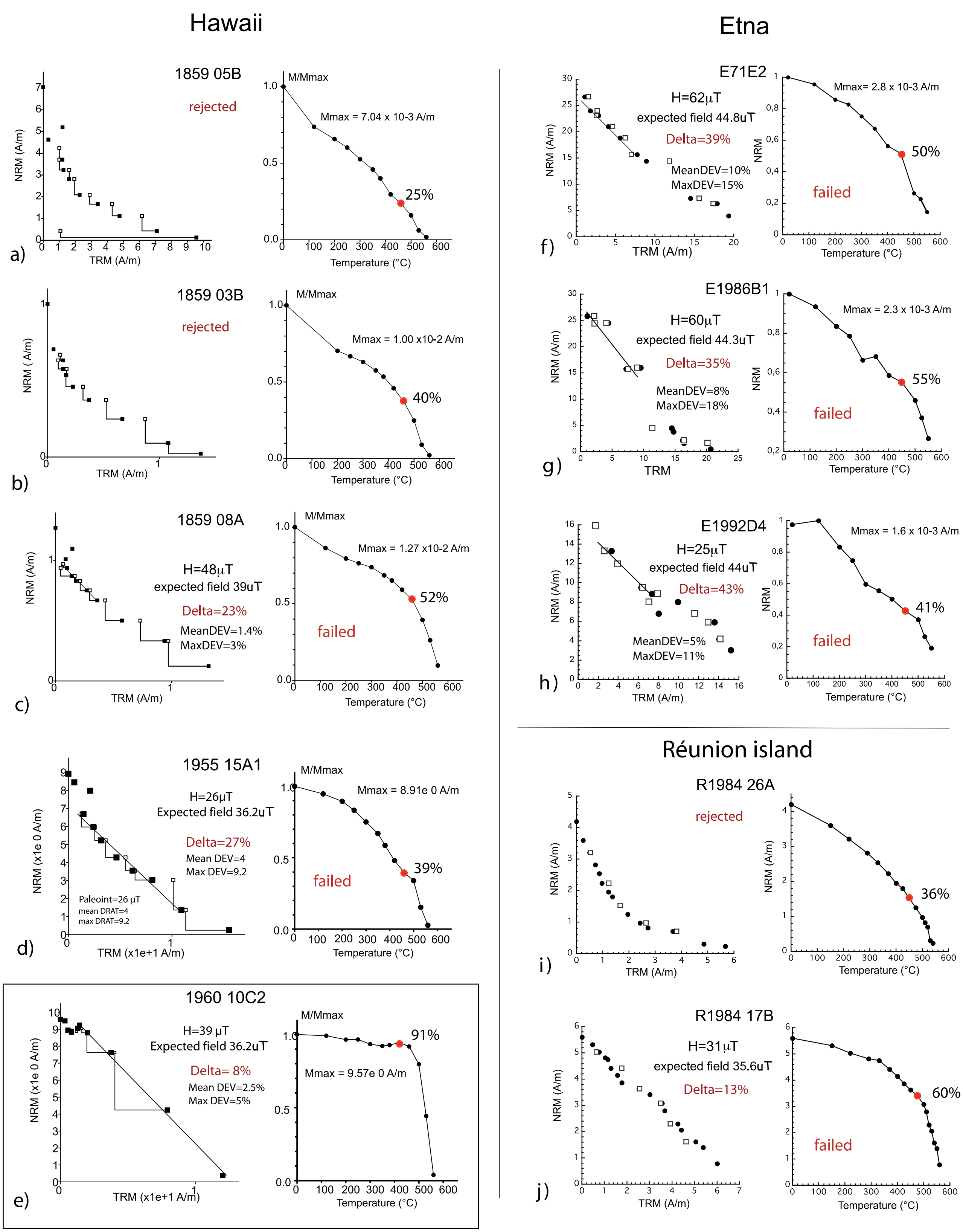

Figure 2. Arai plots and evolution of NRM during thermal demagnetization for samples from (a–e) Hawaii, (f–h) the Etna volcano and (i, j) the Réunion island. Red dots indicate the percent of magnetization remaining at 450°C. Delta gives the deviation between the paleointensity and the expected field intensity at the age of the flow. "Rejected" diagrams are for samples with non linear well defined NRM-TRM slope and/or negative pTRMchecks, while "failed" indicates field determinations that deviate by more than 10% from the expected field intensity. Surrounded diagrams correspond to samples with successful determinations.

Table 1. Statistics of the Experiments for Each Geographic Location[a]

	N_{AraiOK}/N_{total}	$N_{(H<10\%)}/N_{AraiOK}$	$N_{M>70\%}/N_{(H<10\%)}$
Hawaii 1955	4/23	4/4	4/4
Hawaii 1960	14/38	14/14	14/14
Hawaii 1859	0/12	0	0
Etna 1971,1986,1992	0/21	0	0
Réunion 1984	0/19	0	0
La Palma 1949	8/16	7/16	6/7 f factor >0.75
Santorini 1925, 1940	14/22	9/14	9/9

[a]The first column indicates the ratio between the rejected samples based on unsuitable NRM-TRM diagrams and pTRMchecks and the total number of samples used in the experiment. Note that only historical lava flows have been considered. The second column gives the ratio between the successful results (i.e., which deviate by less than 10% from the expected field) and the accepted Arai plots defined above. The third column is the ratio between the number of samples that preserved at least 70% of their magnetization at 450°C and the successful determinations of paleointensity. In the case of the Santorini lava flows with titanomagnetite we have used the f factor.

magnetization beyond 450°C and we did not obtain any acceptable determination of paleointensity (Table 1).

2.4. Canary Islands and Santorini

[9] Interesting results have emerged from the experiments performed from recent flows at the Canary islands and Santorini. The upper sample (TED02C) in Figure 3a comes from a 700 years basaltic old flow from the Teide volcano (La Palma island). Only 12% of its initial magnetization have been preserved after heating at 450°C. Prior to this step the Arai plot exhibits a linear slope with a mean DEV of 6%. However, despite little uncertainties concerning the field estimate at the 13th century, the determination of paleointensity is 19% too high. The next sample (TAC02C2 in Figure 3b) from the 1595 flow in La Palma is also associated with a linear decay of its magnetization but with negative pTRM checks and has thus been rejected. Only 32% of its initial intensity was kept at 450°C. Sample LP49B (Figure 3c) has preserved 32% of its magnetization at 450°C and exhibits two mineralogical phases, likely high titanium titanomagnetite and magnetite. This situation has generated substantial changes during heating and thus negative pTRM checks so that the resulting Arai plot cannot be validated. The last sample (SJ02C in Figure 3d) from the same flow displays the opposite situation with a single mineralogical phase carried by magnetite and a very sharp distribution of its high unblocking temperatures with low DEV values. Eighty percent of magnetization has remained after heating at 450°C which then sharply drops until the Curie temperature. Such ideal conditions yield a value of absolute paleointensity which fits the expected field. Only samples with those characteristics similarly met the objective (Table 1). These results confirm further that a narrow distribution of unblocking temperatures with a unique mineralogical phase is the optimal situation for reliable field determinations.

[10] The consequences of two phases are also well illustrated by the samples from the 1925 and 1940 dacitic lava flows in Santorini. It is striking that the specimens shown in Figures 3e and 3f exhibit nice and linear Arai diagrams with positive pTRM checks (mean DEV = 2%) for the first one and a mean DEV of 9% for the other one. However the paleointensity deviates by more than 12% from the actual field and we are evidently tempted to link this discrepancy to the spectrum of unblocking temperatures, notably to the rapid drop at low temperatures. Clearly again this situation is not favorable and appears here to result from the existence of two mineralogical phases. In contrast, the samples plotted in Figures 3g and 3h display a very abrupt decrease of their magnetization immediately prior to the Curie temperature which is only 300°C. The magnetic parameters do not reveal another significant mineralogical phase and the association of a sharp distribution of grain size with a single mineral yielded a reliable determination of paleointensity. An interesting difference with respect to the other flows is that the magnetization is carried by titanomagnetite. Despite the fact that this mineral has been reported as being unfavorable in some oceanic samples [*Carlut and Kent*, 2002] the present results indicate that it can provide suitable determinations when this is the unique mineralogical phase provided that it is associated with a very narrow range of grain sizes.

3. Discussion and Conclusion

[11] All these experiments performed on a variety of lava flows share several interesting features. First of all they indicate that determinations of paleointensity have failed in presence of two and more well defined magnetic mineralogical phases. We even observed situations with quite acceptable Arai plots which yielded erroneous interpretations exceeding 13% and up to 23% (Table 1), which may cast some doubts regarding the common criteria of acceptance for paleointensity determinations. The amplitude of these deviations cannot be caused by local effects [*Valet and Soler*, 1999]. The presence of several phases is linked to complex evolution of the minerals. Long cooling favors the oxy-exsolution of a single phase of magnetite whereas quenching preserves titanomagnetite. Subsequent heating in the laboratory reactivates a system that is not closed and produces further oxidation of titanomagnetite into magnetite. The second important point is that a sharp distribution of the unblocking temperatures below Tc (Table 1) is the unique optimal situation to obtain successful paleointensity that deviate by less than 10% from the actual field intensity.

[12] A direct consequence is that thermomagnetic experiments are appropriate to discern the presence of several mineralogical phases, but they do not tell anything about grain size distribution. Unfortunately, hysteresis parameters cannot be of any help on this matter since they always indicate pseudo-single domain grains without any clear relation with the success rate of the paleointensity experiments. The present results and those derived from the 1955 and 1960 Hawaiian flows obtained from very different lava samples have confirmed that the most critical parameter is the evolution of the moment during thermal demagnetization which depends on both grain size distribution and magnetic mineralogy. Consequently, the suitable approach for selecting appropriate specimens is to perform thermal demagnetization on twin specimens from the same samples. We thus propose that samples with most of their magnetization (at least 70%) distributed within a very sharp range of unblocking temperatures prior to the Curie point are ideal candidates for obtaining suitable determinations of absolute paleointensity. This yields a straightforward selection of samples with acceptable Arai plots but also guarantees an accurate and more reliable determination of the field than by solely

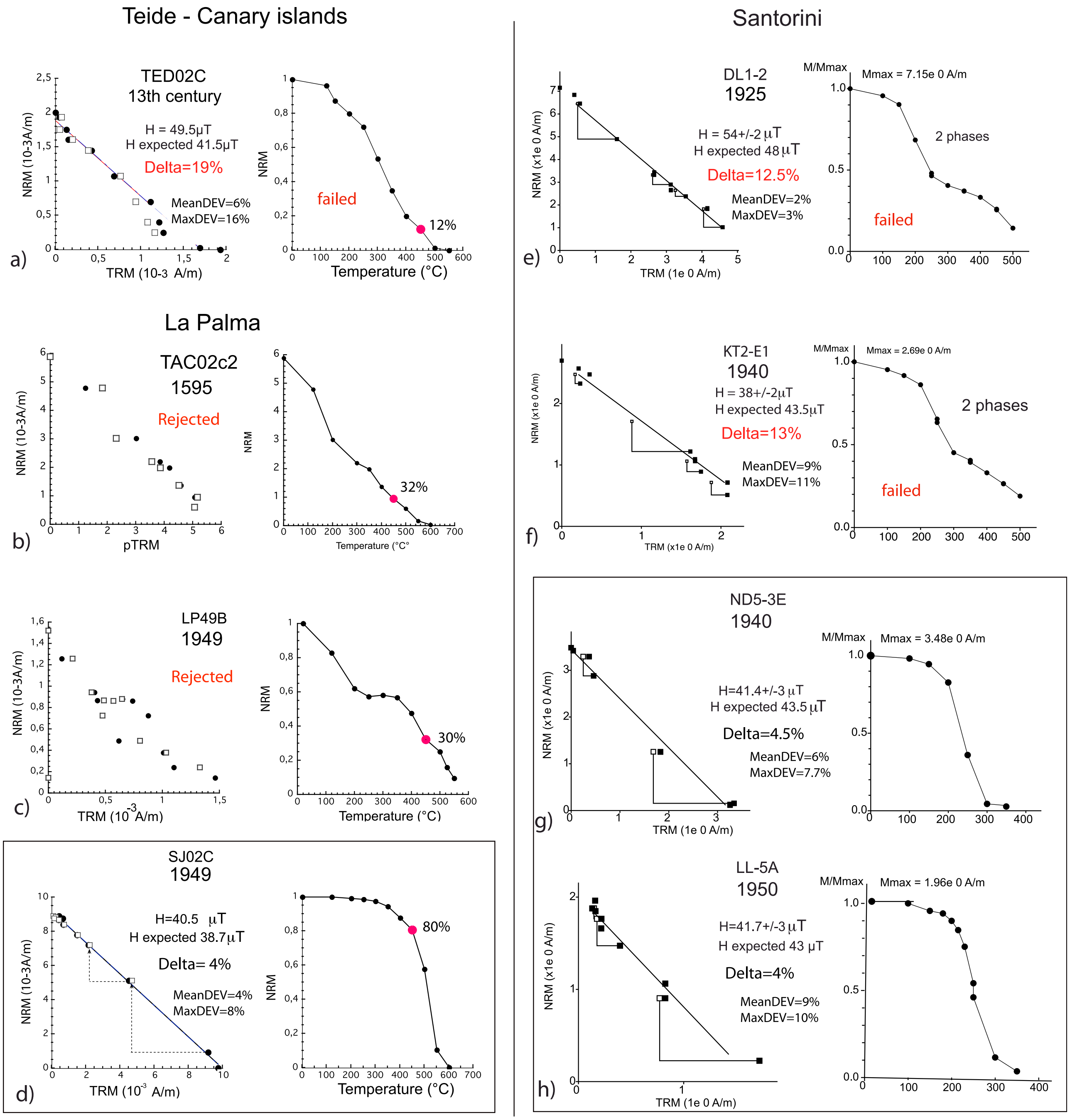

Figure 3. Same as in Figure 2 for samples from (a–d) the Canary islands and (e–h) Santorini.

relying on the quality of the Arai plots. For this reason we would not counsel relaxing the criteria described above. This protocol does not add any constraint because thermal demagnetization provides accurate characteristic directions which can be tested further against those derived from the paleointensity experiments. In fact, this is an efficient approach to document the within flow dispersion of the directions between the two sets of measurements and thus test the fidelity of the vector.

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References

Carlut, J., and D. V. Kent (2002), Grain-size-dependent paleointensity results from very recent mid-oceanic ridge basalts, *J. Geophys. Res.*, *107*(B3), 2049, doi:10.1029/2001JB000439.

Coe, R. S. (1967), Paleointensities of the Earth's magnetic field determined from Tertiary and Quaternary rocks, *J. Geophys. Res.*, *72*, 3247–3262, doi:10.1029/JZ072i012p03247.

Cogné, J. P. (2003), PaleoMac: A Macintosh™ application for treating paleomagnetic data and making plate reconstructions, *Geochem. Geophys. Geosyst.*, *4*(1), 1007, doi:10.1029/2001GC000227.

Cottrell, R. D., and J. A. Tarduno (1999), Geomagnetic paleointensity derived from single plagioclase crystals, *Earth Planet. Sci. Lett.*, *169*, 1–5, doi:10.1016/S0012-821X(99)00068-0.

Herrero-Bervera, E., and J.-P. Valet (2005), Absolute paleointensity and reversal records from the Waianae sequence (Oahu, Hawaii, USA), *Earth Planet. Sci. Lett.*, *234*, 279–296, doi:10.1016/j.epsl.2005.02.032.

Herrero-Bervera, E., and J.-P. Valet (2009), Testing absolute determinations of absolute paleointensity from the 1955 and 1960 Hawaiian flows, *Earth Planet. Sci. Lett.*, *287*, 420–433, doi:10.1016/j.epsl.2009.08.035.

Kissel, C., and C. Laj (2004), Improvements in procedure and paleointensity selection criteria (PICRIT- 03) for Thellier and Thellier determinations: Applications to Hawaiian basaltic long cores, *Phys. Earth Planet. Inter.*, *147*, 155–169, doi:10.1016/j.pepi.2004.06.010.

Pick, T., and L. Tauxe (1993), Submarine basaltic glass: a key to Cretaceous Superchron paleointensities, *Nature*, *366*, 238–242, doi:10.1038/366238a0.

Riisager, P., and J. Riisager (2001), Detecting multidomain magnetic grains in Thellier paleointensity experiments, *Phys. Earth Planet. Inter.*, *125*, 111–117, doi:10.1016/S0031-9201(01)00236-9.

Shcherbakova, V. V., and V. P. Shcherbakov (2000), Properties of partial thermoremanent magnetization in pseudosingle domain and multidomain magnetite grains, *J. Geophys. Res.*, *105*, 767–781, doi:10.1029/1999JB900235.

Selkin, P., and L. Tauxe (2000), Long-term variations in paleointensity, *Philos. Trans. R. Soc. A*, *358*, 1065–1088, doi:10.1098/rsta.2000.0574.

Thellier, E., and O. Thellier (1959), Sur l'intensite du champ magnetique terrestre dans le passe historique et geologique, *Ann. Geophys.*, *15*, 285–376.

Valet, J. P. (2003), Time variations in Geomagnetic intensity, *Rev. Geophys.*, *41*(1), 1004, doi:10.1029/2001RG000104.

Valet, J. P., and V. Soler (1999), Magnetic anomalies of lava fields in the Canary Islands: Possible consequences for paleomagnetic records, *Phys. Earth Planet. Inter.*, *115*, 109–118, doi:10.1016/S0031-9201(99)00071-0.

Valet, J. P., E. Tric, E. Herrero-Bervera, L. Meynadier, and J. P. Lockwood (1998), Absolute paleointensity from Hawaiian lavas younger than 35ka, *Earth Planet. Sci. Lett.*, *161*, 19–32, doi:10.1016/S0012-821X(98)00133-2.

Xu, S., and D. J. Dunlop (2004), Thellier paleointensity theory and experiments for multidomain grains, *J. Geophys. Res.*, *109*, B07103, doi:10.1029/2004JB003024.

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