Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Physics of the Earth and Planetary Interiors 152 (2005) 121–124
PHYSICS OF THE EARTH AND PLANETARY INTERIORS
www.elsevier.com/locate/pepi

Discussion

Reply to Comment on “Historical measurements of the Earth’s magnetic field compared with remanence directions from lava flows in Italy over the last four centuries”, by Tanguy J.C., Principe C., Arrighi S.

Roberto Lanza [a,*], Antonio Meloni [b], Evdokia Tema [a]

[a] *Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso 35, 10125 Torino, Italy*
[b] *Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00144 Rome, Italy*

Received 23 May 2005; accepted 25 May 2005

A comparison of the geomagnetic directions derived from lava flows of Italian volcanoes with those derived from direct historical measurements of the Earth’s magnetic field (Lanza et al., 2005) yielded two main results:

(1) The general agreement between the two data sets already noted by previous authors (Rolph et al., 1987; Incoronato et al., 2002; Tanguy et al., 2003) was better substantiated.
(2) The thermal remanent magnetization (TRM) direction of most flows was shown to deviate from the corresponding historical direction by a small angle θ. In most cases, this angle was larger than the experimental error on the TRM direction as given by the α_{95} semi-angle of confidence of Fisher’s statistics, i.e. $\theta > \alpha_{95}$.

The conclusion drawn from these results was straightforward: a better understanding of the causes of the TRM deviation is required if we are to fully exploit the precision of TRM data from Italian volcanoes when their α_{95} value is less than 2.5–3.0°.

In their comment, Tanguy et al. (2005) clearly state that Lanza et al. (2005) provide “a useful basis of discussion about a controversy remained until now at a latent state”. For further details on this controversy, the unaware reader may refer to Incoronato et al. (2002), Tanguy et al. (2003), Principe et al. (2004) as well as references therein. Because we did not wish to enter into this controversy, we intentionally avoided it in our paper as we do in the present reply. We shall, thus, only limit our discussion to the two other main points raised by Tanguy et al. (2005) and to their considerations regarding methodologies.

The first point concerns our use of the Jackson et al. (2000) global database and modelling, that Tanguy et al. (2005) consider “far from being accurate”. We draw the Italian secular variation (SV) curve using direct measurement values from two different databases: the historical Italian catalogue (Cafarella et al., 1992) for the period 2000 to 1808; the Jackson et al. (2000) global database for the period 1790 to 1600. For this

DOI of original article:10.1016/j.pepi.2005.04.004.
* Corresponding author. Tel.: +39 011 670 5165; fax: +39 011 670 5146.
E-mail address: roberto.lanza@unito.it (R. Lanza).

doi:10.1016/j.pepi.2005.05.001

oldest period, Cafarella et al. (1992) report some seventy declination (*D*) values and only one inclination (*I*) value, that measured in Rome by Athanius Kircher in 1640. In the first version of our paper, we only used the data from Cafarella et al. (1992) and drew the SV curve interpolating the inclination between the 1808 and 1640 measured values. Following the suggestion of a referee (D. Gubbins, personal communication) we did resort to the Jackson et al. (2000) global database and model. This database consists of some 150,000 declination and 20,000 inclination observations between 1510 and 1930 and includes a large amount of data recorded by mariners across the world's oceans (Jonkers, 2003; Jonkers et al., 2003). Summarizing what was written in Lanza et al. (2005).

(1) The global database results do substantially coincide both in *D* and *I* with the Italian historical measurements of the 20th and 19th centuries.
(2) For the 18th and 17th centuries, the difference in the *D* values between the two data sets is less than 1°.
(3) The difference between the *I* values obtained from the two data sets for 1640 is $\Delta I = 2.6^\circ$ (66° measured in Rome, 68.6° from the global database). This discrepancy is comparable to the inclination shallowing of about 2° in the TRM directions obtained from the Etna lava flows and well documented in Fig. 2 of Lanza et al. (2005). This shallowing can result from various causes, including a deflection of the Earth's magnetic field due to the whole volcanic edifice (Lanza et al., 2005), and magnetic refraction (Tanguy et al., 2005).

These results show that for the last two centuries the accuracy of the directions calculated from the Jackson et al. (2000) global database is higher than that of the TRM directions derived from Etna and Vesuvius lava flows. For the 18th and 17th centuries, the possible error in inclination is of the same magnitude as the inclination shallowing. These results show that a careful combination of data collected by sailors around the oceans and good mathematics (Jackson et al., 2000) gives, at least for the italian region, comparable results to those of the best instruments of geo- and archaeo-magnetists. We therefore drew the 18th and 17th centuries part of the SV curve using the results from the Jackson et al. (2000) global database and revised our Table 1 (. . . and we unfortunately forgot to update its heading). Here, the advantage of our approach is that the curve is continuous both in *D* and *I*, and any error in *I* is smoothed over two centuries. It is also worth noting that all the data used to draw the SV curve, reported as D_r, I_r in Table 1 of Lanza et al. (2005), represent the same physical quantity, that is the direction of the Earth's field calculated for a given reference point. The only difference is the way they are calculated. Those after 1800 were derived from a geographical small (Italian) data set, using the simple model of relocation via pole (Noel and Batt, 1990) and time-window average. Those before 1800 were derived from a worldwide data set, using the more sophisticated model of spherical harmonics in space and B splines in time (Jackson et al., 2000).

The second point raised by Tanguy et al. (2005) is that we "mix indistinctly results obtained by means of entirely different methods, with entirely different degrees of confidence and trustworthiness". We have a feeling that these authors missed the sense of our paper. It was not our intention to provide a review of TRM literature data, rather a compilation of data within which authors and original references were always clearly indicated. We then compared this compilation with an independent reference curve derived from a different type of measurements. In our paper, all published TRM directions from Italian volcanic rocks younger than 1631 are brought together and compared to an independent SV curve for the first time. Of course, the comparison criteria are debatable and must be the focus of future improvement. However, it is unlikely that the figures will change significantly. A review would have gone a step further, yet a sound review has to conform to the usual criteria in palaeomagnetism, even more stringent when dealing with archaeomagnetic data. A sound review of archaeomagnetic data from Italian volcanoes faces the problem that in various papers the information needed for an overall quality assessment is obscure or even missing. For the sake of brevity, we only refer to the case of stepwise demagnetization, which is an essential part of any palaeo- and archaeo-magnetic study. Yet, no reference to thermal demagnetization, limited information on alternating field demagnetization, no demagnetization diagrams are shown, for example, in Tanguy et al. (2003). A reviewer may feel uncomfortable when evaluating very precise directions associated to poor rock-magnetic information.

Before discussing methodologies, we note that the reliability of a TRM direction is given by two parameters: precision (α_{95}), which quantifies all the errors throughout the sampling and laboratory procedures; and accuracy, which evaluates the hypothesis that the TRM direction matches that of the ambient field at the time of the rock's emplacement. In the case of historical lava flows, accuracy can be quantified by the deviation angle we called θ, i.e. the angle between the known field direction and the measured TRM direction. It has long been known (Doell and Cox, 1963; Holcomb et al., 1986), and new evidence is continuously put forward (Urrutia-Fucugauchi et al., 2004), that θ is often of the order of some degrees. Thanks to the abundance of written accounts of the eruptions at Etna and Vesuvius, these two volcanoes provide a unique opportunity to analyse volcanic activity documented over four centuries. Comparison of the TRM from 68 flows younger than 1631 with historical direct measurements (Lanza et al., 2005) provides a reasonable estimate of the accuracy to be expected in archaeomagnetic investigation of volcanic rocks and helps in the study of older lava flows, where no direct comparison with the ambient field is possible.

The main concern of Tanguy et al. (2005) is to "separate the wheat from the chaff", where the sieve is a "suitable methodology", and they maintain that the results from core-drilled samples are of lower quality than those obtained by collecting and measuring large hand samples. This last methodology is adequate for archaeomagnetic dating, whereas core-drilling "does not in general allow to reach the high degree of accuracy needed". Their main arguments are that the α_{95} value of the site mean TRM direction from cores is usually higher than that from large samples, and some supposed intrinsic limitations of core-drilling.

In the case of Italian volcanoes, our results show that, because they are smaller than the TRM deviation from the ambient field, α_{95} values less than 2–3° must be handled cautiously, and that a deviation θ of 2.5° may be considered as a reasonable upper threshold for the accuracy. Out of the 68 TRM directions reported in our paper, 23 have a deviation $\theta \leq 2.5°$: 20 of them (i.e. 87%) were derived from core-drilled samples and 3 (13%) from large hand samples. These figures do not change significantly if, instead of our curve, one calculates the deviation using as reference the SV curve anchored to the 1640 direct measurement in Rome, which it seems Tanguy et al. (2005) would consider more reliable. In this case, high-accuracy TRM directions are obtained for 30 flows: 23 of them (77%) sampled by coring and 7 (23%) with large hand samples. The contribution to the high-accuracy directions of the core-drilling method floats, therefore, around 80%, that of large hand samples around 20%. These ratios are fully similar to those with respect to the total number of sampled flows: 55 (i.e. 81%) were sampled by core-drilling (Hoye, 1981; Rolph et al., 1987; Carracedo et al., 1993; Angelino and Incoronato, 1996; Incoronato et al., 2002) and 13 (19%) by collecting large hand samples (Tanguy et al., 2003). The two methodologies concur to high-accuracy TRM directions in the same proportion as they were used in sampling and there is no systematic difference between the standard of accuracy of core-drilling and large hand samples collecting. The fact that some results obtained from cores have a large deviation, i.e. low accuracy, must be thoroughly scrutinized in each particular case and not be ascribed to a peculiar fault of the method, as maintained by Tanguy et al., 2005. These authors do not provide compelling evidence in favour of their contention, but only suggest a variety of possible causes. The above figures, however, show that these causes are not so ubiquitous and do not produce such large errors as claimed by Tanguy et al., 2005. On the other hand, in many cases their effects, if any, can be detected and evaluated using appropriate tools. This is the case of drilling induced magnetization (DIRM), which, unless it persists up to the higher steps of both thermal and alternating field procedures, can be identified and isolated by performing accurate stepwise demagnetization, as shown by Genevey et al. (2002). Most archaeomagnetists using the core-drilling method are in the position to identify unwanted remanence components whatever their source (drilling, viscosity, weathering, hydrothermalism, . . .), as they routinely perform the two types of the above-mentioned stepwise demagnetization.

We conclude with a general consideration on archaeomagnetic investigation of volcanic rocks. It consists of two steps: measurements and interpretation. The first step yields a TRM direction, the second assumes that this direction corresponds to that of the Earth's magnetic field at the time of the rock's emplacement. The precision of the first step is quantified by the α_{95} value associated with the direction, whereas the second remains vague and can only be checked in the case of lava flows of known age and younger than a few centuries. In the early days of rock-magnetism, the main concern was to develop instruments, techniques and procedures suitable to improve the precision of the results. Nowadays, the challenge is to better understand the magnetization processes and to better constrain the assumption that the magnetization direction coincides with that of the external field, which in many cases of volcanic rocks has been proved to be only a first-order approximation.

Acknowledgments

We are indebted to Andy Harris for useful comments and improving the english style. E. Tema acknowledges a fellowship in the frame of the AARCH Network (Archaeomagnetic Applications for the Rescue of Cultural Heritage), Contract EU: HPRN-CT-2002-00219.

References

Angelino, A., Incoronato, A., 1996. Stratigrafia magnetica in aree vulcaniche: esperienze al Vesuvio e all'Etna. 15° Convegno GNGTS, CNR, Roma, pp.13–18.

Cafarella, L., De Santis, A., Meloni, A., 1992. The Historical Italian Geomagnetic Data Catalogue. ING, Rome, 160 pp.

Carracedo, J.C., Principe, C., Rosi, M., Soler, V., 1993. Time correlation by palaeomagnetism of the 1631 eruption of Mount Vesuvius. Volcanological and volcanic hazard implications. J. Volcanol. Geotherm. Res. 58, 203–209.

Doell, R.R., Cox, A.V., 1963. The accuracy of the paleomagnetic method as evaluated from historic Hawaiian lava flows. J. Geophys. Res. 68, 1997–2009.

Genevey, A., Galley, Y., Boudon, G., 2002. Secular variation study from non-welded pyroclastic deposits from Montagne Pelée volcano, Martinique (West Indies). Earth Planet. Sci. Lett. 201, 369–382.

Holcomb, R., Champion, D., McWilliams, M., 1986. Dating recent Hawaiian lava flows using paleomagnetic secular variation. Geol. Soc. Am. Bull. 97, 829–839.

Hoye, G.S., 1981. Archaeomagnetic secular variation record of Mount Vesuvius. Nature 291, 216–218.

Incoronato, A., Angelino, A., Romano, R., Ferrante, A., Sauna, R., Vanacore, G., Vecchione, C., 2002. Retrieving geomagnetic secular variations from lava flows: evidence from Mounts Arso, Etna and Vesuvius (southern Italy). Geophys. J. Int. 149, 724–730.

Jackson, A., Jonkers, A.R.T., Walker, M.R., 2000. Four centuries of geomagnetic secular variation from historical records. Phil. Trans. R. Soc. London Ser. A 358, 957–990.

Jonkers, A.R.T., 2003. Earth's Magnetism in the Age of Sail. John Hopkins University Press, Baltimore, 300 pp.

Jonkers, A.R.T., Jackson, A., Murray, A., 2003. Four centuries of geomagnetic data from historical records. Rev. Geophys. 41, doi:10.10129/2002RG000115.

Lanza, R., Meloni, A., Tema, E., 2005. Historical measurements of the Earth's magnetic field compared with remanence directions from lava flows in Italy over the last four centuries. Phys. Earth Planet. Inter. 148, 97–107.

Noel, M., Batt, C.M., 1990. A method for correcting geographically separated remanence directions for the purpose of archeomagnetic dating. Geophys. J. Int. 102, 753–756.

Principe, C., Tanguy, J.C., Arrighi, S., Paiotti, A., Le Goff, M., Zoppi, U., 2004. Chronology of Vesuvius' activity from AD 79 to 1631 based on archeomagnetism of lavas and historical sources. Bull. Volcanol. 66, 703–724.

Rolph, T.C., Shaw, J., Guest, J.E., 1987. Geomagnetic field variations as a dating tool: application to Sicilian lavas. J. Archaeological Sci. 14, 215–225.

Tanguy, J.C., Le Goff, M., Principe, C., Arrighi, S., Chillemi, V., Paiotti, A., La Delfa, S., Patanè, G., 2003. Archeomagnetic dating of Mediterranean volcanics of the last 2100 years: validity and limits. Earth Planet. Sci. Lett. 211, 111–124.

Tanguy, J.C., Principe, C., Arrighi, S., 2005. Comment on "Historical measurements of the Earth's magnetic field compared with remanence directions from lava flows in Italy over the last four centuries". In: Lanza, R., Meloni, A., Tema, E. (Eds.), Phys Earth Planet. Inter. 152, 116–120.

Urrutia-Fucugauchi, J., Alva-Valdivia, L.M., Goguitchaichvili, A., Rivas, M.L., Morales, J., 2004. Palaeomagnetic, rock-magnetic and microscopy studies of historic lava flows from Paricutin volcano, Mexico: implications for the deflection of palaeomagnetic directions. Geophys. J. Int. 156, 431–442.