Bull Volcanol (2005) 00
DOI 10.1007/s00445-005-0030-9

COMMENT

R. Lanza · E. Zanella

Comments on "Chronology of Vesuvius' activity from A.D. 79 to 1631 based on archeomagnetism of lavas and historical sources" by C. Principe et al., Bull Volcanol

Received: 10 December 2004 / Accepted: 2 September 2005

Abstract This paper shortly reviews the various factors which concur to the accuracy of archaeomagnetic dating of volcanic rocks: the error on the laboratory procedure; the assumption that the archaeomagnetic direction matches the paleofield direction present when the rocks formed; the limits of the model used for dating. The very small "analytical error" claimed in the paper by Principe et al. (2004) mainly depends on their focussing on the precision of laboratory procedures, disregarding the other sources of errors, which in fact are known in the literature to be far from negligible.

Keywords Archaeomagnetic dating · Lava · Accuracy

Introduction

In their recent paper "Chronology of Vesuvius' activity from A.D. 79 to 1631 based on archeomagnetism of lavas and historical sources", Principe et al. (2004) completed a chronological reconstruction of volcanic activity at Vesuvius (Italy) using the remanence direction derived from lavas as an archaeomagnetic dating tool. Obtaining a detailed, dated record or chronology of eruptions is a valuable goal in volcanology, as it can, for example, improve scientific knowledge about a volcanic system and provide an indication of typical repose periods, and thus help in the assessment of volcanic hazard.

However, we draw attention to a methodological aspect of such an analysis which must be kept in mind if such data are to be used and interpreted in an effective manner: this issue is that of error and uncertainty. Here, Principe et al. (2004) state in their conclusions that the "analytical error" of the method is generally less than ±40 years. In addition, on presenting their results in their Table 7, the authors stated that "it has been possible to obtain age determinations within ±40 years, with a higher precision of ±20 years in the best cases". To give an error in such a precise way, where a plus or a minus sign is quoted with a numerical value, implies that there is a definite procedure for its quantitative evaluation so that, given the same experimental data, all studies would obtain the same ± figure. This, however, is not the case in archaeomagnetic dating of lavas.

Editorial responsibility: J. McPhie

R. Lanza (✉) · E. Zanella
Dipartimento di Scienze della Terra,
Via Valperga Caluso 35,
10125 Torino, Italy
e-mail: roberto.lanza@unito.it
Tel.: +39-011-6705165
Fax: +39-011-6705146

Archaeomagnetic direction: error and assumptions

The archaeomagnetic practice is to collect *n* samples from a site, measure their remanence, identify their characteristic remanent magnetization (ChRM), calculate a site mean ChRM direction and to use Fisher's statistics for evaluating its dispersion. Fisher's semi-angle of confidence (α_{95}) is defined by half the apical angle of the cone which is centered on the mean direction and contains the true, unknown direction at a 95% probability level. The α_{95} value is the whole of the errors encountered as part of completing the measurement routine and may be considered as the analytical error affecting the mean ChRM direction of a site.

The main point about archaeomagnetic directions, however, is that if they are to be used for dating, it has to be assumed that they correspond to the paleofield direction at the site from which the samples came. Many causes may be envisaged for misalignment of the ChRM recorded by volcanic rocks with respect to the paleofield present when they formed. We can distinguish three types of processes:

1. Those internal to the lava flow such as magnetic anisotropy and field gradient due to different cooling rates between the various parts of the flow. Here, a detailed examination throughout the whole thickness of a

lava flow unit usually shows large variations of all magnetic parameters, including direction (e.g., Rolph 1997).

2. Those related to the paleofield, the direction of which may have suffered local disturbance due to the terrain effect of the neighboring magnetized outcrops (Baag et al. 1995; Valet and Soler 1999; Knudsen et al. 2003; Tanguy and LeGoff 2004) or have been regionally deflected by the magnetic anomaly caused by the whole volcanic edifice. These effects are well known to geomagnetists, who avoid measuring in volcanic regions.
3. Mechanical factors such as entrainment by the flow of already cooled blocks, tilting of blocks overlying not fully consolidated lava, tectonic tilting due to faults, deformation of the volcanic edifice, etc.

No laboratory technique can prove the alignment of the ChRM to the paleofield. However, one can take precautions in order to reasonably minimize the errors related to the above-mentioned causes. Here 'minimize' does not mean cancel out where the possible occurrence of a systematic misalignment error (Δ_{field}) must thus be taken into account.

Adding α_{95} and Δ_{field} now gives the total error (Δ_{dir}), which affects a site's mean archaeomagnetic direction. It cannot be unequivocally determined, because only α_{95} can be calculated, whereas Δ_{field} derives from having made non-verifiable assumptions. A sound uncertainty analysis is given by Holcomb et al. (1986) in the case of Hawaiian lavas. They estimated the angular standard deviation (ψ_{63}) due to (1) experimental procedure ($\psi=1.5^\circ$), (2) local anomalies ($\psi=1.0$–2.2°) and (3) post-cooling deformation ($\psi=0$–6.0°). They thus evaluated the total dispersion as $\psi=2.9^\circ$. The results from Hawaii cannot be directly extrapolated to Vesuvius, because the two volcanic systems are entirely different. However, the Hawaiian case does show, beyond any doubt, that accurate analysis of uncertainties is a prerequisite for the accurate archaeomagnetic dating of lavas. However, the possible sources of uncertainty are neither discussed nor mentioned in Principe et al. (2004).

Because magnetic properties are not homogenous within a geological unit and the possible causes for ChRM deviation vary from site to site, paleomagnetists resort to statistics. A geological unit is, therefore, sampled at many sites and the site mean ChRM directions are averaged to give the paleomagnetic direction for the unit. A huge amount of literature shows that the method works, and in database compilation the number of sampled sites is a basic standard by which one can assess the quality of a result. The problem with lavas such as those of Vesuvius is that their usually small extent and the typically limited outcrop conditions make sampling at multiple sites difficult. Most data in the previous literature on the Italian volcanoes, as well as in Principe et al. (2004), are thus derived from a single site for each separate lava-flow unit. Thus, the possible occurrence of a systematic deviation cannot be ruled out.

Small ChRM α_{95} values around 1°, like those in Principe et al. (2004), do not imply that the archaeomagnetic direction they refer to has a similar accuracy and cannot be fully exploited in interpretation unless the possible sources of errors are thoroughly examined. Analysis of historical lava-flow units has revealed many cases where the ChRM direction deviated from the Earth's field. In the case of Italian volcanoes, a disagreement of a few degrees between the secular variation (SV) curve derived from historical direct measurements of the Earth's field and the lava-flow unit's remanence directions has long been pointed out in the literature (Rolph et al. 1987; Incoronato et al. 2002; Tanguy et al. 2003) and has been shown to occur for practically all the post-1631 lavas; the ChRM direction of which can be checked against historical direct measurements (Lanza et al. 2005).

Archaeomagnetic dating: model and approximation

Archaeomagnetic dating is not absolute because the direction to be dated always has to be compared to a reference curve. Besides the error on direction (Δ_{dir}), the age uncertainty depends on the robustness of the curve and the methods used for comparison. In Europe, detailed archaeomagnetic curves have been so far obtained for Bulgaria, France and Great Britain. No reference curve is available for Italy. Because at any given time the intensity and direction of the Earth's magnetic field varies from one point to another across the Earth's surface, the use of a reference curve is only possible through a model, which should represent the field over the region from which the archaeomagnetic data comes. In archaeomagnetism, directions from different points are usually compared using the relocation via pole method (Noel and Batt 1990). This method takes into account only the first terms of the spherical harmonic series which represents the Earth's field. It is approximate and the relocation error (Δ_{rel}) that it introduces becomes higher as the between-site distance increases. Comparison among modern observatory data gives an order of magnitude estimate on the Δ_{rel} values (Table 1). In addition, there is no reason why Δ_{rel} should be constant in time over large distances. Analysis of historical data suggests that Δ_{rel} between Rome and Paris varied in the range of 1°–3° during the last centuries (Lanza et al. 2005).

Table 1 Relocation error between the Italian geomagnetic observatory, L'Aquila, and three European geomagnetic observatories at 1981.5. Symbols: D and I measured direction; D_r and I_r L'Aquila direction relocated to the other observatories; Δ_{rel} relocation error

Country, observatory	D, I (°) measured	D_r, I_r (°) relocated	Δ_{rel} (°)
Italy: L'Aquila	0.0, 58.4	//	//
Bulgaria: Panagyurishte	1.9, 59.2	0.8, 58.6	0.9
France: Chambon-la-Forêt	355.8, 63.7	359.1, 63.3	1.5
Germany: Fürstenfeldbruck	359.1, 63.9	359.8, 63.3	0.7

The actual reference curve used for dating is not clearly indicated in Principe et al. (2004), where they first refer to the Tanguy et al. (1999) Mount Etna and the French (Bucur 1994) SV curves, before writing "... that *this* curve can be used confidently for dating Vesuvian lava samples (see also Tanguy et al. 2003)". For the period AD 800–1200, to which the lavas in Principe et al. (2004) are attributed, the robust French curve relies on some 40 archaeologically dated points, whereas the Mount Etna curve only consists of nine points whose traditional literature age is "presumed" (Tanguy et al. 1999). These nine lavas have therefore been assigned a new magnetic age on the grounds of comparison with the French SV curve (Tanguy et al. 2003). In conclusion, whichever curve Principe et al. (2004) used, it is clear that their time frame is given by the French curve. This entails a Δ_{rel} of some 1–3°, which is neither taken into account in Principe et al. (2004) nor in Tanguy et al. (2003).

As far as the procedure for comparison of a single lava flow unit direction with the reference curve is concerned, Principe et al. (2004) only quoted Tanguy et al. (2003), so that one can conclude that they used the technique that LeGoff et al. (2002) devised for the French archaeomagnetic curve. This technique takes a statistical approach towards giving an age interval and an associated probability level which quantifies the agreement between the direction to be dated and the reference curve, and is thus used to evaluate the reliability of the dating. The probability level is a basic parameter of the procedure; yet, its values are neither given in Principe et al. (2004) nor in Tanguy et al. (2003).

Conclusion

Principe et al. (2004) disregard the Δ_{dir} and Δ_{rel} errors whose sources we have outlined above. Both errors may be of the same order of magnitude as α_{95} and will affect the age interval and the associated probability level. The analytical error of archaeomagnetic data is only related to the mean ChRM directions that are the final result of the laboratory measurements. Archaeomagnetic dating introduces further errors due to the limits of the assumptions and the approximation of the models. Precision in ChRM determination alone cannot be transformed to accuracy in dating, especially for regions deprived of a sound reference curve, as in Italy. Discussing the errors is much easier than finding a way to take them into account, yet passing them over is not a solution. The plus-or-minus "analytical errors" in Principe et al. (2004) are age uncertainties to be considered cautiously. It must be kept in mind that favoring a more conservative approach and more stringent criteria inevitably results in larger error values. Similarity in age is a strong argument in assigning different lava flow units to a single eruption; thus, the evaluation of age uncertainty is of paramount importance in modeling the past activity of volcanoes.

Acknowledgments We are indebted to Andy Harris for useful comments and improving the English style.

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