Comment on "Recent eruptive history of Stromboli (Aeolian Islands, Italy) determined from high-accuracy archeomagnetic dating" by S. Arrighi et al.

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1. Introduction

[1] *Arrighi et al.* [2004] (hereinafter referred to as AR2004) recently reported paleomagnetic directions gathered from Stromboli volcano by using the unconventional "large sample method" (LSM). These directions are partly different and have smaller confidence cones than those previously reported by *Speranza et al.* [2004] (hereinafter referred to as SP2004) for the same spatter lavas by using the traditional (core-drilling and systematic stepwise demagnetization) paleomagnetic technique. Hence AR2004 conclude that "traditional paleomagnetic sampling cannot yield sufficient precision", and is therefore unsuitable to study the paleosecular variation of the geomagnetic field recorded in volcanics, and to use it as a dating tool. Here we contend that the laboratory procedures and analysis methods employed by AR2004 yield a fictitious improvement in statistical uncertainty. We conclude that the traditional paleomagnetic techniques provide a more realistic estimate of archeomagnetic dating and related uncertainties.

2. Laboratory Procedures

[2] AR2004 do not show demagnetization diagrams and do not explicitly indicate how they evaluated paleomagnetic directions from each sample. However, some more information is given by *Tanguy et al.* [2003] (hereinafter referred to as TAN2003), who report on the LSM applied to other active Italian volcanoes, and by *Arrighi* [2004]. TAN2003 state that "the retained declination and inclination were determined after the last alternating field (AF) demagnetization", that is at 15–20 mT peak AF. This is the so-called "blanket" demagnetization treatment. It has been demonstrated that paleomagnetic data obtained in lava flows by incomplete magnetic cleaning, such as those obtained in the '60s–'70s, lead to significant misconceptions about the nature of the average paleomagnetic field during geological past [e.g., *McElhinny*, 2004].

[3] Moreover, the blanket method assumes magnetic uniformity throughout the rock. However, AR2004 did not report data about the magnetic mineralogy of their samples. On the other hand, SP2004 showed that Stromboli spatter are characterized by different coercivity spectra, likely due to a high degree of oxidation of such thin volcanics, and that often their remanence direction keeps changing up to ca. 60 mT peak AF. Therefore, the direction after 15–20 mT AF may be far from the characteristic remanent magnetization (ChRM) direction. Both TAN2003 and *Arrighi* [2004] (and we suppose the same holds for AR2004) state that they preferred to stop the AF cleaning because of the low resistance of thermoremanent magnetization with respect to the AF demagnetization. This is contradicted by the experimental evidence reported by SP2004, who isolated a ChRM in the 60–150 mT peak AF range (see SP2004, Figure 2).

[4] The data used by AR2004 to provide "high-accuracy archeomagnetic dating" have been apparently obtained with incomplete cleaning procedures, not analysed by principal component analysis (PCA) and not supported by detailed rock magnetic investigations. We think the data reported by SP2004 represent better the paleomagnetism of Stromboli spatter lavas, since they rely on full stepwise demagnetization, determination of a ChRM by PCA at AF peaks higher than those applied by AR2004, and investigation of the magnetic mineralogy.

3. Statistical Treatment and Precision of "Archeomagnetic Dating"

[5] Unless differently stated, in paleomagnetism the evaluation of the site-mean direction is made by discarding samples showing unreliable demagnetization diagrams. But AR2004 applied a blanket treatment to their samples, so that this criterion of sample selection could not be applied. Nevertheless, AR2004 discarded many (18 out of 70) of their spatter lava samples. Their small α_{95} values (1.0° to 1.7°) constitute the rationale for the high-precision claimed for their LSM method. They state that a α_{95} value of 2° "is the upper limit we accept in our rather stringent data selection procedure". Yet, their low α_{95} values may result from rejection of samples, for which no explanation is given. AR2004 stress the comparison of their site S1 to site Str04 of SP2004. They claim the two sites are "common", but provided a significantly different paleomagnetic direction and reduced statistical uncertainty for S1 (α_{95} = 1.0° against α_{95} = 4.3° for Str04). However, AR2004 discarded 5 out of the 17 samples from site S1. We note

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that the demagnetization diagrams reported by *Arrighi* [2004] for two pilot samples from site S1 show stable paleomagnetic declinations of ~3° and ~7°, consistent with the mean declination of site Str04 (6.1°), but inconsistent with the mean declination of site S1 as reported by AR2004 (−4.7°). *Arrighi* [2004] also shows 7 demagnetisation diagrams for pilot samples from sites S2, S3, and S9, all pointing to positive declination values. Nevertheless, AR2004 reported mean declinations between −4.1° and −5.0° for these sites.

[6] Even if the small α_{95} values from AR2004 derive from a justified rejection of "outliers", the question arises as to whether such values have a physical meaning, i.e. whether the confidence cones contain (with a 95% probability) the direction of the geomagnetic field at the time of cooling. This assumption is crucial for pushing the use of paleomagnetism as a "high-accuracy" dating tool in volcanic rocks. This hypothesis cannot be tested at Stromboli, because the scattered spatter sampled are not historically dated, so that the paleomagnetic and the expected field directions cannot be compared. Conversely, such comparison was feasible for historical lavas from Etna [*Lanza et al.*, 2005] (hereinafter referred to as LAN2005). Here eruption dates are precisely known, and the geomagnetic field is defined from historical measurements. LAN2005 show that most of the remanence directions defined by an $\alpha_{95} < 2.5°$ deviate significantly from the coeval expected field direction, by an angle larger than the paleomagnetic α_{95} value. This discrepancy is observed for both the classical paleomagnetic and the LSM method, independently by the fact that the latter yielded smaller α_{95} values. Consequently, high-precision determination of paleomagnetic directions in volcanic rocks (i.e. $\alpha_{95} < 2°$) definitely does not translate into an equivalent precision on dating, as AR2004 claim for Stromboli volcanics. If not artificially obtained by arbitrary discarding of samples with "anomalous" directions, very low α_{95} values (ca. 1°) may result as an effect of undersampling of a volcanic rock with variable (paleo)magnetic properties. In fact, local perturbations of the geomagnetic field caused by the volcano and by the cooling lava flow, heterogeneities in the magnetic mineralogy, magnetic anisotropy and post-cooling movement of the flow unit induce within-flow variation and also affect the fidelity of the paleointensity record [e.g., *Biggin et al.*, 2003].

4. Spatter Ages

[7] AR2004 question the finding of SP2004 that the XX century eruptions spread spatter over most of the western Stromboli flank. They suggest conversely that such spatter are mostly distributed on the northern flank. But AR2004 found the same number of spatter datable to the XX century (one) on both the western (S8) and the northern (S1) flanks. AR2004 also question the statement from SP2004 that "no paroxysms are inferred to have occurred before 1400 AD", since they refer two spatter to 550 AD. Yet SP2004 considered only reference geomagnetic data after 600 AD, following *Rosi et al.* [2000], who state that volcanic activity able to produce spatter occurred not before the III to the VII centuries AD. If we consider also possible spatter eruption dates older than 600 AD, then there are at least four sites from SP2004 (Spa07, Spa10, Spa15, Str04) yielding a direction similar to the two 550 AD spatter sites from AR2004. Therefore, making this assumption, these four spatter sites from SP2004 are compatible with a VII-VI century AD age as well. AR2004 also compare the directions (and the inferred ages) of some spatter sampled by them to "close" spatter studied by SP2004, and underline their difference. But comparing directions from proximal spatter is meaningless, since it is impossible to tie them to the same eruption.

5. Reference Curves

[8] AR2004 state that "the reference curve used by SP2004 is not clearly defined, does not show any reference point and does not have the low level of uncertainty that is required for accurate dating". The first two statements are not true, since the curve is unequivocal, and the dates shown represent the reference points. The uncertainty of the reference curve was not evaluated (nor addressed) by SP2004. On the other hand, we point out that the low uncertainty of the "south Italian volcanic reference curve" created by TAN2003 and used by AR2004 may not be real, given the errors of field recording documented by LAN2005 at Etna for all paleomagnetic results. Moreover, for ages older than ca. 1300 AD, TAN2003 assign a new "magnetic age" to Italian lava flows previously undated or differently dated, relying on the comparison with the relocated French archeomagnetic curve. Then, they (and AR2004) consider such indirectly dated (or re-dated) remanence directions as independent reference points for dating other volcanic rocks (as those from Stromboli): an obvious circular reasoning.

[9] When relocating the French archeomagnetic curve, AR2004 disregard the westward drift of the nondipole field for the last 2000 yrs (0.38°/yr according to *Merrill et al.* [1996]), introducing an age error of some 30–40 yrs for similar trends in geomagnetic elements, considering the longitude differences between Stromboli and France. Yet, 30–40 yrs is the precision that AR2004 claim for archeomagnetic dating at Stromboli. Finally, AR2004 ignore the direct measurements of the geomagnetic field done in Italy since 1640 AD [*Cafarella et al.*, 1992].

6. Conclusions

[10] The LSM used by AR2004 at Stromboli is different from the laboratory standards routinely adopted by the paleomagnetic community. We point out that their low α_{95} values likely arise from arbitrary rejection of data and/or undersampling, and are smaller than the angle which may often exist between the paleomagnetic direction and the coeval direction of the geomagnetic field. This bias may also affect the whole "south Italian volcanic reference curve" used by AR2004. We conclude that the level of high-resolution archeomagnetic dating claimed by AR2004 is not realistic. Uncertainties of the order of 2–4° represent better the nature of the paleomagnetic recording process in volcanic rocks.

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