Geomagnetic Secular Variation in the Canary Islands: paleomagnetic data, models and application to paleomagnetic dating

Variación Secular Geomagnética en las Islas Canarias: datos paleomagnéticos, modelos y aplicación a la datación paleomagnética

Francisco Javier PAVÓN CARRASCO[1], Víctor VILLASANTE MARCOS[2]

[1] Dpto. Geofísica y Meteorología
F. CC. Físicas, Universidad Complutense de Madrid
flpavon@fis.ucm.es

[2] Observatorio Geofísico Central
Instituto Geográfico Nacional
vvillasante@fomento.es

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RESUMEN
Este trabajo explora la posibilidad de usar la variación secular del campo geomagnético para la datación paleomagnética de coladas recientes en las Islas Canarias, lo que podría contribuir al conocimiento de la evolución reciente del volcanismo canario y sus riesgos asociados. Se ha evaluado la variación secular en las Islas Canarias durante los últimos 400 años a partir de datos paleomagnéticos ya publicados de coladas de lava históricas bien conocidas (Soler et al., 1984). Se presenta una curva de variación paleosecular (PSVC) regional, calculada mediante la estadística bayesiana, y se compara con modelos geomagnéticos globales construidos a partir de observaciones históricas e instrumentales de los últimos cuatro siglos (modelo GUFM1, Jackson et al., 2000; IGRF-11, IAGA, 2009) y de datos arqueomagnéticos y paleomagnéticos de los últimos 3 ka (modelo ARCH3K.1, Korte et al., 2009). El modelo ARCH3K.1 junto con el modelo regional europeo SCHA.DIF.3K (Pavón-Carrasco et al., 2009) relocalizado a Canarias, han sido usados para obtener edades paleomagnéticas de las coladas históricas, que se han comparado con las edades históricas para estimar el error esperable para coladas más antiguas que se daten mediante este procedimiento. Se propone una datación paleomagnética para dos coladas más antiguas (Lavas Negras del Teide, Tenerife; Montaña Quemada, La Palma) y se compara con las edades radiométricas publicadas.
Palabras clave: variación paleosecular geomagnética; PSVC; coladas de lava; Islas Canarias; datación paleomagnética.

ABSTRACT
This work explores the reasonability of using the Geomagnetic Secular Variation to date recent lava flows in the Canary Islands, which could contribute to improve the knowledge about the recent vol-

canic evolution of the Canary Islands and the corresponding volcanic hazards. An evaluation of the secular variation in the Canary Islands during the last 400 years is performed with published paleomagnetic data from well known historical lava flows (Soler et al., 1984). A regional Paleosecular Variation Curve (PSVC) has been calculated using the Bayesian statistics and has been compared with global geomagnetic models constructed from historical and instrumental geomagnetic observations for the last four centuries (GUFM1 model, Jackson et al., 2000; IGRF-11, IAGA, 2009) and from archeomagnetic and paleomagnetic data for the last 3 ka (ARCH3K.1 model, Korte et al., 2009). The global ARCH3K.1 model and the regional European SCHA.DIF.3K model (Pavón-Carrasco et al., 2009) relocated to the Canary Islands have been used to obtain paleomagnetic ages for the historical lava flows, which have been compared with historical ages to estimate the error that could be expected to affect any paleomagnetic ages obtained by this procedure in older lava flows. A paleomagnetic dating of two older lava-flows (Lavas Negras del Teide, Tenerife; Montaña Quemada, La Palma) is proposed and compared with radiometric ages.
Key words: geomagnetic paleosecular variation; PSVC; lava-flows; Canary Islands; paleomagnetic dating.

SUMMARY: 1. Introduction. 2. Data and Methodology. 3. Results. 4. Conclusions. 5. Acknowledgements. 6. References

1. INTRODUCTION

Various K-Ar and Ar-Ar dates have been determined for old lava-flows in the Canary Islands, leading to a general picture of their long-term temporal evolution and volcanic history (see for example Guillou et al., 1996; Guillou et al., 2004a, 2004b; Paris et al., 2005; a general picture of the Canary Islands temporal evolution can be found in Vera, 2004). In contrast, very few reliable dates of recent (few thousands of years) volcanic events are found in the scientific literature (Carracedo et al., 2007; Rodríguez-González et al., 2009). Almost all of them were obtained by radiocarbon dating of burnt organic matter (charcoal) trapped between different lava-flows, not by direct dating of volcanic products. This could raise doubts in some cases. There is also a published Ar-Ar dating of a recent lava flow (Quidelleur et al., 2001), corresponding to the last eruption from the Teide summit ("Lavas Negras del Teide"). The absence of a comprehensive volcanic chronology for the last thousands of years is a serious problem regarding the study of the recent volcanic history of the islands, the statistical assessment of spatial-temporal volcanic patterns and their hazard implications. This is especially serious when dealing with complex, evolved and historically active stratovolcanoes of which no eruptions have been monitored during instrumental era, but whose temporal evolution may be governed by non-random physical processes. This is the case of the central volcanic complex of Tenerife Island, dominated by Teide and Pico Viejo volcanoes. Any dating tool contributing information on the recent volcanic history of the Canary Islands, and in particular of Tenerife, would be welcome. Such might be the case of Paleomagnetism applied to the study of the secular variation of the geomagnetic field. This tool has been already applied to other volcanic regions (see for example Tanguy et al., 2003; Speranza et al., 2008; Tanguy et al., 2009), although it presents its own problems that have to be properly considered (Baag et al., 1995; Knudsen et al., 2003; Lanza et al., 2005). Usually, archeomagnetic data retrieved from heated archeological structures (ceramic or metallurgical kilns, heating chambers of baths, burnt houses and walls, ancient fire hearts, etc.) are used to unravel the geomagnetic field behaviour during the last thousands of years, constructing the corresponding Paleo Secular Variation Curve (PSVC). These studies are by necessity regional, because of the non-dipolar character of the geomagnetic field, and therefore different curves need to be constructed for different regions. In addition to archeomagnetic data, paleomagnetic directions obtained from well dated lava flows and lacustrine sediment cores can be incorporated into the PSVC. Once the PSVC for a particular region is constructed, it can be used to date new lava flows by means of paleomagnetism alone. Additionally, PSVCs and well dated paleomagnetic directions are fundamental to construct regional and global models of the geomagnetic field temporal behaviour and to investigate the physical processes behind it.

In the Canary Islands there are very few well dated recent paleomagnetic directions and no archeomagnetic information at all. Most paleomagnetic studies have been devoted to old lava flows, especially to investigate the Matuyama-Brunhes transition (Valet et al., 1999; Quidelleur et al., 2003), different old geomagnetic field excursions (Quidelleur&Valet 1996; Quidelleur et al., 1999; Quidelleur et al., 2002; Singer et al., 2002), paleosecular variation regimes during the Brunhes chron for ages older than 134 ka (Széréméta et al., 1999) and to construct magnetostratigraphic columns of ancient volcanic series (Carracedo 1979; Guillou et al., 1996; Guillou et al, 2004a, b; Paris et al., 2005; Leonhardt&Soffel, 2006). An exception to this are the works of Soler et al. (1984) and Quidelleur et al. (2001), in which most of the historical lava flows erupted after the islands were conquered and (re)populated by the Spanish and whose dates and extension are well established on historical grounds, were studied. In this paper we use these paleomagnetic data from historical flows to construct a first PSVC of geomagnetic field temporal evolution in the Canary Islands, restricted to the last 400 years. We also explore the possibility of using both global (*in situ*) and European regional (relocated to the Canary Islands) geomagnetic models for the last thousands of years to obtain paleomagnetic ages of recent lava-flows, and we estimate the probable errors that will arise when using this procedure.

2. DATA AND METHODOLOGY

Data

The paleomagnetic data used in our modelling were first published by Soler et al. (1984) and later by Quidelleur et al. (2001). They refer to 13 different historical lava flows extruded between 1585 (Tahuya) and 1971 (Teneguia) in the islands of Lanzarote, La Palma and Tenerife (see Figure 1 for location, dates and paleomagnetic directions).

In Table 1, numerical values of the directional angles (D, I), statistical parameters (k, α_{95}) and number of samples (N) used for the calculation of mean paleomagnetic directions are shown. Although the number of samples is low in some cases, the α_{95} confidence angles are small, and therefore the statistical quality of the data seems in principle acceptable. The paleomagnetic directions were calculated mainly from AF demagnetization plots, after discarding soft secondary magnetic components. One potentially serious problem with the data is that Soler et al. (1984) sampled just one site per lava flow. As several works have shown (Baag et al., 1995; Valet&Soler, 1999; Knudsen et al., 2003; Tanguy&Le Goff, 2004), significant spatial magnetic anomalies are created by the topography and the remanent/induced magnetizations of previous lava flows which can affect the magnetic field direction preserved in younger flows emplaced over them. Sampling just one site per flow does not allow accounting for this effect, which can be mitigated only if several separated sites per flow are sampled and averaged. Therefore, the paleomagnetic directions reported by Soler et al. (1984) could in principle reflect not only the geomagnetic secular variation, but also the disturbing effect of older lava flows. An additional potential problem is the inclination shallowing that has been observed to affect the thermoremanent magnetization (TRM) in lava flows from other places (Lanza et al., 2005). These error sources can potentially affect the paleomagnetic directions despite their good apparent statistical quality.

Two additional lava flows (Lavas Negras del Teide and Montaña Quemada, in Tenerife and La Palma respectively) which were not included in Figure 1 do appear in Table 1. These two lava flows extruded previously to the historical period and their dates have been obtained by ^{14}C and Ar-Ar dating (Hernandez-Pacheco&Valls, 1982; Quidelleur et al., 2001; Carracedo et al., 2007). Their paleomagnetic directions have not been used to calculate our PSVC, because of the significant dating uncertainties (comparing to historical flows) and also because the Lavas Negras flow seems to be 3-5 centuries older than the 400 year period for which historical lava flows allow a better temporal resolution. We have preferred to include in our model just the last 400 years and use Lavas Negras and Montaña Quemada data to perform an independent paleomagnetic dating with both global and European regional secular variation models (*in situ* and relocated to the Canary Islands, respectively).

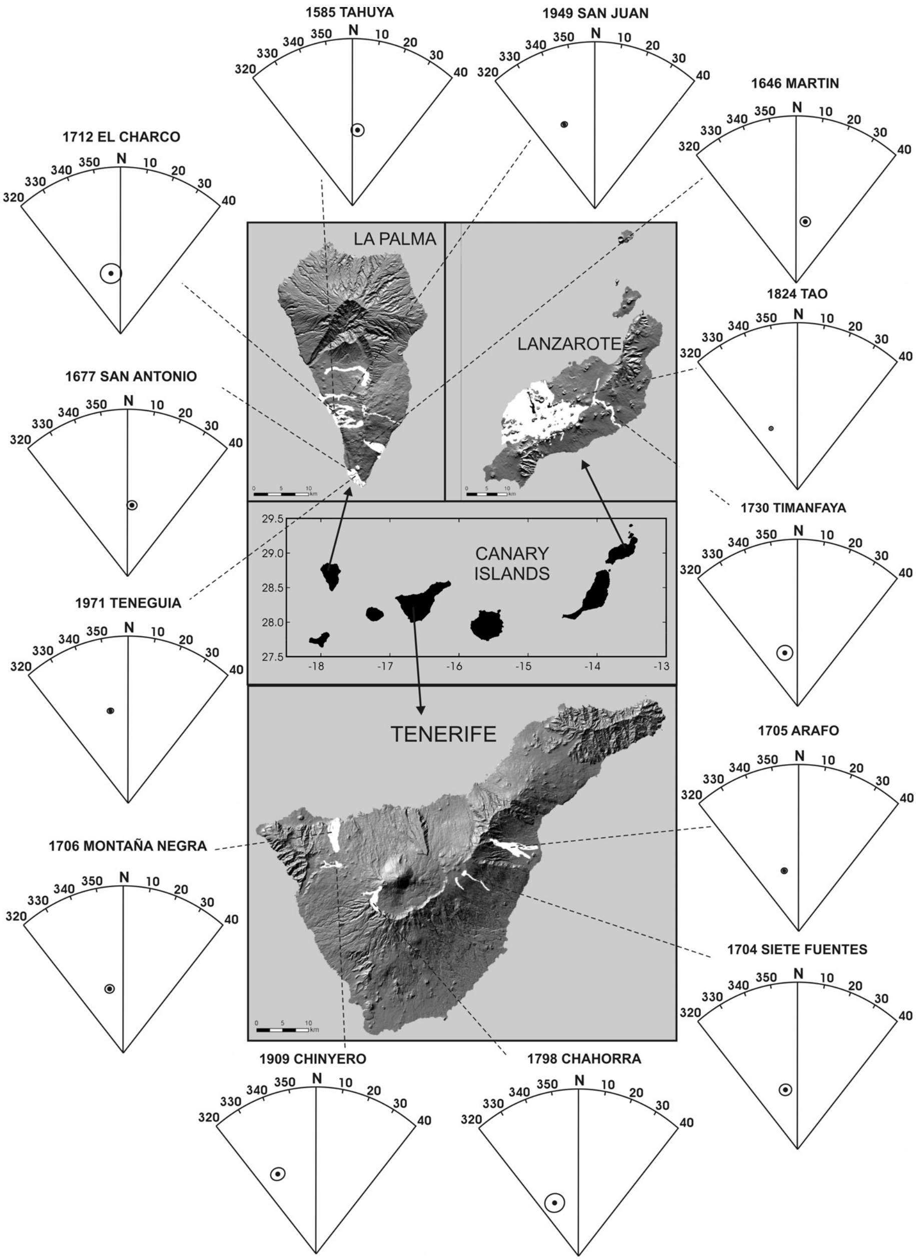

Figure 1. Location, ages and names of historical lava flows (in white) in the Canary Islands and mean paleomagnetic directions obtained by Soler et al. (1984). Ellipses in the equal-area stereographic projections represent the α_{95} error of the paleomagnetic directions.

Table 1. Paleomagnetic directions published by Soler et al., 1984.

Eruption	Date (AD)	N	D (º)	I (º)	k	α_{95} (º)
Tahuya	1585	4	4.2	52.5	811	3.2
Martin	1646	6	8.6	57.2	659	2.6
San Antonio	1677	6	3.6	52.1	724	2.5
Siete Fuentes	1704	9	348.6	57.9	277	3.1
Arafo	1705	7	346.7	57.0	1530	1.5
Montaña Negra/Garachico	1706	8	348.0	55.3	585	2.3
El Charco	1712	5	351.1	57.6	210	5.3
Timanfaya	1730	4	346.7	61.0	536	4.0
Chahorra	1798	6	335.9	59.2	175	5.0
Tao	1824	5	336.7	54.6	5953	1.0
Chinyero	1909	6	334.5	42.4	359	3.5
San Juan/Nambroque	1949	8	340.1	41.8	1308	1.5
Teneguia	1971	7	349.2	39.2	1568	1.5
Lavas Negras Teide	1200 ± 300 (1) 850 ± 140(2)	7	358.6	21.8	3082	1.1
Montaña Quemada	1530 ± 60 (3) 1470-1492(4)	6	358.7	21.6	2023	1.5

(1) Ar-Ar dating by Quidelleur et al. (2001).
(2) ^{14}C dating by Carracedo et al. (2007).
(3) ^{14}C dating by Hernández-Pacheco&Valls (1982).
(4) Aboriginal Guanche tradition (Hernández-Pacheco&Valls, 1982).

Construction of a Paleo Secular Variation Curve

The classical approach to define the paleo secular variation (PSV) in a region is to calculate a reference curve (PSVC) from paleomagnetic directions. A high density of paleomagnetic data, well-distributed in time, from a small region (usually less than 600 – 900 km radius) is needed. This can be obtained from heated archeological structures, which are well-dated and not disturbed (archeomagnetic curves), and from well-dated volcanic materials. Archeomagnetic data are usually better due to simpler and well known thermoremanent magnetization (TRM) acquisition processes. A combination of both types of data are sometimes used (Tema et al., 2006, 2010), while at other times only volcanic paleomagnetic data are used (Tanguy et al., 2003).

To build a PSVC, paleomagnetic data are transferred from the sampling place to a reference point by the Conversion Via Pole (CVP) method (Noël and Batt, 1990). This relocation process introduces an error, which can be evaluated for the present time through the International Geomagnetic Reference Model (IGRF) and for the last 400 years through the historical GUFM1 model (Jackson et al., 2000). The relocation error for the present European geomagnetic field increases linearly with the relocation distance (a maximum of 7º for a 1700 km radius; Casas&Incoronato,

2007). For a small region, as the case of the Canary Islands, these errors are commonly within the uncertainty of paleomagnetic directions. Consequently, if the harmonic content of the geomagnetic field was similar in the past, similar errors to the present are expected, which should be included in the paleomagnetic uncertainty. A study for the relocation error in the Canary Islands is developed in the next section.

In order to obtain the most appropriate PSVC according to the temporal data distribution, several methods have been developed during the last decades: the moving window technique (e.g. Sternberg and McGuire, 1990), the bivariate Le Goff statistics (Le Goff et al., 2002) and the most recent approach, the hierarchical Bayesian statistic (Lanos, 2004). In the present paper, in order to obtain a PSVC for the Canary Islands for the last 400 years, we prefer to use the Bayesian modelling based on roughness penalty (Lanos, 2004). The weighting process depends on the data uncertainties which, for directional data, are given by the α_{95} (Fisher, 1953).

Paleomagnetic dating process

In this work we have followed the methodology described by Lanos (2004) using the probability density functions of the three geomagnetic field elements: declination, inclination and intensity. The undated paleomagnetic element *D* is considered normally distributed at a fixed time *t*, with mean value $\overline{D}$ and standard deviation error σ_D, i.e., $D: N(\overline{D},\sigma_D^2)$. In the same way, the geomagnetic field element provided by the master curve *G(t)* at the same fixed time is supposed normally distributed with mean and standard deviation given by $\overline{G}$ and σ_G : $G(t): N(\overline{G}(t),\sigma_G^2(t))$. At the time *t*, the conditional probability density (or likelihood) of the observation (non-dated paeomagnetic element) is given by the next formula:

$$PDF_D(t) = p(D|G,t) = \int_{-\infty}^{+\infty} p(D|G,D,t)\cdot p(D|G,t)\cdot dD \quad (1)$$

In paleomagnetism, generally, directional information (i.e., declination and inclination) is the most typical measurement which is carried out in paleomagnetic laboratories, since the process to obtain intensity information is more complicate and takes more time. In this sense, the paleomagnetic data will be constituted by declination and inclination data and, in some cases, intensity data.

To find the most probable age of the paleomagnetic data we have to combine the probability density functions (PDF) of the geomagnetic field elements. To obtain more accurate dates we must considered the full geomagnetic field vector (declination, inclination and intensity) or, if the intensity data is not available, the directional vector (declination and inclination).

Another important factor in this dating process is related with the own behaviour of the geomagnetic field, which is shown by the PSVCs. A rapid change recorded in the master PSVC can allow us to obtain a more precise date than in periods of slow change. Finally, when paleomagnetic data are dated, similar direction/intensity values could be observed for different epochs. This can generate non-uniqueness problems. In this case, more information as stratigraphy, geological or archeological context, etc., must be used in order to distinguish between alternative ages.

Here we use paleomagnetic directional data defined by just two magnetic elements, declination and inclination (D and I), and therefore the geomagnetic field intensity is not used. We will obtain a directional PSVC, and we will use just the directional information contained in the geomagnetic models for paleomagnetic dating, although in some of them intensity information is also available. In principle, the introduction of intensity could allow better dating precision thus reducing non-uniqueness problems, but the experimental procedure to estimate paleointensities can also introduce great uncertainties.

3. RESULTS

The first step to develop a regional PSVC is to choose a particular location as the main reference point to where all paleomagnetic directions will be relocated by the CVP method (Noël&Batt, 1990). In our case, we have chosen a reference point (P0) in Santa Cruz de Tenerife with geographic coordinates 28.47º N, 16.25º W. To estimate the time-averaged errors expected to affect the relocation procedure for different epochs in the studied region (Figure 1), we have used the GUFM1 model based on historical geomagnetic observations during the last four centuries (Jackson et al., 2000). Using knotpoints separated by 50 years in the period 1600-1950, we have calculated the geomagnetic field direction expected from GUFM1 in a 0.1º x 0.1º geographical grid. These directions have been relocated to our reference point by CVP and they have been compared with the GUFM1 direction at P0 for each temporal knotpoint. As expected for small regions, the relocation errors remain below 1º throughout the entire period, therefore they are lower than the mean value of the α_{95} (2.8 ± 1.4º, 1σ) of the paleomagnetic directions, thus indicating that the construction of a PSVC centred at P0 from these data is acceptable.

The calculated bayesian PSVC is represented in Figure 2, where different plots for declination and inclination are shown, together with an equal area projection. In addition to the bayesian PSVC, three curves calculated at P0 from the following global models are also plotted in Figure 2: the GUFM1 model for the last 400 years, developed from geomagnetic historical and instrumental observations made by sailors and geomagnetic observatories (Jackson et al., 2000); the ARCH3K.1 model (Korte et al., 2009), obtained from archeomagnetic data and lava-flow paleomagnetic directions for the last 3 ka (including the data of Soler et al., 1984, which we are using to construct the PSVC) and constrained with the GUFM1 model for the last 400 years; and the IGRF-11, the last version of the international geomagnetic reference field model constructed from instrumental observations since 1900

(IAGA, 2009). Geomagnetic data (mean annual direction) from Las Mesas (1961-1992) and Güímar (1993-present) Observatories at Tenerife are also included since 1961 (Marín-Martínez et al., 2006). Numerical values for D, I and the corresponding errors (σ_D and σ_I, 95% confidence) are calculated from the PSVC with a 20 year spacing from 1590 to 1970 (Table 2).

Table 2. PSVC data-points with a 20 years spacing from 1590 to 1970 (σ_D/σ_I, 95% confidence).

Date	D (º)	σ_D (º)	I (º)	σ_I (º)	Date	D (º)	σ_D (º)	I (º)	σ_I (º)
1590	7.0	8.9	52.9	3.1	1790	-20.8	3.3	57.3	3.2
1610	4.9	8.2	52.7	3.2	1810	-23.0	3.0	56.1	3.1
1630	2.4	7.5	53.2	3.3	1830	-24.8	2.7	54.5	2.9
1650	-0.3	6.8	54.0	3.4	1850	-25.9	2.4	52.4	2.8
1670	-3.2	6.2	55.1	3.4	1870	-26.3	2.2	50.1	2.6
1690	-6.2	5.6	56.2	3.5	1890	-25.9	2.0	47.5	2.3
1710	-9.3	5.1	57.2	3.5	1910	-24.4	1.9	44.9	2.1
1730	-12.3	4.6	57.8	3.4	1930	-21.7	1.8	42.4	1.8
1750	-15.4	4.1	58.1	3.4	1950	-17.7	1.7	40.3	1.5
1770	-18.2	3.7	57.9	3.3	1970	-12.1	1.7	38.8	1.2

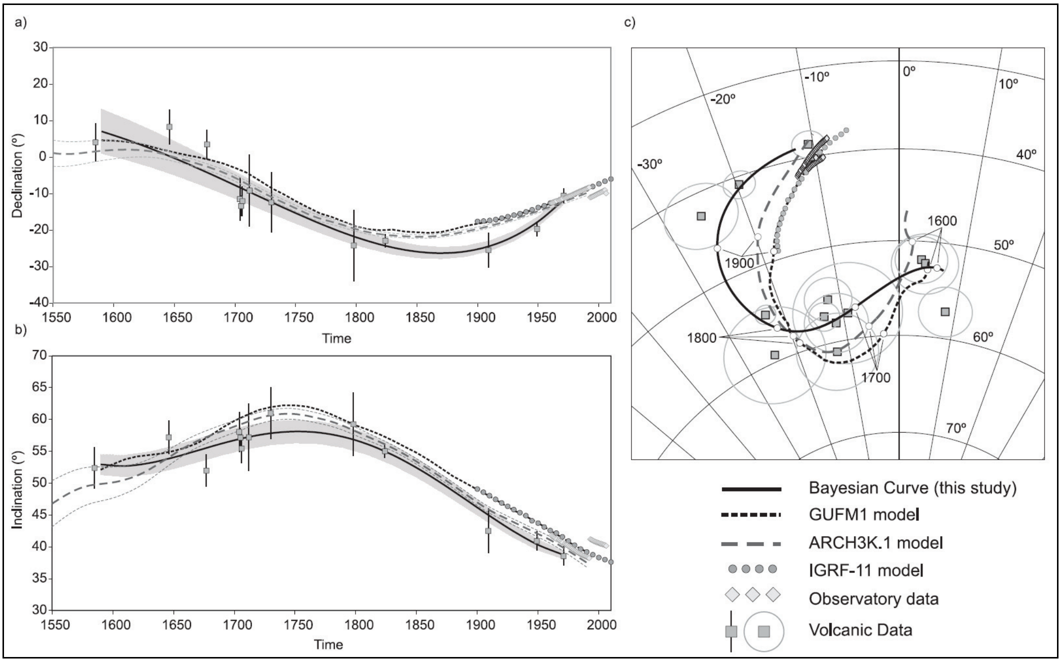

Figure 2. Calculated bayesian PSVC, original paleomagnetic data, global geomagnetic models GUFM1, ARCH3K.1 and IGRF-11, and geomagnetic data from Las Mesas and Güímar Observatories at Tenerife: a) declination *v*. time; b) inclination *v*. time; c) equal area stereographic projection of D and I; white circles are drawn over the models' curves each 100 years to represent time.

The comparison of the paleomagnetic data/PSVC with the above mentioned geomagnetic models and data-sets rests on the following logic: local observatory data should be in principle the best recorders of the real behaviour of the geomagnetic field in the Canary Islands, although it will be seen that Güímar data are greatly affected by local crustal magnetic anomalies; in spite of local direct geomagnetic data, IGRF-11 is by far the best representation of the geomagnetic field and its temporal variation since 1900 AD; for the last 4 centuries, the best available extension of IGRF-11 is the GUFM1 model, based also on instrumental data and coincident with IGRF-11 for the 20^{th} century; for earlier times, we have to rely on the global model ARCH3K.1, valid for the last 3 thousand years. Although ARCH3K.1 is constrained by GUFM1, they do not coincide for the last 4 centuries, and because of this we have included both in Figure 2. This set of models represents the best knowledge we have at this moment about the recent evolution of the global geomagnetic field and therefore it is the only reference against which to compare Canary Islands paleomagnetic directions.

It can be observed that the best fit to the paleomagnetic data is achieved by the bayesian PSVC, as expected from the fact that the rest of the models include many other data. Angular deviation between our bayesian PSVC and the global models, and between GUFM1 and ARCH3K.1 models themselves is plotted in Figure 3. In almost the whole temporal-range the deviation between the PSVC and the models is greater than between the two models, which is logical considering that the ARCH3K.1 model has been constrained by GUFM1 data. In general, deviations of the PSVC are between 2 and 4 degrees, never exceeding 6 degrees, and are greater with GUFM1 than with ARCH3K.1.

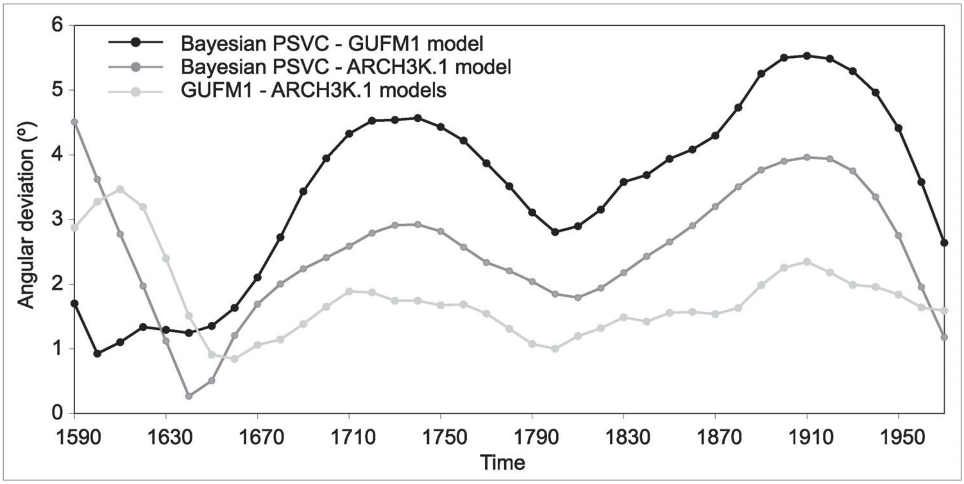

Figure 3. Angular deviation between the bayesian PSVC and GUFM1 and ARCH3K.1 global models.

The observed differences between paleomagnetic data/PSVC and the global models call for an explanation, especially in the case of GUFM1, which is generated from instrumental data and therefore deserves the greatest confidence. In this context the deviations of the paleomagnetic direction of the last lava-flows extruded in the Canary Islands (Chinyero in Tenerife, 1909; San Juan in La Palma, 1949; Teneguía in La Palma, 1971) from the expected instrumental geomagnetic directions are noticeable. In particular, these three lava-flows provided paleomagnetic inclinations systematically lower than the inclinations obtained from direct instrumental measurements. This is generally true also for the whole temporal range: the Bayesian PSVC shows lower inclinations than GUFM1 model. As was stated in the "Data and Methodology" section, the paleomagnetic data used to construct the PSVC could in principle be affected by two first-order error sources, apart from the usually random errors coming from any careful experimental procedure. First, they can reflect the magnetic disturbing effects of the topography and magnetization of older, underlying lava-flows (Baag et al., 1995; Valet&Soler, 1999; Knudsen et al., 2003; Tanguy&Le Gof, 2004), since just one site per lava-flow was sampled. And second, a systematic inclination shallowing has been detected in lava-flow paleomagnetic directions elsewhere (Lanza et al., 2005), probably due to either anisotropic magnetic effects related to preferential grain orientation induced by the magma flow itself or to complex within-flow inhomogeneous patterns in magnetization acquisition, with some parts of the flow acquiring their TRM early in the cooling process and probably affecting the subsequent magnetization of other parts. These two error-sources could explain the deviations between paleomagnetic and instrumental data, explaining the low reliability of the obtained PSVC.

Since almost all the historical lava flows in the Canary Islands have been used to construct the PSVC for the last 400 years, this curve by itself is not a useful tool for dating lava flows of unknown age. In order to asses this problem we need to extend the PSVC to older times, which can be done just by three ways: obtaining new paleomagnetic and geochronologic data of older lava flows of the last few thousands of years; relocating by CVP the already constructed European geomagnetic regional models to the Canary Islands, if it is found that the error introduced by this relocation is generally smaller than the statistical errors affecting the paleomagnetic directions themselves; or using directly the global geomagnetic models extending back into older times for *in situ* dating in the Canary Islands. We have explored the second and the third strategies, and the results are shown in Figures 4 and 5. In the first place, we have estimated the Madrid-to-Tenerife relocation errors expected from three different global geomagnetic models: GUFM1 (Jackson et al., 2000); ARCH3K.1 (Korte et al., 2009); and CALS7K.2 (Korte&Constable, 2005), which is a global model for the last 7 ka obtained from archeomagnetic, lava-flow and sedimentary data. The introduction of CALS7K.2 model is necessary if we want to extend our analysis to epochs earlier than 3 ka BP, since it is the only published global model extending so far in time; nevertheless, we have to take into consideration that this model includes sedimentary data and therefore is affected by the corresponding uncertainties (i.e. inclination shallowing), which explain the significant differences between CALS7K.2 and ARCH3K.1. The expected errors are calculated in the following way: first we calculate the geomagnetic direction at Madrid for a given time (t) according to a certain global model; then we relocate it by CVP to our point P0 in Tenerife; and finally we obtain the angular deviation between this relocated direction and the *in situ* geomagnetic direction at the same time t at P0 deduced directly from the corresponding model. As can be seen in Figure 4, these relocation errors are always smaller than ~7º for the last seven thousand years, with mean values of 1.9º (CALS7K.2), 2.8º (ARCH3K.1) and 2.4º (GUFM1). The mean relocation errors are comparable or smaller than the usual paleomagnetic errors (α_{95}), and thus it seems *a priori* that paleomagnetic dating of lava-flows in the Canary Islands with relocated European models can be a practical approach, having always in mind the corresponding errors in temporal dating resolution. Nevertheless, there are specific epochs for which relocation errors seem to reach 7º, higher than usual paleomagnetic errors, implying bigger potential dating uncertainties for these epochs when using relocated models.

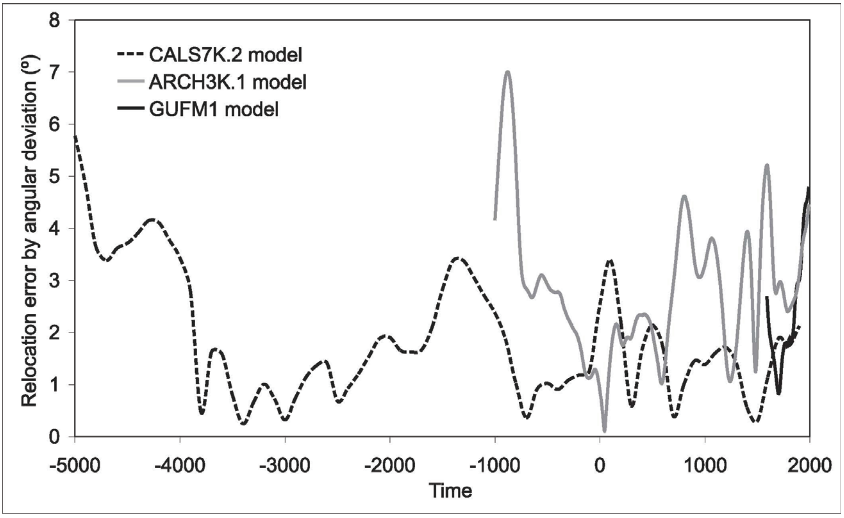

Figure 4. Relocation error versus time expected from different global models.

In Figure 5, the historical lava-flows of Table 1 have been dated paleomagnetically using ARCH3K.1 and SCHA.DIF.3K models (see "Data and Methodology" for the detailed dating procedure). Figure 5a presents paleomagnetic ages obtained *in situ* with the global model ARCH3K.1 *versus* historical (original) ages. Taking into account the paleomagnetic confidence angles, the fitting is very good, with the exception of San Antonio lava-flow (La Palma, 1677). In Figure 5b, the paleomagnetic dating has been performed with SCHA.DIF.3K model. This European regional model has been used to calculate the corresponding PSVC at Madrid for the last 3 ka. The curve has been subsequently relocated by CVP to the reference point P0 at Santa Cruz de Tenerife and it has been used to obtain the paleomagnetic ages, which are plotted *versus* historical ages. In this case, as SCHA.DIF.3K model do not include ages younger than 1900, no dating has been obtained for the three 20th century eruptions. The fit is acceptable if error bars are considered, but nevertheless it is clearly worst than with ARCH3K.1. We have to remember that the Canary Islands historical paleomagnetic data of Soler et al. (1984) were used to generate the ARCH3K.1 model. This, together with the absence of relocating errors, explains the better fit. It would be obviously better to use independent lava-flow data not included in ARCH3K.1 model to test its performance in paleomagnetic dating, but unfortunately there is an almost total scarcity of data (see next paragraphs). It seems that dating with the relocated curve of SCHA.DIF.3K tends to give slightly too young ages for the historical flows.

Figure 5c shows a comparison between the paleomagnetic ages obtained with ARCH3K.1 model both *in situ* and relocated from Madrid to Tenerife. The differences between both procedures are remarkable small, strengthening the conclusion that using either global or European relocated models for the Canary Islands can be a good approach to obtain approximate ages.

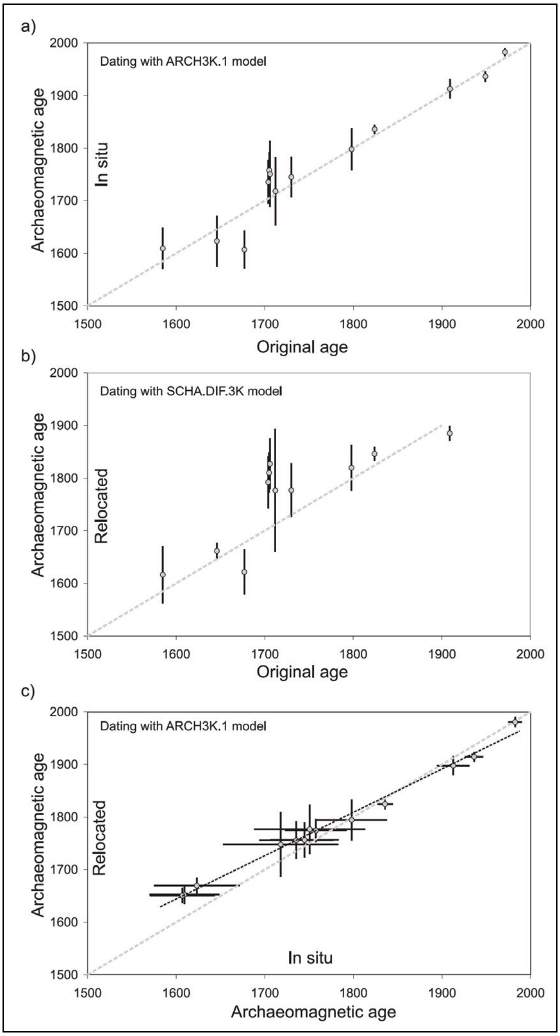

Figure 5. Paleomagnetic ages v. historical (original) ages for lava-flows in Table 1, according to the procedure described in the text (a and b). Paleomagnetic "relocated" v. "in situ" ages obtained with ARCH3K.1 model (c).

As a last exercise, new paleomagnetic ages have been obtained for the two oldest lava-flows listed in Table 1, which are not included in ARCH3K.1 model: Lavas Negras del Teide (Tenerife) and Montaña Quemada (La Palma). To do it we have used the PSVCs obtained both from ARCH3K.1 (calculated *in situ* at P0) and from

SCHA.DIF.3K (relocated to P0 from Madrid). It can be seen that the paleomagnetic inclination of both lava-flows is very low (~22º). For the last 3 ka, there is just one epoch where compatible values of D and I are reached: around the year 1350 A.D. The precise mathematical paleomagnetic dating gives the following ages (see Figure 6): between 1302 and 1416 AD for Montaña Quemada; and between 1302 and 1414 AD for Lavas Negras del Teide.

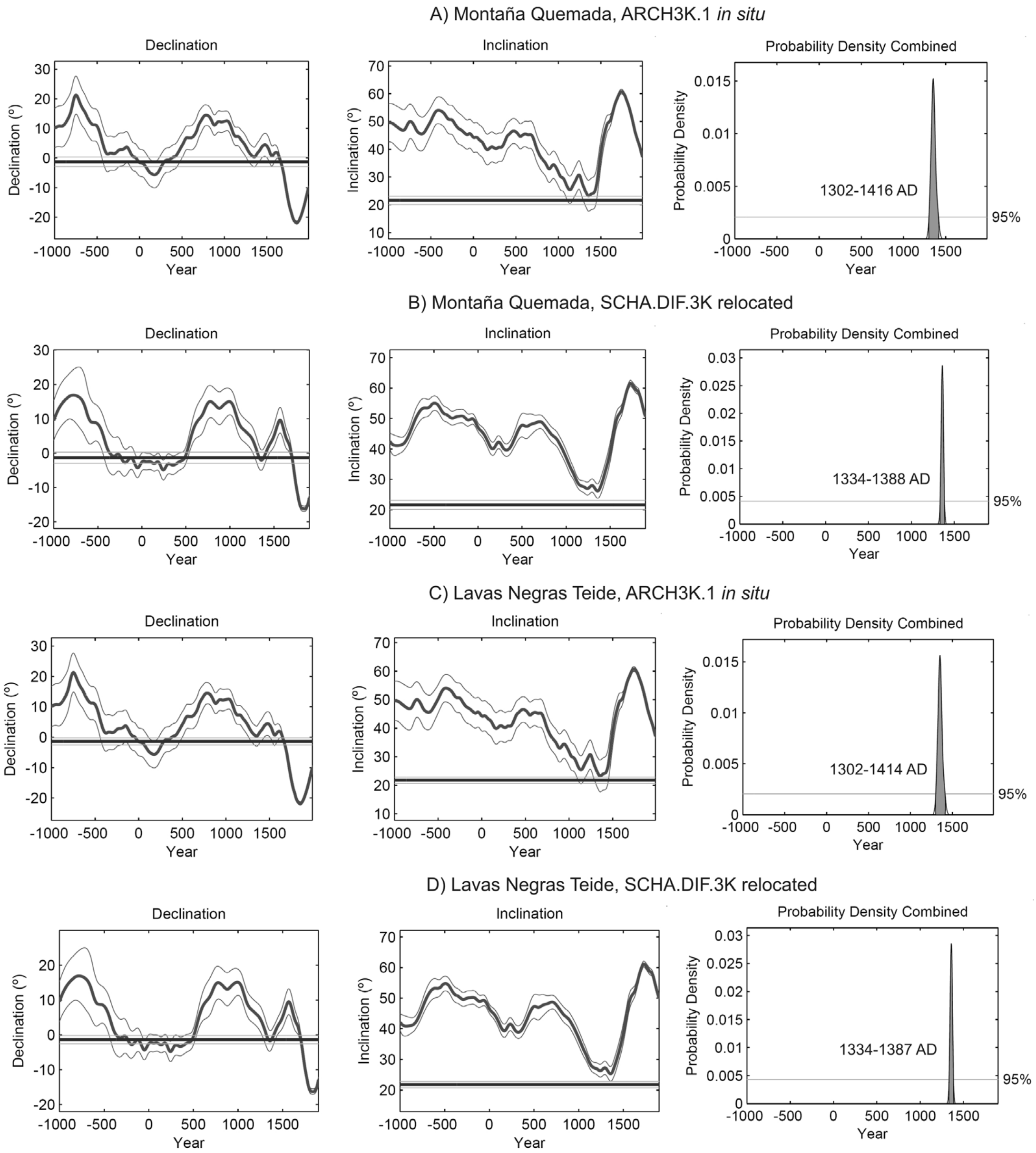

Figure 6. Paleomagnetic dating of Montaña Quemada and Lavas Negras del Teide sub-historical lava flows using ARCH3K.1 global model *in situ* and SCHA.DIF.3K European regional model relocated to P0 in Tenerife. Horizontal lines correspond to the paleomagnetic directions of Montaña Quemada and Lavas Negras lava-flows.

Both flows have essentially the same paleomagnetic age, because their paleomagnetic directions are themselves almost identical. The ages provided by the two models (global *in situ*, regional relocated) are coincident. The apparent better precision obtained by SCHA.DIF.3K is due to the fact that the relocated curve does not reach values of inclination as low as the paleomagnetic directions or the curve obtained from ARCH3K.1, probably due to the inherent relocation error. No real significance should thus be placed in this apparent better precision.

For Lavas Negras, the paleomagnetic age is fully compatible with Ar-Ar data (Quidelleur et al., 2001). The age obtained by ^{14}C (Carracedo et al., 2007) is clearly older and the paleomagnetic age does not fall within the error interval, even if a generous error of two centuries is ascribed to the paleomagnetic dating procedure. This could indicate that the published ^{14}C dating is not representative of the actual age of Lavas Negras; since ^{14}C dating is performed on accompanying burnt organic matter and not on volcanic material itself, great uncertainties can affect its results. On the other hand, the two already described error-sources could affect the paleomagnetic data, although the very good concordance with Ar-Ar results leads us to place more confidence on them.

The paleomagnetic age of Montaña Quemada is 1-2 centuries older than the proposed age from both ^{14}C dating and the study of aboriginal Guanche tradition (Hernández-Pacheco&Valls, 1982), these two methods being compatible between them. In this case, it is possible than some errors are affecting the paleomagnetic data, probably inclination shallowing. But errors in the ^{14}C age can neither be discarded, since this method does not directly date the volcanic material. Even if we assume that the discrepancy is entirely due to paleomagnetic errors, paleomagnetic dating with the described procedure appears to be a very good approach, if temporal errors of around two centuries are allowed. This precision is comparable or better than Ar-Ar dating of young lava-flows, and it is good if one is interested in a general volcanic history for the last few thousands of years and not in a very precise dating of a particular lava-flow. Nevertheless, more accurate paleomagnetic data from well-dated lava-flows are needed to obtain a better estimation of the potential errors affecting paleomagnetic dating.

4. CONCLUSIONS

It has been shown that Canary Islands paleomagnetic data obtained from historical (last 400 years) lava-flows can be used to properly construct a regional PSVC, although this curve shows a poor reliability when compared to instrumental models, indicating that great attention must be placed on the error sources that can potentially affect paleomagnetic directions. In particular, great care must be taken when planning paleomagnetic sampling and several sites per lava-flow should always be sampled and studied. Although its importance is difficult to estimate *a priori*, inclination shallowing should always be considered as a probable error affecting the paleomagnetic directions, in addition to the statistical confidence angle α_{95}. Low values of α_{95} are by themselves not sufficient to assure that a paleomagnetic direction is representative of the local geomagnetic field. The systematic measurement of magnetic anisotropy parameters is highly recommendable to asses their possible influence in inclination shallowing problems.

The Bayesian PSVC obtained in this work is restricted to the last 400 years, due to the lack of paleomagnetic and geochronologic data. In this interval, the geomagnetic secular variation pattern in the Canary Islands as revealed by the PSVC is generally coherent with the results obtained from geomagnetic models constructed both from historical/instrumental and archeomagnetic/paleomagnetic observations (GUFM1, ARCH3K.1, IGRF-11). The important observed differences, probably due to the error-sources described previously, indicate the low reliability of the obtained PSVC as a dating tool; nevertheless, since almost all the lava-flows known to have erupted in the Canaries in the historical period have been used to construct the curve, it could not be considered a useful dating tool even if its quality was higher. A particular comment about the data registered at Las Mesas and Güímar Geomagnetic Observatories can be made: a "jump" in the behaviour of the geomagnetic elements D and I is observed in coincidence with the change in operations from Las Mesas (which operated between 1961 and 1992) to Güímar (which has operated from 1993 to the present). This jump is observed both in plots of D and I *versus* time, but is better shown in the equal area stereographic projection (see Figure 2), where data from both observatories are almost superposed. This anomalous behaviour is due to the location of Güímar Observatory at the edge of a significant crustal negative magnetic anomaly (see García et al., 2007 for Tenerife aeromagnetic data). This illustrates a typical problem that affects geomagnetic observations within volcanic islands, which usually present a very heterogeneous and strong crustal magnetization that disturbs the local geomagnetic field. This problem is essentially the same, but in a bigger scale, as the one which arises from the magnetization of older lava-flows affecting the geomagnetic field direction recorded by younger flows emplaced over them.

As the main motivation of this work was the evaluation of the potential use of geomagnetic paleosecular variation as a dating tool in order to improve the knowledge about the recent volcanic history of the Canary Islands, we have investigated the possibility of using both global and European regional geomagnetic models spanning the last 3 ka for paleomagnetic dating in the Canary Islands. It has been shown that *in situ* dating with global model ARCH3K.1 (Korte et al., 2009) provides very good results for the last centuries, although more independent paleomagnetic and geochronologic data would be needed to corroborate it. Worst results are obtained when dating with the relocated curve obtained from European regional model SCHA.DIF.3K (Pavón-Carrasco et al., 2009), although if the paleomagnetic errors are considered the results are good enough. As the model ARCH3K.1 includes the Canary Island paleomagnetic data for the last 4 centuries and because the relocation procedure introduces an error, it is not a surprise that more precise ages are obtained by this model. Nevertheless, Madrid-to-Tenerife relocation errors for the last 7 ka are estimated from global models to be lower than 7º, with average values below 2.8º, which are comparable to usual paleomagnetic confidence angles

(α_{95}). This indicates that the use of a relocated curve is a good approach if dating uncertainties of ~1-2 centuries are allowed. Nevertheless, a good and temporally extended PSVC developed in situ or global models seem always preferable to relocated models or PSVCs.

A final test using two independent sub-historical lava-flows has been conducted: paleomagnetic ages were obtained with both ARCH3K.1 (*in situ*) and SCHA.DIF.3K (relocated) for Lavas Negras del Teide and Montaña Quemada lava-flows. Lavas Negras paleomagnetic age shows a very good agreement with the published Ar-Ar dating (Quidelleur et al., 2001). The better precision of the paleomagnetic dating seems to indicate that the published ^{14}C age (Carracedo et al., 2007) is too old and possibly does not reflect the actual age of the volcanic material. The paleomagnetic age obtained for Montaña Quemada is slightly older than the published ^{14}C and Guanche tradition ages (Hernández-Pacheco et al., 1982). In this case, although some doubts about the applicability of ^{14}C age to the volcanic material can not be discarded, the paleomagnetic direction could be affected by inclination shallowing, not reflecting the actual age of the flow. In any case, uncertainty of paleomagnetic ages seems to be lower than 1-2 centuries. This result leads us to conclude that paleomagnetic dating of recent lava-flows in the Canary Islands using the available global and European regional geomagnetic models for the last thousands of years is a very promising tool, although more accurate paleomagnetic and geochronologic data are needed to asses the importance of the different error sources affecting the dating procedure.

A final consideration concerning the applicability of this methodology should be made: it is well known that geomagnetic secular variation averages to zero on time-scales of ~ 10 ka, implying that similar values of the paleomagnetic elements (i.e. D and I) can be observed in many different epochs. Thus, before attempting to paleomagnetically date any recent lava-flow, it is of obvious importance to count with independent geological information assuring us that it is not older than the whole interval included in our secular variation curves or models (3 ka for ARCH3k.1, 7 ka for CALS7K.2).

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