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Secular variation of the Earth's magnetic field in the Balkan region during the last eight millennia based on archaeomagnetic data

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SUMMARY

The first archaeomagnetic secular variation (SV) curves for the whole Southern Balkan Peninsula are presented. These are based on all data within a 700 km circle centred at Thessaloniki (40.60ºN, 23.00ºE). This data set consists of 325 directional and 625 intensity data mainly from Greece, Bulgaria, Serbia and southern Hungary. Some data from southern Italy are also included. The sliding moving window technique, was used to calculate a continuous SV curve for intensity while the directional SV curves were calculated using the bivariate extension of the Fisher statistics. These curves are well constrained and clearly show the main features of the geomagnetic field variation in this region during the last eight millennia. Comparisons with the predictions of the SCHA.DIF.3K and SCHA.DIF.8K regional and the CALS7K.2 and ARCH3K.1 global geomagnetic field models show a good agreement for the last 3000 years but differences for older times. The Balkan SV curves identify several rapid changes of the geomagnetic field in eastern Europe and can be used as reference curves for archaeomagnetic dating in the Balkan Peninsula.

Key words: Archaeomagnetism; Palaeointensity; Palaeomagnetic secular variation.

1 INTRODUCTION

The study of the Earth's magnetic field and its variations in the past remains a key issue for Earth sciences. In the last decade, a considerable number of directional and intensity data of increasing accuracy have been produced and data sets at country (e.g. Schnepp *et al*. 2004; Gómez-Paccard *et al*. 2006a; Tema *et al*. 2006) and/or global (Korte *et al*. 2005; Korhonen *et al*. 2008; Genevey *et al*. 2008; Valet *et al.* 2008; Donadini *et al*. 2009) level have been compiled. Although these data sets are traditionally used to construct reference secular variation (SV) curves for individual countries, they may also involve data from neighbouring countries (Schnepp & Lanos 2005; 2006; Gómez-Paccard *et al*. 2006b). Several SV curves are now available in Europe, including France (Bucur 1994; Gallet *et al*. 2002), the Iberian Peninsula (Gómez-Paccard *et al*. 2006b), Germany (Schnepp & Lanos 2005), Austria (Schnepp & Lanos 2006), Italy (Tema *et al*. 2006), the United Kingdom (Zananiri *et al*. 2007) and Hungary (Márton & Ferencz 2006; Márton 2010). However, most of these comprise only directional data and extend over only the last three millennia.

Balkan archaeomagnetic studies started in 1967 with the work of Mary Kovacheva (Palaeomagnetic Laboratory of the Geophysical Institute of the Bulgarian Academy of Sciences) to which a considerable number of both directional and intensity data from Bulgaria has been added since (Kovacheva 1969; 1980; Kovacheva & Toshov 1994; Kovacheva 1997; Kovacheva *et al*. 1998; Jordanova *et al*. 2004; Kostadinova & Kovacheva 2008; Donadini *et al*. 2010) and is still being continuously updated (Kovacheva *et al*. 2009). Nowadays, the Bulgarian database is the richest in Europe, covering the last 8000 years. In Greece, systematic archaeomagnetic investigations started at the late 1970s (Walton 1979; Liritzis & Thomas 1980; Thomas 1981; Aitken *et al*. 1989; Downey & Tarling 1984; Papamarinopoulos 1987; Tarling & Downey 1989) although some early archaeomagnetic results were published by Belshé *et al*. (1963). In contrast with the general situation in Europe, where the number of directional archaeomagnetic data is by far larger than the palaeointensity data, in Greece there is an abundance of palaeointensity determinations. However, although in larger quantities, such results have been obtained by different specialists, using different techniques and methods and thus in several cases their reliability is uncertain (Liritzis 1989; Kovacheva 2003). Nevertheless, since 2000, a considerable number of high quality archaeomagnetic data have been obtained in Greece. De Marco *et al*. (2008a) re-examined and re-evaluated all previously published intensity data and proposed a Greek intensity SV curve covering the last 7000 years. For the other Balkan countries, some data are available for Serbia (Kovacheva & Veljovich 1977; Kovacheva *et al*. 2009) and Romania (Suteu *et al*. 2008) but, to our knowledge, there are very few published data for Turkey (Bucha & Mellaart 1967) and none for Albania, despite both countries having many potential sites available for archaeomagnetic analysis.

Historic and prehistoric finds in the south Balkan area often share similar characteristics, mainly due to the easy communication paths on both land and sea. For example, the Neolithic archaeological site of Promachon-Topolnitza, situated on the Greek–Bulgarian borders, was once a unique settlement while today half of it belongs to Greece and half to Bulgaria. Taking into account that there is no reason for national borders to constrain the study of Earth's magnetic field behaviour, the first archaeomagnetic SV curves for the whole southern Balkan region have been determined based on all data within a 700 km circle centred at Thessaloniki. The proposed SV curves allow a better description of the evolution of the Earth's magnetic field over the last 8000 years in the Balkan area and can be used for archaeomagnetic dating based on the full geomagnetic field vector (declination, inclination and intensity).

2 THE DATA SET

As the Earth's magnetic field varies from one geographic region to another, its spatial variations must be taken into account when dealing with archaeomagnetic data from different sites. In archaeomagnetism, the most commonly used method for relocating remanence vectors to a reference point is the relocation via pole method (Tarling 1988; Noel & Batt 1990), whereas spatial corrections for geomagnetic intensities are usually based on the virtual axial dipole moment. According to the conversion via pole method, the D, I values measured at the sampling site can be used to calculate the virtual geomagnetic pole (VGP), whose position is in turn used to derive the D, I values at another site. This allows data from different localities within a region to be compared and a reference curve to be drawn after relocating all data to the same reference site. Noel & Batt (1990), using data from the International Geomagnetic Reference Field, have shown that, for a region of radius 900 km (centred on Meriden in their study), the mean relocating error is $\sim$1.2°, similar to the typical sample orientation and measurement errors in archaeomagnetism. Casas & Incoronato (2007) published a detailed analysis of the distribution of the relocation errors in both direction and intensity and showed that in Europe, errors are restricted to about 0.25°/100 km and 100–200 nT/100 km. Based on these observations, SV curves are usually built using data from $<$1000 km radius areas; for example, a 900 km radius circle centred at Madrid was used for the calculation of the SV curve for the Iberian Peninsula (Gómez-Paccard *et al*. 2006b). In this study a radius of 700 km has been chosen to further restrict any relocation errors. Thessaloniki (40.60°N, 23.00°W) is close to the geographic centre of the Balkan Peninsula and was therefore chosen as the central reference point.

To include both directional and intensity data within the selected area, the GEOMAGIA50 global database (Donadini *et al*. 2006; Korhonen *et al*. 2008; Donadini *et al*. 2009) was used, updated with some data from Greece (De Marco 2007; Nachasova *et al*. 2007; 2008; De Marco *et al*. 2009; Aidona *et al*. 2010; Spassov *et al*. 2010; Spatharas *et al*. 2011) and Bulgaria (Donadini *et al*. 2010) that were not included in the GEOMAGIA50 (http://geomagia.ucsd.edu). The initial Balkan data set consists of 334 directional and 646 intensity values mainly coming from Bulgaria, Greece, Serbia, Romania, and Hungary (Fig. 1), with some data from southern Italy.

However, when using large numbers of data from global data sets problems regarding their reliability may be important. This includes possible errors in the original data and also those that may occur when being transferred to the database. To counteract this latter problem, the original data have been used whenever possible. A direct cross-check between the data in the GEOMAGIA50 database and the original data identified errors in specific collections. For example, there were inaccuracies in the Greek data from Thomas (1983) and Nachasova *et al*. (2002). The corrected data using the PhD thesis of Thomas (1981) instead of Thomas (1983) and some clarifications about the data from Nachasova *et al*. (2002), (2007), (2008) are given in the Appendix. Most of the entries included in the global data sets are based on data from different countries, obtained by many different authors who often follow different laboratory protocols, and therefore not all data can be considered equivalently reliable. Various selection and/or ranking criteria have been proposed mainly for the evaluation of the intensity data (Chauvin *et al*. 2000; Genevey *et al*. 2008) that are more complex than the directional data. Such criteria are based on the method used, the number of samples, the standard deviation, the applied anisotropy and cooling rate corrections. However, applying such selection criteria in the Balkan data set would result to the rejection of most of the Bulgarian and Greek archaeointensity data obtained before and during the 1980s, mainly because of the small number of samples and the lack of partial thermoremanent magnetization (pTRM) checks during intensity experiments and anisotropy corrections based on the TRM anisotropy tensor (Genevey *et al*. 2008). However, Kovacheva *et al*. (2009) have recently re-examined and re-evaluated older data by performing new experiments that showed good agreement with the older ones and confirmed the good quality of data that do not necessarily satisfy the selection criteria mentioned above. Regarding the Greek data, Genevey *et al*. (2008) have carefully investigated the reliability of the intensity data from Aitken *et al*. (1989) and Burakov & Nachasova after 1986 that miss p-TRM checks and TRM anisotropy tensor correction. The authors concluded that there was a satisfactory consistency with other high quality results, deciding that 'rejecting such data may be therefore too severe'. Donadini *et al*. (2009) thoroughly discussed the quality of the GEOMAGIA data set and they suggested that statistical rejection of outliers is the best strategy for a global analysis of the geomagnetic field, even though this does not mean that some inaccurate observations may still be included in the reference data set. In this study, to reject outliers, an initial filter was applied based on the statistical uncertainty of the data, as proposed by Pavón-Carrasco *et al*. (2010) in the most recently published regional geomagnetic field models. Data with semi-angle of confidence α_{95} three times higher than the mean α_{95} and the standard deviation σ_F three times the mean σ_F have been rejected. The mean values of α_{95} and σ_F are 3.4° and 3.6 μT, respectively. The semi-angle of confidence α_{95} was available for all data while data without σ_F information (109 data, mainly coming from Greece) have been assigned a σ_F of 5 μT, as suggested by Donadini *et al*. (2009). Data with age uncertainties greater than 300 yr were also rejected. For some data, no age uncertainty information was available. When dealing with archaeological material, it is often difficult to say if the lack of errors in ages is due to a lack of information or because of very accurate dating that for some cases is possible (e.g. bricks from well-dated Greek churches, see Liritzis 1989). However, for statistical reasons, an error of $\pm$ 50 yr was assigned to all data with missing age uncertainties. Applying these selection filters, a total of nine directional and 21 intensity data have been eliminated. The distribution of the α_{95} and σ_F of the filtered data shows that the quality of data is generally good, with $\alpha_{95} \leq 5°$ for the 86.6 per cent of the directional data and $\sigma_F \leq 6\ \mu$T for the 91.4 per cent of the intensity data (Fig. 2). The final data set consists of 325 directional (179 from Bulgaria, 77 from Greece, 38 from south Italy, 15 from Hungary, 10 from Serbia and six from Romania) and 625 intensity (301 from Greece, 288 from Bulgaria, 29 from Serbia and seven from south Italy) data that cover the last eight millennia.

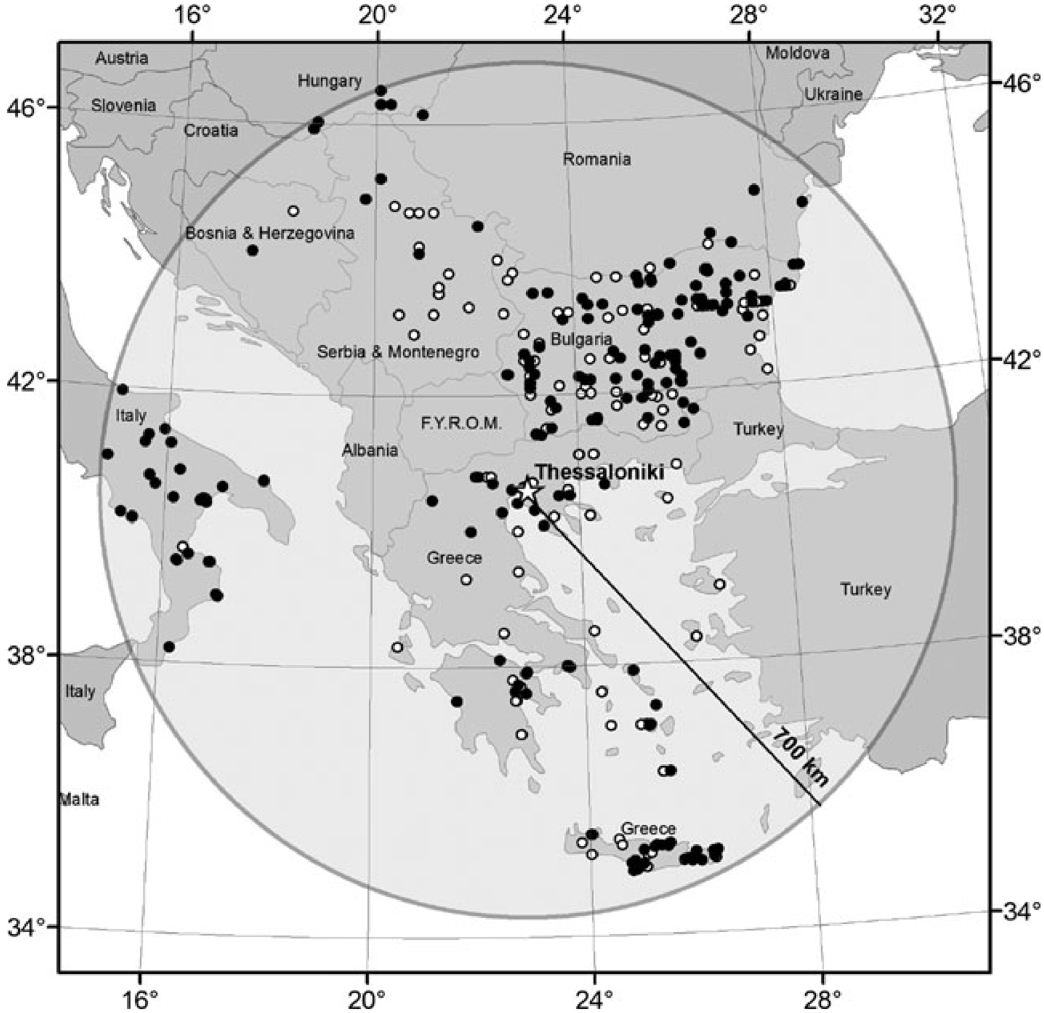


Figure 1. Geographic distribution of the Balkan directional (black dot) and intensity (white dot) data included within a 700 km radius circle centred at Thessaloniki (40.60° N, 23.00°E).

The contribution of data from different countries and of different time periods, resulted in an almost continuous temporal coverage (Fig. 3). Nevertheless, data for the last three millennia remain by far the most numerous. Some lack of both directional and intensity data is observed for the periods 3700–3200 BC and 2200–1600 BC. All data have been relocated to Thessaloniki and are plotted versus time (Fig. 4). Directional data from the different Balkan countries are in very good agreement between each other. For times older than 2000 BC, most of the data come from Bulgaria supplemented by some data from Serbia, which are very consistent with the Bulgarian directions. Higher dispersion is observed at the intensity data (Fig. 4c), mainly for the period between 2500 BC and 500 AD. From 2000 BC to 500 BC the Greek intensities show systematically lower values with respect to the Bulgarian and Serbian data for the same time period. Donadini *et al*. (2007), Genevey *et al*. (2008) and most recently Donadini *et al*. (2009) discuss in detail the most probable origins of palaeointensity related problems. These may be due to subjective interpretations of the Arai diagrams which often lead to overestimations of the palaeointensities if only the lower temperature steps are taken into account (Donadini *et al*. 2009), to different laboratory protocols used by various research groups and/ or to often missing anisotropy and cooling rate corrections. Greek data for the period around 1000 to 500 BC mainly come from the studies of Walton & Balhatchet (1988) and Walton (1990). These authors support that the intensities they obtained were considerably lower than older data and they attribute this discrepancy to magnetic alteration non-detected in previous studies that leaded to an overestimate of the ancient field intensity (Walton 1984; Walton 1990). An important discrepancy is also observed around the 4th century BC. For that period, a considerable number of Greek data show very high intensities. These results come from the studies of Nachasova *et al*. (2007, 2008) that studied ceramics from the Greek islands of Kos, Lesbos, Thasos, Chios, Rodos and from Asia Minor found in the archaeological sites of Nymphaion and Panticapeaum (Crimean Peninsula). Such high intensities for this period are also supported by data from southern Italy (Evans 1986; Hill *et al*. 2008) and by the high quality results from three Hellenistic kilns at Katerini, Greece (De Marco *et al*. 2008b) with a mean site intensity $F_{\text{site}} = 85.8\ \mu\text{T}$. As the scatter of the intensity data and the differences for some time periods are important, the general features of the geomagnetic field in the Balkans were estimated by calculating an averaged SV curve.

3 THE BALKAN SECULAR VARIATION CURVE

Several statistical analyses have been proposed for the calculation of archaeomagnetic SV curves. Among them, the most widely used

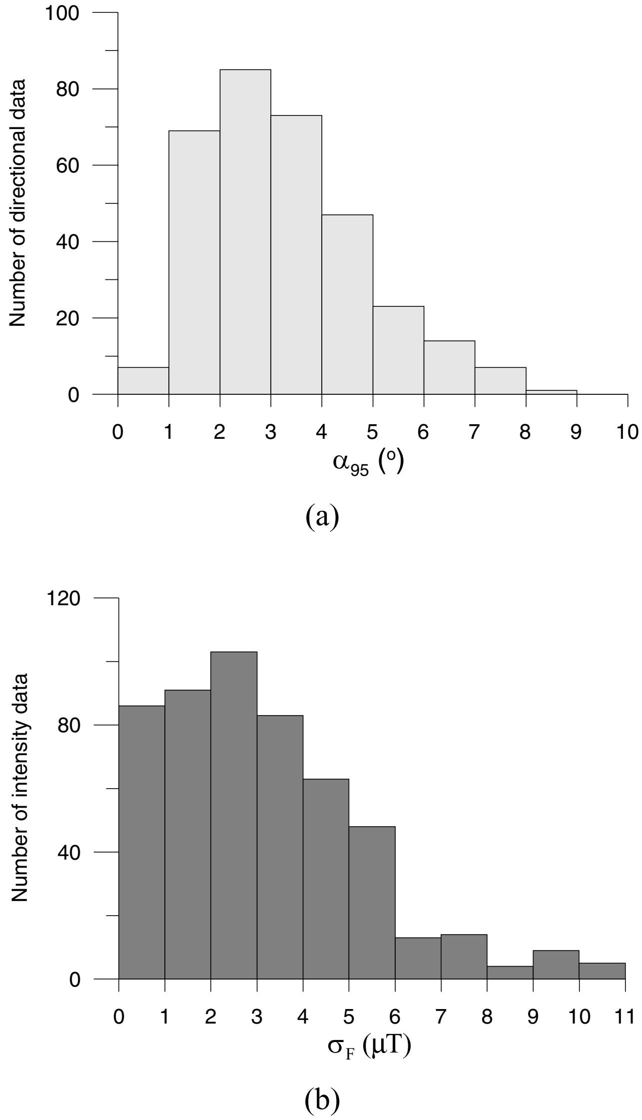


Figure 2. Distribution of the (a) α_{95} and (b) σ_F of the selected Balkan directional and intensity data, respectively.

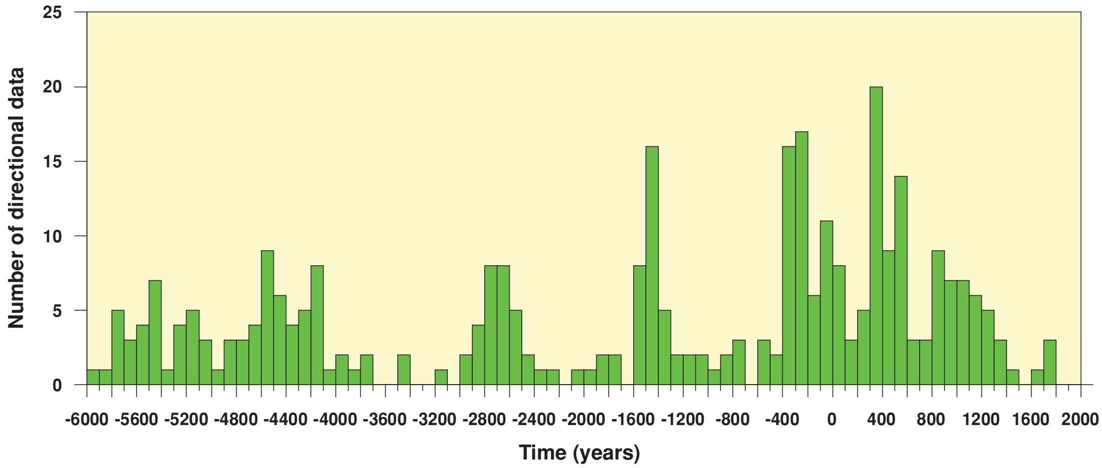
methods for curve building are the moving average technique (Le Goff 1990; Le Goff *et al*. 1992; 2002) and the most recently proposed hierarchical Bayesian approach (Lanos 2004; Lanos *et al*. 2005). Both methods give very similar results (Gómez-Paccard *et al*. 2006b; Márton & Ferencz 2006); the main differences being the smoothing degree and the estimation of the error margins (Lanos *et al*. 2005, Gómez-Paccard *et al*. 2006b). In this study, the Balkan SV curves were calculated using the sliding moving window method applying the bivariate approach for the average direction calculation (Le Goff *et al*. 1992; Daly & Le Goff 1996; Le Goff *et al*. 2002), as previously done for the French SV curve (Gallet *et al*. 2002). According to this technique, data are weighted on the proportion of their dating range that overlaps each time window and vectorial mean directions are calculated through successive time intervals. No further weighting (based on α_{95} and σ_F errors) is applied (for details on the technique, see Le Goff *et al*. 2002). The mean directions are estimated using the bivariate extension of the Fisher statistics. The directional computations were carried out using the program developed by Le Goff *et al*. (2002) (available online at: http://www.ipgp.fr/~legoff/DownLoad-Modules) that gives also the possibility to automatically adjust the window size and the step interval (half of the moving window size) according to the data density within each time window. Several curves were computed using sliding windows of different durations (80, 100, 150 and 200 yr) as well as the automatically adjusted windows with minimum size of 50 yr and maximum window size of 200 yr. In all cases very similar results were obtained, demonstrating the stability of the SV path during smoothing. The final curves for direction were obtained using the automatically adjusted time windows (Le Goff *et al*. 2002) and the intensity curve using moving windows of 200 yr overlapped by 100 yr, which reasonably reflects the resolution allowed by the present data set, avoiding important wiggle effects. The calculated curves are plotted along with the original data in Fig. 5.

The declination and inclination curves obtained are continuous and well constrained for almost all the last 8000 years and they clearly describe the main features of the Earth's magnetic field variations in the area (Fig. 5). They show western declinations around 6000 BC that are accompanied by an inclination maximum at 5900 BC. Then declination rapidly increases towards eastern values and reaches a maximum at 5200 BC while at the same time inclination decreases with low values around 5200 BC. From 5200 BC to 4100 BC the declination shows small variations and remains eastern while around 3800 BC a declination decrease (western declination) is observed followed by almost constant and around zero values during the 3rd millennium BC. For the periods around 3500 BC and 2200 BC the directional curves are characterized by large error bars because of the small number of reference data. However for the last 4000 years the curves are very detailed showing a clear declination maximum at 900 BC followed by a rapid decrease up to 400 BC. A similar pattern can also be noted in the recent AD times, when eastern maximum is recorded at 1400 AD followed again by an important decrease that leads to western declinations around 1800 AD. Clear inclination minima are observed at 300 AD and 1300 AD and inclination maxima at 1000 AD and 1600 AD.

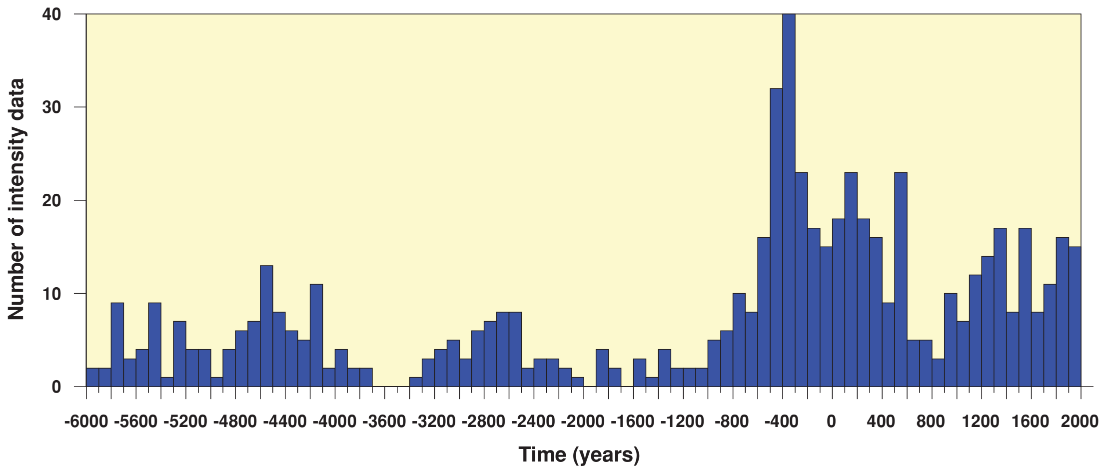
Several features of the geomagnetic field intensity variation during the last eight millennia can be seen (Fig. 5c). High values appear at the end of the 6th millennium BC. High intensity peaks are also observed around 4500 BC and 3700 BC. From 3200 BC to 500 BC the intensity seems to gradually increase with some fluctuations and intensity peaks around 2500 BC, 1600 BC, 1000 BC and 500 BC. During the roman period intensity is quite stable around 60 μT. During the last 1000 years a strong decline is recorded, with only a short exception of a small intensity increase around 1600 AD.

4 COMPARISON WITH GLOBAL AND REGIONAL GEOMAGNETIC FIELD MODELS

The Balkan curves are compared with the CALS7K.2 and ARCH3K.1 global, and the SCHA.DIF.3K and SCHA.DIF.8K regional geomagnetic field models. The CALS7K.2 belongs to the first series of the CALS family of continuous global geomagnetic field models and is determined by regularized least-squares inversion of archaeomagnetic, volcanic and lake sediment data using spherical harmonics in space and cubic B splines in time (Korte & Constable 2005). It is the only global model available up to now that covers the past 7000 years, from 5000 BC to 1950 AD. Following the same modelling concept with the CALS models, Korte *et al*. (2009) have recently proposed the ARCH3K.1 archaeomagnetic model which is based on the updated global database published by Donadini



(a)



(b)

Figure 3. Time distribution of the Balkan (a) directional and (b) intensity data.

et al. (2009). The ARCH3K.1 that contains only data coming from archaeological material and volcanic rocks has a higher resolution in Europe that makes it more reliable for archaeomagnetic applications than the models including sediment records (Korte *et al*. 2009). Nevertheless, this model covers only the last three millennia. An intermediate approach between global models and local SV curves is the calculation of regional models. Pavón-Carrasco *et al*. (2009) have proposed a regional archaeomagnetic model that produces the geomagnetic field variations in Europe for the last 3000 years, modelling together the three geomagnetic elements. This model, SCHA.DIF.3K, has been obtained by least sums of absolute deviation inversion of archaeomagnetic data using spherical cap harmonics for the spatial representation of the field and sliding windows in time. In the model's input database (essentially based on the database of Korte *et al*. 2005) only archaeological material has been used and no lake sediment and lava flow data were considered (Pavón-Carrasco *et al*. 2009). The SCHA.DIF.3K model directly predicts the geomagnetic field at the site of interest, avoiding, in this way, any eventual relocation error. To extend the SCHA.DIF.3K model predictions backwards in time, Pavón-Carrasco *et al*. (2010) have recently proposed the SCHA.DIF.8K regional model that is based on a selected compilation of both sedimentary and archaeomagnetic data and predicts the geomagnetic field variations from 6000 BC to 1000 BC (Pavón-Carrasco *et al*. 2010).

Comparison of the Balkan curves with the models' predictions (Fig. 6) shows good agreement for the last 3000 years but some differences for periods older than 1000 BC. For this reason the two time intervals are discussed separately; first the last 3000 years and then the 5000 years before. The eastern declinations clearly seen in the Balkan curves around 1000 BC are also well predicted by the ARCH3K.1 and SCHA.DIF.3K models. A very good agreement is also noted for the period from 500 BC to 1000 AD with a well-documented declination low around 700 AD. The two inclination lows around 300 AD and 1350 AD are in excellent agreement among all curves and the two inclination high peaks around 800 AD and 1600 AD are also well shown in both the Balkan curves and the models. The intensity curve fits reasonably the models; nevertheless the ARCH3K.1 model shows slightly smoother intensity values. Both the Balkan and SCHA.DIF.3K curves show some small fluctuations that are probably the result of the smoothing and modelling techniques applied and do not necessarily have any physical meaning.

For periods older than the last three millennia, only the CALS7K.2 and SCHA.DIF.8K models are available for comparison. However, both models include sedimentary records in their

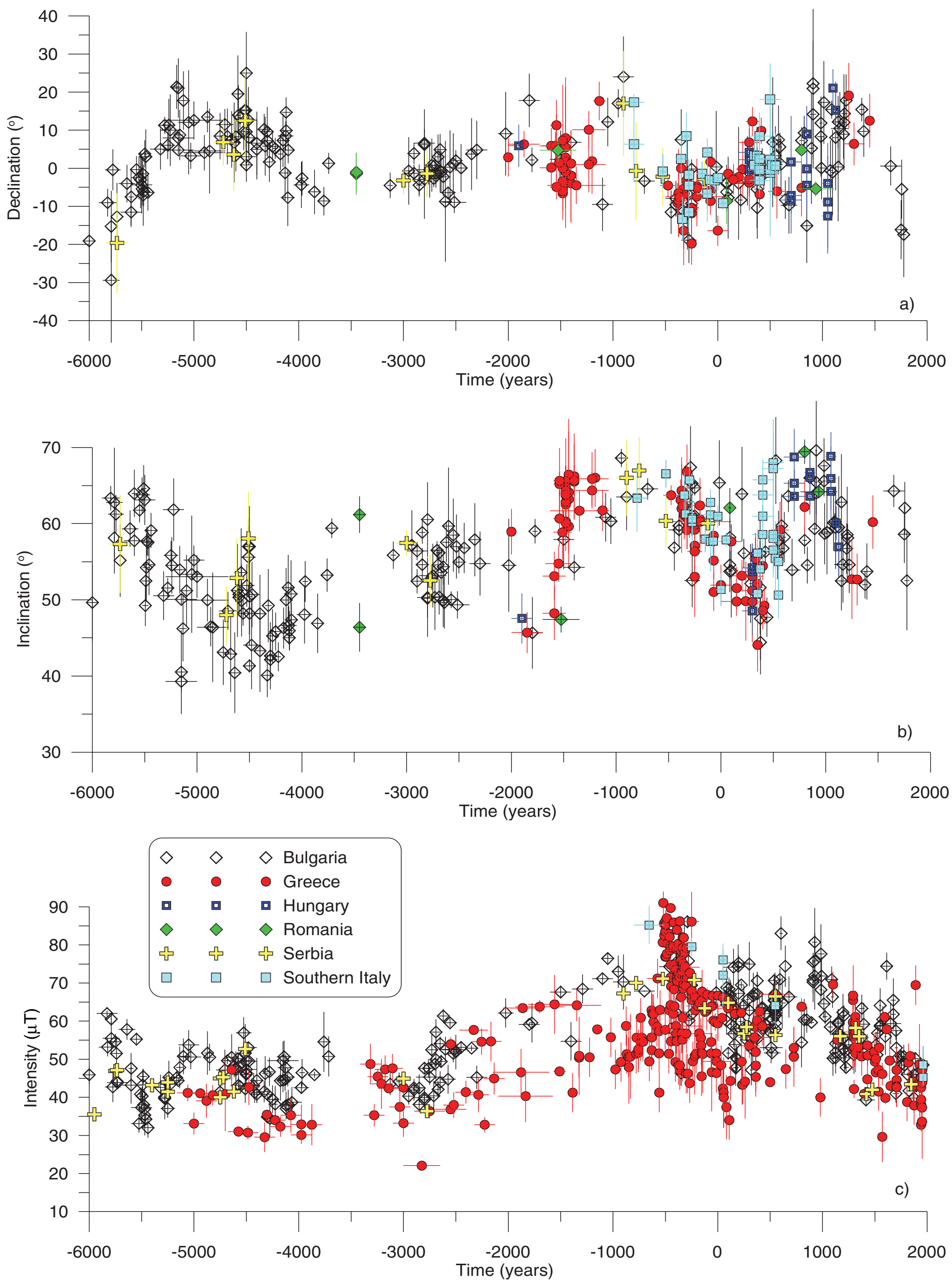


Figure 4. Balkan (a) declination, (b) inclination and (c) intensity data plotted versus age together with measurement errors (dD, dI, σ) and age uncertainties. Different symbols correspond to data coming from different countries of the Balkan Peninsula. All data are reduced to Thessaloniki (40.60° N, 23.00° E).

reference database and therefore suffer from an over-smoothing effect due to the already smoothed raw data and to a possible compaction effect of the lake sediment data. Indeed, the CALS7K.2 global model shows regularly important smoother variations compared with the Balkan curves. Such over-smoothing is clearly visible for the 1000 BC to 500 BC period, where both the Balkan and the regional model curves show high declinations while the CALS7K.2 model show stable and around zero values. The SCHA.DIF.8K model fits the Balkan curves better. The declinations predicted from the SCHA.DIF.8K model are in good agreement with the Balkan declination curve and lie mostly within its error band. However some important differences are observed at the inclination curve where the SCHA.DIF.8K model shows smoother variations missing most of the short term variations and recording much smoother maxima and minima (e.g. 4300–4600 BC). The intensity SCHA.DIF.8K curve successfully matches the general trend of the intensity variation in the Balkan area showing some main characteristics, for example, the intensity minimum at 5500 BC and some slight maxima at

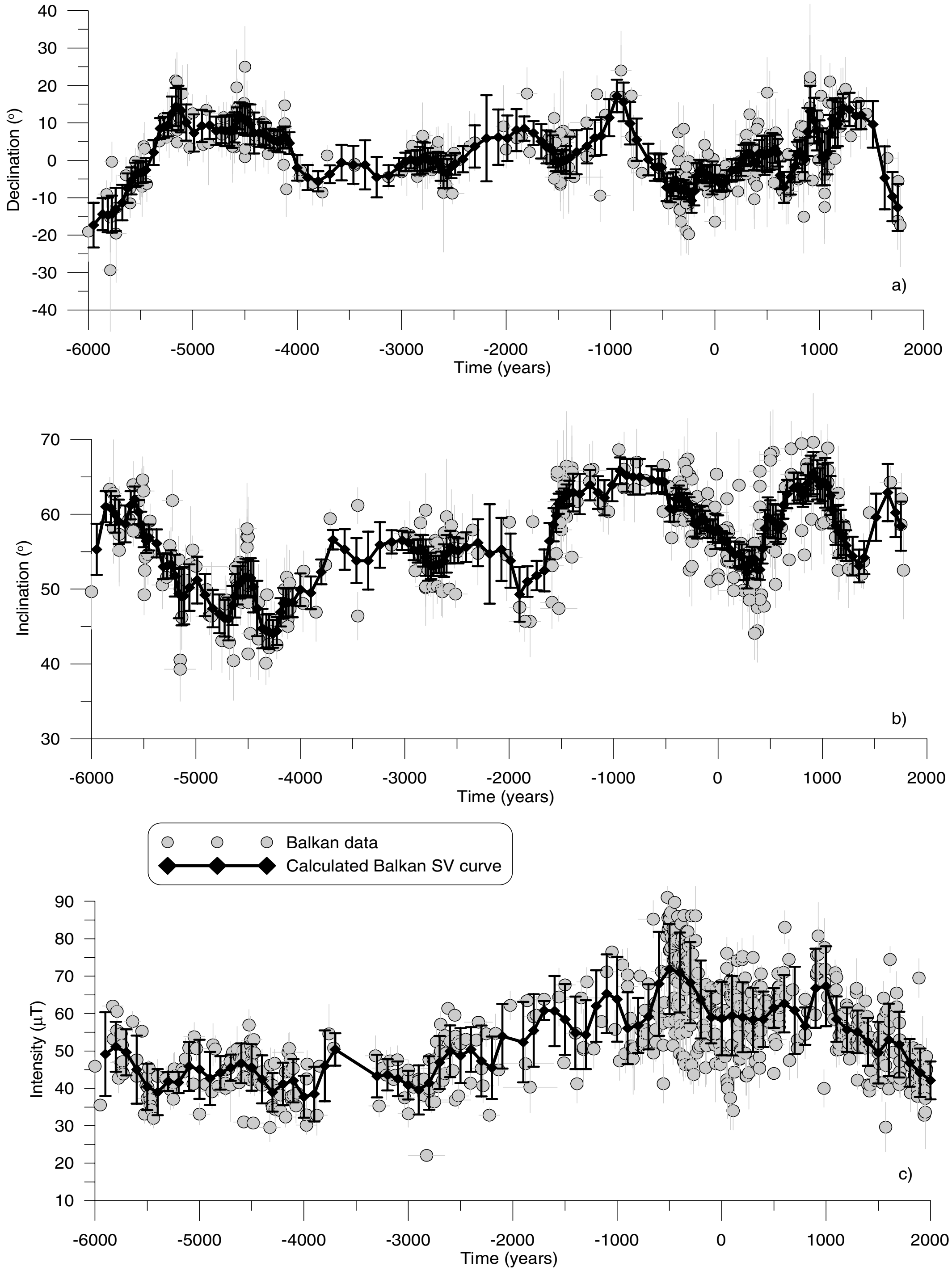


Figure 5. The computed Balkan SV curves for (a) declination, (b) inclination and (c) intensity with uncertainties bars plotted together with the raw data.

4500 BC and 4200 BC, but again it shows a smoother intensity variation path. As previously discussed, this smoothing effect noted in the SCHA.DIF.8K model could be due to the use of lake sediment data which tend to smooth the variation pattern (Pavón-Carrasco *et al*. 2010). However, regional models seem to better describe local variations of the geomagnetic field than do the global models.

5 ARCHAEOMAGNETIC JERKS

Genevey & Gallet (2002) and Gallet *et al*. (2003) have indentified, in the French archaeomagnetic records over the last three millennia, several periods characterized by rapid changes of the geomagnetic field that they called 'archaeomagnetic jerks (AMJ)'. According to these authors, AMJ are defined as short periods (<100 yr) when sharp changes in the direction of the geomagnetic field coincide with intensity maxima. Gallet *et al*. (2003; 2005) have detected four AMJ for the last 3000 years analysing data from western Europe and eastern Mediterranean. However, the origin of these jerks and their geographic appearance is still unclear (Dumberry & Finlay 2007; Gallet *et al*. 2009). Gallet *et al*. (2005) initially proposed that they are possibly related to episodes of strongly inclined dipole while Dumberry & Finlay (2007) suggested that they may be caused

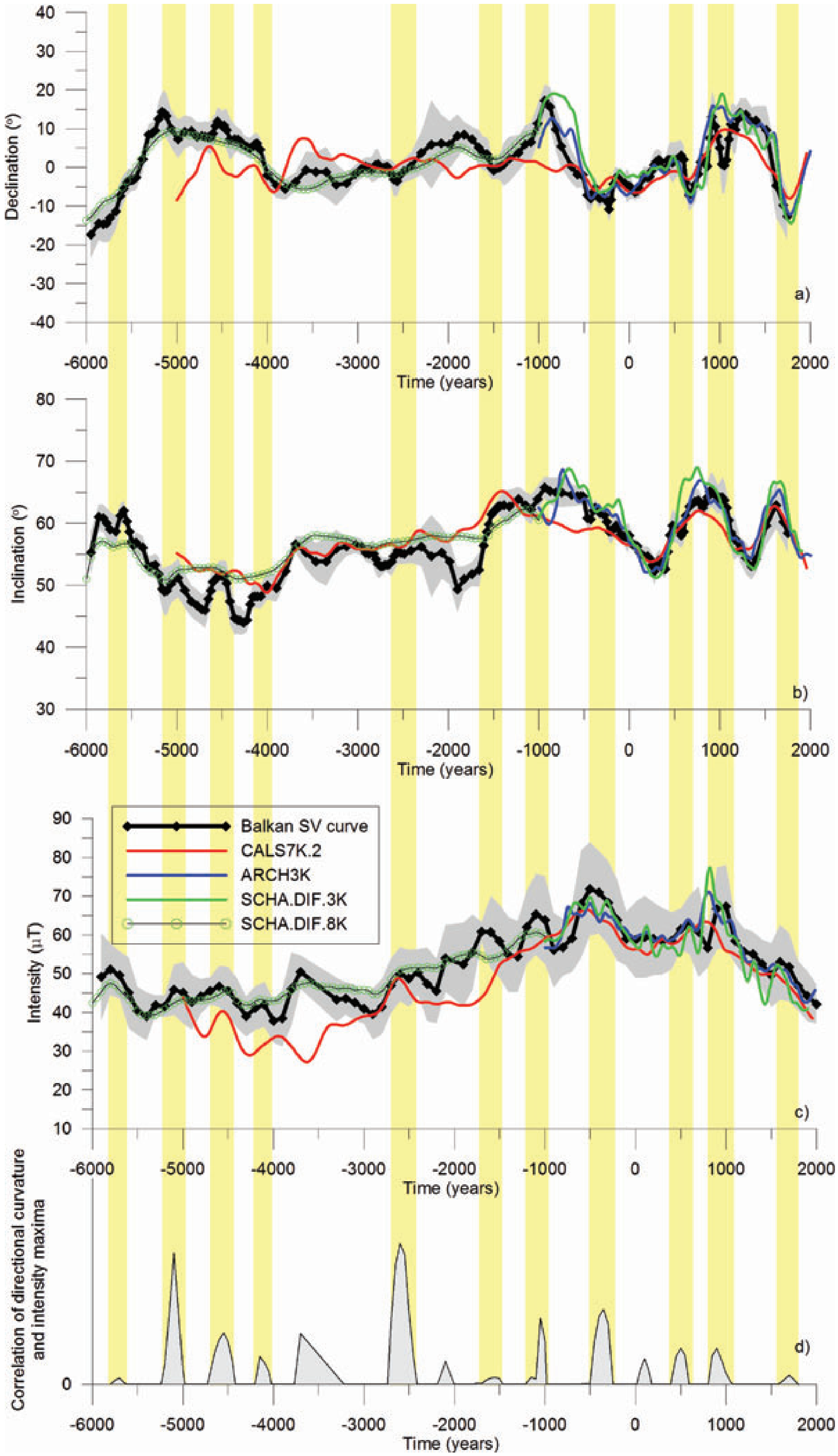


Figure 6. The Balkan (a) declination, (b) inclination and (c) intensity SV curves (black diamonds) accompanied by the uncertainties envelopes (grey bands) plotted together with the predictions of the CALS7K.2 and ARCH3K.1 global and SCHA.DIF.3K and SCHA.DIF.8K regional geomagnetic field models; (d) Correlation of directional curvature and intensity maxima. The yellow vertical bands show the possible archaeomagnetic jerks identified for the last 8000 years. All curves are calculated at Thessaloniki (40.60º N, 23.00º E).

by a change in the direction of the dominant azimuthal flow near to the core surface in the vicinity of the observed sites. Nevertheless, Finlay (2008) studying time-dependent geomagnetic field models constructed from global databases of historical and archaeomagnetic data spanning the past 400 years, found no evidence for rapid large amplitude motions of the geomagnetic dipole towards low latitudes in 1600 AD and 1800 AD required by the tilting dipole hypothesis of Gallet *et al*. (2005).

The Balkan SV curves can be used to check if the AMJ identified in Western Europe are also visible in south-eastern Europe. Following the definition of the AMJ proposed by Gallet *et al*. (2003, 2005), the curves were examined for periods when there were simultaneous occurrences of intensity maxima and directional curvature changes. The changes in curvature of the directional curve and the intensity maxima were computed by applying the equations used by Pavón-Carrasco *et al*. (2010), after slightly smoothing both directional and intensity curves to eliminate spurious effects due to locally scattered data and window technique computations. The correlation of the directional curvature and intensity maxima (Fig. 6d) indicates that several possible AMJ may have occurred in the Balkan Peninsula during the last eight millennia; the best defined are around: 5800 BC, 5100 BC, 4600 BC, 4100 BC, 2500 BC, 1600 BC, 1000 BC, 450 BC, 600 AD, 900 AD and 1650 AD (Fig. 6). Many of these are consistent with the AMJs proposed by Pavón-Carrasco *et al*. (2010) (fig. 11c, in Pavón-Carrasco *et al*. 2010) who used the SCHA.DIF.3K and SCHA.DIF.8K models predictions to calculate the spatial averaged maxima intensity and curvature over Europe. Nevertheless, not all the AMJs proposed by Gallet *et al*. (2005) and Pavón-Carrasco *et al*. (2010) were indentified in the Balkan curves, generally because no clear intensity maxima were recorded (Fig. 5); for example, for the AMJ1400 and AMJ 200 proposed by Gallet *et al*. (2005), the Balkan curves show clearly sharp changes in the direction but these are not accompanied by well defined intensity maxima. However, it should be taken into account that the intensity reference data in the Balkan curves, although numerous, are strongly dispersed for certain periods and therefore some of the intensity maxima and minima are less evident if the uncertainties of the curves are considered. Improvements in the precision of the intensity curve, by obtaining high quality intensity data from well-dated archaeological material, is still necessary to reach clear conclusions about the presence and the frequency of AMJs in Europe.

6 CONCLUSIONS

It is considered that both directional and intensity archaeomagnetic SV curves for the Balkan Peninsula are now quite well established for the last 8000 years. These curves are based on a large number of data within a 700 km radius of Thessaloniki and allow a complete description of the full geomagnetic field vector (declination, inclination and intensity) for this area. They can be used as reference curves for archaeomagnetic dating even in countries where for the moment only few or no data are available (e.g. Albania, Romania and Turkey), though attention should be paid for the time intervals where they are characterized by large errors. The proposed Balkan curves clearly describe the main characteristics of the variation of Earth's magnetic field and can contribute to better understand the possible rapid changes of the geomagnetic field (AMJ) previously indentified in western Europe.

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APPENDIX

Data from Thomas (1981)

In this study, the Greek archaeointensity data from Thomas (1981) have been used rather than the data included in the GEOMAGIA50 database that come from the later publication of Thomas (1983), where, however, no table with individual results and discussion on the data retrieved from a figure, is included. Thomas (1981) has performed thorough laboratory work including magnetic mineralogy experiments, viscosity measurements and anisotropy tests and according to these, she has rated her results in four categories: 1 (very good), 2 (good), 3 (medium) and 4 (poor/rejected). In this study only the very good and good results have been used and are listed in the Table A1 below.

Data from Nachasova *et al*. (2002)

In this study, data from Nachasova *et al*. (2002) found in the GEOMAGIA50 database have been replaced by the data from the most recent publications of Nachasova *et al*. (2007) and (2008). Corrections have been applied to the geographic coordinates of the data, referred as Lat = 39.50º and Long = 30.00º in the GEOMAGIA50 database. Nachasova *et al*. (2007), (2008) have studied ceramics imported from the Greek islands of Kos, Lesbos, Thasos, Chios and Rhodes and from Asia Minor (Heracleia and Sinop), found at the archaeological sites of Nymphaion and Panticapaeum at the Crimean Peninsula. In the reference data set of this study, data from Sinop (from Table A1 in Nachasova *et al*. 2008) and Heracleia that are outside of our study area (Burakov, personal communication, 2011) have been excluded. For the rest of data, the geographic coordinates of Chios Island (Lat = 38.60º, Long = 26.10º) have been used as Chios is situated more or less in the centre of the Kos, Lesbos, Thasos, Chios and Rhodes geographic area.

Table A1. Archaeointensity results from Greece, from the tables 6.4, 6.8 and 6.11 of Thomas (1981). Columns: Age = the age of the sites is based on Radiocarbon and Thermoluminence dating of several occupation levels related with the studied material. For the Sitagroi site three different ages for individual levels are proposed (A, B, C) according to the occupation phase of the site. In the table above the age B is used as, according to Thomas (1981), it is the most probable age; σ_{Age} = age uncertainty in years. For the Sitagroi site a mean age uncertainty of 100 yr is used, according to radiocarbon data. Data from Sesklo/Dimini listed above have not been used in this study because of $\sigma_{\mathrm{Age}} > 300$ yr; Lat/Long = site latitude/longitude; N/n = number of samples/specimens. In most cases results come from only one or two specimens but in a time interval of 100 to 200 yr at least three results are available; F_{a} = intensity in μT; σ_{Fa} = standard deviation; Locality; Site; Reference. For further details see Thomas (1981).

Age	σ_{Age}	Lat (º)	Long (º)	N	n	F_{a}	σ_{Fa}	Locality	Site	Reference
−1878	270	35.42	24.52	-	5	43.8	5.8	Crete	Greece	Thomas (1981)
−1834	260	35.18	25.03	-	3	37.8	6.4	Crete	Greece	Thomas (1981)
−1558	250	35.33	24.57	-	5	60.5	7.3	Crete	Greece	Thomas (1981)
−1345	231	35.10	26.25	-	5	60.1	3.9	Crete	Greece	Thomas (1981)
−10	140	35.08	25.68	-	6	46.3	2.9	Crete	Greece	Thomas (1981)
−5918	570	39.35	22.80	1	1	48.7	7.2	Sesklo, Dimini	Greece	Thomas (1981)
−4722	419	39.35	22.80	1	1	32.7	4.8	Sesklo, Dimini	Greece	Thomas (1981)
−4563	370	39.35	22.80	1	1	44.0	5.5	Sesklo, Dimini	Greece	Thomas (1981)
−4440	590	39.35	22.80	1	1	42.8	4.0	Sesklo, Dimini	Greece	Thomas (1981)
−3833	388	39.35	22.80	1	1	44.7	16.6	Sesklo, Dimini	Greece	Thomas (1981)
−3404	390	39.35	22.80	1	1	50.7	2.2	Sesklo, Dimini	Greece	Thomas (1981)
−5060	100	41.10	24.02	1	1	41.4	2.2	Sitagroi	Greece	Thomas (1981)
−5000	100	41.10	24.02	1	1	33.3	2.9	Sitagroi	Greece	Thomas (1981)

Table A1. (*Continued*.)

Age	σ_{Age}	Lat (°)	Long (°)	N	n	F_a	σ_{Fa}	Locality	Site	Reference
−4940	100	41.10	24.02	2	2	41.3	1.1	Sitagroi	Greece	Thomas (1981)
−4880	100	41.10	24.02	2	2	39.3	4.5	Sitagroi	Greece	Thomas (1981)
−4820	100	41.10	24.02	1	1	40.8	2.7	Sitagroi	Greece	Thomas (1981)
−4700	100	41.10	24.02	1	1	41.1	9.8	Sitagroi	Greece	Thomas (1981)
−4640	100	41.10	24.02	1	1	47.5	4.5	Sitagroi	Greece	Thomas (1981)
−4575	100	41.10	24.02	1	2	31.2	1.5	Sitagroi	Greece	Thomas (1981)
−4485	100	41.10	24.02	1	1	30.9	1.8	Sitagroi	Greece	Thomas (1981)
−4475	100	41.10	24.02	1	1	42.9	4.7	Sitagroi	Greece	Thomas (1981)
−4325	100	41.10	24.02	1	2	29.7	3.9	Sitagroi	Greece	Thomas (1981)
−4225	100	41.10	24.02	2	2	34.2	0.1	Sitagroi	Greece	Thomas (1981)
−4175	100	41.10	24.02	2	2	32.5	2.7	Sitagroi	Greece	Thomas (1981)
−4075	100	41.10	24.02	1	1	35.5	4.6	Sitagroi	Greece	Thomas (1981)
−3975	100	41.10	24.02	1	1	30.3	1.5	Sitagroi	Greece	Thomas (1981)
−3975	100	41.10	24.02	1	1	33.1	5.2	Sitagroi	Greece	Thomas (1981)
−3875	100	41.10	24.02	1	1	33.0	5.4	Sitagroi	Greece	Thomas (1981)
−3315	100	41.10	24.02	1	1	49.0	5.4	Sitagroi	Greece	Thomas (1981)
−3280	100	41.10	24.02	1	1	35.5	3.0	Sitagroi	Greece	Thomas (1981)
−3245	100	41.10	24.02	1	1	45.7	2.1	Sitagroi	Greece	Thomas (1981)
−3210	100	41.10	24.02	1	1	43.8	6.6	Sitagroi	Greece	Thomas (1981)
−3175	100	41.10	24.02	1	1	47.6	3.7	Sitagroi	Greece	Thomas (1981)
−3140	100	41.10	24.02	1	1	42.6	1.2	Sitagroi	Greece	Thomas (1981)
−3105	100	41.10	24.02	1	3	47.9	3.8	Sitagroi	Greece	Thomas (1981)
−3035	100	41.10	24.02	1	1	37.7	4.9	Sitagroi	Greece	Thomas (1981)
−3000	100	41.10	24.02	2	2	42.8	1.9	Sitagroi	Greece	Thomas (1981)
−3000	100	41.10	24.02	1	1	33.4	3.6	Sitagroi	Greece	Thomas (1981)
−2520	100	41.10	24.02	1	1	38.2	3.4	Sitagroi	Greece	Thomas (1981)
−2405	100	41.10	24.02	1	1	41.6	3.0	Sitagroi	Greece	Thomas (1981)
−2285	100	41.10	24.02	1	1	40.9	4.6	Sitagroi	Greece	Thomas (1981)
−2255	100	41.10	24.02	2	2	54.9	3.5	Sitagroi	Greece	Thomas (1981)
−2225	100	41.10	24.02	2	2	33.0	2.0	Sitagroi	Greece	Thomas (1981)
−2165	100	41.10	24.02	1	1	55.0	5.2	Sitagroi	Greece	Thomas (1981)
−2135	100	41.10	24.02	1	2	45.2	4.2	Sitagroi	Greece	Thomas (1981)