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THE ARCHAEOINTENSITY OF THE EARTH'S MAGNETIC FIELD RETRIEVED FROM PAMPEAN CERAMICS (SOUTH AMERICA)*

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Absolute intensity determinations using the Coe variant of the Thellier method have been carried out on some selected pottery fragments collected in the wetlands of the lower Paraná (Pampean region, Argentina) in order to construct the first archaeointensity master curve for South America. Associated radiometric ages range between 1640 ± 70 and 730 ± 70 BP. Twenty-one samples (five fragments) out of 46 studied (eight fragments) provided successful absolute intensity determinations. The fragment-mean archaeointensity values obtained in this study range from 21.9 ± 2.3 to 42.6 ± 5.4 μT, with corresponding virtual axial dipole moments (VADMs) ranging from 4.0 ± 0.5 to 8.1 ± 1.0 x 10^{22}Am^2. This corresponds to a mean VADM of (6.4 ± 1.8) × 10^{22} Am^2. The synthetic record retrieved from southern Argentina and Brazil consists of 17 mean archaeointensities distributed between approximately AD 700 and AD 1700. The data set shows several distinct periods of fluctuations of quite large intensity. However, most data are concentrated into a relatively narrow time period from AD 950 to AD 1300. Three general features may be detected: the time intervals from about AD 950 to 1130 and 1350 to 1480 are characterized by quite monotonic increases of geomagnetic intensity, while some decrease is observed from AD 1150 to 1280. These variations may be speculatively correlated to climate changes over multi-decadal time scales. Important differences are observed between the data and the geomagnetic field predictions derived from recently reported global models, which reinforces the importance of regional reference curves for dating purposes.

KEYWORDS: ARCHAEOMAGNETISM, GEOMAGNETIC FIELD, POTTERY, PAMPA, PARANÁ, ARGENTINA, CLIMATE CHANGE

INTRODUCTION

Many archaeological materials contain magnetic particles and acquire a magnetization at some specific time that depends on the direction and intensity of the Earth's magnetic field. The time of acquisition of magnetization can be determined by comparison of the magnetic parameters of such materials from an archaeological site with an already dated record of the past geomagnetic field in the same region, known as a master curve. Where the past variations of Earth's magnetic field, and thus the master curves, are well established, such as in Europe, archaeomagnetic dating can be as precise as the more expensive radiometric dating, and does not depend on the availability of suitable carbon-bearing material.

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Archaeomagnetism may be considered as an almost ideal example of interdisciplinary research. It allows revelation of the fine characteristics of the evolution of the Earth's magnetic field during the past few millennia retrieved from baked archaeological materials such as potteries, bricks and furnaces, among others (Gallet *et al.* 2009). The Earth's magnetic field is generated by geodynamic processes in the Earth's liquid outer core and is not static, as its direction and strength vary over time. Thus, knowledge of the characteristics of the ancient geomagnetic field can provide important information in order to better understand and constrain the processes related to the evolution of the Earth's deep interior. On the other hand, the archaeologist stands to learn about the relative and absolute dating of baked features (Tarling 1983; Eighmy and Sternberg 1990; Sternberg 2008). Recent investigations also suggest a connection between the geomagnetic field and climatic changes during the Holocene (Courtillot *et al.* 2007).

The whole of South America may still be considered as *terra incognita,* from an archaeointensity point of view. Apart from some limited studies in Peru (Shaw *et al.* 1996) and Ecuador (Bowles *et al.* 2002) using modern techniques, no systematic measurements have been performed. The principal limitation of studies of this kind is that most archaeological material available for archaeomagnetism is not oriented. Thus, relatively few palaeodirections (magnetic declination and inclination) of the geomagnetic field could be obtained. In contrast, an absolute archaeointensity study has the great advantage that no oriented material is required. Hartmann *et al.* (2010) recently reported the first archaeointensity results from north-east Brazil obtained from 14 groups of architectural brick fragments sampled in the city of Salvador, Bahia State. However, the study is restricted to a very narrow time interval between the middle of the 16th century and the beginning of the 19th century. Moreover, the general pattern of the archaeointensity record obtained is quite different for two different studied sites, probably because of the non-dipole components of today's geomagnetic field.

Here, we report new absolute archaeointensity results from Pampean ceramics (Argentina), which present several advantages: (1) the samples come from well-constrained, modern excavations; (2) they may be unambiguously correlated with available radiometric dates (Acosta, 2005); and (3) they mainly contain magnetically stable minerals such as Ti-poor titanomagnetites, which are expected to faithfully record the Earth's magnetic field during cooling.

THE LOCAL ARCHAEOLOGY AND CONTEXTUAL INFORMATION ABOUT THE POTTERY SAMPLES ANALYSED

The pottery samples analysed in this paper were recovered at four archaeological sites (Cerro Lutz, Las Vizcacheras, Túmulo de Campana site 2 and La Bellaca site 1; see Fig. 1) located in a small area of the wetlands of the lower Paraná (WLP), within a geographical range of 50 km. This area (Fig. 1) is situated in the central-east sector of the Pampean region (Argentina) on parallel 34°SL. In the ecological vein, this landscape belongs to the 'Delta and Paraná islands' unit (*sensu* Burkart *et al.* 1999), one of the most productive ecosystems of the world (Neiff 1999).

These archaeological sites were generated by hunter–gatherer societies that have inhabited the area during the past two millennia, approximately. The first archaeological research in the area dated from the late 19th century and the early 20th century (e.g., Zeballos and Pico 1878; Torres 1902, 1907, 1911). Modern archaeological studies based on multidisciplinary approaches (technology, archaeofauna, isotopic analyses and landscape evolution studies, among others) suggest that the hunter–gatherer systems had low residential mobility with a small terrestrial foraging

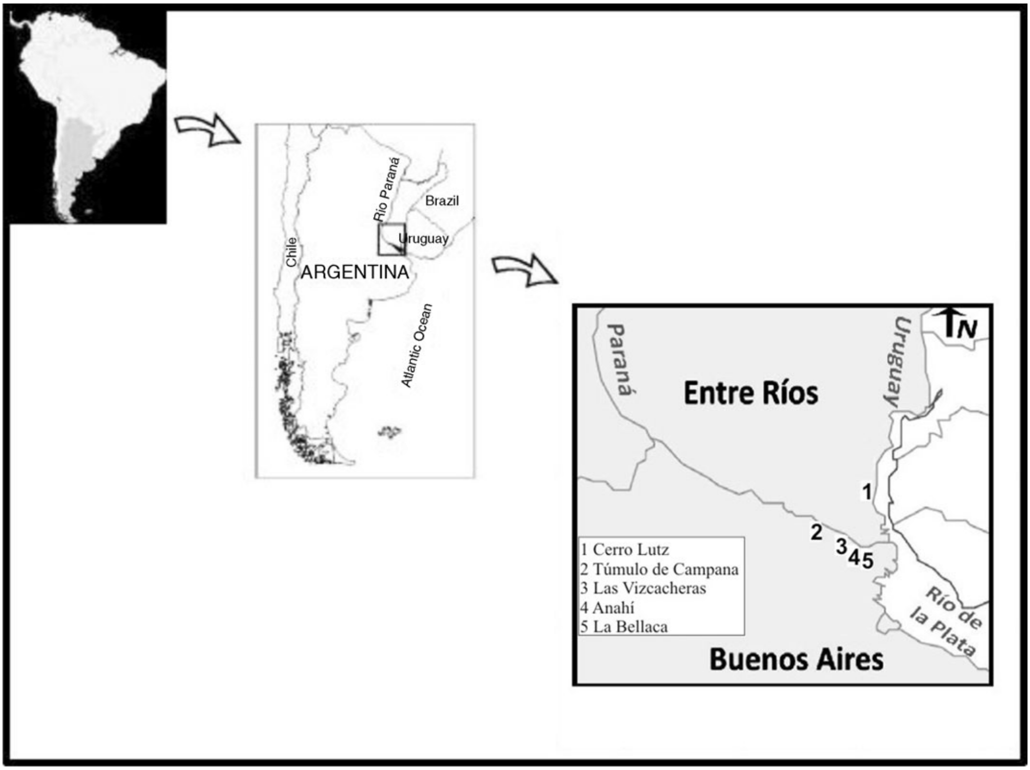

Figure 1 *A schematic location map of the archaeological sites in the wetlands of the lower Paraná.*

range, but that this was possibly extended in fluvial sectors due to the use of canoes (Loponte 2008). Subsistence was mainly based on exploitation and consumption of fish (Silurids and Characiforms) and vegetables, besides systematic and intensive use of deer species (*Ozotoceros bezoarticus* and *Blastocerus dichotomus*) and rodents (*Cavia aperea* and *Myocastor coypus*) (Loponte and Acosta 2004; Acosta 2005; Acosta *et al.* 2007; Loponte 2008). Exploitation of plants would have implied some manipulation, such as incidental domestication (*sensu* Rindos 1984) and/or small-scale production of some species (cf., Loponte 2008). Moreover, a complex technological *package* included a great variety of bone and lithic tools, and pottery vessels for cooking purposes. The ceramic artefacts are small to medium bowls, with a carrying capacity between 1 and 12 litres. All pottery was produced locally, where remains of crude paste and several instruments to smooth the surface of the vessels were also recovered (Loponte 2008). The archaeological layers are organic soils, and the depth of each occupation varies between 40 and 60 cm. Several properties of the archaeological contexts, such as the pottery style, the reassembly of artefacts, the soil micromorphology and the radiocarbon dates, suggest unique occupation of each site. In a few cases, when distinct occupation phases are suspected to coexist, the time interval between them is generally less than 50 years (Loponte 2008).

The present study is supported by seven radiocarbon ages. These ages vary between 1640 ± 140 and 730 ± 140 ^{14}C BP (Table 1). All radiocarbon dates were obtained from bones of hunted prey or burned seeds included in each archaeological deposit associated, in the same layers, with the pottery analysed here (Loponte 2008), except for Cerro Lutz, where radiocarbon

Table 1 *The pottery samples analysed in this study and associated radiometric* (C^{14}) *ages calibrated using a Cal Pal program (for details, see http://www.calpal.de)*

Site	*Latitude*	*Longitude*	*Laboratory code*	^{14}C *AP* ± *1s*	*Calibrated dates* (BP)	*Calibrated dates* (AD)	*Sample dated*
Cerro Lutz	33°38′47″	58°36′20″	LP-1711	730 ± 70	665 ± 66	1285 ± 66	*Homo sapiens* bone
Cerro Lutz			AA77311	796 ± 42	724 ± 30	1226 ± 30	*Homo sapiens* bone
Las Vizcacheras	34°16′81″	58°48′65″	Beta 148237	1090 ± 40	1007 ± 42	943 ± 42	*Lama guanicoe* bone
Las Vizcacheras			LP-1401	1070 ± 60	999 ± 55	951 ± 55	*Syagrus romanzoffiana* seeds
Anahí	34°16′95″	58°48′47″	Beta 147108	1020 ± 70	928 ± 87	1022 ± 87	*Myocastor coypus* bone
La Bellaca	34°23′77″	58°40′14″	LP-1288	1110 ± 70	1048 ± 79	902 ± 79	Mammalian bone
Túmulo de Campana	34°11′54″	58°55′14″	Beta 172059	1640 ± 70	1540 ± 94	410 ± 94	Mammalian bone

dates were obtained from human burials related to pottery samples. The ceramic samples come mainly from unpainted vessels. The fragments were previously washed with distilled water and further divided into at least four pieces, and then embedded into salt pellets in order to treat them as standard palaeomagnetic cores (Morales *et al.* 2009). In total, 46 samples from eight fragments were obtained.

THE MAGNETIC EXPERIMENTS

Rock-magnetic experiments were carried out to find out the carriers of the remanent magnetization and to determine their thermal stability. Additionally, these experiments were used as a pre-selection criterion for the choice of suitable samples and temperature intervals for the archaeointensity determinations. They consisted of measurement of (a) the viscosity index, (b) thermomagnetic curves—low-field susceptibility versus temperature (κ–T)—(c) acquisition of the isothermal remanent magnetization (IRM) and (d) Thellier archaeointensity determination (Thellier and Thellier 1959). We believe that the domain state estimation using room-temperature hysteresis parameters (Goguitchaichvili *et al.* 2001) in terms of the plot of magnetization ratio versus coercivity ratio has no resolution for most natural magnetic materials (i.e., rocks and burned archaeological artefacts).

Prior to the archaeointensity determinations, the viscosity index was determined following procedures described in Prévot *et al.* (1983). This allows estimation of the capacity of a sample to acquire a viscous remanent magnetization (VRM), and is therefore useful for obtaining information about its magnetic stability. Three samples from each fragment were subjected to these experiments, and although the viscosity indexes varied between 0 and 12.9%, most values were lower than 5%.

Low-field susceptibility measurements in air were carried out using a Bartington susceptibility bridge, equipped with furnace. One sample from each fragment was heated up to about 600–650°C at a heating rate of 20°C min^{-1} and then cooled at the same rate. Most of the continuous low-field susceptibility versus high-temperature curves show the presence of a single Ti-poor titanomagnetite magnetic phase (Fig. 2, samples LV and TC). Other samples (LB and CWP) seem to contain two ferrimagnetic phases; a Ti-rich titanomagnetite phase (expressed as the inflection at around 200°C) partially disappears during cooling after heating at high temperatures. Both the Ti-rich and the Ti-poor titanomagnetites seem to coexist in these samples.

Isothermal remanent magnetization measurements at room temperature (Fig. 3) were performed on some selected samples using the AGFM 'Micromag' apparatus in fields up to 400 mT. The IRM acquisition curves were very similar for all samples. Saturation is reached in moderate fields of the order of 150–200 mT, which points to some spinels (titanomagnetites) as remanence carriers (sample LV-1, Fig. 3). The exception is sample LB-2, which is not completely saturated at 400 mT. Some higher-coercivity grains, most probably titanohematites, may coexist in these samples together with titanomagnetites.

Although many absolute intensity determination methods have been proposed, those based on the original Thellier method (Thellier and Thellier 1959), which rely on a stringent physical basis, are considered to be the most reliable techniques to retrieve the strength of the geomagnetic field. In this study, the archaeointensity determinations were carried out using the Thellier-type double heating method, as modified by Coe (1967). The experiments were performed using a TD48-SC furnace; all heating/cooling runs were carried out in air. The reproducibility between two heating runs to the same nominal temperature lies within 2°C. The remanence was measured using a JR6 (AGICO LtD) spinner magnetometer.

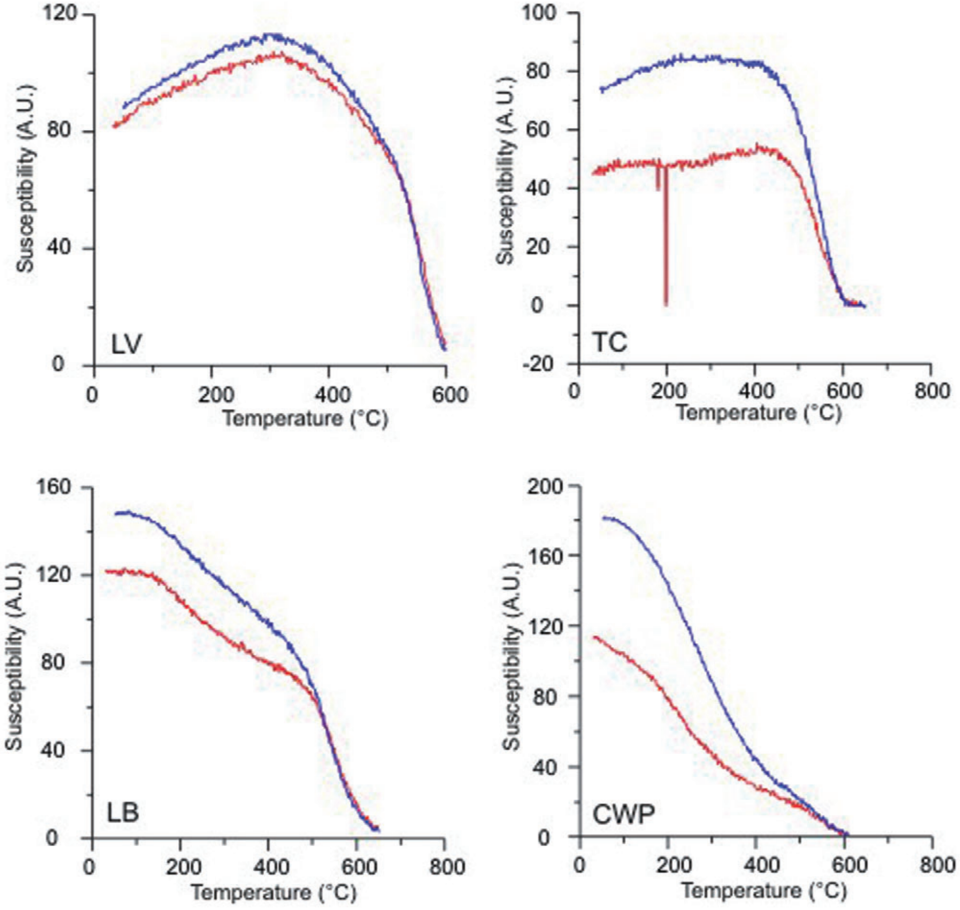

Figure 2 *Susceptibility versus temperature curves for representative samples. The lower (upper) branch corresponds to heating (cooling) curves.*

The archaeointensity experiment was carried out in 10 temperature steps between room temperature and 560°C, and with the laboratory field intensity set to 30 μT. The intensity of the set laboratory fields could be held in all cases with a precision better than 0.15 μT. Whether an archaeointensity determination is considered to be reliable depends on a set of chosen criteria regarding the quality of the experiment, the occurrence of alteration and the presence of multidomain (MD) related remanent magnetization. In the present study, in order to be considered acceptable, the archaeointensity determinations had to satisfy all of the following requirements (see Table 2 and Fig. 4):

(a) On the NRM–pTRM diagram, the number of aligned points (N) ≥ 5, without considering data suspected to correspond to the VRM acquired *in situ*.

(b) NRM fraction factor (f; Coe *et al*. 1978) ≥ 0.4. This means that 40% of the initial NRM was used for archaeointensity determination.

(c) The quality factor (q; Coe *et al*. 1978) ≥ 3.8 (generally above 5; Table 2), with $q = fg/\beta$.

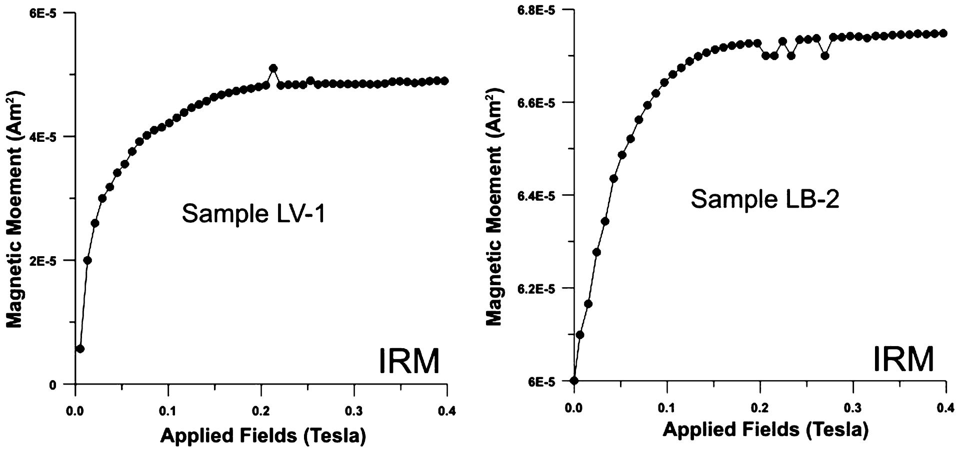

Figure 3 *Examples of isothermal remanent magnetization (IRM) acquisition curves.*

(d) The archaeointensity results obtained from the NRM–pTRM diagrams must not show a clearly concave-up shape, as in such cases remanence is probably related to the presence of multi-domain grains (Levi 1977).

(e) The directions of the NRM end-points at each step obtained from the archaeointensity experiments have to assemble into a reasonably straight line, pointing to the origin in the interval chosen for the archaeointensity determination.

(f) No significant deviation of the NRM directions towards the applied field direction should be observed.

Twenty-one samples (belonging to five fragments—La Bellaca, Las Vizcacheras, Anahí, Cerro Lutz and Túmulo de Campana in Table 2) out of 46 studied provided successful archaeointensity determinations according to the acceptance criteria listed above. Figure 4 displays examples of successful (samples CL-3 and LB1-4) and unsuccessful (sample LB1-1, showing two slopes) archaeointensity experiments, while in Table 2 detailed results of successful archaeointensity determinations are shown. The most common reason for failure of the Thellier absolute intensity experiments is evidence of two different slopes on the NRM–TRM diagrams (the so-called Arai–Nagata plots). This is probably due to magnetic minerals with a multi-domain magnetic structure (Prévot *et al.* 1983).

The cooling rate dependence of the TRM was investigated following a modified procedure described in Chauvin *et al.* (2000). The TRM gained during the last step of the Thellier experiment (575°C) was subsequently designated as TRM1. At the same temperature, a new full TRM (TRM2) was given to all samples, but this time using a long cooling time (~7 h). Finally, a third TRM (TRM3) was created, using the same cooling time (of about 45 min) as that used to create TRM1. The effect of the cooling rate upon the TRM intensity was estimated by calculating the percentage variation between the intensity acquired during a short and a long cooling time (TRM1 and TRM2). The cooling rate effect is calculated as the difference between the fast and slow cooling time acquired magnetizations. It is expressed as a percentage, as TRM = (TRM1–TRM2) / TRM1. Changes in TRM acquisition capacity were estimated by means of the percentage variation between the intensity acquired during the same cooling time (TRM1 and TRM3). A cooling rate correction was applied only when the corresponding change in the TRM acquisition capacity was below 15%.

Table 2 *Archaeointensity results at the sample level. $T_1 - T_2$ is the temperature interval of the intensity determination; N is the number of heating steps used for the intensity determination; m is the slope of the best fit; σ_m is the standard deviation of m; f is the fraction of extrapolated NRM used for the intensity determination; g is the gap factor; q is the quality factor as defined by Coe* et al. *(1978); H is the weighted mean intensity per sample (Prévot* et al. *1983), H_{cor} is the value per potsherd, corrected for the cooling rate effect; H_{Lab} is the intensity of the laboratory field (30 µT); and VADM is the virtual axial dipole moment*

Sites	*Sample*	*Laboratory code*	$T_1 - T_2$	*N*	*m*	$\pm\sigma_m$	*f*	*g*	*q*	*H*	H_{cor}	$\pm\sigma_H$
La Bellaca	LB2–4	10S711	250–540	8	–0.731	0.065	0.535	0.836	5.03	23.13	21.93	1.95
	LB1–4	10S704	250–540	9	–0.794	0.063	0.674	0.855	7.30	25.38	23.82	1.89
	LB1–5	10S705	250–540	9	–0.599	0.043	0.725	0.857	8.58	17.97	17.97	1.29
	LB1–6	10S706	250–540	9	–0.742	0.046	0.679	0.856	9.29	24.61	22.26	1.38
	LB1–7	10S707	250–520	8	–0.779	0.112	0.567	0.797	6.10	27.22	23.37	3.36
									Mean =		21.9	
									s.d. =		2.3	
Las Vizcacheras	LV–3	10S717	20–500	7	–1.205	0.120	0.838	0.798	6.69	38.95	36.15	3.60
	LV–4	10S718	250–540	8	–1.339	0.171	0.656	0.838	4.31	43.53	40.17	5.13
	LV–5	10S719	200–500	8	–2.030	0.236	0.440	0.836	5.20	47.20	45.60	7.08
	LV–7	10S721	200–500	8	–2.096	0.242	0.442	0.834	5.40	53.66	48.30	7.26
									Mean =		42.6	
									s.d. =		5.4	
Anahí	An–2	10S723	250–500	7	–1.482	0.128	0.534	0.824	5.10	48.53	44.46	3.84
	An–3	10S724	20–500	8	–1.225	0.128	0.661	0.808	5.12	37.63	36.75	3.84
	An–4	10S725	20–540	10	–1.081	0.122	0.859	0.859	6.700	35.27	32.43	3.66
	An–5	10S726	250–500	7	–1.292	0.192	0.488	0.819	4.60	41.62	38.76	5.76
									Mean =		38.1	
									s.d. =		5.0	
Cerro Lutz	CL–2	10S730	250–500	7	–1.532	0.130	0.607	0.827	5.90	45.96	45.96	3.90
	CL–3	10S731	20–475	7	–1.199	0.042	0.822	0.817	19.30	38.27	35.97	1.26
	CL–4	10S732	300–500	6	–1.629	0.144	0.555	0.778	5.10	50.30	48.87	4.32
	CL–5	10S733	300–540	8	–1.472	0.118	0.618	0.822	6.36	46.52	44.16	3.54
									Mean =		43.7	
									s.d. =		5.5	
Túmulo de Campana	TC–1	10S736	250–520	8	–1.168	0.140	0.517	0.823	5.60	31.72	28.90	4.20
	TC–2	10S737	300–540	8	–0.984	0.115	0.497	0.754	5.20	32.18	29.52	3.45
	TC–6	10S741	250–500	7	–0.977	0.106	0.569	0.827	4.35	29.31	29.31	3.18
	TC–7	10S742	250–500	7	–0.803	0.076	0.440	0.826	3.81	24.09	24.09	2.28
									Mean =		28.0	
									s.d. =		2.6	

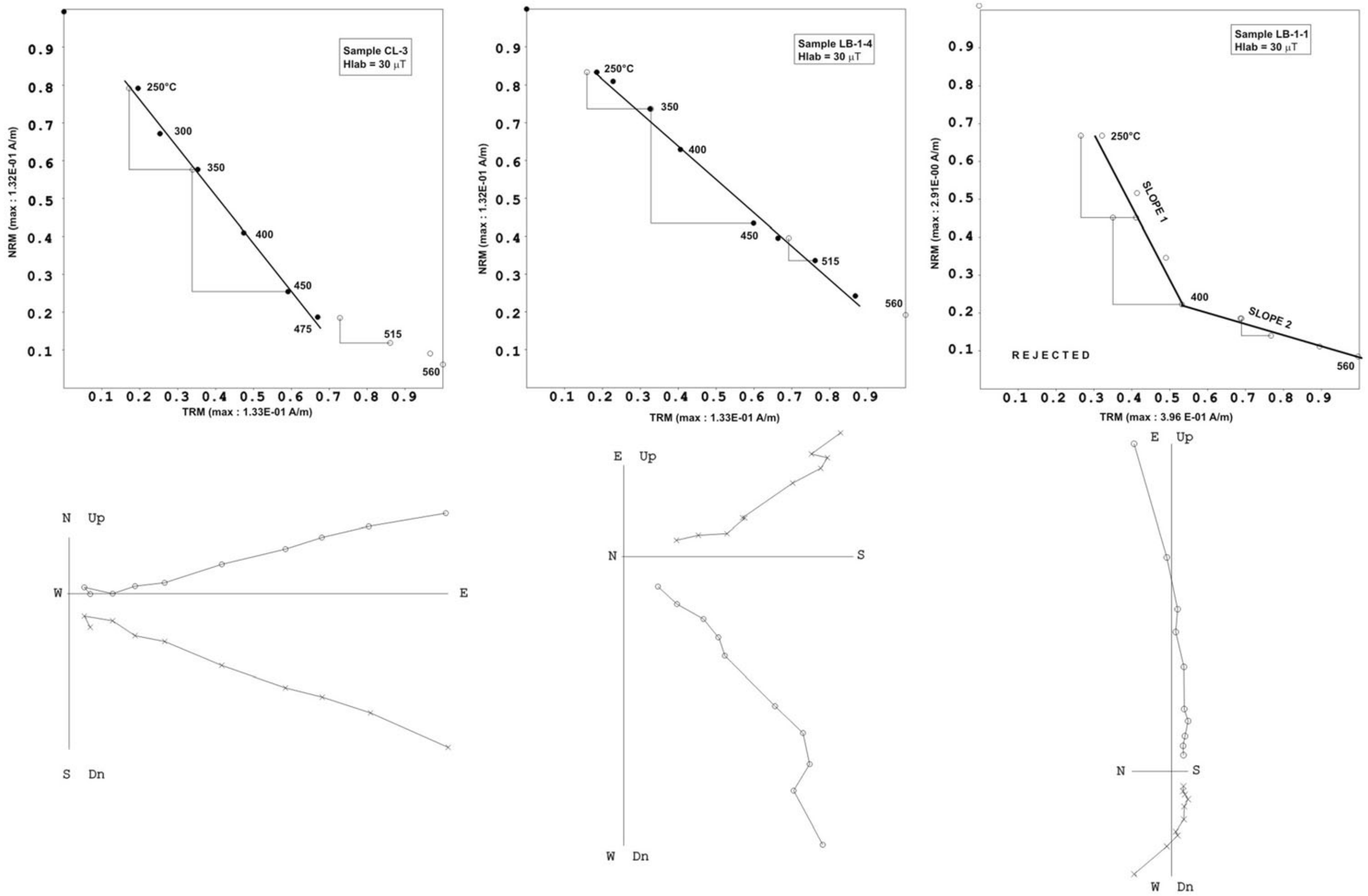

Figure 4 *Representative NRM–TRM plots and associated orthogonal vector demagnetization diagrams for the studied samples.*

TRM anisotropy corrections can be implemented in various ways (e.g., McCabe *et al.* 1985; Chauvin *et al.* 2000; Selkin *et al.* 2000; among others). It essentially requires the creation of a TRM along six mutually perpendicular directions (+X, +Y, +Z, −X, −Y, −Z) by cooling samples from 600°C to room temperature in a known magnetic field. This involves six additional heatings, which may significantly alter the magnetic mineralogy of the samples. To circumvent this time-consuming procedure, individual specimens (belonging to the same fragment; see more details in Morales *et al.* 2007) were embedded into the salt pellet in the six above-described positions. In this way, possible bias due to TRM anisotropy effects would be cancelled, as attested by the results of our various previous test experiments. Numerous ceramic fragments broken into six pieces were thermally demagnetized for this purpose. Sister samples were later embedded into salt pellets and aligned along one of the above-described positions, taking as a reference the flattening plane of the ceramic fragment. Specimens elaborated in such a way were remagnetized by applying a constant magnetic field along the Z-axis of the pellet and were later measured. In general, specimens oriented parallel to the easy plane of magnetization (flattening plane) yielded relatively higher intensities than those oriented perpendicular to it, with differences less than 10%. We then carried out a pseudo-Thellier–Coe experiment with these specimens. Averaged 'ancient' intensities reproduced the laboratory field used to remagnetize the specimens to within 3% (Morales and Goguitchaichvili 2011).

MAIN RESULTS AND DISCUSSION

Rock-magnetic experiments indicate that the main magnetic carrier is Ti-poor titanomagnetite. In a few cases, both Ti-rich and Ti-poor titanomagnetites seem to coexist. Twenty-one samples out of 46 analysed yield reliable absolute intensity determinations (Table 2). For these samples, the NRM fraction f used for determination ranges between 0.44 and 0.86 and the quality factor q from 3.8 to 19.3, being generally greater than 5. The cooling rate correction generally reduced the standard deviation of the mean intensities. The fragment-mean archaeointensity values (Fig. 4) obtained in this study range from 21.9 ± 2.3 to 42.6 ± 5.4 μT, with corresponding virtual axial dipole moments (VADMs) ranging from 4.0 ± 0.5 to $8.1 \pm 1.0 \times 10^{22}$ Am^2. This corresponds to a mean VADM of $(6.4 \pm 1.8) \times 10^{22}$ Am^2. For the data analysis obtained in this study, we prefer to describe the magnitude of the Earth's magnetic field in *microteslas* (local presentation), rather than in terms of the VADM (virtual axial dipole moment). The ideal case is naturally to present results in terms of the VDM (virtual dipole moment), but one should know the true magnetic inclination of samples, which is not the case here.

The mean archaeointensity values obtained in this study are shown in Figure 5, together with other available archaeointensity determinations from southern Brazil (unpublished data by Gelvam Hartmann, available at the GEOMAGIA50v2 database, https://geomagia.ucsd.edu) reduced to our sampling area. In order to derive a South American archaeointensity master curve, Hartmann and co-workers (2011, in press) have initiated a systematic palaeointensity survey of well-dated potsherds from southeastern Brazil. They have presented the first results on pottery collected for the 21 archaeological sites located in 11 cities of the São Paulo State (southeastern Brazil). The age distributions for 21 dated sites are almost evenly distributed from AD 1000 to AD 1900, while two sites only were dated between AD 100 and AD 1000. The intensities obtained in the present study were consistent within sites and between fragments of pottery of similar ages. Intensity values vary from 35 μT (around AD 700) up to a peak of 53 μT around AD 1450, and decrease continuously down to the present-day value of ~30 μT. These strong oscillations suggest that archaeomagnetic data may be very useful for dating pottery in South America. However, the

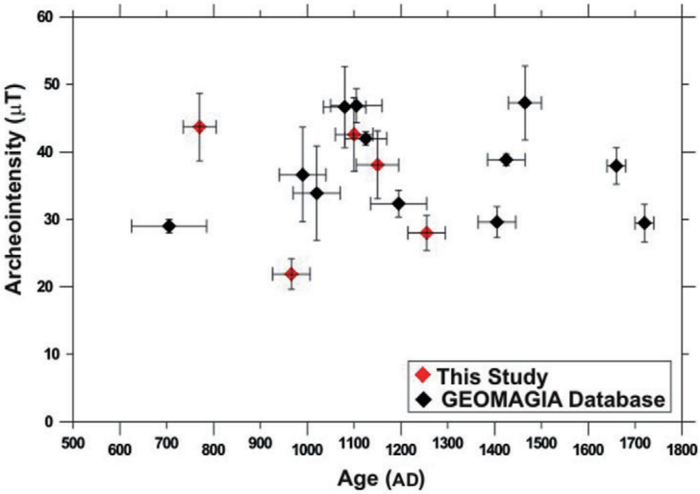

Figure 5 *Mean archaeointensities retrieved from the Pampean archaeological sites together with available data from the studied region (see the GEOMAGIA50v2 database at https://geomagia.ucsd.edu/) against calibrated* C^{14} *ages. (See online for a colour version of this figure.)*

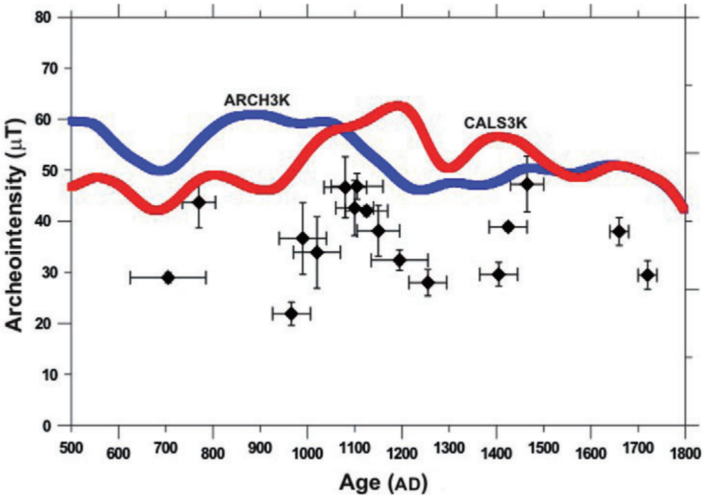

Figure 6 *The general tendency of the archaeointensity data distribution. Also shown are the data derived from the CALS3k.3 and ARCH3K model predictions (Korte* et al. *2009; see also Donadini* et al. *2009). (See online for a colour version of this figure.)*

intensity data were not corrected for TRM anisotropy and cooling rate effects. Despite the relatively long distance between these sites, a remarkable agreement is observed. In contrast, the present data set differs significantly from the global geomagnetic model predictions (Fig. 6). Donadini *et al*. (2009) and Korte *et al*. (2009) recently produced a series of time-varying spherical harmonic models of the geomagnetic field for the past 3000 years. The new CALS3k.3 model uses all available measurements from sediments, lavas and archaeological structures, and currently provides the best global representation of the 0–3 ka field, while archaeological artefacts and lavas are involved to construct the ARCH3K curves. The broad peak defined at about AD 1100 by our data is also predicted by CALS3k.3, but slightly displaced to the right.

As may be deduced from Figure 6, important differences are observed between the data and the geomagnetic field predictions. For some periods (e.g., AD 980 and AD 1250), differences of more than 20 μT are noticed. Significant differences are also noticed for recent periods; for example, AD 1700. It seems that in the case of South America, the CALS3K and ARCH3K curves gave limited resolution.

The record retrieved from southern Argentina and Brazil consists of 17 mean archaeointensities distributed between AD 700 and AD 1700. The data set shows several distinct periods of fluctuations of quite large intensity. However, most data are concentrated into a relatively narrow interval from AD 950 to AD 1300. Three general features may be detected: the time intervals from about AD 950 to 1130 and 1350 to 1480 are characterized by a quite monotonic increase of geomagnetic intensity, while some decrease is observed from AD 1150 to 1280. As suggested by Gallet *et al*. (2006) and Courtillot *et al*. (2007), these fluctuations may be correlated with climate changes over multi-decadal time scales. The cooling (warming) episodes are synchronous to the intensity increase (decrease) and seem to be influenced by the geomagnetic field through the modulation of the cosmic ray flux interacting with the atmosphere. However, in the case of South America, where no reliable climate record is available and the geomagnetic data distribution is still scarce, this hypothesis should be viewed with considerable caution.

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