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Relative paleointensity of the geomagnetic field over the last 21,000 years BP from sediment cores, Lake El Trébol (Patagonia, Argentina)

C. S. G. Gogorza[1,2], M. A. Irurzun[1,2], M. A. E. Chaparro[1,2], J. M. Lirio[3], H. Nunez[3], P. G. Bercoff[2,4], and A. M. Sinito[1,2]

[1]*IFAS- Universidad Nacional del Centro, Pinto 399, 7000 Tandil, Argentina*
[2]*CONICET. Rivadavia 1917-1033 Buenos Aires, Argentina*
[3]*Instituto Antártico Argentino - Cerrito 1248 - Buenos Aires, Argentina*
[4]*Fac. de Matemática, Astronomía y Física, Universidad Nacional de Córdoba, Ob. Trejo 242, Córdoba, Argentina*

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Four cores from Lake El Trébol (Patagonia, Argentina) have been used to estimate regional geomagnetic paleointensity. The rock magnetic studies indicate that the magnetic mineralogy of the clay-rich sediments is dominated by pseudo-single domain magnetite in a range of grain sizes and concentration which are suitable for paleointensity studies. The remanent magnetisation at 20 mT ($NRM_{20\ mT}$) has been normalised using the anhysteric remanent magnetisation at 20 mT ($ARM_{20\ mT}$), the saturation of the isothermal remanent magnetisation at 20 mT ($SIRM_{20\ mT}$) and the low field magnetic susceptibility (k). Coherence function analysis indicates that the normalised records are free of environmental influences. Our paleointensity ($NRM_{20\ mT}/ARM_{20\ mT}$) versus age curve shows good agreement with published record from another lake in Argentina and with records from other parts of the world, suggesting that, in suitable sediments, paleointensity of the geomagnetic field can give a globally coherent, dominantly dipolar signal.

Key words: Relative paleointensity, sediment cores, South America, Lake El Trébol, coherence.

1. Introduction

Sediments from lacustrine environments are frequently studied for directional and relative paleointensity variations of the geomagnetic field. They are attractive recorders of the geomagnetic field due to their continuity, high temporal resolution, and global availability. The conventional method of extracting geomagnetic field information from the signal consists in normalising the natural remanent magnetisation (NRM) with some normaliser. This normaliser should account for changes in magnetic grain size and concentration, which also affect the strength of the NRM signal. Different normalisers have been proposed, such as anhysteric remanent magnetisation (ARM), saturation isothermal remanent magnetisation (SIRM), and magnetic susceptibility k (Tauxe, 1993). Similarity between normalised records obtained using different normalisers is often believed to express the reliability of the paleointensity record. Normalising the record is assumed to minimize the effects of magnetic grain-size distribution and variation of magnetic input, for example determined by environmental effects. Tauxe (1993) reviewed the experimental and theoretical considerations for assessing the reliability of paleointensity data derived from sediments. It is only possible to obtain relative paleointensity estimates from sediments in this way, in contrast to the absolute paleointensity determination from igneous rocks (Kruiver *et al.*, 1999).

During the past decade, numerous studies have been made to recover the relative paleointensity from marine records. (e.g. Tric *et al.*, 1992; Meynadier *et al.*, 1992; Roberts *et al.*, 1997; Channel *et al.*, 2000; Laj *et al.*, 2000; Sagnotti *et al.*, 2001; Stoner *et al.*, 2002). Comparatively, few studies have been made on terrestrial sediments, probably due to their more complex sedimentological characteristics (Peck *et al.*, 1996; Sinito and Nuñez, 1997; Brachfeld and Banerjee, 2000; Nowaczyk *et al.*, 2001; Pan *et al.*, 2001; Brachfeld *et al.*, 2003; St-Onge *et al.*, 2003; Gogorza *et al.*, 2004).

In this paper we present a paleointensity record obtained from four cores taken from Lake El Trébol (Patagonia, Argentina). First, we demonstrate that the sediments are suitable for paleointensity study by addressing the criteria of Banerjee *et al.* (1981), King *et al.* (1982, 1983), Tauxe (1993). We then develop stacked relative paleointensity records using conventional normalisation. The directional parameters corresponding to these cores have already been presented (Irurzun *et al.*, 2006).

2. Site Description

Lake El Trébol, a closed basin (41°04′S 71°29’W), is an oligotrophic, small lake (surface area: 0.4 km^2, maximum depth=11 m), located at 758 m a.s.l. on the east side of the Andean Patagónica Cordillera, in a wooded area with moderate human influence (Fig. 1). At present, no perennial stream discharges into the lake and the hydrological budget is dominated by groundwater influx and losses by evaporation (Bianchi *et al.*, 1999). The area is dominated by humid winds from the west with annual precipitation between 1500 and 1800 mm/year; the average annual temperature is

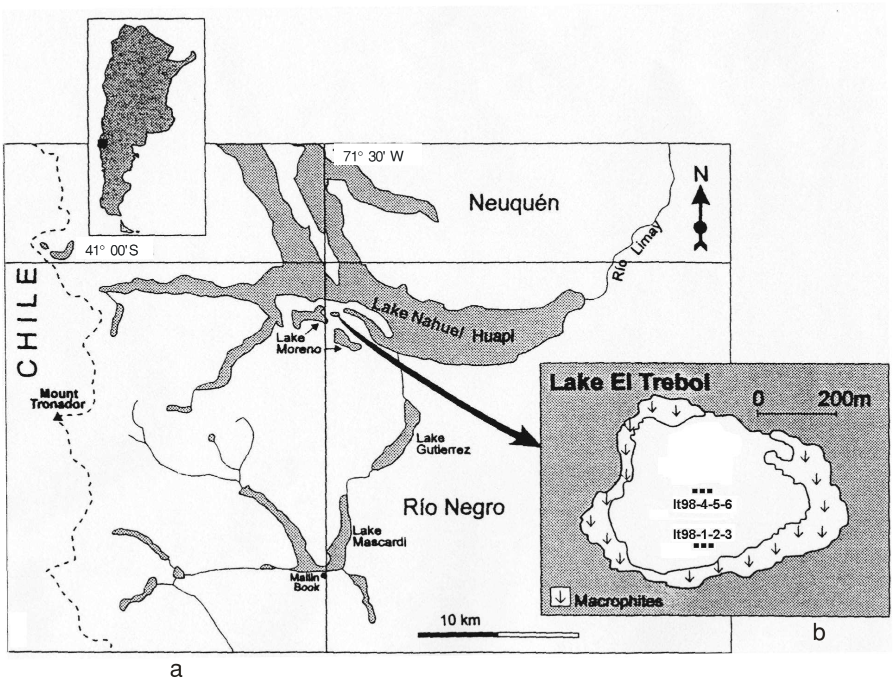

Fig. 1. (a) Geographical location of lake El Trébol. (b) Location of coring sites in the lake.

about 8.7°C.

Advances and retreats of glaciers during the Pleistocene glaciation shaped the surrounding landscape. As a result, numerous glacial melt-water spillways, lakes (e.g. Lake El Trébol and Lake Escondido) and glacio-fluvial deposits were formed (Flint and Fidalgo, 1964, 1969; Rabassa and Clapperton, 1990; Bianchi *et al.*, 1999).

3. Sedimentology

The basement rocks of the basin crop out on the lake coast. Basement exhibits evidence of glacial erosion, and some erratic blocks of different composition are present (Gogorza *et al.*, 2002). The push corer reached the basement (or erratic blocks), going through a sedimentary column, that is represented by the cores (Irurzun *et al.*, 2006). The four cores are sedimentologically similar and represent the most complete sedimentary record from El Trébol Lake to date.

The core labelled lt98-4 was chosen as a master core because it was the longest sedimentary column (figure 2 in Irurzun *et al.*, 2006). Three principal lithologies are present in the sedimentary column, from bottom to top:

(A) It lies over the irregular surface of the Ventana Formation with glacial erosion evidence. The volcanic rocks of the Ventana Formation form the basement of Lake El Trébol and other small lakes in the area (Lake Escondido and Lake Moreno). Between 11.0 and 8.0 m depth, light reddish clayey silt, and very poor in organic matter content. This lithology shows fine parallel lamination composed by alternating thin layers of clastic varves. The individual layers are normally graded. The thickness varies from 1 up to 5 mm and the thicker layers, being in the middle part of the lithology A, suggest a probable local glacial advance. The grain size increases downward. Small dropstones were observed close to the bottom.

(B) Between 8.00 and 6.75 m depth, light grey clay, this lithology shows scarce lamination, especially near the upper section. This is a glaciolacustrine distal facies. The organic matter content, although poor, increases upwards.

(C) Between 6.75 and 0 m depth, core deep dark brown clay, lighter at the base, without lamination. It shows a relative increase of organic matter content in a lacustrine environment similar to that found in the present lakes.

Detailed visual descriptions of the cores along with rock magnetic studies allow the identification of two different facies in Lake El Trébol: a basal glaciolacustrine facies that includes lithologies A, B and tephra layers called "Lake Elpalafquen" facies, and a younger organic rich lacustrine facies (lithologies C and tephra layers) or "Lake El Trébol" facies (Irurzun *et al.*, 2006).

Based on prior work in the region (del Valle *et al.*, 2000) we interpret that lithologies A and B suggest the existence of a big lacustrine system, a paleolake Elpalafquen, with a level 100 m higher than the present Lake El Trébol. A system of glacial lakes contained by the receding glaciers remained during the climate improvement after the last glacial event. The disintegration of this glaciolacustrine system gave rise to many small ice-free lakes, like Lake El Trébol (del Valle *et al.*, 1996).

4. Experimental Methods

A more detailed description of these items is given in Irurzun *et al.* (2006). A brief summary follows. The four cores investigated in this study (lt98-1, lt98-2, lt98-4, lt98-5) were recovered at water depths of about 10 m from Lake El Trébol in 1998 using a push corer installed on a raft with a central hole. The cores of 6 cm diameter were recovered in 2 m long sections, with a common internal orientation, but were not orientated relative to magnetic north. The compaction is minimum. The sediments were extruded

Table 1. δ^{13}C, radiocarbon and calibrated ages[a].

Core	Material	Depth (cm)	Shortened depth (cm)	Date RCYBP±2σ	δ^{13}C[b] (‰)	Calibrated age±2σ (years)
lt98-4	sediment	240	214.5	3206±42	−28.02	3464±98
lt98-4	sediment	439.5	363	7076±51	−25.974	7910±96
lt98-4	sediment	558.5	424	9886±54	−26.5	11007±316

[a]Irurzun, M. A., C. S. G. Gogorza, A. M. Sinito, J. M. Lirio, H. Nunez, M. A. E. Chaparro, Paleosecular variations recorded by sediments from Lake El Trébol, Argentina, *Phys. Earth and Planet. Inter.*, **154**, 1–17, 2006.
[b]These δ^{13}C measurements provide information to correct the ^{14}C ages to δ^{13}C of -250/00.

using the included piston. There is no overlap between the 2 m long sections but they are extracted in a complementary way, so that no section were lost, i.e. if a section is missing in a core, it is present in another one. The position of the sampling sites and the main characteristics of the four cores are given in Fig. 1. These cores have been kept moist and refrigerated since they were collected, virtually eliminating the effect of core storage on the remanence.

One half of each core was subsampled with cubic plastic boxes of 8 cm^3. In total, 1270 subsamples were obtained. Sub-sampling for rock magnetic studies and for ^{14}C and δ^{13}C analysis was carried out.

The nature of the magnetic minerals in the studied sediments has been carefully investigated (Irurzun *et al.*, 2006). The following measurements were performed for all samples: NRM; magnetic susceptibility at low frequency (specific, X and volumetric, k); isothermal remanent magnetisation (IRM) in increasing steps up to 1.2 T, reaching the SIRM; back field, in growing steps until cancelling the magnetic remanence; anhysteric remanent magnetisation ($ARM_{100\ mT}$), with a direct field of 0.1 mT and a peak alternating field of 100 mT. Associated parameters calculated by Irurzun *et al.* (2006) were also used: S-ratio ($IRM_{-300\ mT}$/SIRM), remanent coercitive field (H_{CR}), SIRM/k, $ARM_{100\ mT}/k$ and SIRM/$ARM_{100\ mT}$. In addition to these, hysteresis curves and temperature dependence of SIRM were obtained for a set of discrete samples.

The hysteresis parameters were obtained using a VSM Lake Shore 7300 with a maximum applied field of 1.5 T. Thermal demagnetisation was made by a Thermal Specimen Demagnetiser, model TD-48 ASC Scientific. Stepwise thermal demagnetisation curves were represented and critical temperatures (T_C) were estimated.

The depth scales of all the cores were adjusted to the depth scale of a chosen master core (lt98-4) using lithology and X tie lines for correlation (Gogorza *et al.*, 1999, 2001, 2002, 2004). One of the most important problems in lake sediments of a volcanic area is the presence of abundant tephra layers along the sequence. On the one hand, the tephra layers represent rapid instantaneous deposition of thick layers, whereas the rest of the sediments represent slow accumulation. On the other hand, tephra is not a very good magnetic recorder of directions (Peng and King, 1992; Gogorza *et al.*, 1999). For these reasons, after the identification of the tephra layers, they were removed from the sequence and the gaps that were produced along the profiles by their removal were closed, obtaining a "shortened depth" scale. This method was described in detail by Gogorza *et al.* (1999).

5. Chronology

Three accelerator mass spectrometer (AMS) radiocarbon dates were obtained for this work by the AMS Laboratory of the University of Arizona, which were converted into calendar years using the calibration curves of Stuiver and Reimer (1993). The information about each sample, including radiocarbon years before present (RCYBP) and calibration ages, is listed in Table 1 (Irurzun *et al.*, 2006).

Distinctive magnetic features of El Trébol D and I record, close to the dated levels, were identified and correlated with similar features of the PSV curves from Lake Escondido (41°S, 71°30′W, Gogorza *et al.*, 2002); so three connecting points were defined (Irurzun *et al.*, 2006). This correlation was consistent with the age scale determined for Lake Escondido. The three connecting points define four zones; within each zone new tie points were determined (based on visual inspection of the curves). On the basis of this correlation, a total of 44 tie points were defined. Ages of the most distinctive declination peaks were transferred to the Lake El Trébol record and inclination features were matched. Minor changes in inclination and declination were then correlated (Irurzun *et al.*, 2006). The lowest correlation point between Lake El Trébol and Lake Escondido was at a sediment depth of 710 cm in Lake El Trébol, which means a calibrated age of about 19,000 years. If the same sedimentation rate is assumed for the additional 140 cm, the resulting basal age for the base of the profile of Lake El Trébol is ca. 21,000 calibrated years (Irurzun *et al.*, 2006).

6. Results

6.1 Magnetic properties

The first reliability tests for sedimentary paleointensity are the rock magnetic criteria suggested by Banerjee *et al.* (1981), King *et al.* (1982, 1983), Tauxe (1993). These are (1) the remanence must be carried by stable magnetite grains ranging in size from 1–15 μm, (2) the concentration may not vary by more than a factor of 10, (3) the normalisation parameters must account for the variability in the contribution of the grain carrying the remanence (controlled largely by changes in concentration and grain size). Those samples that do not meet the criteria for magnetic uniformity have been omitted from our estimates of the relative paleointensity of the geomagnetic field (about 20%). Rock magnetic measurements were performed on set of samples and some of the results are summarised in Fig. 2.

Thermal demagnetisation of SIRM shows no evidence for a contribution from minerals other than magnetite for samples of lithologies A-B (Fig. 2(a)). However, thermal demagnetisation of samples of lithology C indicates a con-

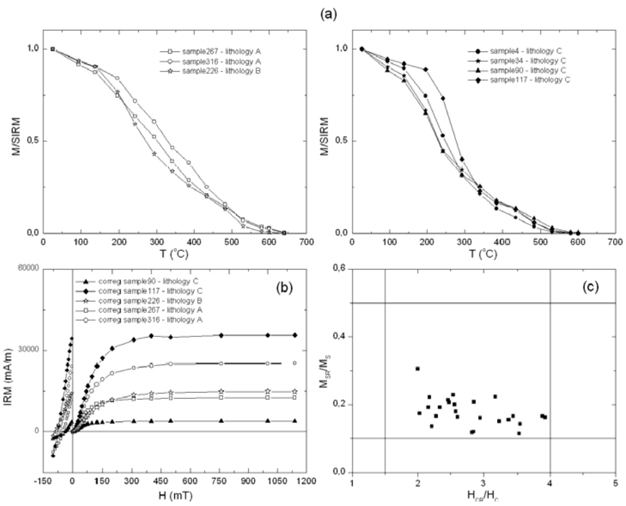

Fig. 2. (a) Thermal demagnetisation curves of SIRM for three samples from the lower part of the sequence and four from the upper one. (b) IRM acquisition curves of samples from different lithologies. (c) Hysteresis parameter ratios, H_{CR}/H_C vs. MRS/MS for estimation of grain size.

centration of unblocking temperatures below 300°C, implying the presence of more than one magnetic mineral (Fig. 2(a)). These results are indicative that magnetite is the dominant magnetic carrier of remanence in the cores, but the presence of a low proportion of titanomagnetite in the younger section cannot be excluded.

Stepwise acquisition of the isothermal remanence in fields up to 1.2 T shows that about 90% of the SIRM is acquired at an applied field between 200 and 300 mT. Progressive removal of this SIRM by back-field demagnetisation indicates remanence coercivity (H_{CR}) between 40 and 80 mT (Fig. 2(b)). These results indicate that magnetite is the dominant magnetic carrier of remanence in these samples. The studies reported in Irurzun *et al.* (2006) indicate that the cores are characterised by an S-ratio that varies between 81 and 99% (average 91±3%) in lithology C (except two samples whose S-ratio values are 78 and 79%, respectively) and that varies between 86 and 96% (average 92±2%) in lithologies A and B, indicating the predominance of low-coercivity minerals like (titano-) magnetite (Meynadier *et al.*, 1992).

Grain size changes of magnetic minerals were examined by measuring ratios of both hysteretic and other magnetic parameters. Hysteresis parameters are useful for determining grain size and domain state of magnetite particle (Day *et al.*, 1977). In Fig. 2(c) we summarize the hysteresis properties for the analysed specimens: saturation magnetisation (MS), saturation remanence (MSR also SIRM), coercive force (H_C), and coercivity of remanence (H_{CR}). The hysteresis ratios are consistent with a dominant low-coercivity ferrimagnetic component (most likely magnetite) that is of PSD range (Pseudo Single Domain) magnetic grain size.

A rather uniform grain size along the sequence is also confirmed by the down-core changes in the ratios $ARM_{100\ mT}/k$ and $ARM_{100\ mT}$/SIRM; higher ratios indicate a smaller grain size and a higher proportion of single-domain (SD) grains (Hunt *et al.*, 1995). In Fig. 3 it can be seen that the variation of $ARM_{100\ mT}/k$ and $ARM_{100\ mT}$/SIRM is about 3.

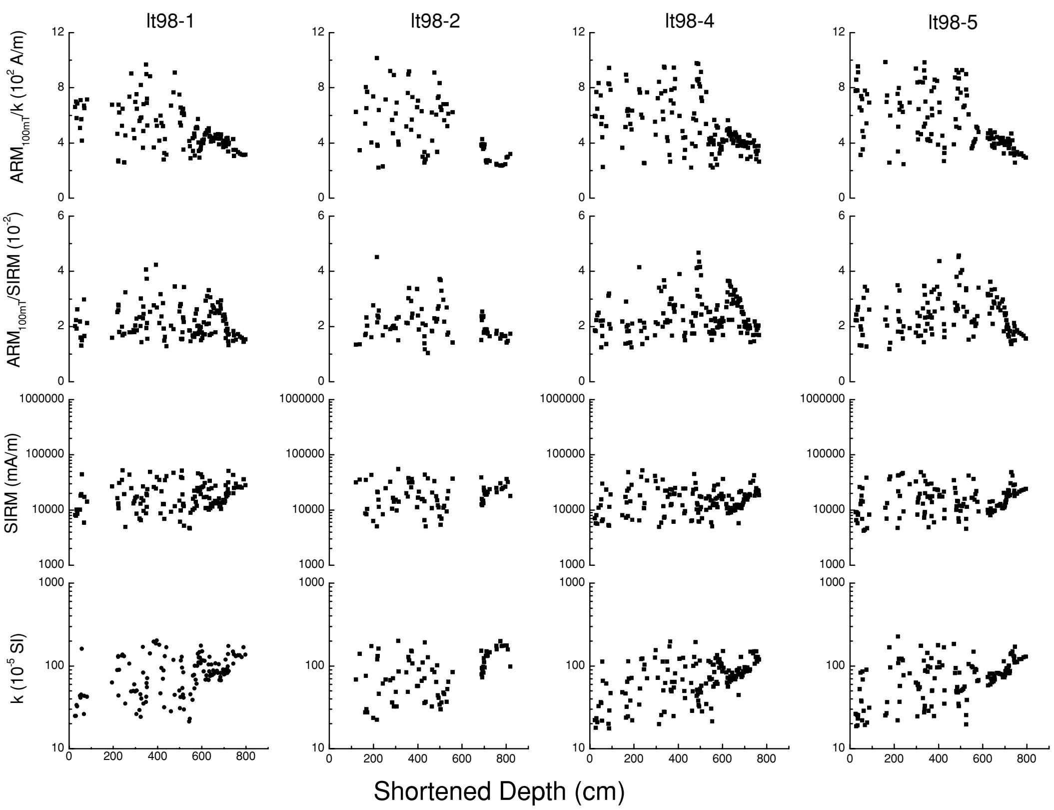

Fig. 3. k, SIRM, $ARM_{100\ mT}$/SIRM and $ARM_{100\ mT}/k$ records vs. shortened depth from cores lt981, lt98-2, lt98-4 and lt98-5.

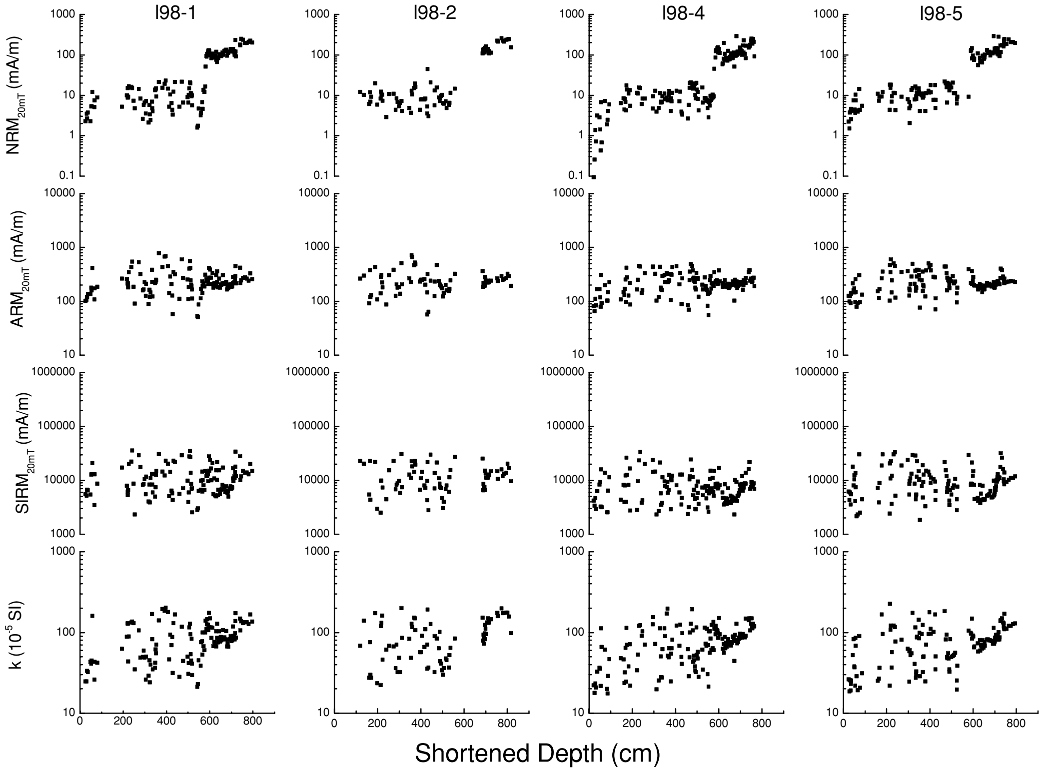

Fig. 4. k, $SIRM_{20\ mT}$, $ARM_{20\ mT}$ and $NRM_{20\ mT}$ records vs. shortened depth from cores lt981, lt98-2, lt98-4 and lt98-5.

The variation in the concentration of magnetic minerals can typically be monitored by the measurements of k and SIRM. The latter is usually regarded as a better parameter to use for this purpose because it has no systematic grain dependence, while the former can be affected by superparamagnetic (SP) grains (Pan *et al.*, 2001; Gogorza *et al.*, 2004). Figure 3 shows that the ratio of the maximum to minimum value of k and SIRM does not exceed a factor of about 10, proposed as an upper limit for relative paleointensity studies in sediments (Tauxe, 1993).

We conclude that the uniformity of rock magnetic results from these cores in terms of magnetic mineralogy, concentration and grain size is well within the criteria proposed for relative paleointensity studies (King *et al.*, 1983; Tauxe, 1993).

6.2 Directional records

Lake El Trébol sediments record a stable, single component of remanence with an easily isolated characteristic component of remanence (Irurzun *et al.*, 2006). Little viscous remanence is observed (Irurzun *et al.*, 2006), and when present, it is generally removed by 10 or 15 mT peak AF demagnetisation. Principal component analysis was carried out using four steps from 15–30 mT demagnetisation levels. The maximum angular deviations (MAD angles) are generally $<4.2^\circ$ in lithologies A and B and $<7.5^\circ$ in lithology C. Highest MAD angles (about 9.3°) were eliminated. These occur in the upper meter corresponding to spurious data at the top of the highly water saturated cores or they could clearly be attributed to artefacts at the top or bottom of some core sections (about 5% of the data). A univectorial characteristic remanence component is obtained by peak AFs of 20 mT (Irurzun *et al.*, 2006). Data at this demagnetisation level were therefore used for paleointensity normalisation.

6.3 Relative intensity estimates

To obtain the paleointensity records, normalised remanence were generated using values of NRM, ARM and SIRM after AF demagnetisation at 20 mT. This peak is sufficient for complete removal of secondary components present in the NRM. The records of $NRM_{20\ mT}$, $ARM_{20\ mT}$, $SIRM_{20\ mT}$ and k are shown in Fig. 4 on a common depth-scale for the four cores. There is good consistency between corresponding $ARM_{20\ mT}$, $SIRM_{20\ mT}$ and k, implying the $NRM_{20\ mT}$ intensity is mostly modulated by changes in the geomagnetic field rather than by the environmental factors.

For each core, we have obtained three estimates of normalised field intensity using $ARM_{20\ mT}$, $SIRM_{20\ mT}$ and k as normalising parameters. The results are shown in Fig. 5 on a common depth-scale for the four cores. The range of the changes is different in the upper ("Lake Trébol" facies) and lower section ("Lake Elpalafquen" facies); for this reason, the records are scaled by their respective mean values in order to be compared.

The consistency of the records from the different cores is a necessary consequence, but it also provides evidence that the sediments reliably record changes in the geomagnetic field intensity (Tauxe, 1993; Lehman *et al.*, 1996).

Stacking provides a method for determining the "true" character of the record, as spurious features in individual records should be averaged out by the stacking process (Stoner *et al.*, 2002). In order to yield the composite profile, the individual normalised paleointensity records were stacked. To perform this average, it is necessary to have data at the same depth for each core. For this reason, a lin-

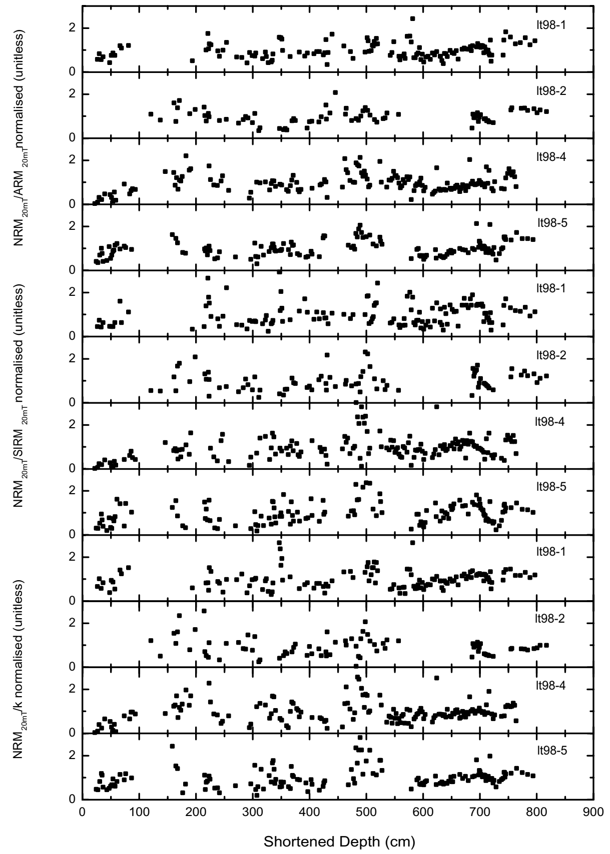

Fig. 5. Normalised $NRM_{20\ mT}/k$, $NRM_{20\ mT}/SIRM_{20\ mT}$ and $NRM_{20\ mT}/ARM_{20\ mT}$ records vs. shortened depth from cores lt98-1, lt98-2, lt98-4 and lt98-5.

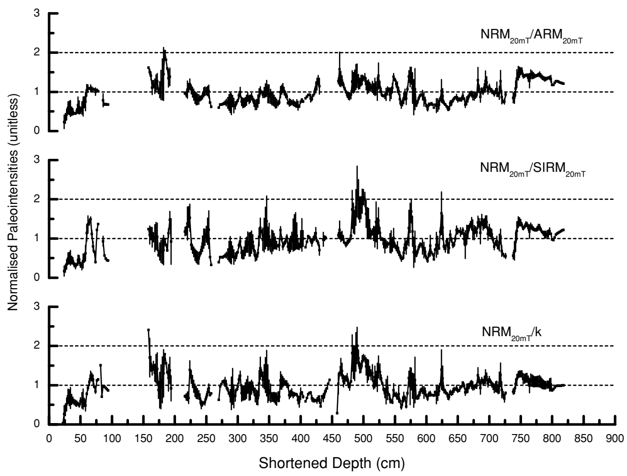

Fig. 6. Stacked $NRM_{20\ mT}/ARM_{20\ mT}$, $NRM_{20\ mT}/SIRM_{20\ mT}$ and $NRM_{20\ mT}/k$ records vs. shortened depth.

eal interpolation was carried out, obtaining data every 2 cm. The stack was then determined using the arithmetic mean at each interpolated sampling point and the 2σ have been calculated for the error bars (Fig. 6).

Relative paleointensity profiles as a function of ^{14}C years B.P. using different normalisers are shown in Fig. 7.

6.4 Coherence function analysis

We carried out a coherence function analysis on the records to test the efficiency of the normalisations in re-

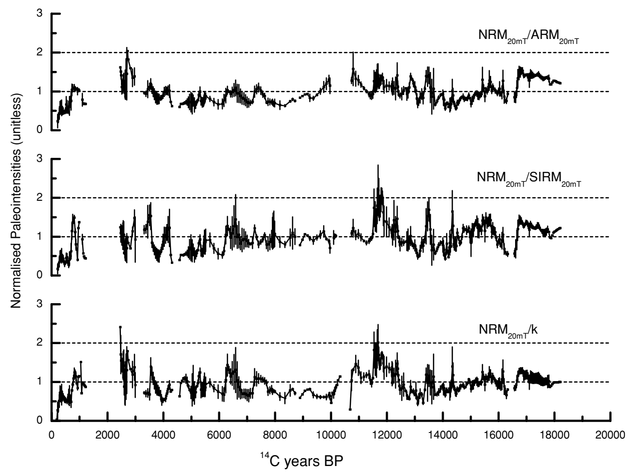

Fig. 7. Stacked $NRM_{20\ mT}/ARM_{20\ mT}$, $NRM_{20\ mT}/SIRM_{20\ mT}$ and $NRM_{20\ mT}/k$ records vs. ^{14}C years BP.

moving the effects of climatic/environmental factors over specific frequency ranges. If the paleointensity record ($NRM_{20\ mT}/ARM_{20\ mT}$, etc.) and the related normaliser ($ARM_{20\ mT}$, etc) do not show significant coherence, one may be confident that the paleointensity normalisation is not significantly affected by lithological or other environmental factors.

It is shown in Fig. 8 that at 95% confidence level $NRM_{20\ mT}/SIRM_{20\ mT}$ is coherent with its normaliser at some periods. It shows that we should not put too much faith in that normalisation. This behaviour is reduced to shorter periods by k normalisation and missing by $ARM_{20\ mT}$ normalisation. This analysis indicates that the parameter $ARM_{20\ mT}$ is the more appropriate normaliser in these sediments (not coherent frequencies above the 95% confidence level) and that the $NRM_{20\ mT}/ARM_{20\ mT}$ record is not affected by climatic or lithologic factors but represents a true geomagnetic signal.

The spectral analysis of normalised remanences, normalisation parameters and coherence test (Fig. 8) were carried out following the method of Tauxe and Wu (1990) using MATLAB 6.1 software.

7. Comparison with Other Records

All of the above-described tests for assessing the reliability of relative paleointensity records are important; however, the most powerful test is whether there is agreement within the same geographic region, agreement between different depositional environments, and, ultimately, broad scale agreement between records from around the world (Roberts *et al.*, 1997). The comparison of our normalised intensity record ($NRM_{20\ mT}/ARM_{20\ mT}$) with existing paleointensity records may also provide information about the dipolar and no-dipolar nature of the main characteristics of the geomagnetic field during the studied period.

A comparison of $NRM_{20\ mT}/ARM_{20\ mT}$ with relative paleointensity records from the Southern and Northern Hemispheres is shown in Fig. 9(a)–(c). In Fig. 9(a) the comparison is restricted to records with radiocarbon chronologies: our records—the previous results from Lake Escondido

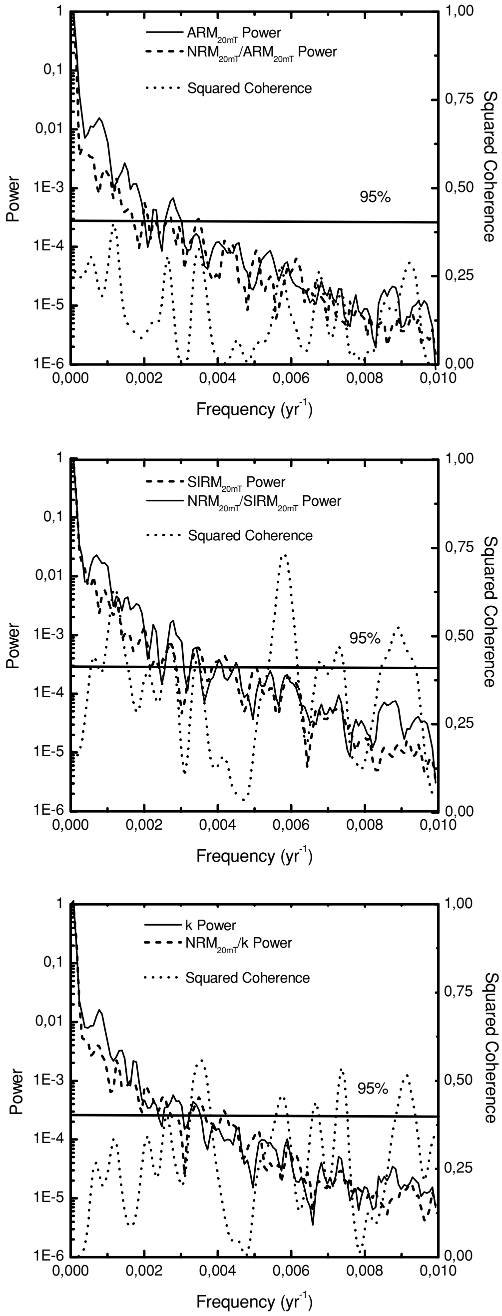

Fig. 8. Spectral analysis of three normalisation parameters ($ARM_{20\,mT}$, $SIRM_{20\,mT}$ and k) and three normalised remanences ($NRM_{20\,mT}/ARM_{20\,mT}$, $NRM_{20\,mT}/SIRM_{20\,mT}$ and $NRM_{20\,mT}/k$). Coherence tests results are shown. The 95% confidence level is denoted by the horizontal line.

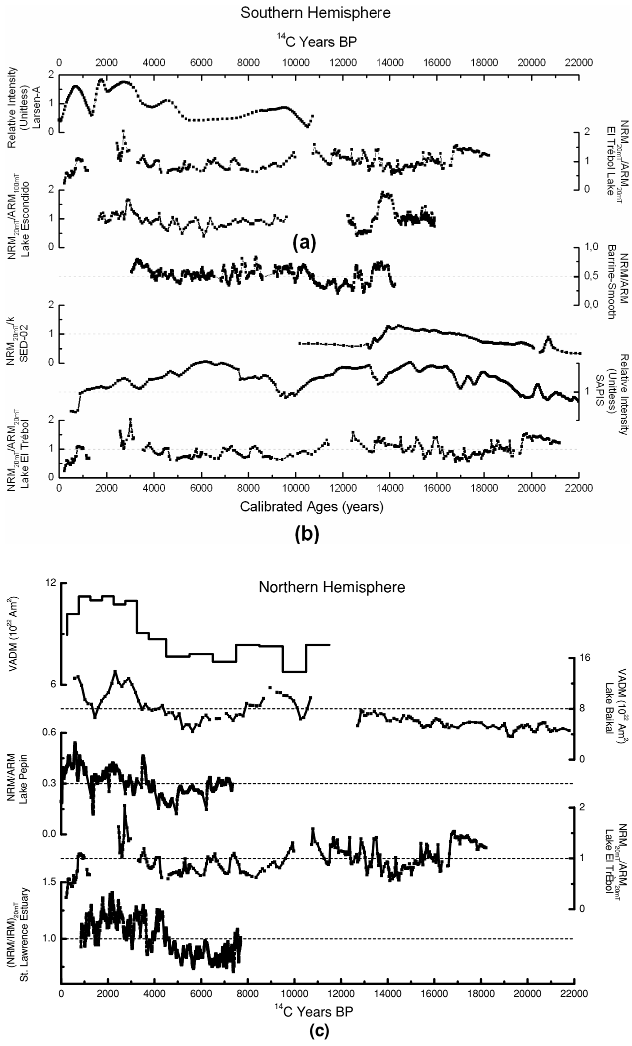

Fig. 9. Southern Hemisphere: (a) Comparison of normalised intensity record from the Lake El Trébol stack with relative paleointensity records from Larsen-A Ice Shelf and Lake Escondido in radiocarbon ages, (b) Lake Barrine, SEDANO-02 core and SAPIS stack in calibrated ages; Northern Hemisphere: (c) a global compilation of archeomagnetic data, Lake Baikal, Lake Pepin and St. Lawrence Estuary in radiocarbon ages.

(Gogorza *et al.*, 2004)—a sedimentary sequence collected from beneath the former Larsen-A Ice shelf, Antarctic Peninsula (Brachfeld *et al.*, 2003); and the record of Lake Barrine (Constable, 1985) whose chronology is a hybrid ^{14}C/Calendar Age. There is very good agreement between the records of the post-glacial section [0–10,000 RCYBP], displaying a high at about 2700 RCYBP in the Lake El Trébol and Larsen-A records, at about 2900 RCYBP in the Lake Escondido record and about 3280 RCYBP in the Lake Barrine record. Following this high, an oscillating behaviour superimposed on a long trend below the mean between 3500 and about 10,000 RCYBP is observed. Both records, from Larsen-A and from Lake El Trébol, shows an increasing behaviour from about 200 RCYBP to about 750 RCYBP and a decreasing behaviour from this high to about 1200 RCYBP. A smoothing (running average of five points) was applied to the raw data recorded on Lake Barrine (figure 5(b) from Constable, 1985) to avoid abrupt variations in paleointensity records. Some of the discrepancies in timing between Lake Barrine and the other records could be due to inaccuracies in dating in the Australian records (Constable, 1985). Lake El Trébol and Lake Barrine show some similarities: both records exhibit a decreasing behaviour between 10700 to 11300 RCYBP (actually Lake Barrine shows this behaviour since 10300 RCYBP but it is not possible to compare this with Lake El Trébol because there is a gap at this age). Finally, a notorious high observed—at about 13500 RCYBP—in the Lake Escondido record is not exactly coincident, neither in time nor in amplitude, with the peak observed at about 13450 RCYBP in Lake El Trébol and Lake Barrine. For this reason, we have doubts that they are reflecting the same feature.

Figure 9(b) shows our present record, the results from South Atlantic geomagnetic paleointensity stack, SAPIS (Stoner *et al.*, 2002) and one of the three cores (SEDANO) collected from Antarctic late Pleistocene sediments (Sagnotti *et al.*, 2001). In these cases, relative paleointensities are represented against calibrated ages. We must take care when dealing with the pre-glacial section. As was emphasized in Gogorza *et al.* (2004), the normalised remanence records in the 0–20,000 years of the SAPIS stack (Stoner *et al.*, 2002) should be viewed with caution, because of the perturbation induced by the presence of ultra-fine magnetite in the upper part of some of the cores used for the stacking process. This could explain misalignment between paleointensity features in our record and the results from SAPIS, although a clear low in the interval 8600–11,300 years is shown in SAPIS and in the Lake El Trébol records. All the records contain a 13,200 and 19,400 years low and the 19,800 high, although these features are not exactly coincident neither in time nor in amplitude. Further studies would be necessary to draw a reasonable conclusion about the pre-glacial paleointensities from lakes of South Argentina (Gogorza *et al.*, 2004).

Figure 9(c) shows the comparison of our record with the relative paleointensity from Lake Pepin (Brachfeld and Banerjee, 2000), St. Lawrence Estuary (St-Onge *et al.*, 2003), Lake Baikal (Peck *et al.*, 1996) and a compilation of archeomagnetic data (Yang *et al.*, 2000). The agreement between the paleointensity records presented is quite good, especially for the time interval 200–10,000 RCYBP. The distinct long trend between ∼3000 and 10,000 RCYBP could clearly be identified in all records, which is consistent with the global absolute paleointensity results derived from archaeological material (Yang *et al.*, 2000). Comments similar to those presented in Gogorza *et al.* (2004) about the surprising agreement observed between the records from lakes that are thousands of kilometres away, may be carried out in this work. In the time interval 10,700–21,000 RCYBP, inter-lake comparison of the records is difficult; the similarities are limited. The reasons for this difference are not clear. The more notorious characteristic is, in general, a long trend decrease in the Lake El Trébol record that is matched by a long trend decrease in the Lake Baikal record. However, there are sub-millennial features that are not found in both records.

8. Discussion

There is a clear difference in the behaviour of the inter-parametric ratios $ARM_{100\ mT}$/SIRM and $ARM_{100\ mT}/k$ (Fig. 3) between both the El Trébol and Elpalafquen facies. The behaviour observed in Fig. 3 suggests that the magnetic grain size was coarser in sediments from Elpalafquen facies than sediments from Lake El Trébol facies (Gogorza *et al.*, 2004; Irurzun *et al.*, 2006). The changes of behaviour of the studied parameters coincide with the end of the transition from the last glaciation of the Holocene, as indicated by the refinement of bulk sediment particle size above this boundary. The observed shift from coarser to finer PSD magnetite therefore could be the result of a major change in sedimentology, indicating a change in the source of relative flux-density of detrital input from different sources to the site of deposition (Nowaczyk *et al.*, 2001).

The magnetic parameters (SIRM and k; Fig. 3) show strong variations with a lot of spikes in the upper section of the sequence; while the lower part appears much smoother with comparatively little variations, indicating a rather monotonous sedimentation, but, the mean values are similar for both facies (Gogorza *et al.*, 2004). This behaviour could be explained by a heterogeneous sediment composition in the upper part which arises from larger environmental changes.

The observed down-core trend in $NRM_{20\ mT}$ (Fig. 4) is an indicator of significant variations between the upper and lower parts of the sequence. This is probably a consequence of a combination of factors like differences in concentration of magnetite and less efficient recording due to grain size and/or lithology effects (Gogorza *et al.*, 2004). The apparent decrease in the minerogenic content of the sediments, reflected by a decrease in $NRM_{20\ mT}$ and an increase in water content, could be attributed to a slow retreat of the glaciers from the lake catchment during the Late Glacial, also resulting in a decrease in grain size (Frank *et al.*, 2002). Warming up causes retirement of glaciers and an increase of the melt water stream, then there is decreasing of suspended sediment concentration and therefore, a decrease in the magnetic mineral content (Harwart *et al.*, 1999).

The paleointensity proxy of choice is generally either NRM/IRM or NRM/ARM. Both remanences in the ratios are measured after demagnetisation at a particular peak AF in order to eliminate viscous or other low-coercivity contributions to remanence. The normaliser (IRM or ARM) should activate the same grain population as that which carries the NRM. The objective is to compensate for changes in concentration of remanence carrying grains (Channell, 1999). Volume (low field) susceptibility k is occasionally used as the normaliser. However, large multidomain magnetic grains (and paramagnetic and superparamagnetic grains), which could be important contributors to susceptibility, would not be important contributors to the remanence. Susceptibility is therefore not usually the preferred normaliser (Channel *et al.*, 1999).

Although the three methods of normalisation yield essentially the same intensity records, we have chosen $ARM_{20\ mT}$ as the preferred normaliser based on the results of coherence function analysis: lack of coherence between the normalised remanence and bulk mineral magnetic parameters provide the evidence that the paleointensity normalisation ($NRM_{20\ mT}/ARM_{20\ mT}$) is not affected by lithological or other environmental factors. Moreover, ARM is preferred because it is similar to thermal remanence which is the presumed origin of remanence in detrital grains (Levi and Banerjee, 1976; Tauxe and Wu, 1990).

When we compare our record with marine cores -SED-02 (Sagnotti *et al.*, 2001) and SAPIS (Stoner *et al.*, 2002)-, we have to face the problem of different methods of dating (Lehman *et al.*, 1996). The lacustrine sections are usually characterised by larger sedimentation rates, improving the time resolution of the record. However, in most cases, temporal changes in the magnetic mineralogy and granulometry are greater than in the best marine cores (Lehman *et al.*, 1996). It is difficult to determine whether the differences observed between the records within the interval 13,000–20,000 years in Lake El Trébol, came from an incorrect time correlation or from different rock magnetic characteristics. Difficulties also arise for the high-frequency part of the record, because short-lived intensity fluctuations may have been recorded with different resolutions between records, precluding their unambiguous recognition (Lehman *et al.*, 1996). In general, our records and the marine records studied show similar trends, although it is not possible to obtain a close correlation among them. For this reason, it would be necessary to carry out more comparative analysis to reach a convincing conclusion.

In summary, broad-scale similarities between the timing of the features in the various records are encouraging and suggest that a predominantly global signal is recorded by Lake El Trébol sediments (Roberts *et al.*, 1997; Valet, 2003).

9. Conclusions

The composite $NRM_{20\ mT}/ARM_{20\ mT}$ curve represents an estimate of geomagnetic paleointensity variations in South-Western Argentina. The obtained records meet the strictest criteria for relative paleointensity records: the most commonly applied mineral magnetic criteria, paleomagnetic stability, agreement between results of different paleomagnetic normalisation and agreement with records obtained from other geographical areas. The dominant remanence carrier is magnetite and titano-magnetite within the pseudo-single domain (PSD) grain size and the concentration of these minerals change in a factor of ten.

From the comparison of the relative paleointensity records was observed that the (millennial-scale) longer wavelength ($\sim 10^3$–10^4 year) features can be correlated over many thousands of kilometres suggesting that the longer period content is controlled by the global-scale geomagnetic field.

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C. S. G. Gogorza (e-mail: cgogorza@exa.unicen.edu.ar), M. A. Irurzun, M. A. E. Chaparro, J. M. Lirio, H. Nunez, P. G. Bercoff, and A. M. Sinito