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Physics of the Earth and Planetary Interiors 145 (2004) 219–238

PHYSICS OF THE EARTH AND PLANETARY INTERIORS

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Paleointensity studies on Holocene–Pleistocene sediments from lake Escondido, Argentina

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Received 1 September 2003; received in revised form 29 March 2004; accepted 30 March 2004

Abstract

Relative changes in geomagnetic field intensity over the last 16,000 years BP were recovered from the study of four cores obtained from Lake Escondido (South Argentina). Rock magnetic analysis shows that the main magnetic mineral is magnetite, the concentrations being mainly between 0.01 and 0.1%, and the grain size between 1 and 8 μm. In order to fulfil the criteria for assessing the reliability of paleointensity data derived from sediments [Rev. Geophys. 31 (1993) 319], the samples whose concentrations and size are beyond this range were rejected. The remanent magnetisation at 20 mT ($NRM_{20\,mT}$) was normalised using the anhysteric remanent magnetisation ($ARM_{100\,mT}$), the saturation of the isothermal remanent magnetisation (SIRM) and the low field magnetic susceptibility (k). Coherence function analysis indicates that the records are not significantly affected by local environmental conditions. This suggests that the variations in normalised remanence are mostly likely due to geomagnetic paleointensity fluctuations. $ARM_{100\,mT}$ is the best normaliser for the Lake Escondido sediments. The record of relative paleointensity ($NRM_{20\,mT}/ARM_{100\,mT}$) shows peaks and troughs whose amplitudes are similar to those in the St. Lawrence Estuary, Lake Baikal, Lake Pepin and Larsen-A Ice shelf data set and a stack of archeomagnetic data given as virtual axial dipole moment (VADM).

Keywords: Relative paleointensity; Holocene; South America; Lake Escondido; Coherence

1. Introduction

One of the first motivations for investigating the magnetism of rocks was to study the behaviour of Earth's magnetic field in the past. The magnetic field is a vector field, having both direction and intensity, and a complete understanding of it requires study of the full vector properties. However, paleointensity determinations are much more difficult than directional ones, and the majority of paleomagnetic studies are concerned only with directional variability of the field.

Absolute values of paleomagnetic field intensity require the paleomagnetic analysis of materials such as lavas and baked archaeological artefacts that contain thermally acquired natural remanent magnetisation (NRM). However, such materials are notoriously poor

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0031-9201/$ – see front matter
doi:10.1016/j.pepi.2004.03.010

in their spatial and temporal coverage, require laborious measurement, and are often difficult to be dated precisely (Tauxe, 1993). On the other hand, sedimentary sequences offer the advantages of continuous high-resolution records of the NRM. Relative paleointensity variations can be estimated by normalising the NRM in rapidly deposited sediment sequences. It is important to bear in mind that the paleomagnetic intensity is controlled not only by the Earth's magnetic field but also by the magnetic mineral assemblages contained in the samples. Moreover, the mechanism for the acquisition of the remanent magnetisation plays another important role. Typically, SIRM, ARM and k are used as normalisers of NRM to correct or normalise the variation in the density of remanence carriers in the sediment. The interpretation of the geomagnetic intensity record for sediments is usually difficult, because the records can be biased by environmental effects (Lund and Schwartz, 1999; Kruiver et al., 1999).

There are a series of papers that establish a set of criteria for reliability of sediments for relative paleointensity (e.g. Banerjee et al., 1981; King et al., 1982, 1983; Thouveny, 1987; Tric et al., 1992). Tauxe (1993) reviewed the experimental and theoretical considerations for assessing the reliability of paleointensity data derived from sediments. The basic requirements which a sediment should fulfil for reliable paleointensity determinations are that the NRM must be carried by stable magnetite, preferably in the grain size range of about 1–15 μm, the detrital remanence must be an excellent recorder of the geomagnetic field, concentration variations must be lower than about an order of magnitude, and the normalisation should be preferably done by several methods, all yielding consistent results. Besides these tests for magnetic uniformity, several other criteria should be applied, including: (1) a stable, well defined, single component of magnetisation should characterise the NRM at the demagnetisation level used for paleointensity normalisation; (2) the detrital remanent magnetisation must be a reliable recorder of the geomagnetic field orientation, with no evidence of inclination error; (3) records obtained from multiple normalisation parameters should agree; (4) coherence between paleointensity determinations and the magnetic parameters used for normalisation should be minimal and (5) duplicate or multiple records from a given region should agree within the limits of the common time scales (Tauxe, 1993).

There are numerous studies that have recovered the relative paleointensity from marine cores (Guyodo and Valet, 1996; Cisowski and Hall, 1997; Roberts et al., 1997; Channell, 1999; Channell et al., 2000; Laj et al., 2000; Stoner et al., 2002). However, few studies have been made on terrestrial sediments, probably due to their more complex sedimentological characteristics (Levi and Banerjee, 1976; Peck et al., 1996; Brachfeld and Banerjee, 2000; Nowaczyk et al., 2001; St-Onge et al., 2003). Comparatively, there are not paleointensity results from South America, except for preliminary studies carried out on one core from El Trébol Lake (Sinito and Nuñez, 1997). This paper describes relative paleointensity results from cores obtained from Lake Escondido. The directional parameters corresponding to these cores have already been presented (Gogorza et al., 2002).

2. Site description

Lake Escondido is a small closed basin of about 130,000 m^2 and a depth up to 8.3 m, related to series of large glacier-carved lakes. It is situated on the east side of the Andean Patagónica Cordillera; in the Llao Llao area, 20 km NW of San Carlos de Bariloche City (about 41°S, 71°30′W), at an altitude of 800 m above sea level (Fig. 1). Strandlines surrounding lakes at higher levels indicate the former presence of large paleolakes in many areas along the Andes and the Patagonian Steppe in South America. The network of Late Pleistocene glacial paleolakes was extended over the chain of recent Great Lakes (Lake Nahuel Huapi, Lake Gutiérrez, and Lake Mascardi) and smaller lakes like Lake Escondido and Lake El Trébol (Tatur et al., 2002).

Volcanic rocks of Tertiary (Eocene) age assigned to Ventana Formation outcrop in the Lake Escondido area (González Díaz and Nullo, 1980). These rocks show evidence of glacial erosion by Andean glaciers during Late Pleistocene. The Ventana Formation is partially covered by Late Pleistocene–Holocene deposits, consisting principally of glacial related sediments and abundant volcanic ash layers (tephra). These layers thicken westwards, in the direction of the main effusive centres. Feruglio (1941), Gonzalez Bonorino

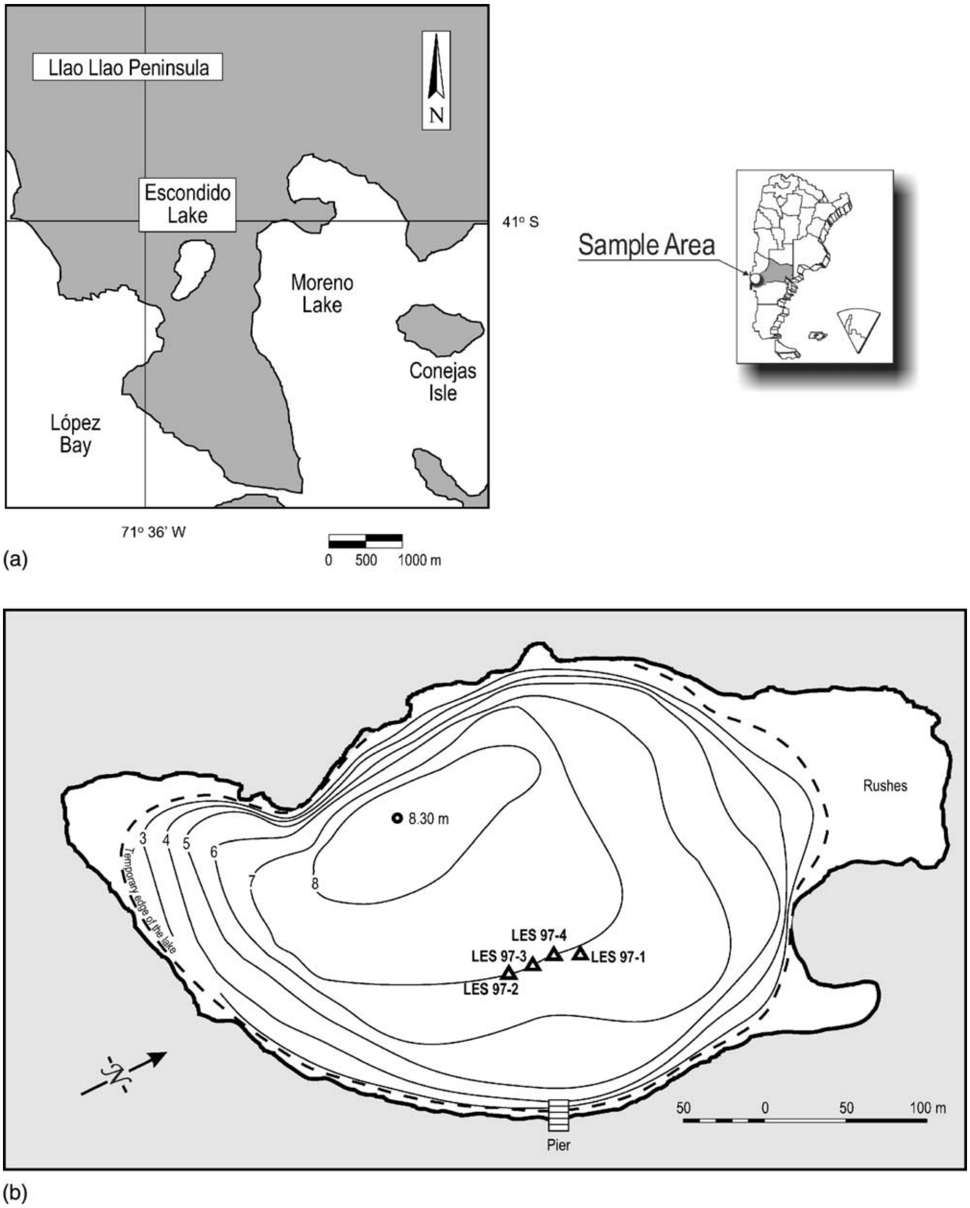


Fig. 1. (a) Geographical location of lake Escondido. (b) Location of coring sites in the lake.

(1973, 1979) and González Díaz and Nullo (1980), among others, have described the regional geological features of the Andean Patagónica Cordillera and studied the geology and stratigraphy of the southern zone of Nahuel Huapi Lake area. A brief report of their conclusions was summarised by Gogorza et al. (1999, 2002).

3. Field work, sampling, sedimentology and radiocarbon dating

A detailed description of these items can be found in Gogorza et al. (2002). A brief summary follows. Four cores (labelled les97-1, les97-2, les97-3 and les97-4, respectively) were collected in water depths of about

7 m using a push-corer installed on a raft with a central hole. We successfully cored to basement (or erratic blocks), recovering four sediment columns of 6 cm diameter and up to 12.3 m thick. The locations of the core sites are shown in Fig. 1. The recovered sediment sequences consist of several separate and successive push-core segments with a maximum length of 2 m, with a common internal orientation, but not orientated relative to magnetic north. There is no overlap between the 2 m long segments, and no section gets lost. The compaction is minimal. The sediments were extruded using the included piston.

The cores were subsampled with plastic cubic boxes of 8 cm^3. In total, 1347 subsamples were taken. Subsampling for rock magnetic studies and for ^{14}C and $\delta^{13}C$ analyses was also carried out.

The four cores are sedimentologically similar, and represent the most complete sedimentary record from Lake Escondido to date. Three principal lithologies are present in the Lake Escondido sediment column. From bottom to top: light reddish clayey silt (A), light grey clay (B) and dark brown organic-rich clay with high water content (C).

About 100 tephra layers are interbedded in lithologies A, B and C. They can be easily identified, allowing good lithological correlation between cores. The frequency and thickness of tephra increases upward. Up to 30 conspicuous tephra layers along the whole sedimentary column were recognised.

Two different facies can be recognised on Lake Escondido: a basal glacio-lacustrine facies ("Lake Elpalafquen" facies), that includes lithologies A, B and tephras, and a younger organic-rich lacustrine facies (lithologies C and tephras) or "Lake Escondido" facies. "Lake Elpalafquen" facies have been recognised within cores from other lakes of the area and on outcrops (del Valle et al., 2000), and represent sedimentation during Late Pleistocene times when a large pro-glacial lake named Elpalafquen (del Valle et al., 2000) existed in the region. The "Lake Escondido" facies represent lacustrine sedimentation under no direct influence of glaciers. These sediments were deposited mainly during the Holocene, after the collapse of Lake Elpalafquen, which gave rise to the formation of the present lakes of the region. The palynological studies of Jackson (1996) and Bianchi (2000) show a clear climatic improvement (warming trend) recorded by the "Lake Escondido" facies.

The age scale for this study was provided by AMS radiocarbon dates described in previous works (Gogorza et al., 1999, 2002; Bianchi, 2000). AMS ^{14}C ages are listed in Table 1. During the field work, made in order to obtain the cores studied by Gogorza et al. (1999), a small clam was found living at the sediment–water interface. This clam was identified to the genus *Diplodon* (Castellanos, 1959, 1960), and was determined to be 5-year-old based on annual growth lines. The clam was dated to assess the

Table 1
The $\delta^{13}C$, radiocarbon and ^{14}C years BP

Core	Material	Depth (cm)	Shortened depth (cm)	Date ^{14}C years BP $\pm 2\sigma$	$\delta^{13}C$ (‰)	Calibrated (age $\pm 2\sigma$, years)	References
es3	Clam	0	0	123.3 ± 0.7%[a]	[b]	0 ± 150	Gogorza et al. (1999)
es3	Sediment	74	48	1325 ± 110	[b]	1272 ± 110	Gogorza et al. (1999)
les97-1	Cuticle	91	84	1870 ± 80	−27.8	1815 ± 175	Bianchi (2000)
les2	Sediment	95	90.5	2300 ± 130	[b]	2319 ± 130	Gogorza et al. (1999)
les97-1	Wood	218	168	4210 ± 90	−25.4	4743 ± 287	Bianchi (2000)
les2	Leaf	265	199	5235 ± 130	[b]	5937 ± 130	Gogorza et al. (1999)
les2	Sediment	330	235.5	7950 ± 150	[b]	8641 ± 150	Gogorza et al. (1999)
les97-4	Sediment	574.5–582	280	9840 ± 80	−24.3	10995 ± 224	This work
les97-1	Leaf	374	301	11150 ± 280	−28.5	13059 ± 600	Bianchi (2000)
les97-4	Sediment	677–682.5	322	11620 ± 80	−23.5	13549 ± 400	This work
les2	Sediment	391.5	355	12050 ± 190	[b]	14005 ± 380	Gogorza et al. (1999)
les97-2	Sediment	878.5–883.5	492	14450 ± 100	−25.9	17313 ± 405	Gogorza et al. (2002)
les97-4	Sediment	1058–1063	724	15680 ± 120	−27.1	18576 ± 413	Gogorza et al. (2002)

[a] ^{14}C activity of 5-year-old clam (genus *Diplodon*) was $123 \pm 0.7\%$ of the modern atmospheric activity of ^{14}C.
[b] Dates are based on $\delta^{13}C$ standardised to −25‰ with respect to the PDB standard.

potential for ancient dead carbon within the basin. If the age of the clam (which was living and sampling the carbon at the sediment water interface) came back older than modern, it could be inferred that the organism was sampling dead carbon. The final results indicate the basin is not receiving dead carbon; the ^{14}C activity of the clam measured $123.3 \pm 0.7\%$ of the 1950 pre-bomb ^{14}C activity, consistent with the modern atmospheric ^{14}C concentration for the region (Jackson, 1996).

4. Magnetic studies

In order to characterise these lake sediments and to assess the reliability of paleointensity data derived from them and to carry out the normalisation, a set of laboratory experiments performed in a former work (Gogorza et al., 2002) were analysed.

The following measurements were performed: 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 Gogorza et al. (2002) were also used: ($IRM_{-300\,mT}$/SIRM), remanent coercitive field (H_{CR}), SIRM/k; $ARM_{100\,mT}/k$ and SIRM/$ARM_{100\,mT}$.

Additional studies were carried out in this work: magnetic demagnetisation from NRM to determine median destructive field (MDF_{NRM}), partial anhysteric remanence (pARM), hysteresis curves and temperature dependence of SIRM. NRM, X, k, SIRM and $ARM_{100\,mT}$ were obtained for all samples; the rest of the magnetic parameters were measured for a group of selected pilot samples from different lithologies.

The studies of pARM were carried out using a peak AF of 100 mT (the rate of decrease was 17 μT per cycle), and applying a DC field of 50 μT over specific AF windows. A width of 5 mT for the window (it was moved into a range between 5 and 100 mT) was chosen.

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 the Thermal Specimen Demagnetiser, model TD-48 ASC Scientific. Stepwise thermal demagnetisation curves were represented and critical temperatures (T_C) were estimated.

5. Reliability of sediments as paleointensity recorders

New analyses of the data were carried out to complete the study of reliability of paleointensity results. These results and those obtained by Gogorza et al. (2002) are briefly summarised to demonstrate that the sediments meet the established criteria for relative paleointensity determinations.

Since the profiles of the different parameters are presented as function of "shortened depth" a brief description of the method used to obtain this depth is given below.

As explained in former papers (Gogorza et al., 1999, 2001, 2002), k logs can be used to define tie lines, which describe the lithostratigraphic correlation of cores of the same lake and are, in general, consistent with the lithology. The depth scales of all the cores were adjusted to the depth scale of a chosen master core (les97-2) using lithology and X tie lines for correlation. One of the most important problems in lake sediments of volcanic areas, 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).

5.1. Mineral-magnetic characteristics

Reliable paleointensity estimates require uniformity of concentration of magnetic grains and magnetic mineralogy (Tauxe, 1993). Stepwise acquisition of the isothermal remanence in fields up to 1.2 T shows that

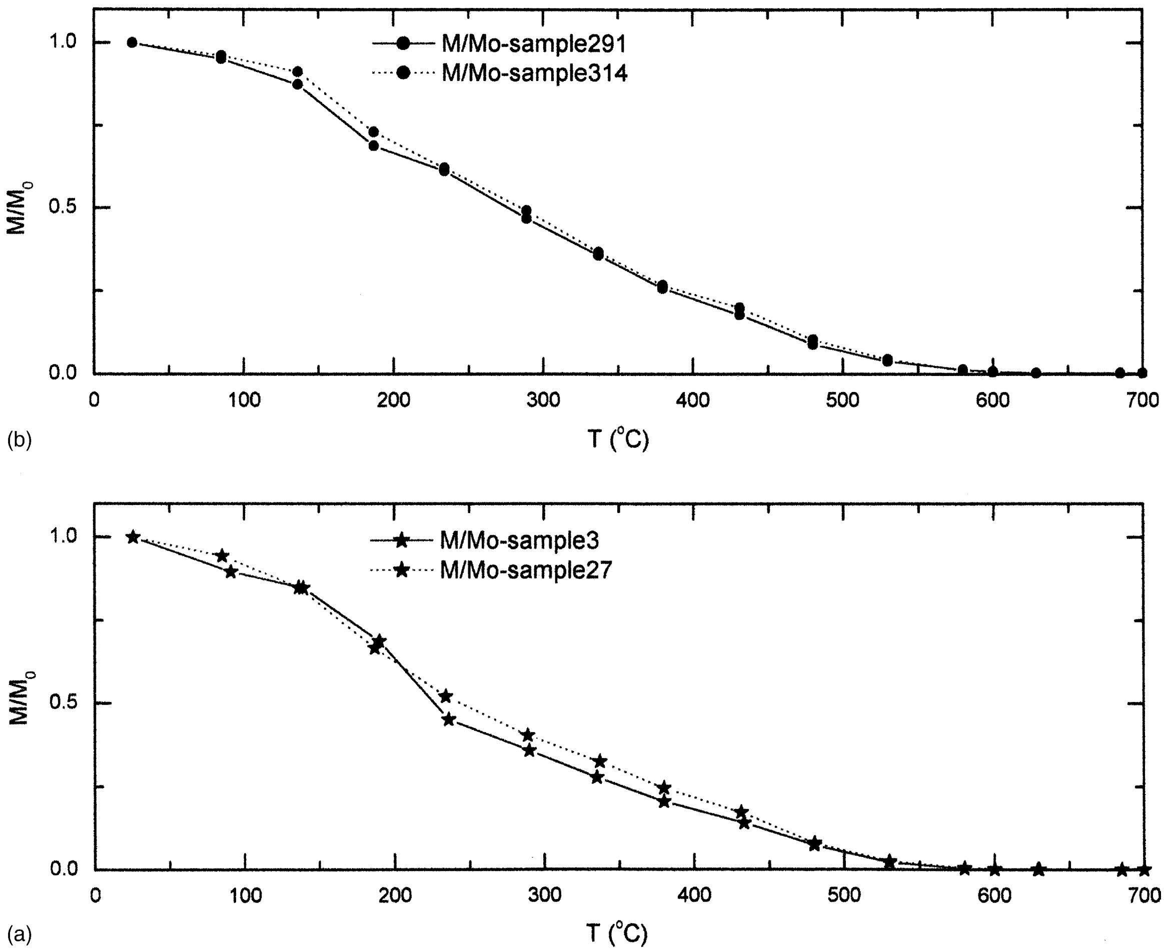


Fig. 2. Thermal demagnetisation curves of SIRM for two samples from the upper part of the sequence (a) and two from the lower one (b).

between 82 and 95% of the SIRM is acquired at an applied field of ≤300 mT. Progressive removal of this SIRM by back-field demagnetisation indicates that H_{CR} varies between 61 and 86 mT. Fig. 2 shows thermal demagnetisation curves of SIRM for four samples, two from the upper part of the sequence ("Lake Escondido" facies) and two from the lower part ("Lake Elpalafquen" facies). Although Curie temperature is about 580 °C for all samples, the curves of Fig. 2a show a minor inflection, which suggests the presence of more than one magnetic mineral. These results indicate that magnetite is the dominant magnetic carrier of remanence in these cores, but the presence of a very low proportion of titanomagnetite in younger section cannot be excluded.

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 size dependence, while the former can be affected by super-paramagnetic (SP) grains (Pan et al., 2001). From Fig. 3, which shows *k* versus SIRM for all samples, we can estimate that the concentration varies between 0.01 and 0.1% (Thompson and Oldfield, 1986). In order to meet the criteria for uniformity in terms of concentration (Tauxe, 1993),

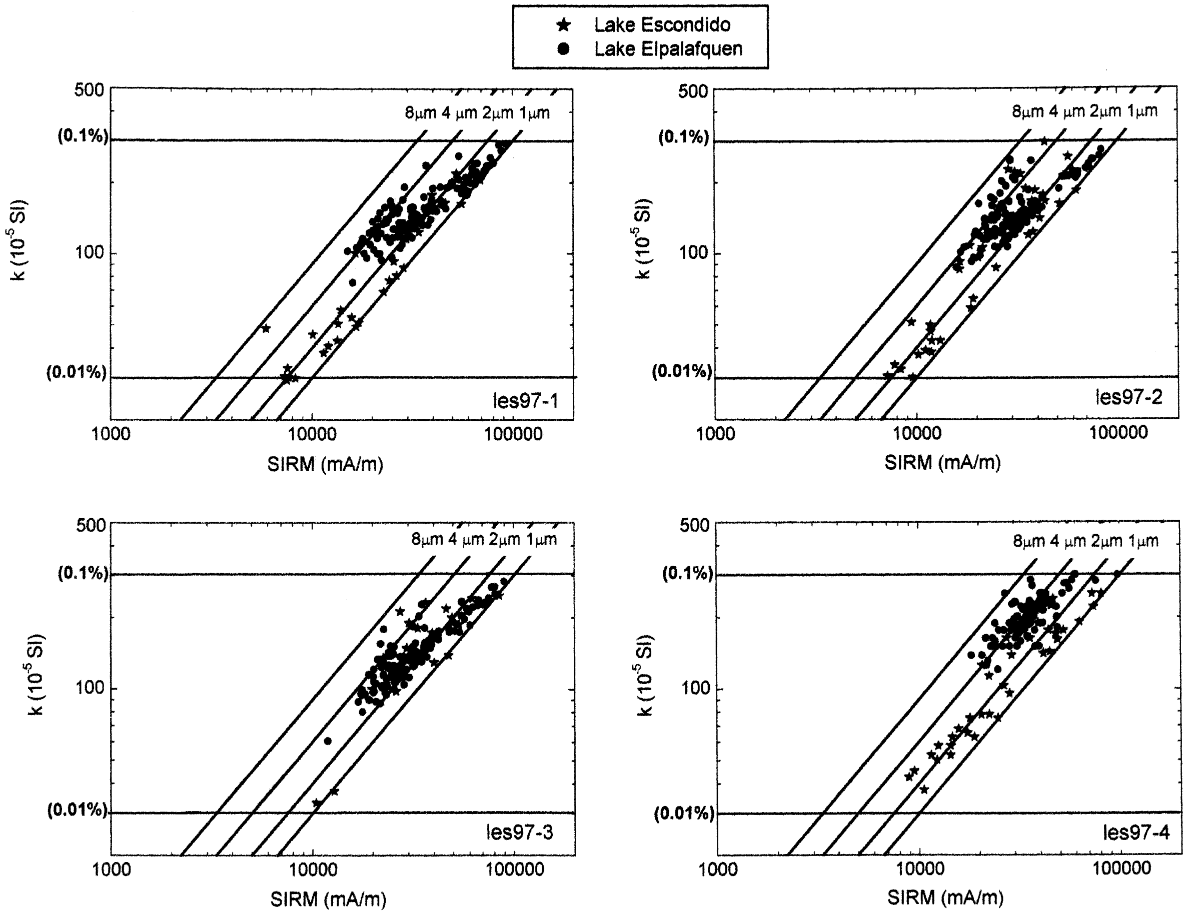


Fig. 3. k vs. SIRM for all samples in order to estimate concentration and grain size according to Thompson and Oldfield (1986).

those samples whose concentrations are beyond this range were rejected.

5.2. Magnetic granulometry

Down-core homogeneity in grain size is an important factor for reliable estimation of the relative changes of paleointensity of the geomagnetic field (King et al., 1983; Tauxe, 1993; Lehman et al., 1996). Here we used several different approaches to estimate grain size. We determined the MDF_{NRM}, the $ARM_{100\,mT}/k$ ratio, the $ARM_{100\,mT}$/SIRM ratio, and k versus SIRM, pARM, and hysteresis parameters.

MDF_{NRM} values are between 26 and 35 mT, within the range of those generally found for other Late Pleistocene–Holocene lake sediments from the area (Gogorza et al., 2002). These values are consistent with the predominance of magnetite as magnetic carrier in the samples.

From Fig. 3, which shows k versus SIRM for all samples (Thompson and Oldfield, 1986) we can estimate that the grain size varies between 1 and 8 μm. In order to meet the criteria for reliability of paleointensity data (Tauxe, 1993), those samples which are beyond this range were rejected.

Fig. 4a shows normalised pARM versus applied field (H). The position of the peak pARM acquired indicates an estimated grain size of about 1 and 4 μm (Jackson et al., 1988).

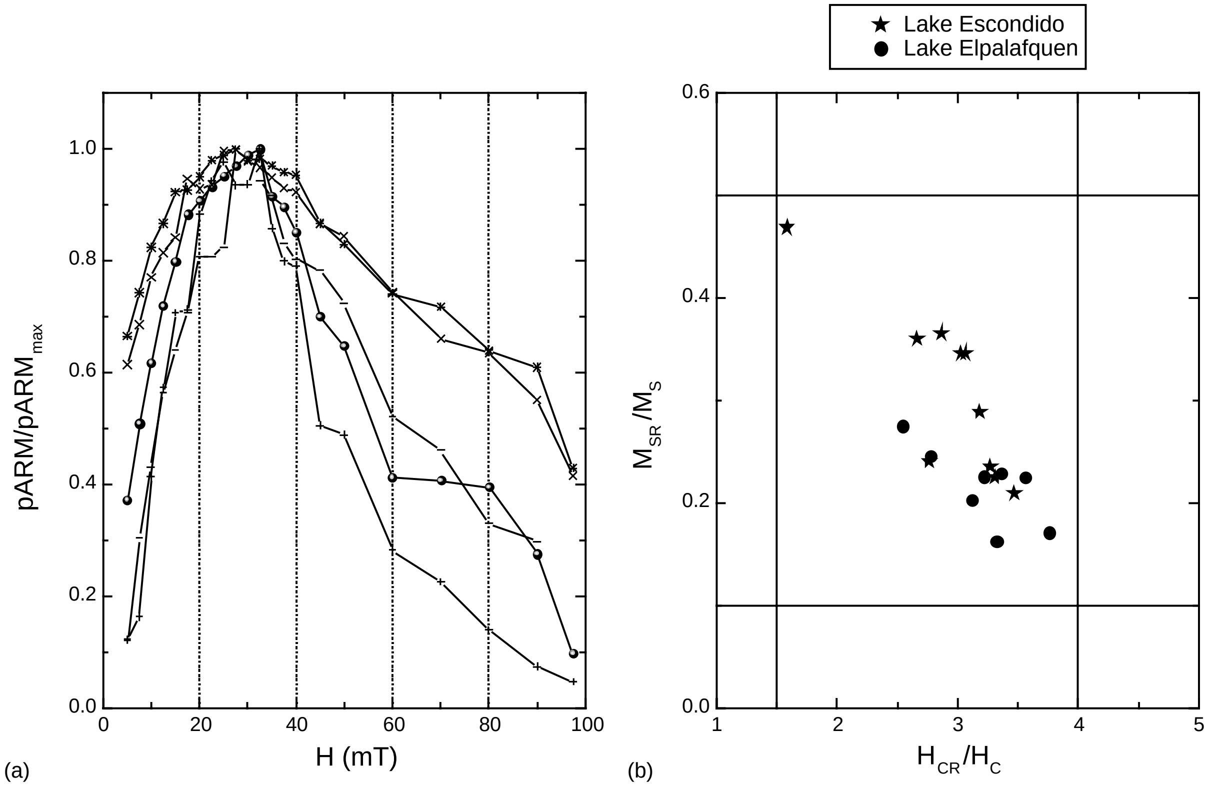


Fig. 4. (a) Normalised pARM vs. H for pilot samples and (b) hysteresis parameter ratios, H_{CR}/H_C vs. M_{RS}/M_S for estimation of grain size.

The hysteresis parameter ratios, H_{CR}/H_C and M_{RS}/M_S vary between 2.5 and 3.7 (except one sample, 1.6) and 0.17–0.3 (except one sample, 0.4), respectively. These results indicate that the magnetite grains are pseudo-single-domain (PSD) size (Fig. 4b).

Changes in the ratios of $ARM_{100\,mT}/k$ and $ARM_{100\,mT}$/SIRM imply changes in grain size, higher ratios indicating smaller grain size and a higher proportion of single-domain (SD) grains provided that chemical composition of the grains is constant (Hunt et al., 1995). Fig. 5 shows that the variation of $ARM_{100\,mT}/k$ and $ARM_{100\,mT}$/SIRM with the "shortened depth" of these sediments is lower than 3, which indicates a rather uniform grain size along the sequence.

After these analyses we can confirm that the mineral-magnetic characteristics described above indicate that the sediments of the Lake Escondido meet stringent criteria for relative paleointensity determination.

5.3. Paleomagnetic stability

Stability of the magnetisation was analysed by alternating field (AF) demagnetisation (Gogorza et al., 2002). For core les-97, every fourth sample was chosen as a pilot sample. Pilot samples were demagnetised successively at 2.5, 5, 10, 15, 20, 25, 30, 40, 50 and 60 mT peak field. Most of the samples show no systematic change in the direction of their remanent magnetisation, which could easily be removed at AF demagnetisation at 10 or 15 mT, therefore, they mostly have a single component. We have chosen the value of the NRM after the 20 mT step as representative of the stable characteristic remanent magnetisation ($NRM_{20\,mT}$) and we have used this value for constructing the normalised intensity records.

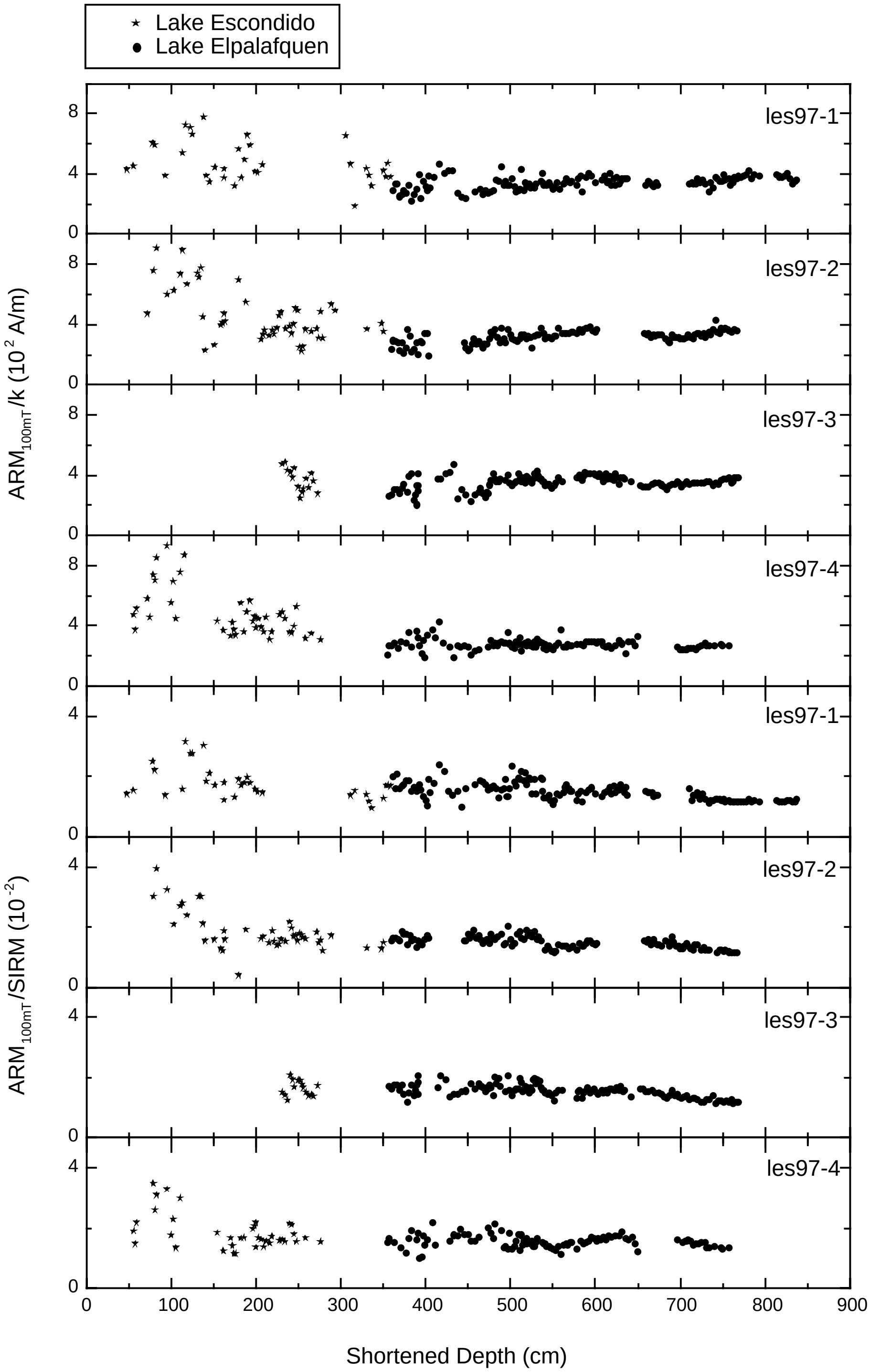


Fig. 5. $ARM_{100\,mT}$/SIRM and $ARM_{100\,mT}/k$ records vs. shortened depth from cores les97-1–4.

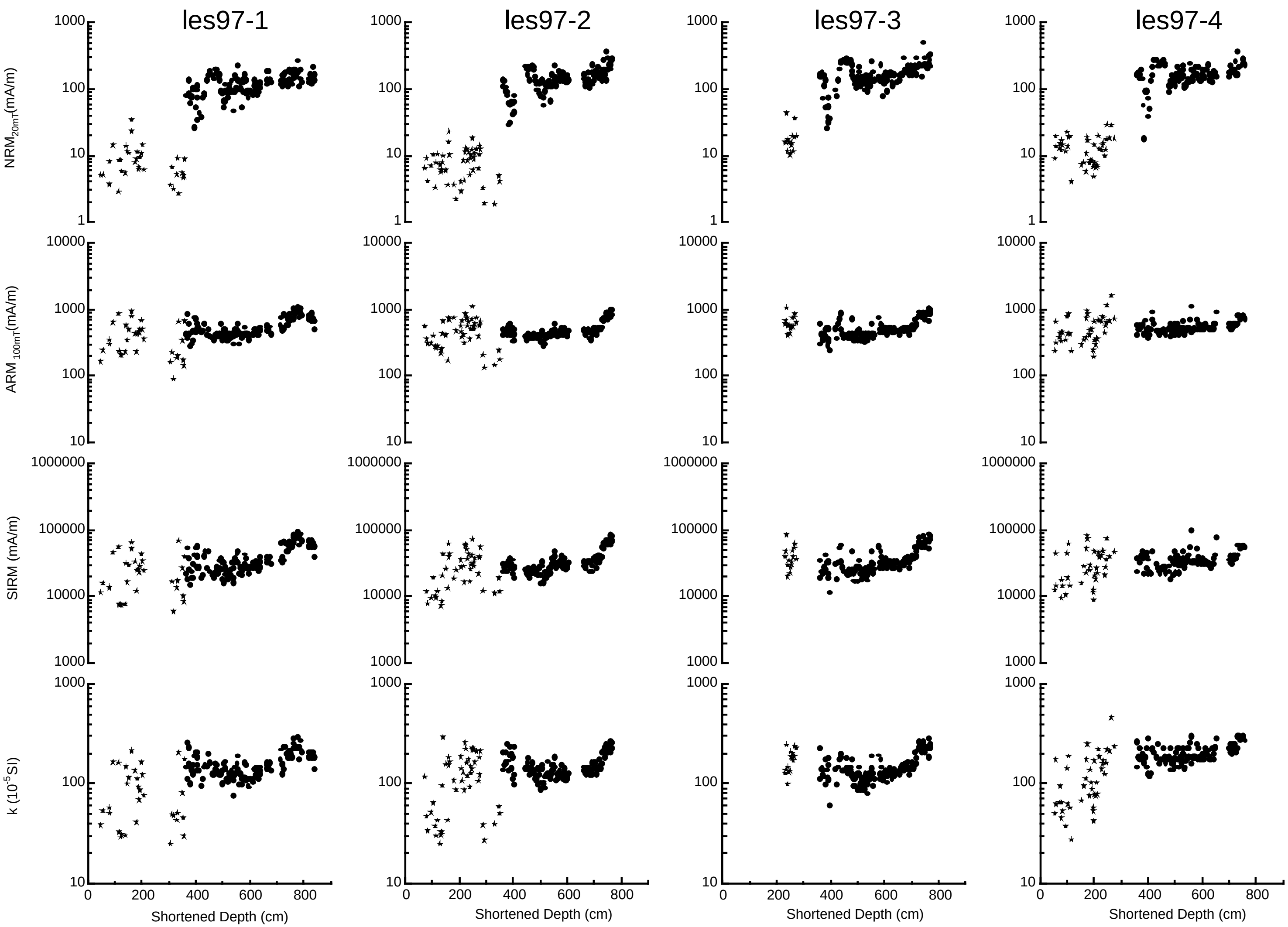


Fig. 6. k, SIRM, $ARM_{100\,mT}$/SIRM and $NRM_{20\,mT}$ records vs. shortened depth from cores les97-1–4.

6. Normalisation methods

Fig. 6 shows $NRM_{20\,mT}$, $ARM_{100\,mT}$, SIRM and *k* versus shortened depth for cores les97-1 to les97-4. We observed that there is good agreement between $ARM_{100\,mT}$, SIRM and *k*, it means that NRM intensity is mainly managed by changes in the geomagnetic field rather than by environmental factors. $ARM_{100\,mT}$, SIRM and *k* vary by a factor of about 10, within the range considered to be appropriate for paleointensity studies (Tauxe, 1993).

For each core, we have obtained three estimates of normalised field intensity using $ARM_{100\,mT}$, *k* and SIRM as normalising parameters. For each core, the three normalised records are similar and support the hypothesis that they represent a geomagnetic signal rather than an artefact of sedimentary magnetisation processes. However, a different behaviour is clear in the upper and lower sections. In the upper section, belonging to the "Lake Escondido" facies, the mean values are lower than in the "Lake Elpalafquen" facies. In order to compare the records they are both normalised by their respective mean values (Fig. 7).

The results of the four cores were then integrated into a single curve by a stacking process, consisting of an arithmetical average. In order to carry out this average, it is necessary to have data at the same depth for each core, for this reason a interpolation was performed, getting data every 20 cm (Fig. 8). The error interval, consisting of the standard deviation, is also shown. The three methods of normalisation give similar results, which indicates that environmental effects are small, as expected from the uniformity of the magnetic properties in the cores derived from the stringent constraint that we asked to the sediments.

It is worthwhile to discuss the different amplitude of the peak observed at about 100 cm depth (Fig. 8). This peak is lower for the ratio $NRM_{20\,mT}/ARM_{100\,mT}$, i.e. the values of $ARM_{100\,mT}$ are higher than the values of SIRM and *k*. Since ARM is better recorded by finer grains and Fig. 5 shows at the same depth a change that reflects the presence of finer grain in this zone, these results are consistent, and suggest that $ARM_{100\,mT}$ is the more appropriate normaliser parameter.

In order to analyse the different parameters as function of time and to compare our results with previously published paleomagnetic records, mostly derived from uncalibrated ^{14}C dates, a transfer function from Radiocarbon Years Before Present (^{14}C years BP) to shortened depth was defined using the data of Table 1. Relative paleointensity profiles as a function of ^{14}C years BP are shown in Fig. 9.

7. Power spectral and coherence function analysis

To confirm that the normalised records ($NRM_{20\,mT}/ARM_{100\,mT}$, $NRM_{20\,mT}/k$ and $NRM_{20\,mT}$/SIRM) are free of environmental influences, spectral analyses of normalised remanences, normalisation parameters and coherence test were carried out following the method of Tauxe and Wu (1990). Their argument is that if the normaliser and the intensity record exhibit significant coherence, then the remanence may not have been adequately corrected for environmental effects. This test has been advocated as a means of assessing relative paleointensity data quality (Tauxe, 1993). Spectral analysis and calculation of coherence spectra were performed using MATLAB 6.1 software.

7.1. Lake Escondido facies

It is shown in Fig. 10 that at the 95% confidence level, $NRM_{20\,mT}/ARM_{100\,mT}$ is generally incoherent with its normaliser. On the other hand, $NRM_{20\,mT}/k$ and $NRM_{20\,mT}$/SIRM are not coherent with their normaliser for most frequencies except at periods of about 140 and 207–211 years. There is a widespread geographic occurrence of 200-year cycles in a variety of terrestrial records such ^{14}C anomalies in tree rings (Stuiver and Braziunas, 1993) and ^{10}Be concentrations in ice cores (Raisbeck et al., 1990). The 200-year cycles are well-documented in Minnesota during the Holocene in varves thickness records from several lakes (Anderson, 1992; Slawinksi, 1998), in the Antarctic Peninsula in multiproxy records from a sediment core retrieved from a deep basin (Leventer et al., 1996), in the Maya Lowlands in drought frequencies (Hodell et al., 2001) and in Africa through paleolimnological proxies (Verschuren et al., 2000). The spectral features at 200 years in the normalised intensity record is likely a climatic signal that has not been satisfactorily removed by the normalisation process.

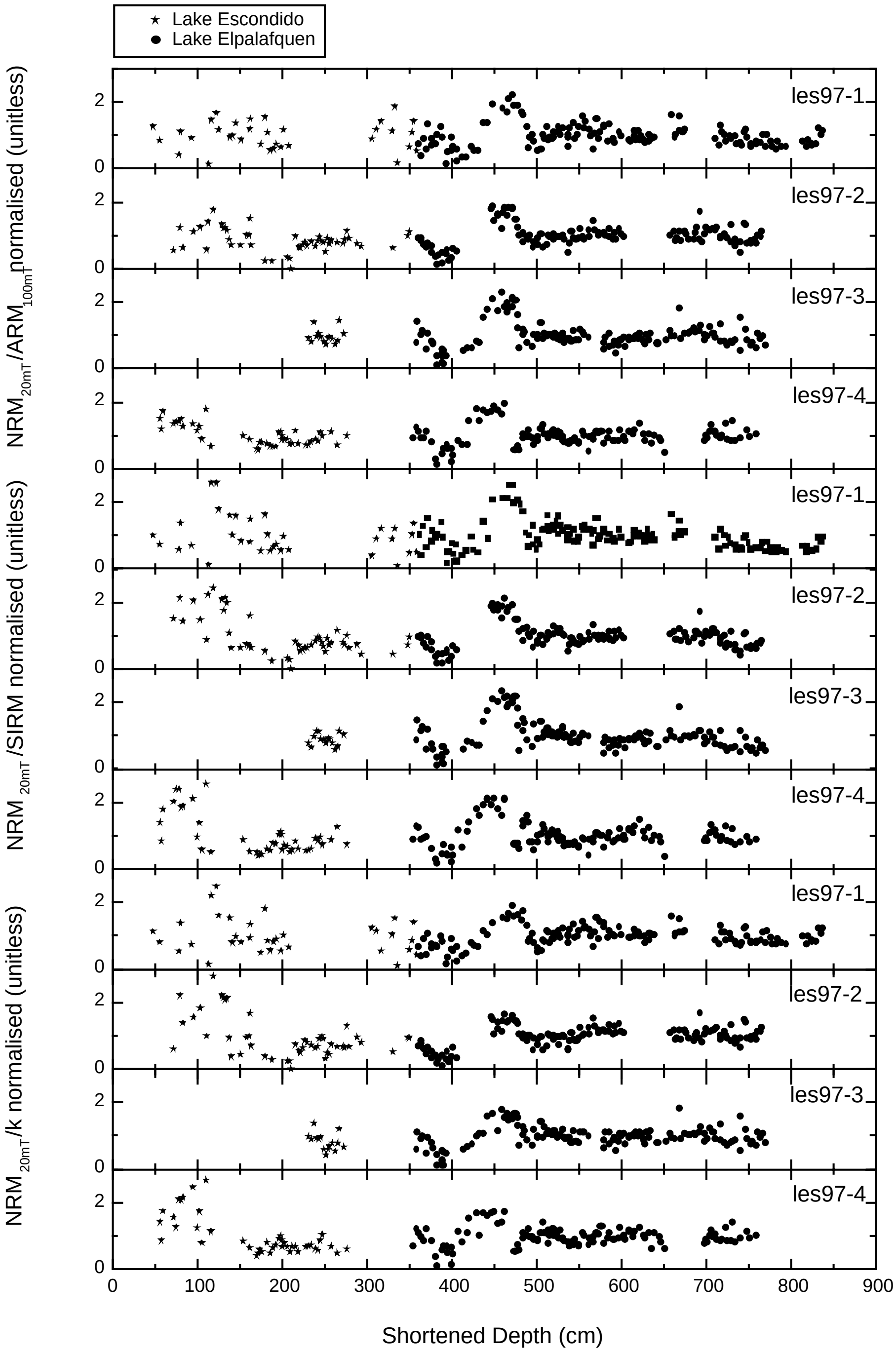


Fig. 7. Normalised $NRM_{20\,mT}/k$, $NRM_{20\,mT}$/SIRM and $NRM_{20\,mT}/ARM_{100\,mT}$ records vs. shortened depth from cores les97-1–4.

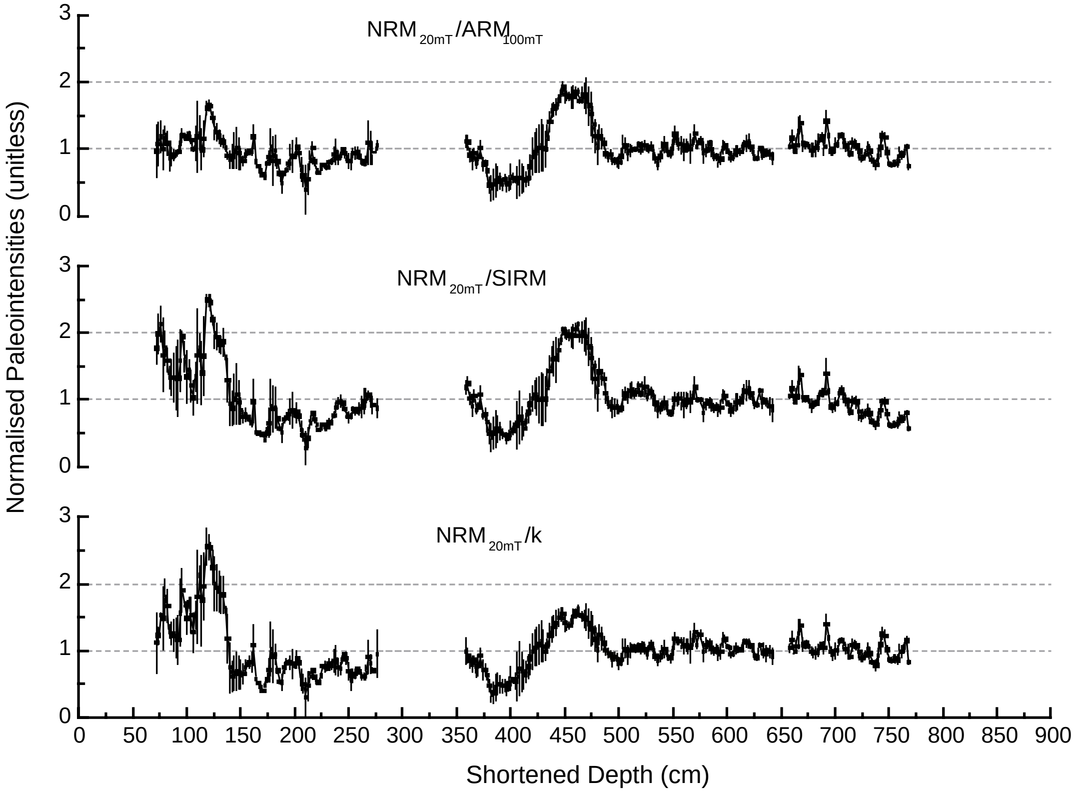


Fig. 8. Stacked $NRM_{20\,mT}/ARM_{100\,mT}$, $NRM_{20\,mT}/SIRM$ and $NRM_{20\,mT}/k$ records vs. shortened depth.

7.2. Lake Elpalafquen facies

The analysis suggests that the normalised curves are not coherent with the parameters of normalisation (Fig. 10). This analysis indicates that the parameter $ARM_{100\,mT}$ is the more appropriate normaliser in these sediments (not coherent frequencies above the 95% confidence level) and that the $NRM_{20\,mT}/ARM_{100\,mT}$ record is not affected by climatic or lithologic factors but represents a true geomagnetic signal. This result is consistent with the results suggested by the grain size analysis (item 6).

8. Comparison with relative paleointensity records

We have compared our normalised intensity record ($NRM_{20\,mT}/ARM_{100\,mT}$) with relative paleointensity records from Southern and Northern Hemisphere (Fig. 11a–c).

Fig. 11a shows our record and the results from a sedimentary sequence collected from beneath the former Larsen-A Ice shelf, Antarctic Peninsula (Brachfeld et al., 2003). Relative paleointensities are represented versus radiocarbon ages. Our record shows some similarities to Larsen record, displaying a high at about 3000 RCYBP, preceded by a relative low from 5500 to 7500 RCYBP. Although this low is smoother in Larsen results, the trend of both records is comparable. Fig. 11b shows our record and the results from South Atlantic geomagnetic paleointensity stack, SAPIS (Stoner et al., 2002) and from three cores (SEDANO) collected from Antarctic late pleistocene sediments (Sagnotti et al., 2001). In these cases relative paleointensities are represented versus calibrated ages. The lack of correlation between our record and the results from SAPIS may be attributed to the perturbations introduced by the presence of ultra-fine magnetite in the upper part of some of the cores used for the SAPIS stack. This reason is mentioned by

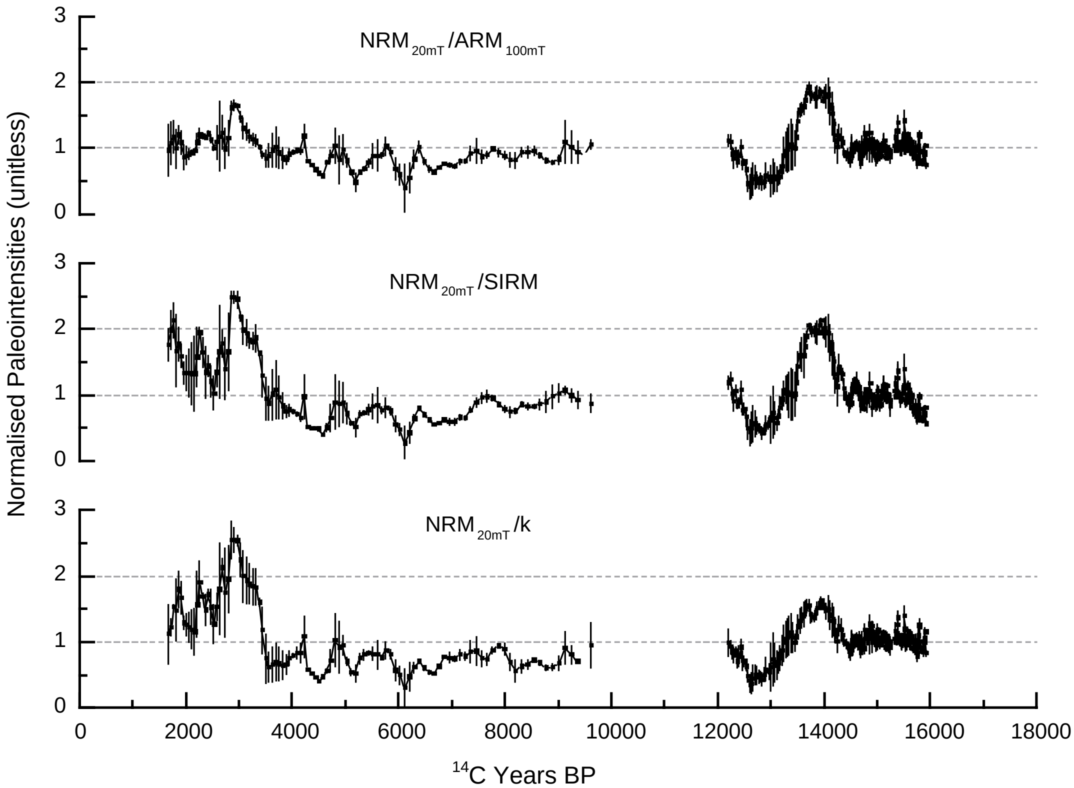


Fig. 9. Stacked $NRM_{20\,mT}/ARM_{100\,mT}$, $NRM_{20\,mT}/SIRM$ and $NRM_{20\,mT}/k$ records vs. ^{14}C years BP.

Stoner et al. (2002) to explain the differences existing in the 0–25 ka interval between SAPIS and NAPIS stack. The comparison from our record and those from Sagnotti et al. (2001) shows some similarities with SED-06 and SED-04 results, a low and a high in the lower part of the sequences are observed in both records, although a lag between them is observed.

Fig. 11c shows the comparison of the post-glacial section [0–10,000 RCYBP] of our normalised intensity record ($NRM_{20\,mT}/ARM_{100\,mT}$) with the relative paleointensity record 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 five records are similar in shape from ∼1700 to 9600 years. BP with values above and below the mean, which is consistent with global absolute paleointensity estimates derived from archaeological material (Yang et al., 2000). Assuming that not all the record age models are necessarily correct, it is interesting to note that in some intervals the Lake Escondido record is in better agreement with the record from St. Lawrence Estuary. At other intervals the Lake Escondido and Lake Pepin record shows the closest agreement (e.g. the long trend between ∼3400 and 7350 years BP). Surprising agreement is observed between the record of Lake Escondido and the record of Lake Baikal, taking into account that both lakes are thousands of kilometres away. A peak around 2300 years. BP and an oscillating behaviour superimposing on a long trend below the mean between ∼3400 and 8000 years. BP is observed in both records. Values above the mean between ∼1700 and 3400 years and values below the mean between ∼3400 and 7350 years. BP are observed in both Lake Escondido and Lake Pepin records. Such behaviour is also observed in Holocene absolute paleointensity estimates (Yang et al., 2000), supporting Lake Escondido and Lake Pepin records in

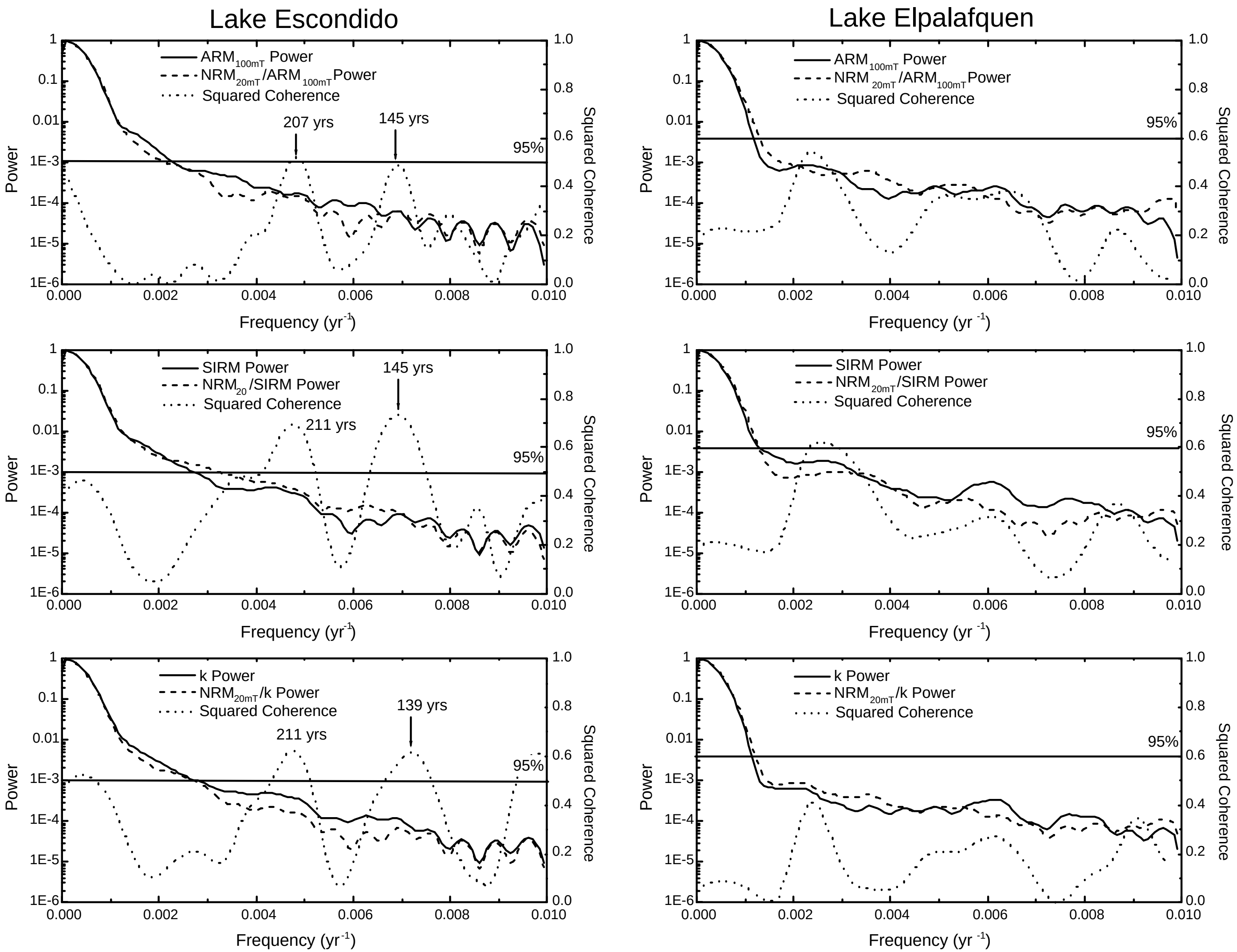


Fig. 10. Spectral analysis of three normalisation parameters ($ARM_{100\,mT}$, SIRM and k) and three normalised remanences ($NRM_{20\,mT}/ARM_{100\,mT}$, $NRM_{20\,mT}/SIRM$ and $NRM_{20\,mT}/k$). Coherence tests results are shown separately for samples from facies Escondido and Elpalafquen. The 95% confidence level is denoted by the horizontal line.

that time interval. The relative paleointensity peak at ∼2900 years BP in Lake Escondido is not observed in Lake Pepin and St. Lawrence Estuary records but it is present in Lake Baikal and the absolute paleointensity estimates (Fig. 11c), supporting this feature at that time. In brief, clear common features are found in all the sedimentary records (Fig. 11c), suggesting a possible common geomagnetic origin.

We compared our pre-glacial record with the record of Lake Baikal (Fig. 11c) and the results were mixed. The comparison with records of the same age obtained from marine cores is more difficult. Marine records are usually characterised by lower sedimentation rates than lacustrine records. Consequently, short-lived intensity fluctuations may have been recorded with different resolution, precluding their unambiguous recognition (Lehman et al., 1996). There are additional problems because different methods of dating are used to analyse marine records. In brief, it would be necessary further comparative analyses to draw a reasonable conclusion about the pre-glacial paleointensities obtained from Lake Escondido.

9. Discussion

Inter-parametric ratios reflecting magnetite grain size variations are shown in Fig. 5. $ARM_{100\,mT}/SIRM$

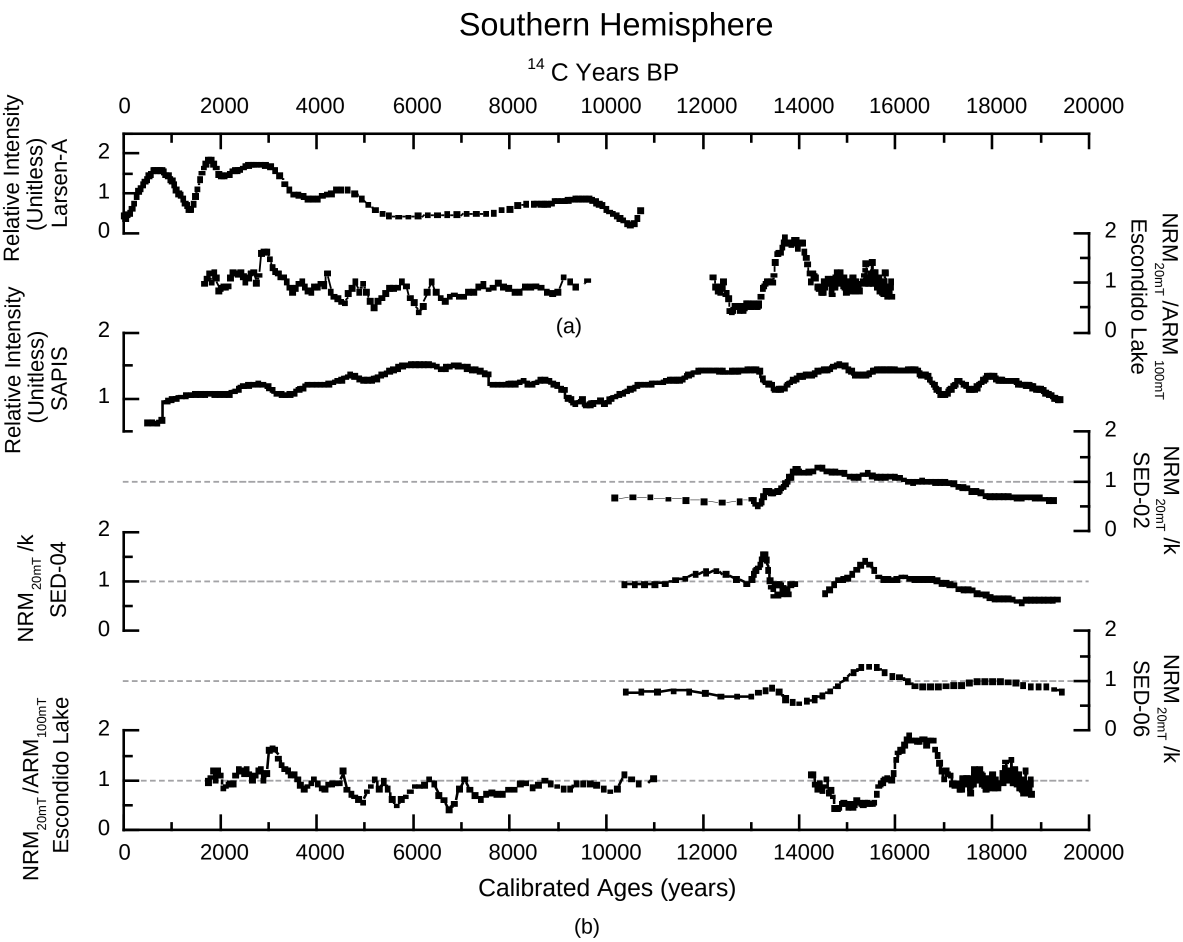
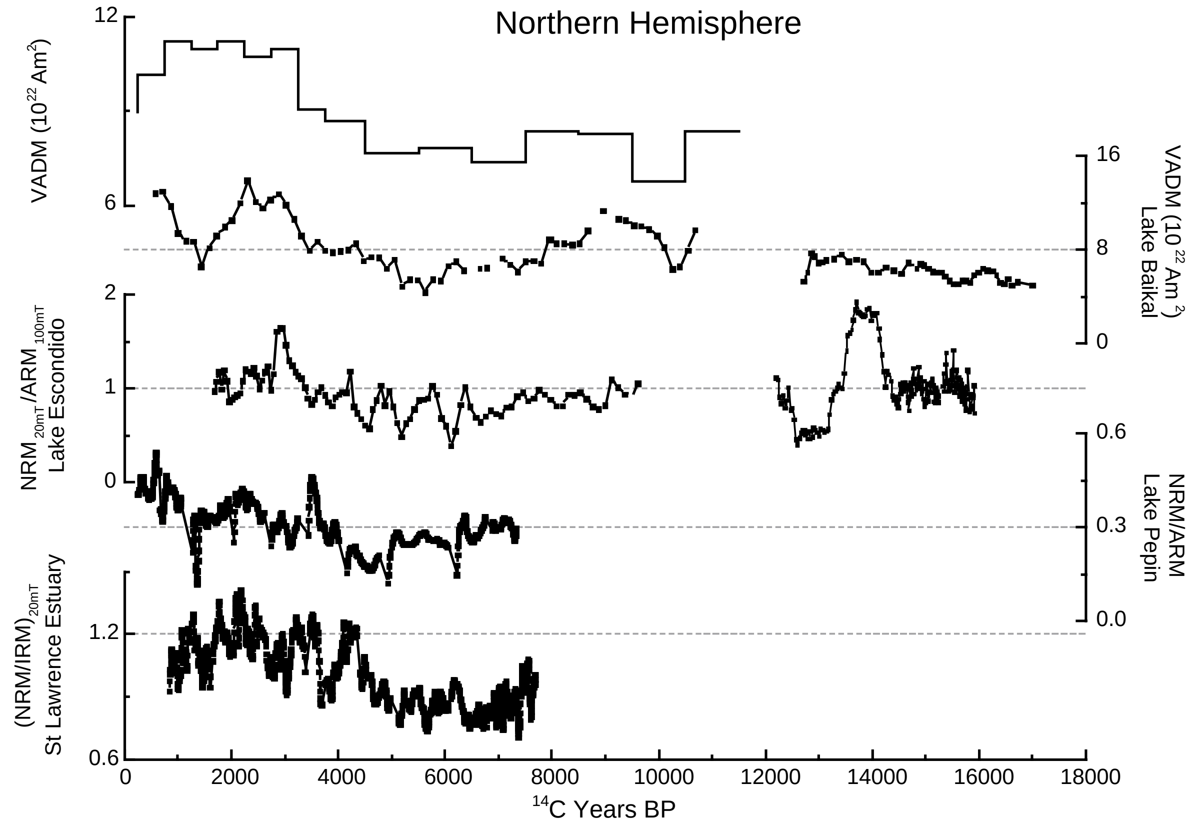


Fig. 11. Comparison of normalised intensity record from the Lake Escondido–Elpalafquen stack with relative paleointensity records from Larsen-A Ice Shelf (a), SAPIS stack and SEDANO cores (b) Lake Pepin, St. Lawrence Estuary, Lake Baikal and a global compilation of archeomagnetic data (c).



(c)

Fig. 11. (*Continued*).

is purely a ratio of two remanence dependent parameters; thus, it reflects the ferrimagnetic grain size better than ratios that include susceptibility. The behaviour of $ARM_{100\,mT}/SIRM$ and $ARM_{100\,mT}/k$ suggests than the magnetic grain size was coarser in sediments from Elpalafquen facies than sediments from Escondido facies. Furthermore, it is possible to observe in Fig. 3 that the mean value of grain size of the samples of Escondido facies are lower than the mean value of grain size of the samples of Elpalafquen facies.

The down-core profiles patterns of the different magnetic parameters ($ARM_{100\,mT}$ and SIRM intensities and k) look very similar (Fig. 6). A high dispersion is present in the upper section of the sequence (Lake Escondido facies), while the lower part (Elpalafquen facies) is more uniform, although the mean values are similar for both facies (except les97-1 where slight differences between lower and upper section are observed) (Fig. 6) (Gogorza et al., 2002). On the other hand, $NRM_{20\,mT}$ values from the upper part is an order of magnitude lower that the values of the lower part. This is probably a consequence of a combination of factors like differences in concentration of magnetite (observed in Fig. 3) and less efficient recording due to grain size and/or lithology effects (high water content, clay content, etc.).

Fig. 7 shows good agreement between cores for the same ratio as well as between different ratios for a given core. The differences in the behaviour of the normalised $NRM_{20\,mT}$ in the four cores, may be explained as a consequence of slight differences in the amount of magnetite or in the mean of the grain size in the four cores (Lehman et al., 1996). Although the upper section shows more scattered results, a trend to a slight increase of the ratios between 50 and 250 cm depth and a decrease between 250 and 400 cm is observed.

In the lower part a significant peak between 425 and 475 cm and uniform values around 1 from 475 cm to the bottom are observed. The section between 75 and 180 cm shows lower values in $NRM_{20\,mT}/ARM_{100\,mT}$ than $NRM_{20\,mT}$/SIRM and $NRM_{20\,mT}/k$, which indicate that the magnetic mineral assemblage are dominated by finer grains. These grains are more efficient carriers of detrital remanent magnetisation and ARM than of SIRM and k (Brachfeld and Banerjee, 2000). The behaviour of the records of $ARM_{100\,mT}$/SIRM and $ARM_{100\,mT}/k$ (Fig. 5) supports this statement.

The stacked ratios (Fig. 8) show more similar behaviour than the individual results, but smoother. $NRM_{20\,mT}/k$ and $NRM_{20\,mT}$/SIRM show more scattered results in the upper section than $NRM_{20\,mT}/ARM_{100\,mT}$. It is necessary to keep in mind that the upper 300 cm spans 7500 radiocarbon years while the lower 400 cm spans 4000 radiocarbon years. For this reason, the behaviour of the upper section may be explained by larger environmental changes.

The most significant feature is the peak (a two-fold increase in normalised intensity) at 475 cm "shortened depth". There are not distinctive changes in the concentration or grain size that account for this behaviour, which may genuinely reflect changes in the geomagnetic signal. However, this feature is not observed when the records are compared with the records of Lake Baikal, and further studies would be necessary to draw a conclusion about it.

Although there are different opinions about the normalisation process, several authors have indicated that ARM is the best normalisation factor (Johnson et al., 1975; Levi and Banerjee, 1976; King et al., 1983). Levi and Banerjee (1976) pointed out that susceptibility, similar to saturation magnetisation, is measured in the presence of a field and hence is hard to relate to remanence, which is measured in zero field. Johnson et al. (1975) advocated the use of anhysteric remanence because it is particularly sensitive to single-domain particles. Part of the reason for the preference of anhysteric remanence is the argument that the detrital magnetic grains in a sediment presumably acquired their individual moments as a thermal remanence prior to deposition (Tauxe, 1993). Another argument is that the magnitude of ARM is a few tens to hundreds of times that of NRM, whereas SIRM is typically thousands of times larger (Tauxe, 1993). In our paper, the main arguments that favour the choice of $ARM_{100\,mT}$ are the results of the coherence test and the analysis of grain size. At the 95% confidence level the normalised intensity is not coherent with the normaliser in Escondido and Elpalafquen records. Significant coherence above the 95% confidence limit is observed for both k and SIRM normalisation in Lake Escondido records. Besides, ARM is better recorded by fine grains and the more significant differences among the three ratios are just observed in the upper part, where the grains are finer. On the other hand, when the records of the three normalised paleointensities are compared with records of other parts in the world, $NRM_{20\,mT}/ARM_{100\,mT}$ shows the best agreement. Taking into account our results and the opinion of numerous authors, who advocated the use of ARM, we set $NRM_{20\,mT}/ARM_{100\,mT}$ as our paleointensity records.

The relative paleointensity records that were analysed are located in distinct sedimentary environments representing four different places situated thousands of kilometres away from Lake Escondido. The good agreement is suggestive of a dominant global (i.e. dipolar) character of these records. They also reflect the general trend of the Earth's dipole moment (Fig. 11). The discrepancy between the pre-glacial records of Lake Escondido could be explained as a local characteristic due to a non-dipolar source but more data would be necessary to draw a conclusion about this behaviour.

10. Conclusions

We have shown that the sediments from Lake Escondido meet the criteria required for the construction of a reliable paleomagnetic record. The $NRM_{20\,mT}$ is carried by magnetite of grain size 1–8 μm (PSD) and the mineral concentration varies between 0.01 and 0.1%. $ARM_{100\,mT}$ is the best normaliser for the Lake Escondido sediments. $NRM_{20\,mT}/ARM_{100\,mT}$ shows no coherence with its normaliser. Our normalised intensity record ($NRM_{20\,mT}/ARM_{100\,mT}$) shows good agreement with Lake Pepin, St. Lawrence Estuary, Lake Baikal, Larsen-A Ice shelf records and an absolute paleointensity global record. There is a relative agreement of our records with two cores (SEDANO) collected from Antarctic late pleistocene sediments, and no agreement with SAPIS record.

Acknowledgements

The authors wish to thank Universidad Nacional del Centro de la Provincia de Buenos Aires, Instituto Antártico Argentino, CONICET and Universidad de Buenos Aires and Martín Santiago and Nestor Villacorta for their help on the field. They wish to thank sincerely S. Brachfeld, J. Peck, J. Stoner and G. St-Onge for generously sharing their data. We thank L. Sagnotti for generously sharing his data and also for his helpful comments. Thanks are due to Alan Chave for his help about coherence test. The authors are also indebted to the anonymous reviewers for their useful suggestions.

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