Physics of the Earth and Planetary Interiors 184 (2011) 41–50

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Paleosecular variation and paleointensity records for the last millennium from southern South America (Laguna Potrok Aike, Santa Cruz, Argentina)

C.S.G. Gogorza[a,b,*], A.M. Sinito[a], C. Ohlendorf[b], S. Kastner[b], B. Zolitschka[b]

[a] IFAS, Universidad Nacional del Centro, Pinto 399, 7000 Tandil, Argentina; CONICET, Rivadavia 1917, 1033 Buenos Aires, Argentina
[b] Institute of Geography (Geopolar), University of Bremen, Celsiusstr. FVG-M, D-28359 Bremen, Germany

ARTICLE INFO

Article history:
Received 29 March 2010
Received in revised form
20 September 2010
Accepted 17 October 2010

Edited by: Keke Zhang.

Keywords:
Paleosecular variation
Relative paleointensity
ICDP
PASADO
Southern Hemisphere

ABSTRACT

High-resolution paleo- and rock magnetic studies were performed on a group of four sediment cores from Laguna Potrok Aike (Santa Cruz, Argentina) representing the time period AD 1300–2000. The rock magnetic analyses show that the main magnetic mineral is (titano)magnetite with a concentration between 0.01 and 0.08%, and a grain size of 4–15 μm. This study is helpful in order to complete the paleosecular variation (PSV) and paleointensity type curves for South America which do not have a detailed record for the last millennium. The comparison with the study carried out for Lake El Trébol shows a very good agreement, supporting that PSV records of south-western Argentina can be developed into a stratigraphic correlation tool on a regional scale.

1. Introduction

It is a well-known fact that the Earth's magnetic field varies in intensity and direction during time. In particular, recent studies provide evidence for a possible imminent change of polarity or an excursion of the geomagnetic field (Hulot et al., 2002; Constable and Korte, 2006). For this reason, studying records of the last centuries is of vital importance to explore the persistence of the observed decrease of the geomagnetic field. In order to produce accurate global models of the geomagnetic field and its secular variation, data for PSV reconstruction should be evenly distributed and as wide as possible across the Earth's surface (Barraclough, 1991). However, experimental results from the Southern Hemisphere are scarce in comparison to those from the Northern Hemisphere. During the last decade we therefore have made an effort to reconstruct the behaviour of the Holocene geomagnetic field by studying sediment records from a group of lakes from south-western Argentina (Gogorza et al., 1999, 2000a,b, 2002, 2004, 2006, 2008; Irurzun et al., 2006, 2008, 2009). Nevertheless, our regional knowledge and understanding of the PSV during the last millennium is still not satisfying. Here, we report new results of PSV and paleointensity records from Laguna Potrok Aike in an attempt to improve our knowledge about the behaviour of the geomagnetic field in this region for the last centuries.

2. Site description, sedimentology and chronology

Laguna Potrok Aike is a maar lake located in the Province of Santa Cruz, Southern Patagonia (Argentina). Roughly 120 km west of the city of Río Gallegos, and 80 km north of the Strait of Magellan, it is situated in the Pali Aike Volcanic Field (51°58′S 70°23′W) (Zolitschka et al., 2006).

The Laguna Potrok Aike, Santa Cruz, Argentina, reveals an unprecedented continuous high resolution climatic record for the steppe regions of southern Patagonia. Haberzettl et al. (2008) indicate that seismic reflection studies in the Laguna Potrok Aike revealed an erosional unconformity associated with a sub-aquatic lake-level terrace at a water depth of 30 m. Radiocarbon-dated, multi-proxy sediment studies of a piston core from this location indicate that the sediment below this discontinuity has an age of 45 kyr BP (Oxygen Isotope Stage 3), and were deposited during an interval of high lake level. Pollen, diatom assemblages and geochemical sediment proxies of the sediment record from Laguna Potrok Aike provide new data about the vegetation and climate history since 16,100 cal BP of the drylands in the Patagonian Steppe,

* Corresponding author. Tel.: +54 2293 439660; fax: +54 2293 439669.
E-mail address: cgogorza@exa.unicen.edu.ar (C.S.G. Gogorza).

0031-9201/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.pepi.2010.10.011

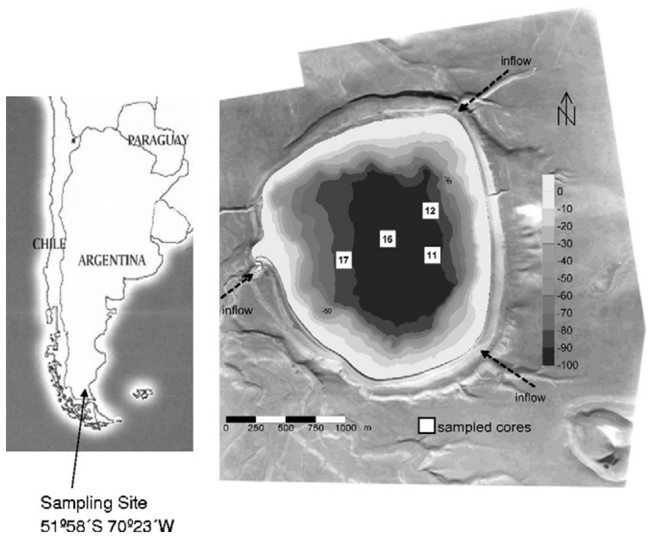

Fig. 1. Location of Laguna Potrok Aike with coring sites.

some 80 km east of the Andes on the southernmost Argentinean mainland (Wille et al., 2007). These data record increasing temperatures and decreasing moisture availability resulting in falling lake levels in the steppe culminating in the lowest lake levels around 7640 cal BP, between 6000 and 2300 cal BP cyclic seasonality fluctuations in the steppe and the Andes and after 2300 cal BP the research area became increasingly humid and the Andean Forest underwent changes in floristic composition.

Haberzettl et al. (2005) detected (applying multi-proxy approach) rapid climatic changes before the turn of the first millennium followed by medieval droughts which are intersected by moist and/or cold periods of varying durations and intensities. The 'total inorganic carbon' content suggests that during the late Middle Ages (ca. AD 1230–1410) the lake level was rather low representing a signal of the 'Medieval Climate Anomaly' in southeastern Patagonia. At the beginning of the 'Little Ice Age' the lake level rose considerably staying on a high level during the whole period. Subsequently, the lake level lowered again in the course of the 20th century.

On the other hand, previous studies carried out at Laguna Potrok Aike by Haberzettl et al. (2005) reveal a continuous and high-resolution sedimentary record. The sediment sequence is characterized as minerogenic with only minor amounts of organic carbon and biogenic silica but with varying contents of calcite. All cores consist of brownish gray laminated silts with variations in the shades of gray and brown (Haberzettl et al., 2005). Based on sedimentological characteristics core PTA05-17 was subdivided into three lithological units as indicated in Fig. 2. For paleomagnetic studies this core was chosen as the master core.

Forty-six gravity cores with lengths up to 49 cm were recovered from this lake during a field campaign in 2005 using an UWITEC Kajak corer. In this study a selection of four cores is analysed, three cores (PTA05-11, PTA05-12 and PTA05-16) were collected from the 100 m deep central basin and one core (PTA05-17) from a slightly shallower 90 m deep part (Fig. 1). After the cores were split lengthwise and described, they were stored in a cool room at 4 °C until sub-sampling.

The correlation of the four cores is based on the results of high-resolution logs of magnetic susceptibility and XRF-scanning data with 4 and 1 mm resolution, respectively. The chronology has been transferred to the cores used in this study based on the age/depth model that was determined for PTA02-4 (Haberzettl et al., 2005) and in combination with the reference core PTA05-33 that was primarily correlated to PTA02-4 (Kastner et al., 2010).

3. Methods

Magnetic measurements were made to characterize sediments and to investigate their response to a variety of applied magnetic fields. The response is mainly driven by the mineralogy as well as concentration and grain-size distribution of magnetic carriers. The procedure used for magnetic measurements was as follows:

1. Cores were sub-sampled continuously with cubic plastic boxes (20 mm × 20 mm × 20 mm) that were pressed into the surface of the open core face. A total of 69 samples were obtained from the four cores investigated. It is important to take into account that the samples were taken one next to another and that the size of 20 mm represents about 30 years, then the different magnetic parameters that we plot, although they are represented by a point, located in the centre of the sample, indeed are showing average values for the corresponding interval.
2. Magnetic susceptibility was measured at low frequency (k_{low} at 470 Hz) and high frequency (k_{high} at 4700 Hz). The difference between both measurements was used to calculate the frequency dependent susceptibility [$F(\%) = (k_{low} - k_{high}) \times 100/k_{low}$]. This parameter reflects the presence of very fine (<0.03 μm for magnetite) ferrimagnetic grains in the super-paramagnetic state (SP) of the sediment record.
3. Stability of the magnetisation was analysed by alternating-field (AF) demagnetisation. Samples were demagnetised successively at peak fields of 2.5, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70 and 100 mT.
4. Acquisition of the anhysteretic remanent magnetisation ($ARM_{100\,mT}$) was carried out with a direct field of 0.1 mT and an alternating field between 2.5 and 100 mT. After acquisition, the ARM was demagnetised stepwise using eleven successive steps at 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 and 100 mT.
5. Acquisition of isothermal remanent magnetisation (IRM) was determined in growing steps until 1 T reaching the saturation isothermal remanent magnetisation (SIRM) and in growing steps back until cancelling the magnetic remanence. These measurements were used to calculate the S_{ratio} ($IRM_{-300\,mT}$/SIRM), the "hard" IRM (HIRM = ((SIRM + $IRM_{-300\,mT}$)/2)/SIRM), and the remanent coercivity field (B_{CR}). SIRM was stepwise demagnetised using the same steps like for ARM.
6. Combined magnetic parameters were calculated ($ARM_{100\,mT}/k$ and $ARM_{100\,mT}$/SIRM). Also, and as a first estimate of relative magnetic grain-size variations, the median destructive field of the NRM (MDF_{NRM}) was determined.

A Minispin spinner fluxgate magnetometer (Molspin Ltd.) was used for the measurements of remanent magnetisation. Magnetic susceptibility was measured using a Bartington MS2 Susceptibilimeter, and an alternating field demagnetiser Molspin Ltd. was used to separate components of magnetisation. A pulse magnetiser IM-10-30 (ASC Scientific) and alternating field demagnetiser (Molspin Ltd.) with an ARM device were used for IRM and ARM acquisition experiments, respectively.

4. Rock magnetic studies

The goal of analysis of rock magnetic parameters is to characterize the magnetic properties of the sediments because establishment of paleomagnetic and paleointensity records requires magnetic carriers with certain characteristics.

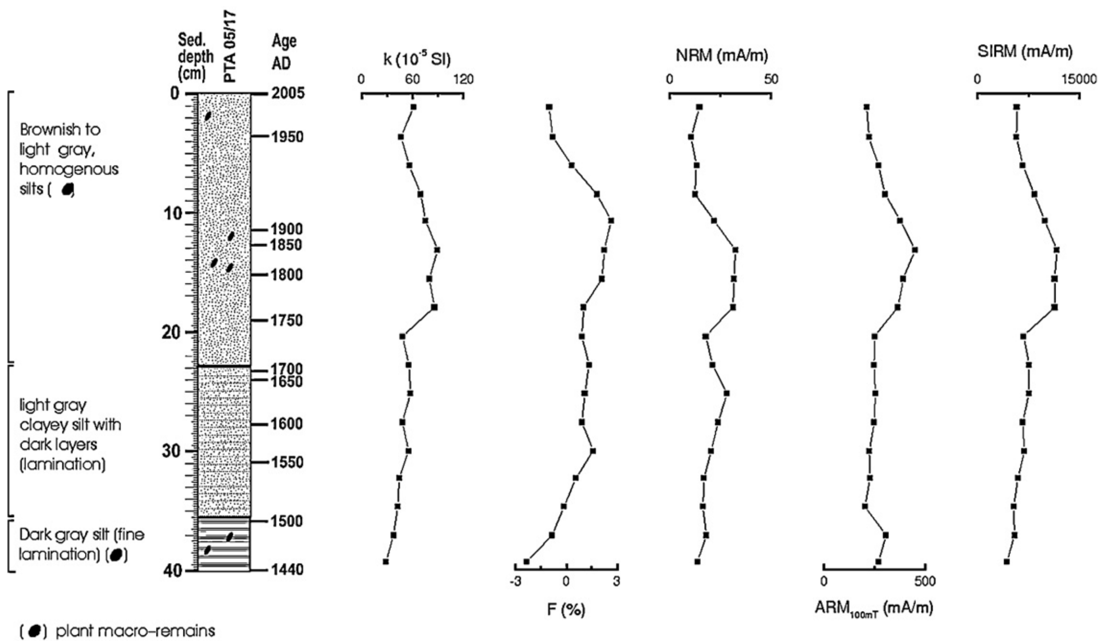

Fig. 2. Logs of lithology, susceptibility (k), F (%), intensity of natural remanent magnetisation (NRM), saturation anhysteretic remanent magnetisation ($ARM_{100\,mT}$), saturation isothermal remanent magnetisation (SIRM) for core PTA05-17 versus depth and time.

4.1. Mineral-magnetic characteristics

Down-core plots of k, F, NRM intensity, $ARM_{100\,mT}$ and SIRM of the master core (PTA05-17) are shown in Fig. 2 along with the lithology. Profiles of these parameters are comparable for all cores across the lake basin. They show changes in their pattern that could be associated with lithological variations as displayed in Fig. 2. This suggests that their behaviour is mostly influenced by changes in concentration of magnetic minerals. Although the visible plant fragments were excluded for these studies, the decrease in k at the top and at the bottom of the record could be associated with the presence of not completely excluded macro plant remains. The observed coherence of k with remanence parameters indicates that there are no significant paramagnetic contributions along the core. Finally, the record of the F shows that SP materials are not important.

k values vary between 23 and 110×10^{-5} SI, and $ARM_{100\,mT}$ and SIRM oscillate between 0.05–0.45 A/m and 2–12 A/m, respectively. They show a slight increase from the bottom to approximately 205 mm – except for a peak observed at about 370 mm in NRM and $ARM_{100\,mT}$. NRM displays a pronounced high at 250 mm not observed in the rest of the records.

Fig. 3 shows the stepwise acquisition of isothermal remanence in fields up to 1.0 T for samples of core PTA05-17. All cores display similar results documenting that about 90% of the SIRM is obtained between 150 and 200 mT. This indicates that low-coercivity minerals are the dominant magnetic carriers. Progressive removal of SIRM by back-field demagnetisation indicates that B_{CR} varies between 25 and 35 mT (Fig. 4) which agrees with the characteristic average value of pure magnetite between 8 and 60 mT according to Peters and Dekers (2003).

The S_{ratio} and HIRM are interpreted to reflect the dominant magnetic minerals and, in particular, to differentiate between soft magnetite and hard hematite minerals (Anderson and Rippey, 1988). Both range from 0.95 to 0.98 and from 0.008 to 0.025 (Fig. 4), respectively, which suggest that magnetic mineralogy is dominated by ferrimagnetic minerals and the contribution of anti-ferromagnetic minerals (hematite-type) is not significant (Oldfield, 1991).

Thermal demagnetisation of acquired SIRM was carried out with core PTA05-17. Some representative stepwise thermal demagnetisation curves are displayed in Fig. 5a. In general, two magnetic phases are observed. Each phase is mainly discriminated from slope changes in the curve of remanent magnetisation, hence unblocking temperatures are determined. The unblocking temperatures of the first phases vary slightly about 250 °C as shown in Fig. 5. These changes of low temperature were also observed by Dankers (1978) in (titano)-magnetite and maghemite. The unblocking temperature of the second component is 580 °C, and the remanence decreases linearly for all samples. The most important changes in remanence are observed in this second magnetic phase, which can be considered as the main magnetic phase, suggesting that the most important magnetic mineral is magnetite.

If the magnetic mineral in sediments is dominated by magnetite, the best way to assess such variations is the bilogarithmic plot of k vs. SIRM (Fig. 6) which was calibrated according to Thompson and Oldfield (1986). From this relationship, we estimate that the concentration of ferrimagnetic minerals varies between 0.01% and 0.08%.

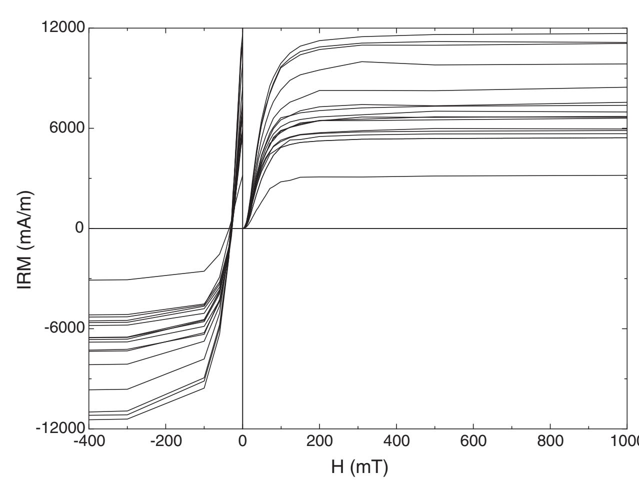

Fig. 3. IRM acquisition curves of samples from core PTA05-17.

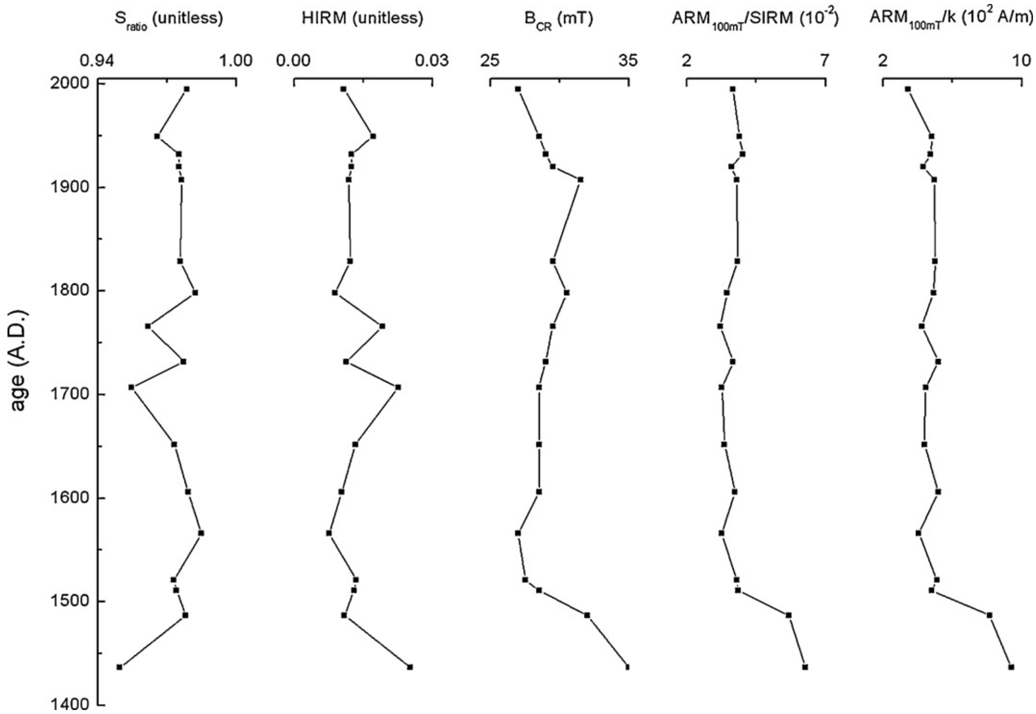

Fig. 4. Down-core variation of selected rock magnetic properties from core PTA05-17. Logs of S (unitless), HIRM (unitless), B_{CR} (mT), $ARM_{100\,mT}$/SIRM (10^{-2}), $ARM_{100\,mT}/k$ (10^2 A/m) vs. time.

4.2. Magnetic granulometry

$ARM_{100\,mT}/k$ and $ARM_{100\,mT}$/SIRM imply changes in grain size, higher ratios indicating a smaller grain size and a higher proportion of single-domain (SD) grains. The latter concerns only remanent magnetisations and is thus independent from paramagnetic and diamagnetic components. This assumption has been questioned for multiphase assemblages (Anderson and Rippey, 1988) and, therefore, interpretation of mixed sedimentary mineral assemblages can be difficult. This analysis is carried out for our samples because the presence of one dominant magnetic mineral – but with varying concentrations – is suggested by the plot of k vs. SIRM (Fig. 6), which results in a straight line and is also supported by results of thermal demagnetisation of SIRM. These ratios (PTA05-17 in Fig. 5) show a drastic increase, which implies an abrupt decrease of the magnetic grain-size during the 15th century. This coincides with the presence of macro plant remains in this section. The combination of low k (Fig. 2) and high ratios of $ARM_{100\,mT}$/SIRM and $ARM_{100\,mT}/k$ suggest a notorious decrease in the magnetic grains. Moreover, these ratios show the same pattern for most of the samples: rather constant values (suggesting reasonable uniformity of the magnetic grain size along the profile) or a slight increase (i.e. decrease in magnetic grain size) since the beginning of 16th century.z

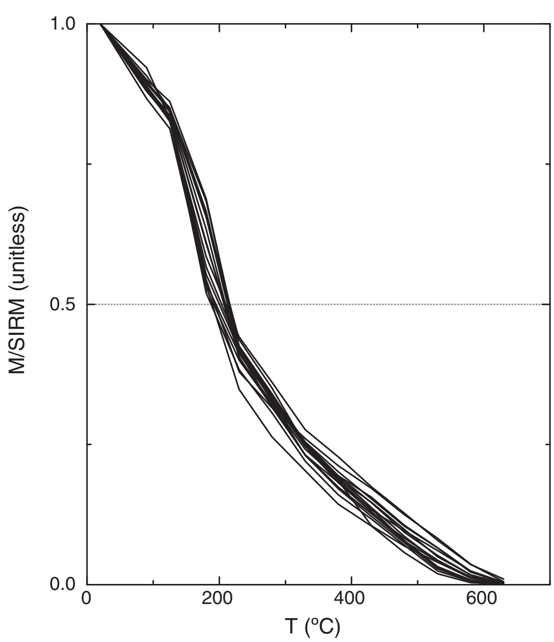

Fig. 5. Thermal demagnetisation curves of SIRM for samples from core PTA05-17.

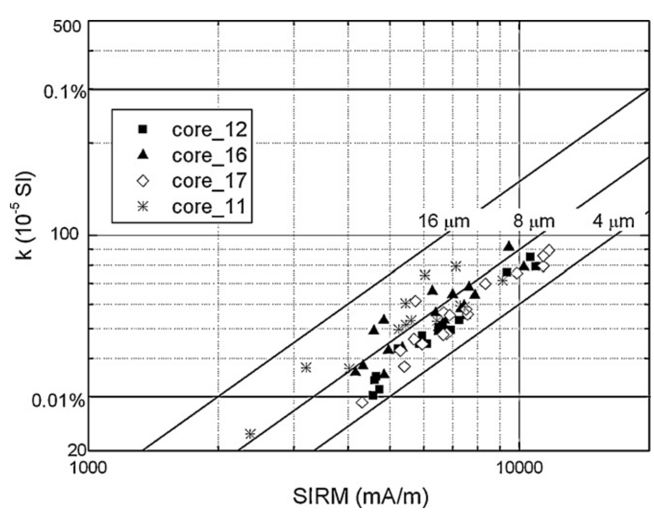

Fig. 6. k vs. SIRM for all samples in order to estimate concentration and grain size according to Thompson and Oldfield (1986).

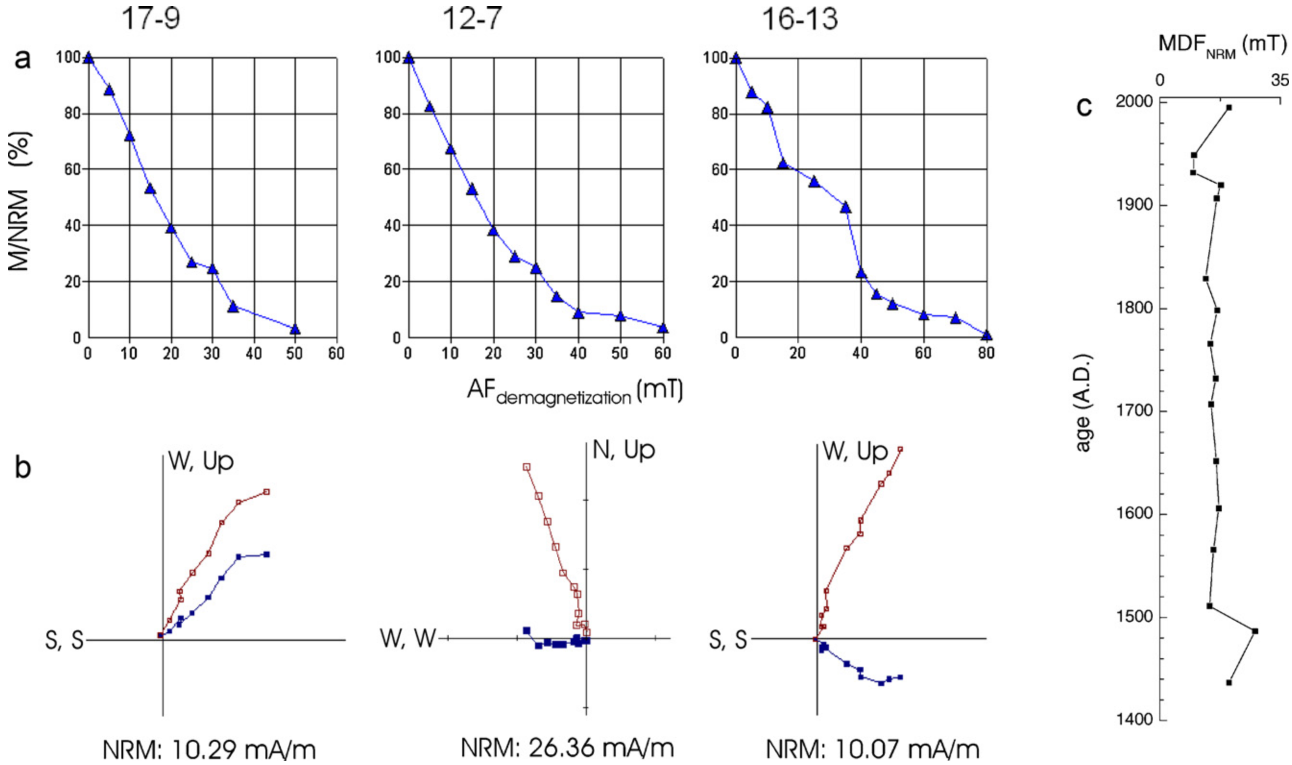

Fig. 7. Typical AF demagnetisation behaviour for sample 9 of core PTA05-17; sample 7 of core PTA05-12 and sample 13 of core PTA05-13. Normalised intensity decay plot (a). Zijderveld diagrams: open and closed symbols represent projections on the vertical and horizontal planes, respectively (b). MDF_{NRM} vs. age (c).

If magnetic minerals are dominated by magnetite, *k* vs. SIRM can be used to estimate the magnetic grain size (Thompson and Oldfield, 1986). Fig. 6 shows this variation for all samples which indicates that the magnetic grain size varies approximately between 4 and 15 μm.

5. Paleomagnetic studies

Representative examples of demagnetisation plots are documented in Fig. 7a. Most of the samples show no systematic change in the direction of their remanent magnetisation during AF demag-

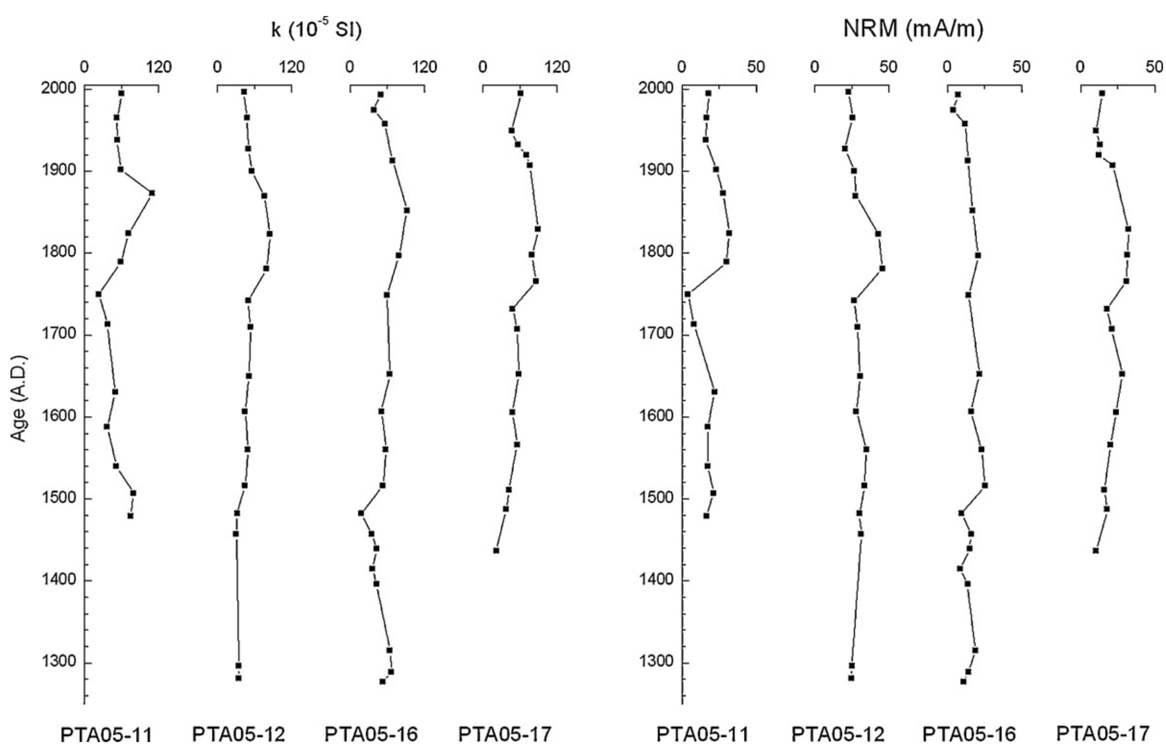

Fig. 8. *k* and NRM logs for cores PTA05-11, PTA05-12, PTA05-16 and PTA05-17.

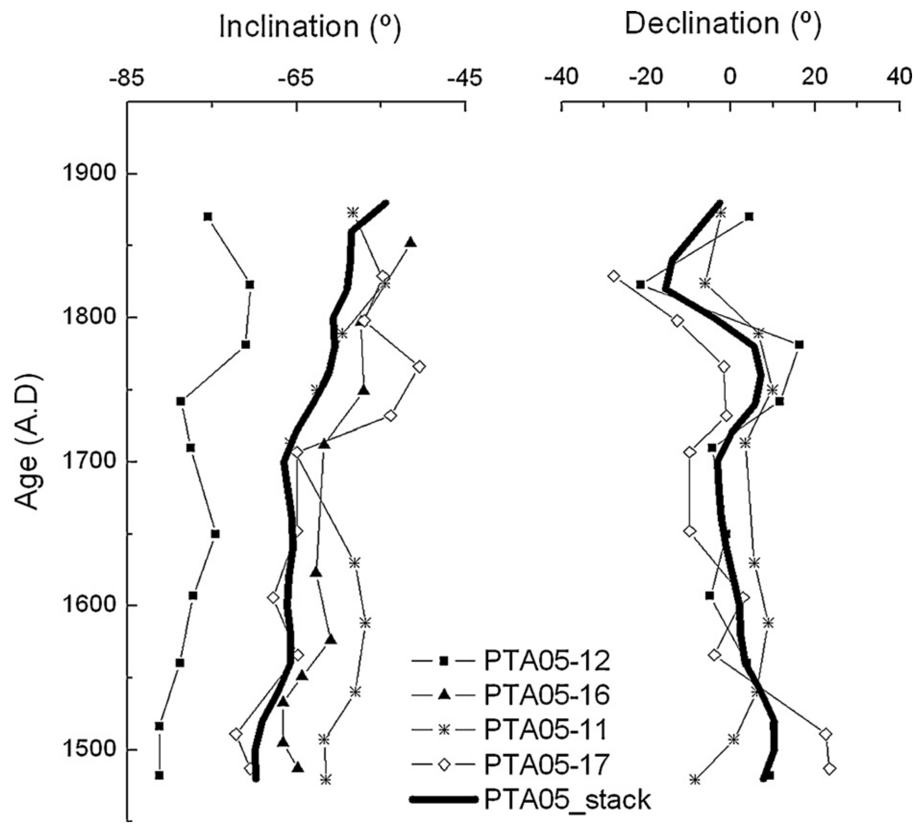

Fig. 9. Inclination and declination logs for cores PTA05-11, PTA05-12, PTA05-16 and PTA05-17 with stacked profile as an arithmetic average vs. time.

netisation. Only a few of them show a small viscous magnetisation, which could easily be removed by AF demagnetisation at 5 or 10 mT (Fig. 7b). Directions of the stable remanent magnetisation were derived using principle component analysis (Kirschvink, 1980) with successive demagnetisation steps. In order to exclude the viscous magnetisation, demagnetisation steps from 0 to 10 mT were not used for the vector analysis in those samples where viscous magnetisation was evident. Since the cores were not drilled orientated relative to magnetic north, the *D* values for each core was centred on the average declination.

The values of MDF_{NRM} obtained from all samples vary between 10 and 36 mT except for a group of samples from the top with values around 4 mT (for PTA05-17 in Fig. 7c). This corresponds to the results obtained for other Holocene lake sediments from these latitudes (Gogorza et al., 1999, 2000a,b; Irurzun et al., 2006, 2008). Moreover, they are typical values expected for (titano)magnetites. This corresponds to the basaltic composition of rocks in the catchment area. The fact that slight differences between the MDF_{NRM} values are due to grain size changes of magnetite particles is confirmed by rock magnetic investigations. However, the low values of MDF_{NRM} observed for the top and in $ARM_{100\,mT}/SIRM$ and $ARM_{100\,mT}/k$ in a lesser extent are indicators of significant variations in magnetic grain size associated with dissolution of magnetic particles. Dissolution of detritic magnetic minerals has been observed in marine and lake sediments deposited during warm periods due to the high content of organic matter. Dissolution tends to preferentially remove more fine-grained than coarse-grained magnetic particles because of their higher surface area-to-volume ratios (Franke et al., 2004). These changes of magnetic parameters which attest that dissolution takes place, were associated with the increase of human impact recorded for this lake as described by Haberzettl et al. (2006). They point out that the human impact at Laguna Potrok Aike is recognizable since the end of 19th century and that introduction of sheep altered the steppe ecosystem distinctly (Hoppe, 1997 in Haberzettl et al., 2006). Moreover, eutrophication of the lake might have been intensified and enhanced soil erosion occurred after the destruction of protecting natural vegetation.

6. Analysis of palaeosecular variation

NRM values range from 3.7 to 45.6 mA/m and show comparable variations between all cores and similar to those observed in the concentration dependent parameter *k* (Fig. 8). The final inclination and declination records for four cores and the stacked profile of arithmetic averages are plotted versus time in Fig. 9. The stacking removes spurious data exhibited by individual records and enhances the signal-to-noise ratio. Hence, the stacked record is often found to show fewer details than individual records (Creer and Tucholka, 1982). In particular, the highly scattered data linked to organic rich layers with low NRM, artefacts at the top or bottom of some core sections and disturbed sections have been eliminated for this discussion. Maximum angular deviations (MAD) according to Kirschvink (1980) are mostly below 5°, except for a few samples, indicating that magnetisation components are well defined. Core PTA05-12 has an average inclination angle significantly lower than the other cores, which suggests that it did not penetrate the sediment perpendicular to the bedding plane. Trends in inclination of all cores are similar, although the amplitude of certain features varies from core to core. They show a slight decrease from bottom to top with two broad maxima at about AD 1640 and 1840 and three local minima at about AD 1500, 1700 and 1880, which suggest a periodicity of about 200 years. Inclination data vary between $-50°$ and $-70°$, except for PTA05-12 with an inclination of $-78.6°$. The mean inclination oscillates around $-64.4 \pm 0.7°$. The expected axial dipole field inclination for the site latitude at 51°58′S is $-68.6°$.

For declination, the record of PTA05-16 was not considered because it shows an anomalous behaviour possibly connected with the extraction process. For the other three cores the declination is fairly defined. From bottom to top a broad maximum is observed at about AD 1500–1520 in PTA05-12 and PTA05-17, this behaviour is also reflected in the stacked profile, a smooth decreasing trend until AD 1700. After that a broad maximum is observed between AD 1720 and 1800 and, finally, declination increased until AD 1880. The relative declination varies between 23° and −21°, except for one sample of PTA05-17 (−28°). The similarity of directional signals obtained from the four cores indicates that the depositional processes that recorded these directional variations are consistent along the profiles.

The Bauer diagrams (Bauer, 1895) corresponding to the record of inclination and declination from Laguna Potrok Aike are shown in Fig. 10. Although the dominant motion is anticlockwise there is a clockwise portion between AD 1780 and 1880. Closed and open loops are observed. In particular, the two closed loops lasted ca. 100 years. The same tendency for successive loops was observed by Gogorza et al. (2000a,b) in the study of the SW Argentinean master curve. This process could be represented by the presence of a wavelength trend with a periodicity approaching the length of the time span of available data (Lund, 1996).

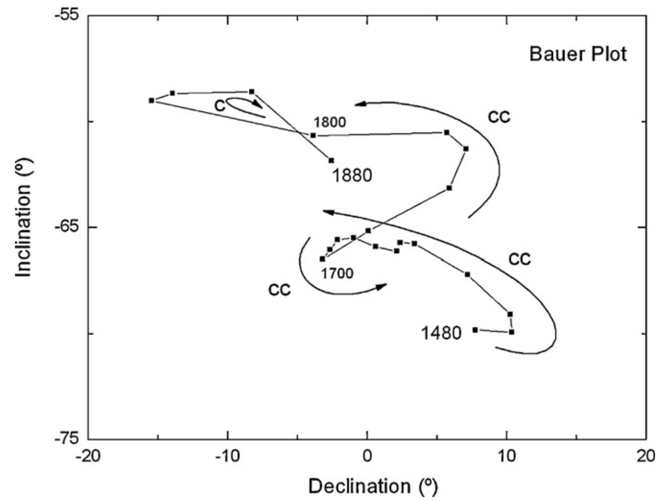

Fig. 10. Bauer plot of average declination and inclination. Arrows indicate trajectories from old to young.

7. Paleointensity studies

The rock magnetic studies confirm that the studied sediments meet stringent criteria for the determination of relative paleointensity (Tauxe, 1993), e.g. the variations in concentration and magnetic grain size of magnetite are smaller than a factor of ten. However, PTA05-11 shows subtle to pronounced differences in concentration and magnetic grain size in comparison with the other three cores (Figs. 6 and 8) and was therefore excluded for paleointensity studies. Diagenetically affected core sections also were excluded. This implies that the top part which corresponds to the 20th century was not taken into account for relative paleointensity studies. Finally, and in order to be cautious concerning variations of magnetic grain size, data older than 16th century were also discarded because the behaviour of magnetic parameters would suggest a distinctive change to lower values in grain size in this period.

In this study the normalised field intensity for each core and for the selected sections were calculated by normalising NRM with ARM, SIRM after a 15 mT AF treatment to remove viscous overprints, and k (Fig. 11). The three normalisation methods yield profiles with broad similarities but differ in amplitude of peaks and troughs. In particular, differences are observed at AD 1880, 1800 and 1600. These differences suggest that some paleoclimatic influence remains in the relative paleointensity records. Linear correlation supports previous results: $NRM_{15\,mT}/ARM_{15\,mT}$ shows

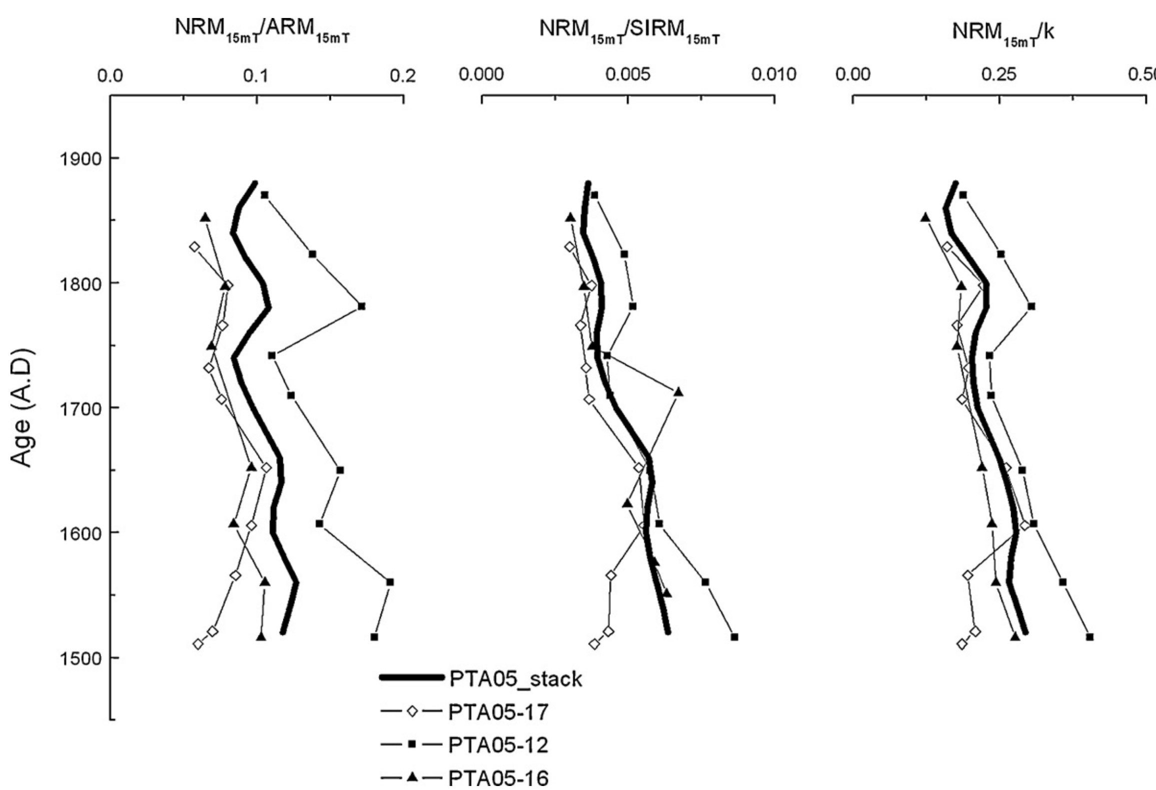

Fig. 11. $NRM_{15\,mT}/ARM_{15\,mT}$, $NRM_{15\,mT}/SIRM_{15\,mT}$ and $NRM_{15\,mT}/k$ records from cores PTA05-11, PTA05-12 and PTA05-17 and the stacked profile after the arithmetical average vs. age.

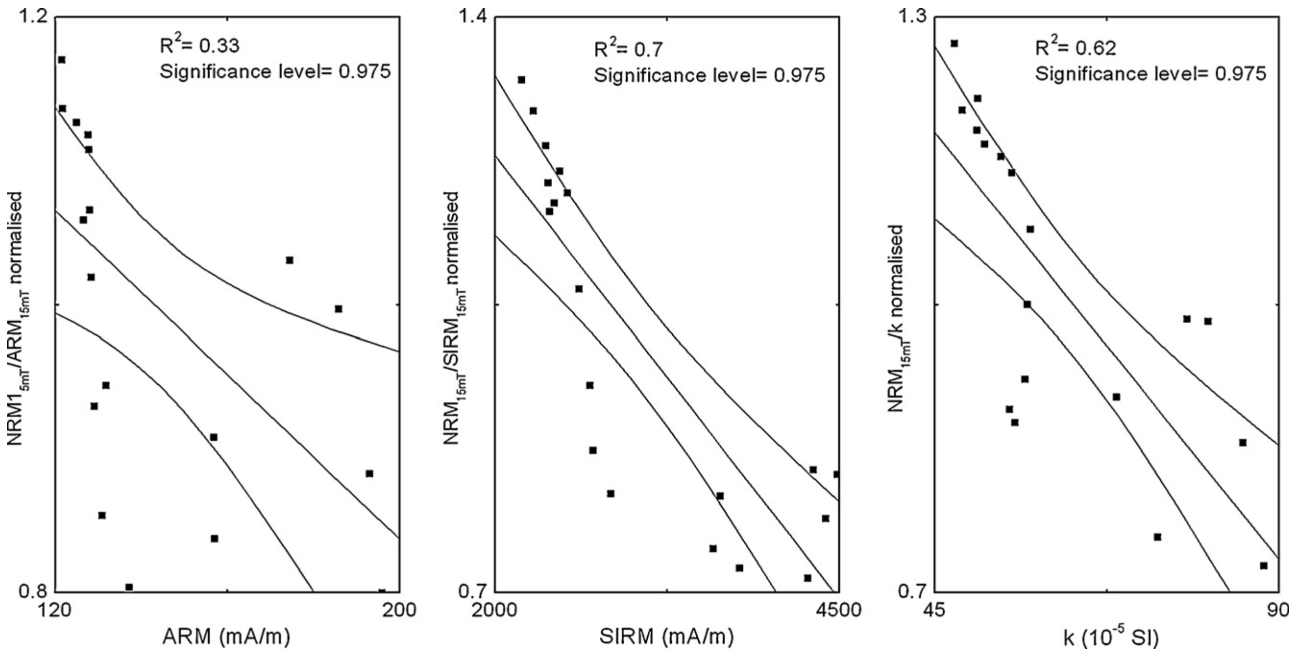

Fig. 12. Linear correlation of the three normalisation parameters ($ARM_{15\,mT}$, $SIRM_{15\,mT}$ and k) and the three normalised remanences ($NRM_{15\,mT}/ARM_{15\,mT}$, $NRM_{15\,mT}/SIRM_{15\,mT}$ and $NRM_{15\,mT}/k$).

a low correlation with its normaliser ($ARM_{15\,mT}$) ($R^2 = 0.33$), but correlation of $NRM_{15\,mT}/SIRM_{15\,mT}$ and $NRM_{15\,mT}/k$ with $SIRM_{15\,mT}$ and k has quite different results with a R^2 of 0.62 and 0.70, respectively (Fig. 12). This analysis indicates that the parameter $ARM_{15\,mT}$ is the appropriate normaliser for these sediments and that the $NRM_{15\,mT}/ARM_{15\,mT}$ record is not affected by sedimentological factors but represents a true geomagnetic signal. This result is consistent with previous grain size analyses.

8. Discussion

8.1. Inter-lake comparison in south-western Argentina

Declination and inclination records and their error interval, considering the standard deviation, from Laguna Potrok Aike are shown in Fig. 13 together with the topmost records from Lake El Trébol (41°04′S 71°29′W), SW Argentina (Irurzun et al., 2006); the two lakes are at a distance of about 1216 km from each other. Both records are compared in order to test the reliability of our paleomagnetic record and to get a better understanding of the historic PSV for Patagonia. Some major features – directional lows and highs – have been labelled using the symbols “A-B-C” in inclination and “b-c” in declination. The PSV record of Lake El Trébol was obtained by stacking records from four cores, each about 11 m long, and the age control was achieved by three accelerator mass spectrometer (AMS) radiocarbon dates, which were converted into calendar years using the calibration curves of Stuiver and Reimer (1993). On the other hand, distinctive magnetic features of the El Trébol declination and inclination records, close to the dated levels (Fig. 9 in Gogorza et al., 2002), were identified and correlated with similar features of PSV from Lake Escondido (41°S, 71°30′W, Gogorza et al., 2002). This three connecting points and four zones were defined. Within each zone new tie points were determined (based on visual inspection). Based on this correlation, a total of 44 tie points were

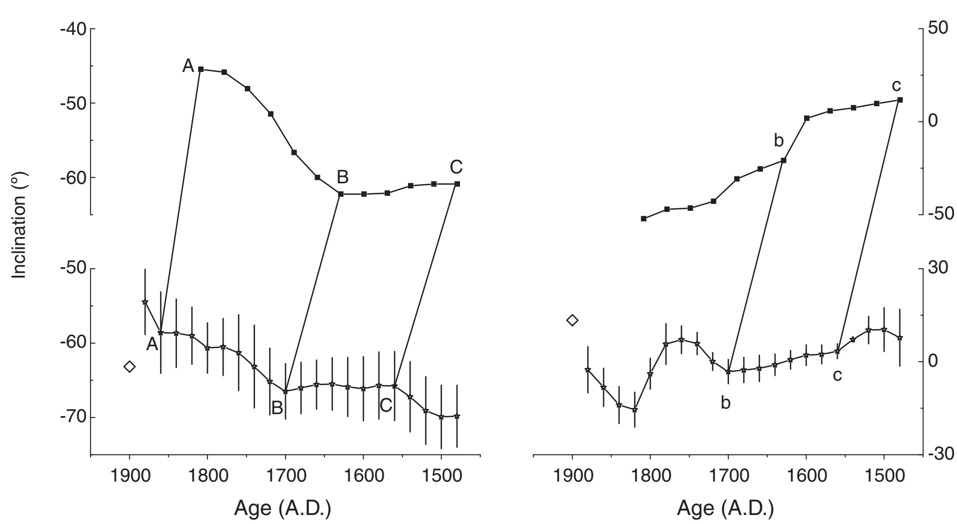

Fig. 13. Comparison of inclination and declination records obtained from Laguna Potrok Aike with records from Lake El Trébol (Irurzun et al., 2006). ◇ Values are computed using the current International Geomagnetic Reference Field as adopted by IAGA.

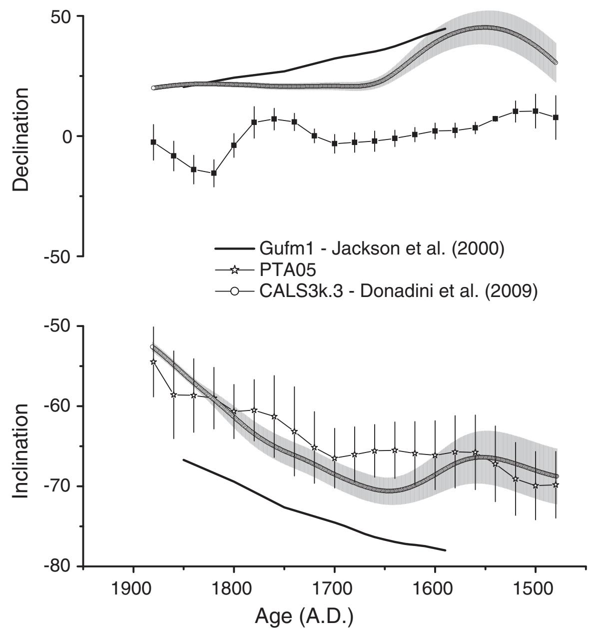

Fig. 14. Comparison of inclination and declination stacks obtained from Laguna Potrok Aike with Gufm1 and CALS3k.3 predictions. The standard deviations are shown.

defined. Ages of the most distinctive declination peaks are transferred to the Lake El Trébol record and inclination features were matched.

The general agreement between the presented inclination and the declination records is good, especially for the correlation of inclination records, also confirming that the signal recorded in these sediments are of geomagnetic origin. Three inclination and two declination features are identified. The mean inclination of Laguna Potrok Aike is higher due to its location. Minor differences of correlatable features are in the range of dating errors. Thus both records can be considered as synchronous within the errors of dating (about ±80 years). The differences in amplitude could be caused by smoothing effects due to different deposition rates and different sediment grain sizes (Yang et al., 2009). Reasons for the observed differences with topmost declination records are not immediately at hand, although the influence of the coring process has to be considered. Moreover, it is possible to note that the pronounced decreasing trend showed in the youngest part in the declination record of Lake El Trébol (Gogorza et al., 2002) is the only notorious change observed along the record. For this reason, as was stated in that paper further work will be necessary to validate it.

8.2. Comparison with models

The declination and inclination records from Laguna Potrok Aike are plotted together with two geomagnetic models, the Gufm1 of Jackson et al. (2000) and the CALS3k.3 of Donadini et al. (2009) (Fig. 14). Concerning the inclination record, both models show the same decreasing trend to lower values of inclination to the present. In particular, our data are in good agreement with the inclination curve derived from the model CALS3k.3, except in the period AD 1600–1700, in which the model predicts higher values of inclinations. On the other hand, significant differences are observed between the Gufm1 model and the results reported in this study, although they show the same trend, the difference between the model and our data increase with age. This model seems to be smoothed and does not take into account regional characteristics of the record. This could be due to the scarce number of data that exists for this region. The comparison between our and the

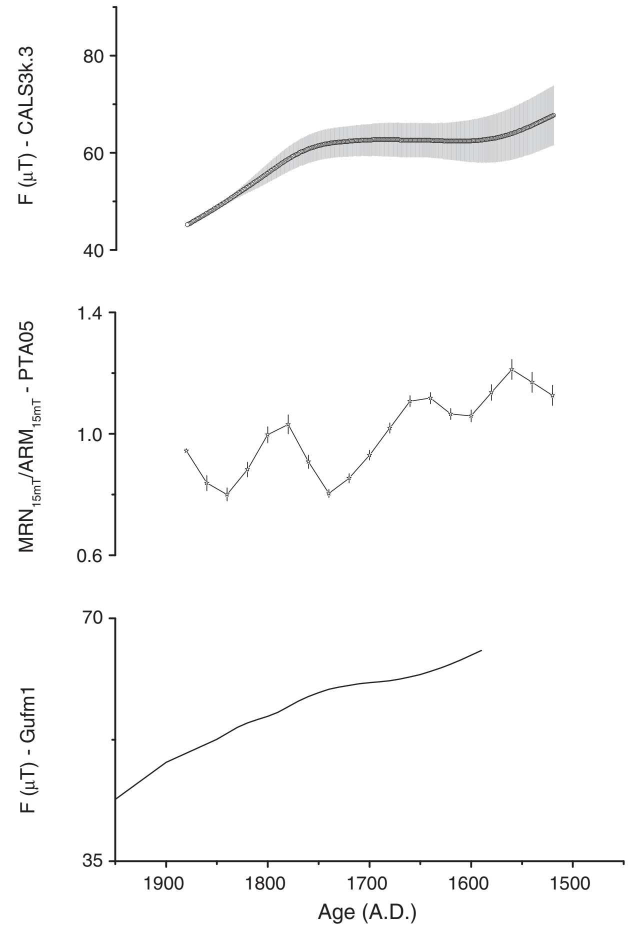

Fig. 15. Comparison of the normalised intensity record $NRM_{15\,mT}/ARM_{15\,mT}$ from Laguna Potrok Aike with Gufm1 and CALS3k.3 predictions. The standard deviations are shown.

modelled declinations is limited to general trends because variations in our declination record are only relative. CALS3k.3 shows an almost constant behaviour between AD 1660 and 1900, only a broad maximum around AD 1550 is observed, whereas the Gufm1 model displays the same decreasing trend like our data, although it does not show the broad maximum that we have noted at about AD 1760. In the same way as inclination profiles, the differences may be caused by a smoothing effect of the models that do not take into account regional characteristics of the records.

The Laguna Potrok Aike paleointensity record is compared with model data of CALS3k.3 and Gufm1 (Fig. 15). In this case and because our record is relative and normalised by its mean value, the comparison is limited to general trends. Both models shows the same decreasing trend than our data, although, it is necessary to point out that none of the models predicts the centennial changes recorded by the sediments of Laguna Potrok Aike. Similar results were found by Hartmann et al. (2010) when they compare their archeointensity determinations for the Bahia region (Northeast Brazil) with the existing historical and archeomagnetic global field models.

It would be interesting to point out that the results reported in this study are in good agreement with the intensity variation curve derived from the models of Jackson et al. (2000) and CALS3k.3 of Donadini et al. (2009), although both models predict intensity values too high with respect to our intensity data between 1700 AD and 1760 AD and too low in 1880 AD. More studies would be necessary to elucidate these questions and to detect any effect that might be related to non-dipolar sources.

9. Conclusions

1. High-resolution secular variation curves of geomagnetic inclination and declination recorded in the lacustrine sediment from Laguna Potrok Aike for the period AD 1880 to 1480 were obtained. The new PSV record can be used to assess the general characteristics of geomagnetic field variability during the studied period and to complete the records obtained previously for these latitudes.
2. The $NRM_{15\,mT}$ is carried by (titano)magnetite with a grain size of 4–15 μm while the mineral concentration varies between 0.01 and 0.08%.
3. Analyses of the curvature of Bauer plots show that clockwise and counter clockwise directions are present with a preponderance of counter clockwise movements.
4. The observed consistency of the PSV records from south-western Argentina confirms, in a preliminary way, that PSV dating may be valuable for historic data on a regional scale. From the comparison with available models it is obvious that more records from the Southern Hemisphere have to be analysed.
5. The relative paleointensity records obtained for Laguna Potrok Aike show that $ARM_{15\,mT}$ is the best normaliser for these sediments. Our normalised intensity record ($NRM_{15\,mT}/ARM_{15\,mT}$) documents a reasonable agreement with the models analysed.

Acknowledgements

We thank all members of the SALSA-team for their help during field work in 2005. C. Gogorza wants to thank the GEOPOLAR team of Geomorphologie und Polarforschung at the University of Bremen (Germany) for their kind assistance she received during her stays in Bremen which were supported by the German Federal Ministry of Education and Research in the framework of the project "Internationale Zusammenarbeit in Bildung und Forschung mit Argentinien Projekt ARG 08/A03", a scholarship of the LAC-ACCESS Programme "Connecting high-quality research between the European Union and Latin American and Caribbean Countries" and funds of Universidad Nacional del Centro (UNCPBA) through the Programme Línea B of SECAT-UNCPBA. Laboratory tasks were supported by the Comisión Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET), Agencia Nacional de Promoción Científica y Tecnológica (ANCyT) and UNCPBA. We are greatly indebted to Dr. Bigwin and an anonymous reviewer for their worthy suggestions.

References

Anderson, N.J., Rippey, B., 1988. Diagenesis of magnetic minerals in the recent sediments of a eutrophic lake. Limnol. Oceanogr. 33 (6, part 2), 1476–1492.
Barraclough, D.R., 1991. Modelling the geomagnetic main field and recent secular variation. Geophys. Astrophys. Fluid Dyn. 60 (1), 3–35.
Bauer, L.A., 1895. On the secular motion of a free magnetic needle. I. Phys. Rev. 2, 455–465.
Constable, C.G., Korte, M., 2006. Is Earth's magnetic field reversing? Earth Planet. Sci. Lett. 246, 1–16.
Creer, K.M., Tucholka, P., 1982. Secular variation as recorder in lake sediments: a discussion of North American and European results. Philos. Trans. R. Soc. Lond. A 306, 87–102.
Dankers, P.H.M., 1978. Magnetic properties of dispersed natural iron-oxides of known grain-size. Thesis, State University of Utrecht, 142 pp.
Donadini, F., Korte, M., Constable, C.G., 2009. Geomagnetic field for 0–3 ka: 1. New data sets for global modeling. Geochem. Geophys. Geosyst. V10 (6), Q06007, doi:10.1029/2008GC002295.
Franke, C., Hofmann, C., von Dobeneck, T., 2004. Does lithology influence relative paleointensity records? A statistical analysis on South Atlantic pelagic sediments. Phys. Earth Planet. Inter. 147, 285–296.
Gogorza, C.S.G., Lirio, J.M., Nuñez, H., Chaparro, M.A.E., Bertorello, H.R., Sinito, A.M., 2004. Paleointensity studies on Holocene–Pleistocene sediments from Lake Escondido, Argentina. Phys. Earth Planet. Inter. 145, 219–238.
Gogorza, C.S.G., Irurzun, M.A., Chaparro, M.A.E., Lirio, J.M., Nuñez, H., Bercoff, P.G., Sinito, A.M., 2006. Relative paleointensity of the geomagnetic field over the last 21,000 years BP from sediment cores, Lake El Trébol (Patagonia, Argentina). Earth Planets Space 58, 1323–1332.
Gogorza, C.S.G., Sinito, A.M., Lirio, J.M., Nuñez, H., Chaparro, M.A.E., Vilas, J.F., 2002. Paleosecular variations 0–19,000 years recorded by sediments from Escondido Lake (Argentina). Phys. Earth Planet. Inter. 133, 35–55.
Gogorza, C.S.G., Sinito, A.M., Di Tomasso, I., Vilas, J.F., Creer, K.M., Nuñez, H., 1999. Holocene secular variation recorded by sediments from Lake Escondido (South Argentina). Earth Planets Space 51, 93–106.
Gogorza, C.S.G., Torcida, S., Irurzun, M.A., Chaparro, M.A.E., Sinito, A.M., 2008. A pseudo-Thellier relative paleointensity record during the last 18,000 years from Lake El Trébol (Patagonia, Argentina). Geofísica Internacional 47 (4), 319–327.
Gogorza, C.S.G., Sinito, A.M., Di Tomasso, I., Vilas, J.F., Creer, K.M., Nuñez, H., 2000a. Geomagnetic secular variations 0–12000 year as recorded by sediments from Moreno Lake (South Argentina). J. South Am. Earth Sci. 13, 627–645.
Gogorza, C.S.G., Sinito, A.M., Vilas, J.F., Creer, K.M., Nuñez, H., 2000b. Geomagnetic secular variations 0–6500 year as recorded by sediments from lakes of South Argentina. Geophys. J. Int. 143, 787–798.
Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). J. Paleolimnol. 33, 283–302.
Haberzettl, T., Kück, B., Wulf, S., Anselmetti, F., Ariztegui, D., Corbella, H., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G., Wille, M., Zolitschka, B., 2008. Hydrological variability in southeastern Patagonia and explosive volcanic activity in the southern Andean Cordillera during Oxygen Isotope Stage 3 and the Holocene inferred from lake sediments of Laguna Potrok Aike, Argentina. Palaeogeogr. Palaeoclimatol. Palaeoecol. 259, 213–229.
Haberzettl, T., Wille, M., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Zolitschka, B., 2006. Environmental change and fire history of southern Patagonia (Argentina) during the last five centuries. Quart. Int. 158, 72–82.
Hartmann, G.A., Genevey, A., Gallet, Y., Trindade, R.I.F., Etchevarne, C., Le Goff, M., Afonso, M.C., 2010. Archeointensity in Northeast Brazil over the past five centuries. Earth Planet. Sci. Lett. 296, 340–352.
Hulot, G., Eymin, C., Langlais, B., Mandea, M., Olsen, N., 2002. Small-scale structure of the geodynamo inferred from the Oersted and Magsat satellite data. Nature 416, 620–623.
Irurzun, M.A., Gogorza, C.S.G., Sinito, A.M., Lirio, J.M., Núñez, H., Chaparro, M.A.E., 2006. Paleosecular variations recorded by sediments from Lake El Trébol, Argentina. Phys. Earth Planet. Inter. 154, 1–17.
Irurzun, M.A., Gogorza, C.S.G., Sinito, A.M., Chaparro, M.A.E., Núñez, H., Lirio, J.M., 2008. Paleosecular variations 12–20 kyr. as recorded by sediments from Lake Moreno (southern Argentina). Stud. Geophys. Geod. 52, 157–172.
Irurzun, M.A., Gogorza, C.S.G., Torcida, S., Lirio, J.M., Nuñez, H., Bercoff, P., Chaparro, M.A.E., Sinito, A.M., 2009. Rock magnetic properties and relative paleointensity stack between 13 to 24 kyr. BP calibrated ages from sediment cores, Lake Moreno (Patagonia, Argentina). Phys. Earth Planet. Inter. 172, 157–168.
Jackson, A., Jonkers, A.R.T., Walker, M., 2000. Four centuries of geomagnetic secular variation from historical records. Philos. Trans. R. Soc. Lond. A 358, 957–990.
Kastner, S., Ohlendorf, C., Haberzettl, T., Lücke, A., Mayr, C., Maidana, N.I., Schäbitz, F., Zolitschka, B., 2010. Southern Hemispheric Westerlies control the spatial distribution of modern sediments in Laguna Potrok Aike. Argentina. J. Paleolimnol. 44, 887–902, doi:10.1007/s10933-010-9462-0.
Kirschvink, J.L., 1980. The least-square line and plane and the analysis of paleomagnetic data. Geophys. J. R. Astr. Soc. 62, 699–718.
Lund, S.P., 1996. A comparison of Holocene paleomagnetic secular variation records from North America. J. Geophys. Res. 101, 8007–8024.
Oldfield, F., 1991. Environmental magnetism: a personal perspective. Quat. Sci. Rev. 10, 73–85.
Peters, C., Dekers, M., 2003. Selected room temperature magnetic parameters as a function of mineralogy, concentration and grain size. Phys. Chem. Earth 28, 659–667.
Stuiver, M., Reimer, P.J., 1993. Extended 14C data base and revised. Calib 3. 0 14C age calibration program. Radiocarbon 35, 215–230.
Tauxe, L., 1993. Sedimentary records of relative paleointensities of the geomagnetic field: theory and practice. Rev. Geophys. 31, 319–354.
Thompson, R., Oldfield, F., 1986. Environmental Magnetism. Allen & Unwin Ltd, 225 pp.
Wille, M., Maidana, N., Schäbitz, F., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schleser, G., Zolitschka, B., 2007. Vegetation and climate dynamics in southern South America: the microfossil record of Laguna Potrok Aike, Santa Cruz, Argentina. Rev. Palaeobot. Palynol. 146, 234–246.
Yang, X., Heller, F., Yang, J., Su, Z., 2009. Paleosecular variations since ∼9000 yr BP as recorded by sediments from maar lake Shuangchiling, Hainan, South China. Earth Planet. Sci. Lett. 288 (1–2), 1–9.
Zolitschka, B., Schäbitz, F., Lücke, A., Clifton, G., Corbella, H., Ercolano, B., Haberzettl, T., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike Volcanic Field as key sites of paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. J. South Am. Earth Sci. 21, 294–309.