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High-resolution paleomagnetic records from Laguna Potrok Aike (Patagonia, Argentina) for the last 16,000 years

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[1] Holocene and Late-glacial records documenting variations in direction and intensity of the geomagnetic field during the last 16,000 cal. BP are presented for Southern Patagonia. This continuous high-resolution terrestrial record from Laguna Potrok Aike (51°58′S, 70°23′W) was recovered within the SALSA (South Argentinean Lake Sediment Archives and modeling) project. Mineral magnetic measurements indicate that pseudo single-domain magnetite is the major carrier of the remanence allowing the reliable determination of stable natural remanent magnetization inclinations and declinations from alternating field demagnetization and principal component analysis. Paleomagnetic secular variation records reveal most of the familiar features of declination and inclination that have previously been reported in other records from South Argentina but conspicuous centennial-scale differences are also observed. The results illustrate the potential of paleosecular variations records for dating sedimentary sequences in southern South America.

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Theme: Magnetism From Atomic to Planetary Scales: Physical Principles and Interdisciplinary Applications in Geosciences and Planetary Sciences

1. Introduction

[2] Paleomagnetic secular variation (PSV) of the Earth's magnetic field obtained from soft lacustrine sediments during the last decades [e.g., *Creer et al.*, 1983a, 1983b; *Constable and McElhinny*, 1985; *Lund and Baneerje*, 1985; *Verosub et al.*, 1986; *Peng and King*, 1992; *Stockhausen*, 1998; *Brandt et al.*, 1999; *Frank et al.*, 2002; *Ojala and Saarinen*, 2002; *Yang et al.*, 2009] have been essential to reconstruct the dynamic behavior of the Earth's geomagnetic field at high-resolution beyond the range of instrumental observations. However, most of the high-resolution paleomagnetic studies were derived from sediments of the Northern Hemisphere and only a few records were obtained from marine sediments of the Southern Hemisphere [*Macrì et al.*, 2005, 2006; *Lund et al.*, 2006a, 2006b]. During the last decade, we have made efforts to reconstruct the behavior of the Holocene geomagnetic field by studying sediment records of lakes from southwestern Argentina [*Gogorza et al.*, 1999, 2000a, 2000b, 2002, 2004, 2006, 2008, 2011; *Irurzun et al.*, 2006, 2008, 2009] to fill the gaps of data distribution for the Southern Hemisphere. In this paper, we present a high-resolution record from Laguna Potrok Aike which provides a reference record for this region and geomagnetic time series data in a previously poorly represented part of the globe. The resolution of the new SALSA record is an order of magnitude higher than any available records in this region up to the present. This is crucial for geomagnetic modeling, taking into consideration that South America is a poorly covered and constrained region [*Korte et al.*, 2005; *Korte and Constable*, 2005; *Korte and Holme*, 2010; *Nilsson et al.*, 2010].

2. Study Area

[3] Laguna Potrok Aike is a maar lake located in southern Santa Cruz, Patagonia, Argentina (51°58′ S 70°23′W). Roughly 90 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 (Figure 1). The geological and volcanological development of these back arc Patagonian plateau lavas has been discussed in detail [*D'Orazio et al.*, 2000; *Ross et al.*, 2011; *Gebhardt et al.*, 2011; *Zolitschka et al.*, 2006]. With a maximum W-E-extension of about 150 km and a maximum N-S-extension of approximately 50 km the Pali Aike Volcanic Field covers an area of ~4500 km^2 [*Mazzarini and D'Orazio*, 2003]. The volcanic setting of Laguna Potrok Aike ensures a strong magnetic component in the material, and the potential to make detailed magnetic measurements.

[4] The roughly circular lake (shoreline development = 1.1) has a maximum diameter of 3470 m (Figure 1). The catchment area (>200 km^2) reaches far south into the Chilean part of the Pali Aike Volcanic Field. However, linear runoff only occurs episodically through a few canyons and arroyos mainly after snowmelt in spring. In summer 2002 the lake level was at 113 m above sea level (a.s.l.) and the maximum water depth was approximately 100 m. Inter-annual lake level fluctuations occur [*Haberzettl et al.*, 2005, 2008]. The water column of Laguna Potrok Aike has stable values for pH (8.7) and temperature (10.4°C) throughout the entire depth profile of 100 m. The absence of any pronounced summer stratification or anoxic hypolimnion in the water column of Laguna Potrok Aike can be explained only by the pronounced exposure of the lake to the extremely strong wind, which causes frequent mixing events during the whole year [*Zolitschka et al.*, 2006]. The total organic carbon content (mean value: 1.8% TOC, n = 97) in the surface sediments of Laguna Potrok Aike indicates low primary productivity, rapid decomposition and recycling of these compounds, and/or dilution by inorganic particles [*Zolitschka et al.*, 2006].

3. Methodology

[5] Two overlapping sediment cores from the 100 m deep central basin (PTA03/12+13) showing a high sedimentation rate [*Haberzettl et al.*, 2007] and one core from 47 m water depth (PTA03/5) showing a much lower sedimentation rate [*Haberzettl et al.*, 2009; *Anselmetti et al.*, 2009] were recovered with an UWITEC piston coring system in 2003

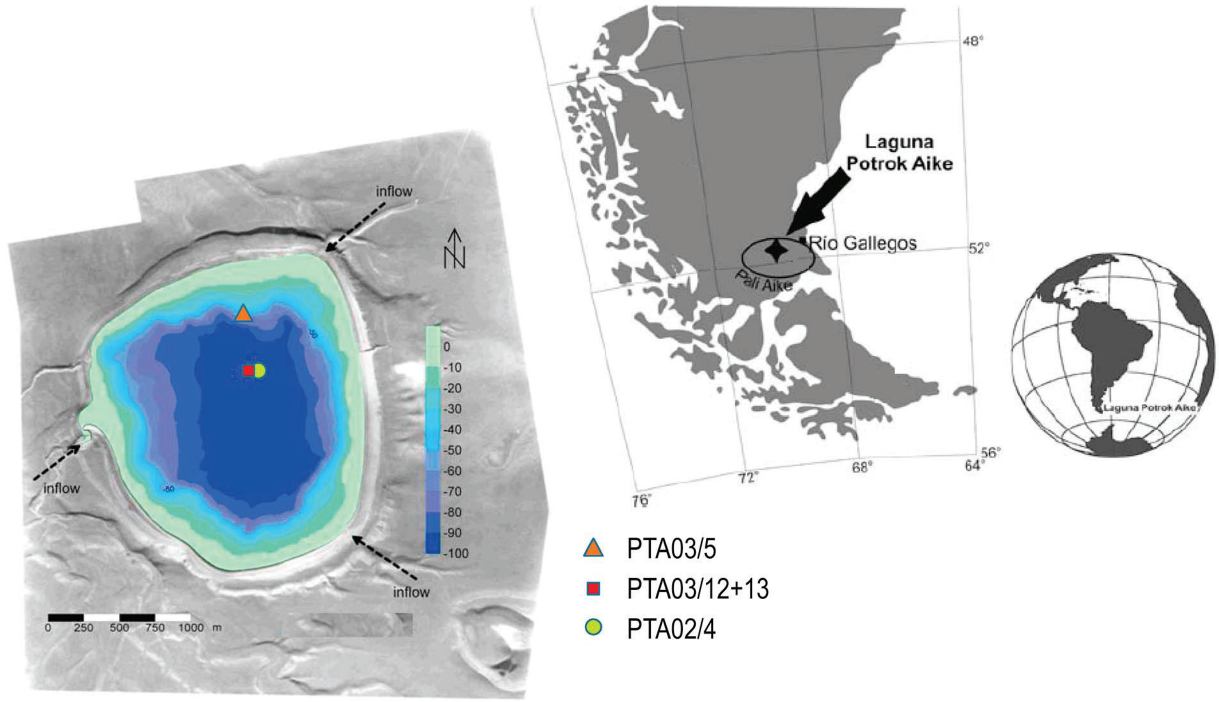

Figure 1. Location maps. Bathymetry of Laguna Potrok Aike and locations of analyzed cores are shown on the inset map.

(Figure 1). In the laboratory sediment cores were stored dark and cool at +4°C. All cores were cut into meter sections and split open, photographed and described lithologically.

3.1. Cores PTA03/12+13

[6] Magnetic susceptibility (κ) measurements were performed on split cores with a Bartington MS2F point sensor at 1 cm intervals [*Haberzettl et al.*, 2007]. The top of the deep basin record was already studied sedimentologically in short gravity core PTA02/4 (95 cm) [*Haberzettl et al.*, 2005, Figure 1] and paleomagnetically in gravity cores PTA05/11, 12, 16 and 17 [*Gogorza et al.*, 2011]. After a detailed correlation of short and piston cores using macroscopic sedimentological features and physical properties, the total length of the composite record PTA03/12+13 was established to 1892 cm. After the core sections were split lengthwise, cubic plastic boxes (8 cm^3) were pushed into the split core faces, and the samples (n = 866) were removed with a plastic spatula. In harder sediments, samples were cut from the core with a sharpened, thin-walled 2 × 2-cm stainless steel tube.

[7] Magnetic susceptibility was measured at low and high frequencies using a Bartington MS2 magnetic susceptibility meter at 0.47 kHz (k_{low}) and 4.7 kHz (k_{high}), respectively. The frequency dependence factor (F_{factor}, (%)) was calculated from the difference between measurements at high and low frequencies, i.e., F_{factor} (%) = 100*(k_{low}-k_{high})/k_{low}.

[8] For the determination of intensity and directions of the natural remanent magnetization (NRM, D and I), samples were measured using a JR6A Dual Speed Spinner Magnetometer (Figure S2 in the auxiliary material).[1] Alternating Field (AF) demagnetization and principal component analysis [*Kirschvink*, 1980] have been applied to determine the characteristic stable inclinations and declinations of the natural remanent magnetization (NRM). About 20% of the samples (n = 190) were completely demagnetized as pilot samples in steps of 5–10 mT (11 steps to a maximum alternating field of 100 mT). These results were used to determine the best procedure for demagnetizing the rest of the samples, which were demagnetized in five steps (5–40 mT).

[9] The following measurements were performed for all samples: the Anhysteretic Remanent Magnetization (ARM) was acquired in a peak alternating field of 100 mT with a steady bias field of 0.1 mT. The Isothermal Remanent Magnetization (IRM) was acquired at room temperature in

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GC003900.

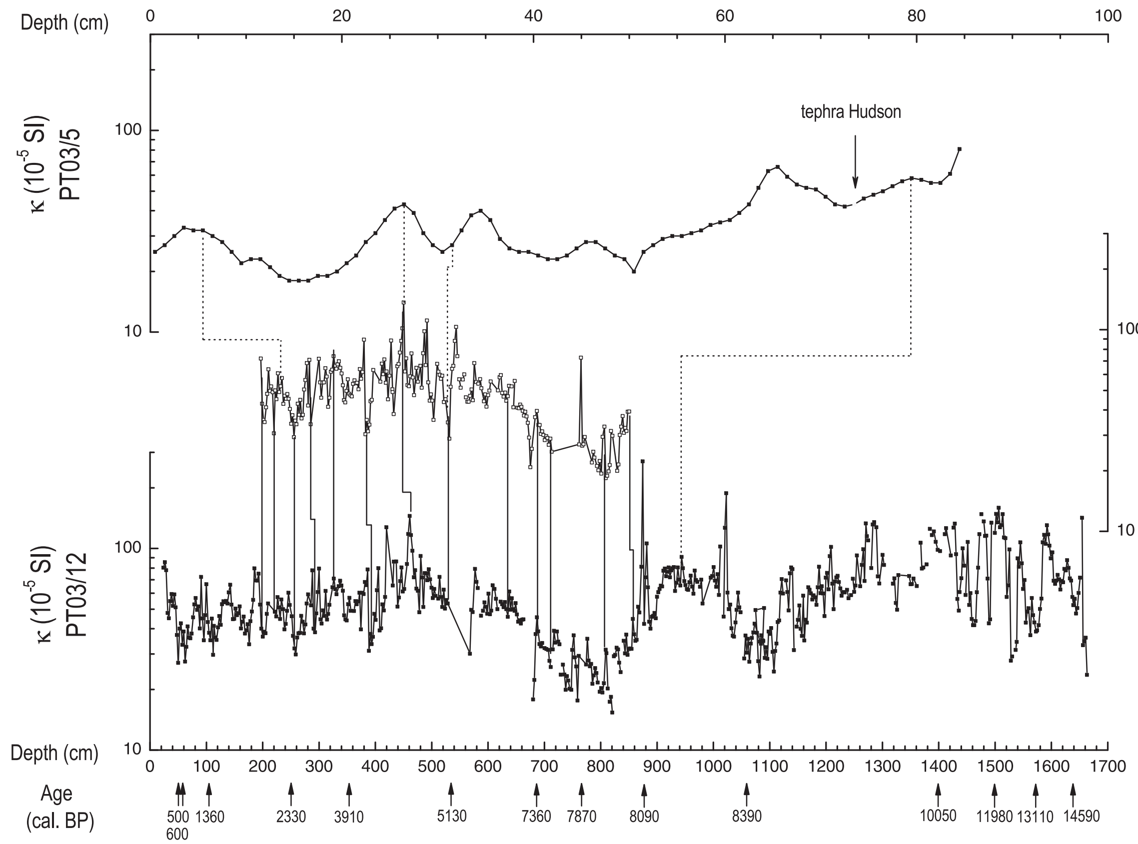

Figure 2. Correlation of magnetic susceptibility (κ) profiles of cores PTA03/12 and PTA03/13 (discrete samples, this work), with data from PTA03/5 (u-channel samples [*Haberzettl et al.*, 2009]).

increasing steps of up to 1.2 T reaching saturation (SIRM) (Figure S2), and in increasing steps back until canceling the magnetic remanence was achieved using a IM-10-30 Pulse Magnetizer (ASC Scientific). Subsequently, AF demagnetization of the ARM and SIRM, respectively, were measured using the same steps as for the NRM demagnetization. Finally, a group of pilot samples (n = 30) was subjected to thermal demagnetization after applying a direct field of 1.2 T, followed by thermal demagnetization in 15 steps from 75°C to 700°C. All magnetizations have been measured at lower speed on a JR6A Dual Speed Spinner Magnetometer.

3.2. Core PTA03/5

[10] Continuous u-channel samples were taken from the core halves in 2008 comprising 168 cm which, due to the lower sedimentation rate, is equivalent to the time period covered by PTA03/12 +13 [*Haberzettl et al.*, 2009, Figure 1]. Magnetic susceptibility was measured at 4 mm intervals using a Bartington MS2E point sensor at the University of Bremen (GEOPOLAR), whereas κ of the u-channel was measured at 1 cm intervals using a Bartington MS2C magnetic susceptibility loop sensor at the Institut des Sciences de la mer de Rimouski (ISMER). Declination, inclination and NRM as well as the induced remanences ARM (using a 0.05 mT DC biasing field), IRM_{300mT} and IRM_{950mT} were measured in progressive AF demagnetization steps from 0 to 70 mT at 5 mT increments using a 2G Enterprises Model 755 cryogenic magnetometer for u-channel and IRM pulse magnetizer. This model is specifically designed for u-channel samples and the measurements were carried out at 1 cm interval; smoothing occurs relative to the half width of the response function, which is between 7 and 8 cm for the instrument design [*Weeks et al.*, 1993].

4. Correlation and ^{14}C Chronology

[11] The age–depth model is based on 16 Accelerator Mass Spectrometry (AMS) radiocarbon dates performed on different material [*Haberzettl et al.*, 2007], and on identification of the Mt Burney tephra [*Kilian et al.*, 2003]. A hard water effect in the sediments of Laguna Potrok Aike has been demonstrated to be absent [*Haberzettl et al.*, 2005]. The sediment/water interface serves as a time marker for

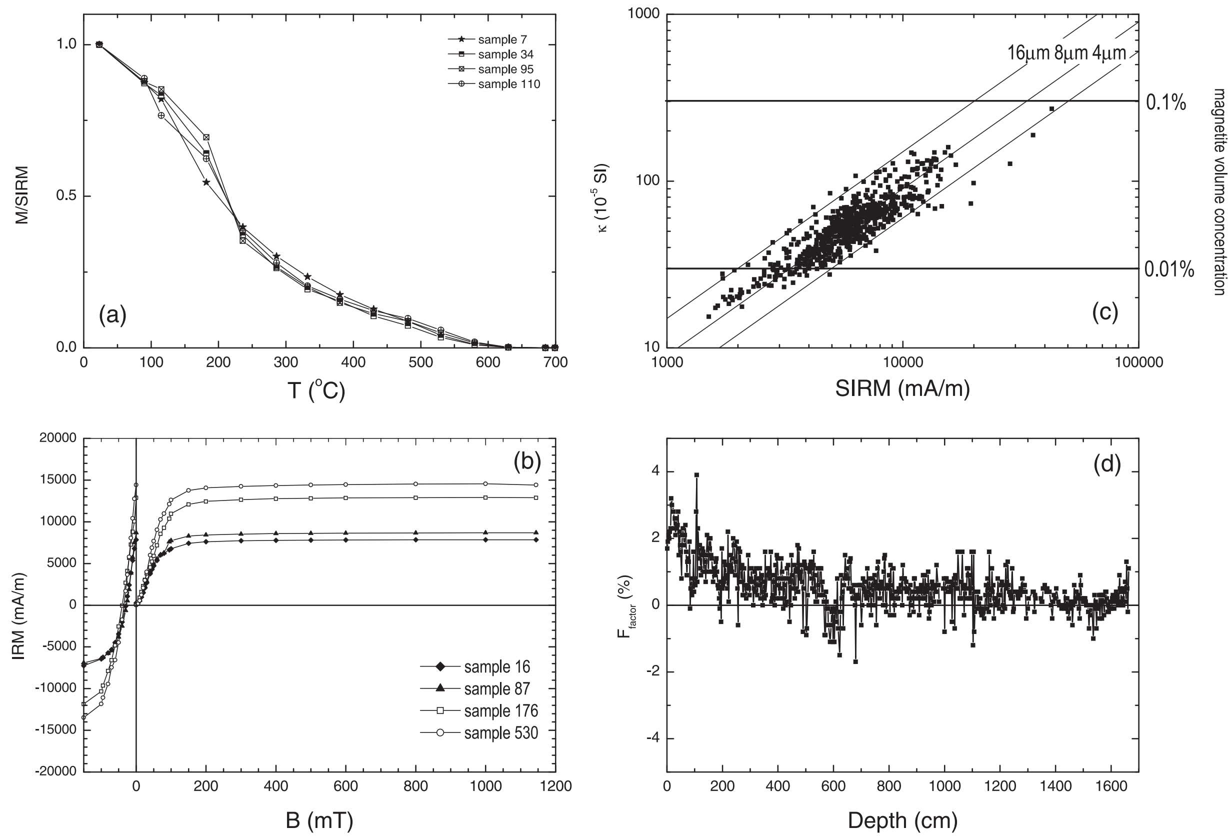

Figure 3. Rock magnetic studies. (a) Thermal demagnetization results of the Saturation of the Isothermal Remanent Magnetization (SIRM) and (b) Normalized Isothermal Remanent Magnetization (IRM) acquisition curves, for representative samples from core PTA03/12. (c) Susceptibility (κ) versus Saturation of the Isothermal Remanent Magnetization (SIRM) for all samples in order to estimate concentration and grain size, according to *Thompson* [1986]. (d) Frequency dependence factor (F_{factor}) versus depth.

the year of coring (2002) for the uppermost section of the record (PTA02/4 [*Haberzettl et al.*, 2005]).

[12] κ and NRM logs were used to define tie-lines for the lithostratigraphic correlation of cores. These tie-lines are consistent with lithology. Figure 2 (Figure S1) shows the κ logs corresponding to PTA03/12+13 and PTA 03/5 and some of the horizons correlation identified for these cores. Sedimentation rates in the central basin (PTA03/12+13) are relatively uniform throughout (0.8–1.4 mm/yr), but there is an abrupt change in the time interval ranging from 7800 to 8700 cal. BP, in which it was estimated to vary between ~5 and 8 mm/yr [*Haberzettl et al.*, 2007].

5. Magnetic Results

5.1. Magnetic Carrier Minerals

[13] The rock magnetic data for the cores are summarized in Figure 3 (Figure S3). Thermal demagnetization of SIRM demonstrates the predominance of magnetite with a Curie temperature of 580°C as the main carrier of magnetization in these sediments. A change in the slope of the heating curves between 200 and 350°C indicates the additional presence of titano(magnetite) and maghemite [*Dankers*, 1978]. Finally, a small magnetization component remaining while heating above 600°C suggests contribution of hematite and/or maghemite to the magnetic properties of a few samples (Figure 3a). Stepwise acquisition of isothermal remanent magnetization (IRM) in fields of up to 1.2 T documents that more than 90% of SIRM were acquired in a field of 200 mT (Figure 3b). Progressive removal of SIRM by stepwise increasing applying reversed fields indicates that the remanent coercive field of the SIRM (B_{CR}) varies approximately between 29 and 64 mT, suggesting that a low coercive magnetic mineral, such as magnetite of pseudo-single domain size (PSD) might be predominant within the sediments. The S_{ratio} (IRM_{300mT}/SIRM) varies between 0.8 and 1,

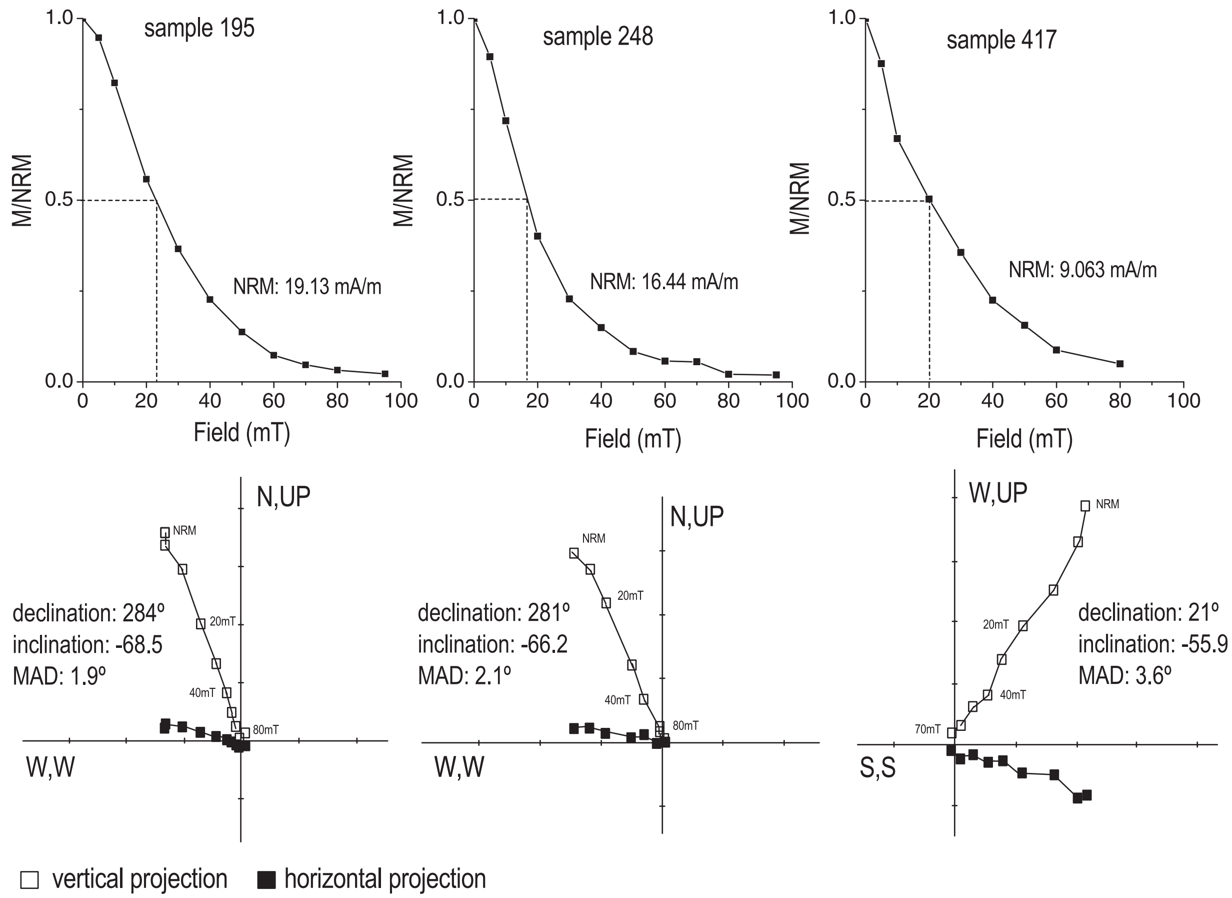

Figure 4. Normalized intensity decay curves and orthogonal vector plots for three pilot samples from core PTA03/12, produced by stepwise AF demagnetization at 5–10 mT steps, up to a maximum field of 95 mT.

with a mean value of 0.969 ± 0.001, indicating magnetite as the dominant magnetic mineral [*King et al.*, 1982; *Thompson*, 1986]. The SIRM-susceptibility plot (Figure 3c) implies that the magnetic concentration ranges from 0.01% to 0.1% magnetite by volume and the SIRM/κ ratio is consistent with a magnetic grain size of 4 to 10 μm. The linearity of the SIRM/κ implies that the grain size does not change much within the sediments. Values of F_{factor} are below 5% (Figure 3d), so superparamagnetic grains do not control the assemblages of magnetic grains [*Bartington Instruments Ltd.*, 1994].

5.2. Direction, Intensity and Stability of NRM

[14] The AF demagnetization results of representative samples are illustrated in Figure 4. As a first estimation for grain size variations the median destructive field (MDF_{NRM}) was calculated. MDF_{NRM} ranges from 6 to 26 mT and NRM intensities are almost completely demagnetized in fields of 60 mT. The orthogonal demagnetization diagrams show that a viscous remanent magnetization - if present at all - is progressively removed between 5 and 10 mT. The first 2 m of core sediments show low MDF_{NRM}, and high contents of organic matter and water contents [*Haberzettl et al.*, 2005]. The spurious paleomagnetic results obtained in this interval suggest that the signal was probably disturbed by the coring process and are therefore no longer discussed.

[15] The characteristic remanent magnetization (ChRM) has been derived from principle component analysis [*Kirschvink*, 1980] of mostly five or more successive demagnetization steps. The samples yielding maximum angular deviation (MAD) values >5° have been eliminated for the discussion of PSV [*Stoner and St-Onge*, 2007]. Since the cores were not orientated relative to magnetic north, the

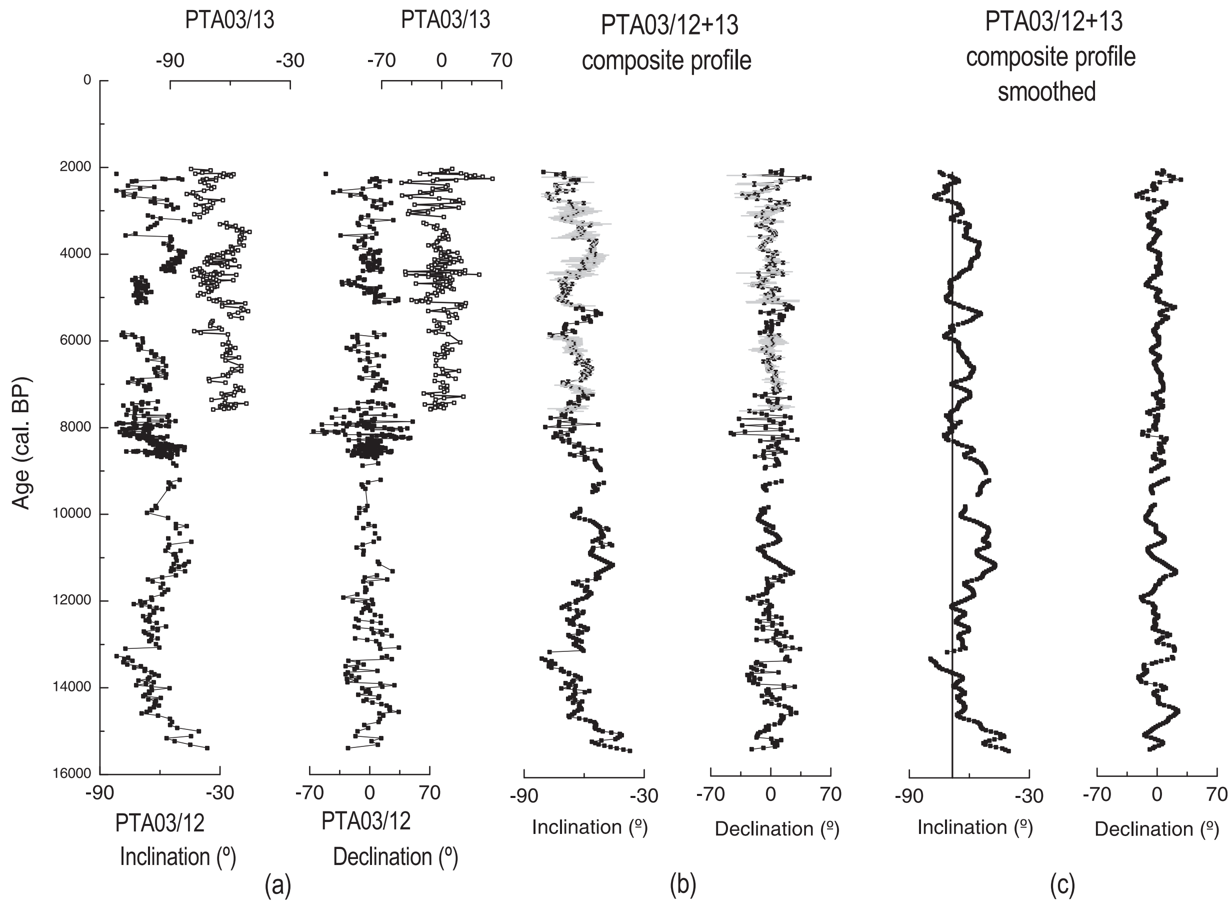

Figure 5. Plots of inclination and declination for (a) cores PTA03/12 (closed squares) and PTA03/13 (open squares), (b) stacking composite profile PTA03/12+13 based on magnetic susceptibility correlation and (c) stacked profile PTA03/12+13 after smoothing process.

declination values for each core are centered about average declination

6. PSV Records

[16] Stacking of individual curves is commonly employed on multiple paleomagnetic records with the aim to obtain more reliable estimates of the temporal variation in the directions of the geomagnetic field [*Gogorza et al.*, 1999, 2000a, 2000b, 2002; *Irurzun et al.*, 2006, 2008]. The declination and declination data from both cores (Figure 5a) were combined to obtain composite records. First, the data were linearly interpolated at constant intervals of 30 years in order to have equivalent age values for both cores. Then, the non-weighted arithmetic average was calculated and standard deviation was used as a measure of scatter. After stacking (Figure 5b), it is necessary to diminish the amplitude of high-frequency changes in the PSV records originating either from disturbance during coring, sampling, palaeomagnetic measurements, and/or remanence acquisition. It was carried out by smoothing the directional data using a five-point adjacent-averaging method, this method essentially takes the average of a user-specified number of data points (n = 5) around each point in the data, and replaces that point with the new average value (Figure 5c). Resulting stable inclinations and declinations are shown in Figure 5c. Inclinations vary mostly between −40° and −80°. The average inclination (∼−62.2° ± 0.4) is lower than the predicted inclination of a geocentric axial dipole field (GAD) of ∼−69° at the latitude of the site (52°S). Despite this difference, the records reflect typical features of paleosecular variation and are comparable from core to core.

7. Relative Paleointensity Records

[17] Rock magnetic characteristics, including the well-defined magnetization component carried by

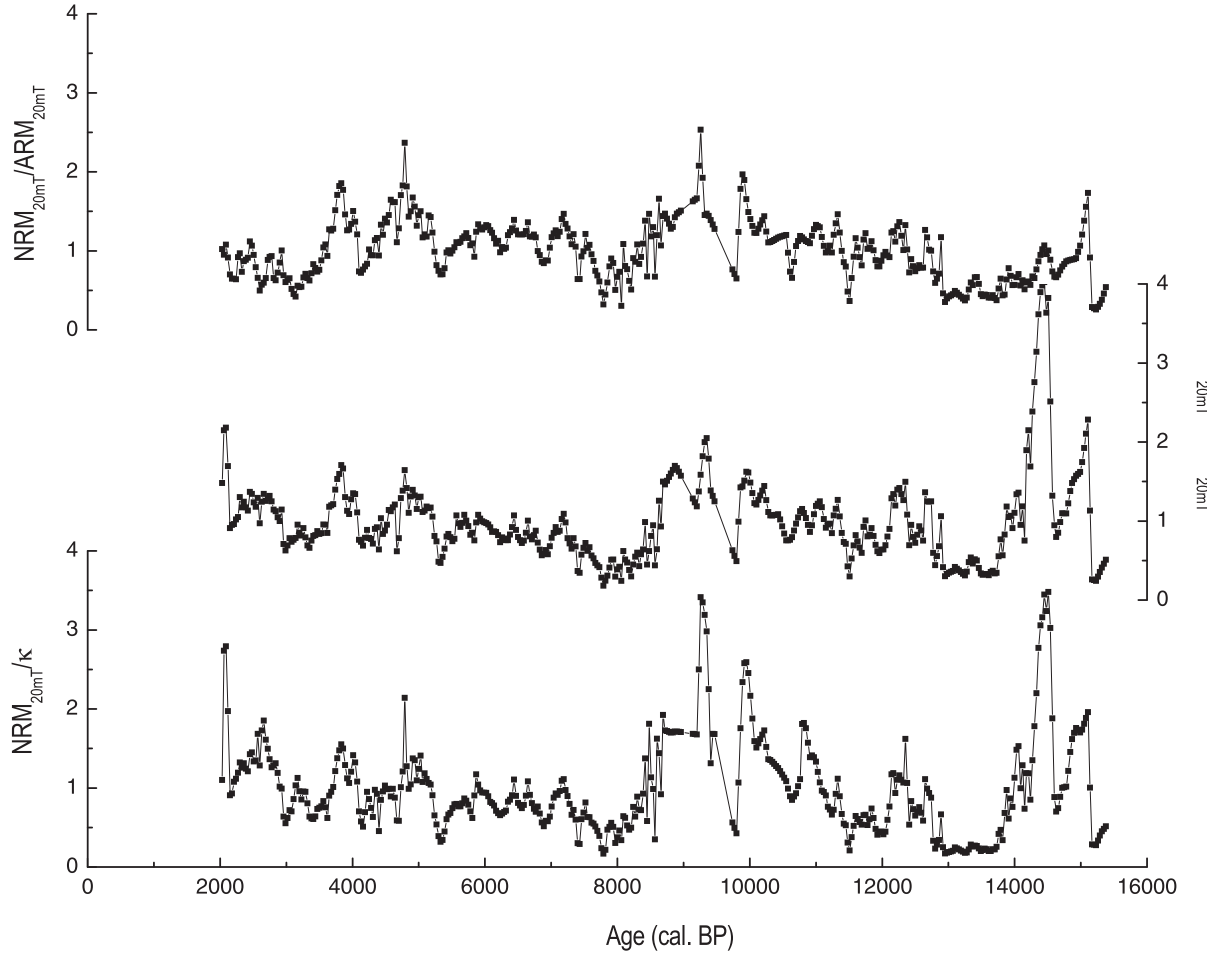

Figure 6. Normalized estimates of relative paleointensity NRM_{20mT}/ARM_{20mT}, $NRM_{20mT}/SIRM_{20mT}$ and NRM_{20mT}/κ ratios versus Age.

pseudo-single domain (PSD) magnetite, and variations of less than a factor of 10 in the magnetic concentration satisfy the standard criteria for paleointensity studies [*Tauxe*, 1993; *King et al.*, 1983; *Stoner and St-Onge*, 2007]. According to the AF demagnetization characteristics of NRM directions (Figure 4), relative paleointensities (RPI) are generated using values of NRM, ARM and SIRM after AF demagnetization at 20 mT (NRM_{20mT}, ARM_{20mT}, and $SIRM_{20mT}$). For each core we obtained three estimates of normalized field intensity using ARM_{20mT}, κ and $SIRM_{20mT}$ as normalizing parameters. In order to compare the different paleointensity estimates, the stacked values of NRM_{20mT}/κ, NRM_{20mT}/ARM_{20mT} and $NRM_{20mT}/SIRM_{20mT}$ were further normalized by dividing each value by their respective arithmetic means (Figure 6). In general, a good agreement between the records can be observed, as expected from the uniformity of the magnetic properties in the cores. The high peak observed in the records of NRM_{20mT}/κ and $NRM_{20mT}/SIRM_{20mT}$ in the interval 14,270–14,570 cal. BP is associated with a peak in k_{ARM}/κ, which suggests a distinctive change to smaller values of magnetic grain size. It implies that this feature in the RPI record is questionable in this period.

[18] In order to check relative paleointensity data quality and to confirm that the normalized records are free of environmental influences, spectral analyses of normalized remanences, normalization parameters and a coherence test were performed following the method of *Tauxe and Wu* [1990]. Spectral analysis using the method of Welch and calculation of coherence spectra were performed using the MATLAB 6.1 software. The coherency analysis further indicates that the normalized intensity curves are not coherent with normalization parameters (no significant frequencies above the 95% confidence level), especially for $NRM_{20mT}/SIRM_{20mT}$ (Figure 7a) and are coherent with each other over most of the frequency range (Figure 7b).

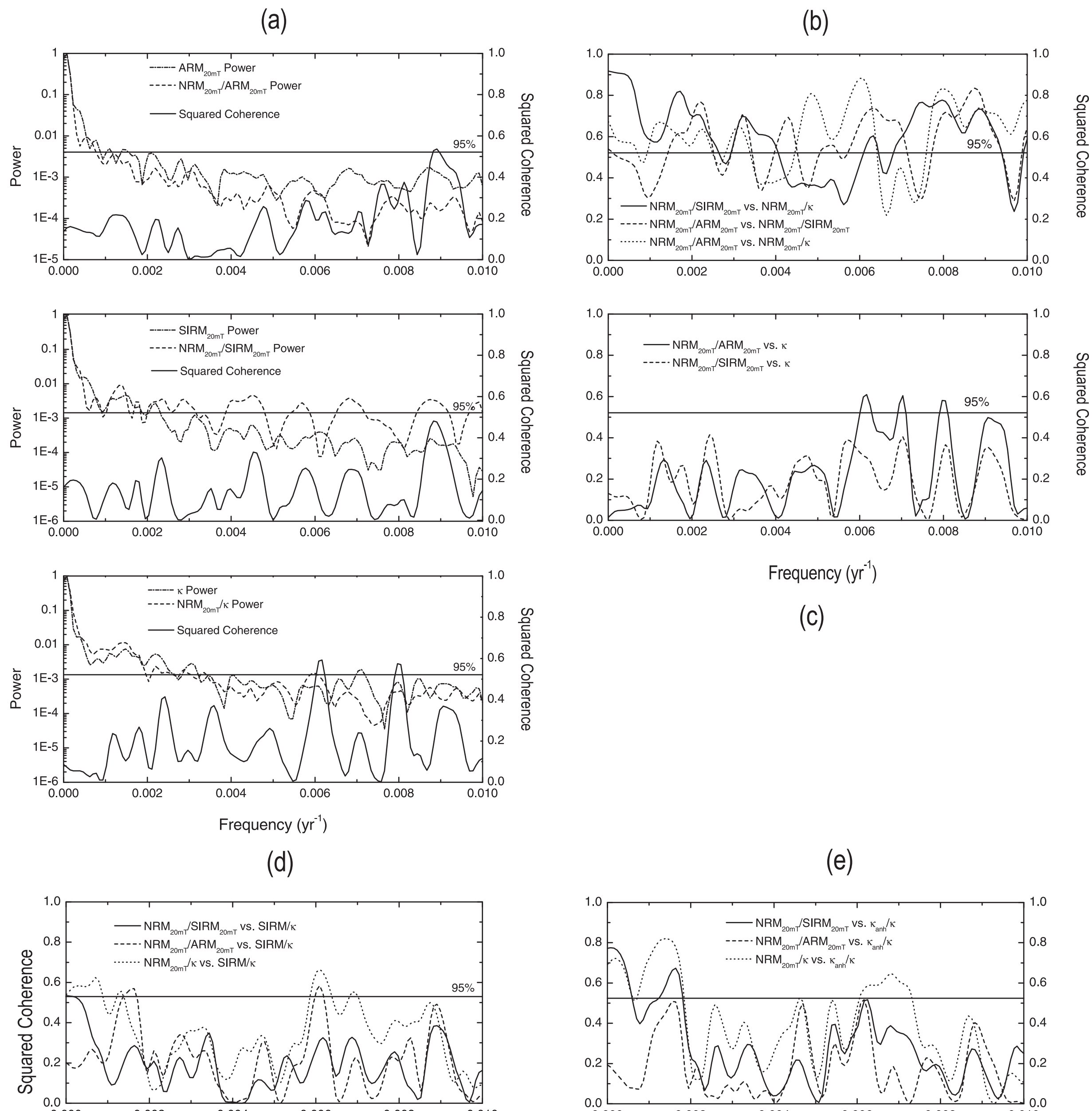

Figure 7. Spectral analysis of three normalization parameters (ARM_{20mT}, $SIRM_{20mT}$ and κ) and three normalized remanences (NRM_{20mT}/ARM_{20mT}, $NRM_{20mT}/SIRM_{20mT}$ and NRM_{20mT}/κ). Coherence tests of relative paleointensity curves with respect to each other and with respect to the normalization parameters, showing that the normalized intensity curves are coherent with each other over the whole range of frequencies, but they are generally not coherent with the normalization parameters.

[19] While all of the stringent criteria for RPI determinations seem to be satisfied, it is still possible that the agreement between records may be due to environmental control that affects the magnetic signal [*Roberts et al.*, 1997]. We perform a coherence analysis on $NRM_{20mT}/SIRM_{20mT}$ and NRM_{20mT}/ARM_{20mT}, a related mineral magnetic (e.g., κ) parameter and related magnetic grain size (e.g., $SIRM/\kappa$ and κ_{anh}/κ) parameters to test if the normalized remanence signal is influenced by environmental (e.g., climatic) factors over specific frequency ranges (Figures 7c, 7d, and 7e). These

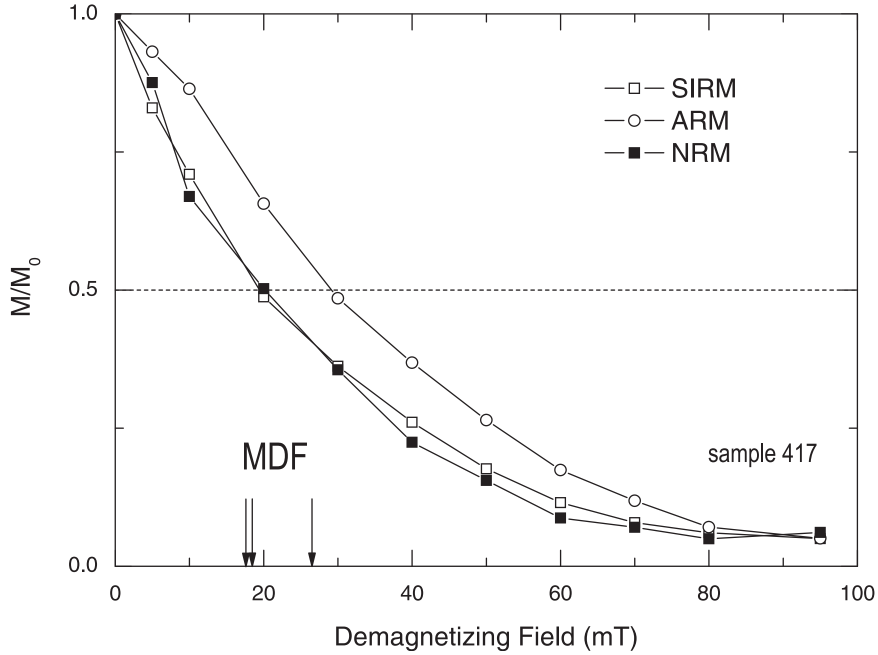

Figure 8. Typical AF demagnetization curves of Natural Remanent Magnetization (NRM), Anhysteretic Remanent Magnetization (ARM) and Saturation of the Isothermal Remanent Magnetization (SIRM) for sample 417 (PTA03/12).

analysis indicate that there is no significant coherence between the $NRM_{20mT}/SIRM_{20mT}$ record and the bulk mineral magnetic parameters at any frequency. On the other hand, $NRM_{20mT}/SIRM_{20mT}$ is not coherent with $SIRM/\kappa$ but, in the case of κ_{anh}/κ, there is no coherence for most frequencies except at the period of about 600 years. A strong cycle with a period of roughly 600 year is apparent in the reconstructed series of the 11-year averaged sunspot numbers based upon the Antarctic data performed by *Usoskin et al.* [2004], in agreement with earlier observations based on cosmogenic isotopes. This cycle could be possibly related to the 650-year periodicity in the ^{14}C data [*Damon and Sonett*, 1991]. It is interesting to point out that a fundamental climatic cycle of about 550 years of alternating drought and moisture has been almost synchronous throughout Europe since 2300 B.C., and may also correspond to similar cycles of bog drying and regeneration in North American bogs [*Hansen*, 1961]. The spectral feature at 600 years in the normalized intensity record is likely a climatic signal that has not been satisfactorily removed by the normalization process. Despite this, we consider that $SIRM_{20mT}$ should be the best normalizer for the sediments; and we show the closer resemblance between NRM and SIRM demagnetization curves if compared to ARM demagnetization curves (Figure 8). This behavior was observed in most of the analyzed pilot samples which were taken along the whole core.

8. Comparison With Other Records

8.1. Comparison With Local Records

[20] During the last few years, several studies have revealed the potential use of PSV of the geomagnetic field as a practical Holocene stratigraphic tool in areas such as the Arctic, where calcium carbonate dissolution and/or contamination with reworked carbon occurs, and datable material is rare [e.g., *Lisé-Pronovost et al.*, 2009; *Barletta et al.*, 2010a; *Ledu et al.*, 2010a, 2010b; *Ólafsdóttir*, 2010; *Antoniades et al.*, 2011; *Willmott et al.*, 2006, *Brachfeld et al.*, 2003]. In order to improve the rough chronology previously obtained by using two tephra by *Haberzettl et al.* [2009], Mt. Hudson: 8100 cal. BP and Mt. Burney: 8680 cal. BP; see Table 1 shown by *Haberzettl et al.* [2009], the PSV of core PTA03/5 were compared with the high-resolution records obtained in this work.

[21] Resolution of the data from the u-channel (PTA03/5) is different when compared to those obtained from discrete samples (PTA03/12+13) because of the considerably lower sedimentation rate for PTA03/5, responsible for a smoothing of the geomagnetic signal and the convolution effects

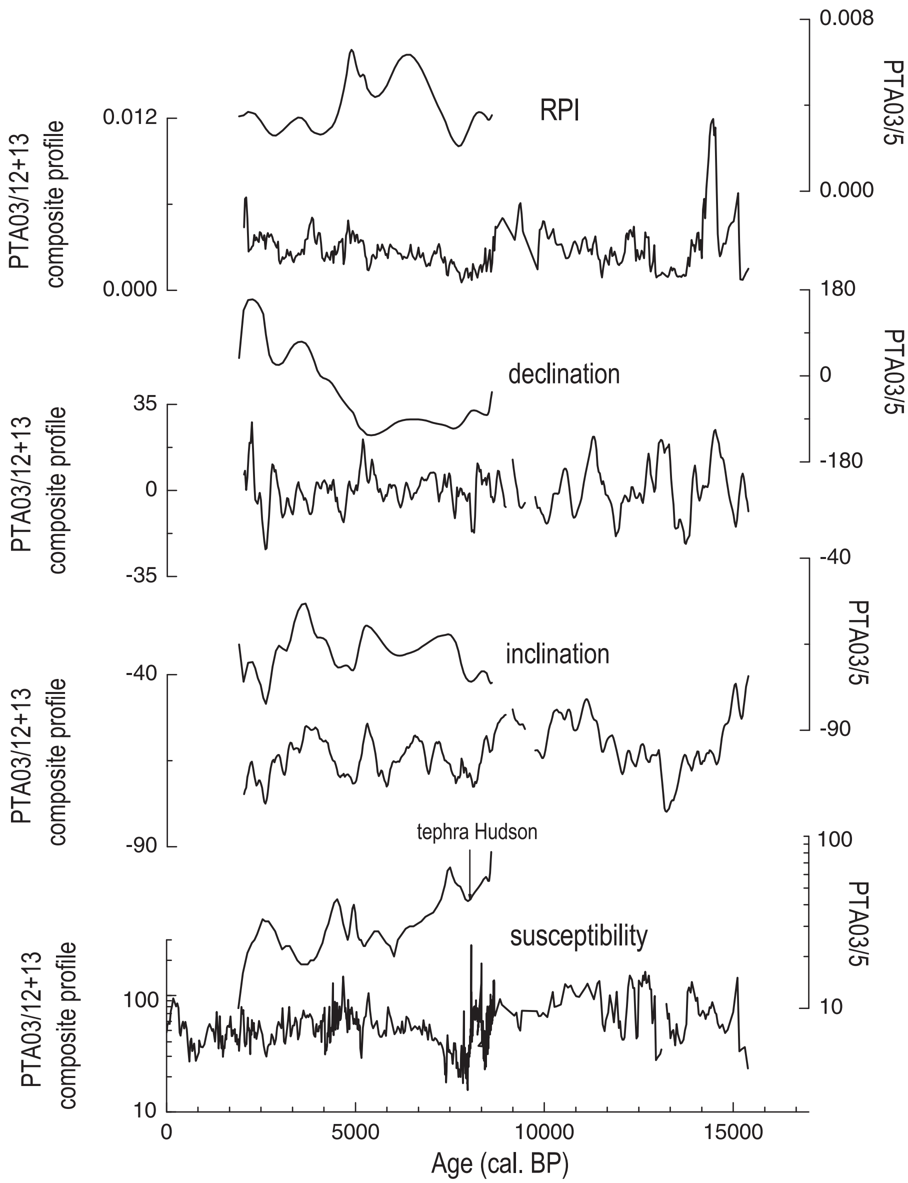

Figure 9. Plots of Relative Paleointensities (RPI); inclination, declination and κ versus Age for PTA03/12+13 (discrete samples) and PTA03/05 (u-channel).

of the u-channel magnetometer measurement system [*Oda and Shibuya*, 1996; *Guyodo et al.*, 2002]. Despite of this, the ages of the PSV features of core PTA03/5 were compared with the records obtained in this study. Although a significant discrepancy is observed in the declination profiles, the inclination shows a fairly good agreement and several features can be traced from record to record (Figure 9). Declination values of core PTA03/5 display large amplitude trends (over ca. 300°; Figure 9), probably an artifact induced by rotation during coring and should be treated with caution. The age transformation proposed following the features labeled in the inclination and RPI records are showed in Figure 9. It is necessary to clarify that the two tephra layers (age 8100 cal. BP, tephra Mt. Hudson and 8680 cal. BP, tephra Mt. Burney) were held as fixed reference points and were not allowed to shift position. We can clearly observe a good agreement between inclinations and RPI records after the age transformation was performed (Figure 9).

8.2. Comparison With Regional Records of SW Argentina

[22] In order to improve the understanding of Holocene to Late Pleistocene PSV in Southern Argentina, a regional comparison of directional records was

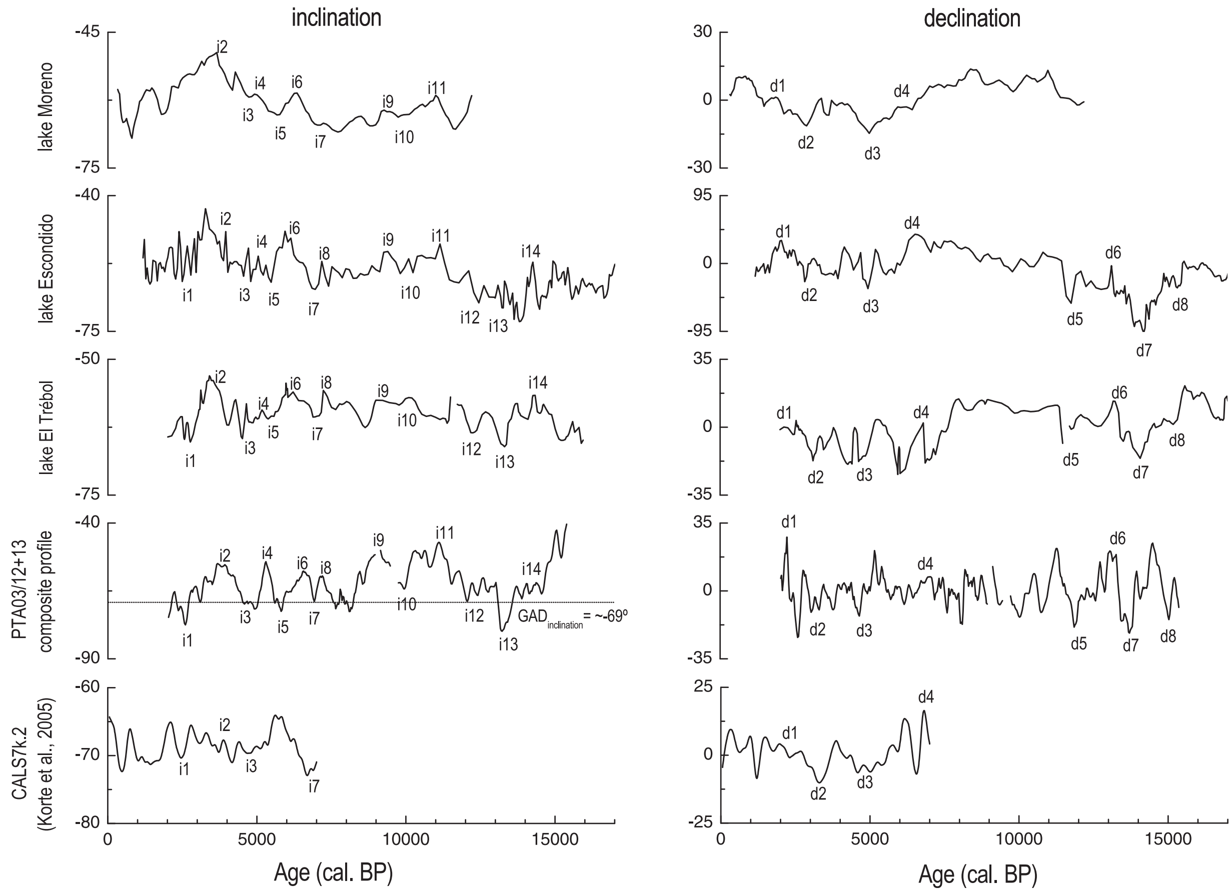

Figure 10. Stacked inclination and declination logs obtained in this work and in the previous work [*Gogorza et al.*, 2000a, 2002; *Irurzun et al.*, 2006] as a function of Age.

performed with the inclination and declination records from Laguna Potrok Aike (this work), with lakes Escondido (41°S, 71°30′W) [*Gogorza et al.*, 2004], El Trébol (41°04′S 71°29′W) [*Irurzun et al.*, 2006] and Moreno (41°5′S, 71°33′W) [*Gogorza et al.*, 2000a], all of which are located more than 1000 km north of Laguna Potrok Aike (Figure 10). Synchronous features of PSV are better observed in sites located nearby, but dominant swings in direction can be coeval up to a distance of 4000 km [*Lund*, 1996; *Barletta et al.*, 2010b].

[23] In general, several highs and lows displayed in the inclination curve of Laguna Potrok Aike are identified as well as in the curves of the other lakes. Some characteristic inclination and declination features are shown using i_n d_n, respectively. Significant inclination lows ‘i2’, ‘i4’, ‘i6’, ‘i8’, ‘i9’, ‘i11’ and highs ‘i1’, ‘i3’, ‘i5’, ‘i7’, ‘i12’ and ‘i13’ are identified. The absence of several of these features and the different amplitude observed in the data of Lake Moreno are due to the fact that they were subjected to a smoothing process after they were stacked [*Gogorza et al.*, 2000a]. The steepest inclinations are observed at about 2600, 5900, 7000 and 13,200 cal. BP at Laguna Potrok Aike and lakes El Trébol and Escondido, although the last feature is less prominent in lake Escondido. The shallowest inclinations are observed at 11,100 and 3500 cal. BP; the last is identified in Laguna Potrok Aike and Lake Escondido. In general, the declination records are least consistent. There are some distinct declination minima at around 2600 and 5000 cal. BP in all the records, and the most pronounced one is observed at about 13,700 (14,100) cal. BP in Laguna Potrok Aike (in lake El Trébol and lake Escondido). Higher frequency variations are observed in the declination records of Laguna Potrok Aike between 7500 and 9500 cal. BP. The apparent lower resolution observed in the other Argentinean lakes could simply be explained by the lower sedimentation rates recorded in Lake Escondido (0.3 mm/year) and lake El Trébol (0.4 mm/year) compared to Laguna Potrok Aike (5–8 mm/year) in most of this period. Finally, the age models of the records and/or inaccuracies in dating methods could explain the

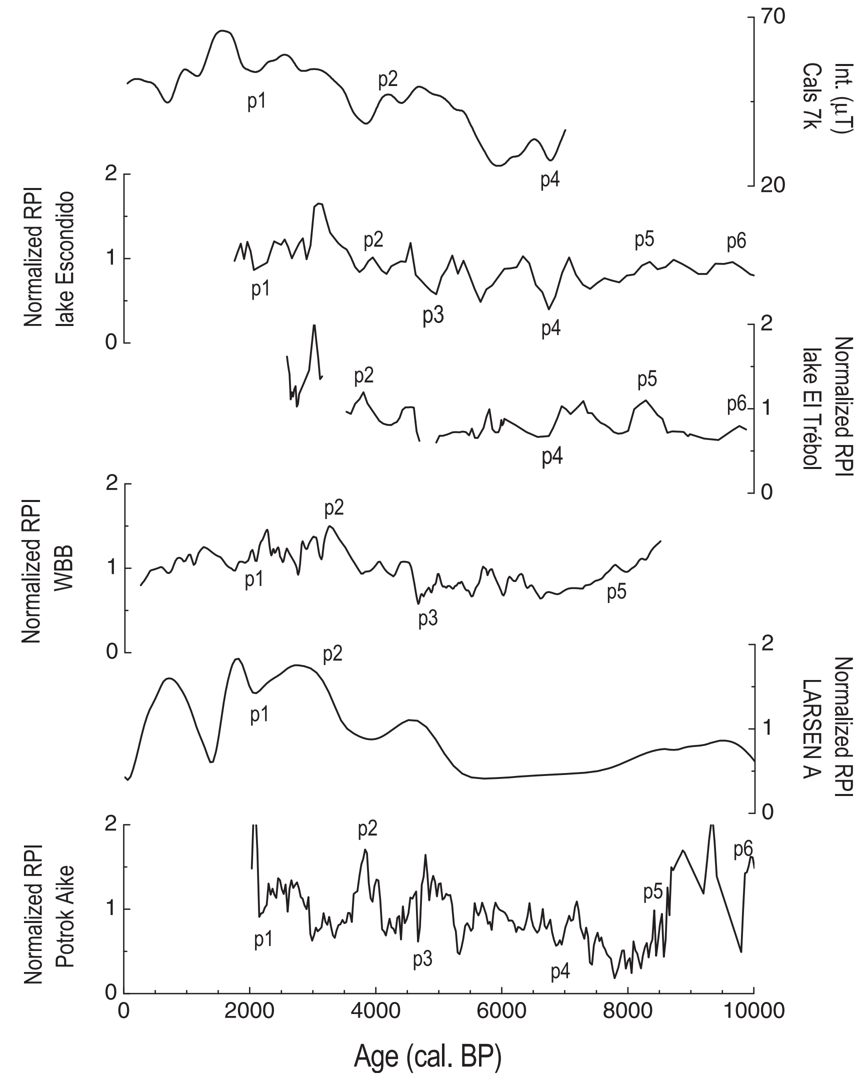

Figure 11. Comparison of the normalized intensity record NRM_{20mT}/ARM_{20mT} from Laguna Potrok Aike with the previous work [*Gogorza et al.*, 2004, 2006] as a function of age and CALS7k output [*Korte and Constable*, 2005]. A sedimentary sequence collected from beneath the former Larsen-A Ice shelf, Antarctic Peninsula [*Brachfeld et al.*, 2003] and a Holocene RPI record from the western Bransfield Basin (WBB), located in the northern Antarctic Peninsula [*Willmott et al.*, 2006].

small discrepancies in timing observed between Laguna Potrok Aike and the other records. Nonetheless, the overall consistency of PSV patterns among these records suggests that these features are common for Southern Argentina. These coeval features also suggest that PSV can provide a useful tool for stratigraphic correlation on a regional scale in Southern South America.

[24] In Figure 11, the RPI record of Laguna Potrok Aike is compared for the last 10,000 years with the records of lakes Escondido NRM_{20mT}/ARM_{100mT} [*Gogorza et al.*, 2004] and El Trébol NRM_{20mT}/ARM_{20mT} [*Gogorza et al.*, 2006] from SW Argentina and the geomagnetic model CALS7K.2 [*Korte and Constable*, 2005]. Similar features are observed which are labeled p1-p6. However, because of the different sedimentation rate, short-term centennial features, such as observed at laguna Potrok Aike, are not resolved in low-resolution composite records, such as lakes Escondido and El Trébol. In particular, a similar long-term trend of increasing intensity from 6700 cal. BP until 3800 cal. BP (3000 cal. BP) is observed in Laguna Potrok Aike (in lakes Escondido and El Trébol). It is interesting to mention that the RPI high around 9300 cal. BP is also observed in North America [*Barletta et al.*, 2010b; *St-Onge et al.*, 2003] and Greenland [*Snowball et al.*, 2010]. Moreover, the paleointensity lows observed

around 3000 and 7500 cal. BP can be correlated with features seen in the sediment cores collected from Hole 1202B in the West Pacific [*Richter et al.*, 2006], Fish Lake [*Verosub et al.*, 1986], the synthetic record OH93 [*Ohno and Hamano*, 1993], and RPI estimates obtained from ByaP2 and ByaP1, the Holocene lake sediment sequence collected in central southern Sweden [*Snowball and Sandgren*, 2004]. The global occurrence of these features suggests that they might be related to dipolar sources.

[25] We analyzed the records of declination and inclination for lake sediment records from SW Argentina and Laguna Potrok Aike using the *MC-CLEAN* algorithm [*Heslop and Dekkers*, 2002]. The *MC-CLEAN* procedure was developed to study the frequency spectra of noisy and unequal spaced paleoclimatic time series. It is based on a series of Monte Carlo simulations which allow a large number of slightly different spectra to be generated for a single input signal, the slight differences between these spectra can be utilized to determine a mean spectrum and confidence intervals both for individual frequency peaks and for the spectrum as a whole [*Heslop and Dekkers*, 2002].

[26] Spectral analysis documents millennial-scale variability in declination and inclination records. The overall conformity between the records is that the significant spectral peaks have periods ranging ∼1000–3000 to 4000 years; longer periods should be regarded with some caution, given the length of some of the lake records. The major peaks for inclination and declination correspond to periodicities of approximately 1200–1500, 2500–2800 and 3400 yr.; longer periods of 5500 and 6500 yr. were observed in inclination and declination records of laguna Potrok Aike and Lake Escondido, respectively. The periodicities obtained from spectral analysis can be divided into two bands: (1) a long-periodicity band consisting of an approximately 6000-yr periodicity for inclination and declination, and (2) a short-periodicity band consisting of approximately 1500-, 2500-, and 3400-yr periodicities for inclination and declination. The longer period may be related to dipolar variability [*Barton*, 1983; *Lund and Baneerje*, 1985], while the shorter ones are probably derived from the source of non-dipolar variation.

8.3. Comparison With Records From Antarctica

[27] We compare our paleointensity record to the results from a sedimentary sequence collected from beneath the former Larsen-A Ice shelf, Antarctic Peninsula [*Brachfeld et al.*, 2003], and a Holocene RPI record derived from two sediment cores from the western Bransfield Basin (WBB), located in the northern Antarctic Peninsula [*Willmott et al.*, 2006] (Figure 11). Some common features could possibly be coeval (p1-p5), although the paleointensity record of Laguna Potrok Aike does not agree with every large-scale feature of these other paleointensity records. It is also important to point out that neither of these Antarctic records was dated using radiocarbon dates, both of them were dated using a paleointensity-based chronology due to the lack of suitable material for radiocarbon dating in Holocene Antarctic shelf sediments [*Willmott et al.*, 2006]. The records of Larsen A were tuned to ABSINT, a global compilation of >2000 archeomagnetic measurements [*Laj et al.*, 2002; *Yang et al.*, 2000]. In WBB, the reference curves used were ABSINT, and an ultra high-resolution sedimentary paleointensity record from the St. Lawrence Estuary, Eastern Canada [*St-Onge et al.*, 2003]. Although dating based on geomagnetic paleointensity is a well proven technique, it is necessary to keep in mind the limitations of both Antarctic studies. On one hand, short-term centennial features such as those observed in the WBB and Larsen A records are not resolved in lower resolution records such as ABSINT. On the other hand, the geographic position between the WBB and St. Lawrence Estuary records is significantly different and far more than 12,700 km. This significant distance could imply the presence of distinctive and different geomagnetic features originating from non-dipolar or even particular hemispheric sources which prevent an inter-hemispheric correlation.

8.4. Comparison With Models

[28] The declination and inclination records from Laguna Potrok Aike are plotted together with the time-varying spherical harmonic model of the geomagnetic field CALS7k.2 of *Korte and Constable* [2005]. As observed from Figure 10, no good agreement is found between the records of Laguna Potrok Aike and the model, although any of the directional features detected in Figure 10 is reproduced in the CALS7k.2 model. The minimums i1, 13 and i7 and the maximum i2 and the minimums d2 and d3 and the maximums d1 and d4 could roughly be identified in the inclination and declination record, respectively. The output of the CALS7K.2 model compares favorably with the RPI record of Laguna Potrok Aike, similar general trends could be identified. In general, 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 which highlight the importance of these studies.

9. Conclusions

[29] We present a high resolution paleomagnetic secular variation and relative paleointensity stack for the last 16,000 cal. BP recorded in a series of sediment cores from Laguna Potrok Aike based on a previously developed radiocarbon- and tephra-based chronology [*Haberzettl et al.*, 2007]. The most likely carrier of the remanence is PSD magnetite and titano(magnetite). We normalized NRM at 20 mT with the intensity of SIRM at 20 mT in order to construct a relative paleointensity record. The Holocene/Late-Pleistocene PSV records from other Southern Argentinean sites show similarities with Laguna Potrok Aike although some discrepancies in the amplitude and age of the features are obvious. These differences are probably caused by smoothing effects due to different sedimentation rates, different sediment grain sizes, inaccuracies in the various chronologies, as well as different measuring techniques (u-channel versus discrete samples) and/or local non-dipole features. Despite this, the PSV records at these sites, which are located more than 1000 km apart, can be correlated between them and with other PSV records from the same lake. Such reproducibility between holes from the same lake and between lakes validates the quality of the paleomagnetic records and suggests that the PSV and RPI profiles from these new high-resolution and well-dated records from Laguna Potrok Aike could be used as a robust regional correlation tool in Southern South America.

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