New detailed paleosecular variation record at Santa Lucía archaeological site (Corrientes province, northeastern Argentina)

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Resumen

Se reporta información paleomagnética de una sección sedimentaria del sitio arqueológico Santa Lucía, provincia de Corrientes (Nordeste de Argentina). El magnetismo remanente natural obtenido en 74 especimenes orientados mostró una remanencia magnética normal e intermedia con bajos valores negativos y positivos de inclinación durante el Holoceno tardío. La magnetización remanente característica fue determinada por desmagnetización progresiva utilizando campos alternos. Los polos geomagnéticos virtuales muestran algunas coincidencias con los registrados durante el Pleistoceno Terminal y Holoceno en otros sitios del cono sur de Sudamérica. Los polos paleomagnéticos calculados con sitios del nordeste de Argentina se localizan ~3-15° alejados del eje de rotación de la Tierra.

Palabras clave: paleomagnetismo, variaciones paleoseculares, Holoceno, Arqueología, Sudamérica, Argentina.

Abstract

Paleomagnetic data from a sedimentary section from Santa Lucía archaeological site, Corrientes province (Northeastern Argentina) are reported. Natural remanent magnetization obtained from 74 oriented cores showed normal and intermediate magnetic remanence with negative and positive low inclination values during the Late Holocene. Characteristic remanent magnetization was determined by progressive demagnetization using the AF method. Virtual geomagnetic poles show some agreement with those registered during the terminal Pleistocene and Holocene in other sites from the southern cone of South America. Palaeomagnetic poles for other contemporaneous sites from northeastern Argentina fall some ~3–15° away from the Earth's rotation's axis.

Key words: paleomagnetism, paleosecular variations, Holocene, Archaeology, South America, Argentina.

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Introduction

Paleomagnetic research recently performed in several archaeological, paleontological and geological deposits located in the southern cone of South America yielded large paleosecular variation (PSV) logs (especially in inclination) during the terminal Pleistocene and Holocene at ~12-0.1 ka (Sinito *et al*., 1997, Nami 1995, 1999, 2006, 2008, Ré *et al*., 2008). To go deeper in the knowledge of the geomagnetic field (GMF) in this part of the continent, a variety of sections of recent sediments were sampled. This paper reports the results of a detailed palaeomagnetic research performed at the Santa Lucía (SL) archaeological site in Northeastern Corrientes province, Argentine Republic. Additionally, by using regional PSV logs previously reported diverse aspects of paleomagnetic records are discussed.

Santa Lucía (30° 20.52´S, 57° 39.25´W) is located on the Uruguay river shoreline, 5 km south of Monte Caseros village (Fig. 1). It is a well-known place due to the quality and quantity of stone tool finds in the earliest periods of the regional archaeological research (Serrano 1932, 1950). The archaeological finds occur in almost 500 m along the surface of the river shore. Test pits showed that there are archaeological remains until 1.10 m depth (Mujica pers. comm.1997). The sampled profile is 2.90 m thick. Five natural strata can be seen I, II, III, IV and V. Level I is mostly sand and pebbles, II, III and V are black, dark brown and brown clays respectively (Fig. 2). The sediments have abundant fine grain quartz and some calcium carbonate with cubic structure (Smorczewski, 1994). Level IV is a yellowish white layer, likely volcanic ash that near SL in south Brazil was dated at ~10-11 ka BP (Miller, 1987). Therefore, this section belongs to terminal Pleistocene and Holocene, lasting the last ~10-11 ka. Here is significant to point out that nearby SL, the Barranca Pelada site (BPS), showed a similar stratigraphy (Fig. 2b). There, an AMS radiocarbon date from a very small sample of organic sediment obtained at 90 cm depth in level II was dated at 3,160 ± 35 yr B.P. (CURL-5506). This date was made from the humic acid fraction of the sediment, which tends to provide more reliable ages for this kind of materials (Pessenda *et al*., 2001). However, it can be considered as a minimum age because the apparent mean residence time of organic components is a significant factor in soil dating (Scharpenseel 1971, Stein 1992).
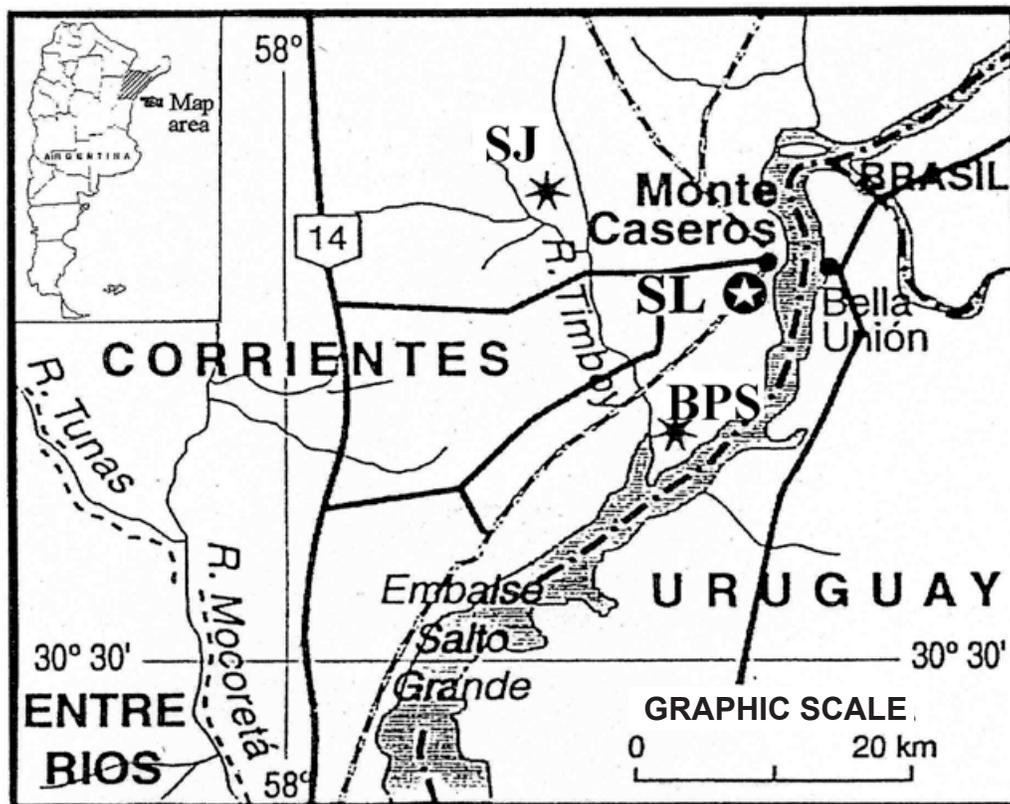
Figure 1. Location of the Santa Lucía (SL), Barranca Pelada (BPS) and San Juan (SJ) sites in southeastern Corrientes Province.

One vertical paleomagnetic sampling (n = 84) was performed to study the GMF directions in the deposit. To collect samples, cylindrical containers 2.5 cm long and 2.5 cm diameter were carefully pushed into levels II (samples SL1 to 31), level III (SL32 to 58), SL 59 to 66 from level IV and 67 to 84 from level V, overlapping each other by about 50 percent. Their strike and dip were measured using a Brunton compass and inclinometer; they were consolidated with sodium silicate after removal and numbered from top to bottom.

Laboratory methods and results

Santa Lucía specimens were processed with progressive alternating field (AF) demagnetization in steps of 3, 6, 9, 12, 15, 20, 25, 30, 40, 60 and 80 mT. Additional steps from 100 to 140 mT were used in some samples (SL1 and SL38, Fig. 3b, e). Samples 14, 34, 40, 44, 47, and 52 were rejected because they loose their orientation. Measurements of the directions and intensity of the natural remanent magnetization (NRM) were done in a DC squid cryogenic magnetomer (2G 755R) and demagnetization was performed with a static three axis AF demagnetizer attached to the magnetometer. In most SL cores, less than 20 percent of the NRM intensity remained at fields of 80 mT (Fig. 3). This behavior suggests titano-magnetite as the dominant carrier of the NRM (Nagata 1961, Stacey and Banerjee 1974, Tarling 1983, Thompson and Oldfield 1986). However, specimens subjected to fields of 140mT suggest hematite or goethite as the principal carrier (Piper 1989). Characteristic remanent magnetization (ChRM) was calculated using principal-components analysis (Kirschvink 1980). Intervals of selected ChRM for each specimen are given Table 1. The samples shown in Figure 3 display similar patterns, going to the origin in the Zijderveld (1967) diagrams (e. g., SL36, 55, 68, 71, 80, Fig. 3d, f-j); thought, some do not converge toward the origin (e.g., SL3, Fig. 3c), in these cases the line have been forced to pass through the origin (anchored line fit, *cf.* Butler, 1992; McElhinny and McFadden, 2001). Maximum angular deviations were generally within low values and most of them ranges between 0° to 5° (n = 48, 64.86%) and 5.1° to 10 (n = 26, 35.14%). Some samples had univectorial behavior (e.g., SL71, Fig. 3i). Other specimens had two magnetic components; some of them had a viscous overprint of the present GMF, removed around 3 to 6 mT (e.g., SL68, SL80, Fig. 3h, j) while other ones showed two vectors, one of them was removed from 30-40 mT (e.g., SL3, SL59, Fig. 3a, g). Samples SL20 and SL38 showed two or three components that could not be well isolated unless remagnetization circle analysis was used (Fig. 3c, e, Fig. 4); both samples were not used in this study. However, it is significant to point out that SL38 carried two

magnetic components in the Zijderveld (1967) diagram (Fig 3e), its stereoplot illustrated in Figure 4a shows that the vector changes from negative to positive inclinations (intermediate or reverse) moving in a great circle. The demagnetization curve depicted in figure 4b displays almost regular decay at 20% of the NRM up to 20 mT, however after a little remagnetization at almost 40% of the NRM remained at field of 140 mT. Many samples showed either high (SL55 and SL80, Fig. 3c, f, j) or low negative inclinations (e.g., SL36, Fig. 3d). A few ones showed westerly (SL55, SL59, Fig. 3f-g) and northwesterly directions (e.g., SL68, SL71 and SL80, Fig. 3h-j). The number and intervals of demagnetization steps used to isolate de ChRM are given in Table 1. As result of this analysis, SL deposit has a normal and intermediate magnetic remanence with negative and positive low
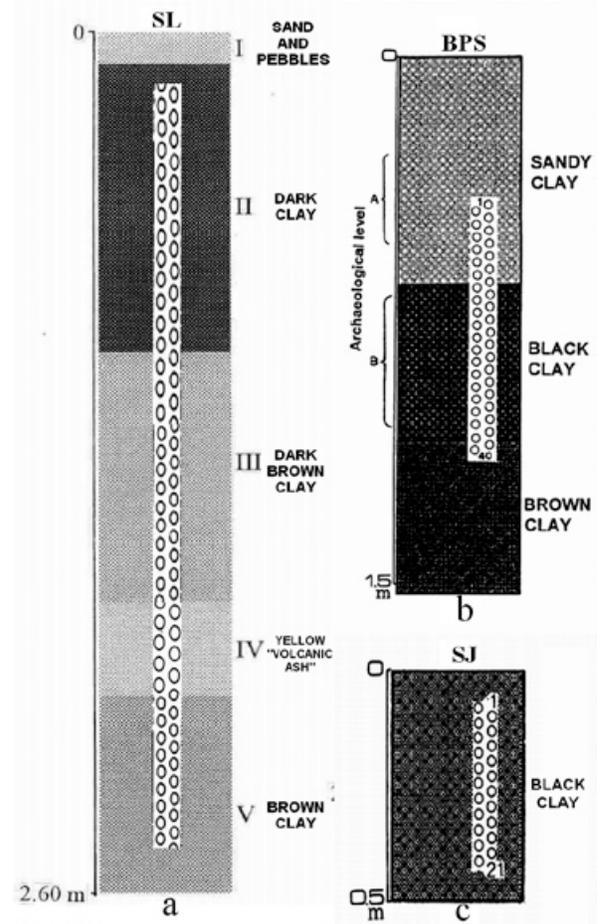
Figure 2. a) Schematic stratigraphic profiles from Corrientes province sites showing the location of the palaeomagnetic sampling related to stratigraphy. Numbers to the right of the sections show numbers of layers and those on the cylinders' top and bottom show the correlative order of the samples. A) Santa Lucía, B) Barranca Pelada, C) San Juan.
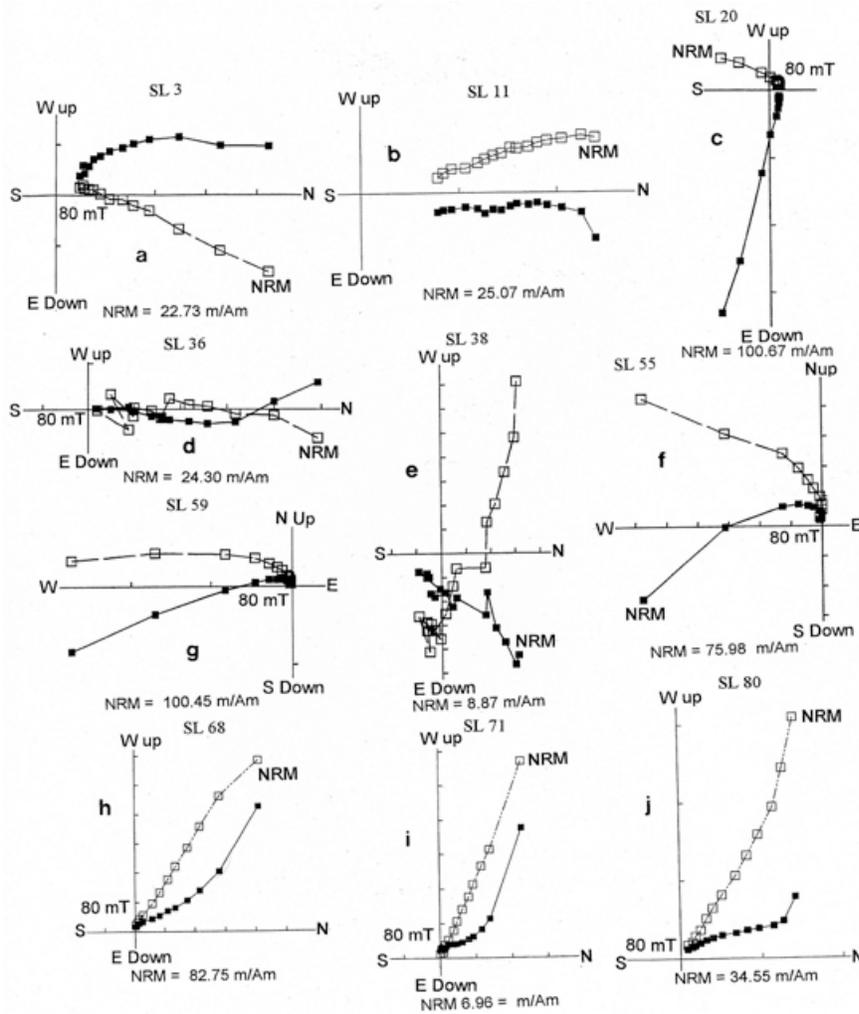
Figure 3. Typical Zijderveld diagrams from the SL section. Solid symbols correspond to the projection onto the horizontal plane, while open symbols are projection onto the vertical plane.
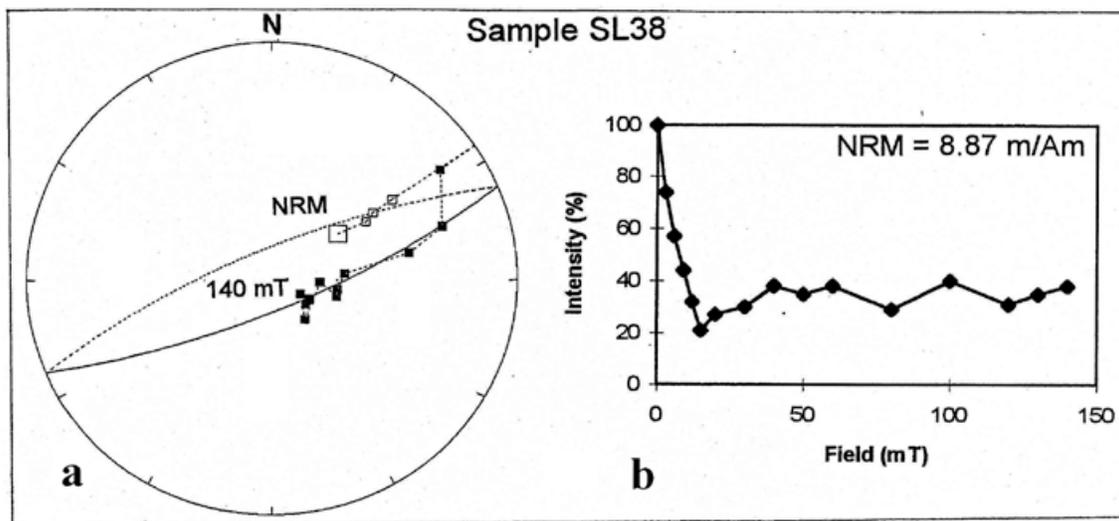
Figure 4. Great circle (a) and curve (b) observed during demagnetization process of SL38 sample.

Table 1. Characteristic remanent magnetization, virtual geomagnetic pole positions, and intervals of each sample. Negatives values show negative inclination or VGP located in the Southern Hemisphere. Intervals of selected ChRM are given in mT. References: D: Declination, I: Inclination, Long.: Longitude, Lat.: Latitude, Int.ChRM: Intervals of selected ChRM, Or.: Origin in the Zijderveld diagram.

Sample	D°	I°	Long. E	Lat.	Int. ChRM	Sample	D°	I°	Long. E	Lat.	Int. ChRM
1	1	-70	121	66	3-Or.	43	1	-5	305	62	20-60
2	333	-67	161	62	0-Or.	45	11	-26	337	71	3-Or.
3	318	-10	237	43	40-Or.	46	357	-43	275	84	12-Or.
4	345	-29	256	70	3-50	48	356	-52	176	86	6-Or.
5	354	9	292	55	3-40	49	346	-46	222	77	9-Or.
6	11	21	319	48	3-60	50	343	-26	255	67	9-Or.
7	20	-13	345	60	6-Or.	51	334	-54	194	68	20-80
8	21	-21	352	63	12-Or.	53	333	-44	216	66	20-Or.
9	3	-16	311	68	12-Or.	54	329	-44	214	63	15-50
10	339	-24	250	64	3-60	55	329	-63	174	62	12-Or.
11	356	-19	291	69	9-140	56	299	-56	188	39	12-40
12	26	-37	17	65	9-Or.	57	232	-75	145	11	20-60
13	353	-27	279	73	6-Or.	58	331	-44	215	64	20-Or.
15	11	-11	328	63	3-Or.	59	288	-45	196	28	12-Or.
16	17	-27	351	68	12-Or.	60	348	-30	262	72	15-Or.
17	7	-24	324	71	9-Or.	61	319	-74	153	50	20-60
18	13	-25	341	69	3-Or.	62	348	-48	216	80	20-Or.
19	10	-10	325	63	15-Or.	63	335	-31	237	64	12-60
21	19	-15	344	61	3-60	65	344	-43	229	75	15-Or.
22	346	-38	244	75	0-Or.	66	327	-56	191	62	9-Or.
23	26	-11	353	55	3-Or.	67	320	-69	164	53	9-Or.
24	349	-5	280	60	9-Or.	68	328	-53	197	63	3-Or.
25	15	-39	5	74	9-Or.	69	323	-56	191	68	3-Or.
26	7	12	314	53	3-Or.	70	337	-63	168	67	3-Or.
27	356	-36	282	79	20-Or.	71	329	-63	174	62	30-Or.
28	3	-22	312	71	9-Or.	72	326	-42	215	59	3-Or.
29	359	8	301	56	2-60	73	327	-60	182	61	6-Or.
30	2	-41	318	83	9-Or.	74	341	-58	179	72	5-80
31	333	-57	187	67	6-Or.	75	355	-51	192	85	6-Or.
32	61	-28	38	32	0-Or.	76	326	-73	152	53	6-Or.
33	342	-19	259	64	2-25	77	345	-36	246	73	3-Or.
35	355	-31	283	76	30-Or.	78	1	-43	313	85	3-Or.
36	6	1	314	59	3-30	79	322	-50	202	57	3-Or.
37	25	-28	5	63	6-Or.	80	343	-60	170	73	3-Or.
39	4	-27	317	74	100-Or.	82	353	-28	278	73	0-40
41	341	-52	199	74	3-Or.	83	333	-48	209	67	0-Or.
42	4	-52	70	86	3-Or.	84	350	-54	183	80	0-15

inclination values. Figures 5a and b illustrates the stereographic projection of ChRM and virtual geomagnetic pole (VGP) calculated from the directions of Table 1. Figure 6 shows changes in the declination and inclination from ChRM isolated for the entire section according to the stratigraphic depth. They clearly show a similar GMF behavior with the most conspicuous long declination and inclination departures depicted between dashed lines and pointed with an arrow. The record of inclination presents a general decreasing trend from -80° at the lower part to 20° at the upper part. The uppermost samples vary widely and there are transitional positions between the swings. An important oscillation in declination, that reaches values of ~40° to the east, is located between SL7 and SL46 samples (level II and top of level III).

Nearby SL, also in the Corrientes province, results obtained at BPS and San Juan (SJ) sites were previously reported (Nami 1999: Figs. 9 and 10b). They also showed unstable records with a similar behavior, suggesting that these variations might reflect the PSV. Figure 7 illustrates the overlapped stratigraphic presentation of each section showing a remarkably match of BPS (samples BPS9 to BPS39) and SJ logs with the
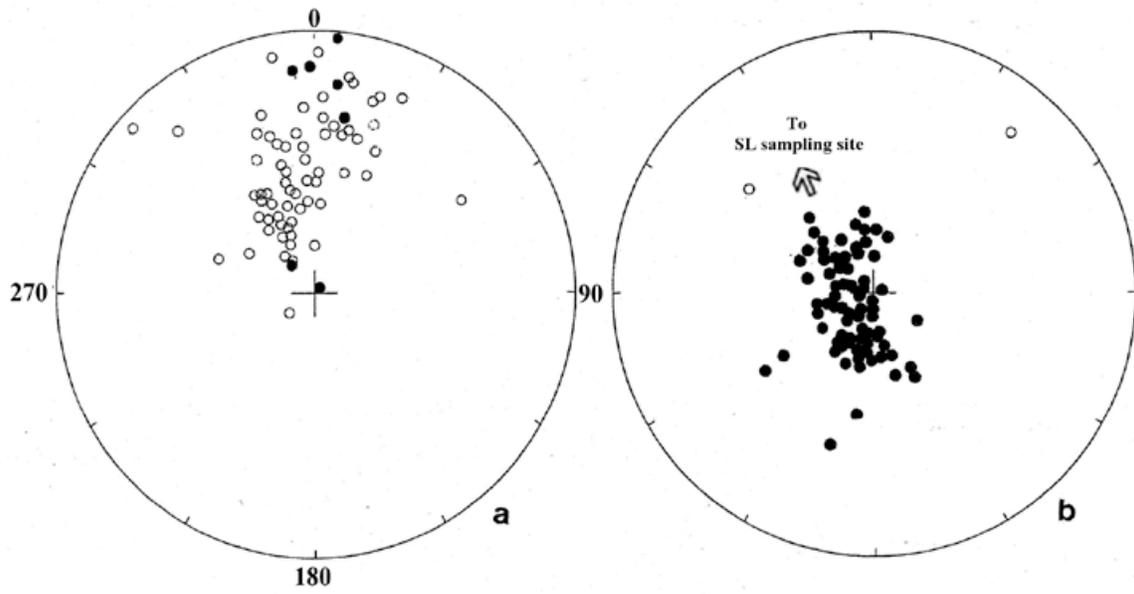
Figure 5. Stereoplots from SL showing: a) directional data (solid and open circles represent positive and negative values, respectively), b) VGPs location. The diagram center corresponds to the Southern hemisphere.
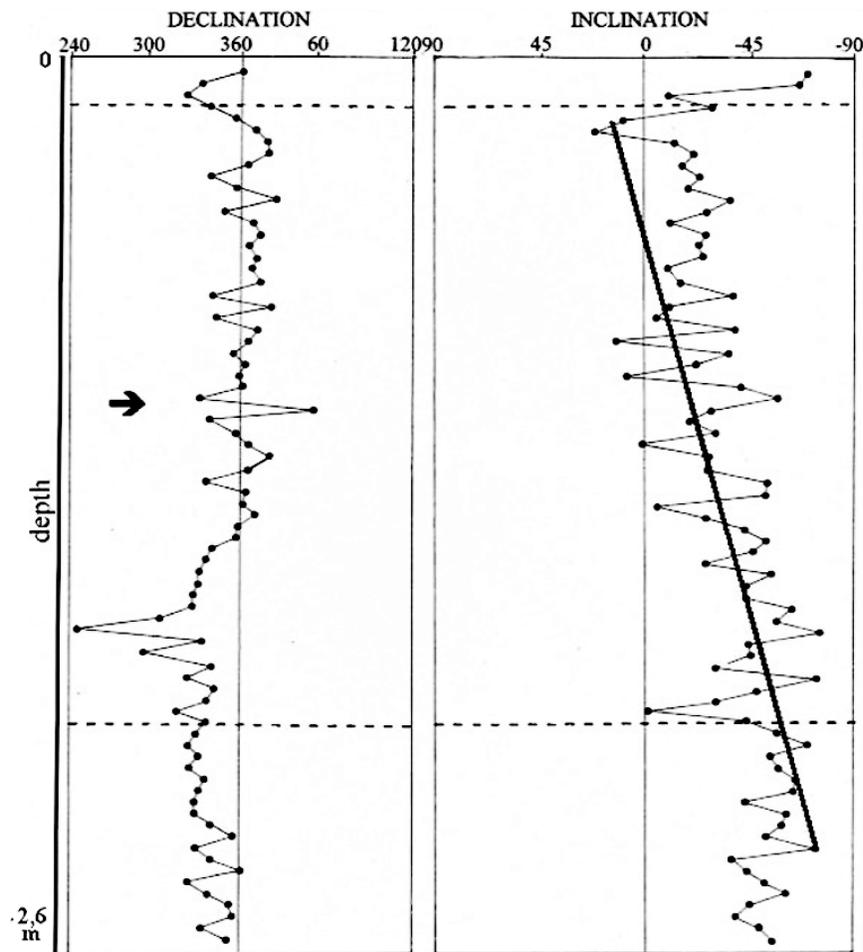
Figure 6. Stratigraphic presentation of the declination and inclination profile from SL. The more conspicuous long direction departures are depicted between dashed lines and pointed with an arrow. The line shows the decreasing trend from ~-80° at the lower part to ~20° at the upper part.
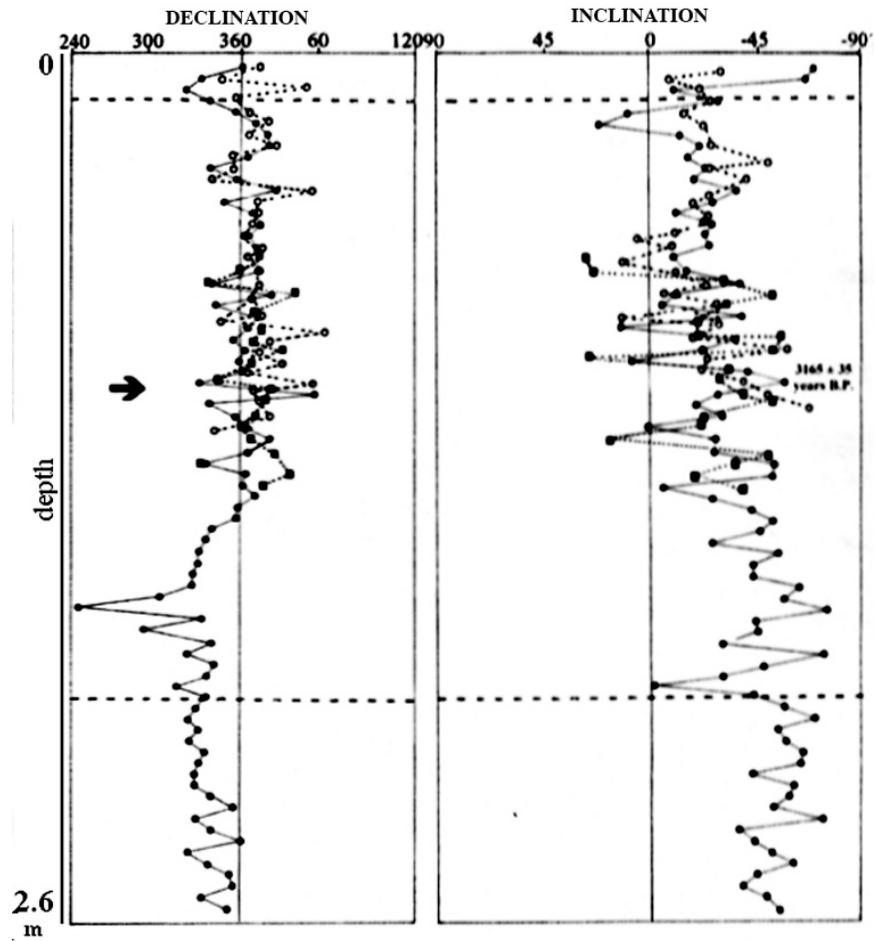
Figure 7. Overlapped stratigraphic presentation of SL, BPS and SJ declination and inclination profiles related with the direct absolute date by 14C obtained at BPS; solid circles and continuous line is SL, open circles and dashed lines illustrates BPS, squares and pointed line represents SJ.

upper and middle part of SL. Hence, it is possible to suggest that BPS might temporally range between ~3.2-0.3 kya and SJ is ~≤3.0 ka (Fig. 7). Furthermore, a smooth curve was constructed with the mean declination and inclination from correlative samples of SL, BPS and SJ sites (Fig. 8). Samples with difference in directions of 45° were not considered in this analysis. The resulting curve was compared with the Lomas del Mirador (LM) log, the nearest place located in eastern Argentina (NE Buenos Aires province) at 803 km southeast of SL. It has an AMS date of 4900 ± 110 yr B.P. (OS–24330). The PSV of LM also recorded low inclination values and easterly directions (Nami 2006). This comparison showed a notably agreement with the upper part of LM curve (Fig. 9). Despite the lost of resolution, the data employed to construct the curve showed in Figure 8 was filtered to eliminate the noise; then, a three-point window was used to define the high frequencies directional changes of the GMF. The results are shown in a log according to depth (Fig. 10). After checking that the directional data from

SL was useful to assess a Fisherian distribution, the site mean direction was computed by Fisher (1953) statistic (Fig. 11). Additionally, a mean direction was calculated using the data from the upper (samples SL1 to SL48 from levels II and III) and the lower part of the section (samples SL 49 to SL 84 from levels III to V), respectively named SLa and SLb (Table 2, Fig. 11). SL mean direction agrees with the IGRF direction (D = -351.5°, I = -32.0°) for 1997, year when the sampling was performed. However, a significant difference is observed with Sla and SLb (Fig 11a). Furthermore, these results were compared with the mean directions calculated for all the previously reported sites located in eastern Argentina (Nami, 1999, 2006). The data belongs from SJ and BPS (Corrientes province), Arroyo Yarará (AY, Misiones province) and LM. As illustrated in Figure 11, BPS, SJ and AY sites shows a similar site mean direction with Sla, and some similarities with the upper part of LM, named LM1a (Table 2).
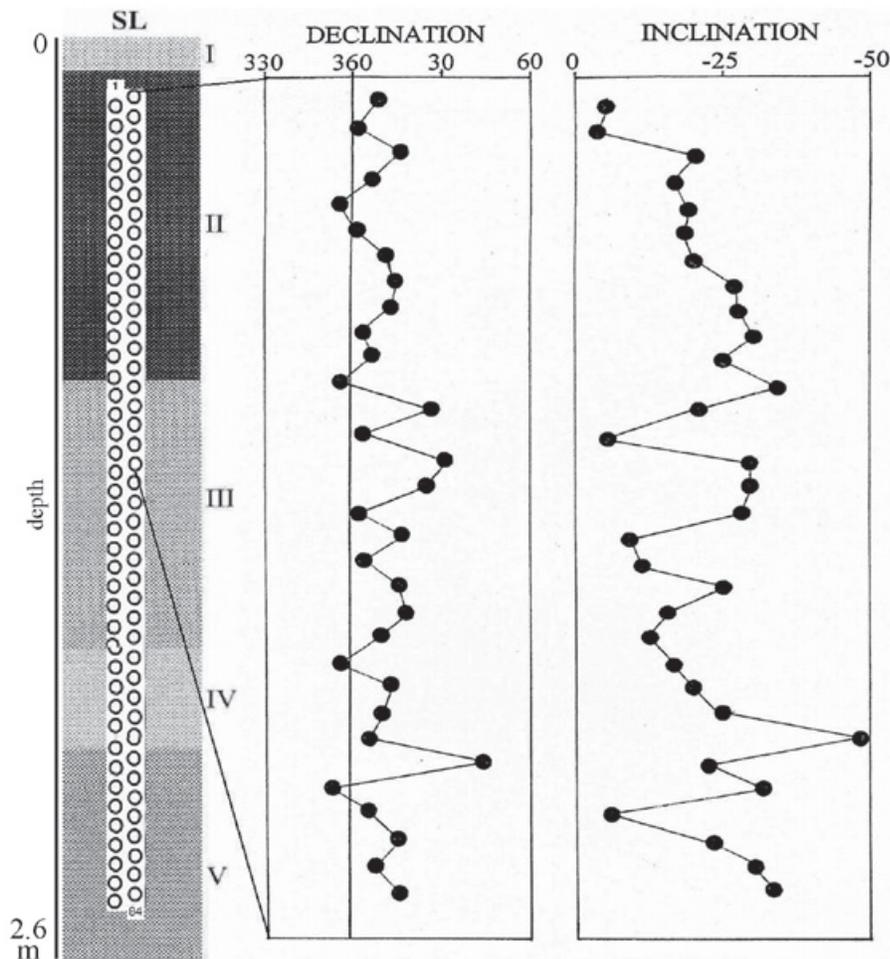
Figure 8. Mean declination and inclination profiles from SL, BPS and SJ related with the SL section and the samples used in this analysis. Samples with 45° a more than difference from the mean were not averaged.

Table 2. Site mean directions of the sites located in Northeastern Argentina. References: RA: relative age, n: number of samples, α95: semi-angle of cone 95% confidence, K: Fisher's precision parameter; R: length of the resultant vector.

Section	Coordinates	RA (ka)	n	D°	I°	k	R	α95
SL	30° 20.52'S, 57° 39.25'W	~ 11- 0.5	74	353.00	-38.63	8.53	64.56	8.5
Sla	Id.	~4-0.5	41	3.17	-25.51	7.40	10.16	9.5
SLb	Id.	~11-4	33	334.30	-52.51	22.52	31.50	5.4
LM1	34°39´S 58°32 W	~ 8/10-0.1	79	7.87	-47.20	9.77	71.02	5.4
LM1a	Id.	~0.1-5	32	351.02	-25.03	10.8	29.12	8.1
LM1b	Id.	~5-8	47	26.63	-58.45	46.85	44.06	3.1
LM2	Id.	~ 8/10-0.1	70	357.7	-48.70	9.78	62.94	5.7
LM2a	Id.	~0.1-5	32	2.69	-27.88	13.07	29.62	7.3
LM2b	Id.	~5-8	38	349.68	-63.93	28.58	36.70	4.4
AY	26° S 55° 21'W	~7-1	14	12.00	-17.84	5.58	11.67	18.5
SJ	30° 57°44'W	~3.2 - 05	21	12.44	-23.09	7.35	18.32	12.6
BPS	30°15'S 57°37'W	~3	34	13.29	-19.26	5.75	28.02	11.3
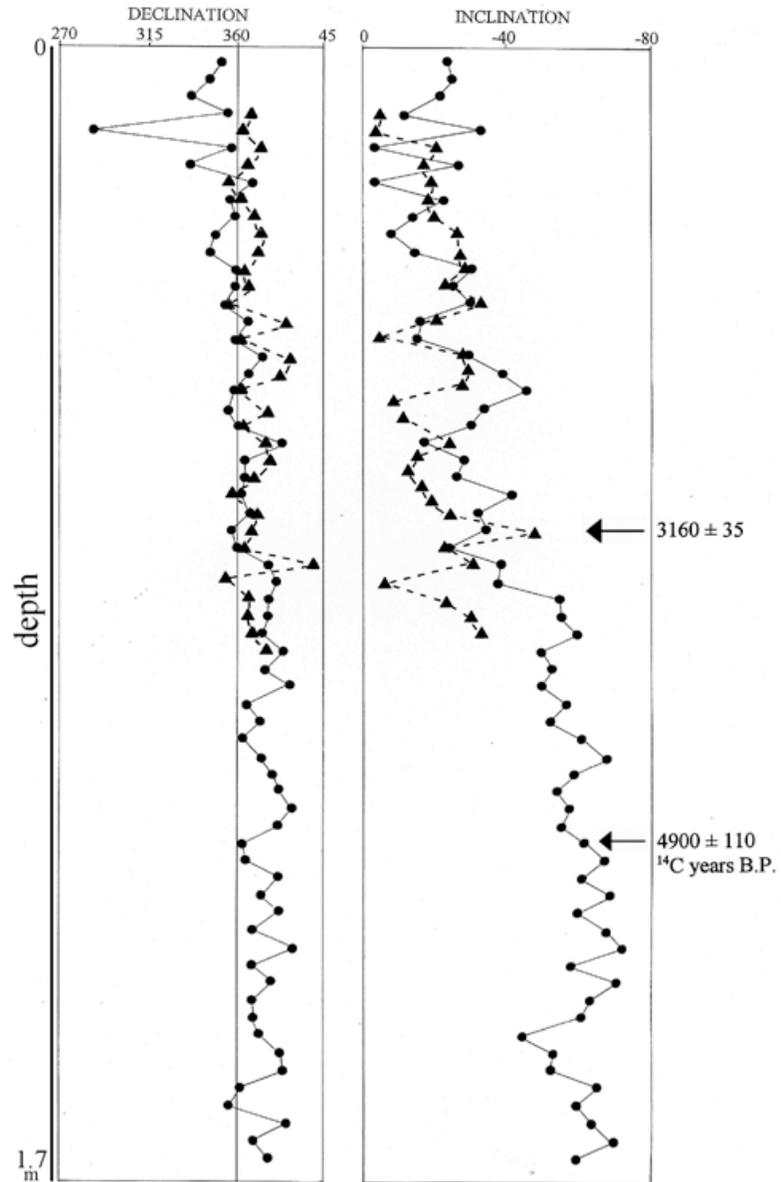
Figure 9. Overlapped presentation of the mean declination and inclination from the sites located in NE Corrientes province (showed in Figure 8) and Lomas del Mirador related with direct absolute dates by 14C. Triangle and dashed lines represents SL, BPS and SJ sites, solid circles and continuous line illustrates LM.

Virtual geomagnetic pole positions were calculated from the declination and inclination data presented in Table 1. When plotted on a present world map, they show intermediate VGPs from the rotation northern latitude axis in the northern Hemisphere between 60° and 30°, and in two patches located in northern North America and Greenland and northern Eurasia (Fig. 12). These positions agree remarkably well with VGPs observed in previous paleomagnetic studies with Latest Pleistocene and Holocene sections from the southern cone of South America (Mena and Nami 2002, Nami 1995, 1999, 2006, 2007, 2008).

Finally, as depicted in Figure 13, the mean geomagnetic poles were computed using all VGPs located within a 40° window around the mean geomagnetic pole (cf. McElhinny *et al*. 1974). The first one was computed using the poles obtained with VGPs from BPS, SJ and SL sites from Corrientes province (CP); the $\alpha95$ of CP include the paleopole determined from the LM site (Fig. 13). It coincides remarkably well with the paleopole called "Mylodon excursion" (ME = 336.7° W. Long, 68.65°S Lat. with [$\alpha95$ 8.2°]) which was calculated using the sites with anomalous directions observed across Argentina and Chile (Nami 1999). Like other poles previously reported they do not agree with the geographical pole and shows ~3-15° difference in relation to the rotation's axis of the Earth (Table 3); as it has previously stated, this fact suggests that a time span of ~10 ka is insufficient to average out geomagnetic secular variations (Mena and Nami 2002, Nami 1999, 2006).
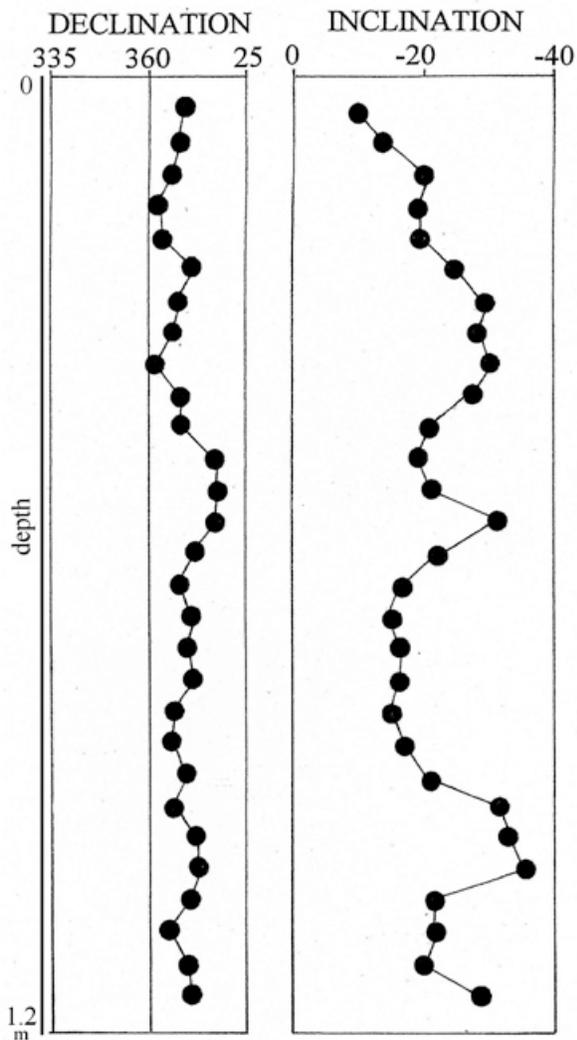
Figure 10. Stratigraphic presentation of the curves obtained with a three-pass window calculated from the mean declination and inclination from the sites illustrated in figure 7.

Table 3. Latest Pleistocene/Holocene geomagnetic poles from Northeastern Argentina, Corrientes province (CP) and Lomas del Mirador (LM) calculated within 40° around the mean; n = number of samples (for LM) and sites (for CP); α95 = semi-angle of cone 95% confidence; K = Fisher's precision parameter, r = resultant vector.

Pole	N (sites)	N (samples)	Long. E (°)	Lat. (°)	α95	R	K
LM	-	137	8.37	83.38	3.5	126.26	12.67
CP	3	-	330.16	75.52	20.7	2.94	36.5

Final remarks

As conclusion of the investigations described above, we have that SL samples recorded normal and intermediate polarity directions far from the present GMF. A ~100° difference in inclination with low values and significant westward shift with fluctuations in declination occurred in the upper (with positive inclination values) and lower parts of the SL section, respectively. However, major swings in inclination are observed between samples SL25 to SL51 and SL48 to SL84. Similar variations were also documented in the paleomagnetic records from NE Argentina. Actually, AY, SJ and BPS sites also registered low and positive inclination values; additionally westerly directions were observed in BPS (Nami, 1999). Nevertheless, LM is the longer comparable detailed record that yielded similar GMF directions with wide amplitude variations
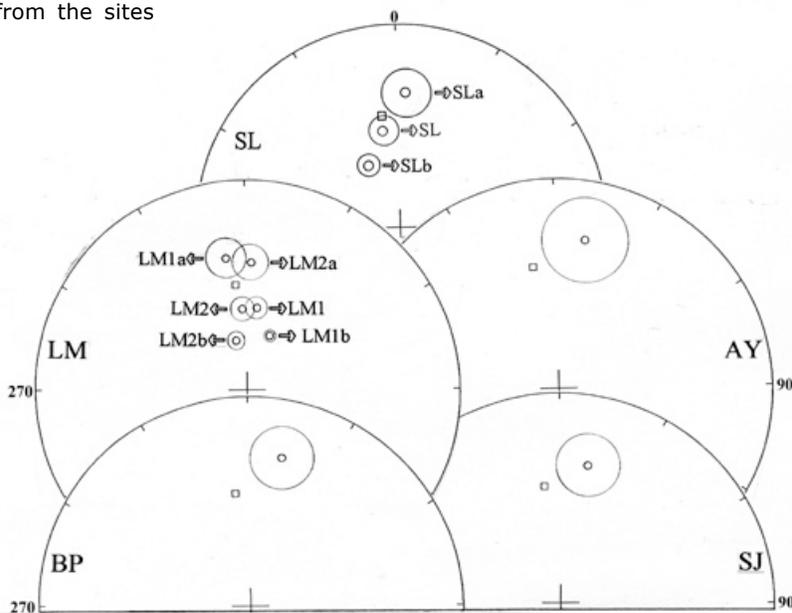
Figure 11. Sites mean magnetization directions for the different sites with normal and intermediate directions from eastern Argentine. The IGRF directions are indicated with squares.
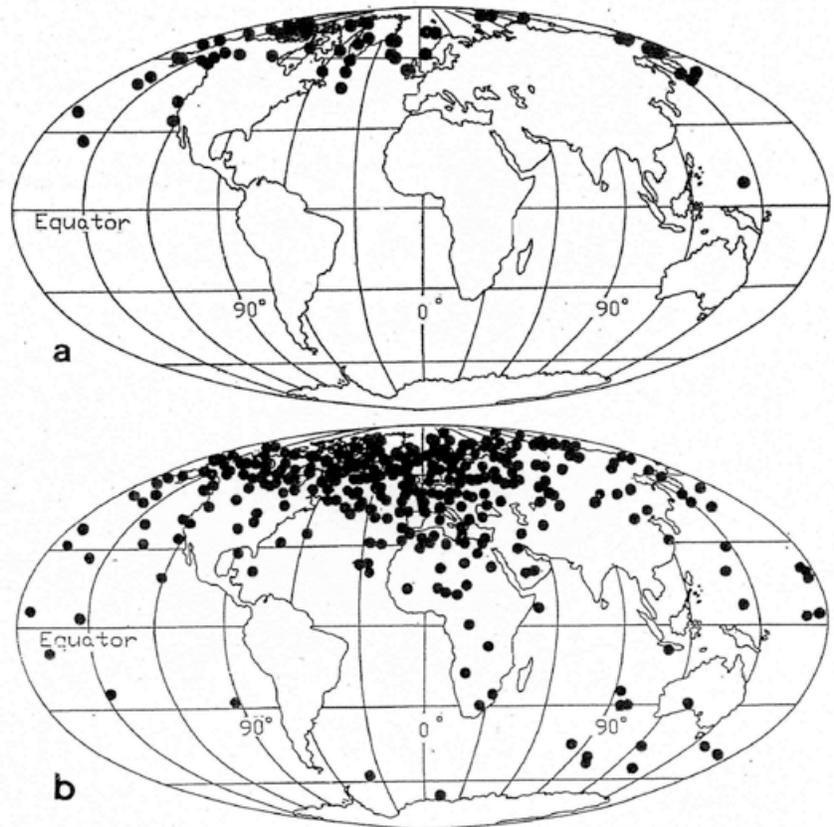
Figure 12. World map shows the location of the VGP obtained using individual samples from SL (a) and the sites with anomalous directions observed during the Latest Pleistocene and Holocene in the southern cone of South America (b).
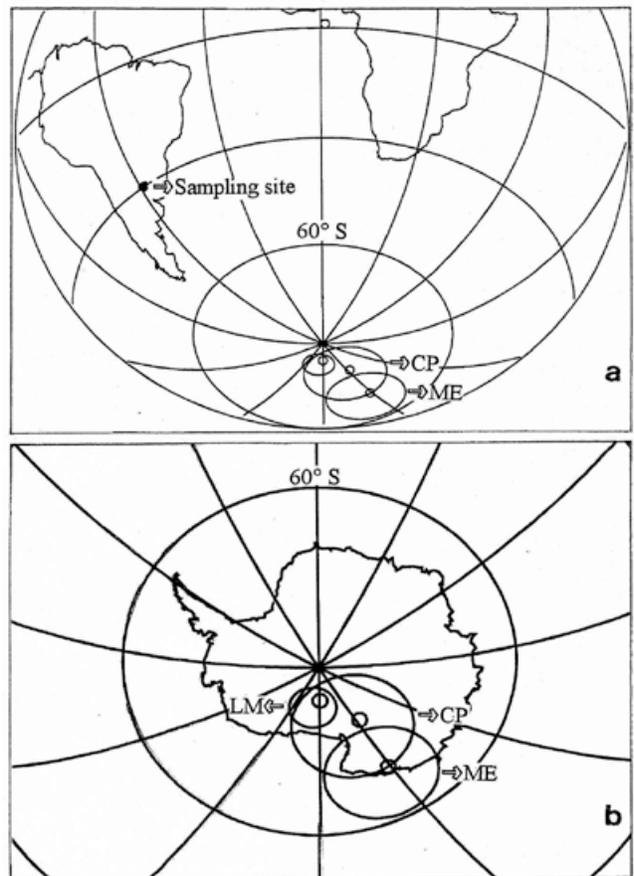
Figure 13. Projection shows the paleo-pole obtained with 40° filter and their confidence interval in relation with the paleo-pole obtained for the other sites from Northeastern Argentina in relation with the sampling site (a) and the Antarctic continent (b).

in declination and a pronounced swing of ~70° in declination recognized at ~5 ka (Fig. 11). Remarkable similarities exist in the decreasing inclination values from ~80° to ≤20/25° in the upper part (Nami 2006). This suggests that the large PSV record observed in northeastern Buenos Aires province has a regional extent confirming the late Holocene age for the low inclination values existing in northeastern and southwestern Argentina (Sinito *et al*., 1997; Gogorza *et al*., 2000; Sinito and Nuñez 1997; Nami 1999; Ré *et al*., 2008).

Acknowledgements

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