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MAGNETIC PROPERTIES OF HOLOCENE EDAPHIZED SILTY EOLIAN SEDIMENTS FROM TIERRA DEL FUEGO (ARGENTINA)

Propiedades magnéticas de sedimentos limosos eólicos edafizados en Tierra del Fuego, (Argentina)

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Abstract: *In this contribution we present preliminary environmental magnetism results from 80 samples collected along an eolian sedimentary sequence with 8 interbedded paleosols. ^{14}C data indicates that the studied record represents the Holocene.The results principally include hysteresis data at room temperature, variation of magnetic susceptibility at two frequencies, and susceptibility at high and low temperatures in selected samples. The results discussed here suggest that the humidity during the formation of the studied paleosols was variable for each one. This means the alternating of wet and dry periods throughout the entire Holocene have been of different intensities. The magnetic results, together with some other properties of the geological record define a high climate variability occurring in the southern extremity of the Americas. A period of higher humidity than the present is suggested by the magnetic parameters during the period represented by the paleosols P7 (471 yrs BP), P5 (5552 yrs BP), P4 (6538 yrs BP) and P2 (age between 7163 and 11308 yrs BP).*

Key words: *Environmental magnetism, paleoclimate, Holocene, eolian sediments, Tierra del Fuego.*

Resumen: *Esta contribución incluye los resultados preliminares del estudio de magnetismo ambiental de 80 niveles muestreados en una secuencia de sedimentos eólicos limosos con 8 paleosuelos intercalados. De acuerdo a las dataciones ^{14}C disponibles la secuencia estudiada contiene registro geológico de todo el Holoceno. Los resultados incluyen principalmente parámetros magnéticos obtenidos en magnetómetro vibrante a temperatura ambiente, susceptibilidad magnética a dos frecuencias y determinaciones de susceptibilidad a altas y bajas temperaturas. Los resultados aquí discutidos, sumados a los de otros proxie climáticos, definen una alta variabilidad climática a estas latitudes de América durante el lapso estudiado. Un periodo de mayor humedad que la actual se insinúa a través de los parámetros magnéticos durante el período representado por cuatro paleosuelos desde el Holoceno medio al tardío; estos son P7 (471 años BP), P5 (5552 años BP), P4 (6538 años BP) y P2 (edad entre 7163 y 11308 años BP).*

Palabras clave: *Magnetismo ambiental, paleoclima, Holoceno, sedimentos eólicos, Tierra del Fuego.*

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This contribution includes preliminary environmental magnetism results from 80 samples collected along an eolian sedimentary sequence with interbedded paleosols. The aim of the study is to determine, on the basis of changes in magnetic mineralogy, the climate changes during the deposition and pedogenesis, taking into account the hypothesis proposed by Orgeira *et al.* (2011a). Briefly, these authors suggest a correlation between water storage and magnetic signal in soils and paleosols developed in loessic sediments. According to them, there are environmental thresholds related with climate variables that affect the *genesis*, preservation or depletion of ferrimagnetic minerals. They present a general quantitative model for the climatic dependence of magnetic enhancement or depletion in loessic soils. The model is based on the widely accepted hypothesis that ultrafine magnetite precipitates during alternating wetting and drying cycles in the soil micropores. The rate at which this occurs depends on the frequency of drying/wetting cycles, and on the average moisture of the soil.

The studied sequence is located in the northern region of Isla de Tierra del Fuego, Argentina (53^0 42'48 .6"S, 68^0 18 '20.3"W), altitude of 71 m above sea level (Fig. 1).

The sequence is formed by a succession of 20 m of eolian silty-fine sand-clay sediments with 8 interbedded paleosol layers (Fig. 2). Radiometric data indicate that the eolian deposition and the edaphic processes started during the Early-middle Holocene (bottom ^{14}C data 9941 ybp) and it was continuous up to the late Holocene (top ^{14}C data 434 ybp) (Coronato *et al.*, 2011a and b) (Table 1, Fig. 2)

The mean annual rainfall in the area is 383 mm and the mean annual temperature is 5.2^0 C (Celsius). The sequence is located in a large area of low atmospheric pressure under the effect of both the westerlies and the Polar Front. Wind blows daily with an average rate of 25 km/h but with frequent periods of higher speeds. The influence of Antarctic air produces short periods of colder and drier climate.

The megadune of Arturo lake is composed of a succession of eolian deposits and paleosols in which a layer of tephra is also interbedded. This sequence is deposited over marine sediments of the Carmen Sylva formation (Codignotto y Malumián, 1981) exposed due to wave action along the southern coast of Arturo lake – a brackish, semi-permanent body of water. Fig. 2 and Table 1 show the thicknesses and physical characteristics of the different strata that make up the sequence. In general terms, the units of eolian deposits are dark brown to olive in color, have thickness of 0.46-1.92m and have high organic matter content (2.97-4.2%), the mean particle size decreases from the base to the top from very fine sand to medium silt in every eolian units. Pedogenetic processes produced dark reddish brown to olive paleosols with actual thicknesses between 0.15m and 0.4m. They have high organic matter content (3.2-5.8%) and the mean particle size decreases from the base to the top from coarse silt to medium-grained silt.

The eolic level 2 and its corresponding paleosol have a larger average grain size, from very fine sand to coarse silt. The pH obtained in the paleosols indicates alkalinity (7.75-8.53), which reflects the salinity of the supply sources of the material, be they the basal marine rocks of the sedimentary sequence or the temporarily dry bed of the lake. The physical characteristics of the more modern paleosols are not too different from those of the present soil. As regards the layer of tephra located in the middle part of the Holocene sequence, its geochemical signature and its relative age allow it to be interpreted as a record of the second Holocene eruption of the Mt. Burney volcano, located 370 km to the northwest.

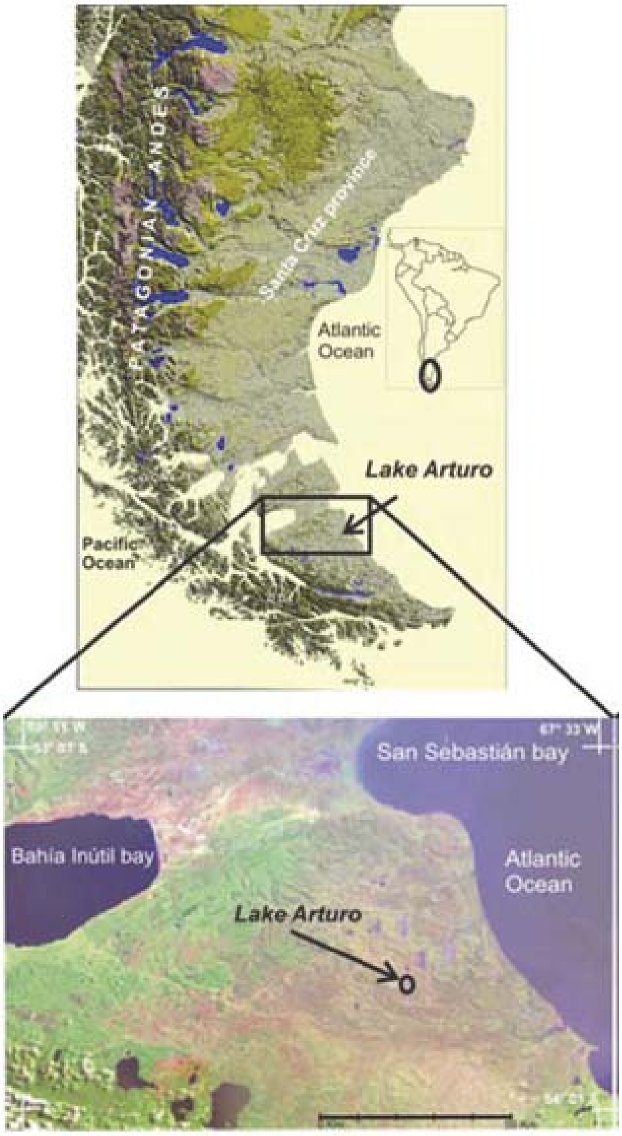
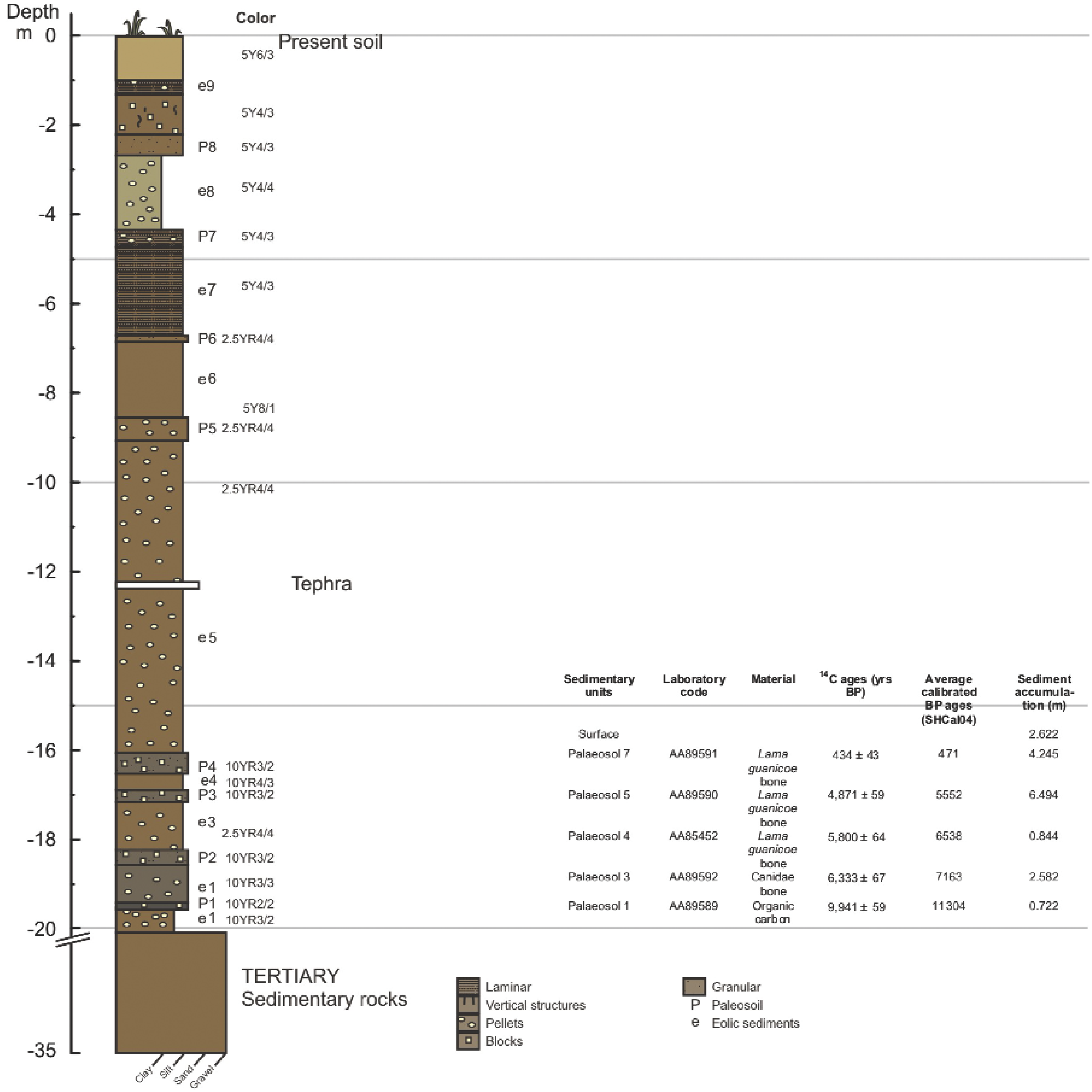


Fig. 1.- Location site, Arturo Lake, Tierra del Fuego, Argentina.

A preliminary analysis of the bio-mineralizations shows the presence of silica phytoliths as part of the mineralogy both in the eolian sediments and in the edaphized layers (Coronato *et al*., 2011b). The larger quantity of silica phytoliths are found in the eolian deposit at the base of the sequence and in its edaphized layer (paleosol 1). In P2 and P3 the concentration falls, while the intermediate eolic layer has a moderate content. Phytoliths are scarce in paleosols P4 to P8 and in their associated eolic layers. The present soil has scarce content of these biomineralizations of plant origin. In general, the majority are morphotypes classifiable as graminaea.



Sedimentary units	Laboratory code	Material	^{14}C ages (yrs BP)	Average calibrated BP ages (SHCal04)	Sediment accumulation (m)
Surface					2.622
Palaeosol 7	AA89591	*Lama guanicoe* bone	434 ± 43	471	4.245
Palaeosol 5	AA89590	*Lama guanicoe* bone	4,871 ± 59	5552	6.494
Palaeosol 4	AA85452	*Lama guanicoe* bone	5,800 ± 64	6538	0.844
Palaeosol 3	AA89592	Canidae bone	6,333 ± 67	7163	2.582
Palaeosol 1	AA89589	Organic carbon	9,941 ± 59	11304	0.722

Fig. 2.- Stratigraphic profile and radiocarbon ages obtained from organic matter and bones deposited into paleosol levels at Arturo lake, Tierra del Fuego, Argentina (53^0 42'48 .6"S, 68^0 18 '20.3"W). Modified from Coronato *et al*., (2011a).

In almost all the stratigraphic sequence volcanic glass can be found, being abundant in the silt and clay fraction, as are amorphous silica remains of size < 5 µm, it is not clear whether they are fragments of phytoliths or altered volcanic glasses.

The radiocarbon ages shown in Table 1 and Fig 2. were obtained from organic matter and bones deposited into paleosol levels. Calibration was performed with SHCal04.14c (McCormarc *et al*., 2004) in conjunction with Calib program (Stuiver and Reimer, 1993) (Coronato *et al*., 2011 a).

Sampling and Laboratory methods

Profile samples were extracted with variable vertical distance in each of the paleosols and one sample was extracted from each soil horizon, such that in the eolic strata the vertical distance widened.

In the laboratory, samples were dried at room temperature and stored in plastic boxes.

The results presented in this contribution include: Hysteretic loops at room temperature measured with a Vibrating Sample Magnetometer (VSM) Molspin. The fraction of ferrimagnetic susceptibility, X_{ferri}, was determined by subtracting from the total susceptibility, X, the susceptibility in high field region, X_{high}; X_{high} was determined with the slope of the hysteresis loop for field values between about 400 mT and 1000 mT. Low (470 Hz) and high (4700 Hz) frequency susceptibilities (X_{LF} and X_{HF}, respectively) were measured with a Bartington MS2 meter. The percentage frequency dependence $X_{FD\%}$ was calculated according to

	Thickness (m)	Color	Organic Matter (%)	pH	Texture (mean particle size in μm)	Average cal BP ages (SHCal04)
Present Soil	1.1	5Y5/3	3.83		Medium silt (17.34)	—
Eolian deposit 9	1.12	5Y4/3	3.72	—	Medium silt (17.12)	—
Paleosol 8	0.39	5Y4/3	4.87	7.75	Medium silt (29.92)	—
Eolian deposit 8	1.72	—	4	—	Medium silt (16.48)	—
Paleosol 7	0.4	—	4.9	8.34	Medium silt (17.64)	471
Eolian deposit 7	1.92	—	3.58	—	Medium silt (16.44)	—
Paleosol 6	0.16	5Y4/3	3.2	8.53	Coarse silt (49.93)	—
Eolian deposit 6	1.75	5Y4/3	,3.02,	—	Medium silt (16.43)	—
Paleosol 5	0.51	2.5Y4/4	3.6	8.48	Medium silt (15.95)	5552
Eolian deposit 5b	3.15	2.5Y4/4	2.97	—	—	—
Tephra layer	0.04	5Y8/1	—	—	—	—
Eolian deposit 5a	3.82	2.5Y4/4	2.97	—	Coarse silt (42.7)	—
Paleosol 4	0.41	10YR3/2	4.19	8.23	Coarse silt (34.22)	6538
Eolian deposit 4	0.43	10YR4/3	3.38	—	Coarse silt (55.31)	—
Paleosol 3	0.15	10YR3/2	3.99	8.23	Coarse silt (40.61)	7163
Eolian deposit 3	1.16	2.5Y4/4	3.41	—	Coarse silt (40)	—
Paleosol 2	0.34	10YR3/2	4.38	8.31	Coarse silt (56.51)	—
Eolian deposit 2	0.91	10YR3/3	3.29	—	Very fine sand (65.23)	—
Paleosol 1	0.28	10YR2/2	5.8	8.18	Medium silt (27.85)	11304
Eolian deposit 1	0.44	10YR4/3	4.2		Coarse silt (40.59)	—

Table 1.- Physical properties of paleosols and underlying eolian deposits from Arturo lake mega dune. ^{14}C Average ages (SHCal04) were performed on *Lama guanicoe* and *Ctenomys sp*. bones in most of the paleosols levels, organic carbon was used only for Paleosol 1 age estimation. Modified from Coronato *et al*., (2011 a).

$X_{FD\%} = 100 \times (X_{LF} - X_{HF}) / X_{LF}$. Measurements of the variation of magnetic susceptibility with temperature in the range of high and low temperatures were done. An AGICO(Advanced Geoscience Instruments CO. Brno, Czech Republic) , model MFK1-FA susceptibilimeter was used. The amplitude of the applied alternating field was 200 A/m, at a frequency of 997 Hz. In the low temperatures the range covered was from -190ºC to 5ºC and in the high temperatures from 30ºC to 700ºC under argon atmosphere. To determine the Curie temperatures, the two-tangents method from Grommé *et al*., (1969) was used; despite the criticisms made by Petrovsky and Kapicka (2006) to this method, in regarding the goals of this work it was considered appropriate to use it.

Results and interpretation of magnetic measurements

Ferromagnetic mineral concentration recorded along the sequence (mass susceptibility between 17 and 7 E-7 m3/kg) is similar to the specific magnetic susceptibility of pampean loess sequences (Orgeira *et al*., 2011b). This fact allows us to compare the magnetic results from both areas to assess the impact of wind speed on the magnetic signal; apparently the magnetic susceptibility does not reflect differences in wind speed in both cited areas.

Fig. 3 shows hysteresis parameters measured in all the samples collected in the profile (M_S, M_{RS} and H_C). The magnetic mineralogy throughout the profile is mainly driven by a low coercitivity fraction, with Hc (coercitivity field) near between 6 and 11 mT.

Values of initial magnetic susceptibility (X), variation of susceptibility with temperature, magnetization of saturation (M_S) and remanent magnetization of saturation (M_{RS}) and coercivity (H_C) for studied samples could indicate that the ferromagnetic mineralogy is dominated by multidomain Ti poor titanomagnetite and /or maghemite.

$X_{FD\%}$ is lower than 5% in all the samples, indicating that the population of superparamagnetic (SP) grains with a diameter in the range between 27 nm and 30 nm is negligible (Eyre, 1997), although anomalous ratios X_{ferri}/M_S (Lascu *et al*., 2010) have been detected in the present soil and in one paleosol (P3, Fig. 3).

In the same figure (Fig. 3.) a marked correlation is also observed between the signatures of Hc and the ratio X_{ferri}/M_S. It should be noted that these increasing peaks are found in the paleosols P3, P5, P8 and present soil. This association would indicate a relative increase of the population of ultrafine ferromagnetic particles with diameter lower than 27 nm, therefore not detected by the variation of susceptibility with frequency. On the other hand, an increment in the SD particle population toward minor grain size, in the range with diameters between 200 nm to 50 nm, can produce an increase in H_C (Williams, Muxworthy and Paterson, 2006). Both phenomena could be associated with the pedogenetic processes.

The results obtained from the variations of magnetic susceptibility with temperature were grouped according to the behavior of the studied samples.

Fig 4. shows the variations of the susceptibility with temperature corresponding to the samples: A1, A4, A7,

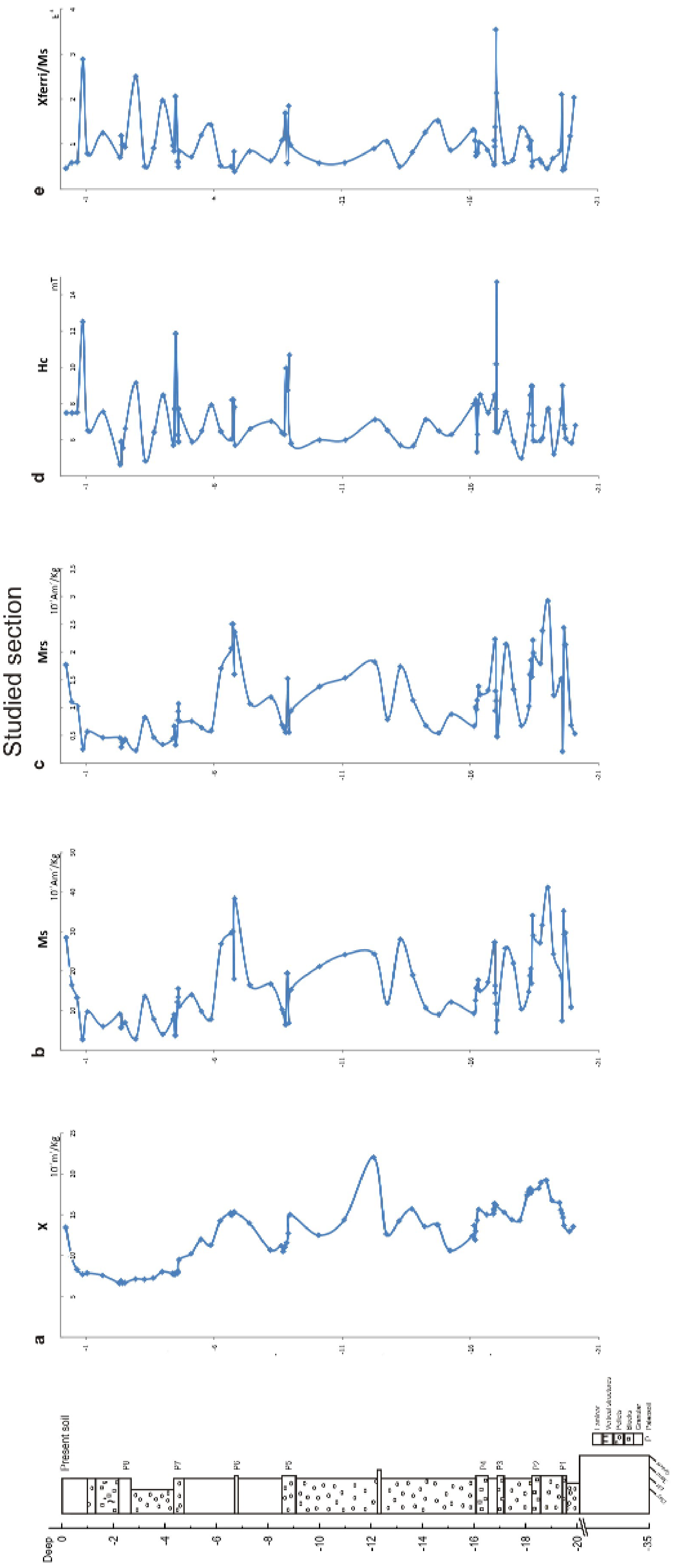


Fig. 3.- Hysteresis parameters measured in all the samples collected in the profile (Ms saturation magnetization, Mrs saturation remanent magnetization and Hc coercivity).

A10, A13, A17, A24, A32, A66 and A70. The location of the samples in the studied profile is the following: A1 (e1), A4 (P1), A7 (e2), A10 (P2), A13 (e3), A17 (e4), A24 (e5), A32 (e6), A66 (P4) and A70 (P3). In these samples, the slight increase in the susceptibility between 250º C and 400 ºC could be associated to generation of new ferrimagnetic minerals. On the other hand, a Curie temperature of approximately 580ºC is correlated with the presence of magnetite; this fact is confirmed by the presence of a wide Verwey transition in the low temperature curves compatible with multidomain (MD) maghematized magnetite (Fig. 5) (Liu *et al*., 2010).

In Fig. 6 the variations in susceptibility with temperature for the samples A37, A44, A48, A59 and A63 are presented. The location of the samples in the studied profile is the following: A37 (e7), A44 (e8), A48 (P8), A59 (P7) and A63 (P5).These show Hopkinson peaks (Dunlop and Ozdemir, 1997) close to 580ºC, which are indicative of single domain (SD) particles. Given that the low temperature curves (Fig. 5) show that A1, A4, A7, A17 and A37 exhibit

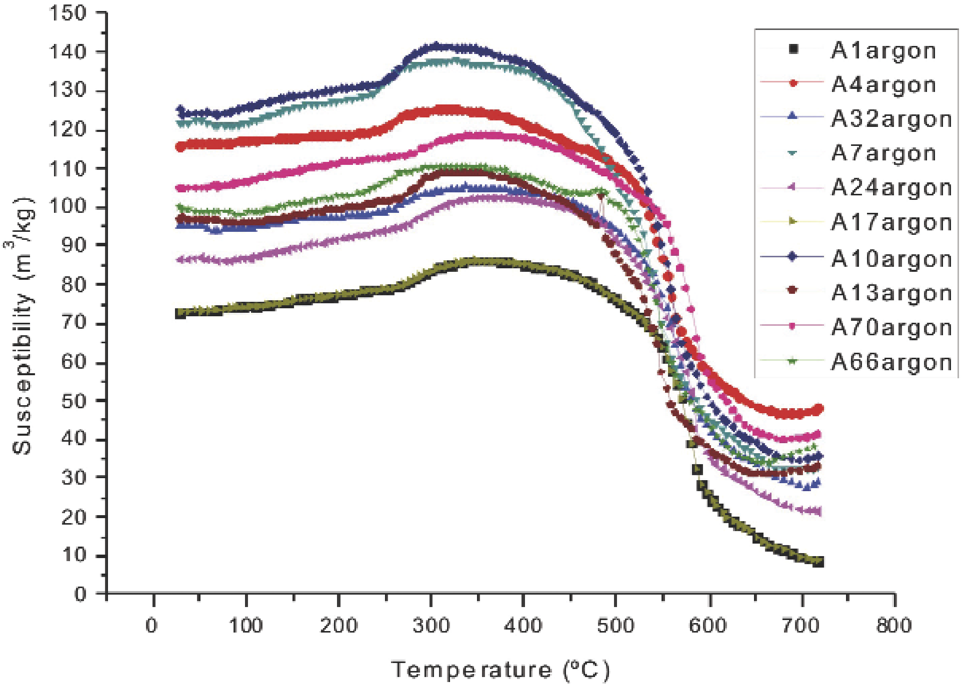


Fig. 4.- High temperature variation of susceptibility carried out in argon atmosphere for A1, A4, A7, A10, A13, A17, A24, A32, A66 and A70 samples. See location of the samples in the text. Susceptibility (x 10^{-6} m^3/Kg).

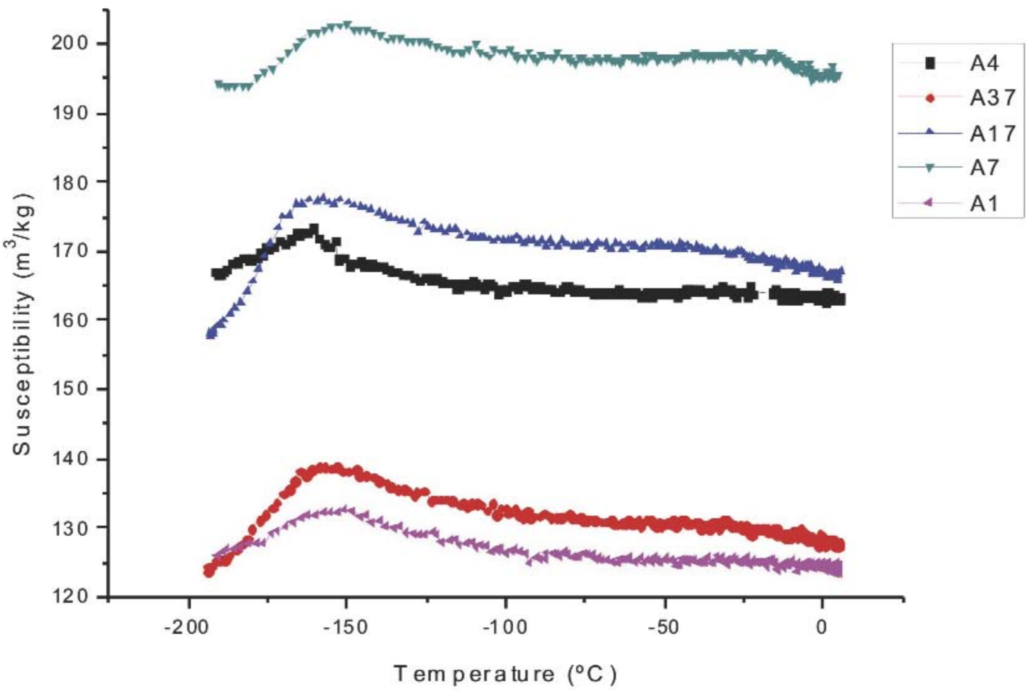


Fig. 5.- High temperature variation of susceptibility carried out in argon atmosphere for A1, A4, A7, A17 and A37 samples. . See location of the samples in the text. . Susceptibility (x 10^{-6} m^3/Kg).

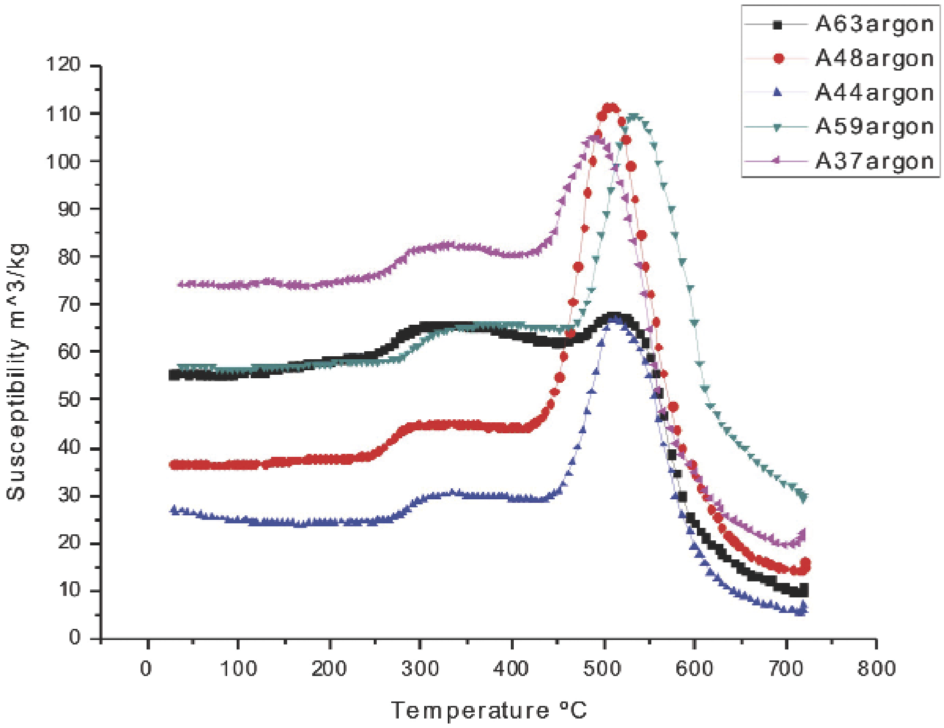


Fig. 6.- High temperature variation of susceptibility carried out in argon atmosphere for A37, A44, A48, A59 and A63 samples. See location of the samples in the text. . Susceptibility (x 10^{-6} m^3/Kg).

an wide Verwey transition, this may suggest a mixture of maghematized MD magnetite and SD magnetite for these samples.

Variations in magnetic parameters along the studied profile suggest that the concentration of ferrimagnetic minerals differs from one paleosol to another (Fig. 7 to 10).

The magnetic parameters obtained from the samples extracted from the paleosols allow their grouping according to their magnetic behavior.

In Fig. 7 the variations of the hysteresis parameters from the samples extracted from the present soil, P6 and P1 are shown. The lower samples in each figure were taken from loessic horizons and consequently correspond to the values of the parent material. In the mentioned figure a moderate increase in the extensive parameters (X, M_S y M_{RS}) can be observed. This increase is associated in P1 and P6 with and increase in the coercitvity H_C; likewise, in the present soil, the higher ratio X_{ferri}/M_S (Lascu *et al.*, 2010) could indicate a higher concentration of SP particles with grain sizes lower than 27 nm, which they cannot be detected by differences of susceptibility measure at two frequencies (470 Hz and 4700 Hz) (Eyre, 1997).

These increases in all hysteresis magnetic parameters can be attributed to the generation via pedogenesis of fine and ultra-fine magnetic particles (SP-SD) and/or a differential concentration of clay size grains in the eluvial horizons.

Another kind of behavior in the magnetic parameters is shown in Fig. 8. This corresponds to the samples extracted from P7, P5, P4 and P2. In these samples a decrease of the extensive magnetic parameters (X, Ms, Mrs) can be seen, associated with an increase in the coercivity Hc. This can be interpreted as a loss of detritic magnetic minerals during pedogenesis, associated with a relative decrease of the particle size through differential concentrations of finer particles in the edaphized eluvial horizons. These paleosols, in accordance with the hypothesis proposed by Orgeira *et al*., (2011a), must have a greater water storage since the redox conditions favored the weathering of the detritic magnetic fraction. The presence of silica (volcanic glass) could have contributed to such a loss (Orgeira *et al*., 2011a).

In paleosol 8 (P8, Fig. 9) a moderate increase toward the top of the profile, is observed in the in the values of M_S and M_{RS}. In the same profile, can be see a decrease in H_C toward the top, which it could be associated with a slight increase in particle size in the grain size distribution, possibly due to the higher concentration of the greater magnetic particles in the top of the profile. However, the shape of the curve of X with minor variations does not maintain a consistent correlation with the other extensive magnetic parameters. This is a consequence of minimal variations in the concentration of the ferrimagnetic minerals, perhaps through eluviation of magnetic particles from the horizons above.

In Fig. 10, P3, a contrast between the behaviors of the concentration parameters can be seen. The H_C values have an increasing peak in one level (-17 m), while near this level, the M_S and M_{RS} values have a decreasing peak. It could be due to concentration of finest magnetic particles fraction in this horizon, related with eluvial pedogenetic processes. X slightly increases which may reflect the presence of a SP fraction, which would be justified by the high X_{ferri}/M_S ratio; the suggested SP particles are not reflected in susceptibility at two frequencies.

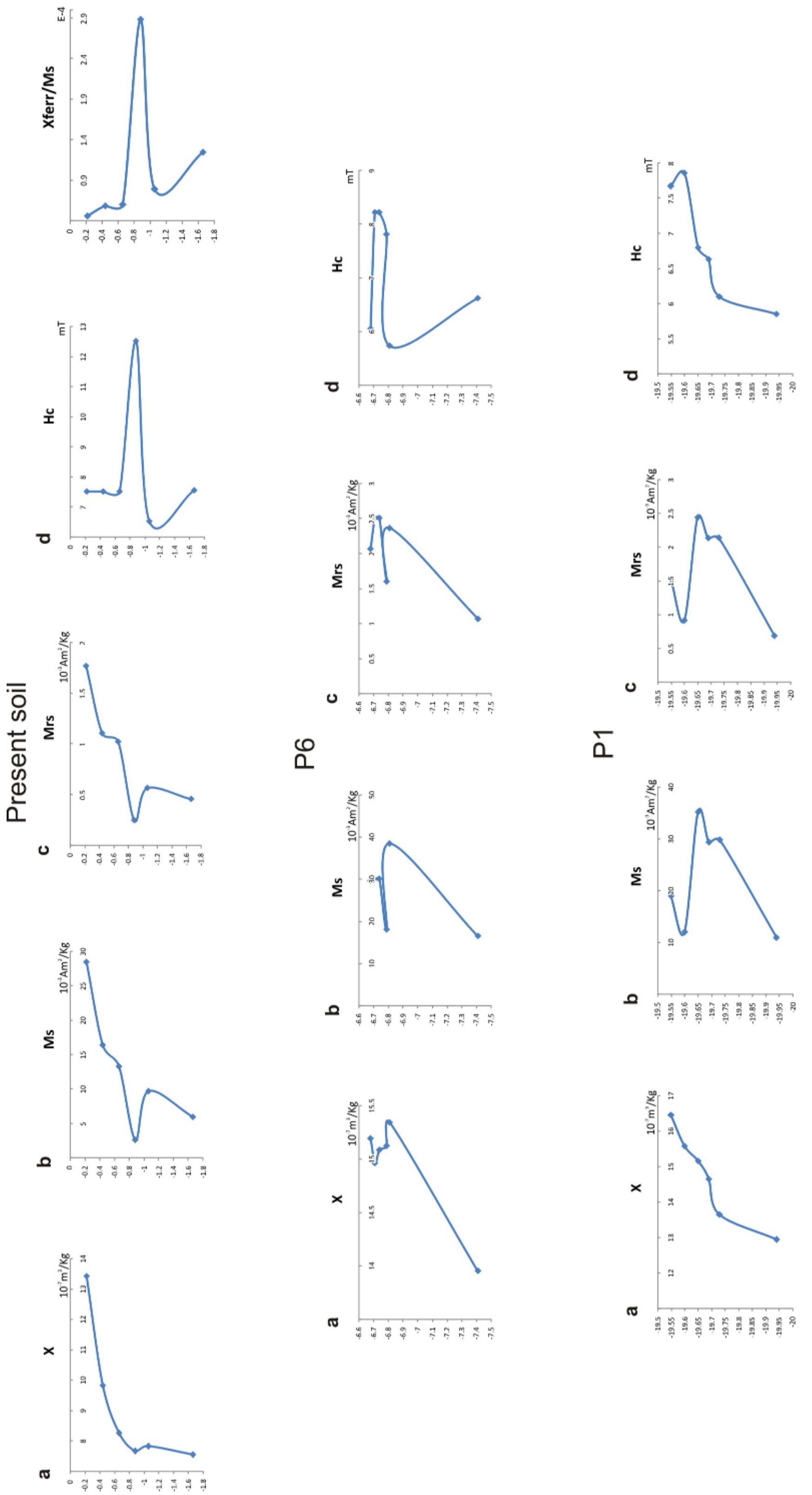


Fig. 7.- Variations of the hysteresis parameters from the samples extracted from the present soil, P6 and P1.

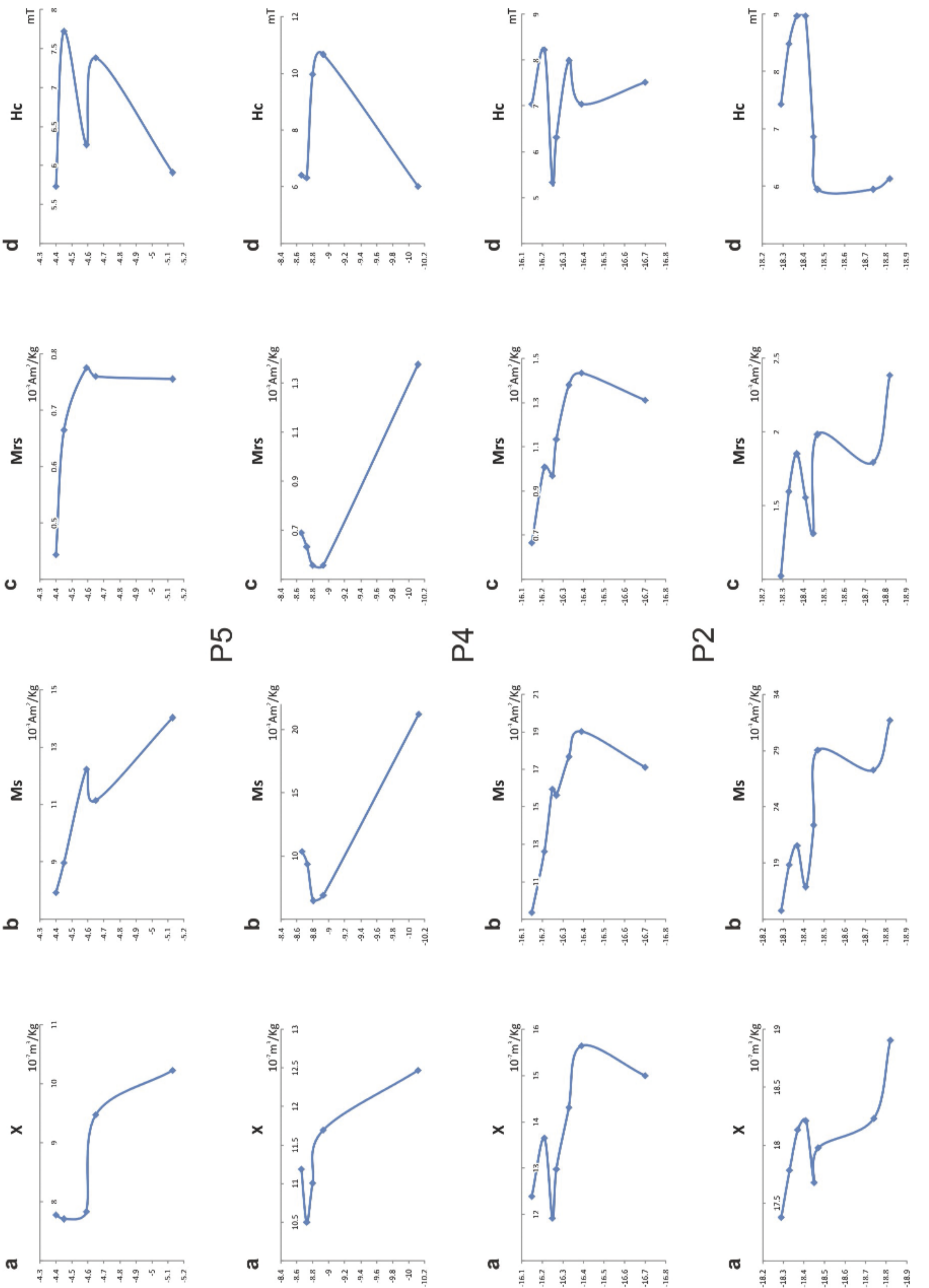


Fig. 8.- Variations of the hysteresis parameters from the samples extracted from P2, P4, P5 and P7.

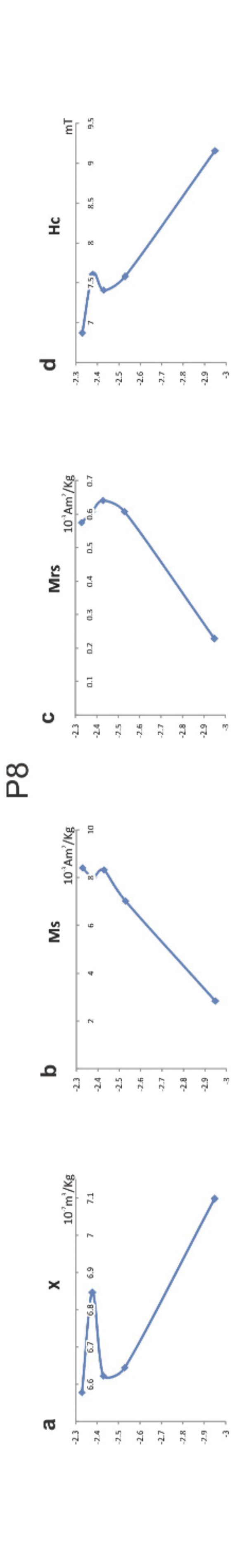


Fig. 9.- Variations of the hysteresis parameters from the samples extracted from P8

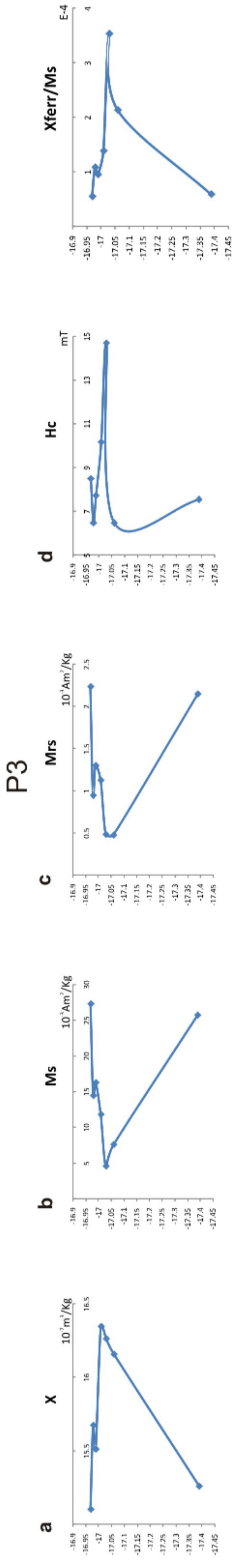


Fig. 10.- Variations of the hysteresis parameters from the samples extracted from P3

Later studies will allow precise interpretations of the magnetic results so far obtained in these two paleosols (P3 and P8). At the present time it is not appropriate to speculate on paleoenvironmental interpretations of these paleosoil using environmental magnetism.

Discussion

The sedimentary sequence of Laguno Arturo provides evidence that in the north of Tierra del Fuego the environmental conditions were variable throughout the Holocene. Arid conditions promoted deflation and eolic accumulation of sediments that were later affected by pedogenesis during wetter periods. These cycles were repeated from ca. 11ky BP until the present reaching a maximum rate of accumulation during the middle Holocene (Coronato *et al*., 2011 b). Given the latitudinal position of the sequence the occurrence of strong thermal changes in the atmosphere capable of triggering physical-biological type pedogenetic processes would not be expected. Rather, the spatial variability that the pressure centres of the southern South America had and the dynamics of their interaction could have caused notable differences in the supply of atmospheric humidity in the region and consequently a change in the values of precipitation. An increase of 100 mm with respect to the present precipitation value (350 mm per year) would put the region in a category close to subhumid, and consequently the action of the wind would be seen to be restricted.

The variations in extensive parameters, such as, magnetic susceptibility, Ms and Mrs along the studied profile suggest that the concentration of ferrimagnetic mineral differs from one paleosol to another.

Taking into account the hypothesis proposed by Orgeira *et al.* (2011a) the obtained magnetic results suggest that the moisture in the different studied paleosols was different during their formation.

The magnetic parameters seem to suggest periods of higher water storage, related with more humid climatic condition, than at present in the paleosols represented by P7, P5, P4 and P2 from the studied profile. In these levels loss of magnetic minerals, mainly by reductive processes, could occurred during the pedogenesis. This implies necessarily higher precipitation in the area during formation of these soils. In contrast, in the present soil, P1 and P6, not only is the preservation of detritic magnetic particles recorded but also an increase in these particles is seen. Consequently the water storage was similar in all of these paleosols and the precipitation would be similar in the time periods they represent.

Greater values of precipitation would have offered a greater availability of water in the region, assured the permanence of water in the lagoons and reduced the availability of source areas of eolian material. The similarity between the physical conditions of the present soil with the paleosols developed since the mid-Holocene to present allows us to establish alternating wet and dry throughout the entire Holocene, with different climate characterizations. The present conditions were established progressively since the mid-Holocene, following the period in which the thickest sediments were deposited, between 6.5ky and 5.5ky BP.

Conclusions

The magnetic results suggest that the humidity during the formation of the studied paleosols was variable for each one. This means the alternating of wet and dry periods throughout the entire Holocene have been of different intensities.

The magnetic results, together with some other properties of the geological record define a high climate variability occurring in the southern extremity of the Americas.

A period of higher humidity than the present is suggested by the magnetic parameters during the period represented by the paleosols P7 (471 yrs BP), P5 (5552 yrs BP), P4 (6538 yrs BP) and P2 (age between 7163 and 11308 yrs BP).

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