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Rock magnetism in modern soils, Buenos Aires Province, Argentina

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ABSTRACT

The influence of climate on the magnetic signal has been investigated assuming it is a first order factor in soil formation. In order to assess the degree of variability of the magnetic signal under different drainage conditions, Mollisols from the Pampean region developed on Pampean loess at varying topographical positions were studied. The sampled sites were located south and north of Buenos Aires in Verónica and Zárate, Pampa Ondulada. The magnetic signal is opposite in the two areas. The generation of superparamagnetic particles (SP) seems to be higher in Zárate. The loss of detrital magnetite could be higher in the less drained soils, in agreement with the hypothesis of loss of detrital magnetite by reductive process. As a simplified interpretation, it is suggested that the differential soil humidity in the studied soils could explain their different magnetic signal. The degree of drainage seems to be the variable that conditions the process of reduction loss.

1. Introduction

Rock magnetism has been applied to loess-palaeosol sequences from many localities throughout the world in order to analyze Late Cenozoic climate variations (Banerjee and Hunt, 1993; Han et al., 1996; Hunt et al., 1995; Bloemendal and Liu, 2005, among others). Only a few publications have been devoted to modern soils (Dearing et al., 1996; Maher, 1998; Jordanova and Jordanova, 1999; Torrent et al., 2006, among others). In this contribution, two modern soil types from the Pampean plain (Buenos Aires Province, Argentina) were studied using rock magnetism and pedological techniques.

Analysis of processes occurring in recent soil formation can be used to understand ancient soil formation. Futhermore, paleosols can be interpreted as a record of past climatic change. Climate, relief, parent material, vegetation and time are factors that influence the soil formation.

The relief is one of the main constraining factors that conditions the characteristics of the forming soils because it influences the soil drainage. Under similar climate conditions and parent material, different types of soils will develop if the relief is different. Physiochemical changes and/or neo-formation of ferromagnetic minerals in the soil could also be affected by the relief.

This contribution tries to determine the influence of climate on the magnetic signal assuming that it is a very important factor in soil formation.

The aim of this study is to determine the degree of variability of the magnetic signal at different geomorphological positions. Modern soils from a restricted area (which are developed on similar parent material, Pampean loess), coming from different geomorphological zones, are studied.

Additionally, it is important to consider other aspects that could modulate the general climatic conditions of a site, such as mineralogy, granulometry, intensity of illuviation, local drainage, among others. These factors define different soil microenvironments, which must be taken into account as first order variables, together with climate.

2. Hypothetical model of the changes in magnetic minerals during edaphic processes

All the processes that may change the magnetic signal in the soils are correlated to the weathering of magnetic minerals. Hydration, hydrolysis and dissolution during humid periods can be subsequently followed by either reduction or oxidation. Reductive loss as well as oxidation may be stressed in acid environments as a result of the magnetite instability in such environments (Buol et al., 1991; McBride, 1994; Faure, 1998). During pedogenesis, humic acids may have supplied the required acidity for such dissolution.

The iron released from the magnetic minerals and the iron coming from other minerals that were altered during the pedogenic processes form amorphous complexes with clays or organic

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material. These complexes could migrate or crystallize as different iron minerals depending on the prevailing environmental conditions.

If a reductive environment changes slowly into an oxidating environment, in neutral pH conditions, a Fe^{2+}/Fe^{3+} complex can crystallize as superparamagnetic magnetite, (SP) (Maher, 1998). The input of dissolved oxygen causes rapid oxidation of Fe^{2+} and precipitation of ferric hydroxides if the pH value is higher than 6. Fe^{2+} persists for a few minutes in oxygenated solutions of pH 7 or higher (McBride, 1994).

SP particles can be also generated in soils by the actions of anaerobic bacteria. This is a biological process, and the permanence of the SP mineral will depend on the environmental conditions (Lovley et al., 1987, among others).

If the amorphous Fe complexes were subject to highly oxidant environments, e.g. a climate with warm and distinct dry periods, in well-drained areas, a high coercivity iron oxide, such as hematite, could be formed. Consequently, the presence of a SP magnetite fraction could be an indicator of climatic conditions with periods of increased rainfall and a drier season. The presence of hematite indicates a seasonal and more extreme warm–dry climate.

The pH value is an environmental property that could change fast in soils as it is in dynamic equilibrium, closely correlated with rainfall, nature and changes of the water table and type of parent material.

In any case, successive cycles of formation and depletion of minerals could lead to a net balance of magnetic minerals. This balance can be negative or positive according to the environmental and climatic conditions of each locality.

3. Sampling area

Sampled soils are located in a loessic plain, characterized by a smooth topography. Well-drained soils (R3 and SZ) are located in the upper sectors of the watersheds, while poorly drained soils (R2 and AP) are located in depressions. The loessic plain is dissected by several small fluvial courses, tributaries of the Plate-Paraná river, and it is known as Pampa Ondulada. In the four soils under study, parent material consists of reddish-yellow sandy–silty loess of late Pleistocene age named Buenos Aires Formation. Granulometric data show that Verónica loess is more clayey than Zárate loess. These soils have a typical Pampean grassland plant association.

Both sampled sites are located in Buenos Aires Province, south and north of Buenos Aires City, respectively (Fig. 1). Soils from Verónica (R3 and R2) are located in the southeastern part of Pampa Ondulada (Undulating Pampa) (35°17.5′S–57°38.8′W) in the transition zone to the neighboring Pampa Deprimida (Depressed Pampa) geomorphic unit. Soils from the other sampled site are from the Zárate area (SZ and AP) (34°10′S–59°3′W) situated in the central part of Pampa Ondulada.

Well-drained soils are strongly developed into thick well differentiated horizons. In general, the Zárate soil is texturally coarser than the Verónica soils. High organic matter values are found in superficial horizons of both areas, though they occur slightly higher in the Verónica R3 soil than in the Zárate soil (2.68% and 1.21% C respectively, Table 1). In both soils, A horizons are more than 30 cm thick, have a dark-brown color (10YR3/1) and a strong medium blocky angular structure. The A horizon of R3 is silty loam, whereas the A horizon of SZ is a sandy loam, both defined as mollic horizons.

Bt (argillic) horizons are formed below the mollic horizons. The strong medium prismatic structures grade to weak prismatic structures downwards. In both cases, Bt horizons are more than 50 cm thick and have a brown color (7.5YR3/2). In soil R3, the Bt horizon is clayey and the SZ soil consists of silty-clayey loam. They have abundant clay skins and slicken sides, indicating expanded clay content and vertic properties (Tables 1 and 2).

The Bt horizons are followed by BC transition horizons and, between 100 and 120 cm depth, a C horizon with silty loam (R3) or sandy loam (SZ) is exposed. The loam has a 7.5YR7/6 Munsell soil color.

The above mentioned features allow us to classify these two soils as Argiudolls. The main ongoing pedogenetic processes are melanization and argilluviation. The formation of mollic superficial horizons needs less time to be formed than the argillic horizon.

According to Birkeland (1999), periods between 1 and 10 ka are necessary for Bt formation, which implies the presence of an endopercolative regime and seasonal water excess to make argilluviation possible. The present pH values are slightly acid for A horizons, becoming alkaline for the rest of the soil profiles. They are more basic in the case of Zárate SZ soil, possibly due to a higher content of $CaCO_3$. The Verónica R3 soil has lower C.E.C. (cation exchange capacity) and in both cases divalent cations predominate in the cation exchange complex (Ca and Mg).

In both poorly drained soils (R2 and AP) superficial horizons fulfill all requirements for mollic diagnostic epipedons, even if they are less dark, weakly structured and thinner than in the above mentioned typic Argiudolls.

Below the A horizons, illuvial Bt horizons with a high concentration of exchangeable Na are found. Accordingly, pH is high (such as 9.2 and 8.8), and these horizons fulfill the requirements for natric horizons. The base of A horizons gives evidence for hydromorphic conditions such as mottles and concretions pointing to the presence of at least a seasonal aquic regime. Consequently R2 and AP soils can be classified as typic Natracuolls. In all the four soils, the cation exchange complex is totally saturated in accordance with a neutral to alkaline environment. Though both poorly drained soils (R2 and AP) have well developed profiles, the degree of development is not as high as in the case of well-drained soils.

Semi-quantitative clay mineralogical results by X-ray diffractometry were also carried out selecting three horizons in all sampled soils (A, Bt and C). The results are presented in Table 3. The Verónica soils are more clayey than the Zárate ones. In all cases illite dominates with values ranging between 45% and 70%, with higher figures for A horizons. Less illite in the Bt and BC horizons shows the importance of the argilluviation process and the presence of an ongoing clay formation process in these soils. Probably part of the smectite found in Bt and BC horizons has this origin. Illites are inherited from loess parent material. Smectites are present in all profiles as secondary clay in Bt horizons. In general, soils from Verónica have more smectites possibly owing to a more recent clay formation. Interstratified clays, usually illite–smectite types, are frequent in all profiles, also pointing to an ongoing transformation process. Finally, kaolinites have an amount of less than 10%, with the highest amount in the AP soil of Zarate. In these cases, kaolinites probably are inherited too. Impurities are quartz and potassium-feldspars. Illites have a good cristallinity; smectites and interstratified clays do not have a good cristallinity. Clay characteristics, their amounts and distribution in profiles, are coherent with the existence of humid climates (around 1000 mm total annual precipitation) for longer periods, as evidenced by neutral to alkaline soil environments.

4. Magnetic results

The measurement of the hysteresis parameters was performed with a vibrating sample magnetometer (VSM) MicroMag (Princeton Measurements Corporation). The room temperature measurements of susceptibility were carried out with a Bartington susceptibilimeter at two frequencies (470 and 4700 Hz).

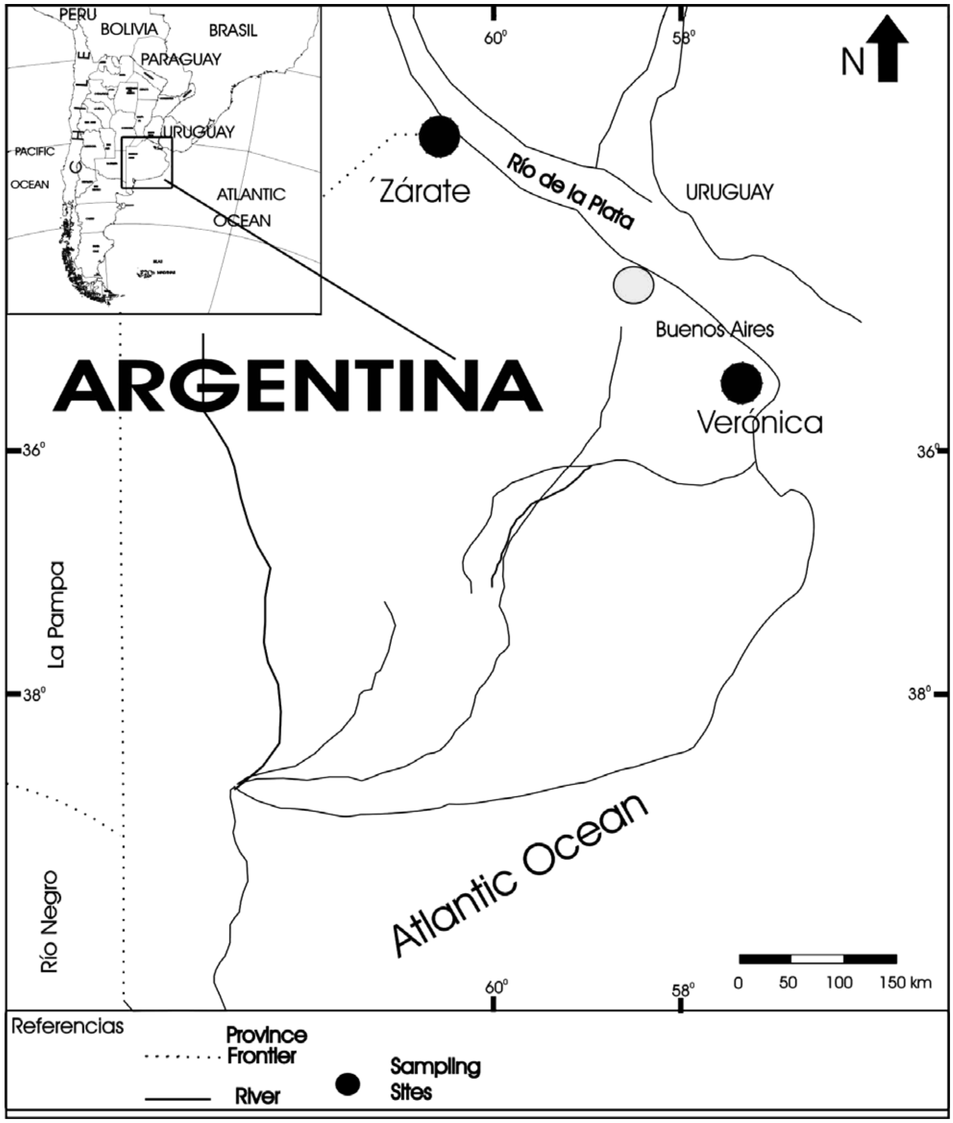

Fig. 1. Location map.

Table 1
Soil analysis of four soils in Zárate and Verónica areas, Buenos Aires

Verónica samples	Clay (%)	Silt (%)	Sand (%)	C (%)	C.E.C. (Cmol/Kg)	pH	Cond. (dS/m)	Ca (Cmol/kg)	Mg (Cmol/kg)	Na (Cmol/kg)	K (Cmol/kg)
R2A1	26.25	65	8.75	2.18	23.5	6	0.31	15.5	3.56	0.65	1.88
R2A2	30.00	62.5	7.5	1.27	25.5	7.35	0.33	17	3.89	0.84	1.79
R2Bt1	37.5	53.75	8.75	0.47	21.1	8.79	1.2	16	3.33	3.68	0.79
R2Bt2	60	37.5	2.5	0.29	22.1	8.74	1.35	16.8	3.41	3.5	2.01
R2BC	52.5	43.75	3.75	0.6	28.1	8.86	0.68	24.67	4.65	4.98	0.9
R3A1	23.75	56.25	20.	2.68	25.5	5.78	0.66	15.6	2.74	0.34	2.12
R3A2	42.50	48.75	8.75	1.66	24.6	6.22	0.59	18.9	3.03	0.47	1.88
R3Bt	65.0	27.5	7.5	0.52	21	7.17	0.37	14.77	3.11	0.59	1.45
R3BC	30.0	57.50	12.5	0.35	23.7	6.76	1.01	15.34	2.65	0.5	1.0

Zárate samples	Clay (%)	Silt (%)	Sand (%)	C (%)	pH	Cond. (dS/m)	Ca (Cmol/kg)	Mg (Cmol/kg)	Na (Cmol/kg)	K (Cmol/kg)
AP A	15	37.5	25	0.88	8.5	0.75	15.5	2.41	2.89	2.11
AP BA	37.5	50	35	0.47	9.21	0.89	16.88	2.5	3.56	2.13
AP Bt	20	55	25	0.34	9.2	0.74	11.88	2.15	3.41	2.12
AP BC	32.5	37.50	30	0.32	9.11	0.46	34.63	2.12	4.89	2.41
AP C	32.5	36.25	31.25	0.28	8.95	0.39	38.25	1.89	1.88	2.22
SZ A	30	40	30	1.21	6.85	0.38	23.06	1.62	0.24	2.51
SZ AB	31.25	46.25	22.50	0.92	7.13	0.45	21.18	1.45	0.20	2.34
SZ Bt1	37.5	47.50	15	0.43	7.46	0.74	20.62	1.36	0.24	1.88
SZ Bt2	20	58.75	21.25	0.35	8.31	0.56	33.43	1.41	2.49	1.64
SZ BC	20	55	25	0.30	8.43	0.54	36.44	2.12	0.87	1.52

Table 2
Soil structure and color of horizons of four soils in Zárate and Verónica areas, Buenos Aires

	Structure	Color
Verónica samples		
R2A1	AB–M–M	10YR5/3
R2A2	AB–M–W	10YR6/2
R2Bt1	P–M–M	10YR4/2
R2Bt2	P–M–W	7.5YR4/2
R2BC	AB–M–W	7.5YR5/4
R3A1	AB–M–S	10YR3/1
R3A2	AB–M–M	10YR2/1
R3Bt	P–M–S	7.5YR3/2
R3BC	AB–L–W	7.5YR7/6
Zárate samples		
AP A	AB–M–S	10YR4/2
AP BA	SB–M–M	10YR5/3
AP Bt	P–M–S	7.5YR3/2
AP BC	P–M–W	7.5YR5/4
AP C	SB–L–W	7.5YR6/4
SZ A	AB–M–S	10YR3/2
SZ AB	AB–M–M	10YR4/2
SZ Bt1	P–M–S	7.5YR3/2
SZ Bt2	P–M–M	7.5YR3/2
SZ BC	AB–L–W	7.5YR6/4

Structure, in order, type, class and grade. AB, angular blocky; SB, subangular blocky; P, prismatic; L, large; M, medium; W, weak; S, strong; M, moderate.

Table 3
Mineralogy of clay fraction by XR diffractometry in selected horizons of Zárate and Verónica areas, Buenos Aires in % of total amount of material

	Smectite	Interstratified	Illite	Kaolinite	Others
R2 A2	15	5	65	10	Q–F–CL
R2 Bt2	35	5	55	5	Q–F
R2 BC	40	10	45	5	Q–F
R3 A1	10	20	70	Tr	Q–F
R3 Bt	40	10	45	5	Q–F
R3 BC	25	10	55	10	Q–F
AP A	5	20	60	15	Q–F
AP Bt	5	20	65	10	Q–F
AP C	25	15	60	Tr	Ca–Q–F
SZ A1	10	25	65	Tr	Q–F
SZ Bt	30	10	50	10	Q–F
SZ BC	30	20	45	5	Q–F

Q, quartz; F, feldspar; Cl, chlorite; Ca, calcite; Tr, content less than 5%.

The obtained values: magnetic susceptibility (X), Factor ((susceptibility Lf − susceptibility Hf)/susceptibility Lf), paramagnetic susceptibility, magnetization of saturation (Ms), remanent magnetization of saturation (Mrs), coercivity (Hc) and coercivity of the remanence (Hcr), for each sample are presented in relation to the different depths in Fig. 2.

4.1. Verónica (R2 and R3 profiles)

The values of coercivity (Hc and Hcr) recorded along the profiles show that the main magnetic mineral is magnetite and/or titanomagnetite (Fig. 2).

The first outcoming feature of the magnetic behavior of these soils is the decaying of the magnetic susceptibility signal (X) to the top of the profile, which is related to the decreasing of Ms and Mrs, having Hc and Hcr relatively invariant. This is interpreted as a decreasing amount of the ferromagnetic minerals. Consequently, a loss of detrital magnetite, as was suggested for paleosols from the same region (Orgeira et al., 1998, 2003), is found as the main process taking place in these soils.

However, the processes involved do not seem to be exactly the same. In the best well-drained soil of this area (R3), the loss process seems to be more intense in the Bt horizon, with a decrease of 40% of X.

The magnetic data suggests a higher loss of detrital magnetite in the R2 soil, characterized by a relatively poor drainage (X falls up to 70%); besides, higher depletion appears closer to the surface in comparison with the R3 soil. The poor drainage plus the higher amount of clay would be the origin of a more intense reductive loss in this soil (McBride, 1994).

Coercivity values show a slight increment at the top of the profile (A2 and AB (note: there is not an AB horizon in the R2 Veronica soil) horizons). This increase could represent a record of genesis of some high coercivity minerals during an oxidative following step in the process of iron minerals evolution.

4.2. Zárate (SZ and AP profiles)

The values of coercivity (Hc and Hcr) (Fig. 2) recorded along the profiles show that the main magnetic mineral is magnetite and/or titanomagnetite.

The behavior of the magnetic signal at this locality is opposite to the one described for the Verónica section.

The increase in the extensive magnetic parameters, such as the magnetic susceptibility, becomes more conspicuous at the most poorly drained profile (AP, BA and Bt horizons). At the best drained site (SZ), the increase grows progressively towards the top.

It must be noted that differences in X values recorded at low and high frequencies are negligible, so that only Lf values are represented (Fig. 2).

The increasing trend of X values at the AP section is in agreement with the variations of the magnetization of saturation (Ms) and remanent magnetization of saturation (Mrs). These magnetic data suggest an increase of ferromagnetic particles, particularly within the illuvial horizon. The correlation of magnetic susceptibility, X, with other extensive parameters, Ms and Mrs is not so clear in the SZ section (Fig. 2).

4.3. Low temperature measurements

Two sets of experiments were done in order to analyze changes in susceptibility as well as in magnetization with temperature. They were used as indicators of SP concentration and grain size, and MD (or PSD) magnetite presence.

In the first set, the susceptibility was measured as temperature changed from 20 K to 300 K, and at the same time the frequency was varied from 400 Hz to 4000 Hz. In Fig. 3, the variation of the percentage of difference in susceptibility at 400 Hz and 4000 Hz with temperature is shown. The curves have a peak near 80 K. The blocking volume V_B at this temperature and frequency (Jackson et al., 1990, among others) is near 20 nm.

In the second set of experiments, the magnetization at different temperatures was measured while heating and cooling in a 2.5 T magnetic field. The complete cycle was:

(i) Cooling from 300 K to 10 K in a 2.5 T magnetic field without measurement.
(ii) Measuring while warming in zero field.
(iii) Cooling from 300 K to 10 K with no field and no measuring. At 10 K, applying a 2.5 T pulse and measuring magnetization in zero field decays while warming to 300 K.
(iv) A 2.5 T pulse at room temperature and measurement while cooling in zero field until 10 K.
(v) Measuring of magnetization while warming from 10 K to 300 K with no pulse being applied and in zero field.

The relative concentration of SP particles was calculated following the substraction method proposed by Hunt et al. (1995). Higher

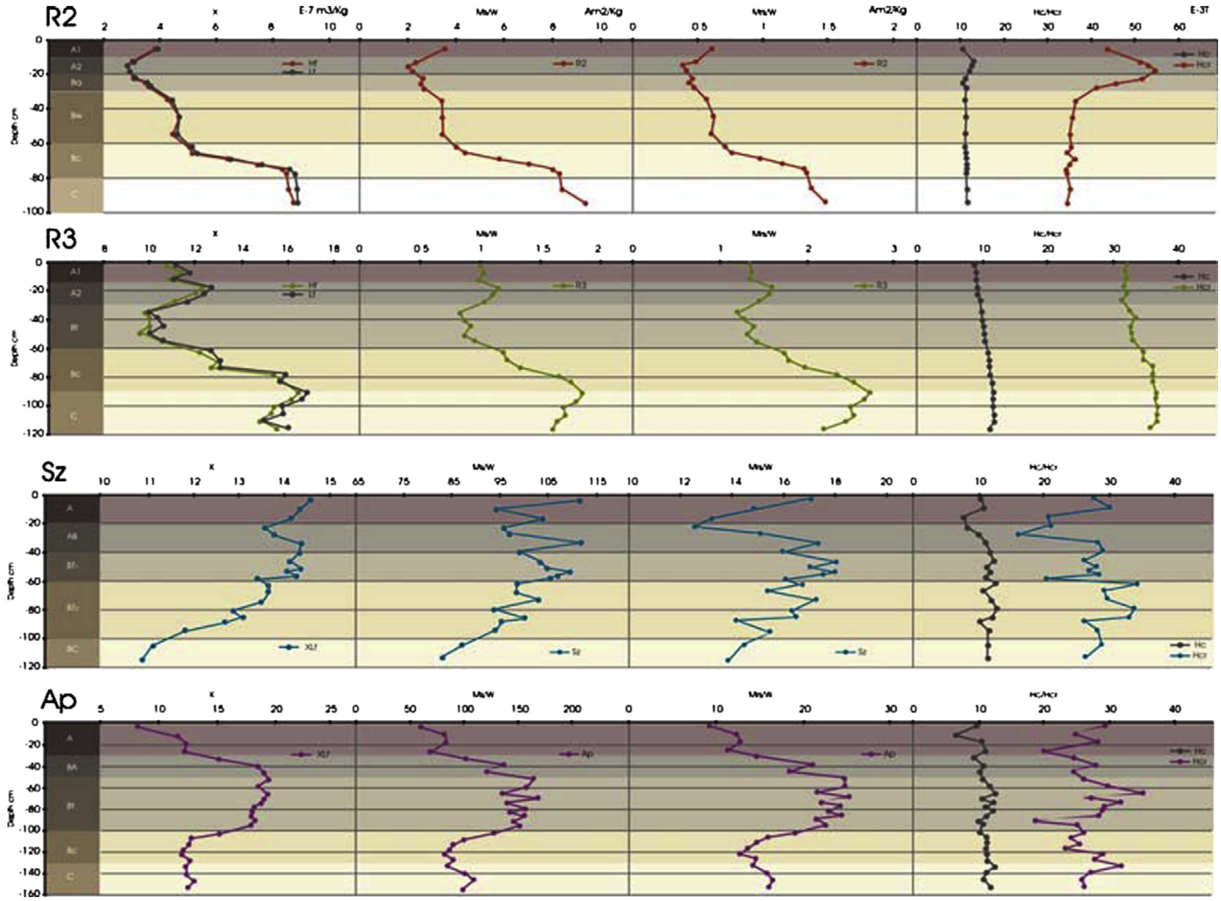

Fig. 2. Rock magnetic results of soil profiles from Verónica (R2, R3) and Zárate (SZ, Ap), Buenos Aires Province, Argentina. *X*, magnetic susceptibility; Ms, magnetization of saturation; Mrs, remanent magnetization of saturation; Hc and Hcr, coercivity and coercivity of the remanence.

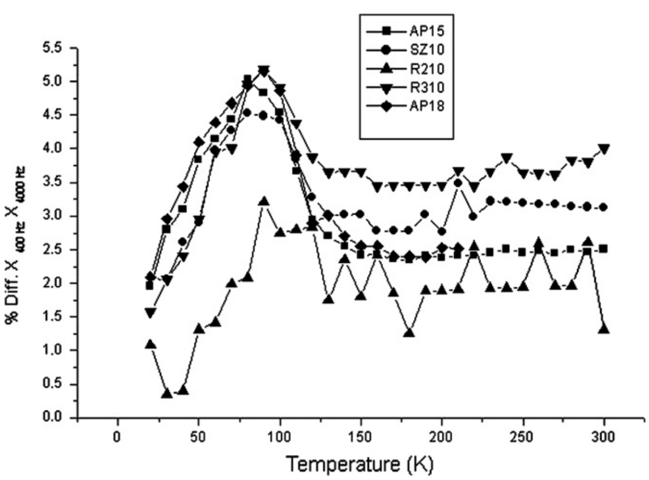

Fig. 3. Difference in % of susceptibility, *X*, between 20 K and 300 K for several samples. The peak is near 80 K, which is in agreement with ca. 20 nm in diameter SP grains. Note that the minor % difference is in sample R210. The shifting of the temperature peak towards higher values is correlated with higher % difference values which can be attributed to higher SP grains diameter.

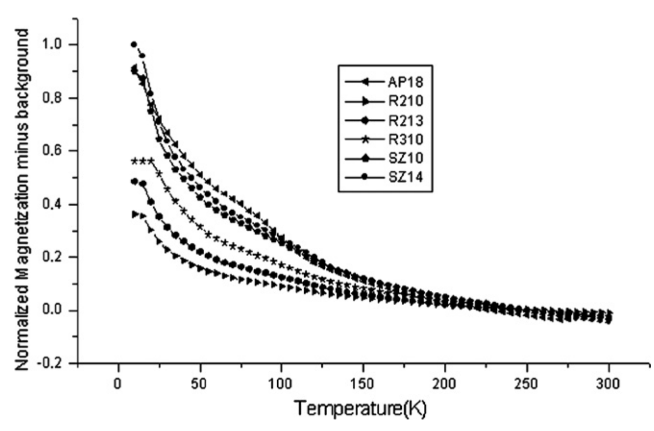

Fig. 4. Thermal demagnetization (20–300 K) of selected samples magnetized during cooling at 2.5 T; the thermal demagnetization of the sample cooled in zero field was subtracted. In order to compare, the curves were normalized to the higher value of sample SZ14.

values were found in the Zárate soils (AP and SZ samples) than in the Verónica soils (R samples). Samples from these two localities show different patterns of the thermal demagnetization curves if normalized. The curves from Zárate (AP18-Bt, SZ10-Bt1 and SZ14-Bt1, Fig. 4) show the characteristic broadening owing to the Verwey transition of PSD grains, and they have higher SP relative values than those from the profiles at Verónica (R210-Bt2, R213-Bt1, R310-Bt). In Verónica samples, the Verwey transition is probably inhibited due to the magnetization process.

Soil samples from Zárate show high SP concentrations, and there are no significant differences between water-logged and well-drained soils. On the other hand, the Verónica soils have smaller SP concentrations than the Zárate sections, and significant differences in SP amounts between R3 (high concentration) and R2 (less concentration).

5. Climatic analysis of sampling sites

Climatic information is not available from the Zárate or Verónica locations, so this study takes into account the neighboring Punta Indio (35°22′S, 57°17′W, 28 m) and San Pedro (33°41′S, 59°41′W, 22 m) records from Climatological Statistics edited by the Servicio Meteorológico Nacional of Argentina only available for the 1961–70, 1971–80 and 1981–90 periods. Results are shown only for the more recent 1981–1990 period, taken as a reference for present climatic conditions.

According to Köppen (1923), both locations belong to the Pampa Húmeda, and they are considered as being under the same major climate type defined as moist climates with mild winters (*Cfa: Humid Subtropical).* However, Verónica (meteorological data from Punta Indio) belongs to a marine coast while Zárate (meteorological data from San Pedro), located 212 km northeast of Veronica, is in a continental environment.

The region is under the South Atlantic Anticyclone (SAA) influence that shifts north to south with the sun, producing changes in seasonal mean wind direction. During spring, a strong east component supplies moisture from the Río de la Plata; during the summer north–northeast winds produce wet and warm air advection and affect both localities. Differences occur in winter when the SAA is located at its southernmost latitudinal position. While San Pedro is still influenced by those winds, the west and southwest wind component increases at Punta Indio, which implies a less humid contribution to the locality. It is important to note that the velocity of the wind at Punta Indio commonly is twice or more than that in San Pedro.

Furthermore, while the annual amplitude of temperature is similar for both locations, the monthly mean temperature is around 1 °C warmer in San Pedro, and the annual average of the daily amplitude affected by the increased continentality is 2 °C higher than in Punta Indio.

Isohyets over the Pampa Húmeda have a northeast to southwest gradient, with a decreasing precipitation rate poleward (Prohaska, 1976). Annual precipitation is 1087.1 mm in San Pedro and 1013.4 mm in Punta Indio; differences are observed in the present wet period from October to March with wetter conditions in San Pedro (750 mm) than in Punta Indio (605 mm).

Precipitation and temperature differences between both locations are reflected in the potential evapotranspiration (PET) rate that is estimated by the Thornthwaite method (Thornthwaite, 1948) and shown in Fig. 5. A minimum PET of 20 mm per month occurs quite uniformly in June–July. During the wet months, higher PET values are registered in Punta Indio than in San Pedro, with maxima recorded in January. Only for the summer months PET exceeds precipitation values, with more noticeable differences for Punta de Indio than for San Pedro.

According to the PET results and the more intense winds for Punta de Indio, the soils moisture in the Veronica region should be considerably less than in Zárate.

Paleoclimate variability during the last 1000 years plays a very important role in the genesis of soils. In the last 20,000 years, two climatic changes of great impact have been recorded. They are the Last Glacial Maximum (LGM), approximately 20–18 ky BP, and the Climatic Optimum between 9 and 6 ky BP. The last 1000 years are considered to have climatic conditions similar to the present.

However, two climatic anomalies of relevance are recorded in Argentina. The cold period of the Little Ice Age (LIA, 15th to 19th centuries) is recognized in Argentina (Heusser, 1961; Politis, 1984). Recently, sediments recovered from saline lakes in northwest Argentina show a LIA signature (Valero-Garces et al., 2000). The superficial sand layers reported to the northwest of Buenos Aires (Hurtado et al., 1985) and southern Santa Fe (Iriondo, 1999), as well as the chronicles of Parras (1943) about environmental conditions during the middle of the 18th century, seem to indicate that the climate in the Pampa Húmeda area could have been drier during the LIA than in the 20th century.

The other climatic anomaly corresponds to the Viking or Medieval Warming period during the 9th to the 14th century. Villalba (1994) shows evidence for the occurrence of a warm anomaly in glaciers and tree ring chronologies of Andean mountains south of 30°S. Furthermore, Cioccale (1999) notes that warmer temperatures prevailed from the latter part of the first millennium until about 1320 AD. This climate was further characterized by "an episode of major climatic stability, with very scarce extraordinary floods and few droughts." During that period the conditions could have been similar to the present ones or even warmer and possibly more humid.

At present, the air masses originating over the South Atlantic Ocean, advected by the SAA from east and northeast, are the origin of humidity in the area. If the direction of the humidity advection remained the same during the last 1000 years, it is valid to suppose that the precipitation gradients and the isohyets also were analogous. The change in the past 1000 years would have involved a displacement of the isohyets toward the northeast in the cold and drier periods such as the LIA and towards the southwest in the warm and humid periods such as the Medieval Warm Period.

The changes produced due to anthropogenic global warming confirm the previous hypothesis. The global average surface temperature has increased by 0.6 ± 0.2 °C since the late 19th century (IPCC, 2001). Accordingly, a positive trend in precipitation has been observed all over the Pampa Húmeda. Hoffmann et al. (1987) shows the displacement of the isohyets approximately 200 km southwestward during the 20th century. Castañeda and Barros (1994) show an increase from a mean of 850 mm during the 1920s to 1150 mm in the 1980s. Most of this increase has occurred

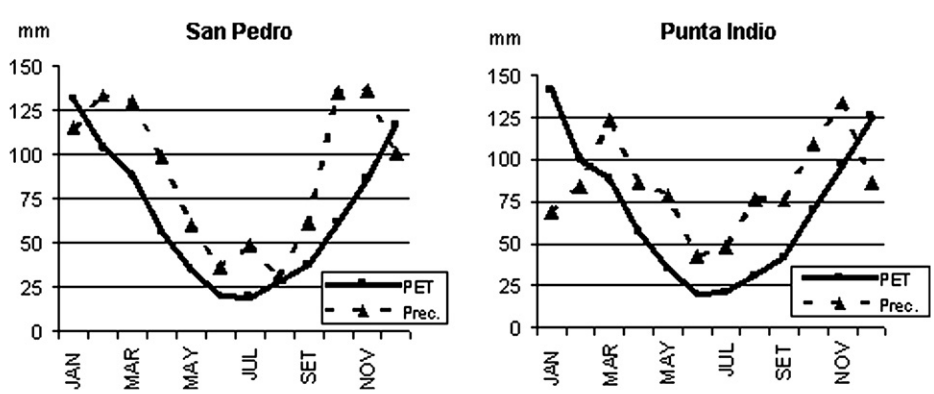

Fig. 5. Monthly average values of potential evapotranspiration (PET) and precipitation (Prec.) for 1981–1990 period.

after 1960. The change is related to a displacement of the SAA to higher latitudes and the subtropical jet at high atmospheric levels (Barros et al., 2000).

Therefore, the current climatic differences between the two areas should have been similar during the period of soil formation, or they may have been slightly increased during the last 6–7 centuries.

6. Discussion

According to the recorded data in the profile at Verónica, there is a negligible amount of SP particles. Thus, the dominant process in these soils could have been a reductive loss of the magnetic minerals with a subsequent partial oxidation in the basic environment at the top of the profile, particularly in R2.

In the case of Zárate, the values of *X*, Ms and Mrs of the poorly drained soil (AP) seem to be indicating a concentration effect of magnetic particles at illuvial horizons, with the maximum values at BA and Bt. For the best drained soil, the increase in *X* and Ms values could be associated with the generation of SP particles.

In contrast, according to the obtained results, different drainage conditions between plain soils of the same area seem to be of less relevance. The main magnetic signal is similar all along the profiles for each studied locality, though some characteristics could appear reinforced by a particular drainage condition (R2 and R3).

The pH values are not relevant for the interpretation because they represent only the present equilibrium of the environment. As mentioned before, the pH value is an environmental property that can change fast in soils for many reasons. It is a property in a dynamic equilibrium, and closely dependent on the rainfall, the nature and changes in the water table and the type of parent material.

As was shown before, high generation of SP particles was detected in present basic soils, demonstrating that the pH values have changed during the soil forming process. The AP soil produced the highest amount of SP grains, and the present pH value is around 9. The present alkaline environment could preserve SP particles.

As was previously shown, the magnetic signal is opposite in the two areas. Two important facts must be taken into account. The generation of SP particles seems to be higher in Zárate. In contrast, loss of detrital magnetite could be higher in Verónica where higher clay content may create different microenvironmental soil conditions, favoring loss of detrital magnetite by reductive processes.

Climatological data suggest that both the Zárate and Verónica sites exhibit hydric excess (precipitation exceeds PET) almost the whole year, and hydric deficit (PET exceeds precipitation) during the summer. But this last phenomenon is more remarkable at Verónica where summer is drier than in Zárate. However, the effect of the wind at Verónica contributes to this climatic differentiation.

As was mentioned before, according to PET and wind values recorded at the meteorological stations Punta Indio and San Pedro, the soil moisture in Veronica could be considerably lower than in Zárate. On the other hand, microenvironmental conditions of Verónica soils (related to higher clay content) reinforce the hypothesis of reductive loss of detrital magnetic minerals. Furthermore, in the case of Verónica, where it has been possible to appreciate the magnitude of the loss of detrital magnetite because the generation of SP in these soils is negligible, the degree of drainage seems to be a variable that controls the process of reductive loss. Different soil humidity in the studied soils could explain the difference in SP particles generated, which are higher at Zárate.

There are two additional comments to be made. As was mentioned before, the degree of argilluviation of the studied soils, as well as their clay characteristic, imply 1–10 ka for the soil formation. As a consequence, the magnetic signal is a result of a long period of a relatively stable humid-subtropical climate. Any type of comparison of soil magnetic signal among different areas must take into account the time involved in the soil history, obtained, for example, on the basis of mineralogical data.

On the other hand, soils from Verónica have more smectites possibly owing to a more recent clay formation. As was shown before, these minerals have a secondary origin. This evidence could suggest that the degree of weathering is highest in this locality. This would imply a maximum evolution of the soil formation, which is in agreement with the interpretation of a loss of magnetic minerals by the action of pedogenic processes.

To summarize, processes affecting the magnetic signal of present soils are diverse and complex. According to the results of this study, the magnetic behavior of a soil must be interpreted by taking into account geological and pedological data. More new data is necessary to confirm the interpretation of the present results.

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