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A magnetoclimatological investigation of Pampean loess, Argentina

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SUMMARY

Magnetic susceptibility has proved to be a very useful tool for understanding Northern Hemisphere loess/palaeosol sequences, both for intersite correlation and for broad climatic interpretation. However, there are two competing magnetoclimatological models that predict completely opposite patterns of variability—the so-called *wind-vigour* and *pedogenic* models. In the former, stronger winds during glacial intervals entrain larger quantities of dense magnetic particles than during interglacials. Glacial loess is therefore more magnetic than interglacial palaeosol (e.g. Kurtak, Siberia). In the pedogenic model, biological and/or chemical processes lead to the neo-formation of magnetic material so that palaeosols are more magnetic than pristine parent loess (e.g. the Chinese Loess Plateau). We are currently extending our investigation of loess/palaeosol sequences to the Southern Hemisphere starting with a new 13 m section in the El Cristo quarry in the city of La Plata, Buenos Aires Province, Argentina. The magnetic susceptibility profile shows a clear sequence of maxima and minima that correspond to lithological variations, but interpretation of these correlations is not straightforward. In the top 4 m of the section, parent material (loess) has high susceptibility whereas palaeosols have low values, consistent with the wind-vigour model. The same pattern is seen for most of the remaining 9 m of section, but there are intervals where gleying has occurred, particularly between depths of 8 and 10 m. Under the waterlogged conditions implied, iron oxides are likely to be removed and any original magnetoclimatological signal is lost (or at least strongly modified). A further complication arises from the measured values of the frequency dependence of susceptibility, which is usually taken to indicate the presence of ultrafine magnetic particles produced during pedogenesis. The El Cristo values fall squarely in between those observed in Siberia and China. An important consideration in attempting to understand the Pampean loess is the fact that it differs markedly in mineralogical composition from its Northern Hemisphere counterparts, being dominated by volcanic material. We have therefore determined the appropriate magnetic properties of samples taken from an ash layer embedded in a typical Argentinean loess sequence. Thermomagnetic analysis shows the ash to be magnetically indistinguishable from the El Cristo deposits. However, its measured frequency dependence of susceptibility cannot explain the intermediate values found there. The overall outcome is that neither of the existing magnetoclimatological models can adequately account for the complexities of the Pampean loess.

Key words: Argentina, magnetic susceptibility, magnetite, palaeoclimate, Quaternary, rock magnetism, sediments.

INTRODUCTION

The great loess deposits of Argentina have been investigated by many geologists since they were first described by d'Orbigny and Darwin in the 1840s. A recent review, including a comprehensive bibliography, is given by Zárate (2003). Over the last two decades, they have attracted the attention of palaeomagnetists attempting to establish a robust chronology by means of geomagnetic polarity stratigraphy (Bobbio *et al.* 1986; Ruocco 1989; Bidegain 1991, 1998), as well as those interested in making palaeoenvironmental/palaeoclimatic reconstructions (Orgeira *et al.* 1998; Nabel *et al.* 1999). As part of this ongoing effort, we report here new results from the coastal plain of Buenos Aires Province (Fig. 1). The main objectives are to compare the appropriate enviromagnetic parameters with corresponding data from thoroughly studied Northern Hemisphere sites (Evans & Heller 2003) and to enquire to what extent,

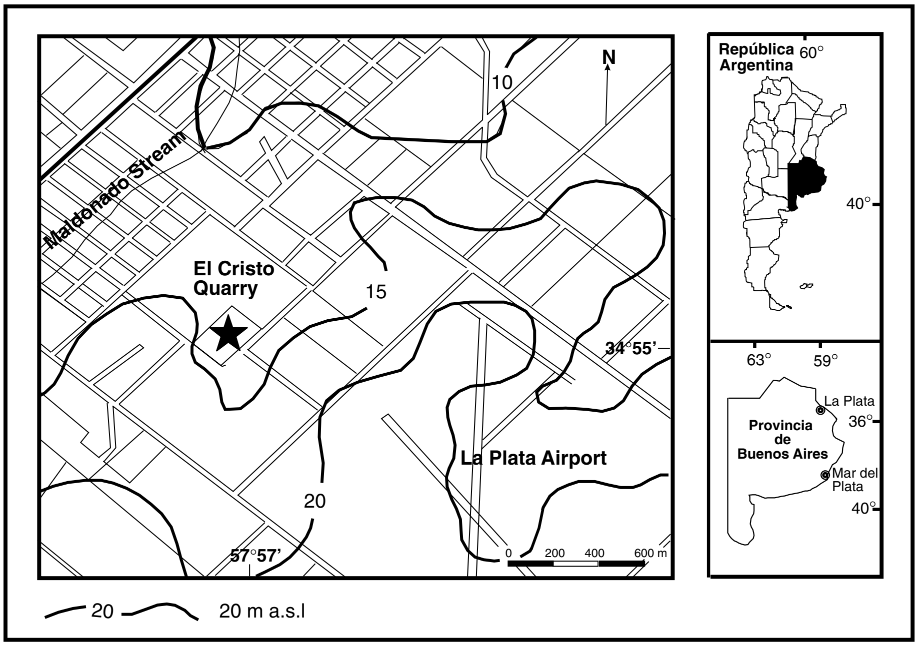

Figure 1. Sketch maps showing the locations of the sites sampled.

if any, they contribute to the debate over the so-called pedogenic and wind-vigour magnetoclimatological models (Evans 2001). An important aspect of such an enquiry concerns the composition of the loess deposits in Argentina, since it was established many years ago that it is mineralogically quite different from the major Northern Hemisphere sequences, being dominated by volcanic material (Teruggi 1957). Therefore, in addition to a loess/palaeosol section in the city of La Plata we have also studied an ash layer from a typical eastern Argentinean loess profile in order to establish the magnetic properties of the initial windfall material from which the loess developed.

METHODS AND RESULTS

The El Cristo loess/palaeosol section

Samples were collected in small plastic boxes at a 10 cm vertical spacing from cleaned vertical faces in the El Cristo quarry situated in the city of La Plata (57.9°W, 34.9°S). Stratigraphically it totals 13 m, comprising an uppermost 1.8 m thick Holocene sequence underlain by 2.4 m of the Buenos Aires Formation, with some 9 m of the Ensenada Formation below that (Fig. 2). The two lower formations are part of the so-called 'Pampean', a general term derived from d'Orbigny's original name (*argile pampéene*) for the loess and loess-like deposits throughout Argentina. The lithological and palaeopedological features germane to this study are indicated in Fig. 2, to which reference will be made below as the corresponding magnetic data are described. The section was recently described by Imbellone & Cumba (2003) who pointed out that palaeosols form the uppermost part of each of the six major units recognized (separated by continuous lines in the leftmost column of Fig. 2). These Bt/Btk/Btkg horizons indicate pedogenic activity during interglacial periods, in each case preceded by loess accumulation during glacial intervals. All the palaeosol A horizons have been removed by erosion, leaving hiatuses of unknown duration.

Prior to the recognition of geomagnetic polarity zones in this general area, the main means of establishing chronological control was by mammalian fossils, but magnetic investigations have now firmly established that the topmost strata of the Ensenada Formation (and all the sediments above, of course) were deposited during the Brunhes Chron (Bidegain 1998). Indeed, the Matuyama–Brunhes boundary has been traced for more than 300 km throughout Buenos Aires Province and the neighbouring Entre Rios Province (Ruocco 1989; Nabel 1993; Bidegain 1999).

The magnetic susceptibility of all samples was determined (in Edmonton) at both operating frequencies (0.465 and 4.65 kHz) of a Bartington MS2B susceptibility meter using the more sensitive (×0.1) range. The low-frequency (χ_{LF}) results range from 15×10^{-8} to 267×10^{-8} m^3 kg^{-1} with a median of 117×10^{-8} m^3 kg^{-1} (Fig. 3). However, the distribution strongly suggests that more than one population is present, as indicated by the marked minimum at about 50×10^{-8} m^3 kg^{-1}. The corresponding high-frequency (χ_{HF}) results yield a very similar picture, slightly shifted to the left, ranging from 14×10^{-8} to 254×10^{-8} m^3 kg^{-1} with a median of 113×10^{-8} m^3 kg^{-1} and a minimum near 50×10^{-8} m^3 kg^{-1} similar to the low-frequency data. The frequency factor F ($= [(\chi_{LF} - \chi_{HF})/\chi_{LF}] \times 100$ per cent), a commonly used indicator of the presence of ultrafine magnetic particles produced by soil-forming processes, ranges from 0.5 to 6.1 per cent with a median value of 3.5 per cent.

Isothermal remanent magnetization (IRM) curves acquired in 15 incremental steps up to a maximum field of 700 mT were determined (in Edmonton) for 17 representative samples spread throughout the profile (indicated on Fig. 2). The acquisition (forward direction) and demagnetization (backfield) curves are all similar and are dominated by low-coercivity minerals. All samples reach at least 96 per cent of their ultimate maximum values in a field of 300 mT (Fig. 4). Remanent coercivities (H_{cr}, the backfield necessary to reduce the saturation IRM (SIRM) to zero) fall in the range 26 to 38 mT, while the SIRMs themselves range from 1.8 to 30 mA m^2 kg^{-1}.

Six samples from stratigraphic horizons representing the major lithological intervals (indicated on Fig. 2) were selected for further mineral magnetic measurements using a variable field, translation balance (VFTB) designed and built in the Munich laboratory

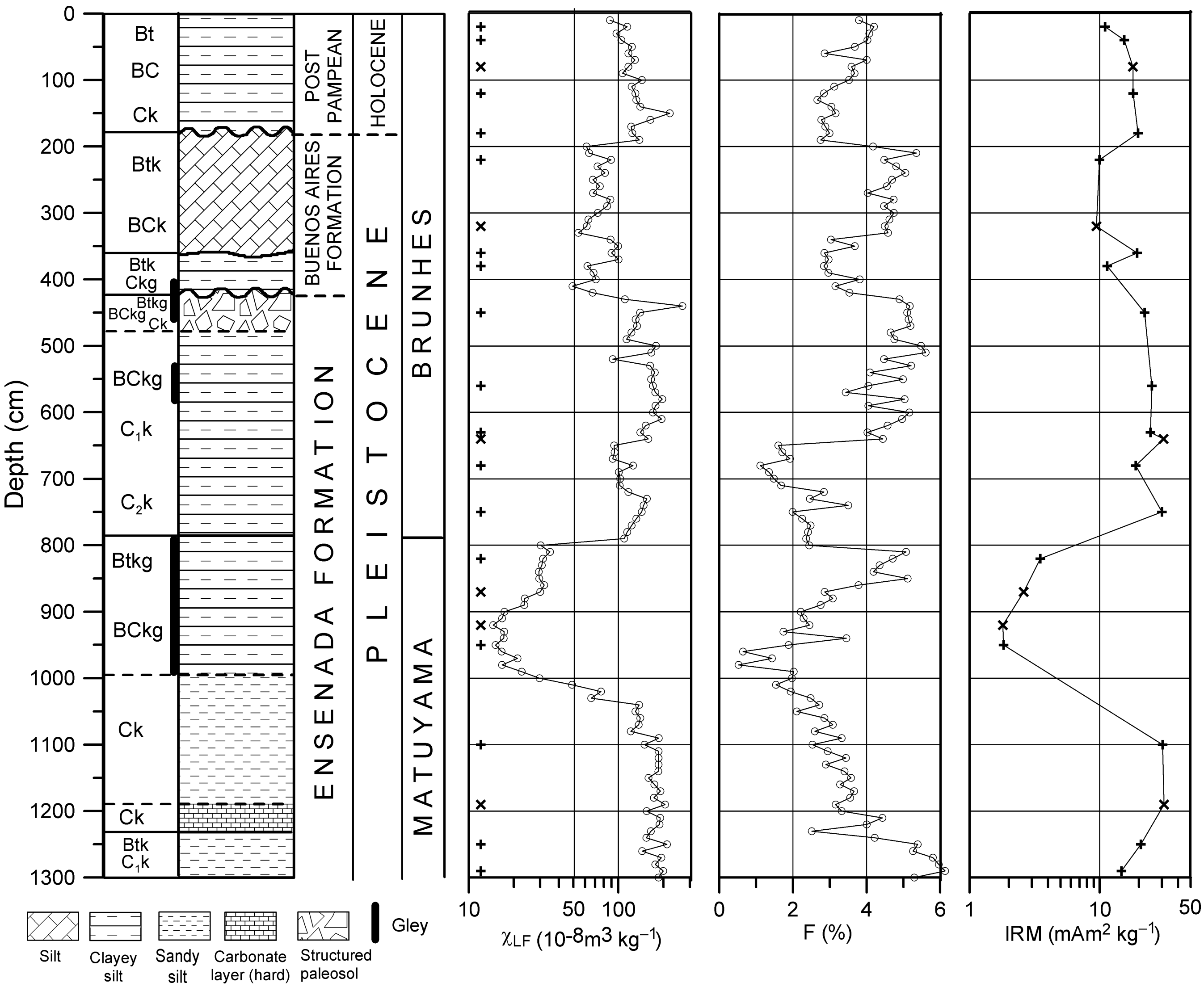

Figure 2. Lithological/palaeopedological profile of the El Cristo Quarry section with corresponding profiles of low-frequency magnetic susceptibility (χ_{LF}), frequency factor ($F = [(\chi_{\mathrm{LF}} - \chi_{\mathrm{HF}})/\chi_{\mathrm{LF}}] \times 100$ per cent), and saturation isothermal remanence (SIRM). Crosses show Munich data and plus signs Edmonton data. Standard palaeopedological notation is used (e.g. Bt, Ck), as given, for example, in Table 3.1 of Retallack (1990). Contacts between the major stratigraphic units recognized by Imbellone & Cumba (2003) are shown as continuous lines in the leftmost column. These are planar, slightly wavy or wavy as indicated in the lithology column. Dashed lines represent gradual boundaries.

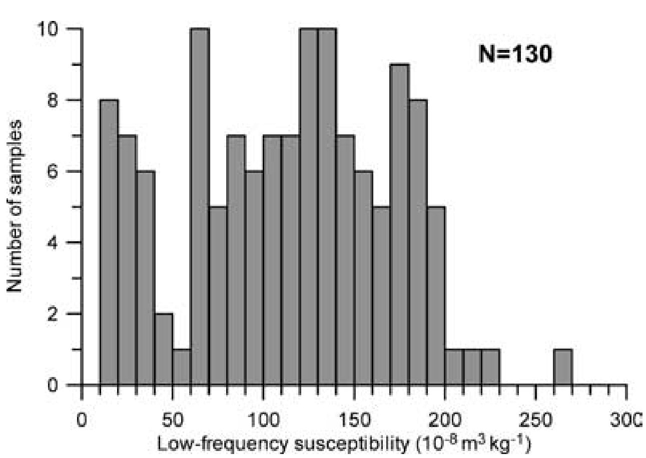

Figure 3. Histogram of low-frequency magnetic susceptibility (χ_{LF}).

by Dr N. Petersen. This versatile instrument sequentially measures stepwise acquisition of IRM, hysteresis loops, stepwise back-field demagnetization and thermomagnetic curves, all on the same (100–300 mg) sample. The maximum field used was 930 mT. During thermomagnetic runs, an $\mathrm{IRM}_{930\mathrm{mT}}$ acquired at room temperature was continuously monitored as the sample was heated up to 700 °C at a rate of 15 °C min^{-1}.

Despite an order-of-magnitude spread in amplitude the normalized thermomagnetic curves are virtually indistinguishable from one another. They all exhibit a steady concave decrease to the Curie point of magnetite (Fig. 5), and the shape of the curves indicates that it occurs over a wide range of grain sizes. The subtle slope change at about 150 °C evident in the stronger samples can be attributed to the presence of surficial oxidation rims of maghemite as described by van Velzen & Dekkers (1999). The IRM data obtained from the Munich VFTB (H_{cr} ranges from 30 to 38 mT and M_{rs} (= SIRM) ranges from 1.8 to 31 mA m^2 kg^{-1}) are entirely

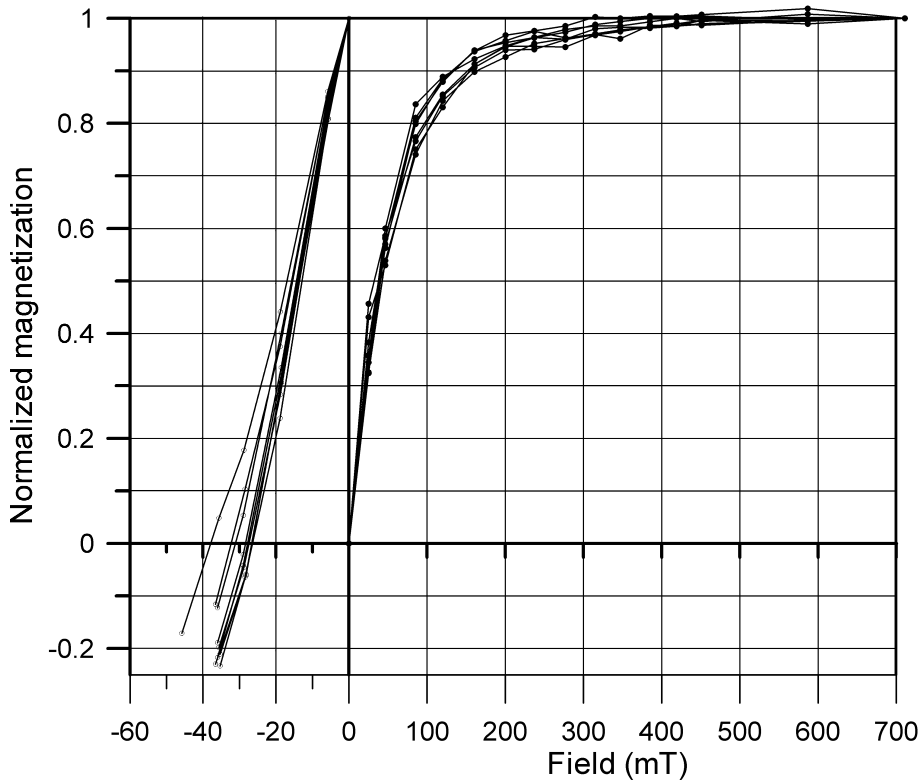

Figure 4. Isothermal remanent magnetization for 17 samples spread throughout the section. Note the change of scale at zero field. The stratigraphic position of each sample is indicated (+) in Fig. 2.

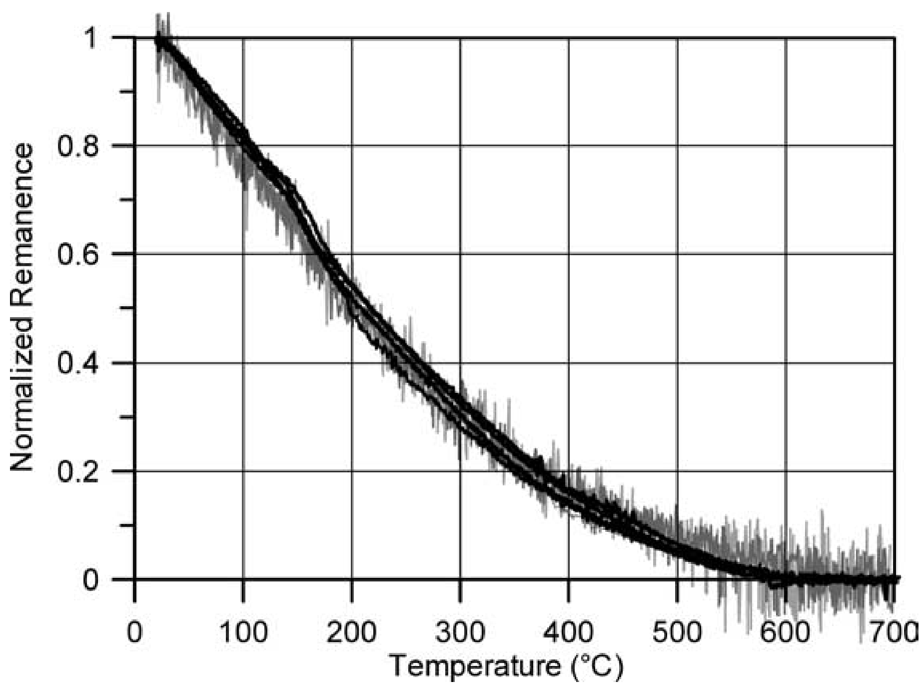

Figure 5. Thermomagnetic curves for the six El Cristo samples (× in Fig. 2) and for the Mar del Plata ash sample. Because they are essentially indistinguishable, all but one of the curves are indicated in black. The data for the weak sample from 920 cm depth is shown in grey to allow the reader to appreciate the fact that, despite its low signal-to-noise ratio, it too has the same shape as the others.

compatible with the Edmonton results. The other hysteresis parameters obtained in Munich are H_c, which shows very little variation (10 to 12 mT), and M_s, which spans more than an order of magnitude (14 to 202 mA m^2 kg^{-1}). The two hysteresis ratios M_{rs}/M_s and H_{cr}/H_c fall in very restricted ranges, 0.15 to 0.18 and 2.9 to 3.8 respectively, in the pseudo-single-domain (PSD) field of the so-called Day plot. This is a widely observed phenomenon that more often than not indicates the presence of mixtures of grain sizes rather than the restricted range that the plotted points at first suggest (Dunlop 2002).

The Mar del Plata ash

Significant ash layers do not occur in the El Cristo section, so we have investigated suitable material from Mar del Plata, some 300 km to the south. This is the area from which Teruggi (1957) obtained much of the material for his definitive study of the nature and origin of the Argentinean loess, but he states that 'the results obtained were also checked with samples collected by the author at different points of Buenos Aires Province'. Our ash sample was collected from the Hipódromo quarry just outside the city of Mar del Plata. The overall sequence is similar to the Pampean loess found at La Plata, there being an alternation of loess-like layers with palaeosol horizons manifested by differences in colour and texture. The ash we sampled has an average thickness of 10 cm and occurs half-way down a 10 m thick section. It is overlain by a 3.5 m thick loess layer, the top of which is estimated to be about 100 kyr old. Obviously, the ash we have studied cannot be regarded as the precise parent material for the entire stratigraphic profile at El Cristo (or anywhere else for that matter). Our purpose is simply to compare the magnetic properties of ash and loess using our Mar del Plata and El Cristo material as test samples. Given that Teruggi (1957) demonstrated the volcanic origin of the Pampean loess, this is an obvious first step. As more and more sites are investigated it should be possible to discern any spatial and temporal trends that may be present.

The same set of VFTB measurements described above was carried out on a sample taken from a random aliquot of the ash. The normalized thermomagnetic curve is indistinguishable from those of the six samples from the El Cristo section (Fig. 5), but the M_{rs} (39 mA m^2 kg^{-1}) and M_s (299 mA m^2 kg^{-1}) values (and their ratio, 0.13) fall outside the corresponding ranges found at El Cristo.

Magnetic susceptibilities were measured on a Bartington MS2B system in the Munich laboratory following the same procedure used in Edmonton. To further probe the characteristics of the ash as a source material we decided to split it into grain-size fractions by passing 100 g of loose, dry ash through sieves with meshes of 200, 140, 100, 80 and 63 μm. The bulk starting material has $\chi_{LF} = 246 \times 10^{-8}$ m^3 kg^{-1} and $F = 1.6$ per cent, but there are notable systematic variations with grain size. The frequency dependence of susceptibility peaks at about 2.5 per cent in the mid-size particles (80–140 μm), and falls well below 1 per cent in the <63 μm fraction (Fig. 6a). However, the mass-specific susceptibility shows the opposite pattern (Fig. 6b), a trend that is strongly reinforced when the actual mass fractions are taken into account. Almost 60 per cent of the susceptibility signal is carried by the <63 μm fraction, whereas particles larger than 100 μm account for less than 10 per cent (Fig. 6c).

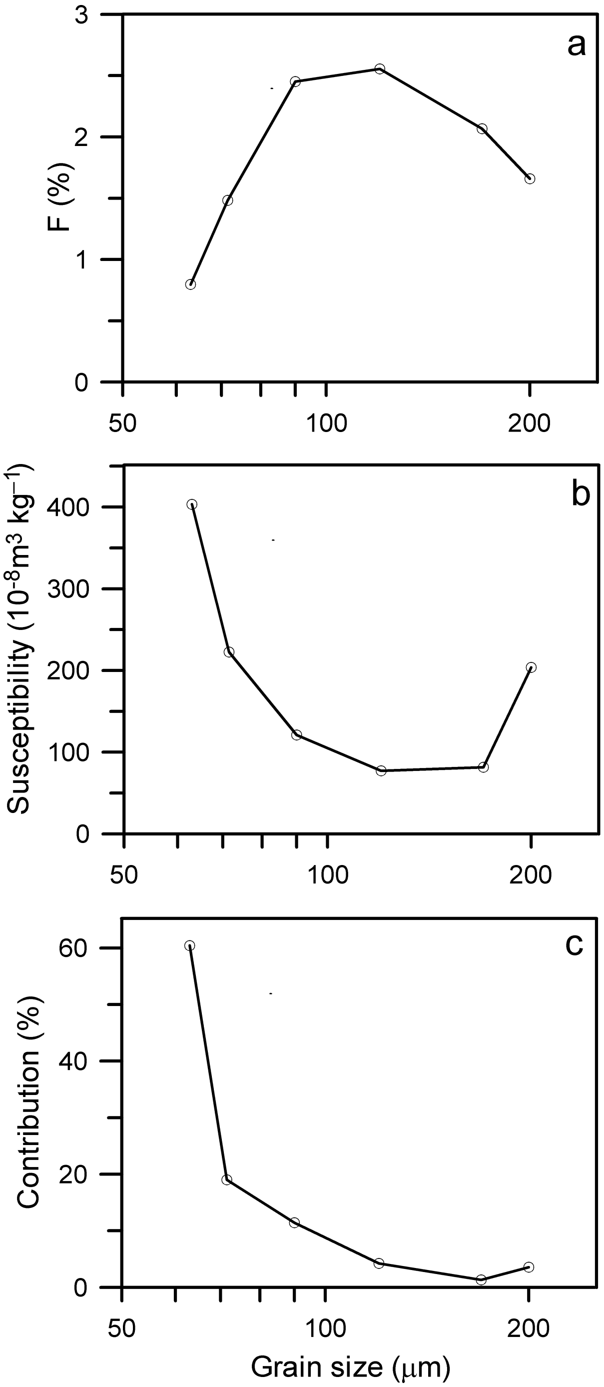

Figure 6. Magnetic susceptibility versus grain size for the Mar del Plata ash. (a) Frequency factor F $(= [(\chi_{LF} - \chi_{HF})/\chi_{LF}] \times 100$ per cent). (b) Mass-specific low-frequency susceptibility (χ_{LF}). (c) Contributions to the overall bulk magnetic susceptibility taking into account the mass fractions represented by each grain size interval. Note that the grain-size axis is logarithmic. Points for the <63 μm fraction are plotted at 63 μm, those for the >200 μm fraction are plotted at 200 μm and those for the other fractions are plotted at their mid-points. Only one sample each was available for the two coarsest fractions, but the other four fractions yielded sufficient material for multiple samples and thus allowed a check on uniformity. The data for F (in per cent) are 0.72, 0.80, 0.87 for the <63 μm fraction; 1.48, 1.49 for the 63–80 μm fraction; 2.60, 2.32 for the 80–100 μm fraction and 2.63, 2.48 for the 100–140 μm fraction. The data for χ_{LF} (in 10^{-8} m^3 kg^{-1}) are 417, 402, 391 for the <63 μm fraction; 225, 220 for the 63–80 μm fraction; 125, 116 for the 80–100 μm fraction and 78, 76 for the 100–140 μm fraction.

DISCUSSION

Bulk magnetic properties

First, we compare the range of magnetic properties obtained from the El Cristo section with corresponding data from two representative Northern Hemisphere sites, one (in China) relevant to the pedogenic model, the other (in Siberia) to the wind-vigour model. The Chinese site (Baoji, 107.1°E, 34.4°N: Wang *et al.* 1990, 1992) is typical of sites where magnetic properties are largely controlled by the complex chemical, physical and biological processes involved in pedogenesis. These result in magnetic enhancement in palaeosols by a factor of two or more. The Siberian site (Kurtak, 91.4°E, 55.1°N: Chlachula *et al.* 1998) on the other hand represents the alternative magnetoclimatological model in which palaeosols appear as magnetic lows and the intercalated loess as magnetic highs resulting

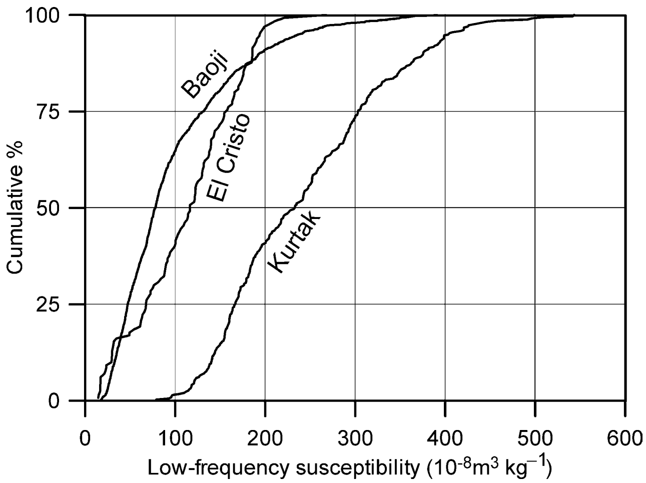

Figure 7. Cumulative distributions of magnetic susceptibilities at Baoji ($N = 1570$), El Cristo ($N = 130$), and Kurtak ($N = 340$).

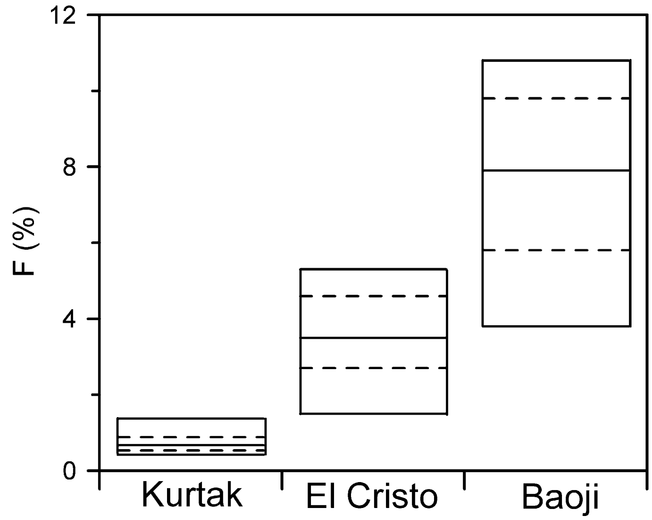

Figure 8. Box percentile plot of F ($= [(\chi_{\mathrm{LF}} - \chi_{\mathrm{HF}})/\chi_{\mathrm{LF}}] \times 100$ per cent) at Baoji, El Cristo and Kurtak. The five horizontal lines in each box represent the 5th, 25th, 50th, 75th and 95th percentiles of the corresponding cumulative distributions.

from more efficient entrainment of dense iron oxide particles during stormy glacial intervals. As in China, the susceptibility ratio is again about two, but in the opposite direction. The cumulative distributions of magnetic susceptibility, regardless of lithology, are plotted in Fig. 7. It is immediately clear that the El Cristo curve is closer to that for Baoji than to that for Kurtak. Median values are 78, 116 and 233 $\times 10^{-8}$ m^3 kg^{-1} for Baoji, El Cristo and Kurtak, respectively. Furthermore, there are significant—and meaningful—differences in the shapes of the curves. At Baoji, there is a rapid rise with virtually no low-value tail. This reflects a combination of the background susceptibility ($\sim 20 \times 10^{-8}$ m^3 kg^{-1}) inherited from the original airfall input and the effects of progressive pedogenesis. Previous work indicates that soil formation must be quite advanced before large increases in susceptibility take place; only when the frequency factor (F) reaches $\sim$10 per cent are the highest susceptibilities achieved (Heller *et al.* 1991). The outcome, at Baoji, is that the cumulative distribution rises rapidly, with almost two-thirds of the values lying below 100×10^{-8} m^3 kg^{-1} and less than one-tenth above 200×10^{-8} m^3 kg^{-1}. In the El Cristo cumulative distribution, the bimodal pattern of Fig. 3 is reflected by the sharp shoulder at low values. Reference to Fig. 2 indicates that the values below $\sim 50 \times 10^{-8}$ m^3 kg^{-1} correspond to gleyed horizons between 8 and 10 m depth, indicating that magnetic particles have been removed by dissolution during waterlogged conditions. This parallels the conclusions of Orgeira *et al.* (1998) and Nabel *et al.* (1999). Finally, the Kurtak distribution possesses neither of the two patterns observed at low values in the other two sites. Rather, it manifests a straightforward distribution with tails at both ends, but with the stronger overall signal suggesting the presence of about twice the quantity of magnetic material.

The IRM data (Fig. 4) indicate that the dominant magnetic species present is a magnetically soft ferrimagnet, such as magnetite or maghemite, but the thermomagnetic curves (Fig. 5) strongly favour magnetite. Comprehensive reference data (Heider *et al.* 1996) indicate that the median volume fraction necessary to explain the Kurtak results is no more than about 0.1 per cent, with correspondingly smaller quantities for Baoji and El Cristo.

The three sites are clearly distinguished by their frequency-dependent susceptibility data (Fig. 8). Here we see that the wind-vigour site (Kurtak) is completely dominated by very low values around 1 per cent, showing that pedogenesis plays a minor role in controlling the magnetic pattern. At Baoji, however, there is clear evidence of a strong pedogenetic control of the magnetic signal. Some 50 per cent of the samples have $F > 8$ per cent, and only about 5 per cent have $F < 4$ per cent; soil formation is well advanced and even the loess layers are sufficiently weathered as to be no longer entirely pristine. Frequency dependence at El Cristo is intermediate, suggesting some form of hybrid signal, or perhaps even requiring an entirely new magnetoclimatological model.

Stratigraphic profiles

In the bulk magnetic susceptibility profile (Fig. 2), five broad stratigraphic zones can be discerned in which the values alternate from being mostly above 100×10^{-8} m^3 kg^{-1} (i.e. 0–2 m, 4.5–8 m, 10.5–13 m) to being mostly below this level (i.e. 2–4.5 m, 8–10.5 m). Starting at the top, there is a gradual increase from the present-day soil to the post-Pampean parent material. However, the opposite trend is seen in the F-factor profile. This part of the section is thus consistent with the wind-vigour model and parallels the Kurtak data minimum $\chi_{\mathrm{LF}} \approx 100 \times 10^{-8}$ m^3 kg^{-1}, maximum $F \approx$ 4 per cent (Chlachula *et al.* 1998). The underlying Buenos Aires Formation consists predominantly of B-horizon silt and has $50 \times 10^{-8} < \chi_{\mathrm{LF}} < 100 \times 10^{-8}$ m^3 kg^{-1}, but with no clear stratigraphic trend. However, the F factor increases abruptly at the top before falling back to $\sim$3 per cent, as found at the base of the overlying post-Pampean sediments. The topmost 4 m of the Ensenada Formation has several peaks and troughs and has many χ_{LF} values exceeding 150×10^{-8} m^3 kg^{-1}. In some cases the F factor is surprisingly high ($>$5 per cent), suggesting that the upper part of this zone has been significantly weathered. The lower part, on the other hand, has much lower F values—as low as 1 per cent—and probably represents the most pristine loess at this site, deposited during glacial times. At 8 m depth the χ_{LF} values fall abruptly and remain low until 10 m, where they rise rapidly. In this 2 m interval there is clear evidence of gleying with a concomitant loss of magnetic particles by dissolution. Note, however, that two stratigraphic subdivisions exist: the upper metre has $\chi_{\mathrm{LF}} \sim 35 \times 10^{-8}$ m^3 kg^{-1}, whereas the lower metre has $\chi_{\mathrm{LF}} \sim 20 \times 10^{-8}$ m^3 kg^{-1}. This is very clearly seen in the F factors, which rise above 5 per cent and fall below 1 per cent in the upper and lower parts,

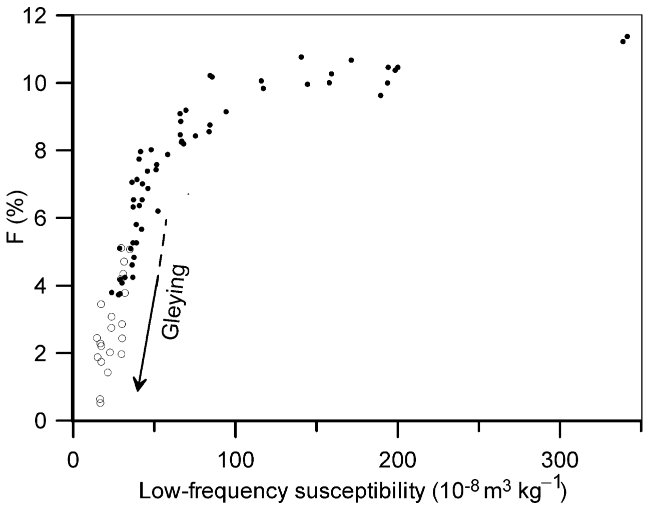

Figure 9. Frequency-dependent magnetic susceptibility (F per cent) versus low-frequency magnetic susceptibility (χ_{LF}) for the stratigraphic interval 8–10 m at El Cristo compared with the corresponding data from the Baoji section in the Chinese Loess Plateau. The pathway resulting from gleying is suggested by the arrow that runs in the opposite direction to pedogenic evolution as described, for example, by Heller *et al.* (1991).

respectively. The very low values are consistent with dissolution, which should preferentially remove the small particles responsible for the frequency dependence of χ_{LF}. In this case, however, the dissolution has also affected larger size ranges, which carry stable remanence, as shown by the marked minimum in the IRM profile (Fig. 2). This being so, the question arises as to the origin of the gleyed material with $F > 5$ per cent (centred at ∼8.2 m depth). We suggest that this is the legacy of an incomplete process, as illustrated in Fig. 9. Here we compare the data from the 8–10 m stratigraphic interval at El Cristo with the results obtained from the entire section at Baoji. In China, as Heller *et al.* (1991) have shown, such a diagram indicates the effect of progressive pedogenesis. Starting from what they refer to as the 'ground level', representing the original airfall deposits, the frequency factor increases rapidly at first before approaching saturation at about 10–12 per cent. Thereafter, further pedogenesis simply increases the bulk susceptibility. It is reasonable to suppose, therefore, that gleying would more or less reverse this process, as suggested by the arrow on Fig. 9. On this model, the higher F values (∼5 per cent in this stratigraphic interval at El Cristo) simply reflect samples that are only partially gleyed. Such material has been arrested on a pathway from higher (interglacial) values (perhaps as high as the maximum values observed in China) down to values approaching zero, as the ultrafine size range is progressively depopulated.

Below 10 m, magnetic susceptibility rises quickly into the fifth, and final, stratigraphic zone where it remains steady at $150 \times 10^{-8} < \chi_{\mathrm{LF}} < 200 \times 10^{-8}$ m^3 kg^{-1} indicating deposition under wind-vigour control during glacial times. However, there is a steady rise in the F factor suggesting that the loess involved is not entirely pristine having been subject to the effects of weathering leading to the production of fine-grained magnetic particles.

The volcanic ash

The thermomagnetic curve of the Mar del Plata ash is very similar to those of the sediments at El Cristo, which themselves are remarkably uniform. In both cases essentially pure magnetite, with a wide range of grain sizes, is the only magnetic mineral present in significant quantities. Particles smaller than 63 μm account for the greater part of the susceptibility of the ash. In terms of the overall susceptibility signal, the ash is scarcely stronger than the strongest horizon at El Cristo (267×10^{-8} versus 246×10^{-8} m^3 kg^{-1}), which would require almost pure ash at several horizons in the El Cristo section. However, the loess of Buenos Aires Province typically has a median grain size of about 45 μm (Teruggi 1957) whereas we find that the Mar del Plata ash has a median size of about 80 μm. The removal of the coarsest grains will emphasize the signal from the smaller ones where we find susceptibility values up to 400×10^{-8} m^3 kg^{-1} (Fig. 6b). As far as magnetic properties go, it is clear that the ash (and many like it, presumably) can be regarded as a realistic source for Pampean loess, both qualitatively and quantitatively. Of course, this is not to deny that processes other than simple aeolian transport (e.g. weathering, pedogenesis, gleying) have been operative.

A difficulty arises, however, when the frequency dependence of susceptibility is considered. On the one hand, the <63 μm fraction is responsible for most of the susceptibility signal, but on the other, this fraction has very low F values. We propose a model in which the larger grain-size fractions become relatively impoverished in monomineralic magnetite particles during transport. This follows from the sorting expected in aeolian sediments, magnetite being about twice as dense as common silicates. In this way, the <63 μm fraction retains more of its original magnetic inheritance than do the coarser fractions. However, the vast majority of the magnetite grains involved will almost certainly be multidomained (MD) since the 63 μm upper limit is enormously greater than the single-domain (SD) threshold. We therefore expect the <63 μm fraction to exhibit very little frequency dependence of susceptibility, as is the case (Fig. 6a). But why do the mid-size (80–140 μm) particles possess higher F values? We suggest that this is due to the presence of silicates containing magnetite inclusions. In this context, Teruggi (1957, p. 327) makes the significant observation that 'opaque inclusions are frequent' in the pyroxene grains found in the sand fraction (>63 μm). There are no data on the typical size of these inclusions, but if the distribution extends down to the submicrometre range we have a ready explanation for the peak F values evident in Fig. 6(a).

Even if the above suggestion is valid, there is still a shortfall as far as the frequency dependence of susceptibility is concerned. A median F value at El Cristo of 3.5 per cent, and a maximum of 6 per cent, thus point to the creation of ultrafine magnetite particles by pedogenesis. The reason why F values near the theoretical maximum of 12 per cent do not occur remains problematic. But since this area of Argentina receives about 950 mm of rainfall annually, whereas Baoji (where F values up to 11 per cent are found) receives no more than 700 mm yr^{-1}, it seems likely that the overall humidity is the controlling factor. This follows from the established fact that magnetic enhancement in soils only goes so far (Han *et al.* 1996). If there is enough moisture available, magnetite starts to be removed from the system, particularly in the smaller particle sizes responsible for the frequency dependence of susceptibility (Maher 1998).

CONCLUSIONS

(1) The El Cristo section possesses magnetic properties that are generally intermediate between the expectations of the wind-vigour and pedogenic magnetoclimatological models. This is particularly so for the frequency dependence of magnetic susceptibility (the so-called F factor).

(2) Magnetite—in a wide range of grain sizes—is the only magnetic mineral present in significant quantities.

(3) Gleying during waterlogged conditions has removed much of the magnetic material from certain stratigraphic intervals.

(4) Some of the gleyed material retains relatively high F factors (>5 per cent), the significance of which is currently unclear. As a working hypothesis warranting further investigation we suggest that such material represents 'arrested gleization'.

(5) An ash at Mar del Plata has magnetic properties compatible with the orthodox view that Andean volcanic activity is the source of the Pampean loess.

(6) The magnetic susceptibility of the ash is predominantly carried by grains in the silt and clay fractions (<63 μm), but the F factor peaks in the mid-sizes (80–140 μm). We attribute this to the presence of small magnetite inclusions in pyroxene grains.

(7) The ash we studied cannot explain the intermediate F factors (up to 6 per cent) observed at El Cristo, for which it is necessary to appeal to the creation of ultrafine magnetite particles by soil-forming processes.

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