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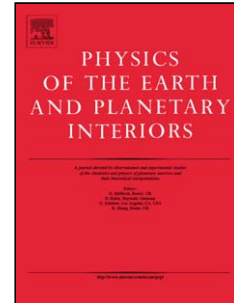
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1 **Palaeomagnetism of the loess/palaeosol sequence in Viatovo (NE Bulgaria) in the**
2 **Danube basin.**

3

4 Diana Jordanova (1), Jozef Hus (2), Jordan Evlogiev (3), Raoul Geeraerts (2)

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6 (1) Geophysical Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Sofia,
7 Bulgaria, e-mail: vanedi@geophys.bas.bg

8 (2) Centre de Physique du Globe de l'IRM, 5670 Dourbes, Belgium, e-mail: jhus@oma.be

9 (3) Geological Institute, Bulg. Acad. Sci., Acad. G. Bonchev Str., bl. 24, 1113 Sofia,
10 Bulgaria

11

12 **Abstract**

13 The results of a palaeomagnetic investigation of a 27m thick loess/palaeosol sequence in
14 Viatovo (NE Bulgaria) are presented in this paper. The sequence consists of topsoil S_0 , 7 loess
15 horizons (L_1 - L_7) and 6 interbedded palaeosols (S_1 - S_6) overlying a red clay (terra rossa)
16 complex. Magnetic viscosity experiments, IRM acquisition, AMS analysis and NRM stepwise
17 alternating and thermal demagnetisation experiments of pilot samples were implemented for
18 precise determination of the characteristic remanence and construction of a reliable
19 magnetostratigraphical scheme. Analysis of IRM acquisition curves using the expectation -
20 maximization algorithm of Heslop et al. (2002) suggests that the best fitting is obtained by
21 three coercivity components. Component 1 corresponds to SD maghemite/magnetite, while
22 component 2 is probably related to the presence of oxidised detrital magnetites. The third
23 component shows varying coercivities depending on the degree of pedogenic alteration of the
24 samples and probably reflects the presence of detrital magnetite grains oxidised at different
25 degree.

26 The relevance of the Viatovo section as a key representative sequence for the loess cover in
27 the Danube basin is confirmed by the presence of geomagnetic polarity changes in the lower
28 part of the sequence. The youngest one recorded in the seventh loess unit L₇ can be identified
29 as corresponding to the Matuyama/Brunhes palaeomagnetic polarity transition. Two normal
30 magnetozones were found in the red clay complex, probably corresponding to the Jaramillo
31 and Olduvai subchronozones of the Matuyama chron.

32

33 **Key words:** loess-palaeosol, viscous remanence, IRM acquisition, IRM component unmixing,
34 magnetostratigraphy, Matuyama/Brunhes boundary, Jaramillo and Olduvai subchronozones,
35 Bulgaria.

36

37 **1. Introduction**

38

39 Palaeomagnetism is one of the rare methods for chronostratigraphical correlation and
40 dating of Middle and Upper Pleistocene loess/palaeosol sediments, mainly because of the
41 time limits of other dating techniques and the lack of micro- and macrofaunal findings with
42 dating significance. The latter is particularly the case with the Viatovo sequence examined
43 below (Evlogiev, 2006). Indeed, other dating methods: amino acid racemification (Wehmiller
44 and Miller, 2000), thermoluminescence (Forman et al., 2000, Singhvi et al., 2001), Optically
45 Stimulated Luminescence (Huntley et al., 1985; Hutt et al., 1988) and radiocarbon (Trumbore,
46 2000) dating are limited in time. On the other hand, records of geomagnetic field reversals
47 such as the position of the Matuyama/Brunhes (M/B) polarity reversal and the possible
48 presence of “excursions” or short-term reversals within the Matuyama and Brunhes chrons are
49 important stratigraphic markers. Especially significant is the contribution of palaeomagnetism
50 to a reliable stratigraphic correlation of the East European loess deposits, in particular in the

51 Danube basin because of the varying sources of aeolian dust, differences in geomorphological
52 relief and climate gradients (Pye, 1987). Investigations of the loess-palaeosol sediments from
53 the Northern Black Sea coastal area by Dodonov et al. (2006) identified the
54 Matuyama/Brunhes boundary at the base of pedocomplex S₇. Nawrocki et al. (2002) found
55 the M/B transition in the sequence of Zahvizdja (East Carpathian Foreland) in an interglacial
56 soil, equivalent to oxygen isotope stage 19. In the Western Black Sea area, Tsatskin et al.
57 (2001) and Gendler et al. (2006) discovered the same polarity boundary respectively between
58 pedocomplexes PK6 and PK7 in Roxolany and in the upper part of PK7 in Novaya Etuliya.
59 The aim of the present study is to establish a reliable magnetostratigraphy of the loess-
60 palaeosol sediments in the low Danube area through detailed rock magnetic (Jordanova et al.
61 2007) and palaeomagnetic investigations of the Viatovo sequence.

62

63 **2. Loess cover in Bulgaria and site description.**

64

65 The recent geomorphological relief in North Bulgaria is blanketed by widespread loess
66 deposits. Loess-palaeosol sequences of various thickness and age occur on certain
67 palaeogeomorphological forms: the Pliocene Denudation Surface (PDS); the Old Abrasive-
68 Accumulative Level (OAAL); Pleistocene river terraces T₆, T₅, T₄, T₃, T₂, T₁, T₀¹ and the
69 Holocene terrace T₀ (Fig. 1a). Each of them has a typical lithology and stratigraphic position
70 (Evlogiev, 1993).

71 The oldest palaeogeomorphologic form, PDS, in North Bulgaria was shaped during
72 the Pliocene along the shore of the Dacian lake basin. It is characterised by an undulating to
73 flat relief in lower Cretaceous limestones and sandstones at an absolute altitude of 200–250m.
74 In the study area, in Viatovo, a number of palaeokarsts assumed to be of Albian age
75 developed and were buried subsequently by kaolinitic sands. The complete sedimentary

76 sequence on the PDS form above the kaolinitic level in this region consists of red clays and a
77 loess/palaeosol sequence of 8 loess horizons and 7 palaeosols according to Evlogiev (2006).
78 The second geomorphologic unit, the OAAL, was formed at the beginning of the Biber glacial
79 about 2.59 Ma ago, by cold invasion and intensification of neo-tectonic movements. As a
80 result, significant hydrological changes occurred. In the realm of the Dacian basin these
81 changes were dominated by erosional incision that sculpted the OAAL relief. Its absolute
82 height is 70-90 m and it is sloping towards the Danube River. The OAAL consists of two
83 facies in the area of Russe: a basal gravel-sand complex (dated at 2.59 - 1.06 Ma) covered by
84 a gravel-clay complex (1.06 - 0.84 Ma). The ages mentioned are deduced from fauna,
85 magnetostratigraphy and geochronology (Evlogiev, 2006). A complete loess/palaeosol
86 complex developed above the fluvio-lacustrine sediments, or the two gravel-clay complexes.
87 The number of loess and palaeosol units on the seven river terraces $T_6 - T_0$ ¹ depends strongly
88 on the age of the terrace formation. Six loess units occur on T_6 but only one on T_1 .

89 The Viatovo loess/palaeosol sequence in NE Bulgaria is exposed in the walls of a quarry
90 that was opened for extraction of kaolin (Fig. 1b). Palaeosols and loess units that could be
91 recognised in the field were numbered and are designated respectively S_1, S_2, \dots and $L_1,$
92 L_2, \dots . The sequence consists of topsoil S_0 , 7 loess horizons ($L_1 - L_7$) and 6 interbedded
93 palaeosols ($S_1 - S_6$) resting on a red clay (terra rossa) complex. In the sampling area, the
94 recent soil S_0 was truncated by quarry activities and only the lower part was preserved,
95 characterised by its dark gray colour and prismatic structure. The upper three palaeosols ($S_1 -$
96 S_3) are dark brown in colour, becoming gradually more reddish towards the bottom part of the
97 units. Abundant reddish crotovinas (burrows) perforate the uppermost soil horizon. A
98 prismatic structure is typical for the middle part of the soil units. Their lower parts are rich in
99 CaCO_3 nodules, reaching sizes of a few centimetres in the bottom of S_2 . Palaeosols $S_4 - S_6$
100 show a brown-reddish to brown-pinkish colour, have a compact clayey prismatic structure

101 and contain CaCO_3 concretions of different sizes (up to 5cm) in their bottom parts. The first
102 loess unit L_1 shows signs of secondary pedogenic alterations. Its colour is dark brown and it
103 has a granular structure with CaCO_3 coatings. Crotovinas, several centimetres in size, are
104 visible over the whole unit and increase in number and size in its lower part. The least altered
105 loess unit is L_2 , yellowish in colour and with abundant CaCO_3 specks. Loess unit L_3 is
106 affected by pedogenic alteration, brown in colour and with abundant CaCO_3 spots. The
107 thickness of unit L_4 is only 50cm and it consists of brown-reddish crumbly loess with large
108 CaCO_3 blocks. Unit L_5 is more powdery loess with CaCO_3 spots that are locally highly
109 concentrated and with red crotovinas in the bottom part. The sixth loess unit L_6 is brown-
110 pinkish in its upper part and becomes brown and more clayey in depth. Dark brown
111 crotovinas are visible over the whole unit. Loess unit L_7 shows also signs of severe
112 weathering. It is brown reddish to brown pinkish in colour, clayey and contains CaCO_3 spots.
113 Downward, it becomes yellowish with large brown reddish veins of clayey silt that occupy
114 about 30% of the total surface in a vertical section. The red clays in the bottom part of the
115 sequence, reaching a total thickness of 5.6m, have a prismatic structure with shiny black Mn
116 coatings on the fractures. Horizontal CaCO_3 lenses (5 to 10cm thick and 20 to 40cm long)
117 occur at about 2.9 m below the top of the red clay complex, which are further down replaced
118 by red clay mixed with large irregular CaCO_3 blocks. The bottom part of the sequence, ending
119 at the kaolin level, is compact yellow sandy clay with some CaCO_3 lenses.

120

121 **3. Methods**

122 The complete sequence has been sampled in four non-overlapping sections. Section 1
123 includes: topsoil S_0 , first loess unit L_1 , first palaeosol unit S_1 and units L_2 , S_2 and L_3 . Section 2
124 covers units S_3 , L_4 , S_4 , L_5 , S_5 and L_6 . Section 3 contains palaeosol S_6 and the underlying loess
125 unit L_7 . The fourth section cuts 5.60 m through the red clays down to the kaolin level. The

126 vertical sections were cut deeply in the walls of the pit in order to reach fresh, non exposed
127 material. As the main units could be followed easily along the walls of the pit (Fig. 1b) and
128 the whole sequence was sampled in only four vertical sections, the risk of overlapping and/or
129 sampling gaps could be avoided. Hence, the total thickness of the complete composite section
130 after adding the four sections is 27m. In total, 275 oriented cylindrical samples (sampling
131 interval of 10cm) for palaeomagnetic analysis were obtained with a hand-held piston driven,
132 split corer, specially designed for the purpose. The corer was driven horizontally in the
133 sediment and the cores oriented with a clinometer, solar and magnetic compass, in the same
134 way as it is commonly done for hard rocks. Mechanical disturbance was minimized as the
135 core (2.5cm in diameter and about 7cm long) can be recuperated by opening the two halves of
136 the corer. Close to section 1, another parallel section encompassing S₀, L₁, S₁, L₂ and S₂ was
137 sampled additionally with a narrower sampling interval of 5cm for verification of the
138 presence (or absence) of the Blake event.

139 Moreover, two decimetre-sized oriented block samples were cut in all the units and loose
140 samples taken from the whole sequence with a sampling interval of 5cm for, respectively,
141 anisotropy of magnetic susceptibility (AMS) measurements and rock magnetic analysis.
142 Remanent magnetisation measurements were carried out in a three-axis cryogenic rock
143 magnetometer of 2G Enterprises, equipped with an in-line alternating field demagnetiser.
144 Isothermal remanent magnetisations were imparted to samples of each unit in a 2G pulse
145 magnetiser in fields up to 2.6T. Small one-inch cubes were cut from the oriented block
146 samples for AMS measurements in a KLY-3S magnetic susceptibility meter.

147

148

149 **4. Experimental results**

150 Rock magnetic properties and grain size analysis of all the units had been investigated in
151 detail before the palaeomagnetic examination started (Jordanova et al. 2007). In brief,
152 magnetic mineralogy deduced from thermomagnetic analysis of magnetic susceptibility,
153 induced magnetisation in strong fields and Mössbauer analysis suggest that magnetite,
154 oxidised magnetite and hematite are the main ferri- and antiferromagnetic phases present.
155 Mössbauer analysis of magnetic separates from S₁ and L₂ yielded more or less similar results.
156 The presence of maghemite was revealed in the strong magnetic fraction of S₁ but not in L₂.
157 The clay content along the sequence does not vary significantly and the mean percentage,
158 both in loess and soil horizons, is around 30. Exceptions are the less altered loess units L₂ and
159 L₅ with lower clay content. The observed high clay content but small differences in clay
160 content between soils and loesses are manifestation of the enhanced weathering and
161 pedogenesis, even during the glacials, particularly in the lower part of the section. All the
162 palaeosol units are characterised by high frequency dependent magnetic susceptibility ($\chi_{FD}\%$)
163 with values up to 12%, pointing to a significant superparamagnetic (SP) fraction. A relatively
164 high content of SP Fe₃O₄ grains can also be assumed for loess units L₁, L₃, L₆ and L₇
165 (Jordanova et al. 2007). The presence in loesses of pedogenic magnetically soft grains in the
166 SP and viscous SP/SD (SD = single domain) state is also supported by the relatively low
167 coercivity (B_c) and coercivity of remanence (B_{cr}) values in these units, comparable to the
168 values attained in the palaeosols.

169 Additional rock magnetic experiments that are presented below yield further information
170 about the nature and magnetic stability of the remanence carriers as well as of the magnetic
171 fabric of all the units.

172 Fifteen samples were prepared from loose materials collected in all the units for a viscous
173 remanent magnetisation (VRM) acquisition experiment. Mechanical redistribution of the
174 grains, randomising any pre-existing remanence was chosen as a “demagnetisation”

175 technique. This option was preferred in order not to change the original domain state as is the
176 case during AF demagnetisation (Jordanova et al. 2007), or mineralogy that often happens
177 when heating loess and soil samples above their Curie-temperatures (T_c) followed by cooling
178 in zero field. Gently crushed and sieved material was pressed into PVC cylinders and sealed
179 with epoxy resin. Spontaneous VRM build-up in an ambient field of $48 \mu\text{T}$ was monitored
180 over 2 months (Fig. 2). Samples from the upper part of the sequence ($S_0 - L_4$) show two
181 different linear segments in the VRM versus $\log(t)$ graphs, separated at the elapsed time of
182 about 6 weeks [corresponding to $\log(t) = 5.57$]. Both palaeosols and loesses (respectively S_0 -
183 S_3 and L_1 - L_4) show this peculiarity in contrast to the units from the lower part of the section
184 ($S_4 - L_7$, red clay). Calculation of viscous acquisition coefficients (S_a), taking separately the
185 two slopes of the VRM($\log t$) relationship (respectively S_{a1} and S_{a2}), reveals the presence of
186 a fraction that acquires viscous magnetisation more slowly. In order to evaluate the
187 significance of an ultrafine grained fraction in the total viscosity, a plot of the S_{a1} coefficients
188 as function of $\chi_{\text{FD}}\%$ (Forster et al., 1994) is given in Fig. 3. The leading role of the
189 concentration on the amount of viscous acquisition is revealed by the good linear correlation
190 between S_{a1} and $\chi_{\text{FD}}\%$ (with correlation factor $R^2 = 0.91$).

191 Stepwise IRM acquisition in pulse fields up to 2.6 T was monitored for 15 samples
192 representative for each lithological unit. Magnetic mineral components contributing to the
193 total remanence were unmixed, following the procedure by Heslop et al. (2002) and applying
194 the IRM Unmix software. The initial state of the samples was an AF-demagnetisation state,
195 which is most suitable when fitting log-normal distributions to IRM acquisition curves
196 (Heslop et al., 2004). The best fit was obtained with a 3-component model and some
197 representative examples are shown in Figure 4. Component 1, which is the main component
198 in the palaeosol samples, is characterised by a relatively low coercivity maximum $B_{1/2}$ at
199 around 27mT in the palaeosol as well as in the loess samples (Fig.4 and Table 1). In the

200 palaeosol samples it contributes from 40 up to 70% (with an average of 51%) to the total
201 IRM. On the other hand, component 2 is the main component in the loess samples with an
202 average contribution of 53% to the total IRM and a coercivity peak around 70 to 80mT. A
203 distinct high-coercivity component, component 3, with quite varying maximum coercivities
204 between about 150 and 960mT can be identified in all samples (Table 1 and Table 2). In
205 general, maximum coercivities of component 3 are lower in palaeosol samples and most
206 weathered loess samples compared to less weathered loesses. Irrespective of the nature of the
207 samples it contributes around 13% to the total IRM (Table 1). A good linear correlation is
208 observed between the absolute intensity of component 1 and the viscous acquisition
209 coefficient S_a and/or S_{a2} (for two-slope curves) (Fig. 5). From the $B_{1/2}$ versus relative
210 contribution graph in Figure 6 and from Table 2 it is clear that the higher the coercivity of
211 component 3, the smaller its relative contribution to the total IRM. Component unmixing for
212 the sample from the recent soil S_0 reveals quite different values for the unmix parameters
213 compared to the palaeosols and this is the reason to enter the data separately in Table 1.

214 Stepwise alternating field and thermal demagnetisations of $IRM(2.6T)$ were applied to
215 several samples in order to gain information about the unblocking spectra of the remanence
216 carriers. The examples given in Figure 7 show a more or less similar behaviour for both loess
217 and palaeosol samples. Median destructive fields (MDF) of $IRM(2.6T)$ are in the range of
218 15.8 - 16.9mT for palaeosols and in the range 17.5 - 21.2mT for loesses (Fig. 7a). This very
219 soft magnetic behaviour is accompanied by relatively high unblocking temperatures as can be
220 seen from the thermal demagnetisation curves (Fig. 7b). Half of the total IRM is
221 demagnetised between 270 and 300°C with a fairly continuous unblocking spectrum up to
222 680°C, above which complete demagnetization of the initial IRM is observed. The slightly
223 enhanced unblocking of IRM at about 300°C, especially in the palaeosol samples, is

224 accompanied by a strong increase at the same temperature in the room-temperature magnetic
225 susceptibility measured after each heating-cooling step (Fig. 7c).

226 Anisotropy of magnetic susceptibility measurements on oriented one-inch cubes, cut
227 from the oriented block samples, reveal a normal sedimentary fabric with average maximum
228 (K_{max}) and intermediate (K_{int}) susceptibility directions in the bedding plane (Fig. 8). The
229 scatter of principal directions is relatively high compared to other loess deposits (Matasova et
230 al., 2001; Hus, 2003; Lagroix and Banerjee, 2004; Zhu et al., 2004) but similar to the loess-
231 palaeosol sequence of Roxolany in Ukraine (Hus, 2003). Only the principal susceptibility
232 directions of specimens from the least weathered loess unit L2 are much less scattered (Fig.
233 8b). Table 3 summarizes the average principal anisotropy parameters lineation (L), foliation
234 (F), corrected degree of anisotropy (P') and shape parameter T (Jelinek, 1981) for palaeosols,
235 loesses and red clay samples, respectively. No highly significant differences among the values
236 for the three groups can be observed. The low degree of anisotropy, less than 4%, is typical
237 for loesses and palaeosols. A slightly higher degree of 7% is obtained for the red clays.

238 The best “cleaning” technique for the determination of the characteristic remanent
239 magnetisation (ChRM) was chosen after stepwise thermal as well as alternating field (AF)
240 demagnetisation test experiments on pilot samples. The AF demagnetisation with increasing
241 maximum amplitude up to 150 mT reveals the presence of a very soft remanence component
242 (Fig. 9). Values of the MDF of NRM (MDF_{NRM}) are in the range 7.0 - 12.0mT for loess and
243 soil samples, consistent with the presence of a significant VRM in both. Moreover, there is a
244 negative relationship between MDF_{NRM} values and the percent relative contribution of the
245 first component from the IRM unmixing (Fig. 10). Figure 11 shows several examples of the
246 directional and intensity changes of loess and soil samples during stepwise thermal
247 demagnetisation. It is clear that besides a stable ChRM component; the samples contain an
248 important unstable component, probably of viscous origin. Cleaning temperatures of 300°C,

249 325°C and 350°C were finally chosen to isolate the ChRM of the whole collection of oriented
250 samples. The depth variation of the ChRM direction (declination D , inclination I) and
251 intensity along the composite section after partial demagnetization at 325°C is given in figure
252 12a. The declination is predominantly eastward and attains relatively high values in the upper
253 part of section 1 (S_1 , L_2 and upper part of S_2), accompanied by relatively low inclination
254 values. One single sample in the upper part of S_1 reaches an anomalous intermediate
255 declination value. Below S_2 , the profile declination varies around zero, but remains
256 predominantly eastward down to loess unit L_7 (Fig. 12a), where it becomes southward
257 accompanied by negative inclinations. This polarity change is interpreted as corresponding to
258 the Matuyama/Brunhes transition. Higher resolution of the directional changes in L_7 was
259 obtained in a parallel section (Fig.12b). The switching of the inclination is observed within
260 the bottom part of loess unit L_7 , where the loess becomes yellowish with large brown reddish
261 veins suggesting strong leaching. Declination does not show any systematic behaviour and
262 remains eastward when inclination becomes negative. Two reversed magnetozones can be
263 recognized in the red clay unit, although in a few samples no stable end-direction could be
264 reached after cleaning at 325°C. Rapid oscillations of declination within the upper part of the
265 red clays (between 22 and 24m depth) complicate the interpretation of the geomagnetic field
266 behaviour in this part of the record. The ChRM signal of a parallel section in the upper part of
267 section 1, sampled at 5 cm interval, did not reveal any indication of short term field reversals
268 or “excursions” similar to the Blake event (data not shown). Wiegank (1977) claimed to have
269 found the latter in unit L_3 of a loess/palaeosol section near Russe on terrace T_6 of the Danube
270 river.

271

272 **5. Discussion**

273 5.1. Remanence carriers and magnetic stability

274 According to the results from previous detailed rock magnetic investigations, magnetite and
275 oxidised magnetites (maghemite) are the main remanence carriers in the palaeosol/loess units
276 of the Viatovo sequence. (Jordanova et al. 2007). Viscous acquisition experiments reported
277 this time contribute to a better understanding of their grain size distribution. The observed
278 two-slope VRM acquisition in samples from the upper units (S₀, L₁, S₁, L₂, S₂, L₃, S₃, L₄) and
279 single-slope in the older units (Fig. 2), probably indicates different populations of viscous
280 grains in the upper part compared to the lower part of the sequence. This is consistent with the
281 differentiation of palaeosol units according to the calculated background susceptibility for
282 each unit in Jordanova et al. (2007). Previous studies by Evlogiev (2006) indicate that the
283 recent soil S₀ and the first three palaeosols are Chernozems, while the older palaeosols show
284 features of forest soils that developed in a more humid climate. Thus, it can be inferred that
285 the soil type (e.g. climate) is the main factor determining magnetic grain size distribution of
286 the pedogenically produced fine grained ferrimagnetic fraction. A possible explanation for the
287 single-slope behaviour is that in the older palaeosols a higher degree of grain surface low-
288 temperature oxidation has led to a more uniform population of viscous maghemite grains. On
289 the other hand, in the dryer conditions of steppe vegetation, when Chernozems are formed,
290 grains are expected still to have a non-oxidised core with oxidised rim. Such grains, in which
291 the two phases are exchange coupled, are responsible for increased bulk coercivity (Van
292 Velzen and Zijdeveld, 1995; Cui et al., 1994; Dunlop and Ozdemir, 1997). The good
293 correlation between $\chi_{FD}\%$ and Sa coefficients, with $R^2= 0.91$, suggests that the concentration
294 of fine viscous SP/SD grains is proportional to the degree of pedogenic enhancement both in
295 palaeosol and loess units (Fig. 3). The dominant role of the fine grained fraction in the
296 determination of magnetic viscosity of the loess/palaeosol samples is revealed by this linear
297 relationship. This implies also that the “in situ” formed pedogenic fraction has a broad grain
298 size distribution, spanning the whole range from SP, viscous SP/SD to stable SD grains.

299 Analysis and modelling of IRM acquisition curves by a set of log-normal probability density
300 functions, applying an expectation – maximization algorithm and the IRMunmix program by
301 Heslop et al. (2002), confirms the above conclusion. The results suggest that the best fit of the
302 experimental data is obtained with a 3-component model (Fig. 4). Component 1 with $B_{1/2}$ of
303 $27 (\pm 3)$ mT on average and dispersion parameter DP of $0.24 (\pm 0.02)$ is identified in both loess
304 and palaeosol samples. It only varies in its relative contribution to the total IRM, with a
305 maximum contribution in the palaeosols and a minimum in the loess samples (Table 1).
306 Similar results have been reported by Spassov et al. (2003a) for the P-component in loess-
307 palaeosol samples from the Lingtai section on the central Loess Plateau of China with $B_{1/2}$ of
308 $31 (\pm 4)$ mT. The second component yields a $B_{1/2}$ value of $35 (\pm 8)$ mT or a slightly lower
309 coercivity compared to the second component of Eyre (1996). The aforementioned data, as
310 well as our data, are slightly higher than the reported $B_{1/2}$ value of 20mT and DP of 0.25 to
311 0.38 by Geiss and Zanner (2006) for the pedogenic component in modern loessic soils from
312 mid-western United States. However, these authors analysed AF-demagnetisation curves of
313 IRM, which yield systematically lower estimations of the bulk coercivity, because the mean
314 interaction field in a sample is a demagnetising field that aids in AF demagnetisation but
315 opposes IRM acquisition (Dunlop and Ozdemir, 1997). On the other hand, we obtained a
316 good linear correlation between the estimated intensity of component 1 and the viscous
317 acquisition coefficients S_a (for single – slope samples) and S_{a2} (for two-slope samples) (Fig.
318 5). It confirms our view that the population of grains above the critical SP/SD size, which
319 acquires an isothermal remanence, is a continuation of a common distribution of the
320 pedogenic fraction.

321 Component 2 is characterized by $B_{1/2}$ of $70 (\pm 12)$ mT and DP of $0.32 (\pm 0.02)$ (Table 1). Its
322 relative contribution is highest in the loess samples with values up to 59% and most probably
323 corresponds to the presence of oxidised detrital magnetites.

324 Interpretation of the third component of the IRM unmixing should take into account the high
325 variability of the coercivity $B_{1/2}$, which is in close relation to the degree of secondary
326 alteration (Table 2). Moreover, the negative linear relationship of $B_{1/2}$ and the relative
327 contribution of component 3 in Figure 6 strongly suggest that this component represents
328 detrital SD-PSD grains with progressively higher degree of low-temperature oxidation of
329 magnetite to maghemite and, finally, hematite. But the observed very soft magnetic behaviour
330 of IRM against AF-demagnetisation (Fig. 7a) suggests that hematite does not contribute
331 significantly to the total remanence.

332 The enhanced unblocking of the isothermal remanence at around 300°C in Figure 7b can be
333 interpreted as being related to the inversion of maghemite (Evans and Heller, 1994). This
334 interpretation is supported by the obtained mean coercivity of the first component of the IRM
335 acquisition, corresponding quite well to the reported values for SD magnetites (Maher, 1988)
336 and maghemites (Enkin and Dunlop, 1987). At the same time, the strong increase in bulk
337 magnetic susceptibility measured after each heating step (Fig. 6c) is probably ~~is~~ due to
338 thermal transformation of the clay minerals and Fe-oxyhydroxides (lepidocrocite, ferrihydrite,
339 goethite) in the presence of reducing agents (organic matter) (Cornell and Schwertmann,
340 1996; Campbell et al., 1997) and partly caused by remanence unblocking. Thermal
341 demagnetisation of IRM(2.6T) (Fig. 7b) indicates also that there is still some remanence
342 demagnetised at temperatures well beyond 620°C. Similar parameters and thermal behaviour
343 have been observed for the detrital component D2 by Spassov et al. (2003a) and interpreted
344 by these authors as being carried by altered detrital magnetites.

345

346 5.2. Palaeomagnetism: ChRM and magnetostratigraphy

347

348 The preservation of the original detrital fabric in weakly consolidated sediments, like loess
349 and palaeosols, is some guarantee in magnetostratigraphical investigations that the directional
350 results are not entirely influenced by secondary alterations and mechanical disturbances. AMS
351 measurements of all the units of the Viatovo section (Fig. 8a) show that despite some high
352 scatter in the distribution of the principal susceptibility directions, a typical depositional
353 magnetic fabric is still preserved with K_{max} on average in the horizontal (bedding) plane and
354 K_{min} in the vertical plane. Shallower inclination values of K_{min} for several samples are
355 obviously due to bioturbation and may be also to clay films (translocation) along vertical
356 cracks as it could be observed in the field. As shown in previous studies (Hus, 2003), “in situ”
357 formation of the pedogenic magnetic fraction does not influence very much the primary
358 magnetic fabric of loess sediments. The better grouping of the K_{min} directions for samples
359 from unit L_2 (Fig. 8b), the loess unit least affected by secondary alterations and bioturbation,
360 confirms our assumption that mechanical disturbance due to bioturbation in the other units is
361 the main cause for the scatter in the principal directions. The low degree of anisotropy and
362 foliation (Table 3) indicate that the magnetic fabric, governed mainly by the ferrimagnetic
363 fraction because of relatively high mean susceptibility values, is quite isotropic.

364 Alternating field demagnetisation of NRM revealed very soft behaviour (Fig. 9) with less
365 than 20% of the original signal left after treatment in a 30mT field. This prevailing
366 contribution of the low-coercivity component (probably responsible for the VRM) led us to
367 choose thermal treatment as the optimal technique for determining the characteristic
368 remanence direction. Furthermore, the observed correlation between MDF_{NRM} and the relative
369 contribution of component 1 (identified by the IRM unmixing procedure in Figure 10 and
370 interpreted as pedogenic maghemite) convinced us that AF cleaning would be less successful
371 in isolating the characteristic remanence carried by the detrital magnetites (component 2) and
372 magnetites oxidised at different degree (component 3).

373 Stepwise thermal demagnetisation experiments revealed the presence of a secondary
374 component more or less in the present day magnetic field direction (Fig. 11), probably of
375 viscous or chemical origin. This component is demagnetised upon heating to 200 – 250°C,
376 which is also indicated by the change in slope of the NRM intensity versus temperature
377 curves. ChRM directions after partial demagnetisation at 300, 325 and 350°C were
378 determined by principal component analysis and show consistent behaviour (Fig. 12). Some
379 scattered directions and the two normal directions at the M/B polarity reversal interval may be
380 due some mechanical disturbance of the loess material and chemical overprinting after
381 deposition as suggested by the presence of large secondary carbonate concretions and clayey
382 reddish veins (see also Zhu et al., 2006). Another reason for the observed rapid directional
383 changes during polarity transitions may be the lock-in depth mechanism in loess-palaeosol
384 sediments and/or chemical overprinting as described in Spassov et al. (2003b). An earlier
385 palaeomagnetic investigation of the lower part of the loess complex near Russe, in the
386 Nikolovo section, located the M/B boundary between units S₆ and L₇ (Butchvarova, 1993).
387 The magnetisation of the red clay unit switches twice from reversed to normal polarity (Fig.
388 12). According to the results of the rock magnetic investigations (Jordanova et al, 2007), the
389 red clay unit may be considered as a thick pedocomplex that formed in subaerial conditions
390 with high weathering potential. Magnetic susceptibility variations suggest the presence of at
391 least two palaeosols (Fig. 12). The two periods of normal polarity correspond with an increase
392 in magnetic susceptibility in the two sub-units. The normal polarity magnetozone revealed in
393 the upper part of the red clay unit is assumed to correspond to the Jaramillo subchronozone
394 (0.99 - 1.07 Ma) or spanning stages 27 to 31 of the $\delta^{18}\text{O}$ chronology (Shackleton et al., 1990;
395 Tiedemann et al., 1994). The second normal polarity event is found in the middle of the red
396 clays. Because of its relatively long duration and the lower age estimate of the red clay
397 complex at 2.6 Ma (Evlogiev, 1993) it can be reasonably assumed that it corresponds to the

398 Olduvai subchron (1.78 - 1.94 Ma). Indeed, the short lived Cobb Mountain event identified in
399 deep-sea sediments (Biswas et al., 1999; Yang et al., 2004) is unlikely to have been recorded
400 or preserved in the record because of a low sedimentation rate, smoothing and post-
401 depositional alterations. Indeed, this event is rarely found in loess/soil sequences (Rolph et al.,
402 1989). The recently reported Kamikatsura and Santa Rosa short-lived geomagnetic excursions
403 in loess unit L₉ of the Chinese loess (Yang et al., 2004) are probably absent in the Viatovo
404 section for the same reasons – the low sedimentation rate as well as the strong secondary
405 alteration of loess unit L₇. The absence of the Blake event in the Viatovo section is not
406 unusual, as discussed in other studies (Zhu et al., 1998; Stevens et al., 2006). Its presence
407 would have been of great importance for the Late-Pleistocene stratigraphy of the
408 loess/palaeosol sequence and for the identification of the last interglacial palaeosol. Indeed, in
409 many loess deposits in Western Europe (Hus and Geeraerts, 1986) the first palaeosol
410 encountered in depth is not an interglacial but an interstadial soil corresponding to stage 3 of
411 the oxygen isotope record (Shackleton et al., 1990). Therefore, the stratigraphy of the upper
412 part of the Viatovo sequence is deduced by correlation of its magnetic susceptibility signature
413 with the astronomically tuned $\delta^{18}\text{O}$ record from ODP site 677 (Fig. 13). According to the
414 previous established correlation between the magnetic susceptibility record of a core taken in
415 the loess/palaeosol sequence in Koriten in NE Bulgaria (Jordanova and Petersen, 1999),
416 palaeosol S₁ in Viatovo is the last interglacial (Eemian) soil (Fig. 13). Stage 3 is witnessed in
417 Viatovo by some high magnetic susceptibility values in the upper part of L₁, similar to the
418 Koriten record. With the two time constraints in the sequence, the Eemian soil and the
419 position of the M/B boundary, the one to one correspondence between magnetic susceptibility
420 variations and the $\delta^{18}\text{O}$ variations in the ODP 677 record strongly suggests that each palaeosol
421 that can be recognised in the Viatovo sequence corresponds to an interglacial.

422

423 **6. Conclusions:**

424

- 425 1. Magnetic mineralogy (nature and magnetic domain state) of the loess-palaeosol units
426 from the Viatovo section deduced from unmixing IRM acquisition curves, VRM
427 acquisition experiments and thermal demagnetization of IRM(2.6T) indicate the
428 presence of pedogenic magnetite/maghemite particles spanning SP, viscous SP/SD
429 and stable SD sizes. Their contribution is especially enhanced in the palaeosols.
430 Detrital magnetic minerals are probably oxidised PSD magnetites, whereas the
431 contribution of hematite to the magnetic properties is insignificant. A three component
432 model fits best the experimental IRM acquisition curves. The third component shows
433 highly variable mean magnetic coercivity among the samples, reflecting the degree of
434 alteration of the original detrital magnetite grains with increasing oxidation.
- 435 2. The magnetic fabric of loess/palaeosol samples from the Viatovo section, revealed by
436 AMS measurements, points to an initial normal sedimentary fabric that has been
437 modified to some degree after deposition by pedogenic processes. Field evidence
438 shows that the scatter of the principal susceptibility directions can be mainly attributed
439 to mechanical disturbances due to bioturbation (presence of crotovinas) and eventually
440 clay migration along cracks.
- 441 3. The record of the Matuyama – Brunhes polarity transition in loess unit L₇ displays
442 several rapid directional changes of the characteristic remanence.
- 443 4. Notwithstanding strong pedogenesis, weathering and viscous overprints, a detailed
444 magnetostratigraphy of the Viatovo section in North Bulgaria could be established.
445 The Matuyama/Brunhes boundary has been recorded in the oldest loess unit L₇
446 present. Two normal polarity magnetozones, discovered in the underlying red clay
447 formation, probably correspond to the Jaramillo and Olduvai subchronozones.

448

449

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453

454 **References:**

- 455 Biswas, D., Hyodo, M., Taniguchi, Y., Kaneko, M., Katoh, S., Sato, H., Kinugasa, Y.,
456 Mizuno, K., 1999. Magnetostratigraphy of Plio-Pleistocene sediments in a 1700-m
457 core from Osaka Bay, southwestern Japan and short geomagnetic events in the middle
458 Matuyama and early Brunhes chrons. *Paleogeogr., Paleoclimatol., Paleoecol.*, 148,
459 233-248.
- 460 Butchvarova, V., 1993. Magnetostratigraphy of Neogene - Quaternary sediments from Eastern
461 and Central Parathetys. Ph. D. Thesis, Bulgarian Academy of Sciences, Sofia (in
462 Bulgarian).
- 463 Campbell, A., Schwertmann, U., Campbell, P., 1997. Formation of cubic phases on heating
464 ferrihydrite. *Clay Minerals*, 32, 615-622.
- 465 Cornell, R. and Schwertmann, U., 1996. *The Iron Oxides. Structure, properties, reactions,*
466 *occurrence and uses.* VCH Verlagsgesellschaft, Weinheim, New York.
- 467 Cui, Y., Verosub, K., Roberts, A., 1994. The effect of low temperature oxidation on large
468 multidomain magnetite. *Geophys. Res. Lett.*, 21, 757 – 760.
- 469 Dodonov, A., Zhou, L.P., Markova, A., Tchepaliga, A., Trubikhin, V., Aleksandrovski, A.,
470 Simakova, A., 2006. Middle-Upper Pleistocene bio-climatic and magnetic records of
471 the Northern Black Sea Coastal Area. *Quat. Int.*, 149, 44-54.

- 472 Dunlop, D. and Ozdemir, O., 1997. Rock Magnetism. Fundamentals and frontiers, (D.
473 Edwards, ed.), Cambridge Studies in Magnetism, Cambridge University Press.
- 474 Enkin, R., Dunlop, D., 1987. A micromagnetic study of pseudo-single-domain remanence in
475 magnetite. *J. Geophys. Res.*, 92, 12 726 – 12 740.
- 476 Evans, M. and Heller, F., 1994. Magnetic enhancement and palaeoclimate: study of a
477 loess/palaeosol couplet across the Loess Plateau of China. *Geophys. J. Int.*, 117, 257-
478 264.
- 479 Evlogiev, J., 1993. Palaeogeography and stratigraphy of the Early Pleistocene in near Danube
480 Northeastern Bulgaria. Ph.D. Thesis, Bulgarian Academy of Sciences, Sofia, (in
481 Bulgarian).
- 482 Evlogiev, J., 2006. The Pleistocene and Holocene in the Danube plain. Doctoral Dissertation
483 Bulg. Acad. Sci., Sofia. (in Bulgarian).
- 484 Eyre, J., 1996. The application of high resolution IRM acquisition to the discrimination of
485 remanence carriers in Chinese loess. *Studia geoph. et geod.*, 40, 234 – 242.
- 486 Forman, S. L., Pierson, J., Lopper, K., 2000. Luminescence Geochronology. . In: Quaternary
487 Geochronology. Methods and Applications. AGU Reference Sheet 4, eds: J. Noller, J.
488 Sowers, W. Lettis Washington, DC, 157 – 176.
- 489 Forster, T., M. Evans and F. Heller, 1994. The frequency dependence of low field
490 susceptibility in loess sediments. *Geophys. J. Int.*, 118, 636-642.
- 491 Geiss, C. E. and Zanner, C.W., 2006. How abundant is pedogenic magnetite? Abundance and
492 grain size estimates for loessic soils based on rock magnetic analyses. *J. Geophys.*
493 *Res.*, 111, B12S21, doi: 10.1029/2006JB004564.
- 494 Gendler, T., Heller, F., Tsatskin, A., Spassov, S., du Pasquier, J., Faustov, S., 2006.
495 Roxolany and Novaya Etuliya – key sections in the western Black Sea loess area:

- 496 Magnetostratigraphy, rock magnetism, and paleopedology. *Quat. Int.*, 152 – 153, 89 –
497 104.
- 498 Heslop, D., Dekkers, M., Kruiver, P., van Oorschot, H., 2002. Analysis of isothermal
499 remanent magnetization acquisition curves using the expectation – maximization
500 algorithm. *Geophys. J. Int.*, 148, 58 – 64.
- 501 Heslop, D., McIntosh, G., Dekkers, M., 2004. Using time- and temperature-dependent
502 Preisach models to investigate the limitations of modelling isothermal remanent
503 magnetization acquisition curves with cumulative log Gaussian functions. *Geophys. J.*
504 *Int.*, 157, 55 – 63.
- 505 Huntley, D., Godfrey-Smith, D., Thewalt, M., 1985. Optical dating of sediments. *Nature*, 313,
506 105 – 107.
- 507 Hus, J., and Geeraerts, R., 1986. Palaeomagnetic and rock-magnetic investigation of Late-
508 Pleistocene loess deposits in Belgium. *Phys. Earth Planet. Inter.*, 44, 21-40.
- 509 Hus, J., 2003. The magnetic fabric of some loess/palaesol deposits. *Phys. Chem. Earth*, 28,
510 689-699.
- 511 Hutt, G., Jaek, I., Tchonka, J., 1988. Optical dating: K-feldspars optical response stimulation
512 spectra. *Quat. Sci. Rev.*, 7, 381 – 385.
- 513 Jelinek V., 1981. Characterization of the magnetic fabric of rocks. *Tectonophysics*, 79, 63-67
- 514 Jordanova, D. and Petersen, N., 1999. Palaeoclimatic record from a loess-soil profile in
515 northeast Bulgaria – II. Correlation with global climatic events during the Pleistocene.
516 *Geophys. J. Int.*, 138, 2, 533-540.
- 517 Jordanova, D., Jordanova, N., Henry, B., Hus, J., Bascou, J., Funaki, M., Dimov, D., 2007.
518 Changes in mean magnetic susceptibility and its anisotropy of rock samples as a result
519 of alternating field demagnetization. *Earth Planet. Sci. Lett.*, 255, 3-4, 390 – 401.

- 520 Jordanova, D., Hus, J. and Geeraerts, R., 2007. Palaeoclimatic implications of the magnetic
521 record from loess/palaeosol sequence Viatovo (NE Bulgaria). *Geophys. J. Int.*, 171,
522 1036-1047. doi: 10.1111/j.1365-246X.2007.03576.x
- 523 Lagroix, F., Banerjee, S., 2004. The regional and temporal significance of primary Aeolian
524 magnetic fabrics preserved in Alaskan loess. *Earth Planet. Sci. Lett.*, 225, 379 – 395.
- 525 Matasova, G., Petrovsky, E., Jordanova, N., Zykina, V., Kapicka, A., 2001. Magnetic study of
526 Late Pleistocene loess/palaeosol sections from Siberia: palaeoenvironmental
527 implications. *Geophys. J. Int.*, 147 (2), 367 – 380.
- 528 Maher, B., 1988. Magnetic properties of some synthetic sub-micron magnetites. *Geophys. J.*,
529 94, 83 – 96.
- 530 Nawrocki, J., Bogucki, A., Lanczont, M., Nowaczyk, N., 2002. The Matuyama – Brunhes
531 boundary and the nature of magnetic remanence acquisition in the loess-palaeosol
532 sequence from the western part of the East European loess province. *Palaeogeogr.*
533 *Palaeoclimatol. Palaeoecol.*, 188, 39 – 50.
- 534 Pye, K., 1987. *Aeolian dust and dust deposits*. Academic Press, Harcourt Brace Jovanovich
535 Publ., London.
- 536 Rolph, T., Shaw, J., Derbyshire, E. and Wang, J.T., 1989. A detailed geomagnetic record
537 from Chinese loess. *Phys. Earth Planet. Inter.* 56, 151-164.
- 538 Shackleton, N., Berger, A. and Peltier, R., 1990. An alternative astronomical calibration of the
539 lower Pleistocene timescale based on ODP site 677. *Trans. Royal Soc. Edinburg Earth*
540 *Sciences*, 81, 251-261.
- 541 Singhvi, A.K., Bluszcz, A., Bateman, M.D., Someshwar Rao, M., 2001. Luminiscence daing
542 of loess-palaeosol sequences and coversands: methodological aspects and
543 palaeoclimatic implications. *Earth Sci. Rev.*, 54, 193 – 211.

- 544 Spassov, S., Heller, F., Kretzchmar, R., Evans, M., Yue, L., Nourgaliev, D., 2003a. Detrital
545 and pedogenic magnetic mineral phases in the loess/palaeosol sequence at Lingtai,
546 (Central Chinese Loess Plateau). *Phys. Earth Planet. Inter.*, 140, 255 – 275.
- 547 Spassov, S., Heller, F., Evans, M., Yue, L., von Dobeneck, T., 2003b. A lock-in model for the
548 complex Matuyama-Brunhes boundary record of the loess/palaeosol sequence at
549 Lingtai (Central Loess Plateau). *Geophys. J. Int.*, 155 (2), 350 – 366.
- 550 Stevens, Th., Armitage, S., Lu, H., Thomas, D., 2006. Sedimentation and diagenesis of
551 Chinese loess: Implications for the preservation of continuous, high-resolution climate
552 records. *Geology*, 34, 10, 849 – 852, doi: 10.1130/G22472.1
- 553 Tiedemann, R., Sarnthein, M., Shackleton, N., 1994. Astronomic timescale for the Pliocene
554 Atlantic $\delta^{18}\text{O}$ and dust flux records of Ocean Drilling Program site 659.
555 *Paleoceanography*, 9, 619-638.
- 556 Trumbore, S. E., 2000. Radiocarbon Geochronology. In: *Quaternary Geochronology.*
557 *Methods and Applications.* AGU Reference Sheet 4, eds: J. Noller, J. Sowers, W.
558 Lettis Washington, DC, 41 – 60.
- 559 Tsatskin, A., Heller, F., Gendler, T., Virina, E., Spassov, S., du Pasquier, J., Hus, J.,
560 Hailwood, E., Bagin, V. and Faustov, S., 2001. A new scheme of terrestrial
561 paleoclimate evolution during the last 1.5 Ma in the Western Black Sea region:
562 integration of soil and loess magnetism. *Phys. Chem. Earth*, Vol. 26, No. 11-12, 911-
563 916.
- 564 Van Velzen, A. and Zijderveld, J., 1995. Effects of weathering on single-domain magnetite in
565 Early Pliocene marine marls. *Geophys. J. Int.*, 121, 267-278.
- 566 Wehmiller, J. F. and Miller, G. H., 2000. Aminostratigraphic Dating Methods in Quaternary
567 Geochronology. In: *Quaternary Geochronology. Methods and Applications.* AGU
568 Reference Sheet 4, eds: J. Noller, J. Sowers, W. Lettis Washington, DC, 187 – 223.

- 569 Wiegank, F., 1977. Untersuchungen zur palaomagnetischen Datierung von Losen und
570 Terrassen-sediment im Norden der Volksrepublik Bulgarien. *Z. geol. Wiss., Berlin*, 5,
571 3, 373-384.
- 572 Yang, T., Hyodo, M., Yang, Z., Fu, J., 2004. Evidence for the Kamikatsura and Santa Rosa
573 excursions recorded in eolian deposits from the southern Chinese Loess Plateau. *J.*
574 *Geophys. Res.*, 109, B12105, doi: 10.1029/2004JB002966.
- 575 Zhu, R., Coe, R.S., Guo, B., Anderson, R. and Zhao, X., 1998. Inconsistent palaeomagnetic
576 recording of the Blake event in Chinese loess related to sedimentary environment.
577 *Geophys. J. Int.*, 134, 867-875.
- 578 Zhu, R., Liu, Q., Jackson, M., 2004. Paleoenvironmental significance of the magnetic fabrics
579 in Chinese loess-palaeosols since the last interglacial (<130 ka). *Earth Planet. Sci.*
580 *Lett.*, 221, 55 – 69.
- 581 Zhu, R., Liu, Q., Pan, Y., Deng, C., Sun, J., 2006. Identifying the origin of the magnetic
582 directional anomalies recorded in the Datong loess profile, northeastern Chinese loess
583 plateau. *Geophys. J. Int.*, 164, 312 – 318.
- 584

Figure and Table caption

585

586

587 Fig. 1. a) Main geomorphological units in NE Bulgaria. Legend: 1- Holocene, Upper- and
588 Middle Pleistocene river and sea terraces; 2- Lower Pleistocene river- and marine
589 terrace T6; 3- Old Abrasive Accumulation Level (OAAL); 4- Pliocene Denudational
590 Surface (PDS); b) View of the loess-palaeosol section in the eastern part of the kaolin
591 quarry in Viatovo.

592 Fig. 2. VRM acquisition experiments for a) loess samples and b) palaeosol samples. Time t is
593 in seconds.

594 Fig. 3. Linear correlation between viscous acquisition coefficients S_{a1} (calculated from the
595 first slope in two-slope curves and from all points for single-slope curves) and percent
596 frequency dependent magnetic susceptibility $\chi_{fd}\%$.

597 Fig. 4. Gradient acquisition plot (GAP) for representative samples from loess and palaeosols
598 fit with a 3-components model using expectation – maximization algorithm of Heslop
599 et al., 2002.

600 Fig. 5. Correlation between viscous acquisition coefficients S_a and the intensity of component
601 1 obtained from the IRM unmixing procedure. In case of two-slope curves, the slope
602 of the second linear segment S_{a2} is taken and plotted as open diamonds. Full squares
603 denote S_a from single slope curves.

604 Fig. 6. Dependence of the relative contribution of each component with the corresponding
605 mean coercivity $B_{1/2}$. Negative correlation is observed for component 3.

606 Fig. 7. Alternating field (a) and thermal (b) demagnetization of IRM(2.6T) of loess and
607 palaeosol samples and the behaviour of room-temperature bulk magnetic
608 susceptibility, measured after each heating step (c).

609 Fig. 8. Stereographic projections (on the lower hemisphere) of the maximum (K_{max}) and
610 minimum (K_{min}) susceptibility axes for loess and palaeosol samples from different
611 units (a) and b) principal susceptibility axes (K_{max} , K_{int} , K_{min}) for samples from
612 second loess unit L_2 only.

613 Fig. 9. NRM intensity changes during stepwise AF-demagnetization of loess and palaeosol
614 samples.

615 Fig. 10. Dependence between the MDF_{NRM} and the relative contribution of component 1,
616 obtained after unmixing IRM acquisition curves for the same specimens.

617 Fig. 11. Thermal demagnetization behaviour (direction and intensity) of representative
618 samples with normal and reversed ChRM directions.

619 Fig. 12. a) Depth variation of bulk magnetic susceptibility, declination, inclination and
620 intensity of the characteristic remanence ChRM (after thermal cleaning at 325°C) in
621 the Viatovo section ; b) Declination, inclination and ChRM along unit L_7 in a parallel
622 section, sampled in more detail.

623 Fig. 13. Correlation of the magnetic susceptibility signatures of the loess/palaeosol sequences
624 in Koriten (Jordanova and Petersen, 1999) and Viatovo with the astronomically tuned
625 $\delta^{18}\text{O}$ changes in ODP 677.

626 Table 1. Mean values of parameters of the three components (log-normal Gaussian functions)
627 representing the best fit to experimental IRM acquisition curves for recent soil S_0 ,
628 loess units and palaeosols separately. Relative contribution of each component is given
629 in percent; $B_{1/2}$ is the coercivity at which the gradient acquisition curve (GAP) is
630 centred; dispersion parameter DP is the width at half intensity of the GAP and
631 represents one standard deviation.

632 Table 2. Parameters of the third component obtained after fitting experimental IRM
633 acquisition curves for different samples.

634 Table 3. Mean values of principal anisotropy of magnetic susceptibility parameters for
635 loesses, palaeosols and the red clay unit. N is number of samples; standard deviations
636 of the mean values are given between brackets.

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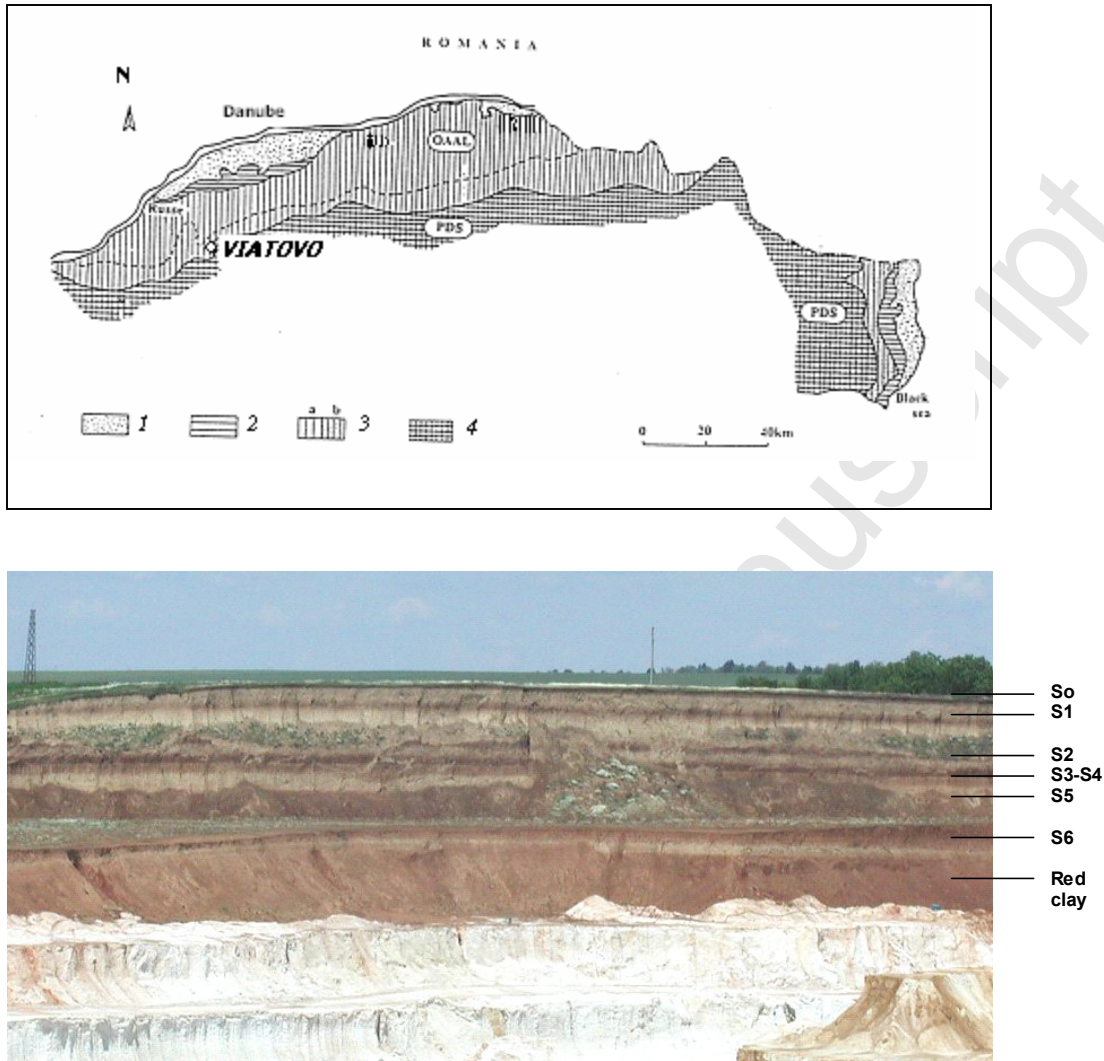


Figure 1

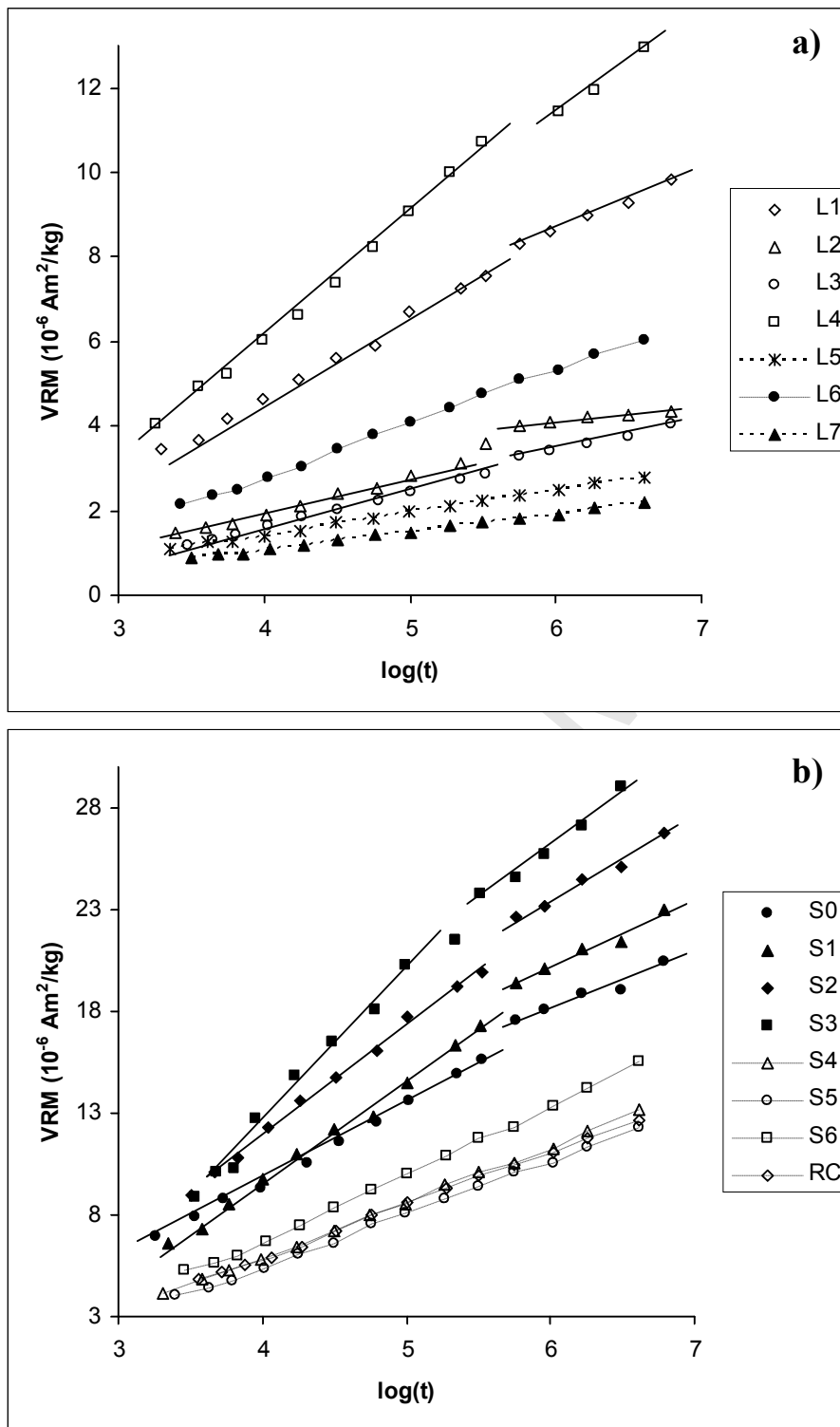


Figure 2

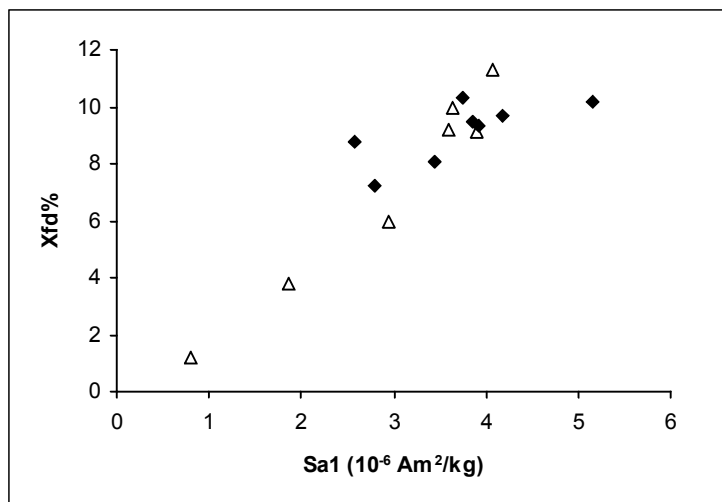


Figure 3

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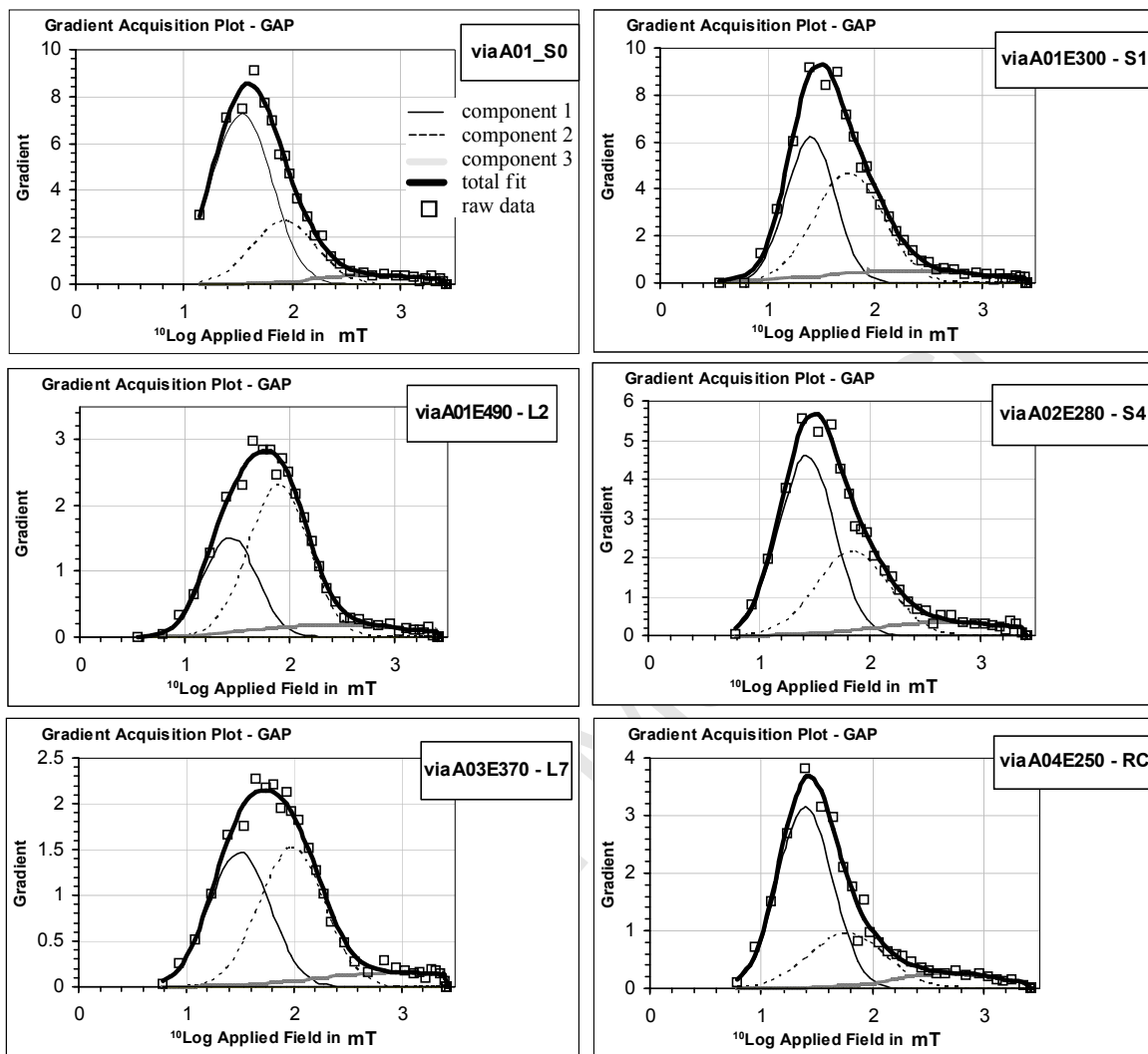


Figure 4

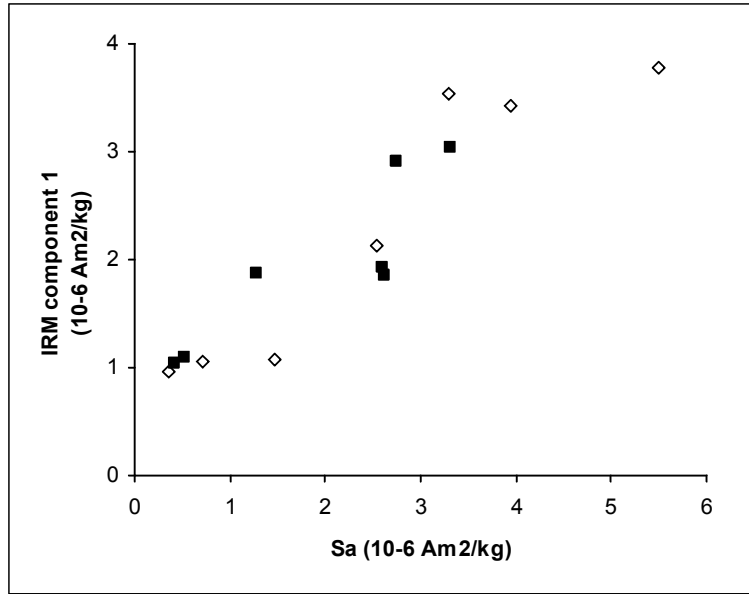


Figure 5

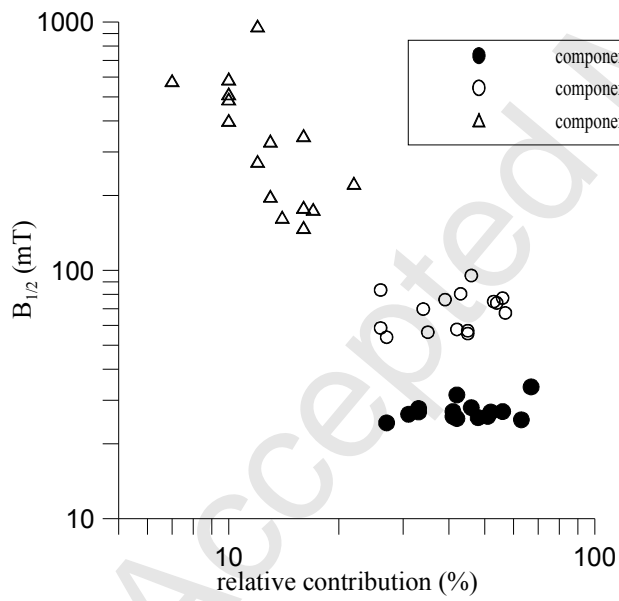


Figure 6

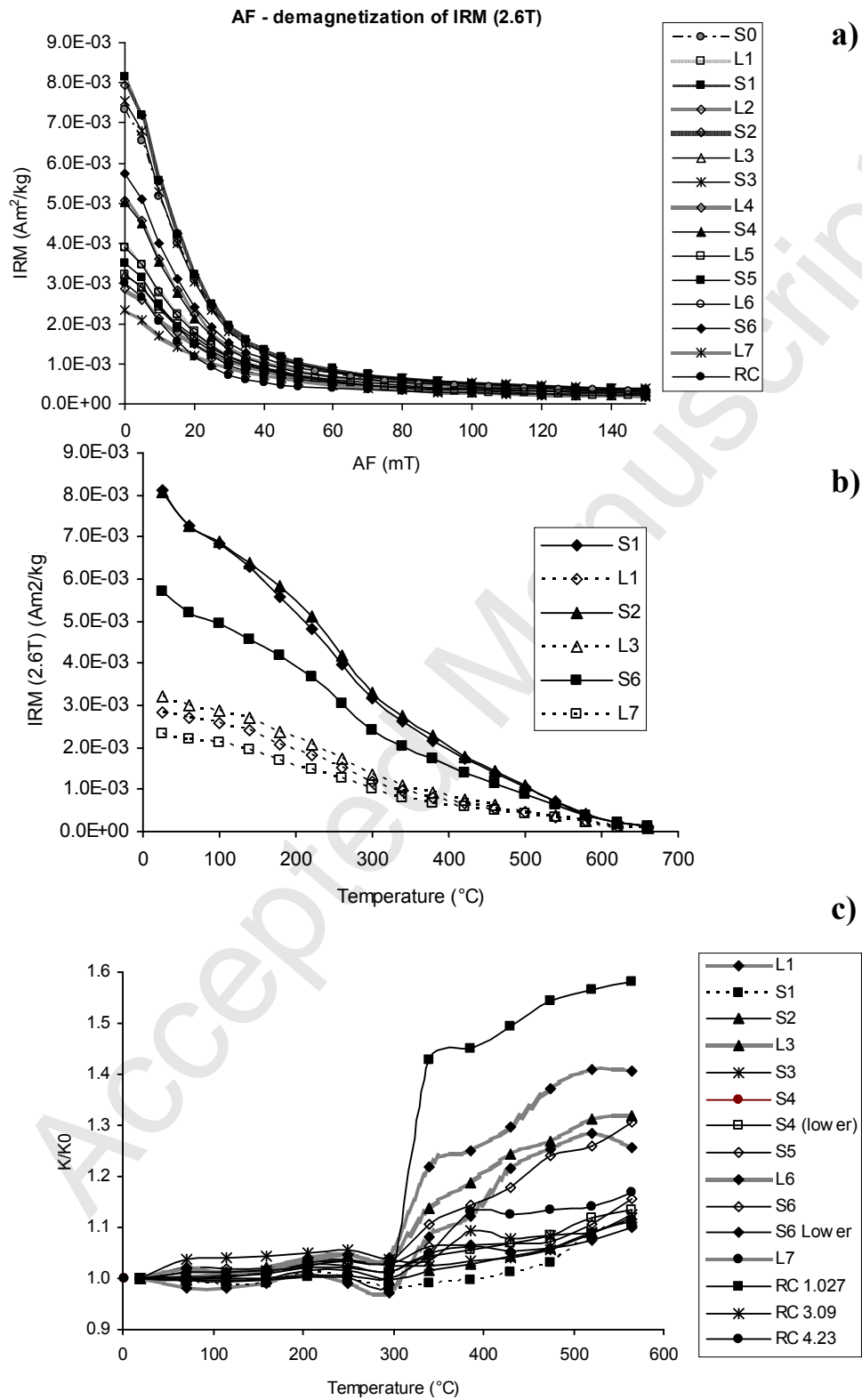


Figure 7

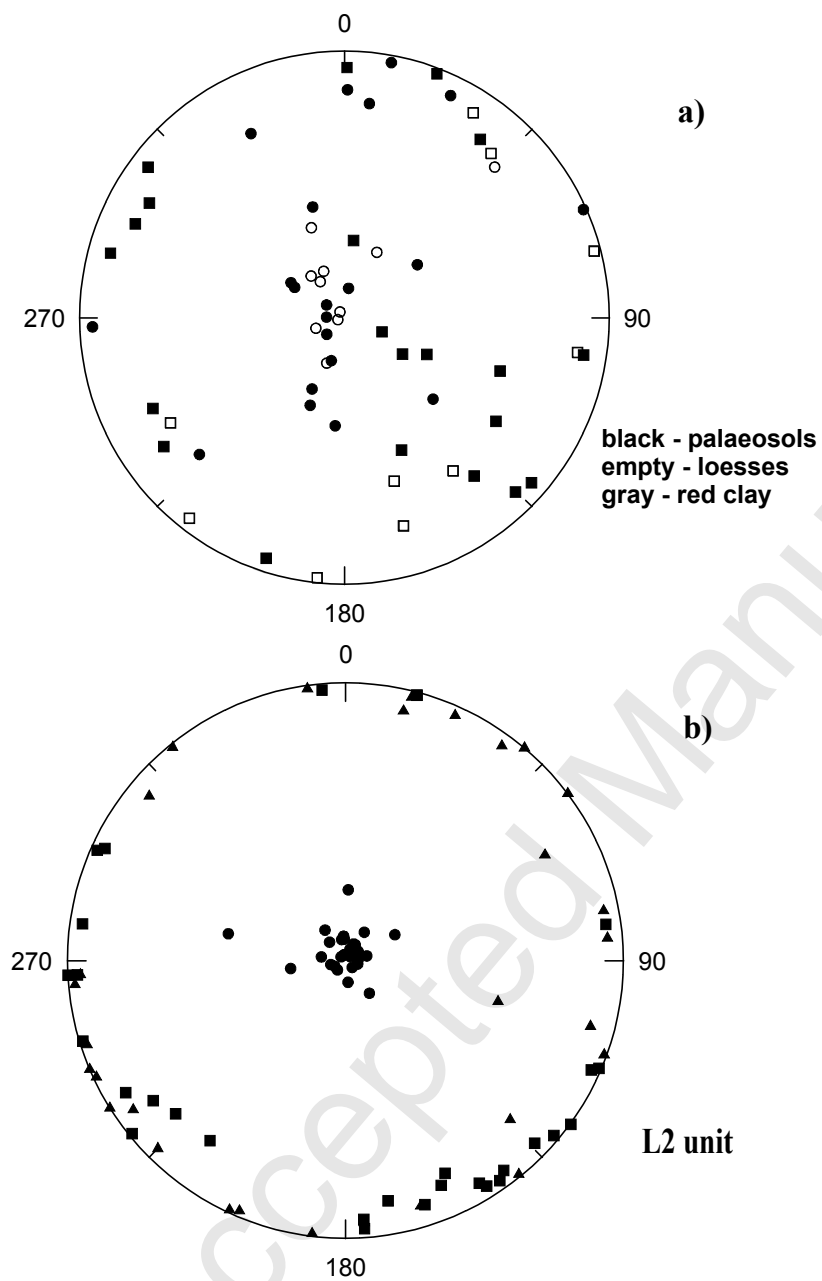


Figure 8

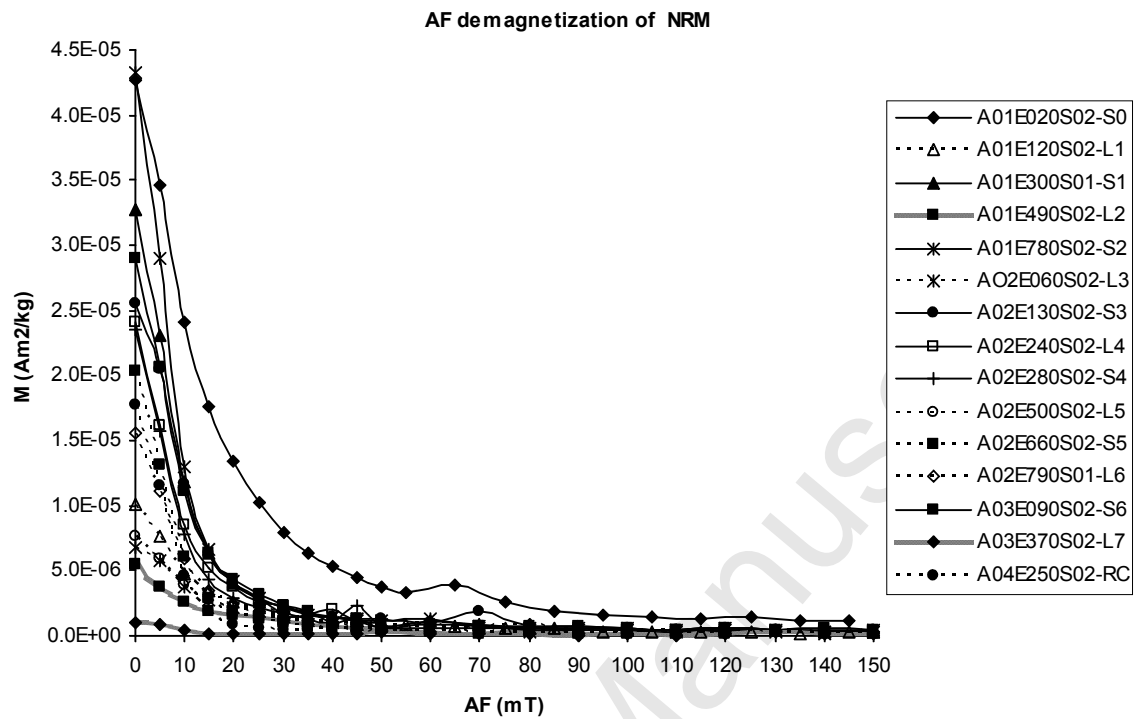


Figure 9

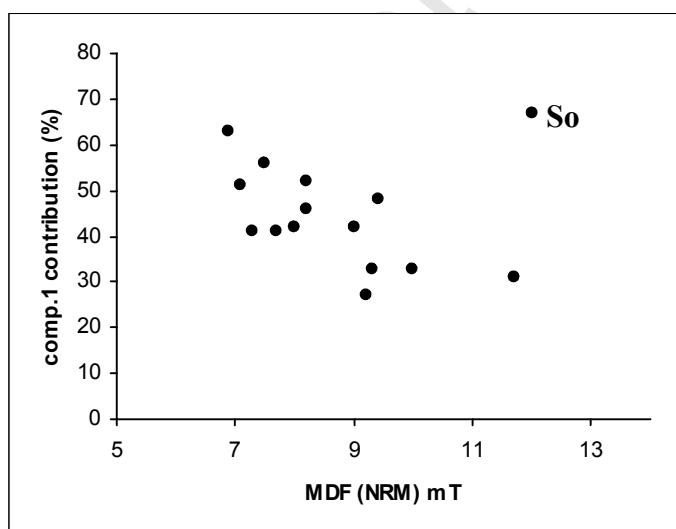
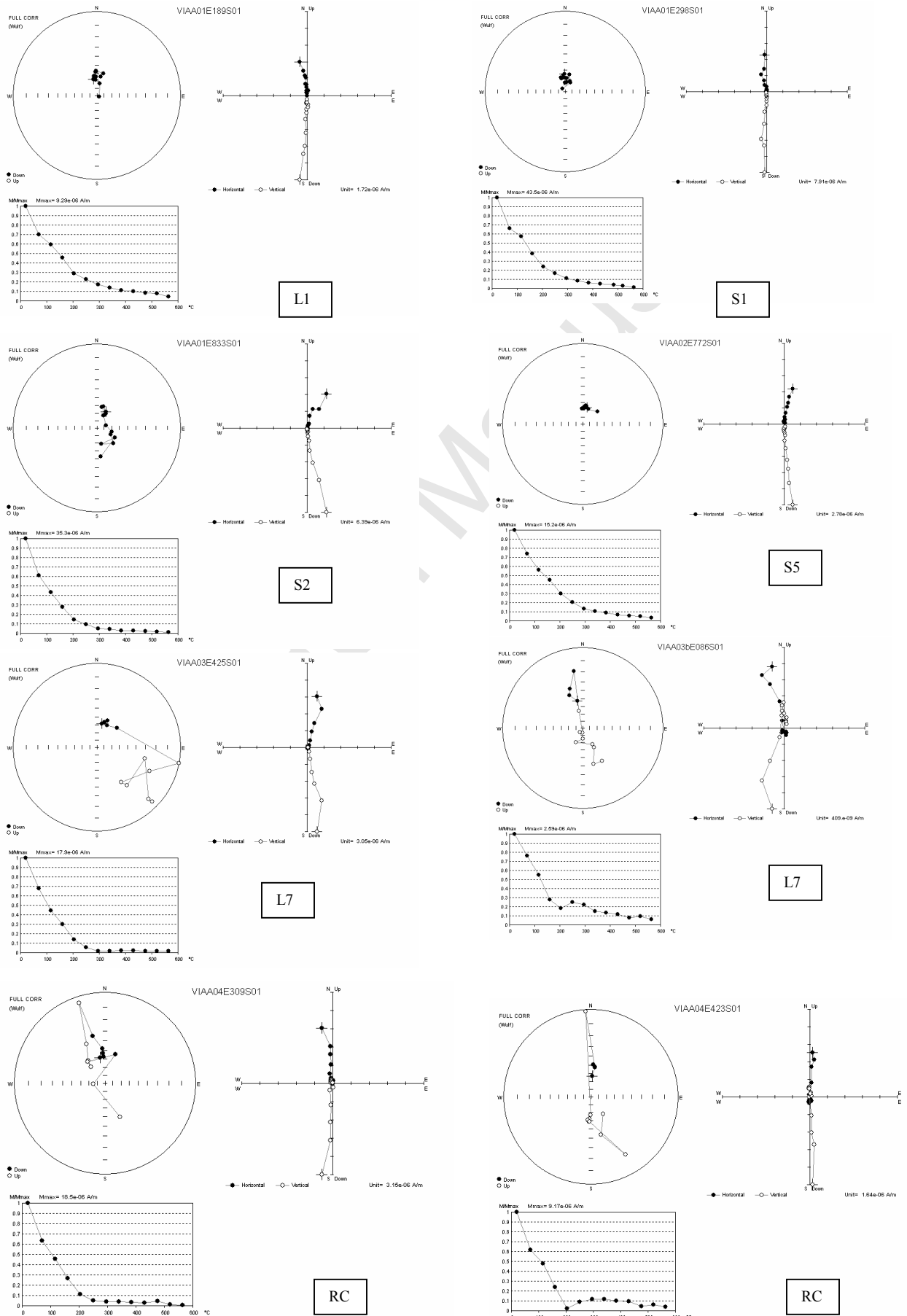


Figure 10

Figure 11



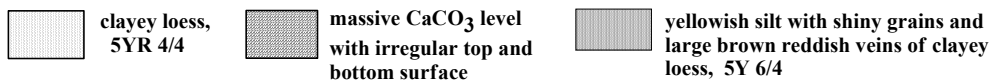
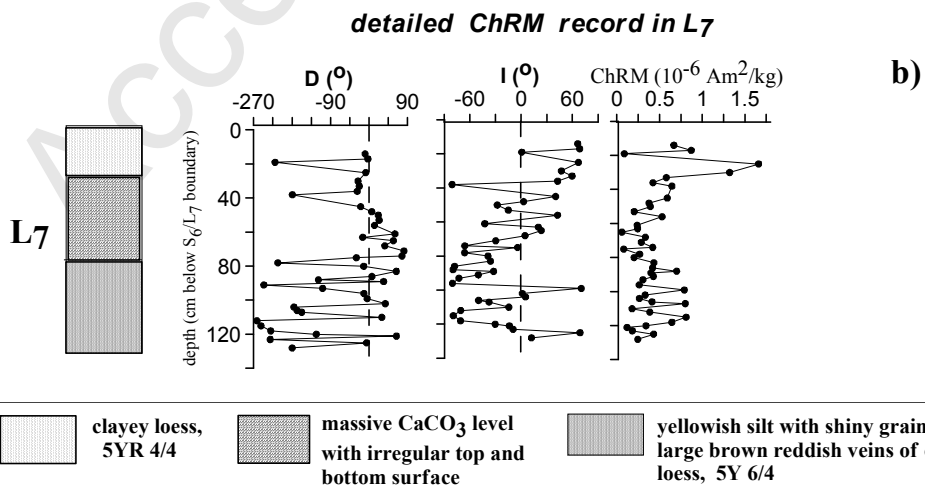
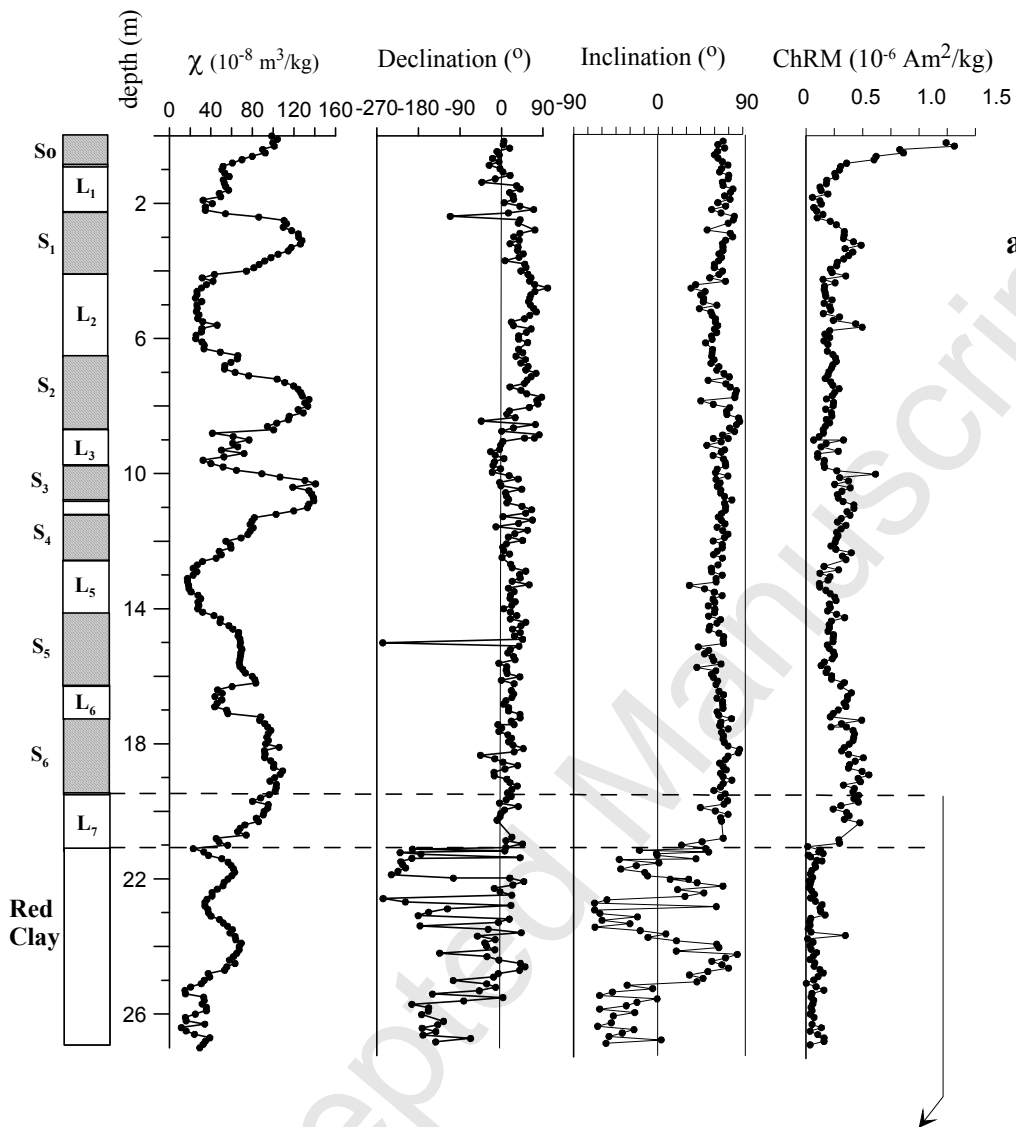


Figure 12

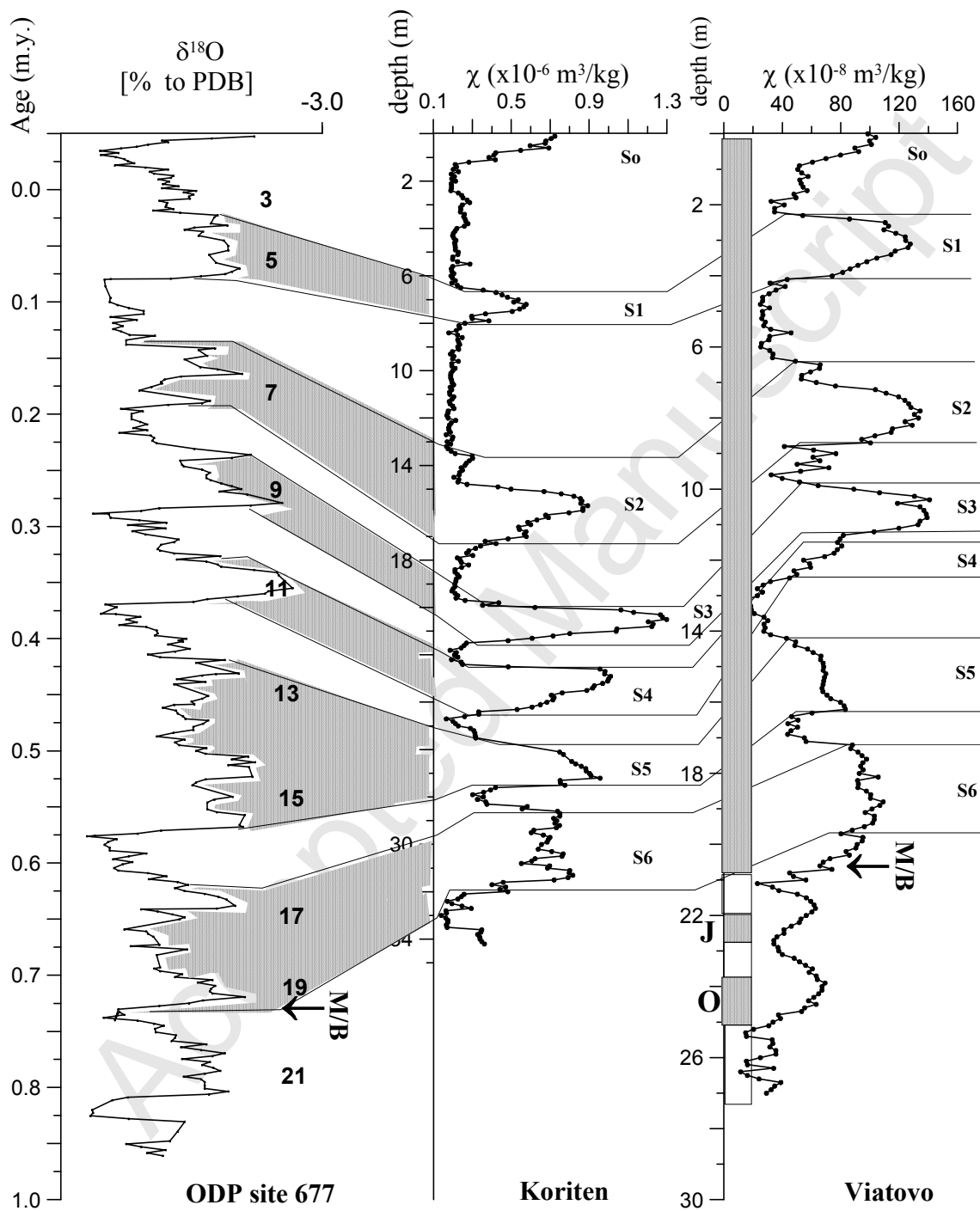


Figure 13

	Component 1			Component 2			Component 3		
	Rel. contr. (%)	B _{1/2} (mT)	DP	Rel. contr. (%)	B _{1/2} (mT)	DP	Rel. contr. (%)	B _{1/2} (mT)	DP
So	67	34	0.28	26	83	0.29	7	582	0.53
loesses	33± 7	27± 2	0.24±0.02	53± 6	75± 11	0.3 ±0.02	13± 3	332±271	0.83± 0.13
palaeosols	51± 8	26± 1	0.23±0.01	34.5± 8	57± 9	0.32 ±0.01	13± 4	224±190	0.73± 0.13
All		27± 3	0.24± .02		70 ± 12	0.32± 0.02		332±225	0.75±0.14

Table 1

sample	unit	component 3		
		contribution (%)	B _{1/2} (mT)	DP(mT)
viaA01E120	L1	16	179.6	0.97
viaA01E490	L2	12	275	0.72
viaA02E060	L3	16	349.4	0.97
viaA02E240	L4	17	176.2	0.83
viaA02E500	L5	13	332	0.83
viaA02E790	L6	10	402.3	0.63
viaA03E370	L7	12	966.3	0.75
viaA01E300	S1	13	198.8	0.83
viaA01E780	S2	14	163.9	0.73
viaA02E130	S3	16	149.1	0.88
viaA02E280	S4	10	513.9	0.62
viaA02E660	S5	22	224.4	0.81
viaA03E090	S6	10	590.6	0.72
viaA04E250	RC	10	489.6	0.49
viaA01E020	So	7	581.7	0.53

Table 2

unit	N	Kmean (x10 ⁻⁶ SI)	L	F	P'	T
palaeosols	21	1491 (377.7)	1.001 (0.001)	1.002 (0.002)	1.004 (0.002)	0.396 (0.463)
loesses	10	555.9 (143)	1.001 (0.001)	1.003 (0.003)	1.004 (0.004)	0.27 (0.486)
Red clay	8	523.7 (337.9)	1.003 (0.002)	1.004 (0.002)	1.007 (0.003)	0.284 (0.297)

Table 3