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Article *in* Physics and Chemistry of the Earth Part A Solid Earth and Geodesy · December 2001

DOI: 10.1016/S1464-1895(01)00141-7

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Phys. Chem. Earth (A), Vol. 26, No. 11–12, pp. 911–916, 2001

1464-1895/01/$ - see front matter

PII: S1464-1895(01)00141-7

A New Scheme of Terrestrial Paleoclimate Evolution During the Last 1.5 Ma in the Western Black Sea Region: Integration of Soil Studies and Loess Magnetism

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Received 30 August 2000; 15 February 2001; accepted 22 March 2001

Abstract. A refined pedostratigraphic scheme in the western Black sea region is proposed on the basis of paleopedological reconstructions coupled with magnetic susceptibility, and other rock magnetic parameters, and Mössbauer spectroscopy. The new scheme matches well with oxygen isotope stages despite local variations in erosion/deposition, strong welding of paleosols and subtle discrepancies in the position of the Matuyama/Brunhes boundary. These limitations are reduced by optimizing resolution of magnetic cycles and paleosol identification. Two humid/warm maxima during the Quaternary are found in pedocomplex PK4 at about 0.5 Ma (corresponding to oxygen isotope stages 13 and 15), and in pedocomplex PK8 related to the Jaramillo subchron. Comparison with the oxygen isotope curve shows that the apparent major driving force of regional soil/loess cyclicity is the 100 ka eccentricity period.

1 Introduction

Paleomagnetic and rock magnetic studies of loess/paleosol sequences in the Western Black Sea region beginning in the 1970s have been included in a regional pedostratigraphic scheme (Veklich 1982). However, until recently the significance of these loess deposits with regard to general Quaternary climate periodicity was unclear. Revision of the position of the Matuyama/Brunhes (M/B) boundary in the section of Roxolany (Dniestre terrace VIII, Ukraine; Heller et al., 1996) allowed Tsatskin et al. (1998) to offer a different pedostratigraphic division of the site. Here, welding (overprinting) of several individual paleosols into composite pedocomplexes (PK) was encountered which could be unraveled by integrating magnetic susceptibility (MS) and petrographic thin section studies. In order to improve the correlation with the deep sea records (Tsatskin et al., 1998), two additional type sections, previously investigated by Soviet workers, Kolkotova Balka on Dniestre terrace V (Velichko, 1990) and Novaya Etuliya on Danube terrace XII (Pospelova and Gnibidenko, 1972; Virina and Faustov, 1973; Faustov et al., 1986) have been studied (Fig.1). Full characterization of the results obtained by soil micromorphology, Mössbauer mineralogy and rock magnetism from these sites is beyond the scope of this paper. Here we address the

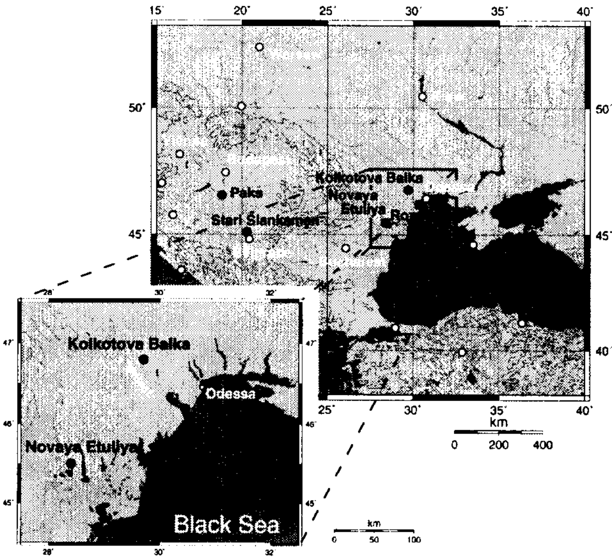

Fig. 1. Western Black Sea region and the sites discussed in the text.

question of stratigraphic implications of micromorphological and magnetic proxies in a region with non-uniform loess deposition, and variable post-depositional preservation and overprinting of paleosols.

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2 Results

2.1. Lithology, magnetic susceptibility (MS) and major geomagnetic boundaries

All the sections show alternation of loess layers with grey, brown or reddish paleosols, with maximal susceptibility of $90x10^{-8}m^3kg^{-1}$ in A horizons. This type of MS cyclicity reflects magnetic enhancement via pedogenesis and is similar to that of China and Middle Asia (e.g. Maher and Thompson, 1999). In the Black sea region, however, MS cycles are not consistent at spatially separated sites, apparently due to welding, or overprinting, of paleosols. Several discrepancies occur in the susceptibility data between the sections (Fig. 2). For example, PK3 at Roxolany demonstrates a distinct triple susceptibility peak, suggesting overprinting of at least three strong paleosols which are also present at Kolkotova Balka constituting the Romny-Kamenka PK unit (Velichko, 1990). In contrast, PK3 at Novaya Etuliya shows only a double peak (Fig. 2). Further, the Vorona PK at Kolkotova Balka, which contains a Late Cromerian fauna (Velichko, 1990; Markova, 1992), lies roughly in the same stratigraphic position as PK4 at Roxolany (i.e. below four PKs), but in contrast, it does not show maximal susceptibility. At Roxolany, the M/B boundary was identified in L6 within a succession of four closely spaced paleosols with distinct, though subtle, MS variations. At Novaya Etuliya, the M/B boundary was found in the upper part of PK7 in a similar lithological unit, while the Jaramillo episode, not recognized in Roxolany, was in PK8 (Spassov, 1998; Fig. 2). Thus, susceptibility curves alone are not sufficient for robust correlation and have to be combined with other data.

2.2. Paleosol typology

Major paleosols were taxonomically identified on the basis of reconstructed soil-forming processes and compared with modern analogs. In the Brunhes chron, paleosols show abundant signs of biological reworking, well developed microstructures and carbonate accretion, all characteristic of modern steppe chernosems (Gerasimova et al., 1992). The double PK4 in the lower third of the Brunhes chron contains, in addition, disrupted reddish clay coatings, that were incorporated into soil aggregates by faunal churning, which suggests more humid/warm environmental conditions than those of chernosem soils. Pedocomplexes of the Matuyama chron demonstrate abundant nodules of Fe oxides and reddening (rubefication) of the groundmass, possibly due to strong disintegration of red clay illuviation features, as known in modern red Mediterranean soils (Fedoroff, 1997). Micromorphology was particularly useful for high-resolution paleoenvironmental reconstructions shown in tabular form in Fig. 3 and more explicitly explained in Tsatskin et al. (1998).

2.3. Magnetic mineral/grain size cyclostratigraphy

In the Black sea region, MS peaks in paleosols occur alongside peaks in frequency-dependent susceptibility, calculated as difference of MS measurements at 0.47 kHz and at 4.7 kHz measuring frequency (Spassov, 1998; Du Pasquier, 1999). This suggests high concentration of superparamagnetic (SP) ferrimagnets in paleosols compared to loesses (Zhou et al., 1990). At Roxolany, maximal production of SP minerals occurs in PK4 at 22 m depth. The measurements of anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM) and hysteresis parameters obtained thus far (details in Spassov, 1998; Du Pasquier, 1999) show that magnetic enhancement in loesses in the Black Sea region is different from that in paleosols. Like in China and Central Asia (Heller and Liu, 1986), this seems to result from differences in magnetic grain size and/or composition. Du Pasquier (1999) was able to demonstrate, by plotting e.g. ARM/SIRM ratio and other magnetic indices along the Roxolany section, that the magnetic mineral/grain-size curve reflects a fine-tuned record of climate change both within loess units and within composite PKs. Interestingly, younger paleosols have ARM/SIRM values quite close to their parent loesses, while older, brown-red and red soils show by far higher ARM/SIRM values. As will be shown below, this may result from both varied sedimentation source and different intensity of pedogenic production/transformation of Fe oxides/hydroxides and clays.

2.4. SP and paramagnetic minerals by Mössbauer mineralogy

Mössbauer spectroscopy studies show that both SP ferric oxyhydroxides and hematite, and paramagnetic minerals, primarily Fe(III) smectite, substantially increase in paleosols as compared to loesses (Gendler et al., 1997). In the course of paleopedogenesis Fe(III) smectite clays have been found to undergo transformation due to fixation of fine-grained hematite and oxyhydroxides in interlayer spaces of their crystal structure. Computer fitting of Mössbauer spectra at 300 K and 80 K demonstrate that fine-grained, less than 12 nm, SP hematite and Fe hydroxides, which act as colour pigments, are present in genetically different paleosols and have bimodal grain size distributions at 7-12 nm and below 5nm (Gendler et al., 1997). It is worth noting that paleosols of the Matuyama chron 1) contain more ultra-fine, less than 5 nm, SP minerals, and 2) contain more hematite than younger soils. The latter accounts for the red colour of the Matuyama chron paleosols and confirms their identification as related to humid/warm Mediterranean environments (see Fig. 3).

3 Discussion

Generalization of data from the above sites allows us to present a summary loess/soil sequence in the Black Sea region, and in this way to address the question of its global significance. The key question then is to correctly place successive paleosols, despite their partial welding (overprinting), with respect to the cyclostratigraphy in the ocean record (Shackleton et al., 1990), taking into account subtle discrepancies in the position of the M/B boundary in terrestrial sequences (Fig. 3).

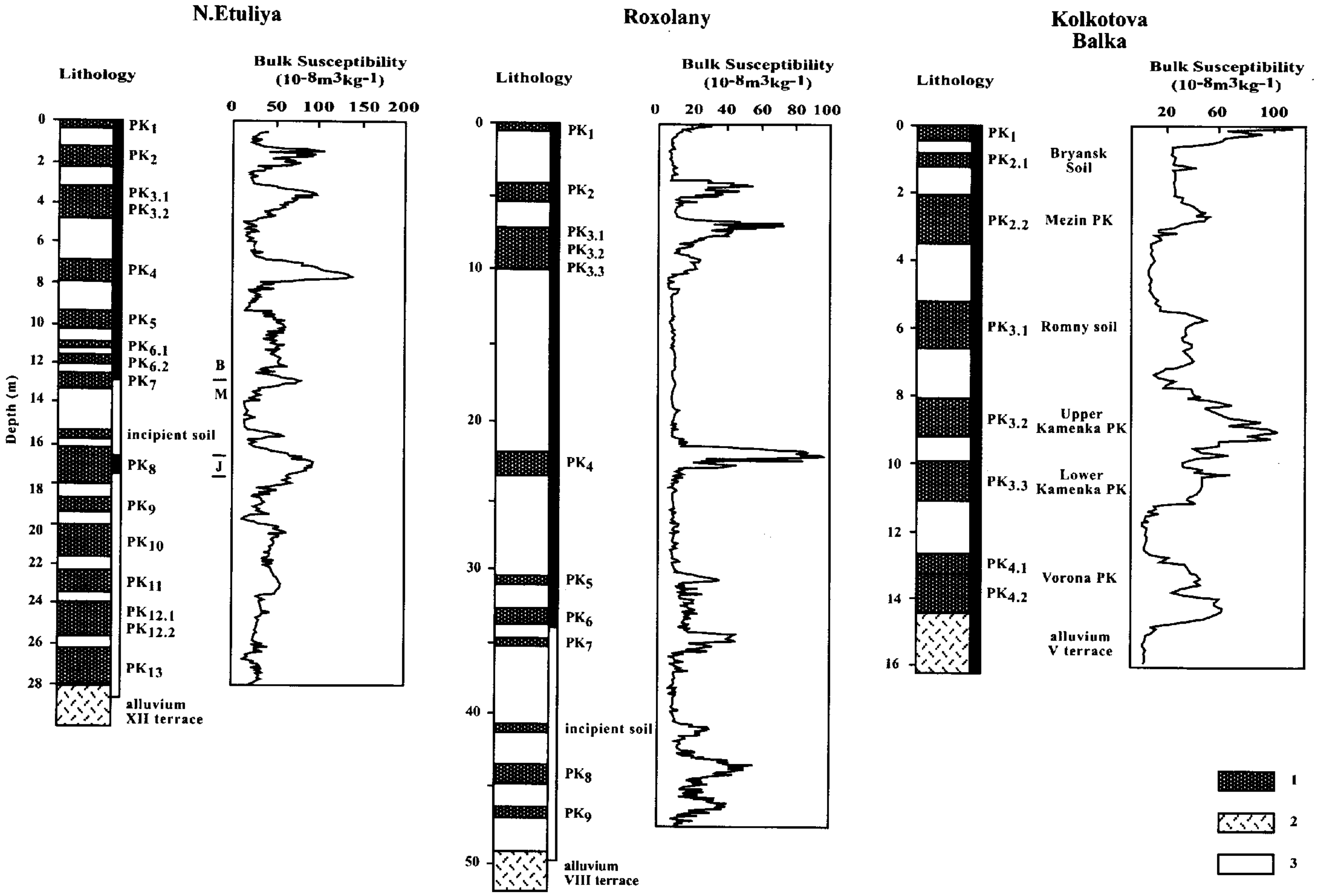

Fig. 2. Lithology and magnetic susceptibility at key sites in the Black Sea region. Stratigraphic nomenclature at Kolkotova Balka from Velichko (1990). 1 - paleosol; 2 - alluvium; 3 - loess. Magnetic polarity column: black - normal; white - reversed polarity.

3.1. Paleosols of the Brunhes chron

Although stratigraphic division of this part of the sequences (Fig. 2) is not identical, we may suggest the following intra-regional correlation. PK2 with a double MS peak is an equivalent of the Late Pleistocene Bryansk soil and Mezin PK at Kolkotova Balka, the latter being assigned (Velichko, 1990) to the marine oxygen isotope stage 5 (MIS 5). The three older Romny, Upper Kamenka and Lower Kamenka paleosols at Kolkotova Balka, each with at least the same strong magnetic enhancement as the Mezin pedocomplex, seem to be included in either a triple or a double PK3. We suggest that the lowest PK3.3 at Novaya Etuliya is lacking due to erosion. It is therefore reasonable to correlate PK3 with MIS 7, 9 and 11. The older Vorona double PK, containing small mammals of Late Cromerian age (Markova, 1992), is equated then with PK4 which was proposed as a regional stratigraphic marker formed during the climatic optimum of the Brunhes chron during MIS 13 (Tsatskin et al., 1998). However, because PK4 consists of at least two welded, strongly developed Mediterranean paleosols with maximal production of SP minerals, we tentatively relate it to the closely spaced MIS 13 and 15 at around 0.5 Ma. Recently Bronger (1999) also suggested that the most strongly developed paleosol F6 at Stari Slankamen (Fig. 1) is related to both MIS 13 and 15. If so, remarkable similarity is obtained between the summary sequence for the Black sea region and the upper part (ca. 600 ka) of the marine isotope curve with characteristic high-amplitude climate fluctuations of a 100 ka periodicity (Fig. 3).

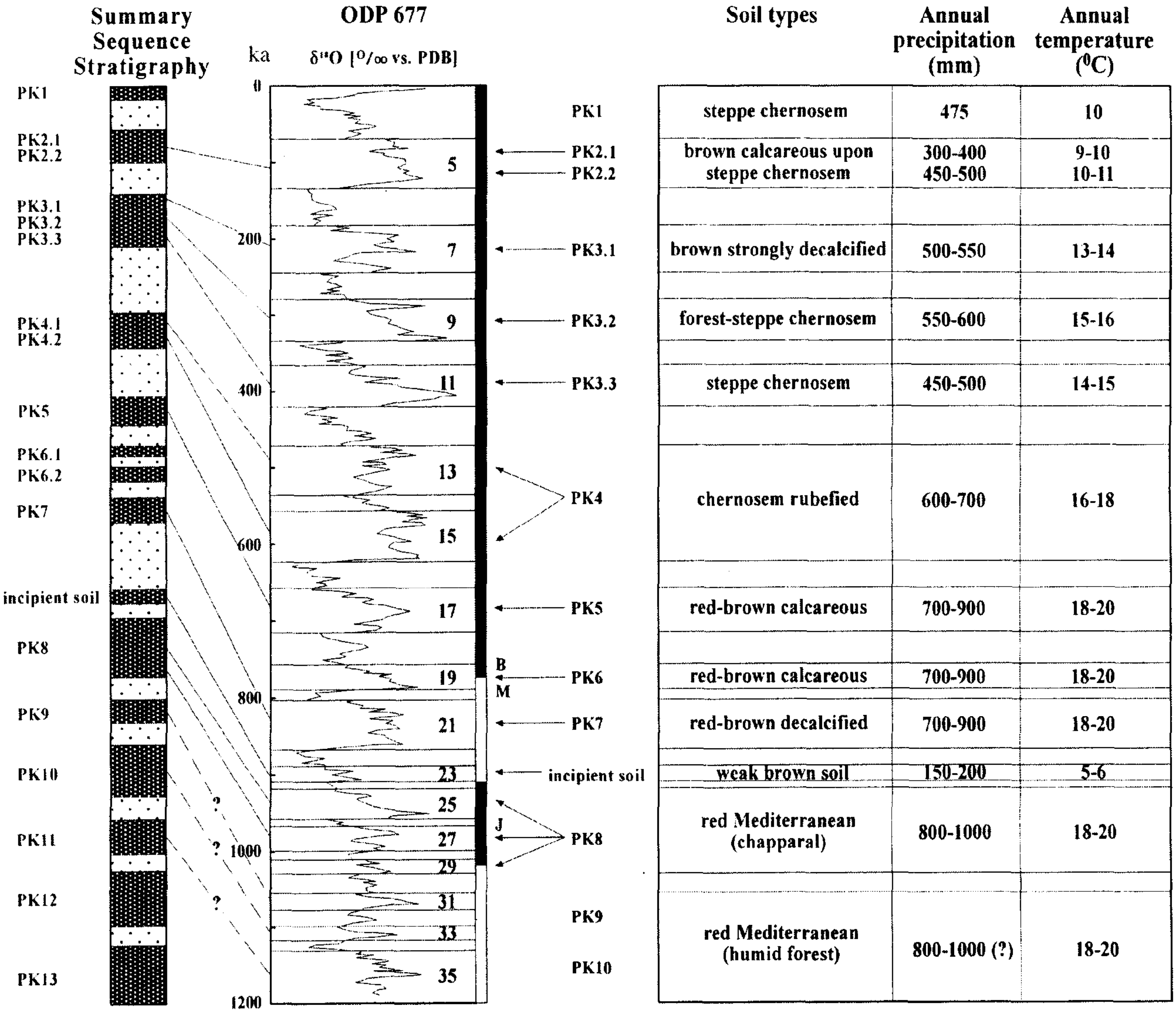

Fig. 3. Correlation of compiled pedostratigraphy in the western Black Sea region with the ODP677 marine oxygen isotope curve (Shackleton et al., 1990). Magnetic polarity column: black - normal; white - reversed polarity. M/B indicates the Matuyama/Brunhes geomagnetic polarity boundary; J - Jaramillo subchron.

3.2. PK5 through PK7 and position of the M/B boundary

The M/B boundary lies in the unit of closely spaced paleosols PK5 through PK7 which are broadly defined as red-brown Mediterranean soils, and therefore should be related to three independent interglacials, with PK7 definitely older than MIS 19 if the above correlation is accepted (Fig. 3). Despite subtle discrepancies between Novaya Etuliya and Roxolany, uncertainty in the position of the M/B boundary in the region resembles that in China where it was found in horizons corresponding either to MIS 20 or 21 (Heller and Liu, 1986). This disagrees with marine sequences where the M/B boundary was observed in interglacial MIS 19 and with results obtained by astronomical tuning (Heslop et al., 2000). We attempted further correlations by optimizing the match of regional refined soil magnetic stratigraphy and oxygen-isotopes curves. As will be shown below, the red-brown soil of PK7 then should be related to stage 21, despite minor shifts of the M/B boundary in our loess sections. This delayed lock-in of the M/B boundary in the loess of the Black Sea region may be explained by similar models as suggested by Spassov et al. (2001).

3.3. Paleosols of the Late Matuyama chron

The second regional optimum of humid and warm Mediterranean conditions is marked by PK8 paleosol about 1 Ma ago. As with the younger 'optimum' of PK4, strong development of PK8 (displaying the Jaramillo episode at Novaya Etuliya), with high production of SP hematite and ferric hydroxides, may be due to overprinting of several successive warm stages, namely MIS 25 and 27. Although the Jaramillo episode was not found at Roxolany, we can establish the regional correlation of PK8 on micromorphological and mineralogical grounds. Interestingly, an incipient paleosol lying below PK7 and above PK8 will perfectly match then with a minor peak of MIS 23 in the oxygen isotope curve. Hence PK7 is to be correlated with MIS 21. All the older paleosols, corresponding to Mediterranean forest environments, are presently difficult to relate to global stages, although it is clear that their development required at least the same time span as the younger paleosols with a ca. 100 ka periodicity.

4 Conclusions

In the Black sea region, loess sequences demonstrate pronounced variability, apparently due to erosion gaps, welding of paleosols, and changing intensity of dust deposition throughout the Quaternary. Hence, even intra-regional correlation of the loess/soil sequences is not obvious and requires multidisciplinary studies. Through studies of thin sections, measurements of ARM intensity, MS and hysteresis parameters as well as Mössbauer spectroscopy we were able to maximize the stratigraphic resolution of magnetic cycles, to establish the sequence of major soil-forming episodes within the welded PKs, and in these ways to refine the regional paleoclimatic record The major chronological constraint is still provided by the M/B boundary, albeit its position at the different sites shows subtle discrepancies and variable delay in remanence blocking. A multidisciplinary approach allowed us to overcome these limitations and to complete our. previous pedo- and magnetostratigraphic scheme of Quaternary aeolian deposits in the western Black sea region (Tsatskin et al., 1998). Comparison with the marine oxygen isotope curve shows an excellent match between oceanic and regional terrestrial records at least for the last 1.5 Ma, and suggests that the apparent (!) major driving force of regional soil/loess cyclicity is the 100 ka eccentricity period.

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Remembrance

Elena Virina, our colleague and devoted friend died on June 28 during a scientific excursion to the Black Sea. We now miss a talented Quaternary scientist, who cared for a productive collaboration between experts in Loess Magnetism and in Paleopedology and who always acted both engaged and modest altogether.