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PALEOGEOGRAPHY

Big Lost Geomagnetic Excursion Recorded in the Loess-Paleosol Sequence in the Southern Part of European Russia, Otkaznoe Section

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Abstract—The paper presents the results of detailed rock magnetic and paleomagnetic studies of the Lower Pleistocene loess-paleosol sequence (LPS) in the Otkaznoe section (Terek-Kuma Lowland). For the first time, the Early Brunhes geomagnetic excursion was recorded in the Otkaznoe section for loess sections in the southern part of European Russia and its continuous paleomagnetic record was obtained. The revealed excursion, covering a 0.22 m zone, is characterized by anomalous/intermediate paleomagnetic directions and the latitudes of the virtual geomagnetic pole (VGP) ~30° and correlates with the marine isotope stage (MIS) 14. The age of the geomagnetic event, determined based on the correlation of variations in magnetic susceptibility with the global oxygen isotope curve ($\delta^{18}O$), is ~540 ka, and its duration is estimated at 2–3 ka. The data obtained make it possible to identify the excursion in the Otkaznoe section as the Big Lost geomagnetic event and use it as a reliable chronostratigraphic marker for regional and global correlations.

Keywords: geomagnetic excursion, Ciscaucasia, Brunhes, Pleistocene, loess-paleosol sequence, East European Plain

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INTRODUCTION

The loess-paleosol sequences (LPSs) of Eastern Ciscaucasia represent the best-preserved terrestrial archive in the southern part of the East European Plain (EEP), documenting climate changes during the Pleistocene. The significant thickness of the loess, exceeding 100 m, along with its stratigraphic completeness, allows for comprehensive studies and provides a high-resolution record. This determines the uniqueness of the LPSs of Eastern Ciscaucasia within Eastern Europe and allows them to be compared to Chinese and Central Asian loess-paleosol sequences. Despite the potential for high informational value and a long history of LPSs research in this region [1–3], challenges remain regarding the chronostratigraphy of these loess-paleosol sections, as well as their correlation with both marine and terrestrial sedimentary archives at regional and global scales.

The Otkaznoe section is the most representative and well-known loess-paleosol section in Eastern Ciscaucasia. Currently, the chronostratigraphic subdivision of the Upper Pleistocene LPS in this section has a fairly reliable justification due to the use of luminescence dating [4]. However, the chronostratigraphy of the Lower and Middle Pleistocene remains controversial. The resolution to this issue can be achieved through high-resolution magnetostratigraphic studies, which have not yet been carried out in this section.

The initial magnetostratigraphic characteristic of the Otkaznoe section was obtained by S.S. Faustov and E.I. Virina during the 1980s and 1990s from core specimens, with a sampling interval from 0.5 to 2.0 m [3, 5]. In particular, these researchers identified the Matuyama-Brunhes (M/B) boundary, which allowed for the determination of the chronostratigraphic position of the Lower-Middle Pleistocene boundary. However, our recent detailed paleomagnetic study of the transition zone of the M/B reversal has revealed not only the M/B boundary itself but also a new chronostratigraphic marker—the precursor to the Matuyama-Brunhes reversal. This result highlights the potential for discovering other magnetostratigraphic markers in other parts of the section.

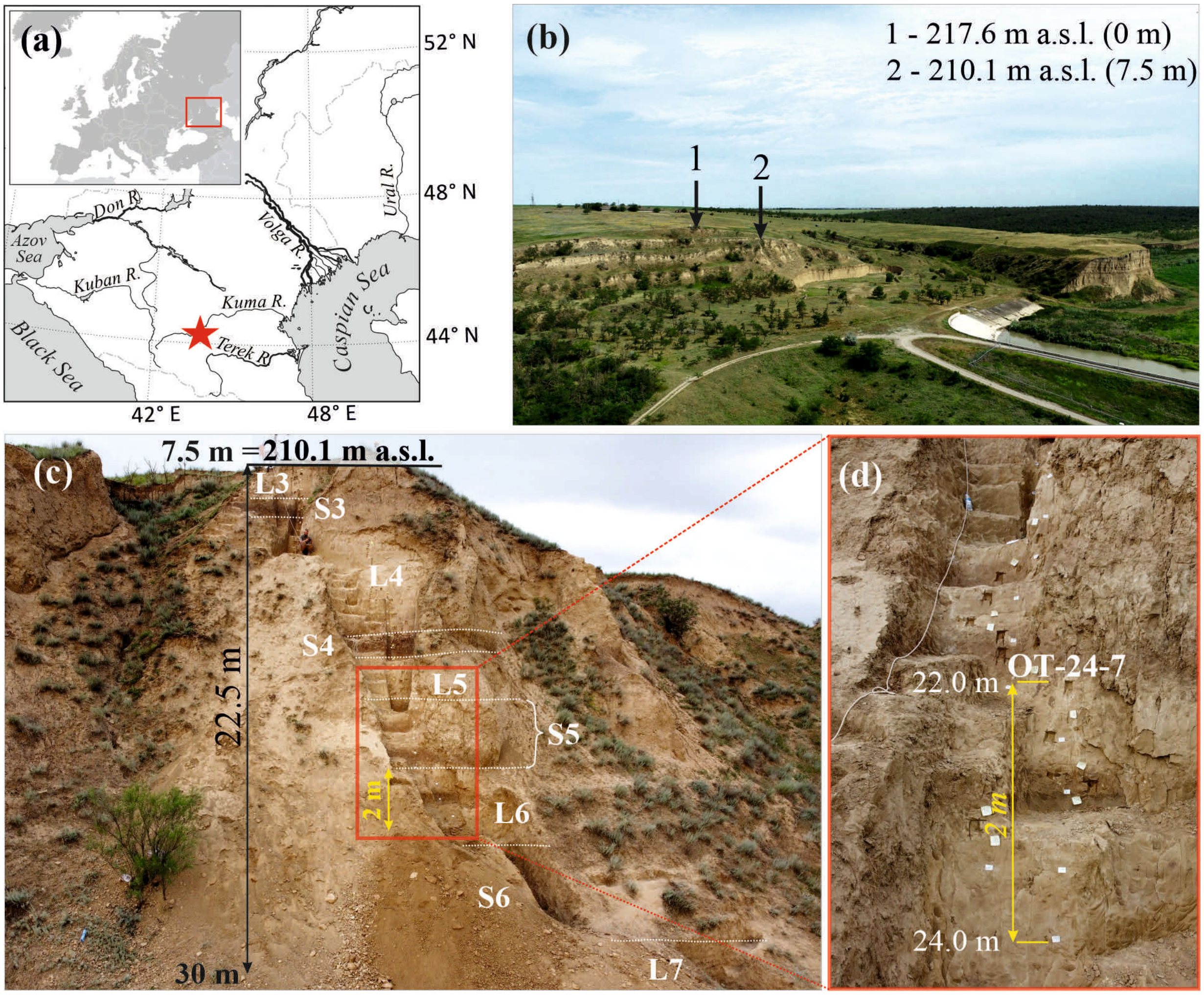

Fig. 1. (a) Location of the Otkaznoe section; (b) general and (c) detailed view of the section at the quarry wall on the right bank of the Otkaznoe reservoir; (d) interval of the section (22.0–24.0 m) where detailed paleomagnetic studies were conducted to identify the geomagnetic excursion.

In this regard, it is an important task to identify short-term geomagnetic events that lasted for the several thousand years, as these could serve as chronostratigraphic markers. In this paper, we present the findings from our high-resolution paleomagnetic studies of the Middle Pleistocene loess-paleosol sequence in the Otkaznoe section.

THE STUDY SECTION AND SAMPLING

The Otkaznoe section (44°17′58″ N, 43°51′49″ E) is located on the bank of the Otkaznoe reservoir within the Terek-Kuma Lowland (Eastern Ciscaucasia), 2.8 km south of the village of Otkaznoe (Fig. 1a). The loess-paleosol sequence of the Middle-Late Pleistocene, with a thickness of about 75 m, comprises eight pedocomplexes (S) separated by loess horizons (L) [2].

In 2023, we conducted a study of a quarry wall located near the dam of the Otkaznoe reservoir. This wall exposes over 30 m of loess-paleosol deposits, showcasing the section interval from L3 to L7 (Figs. 1b, 1c). The examined section corresponds to profile II according to N.S. Bolikhovskaya [5]. As a result of paleomagnetic reconnaissance studies, where sampling was conducted at intervals of 20–30 cm, we identified two stratigraphic levels with anomalous paleomagnetic directions at a depth of 22.7 m from the edge of the quarry (Figs. 1b, 1c). The latitudes of the virtual geomagnetic pole (VGP), calculated from these directions, range from 20° to 25°. To investigate a possible geomagnetic excursion and obtain its detailed paleomagnetic characteristic, we conducted continuous sampling of oriented blocks (20 × 15 × 10 cm) in the section interval 22.0–24.0 m (trench OT-24-7) during the summer of 2024. Sampling was carried out from two parallel trenches (Fig. 1d) and took into account the correction for magnetic declination. A total of 11 blocks from the first trench and 6 blocks from the second trench were collected. These blocks were sawed into specimens at the Institute of

Geography of the Russian Academy of Sciences using a stone-cutting machine with a diamond disk. The blocks were sliced into horizontal (stratigraphic) levels 2 cm thick, and then further cut into standard paleomagnetic specimens (2 × 2 × 2 cm). Between 3 and 5 duplicate specimens were obtained for each stratigraphic level. The total number of paleomagnetic specimens in 2024 amounted to 373: 262 specimens (68 levels) from the first trench and 111 specimens (29 levels) from second trench.

METHODS

Laboratory rock magnetic and paleomagnetic measurements were performed according to standard methods [6, 7] in the Laboratory for the Main Geomagnetic Field and Rock magnetism on the equipment from Shared Research Facilities IPE RAS, as well as in the Rock Magnetic Laboratory of the Faculty of Geology of Moscow State University and the Environment Paleoarchives Laboratory of the IG RAS. Temperature (TH) and alternating field (AF) progressive demagnetization was performed for all specimens from the collection. AF demagnetization was performed up to 110 mT using a demagnetizer attached to a cryogenic (SQUID) magnetometer (2G Enterprises, USA); the number of demagnetization steps was 14. TH demagnetization was carried out in a MMTD80 non-magnetic furnace (Magnetic Measurements, England) up to 590–690°C (9–10 steps). NRM were measured using a JR-6 spin-magnetometer (for TH demagnetization) and a cryogenic (SQUID) magnetometer (for AF demagnetization). The demagnetization results were analyzed using PMTools software. To calculate the paleomagnetic directions (declination D and inclination I) for each stratigraphic level, we averaged the results of principal component analysis (PCA) from duplicate specimens taken from the same level. Using the mean D and I for each stratigraphic level, we calculated the corresponding virtual geomagnetic poles (VGPs).

Bulk magnetic susceptibility (χ) was measured at 10 cm increments across the entire section (146 samples), using a ZH Instruments 150L kappameter (Czech Republic) with a field of 320 A/m at the frequency of 500 Hz. Magnetic susceptibility and anisotropy of magnetic susceptibility (AMS) for the section interval studied in detail (in 2 cm increments) (χ—97 samples, AMS—373 samples) were measured on the MFK-1A kappabridge (Agico, Czech Republic) with a field of 200 A/m at the frequency of 976 Hz. All measurements were normalized to sample mass. Temperature dependence of magnetic susceptibility $\chi(T)$ was carried out using a MFK-1A kappabridge equipped with a CS-3 thermal attachment (Agico, Czech Republic). The samples were heated to 700°C and subsequently cooled back to room temperature. Hysteresis loops and backfield demagnetization curves were obtained on a PMC VSM Micromag 3900 Vibrating Sample Magnetometer (LakeShore, USA) at room temperature with a maximum applied field of 1.5 T and were normalized to mass. The analysis of the coercive spectra of samples using the "cumulative log-Gaussian analysis (CLGA)" method of the normal magnetization curve [8] was carried out in the MAX UnMIX software.

RESULTS

Rock magnetism. The loess and paleosol samples in the studied section interval of 22.0–24.0 m are characterized by a similar magnetic mineral composition, represented by magnetite, hematite and goethite. The presence of magnetite is indicated by a sharp decrease in magnetic susceptibility at the temperatures of 560–585°C (Fig. 2a) on the $\chi(T)$ curve during heating. A further decrease of χ to 700°C reflects the presence of hematite in the samples. A significant increase in magnetic susceptibility when cooled below 300°C may be attributed to the laboratory formation of magnetite/hematite from iron-bearing silicates and hydroxides, such as goethite. The magnetic hysteresis parameters—the coercivity (B_c) and the remanent coercivity (B_{cr}), ranging from 10.37–12.47 mT and 34.35–40.46 mT, respectively. Additionally, the samples exhibit relatively high saturation fields (up to 800 mT), which likely suggests the presence of low-coercivity soft magnetic minerals (magnetite, maghemite) and high-coercivity minerals (hematite, goethite) in the samples (Fig. 2b). This conclusion is confirmed by the CLG analysis of the normal magnetization curve [8], which revealed four components with different coercivities across all samples (Fig. 2c). Component No. 1, with a median saturation field $B_{1/2}$ 37–46 mT, corresponds to magnetite and contributes the majority (up to 82%) to the saturation isothermal remanent magnetization (SIRM). The second component, characterized by a median saturation field $B_{1/2}$ between 105 mT and 137 mT, is identified as hematite, with its content varying from 8 to 16%. Component No. 3, which exhibits high coercivity ($B_{1/2}$ ranging from 534 to 815 mT), contributes up to 13% to the SIRM and is likely associated with goethite. Finally, component No. 4, with coercivity values between 6 and 10 mT, is probably an artifact resulting from log-normal distribution modeling.

The variations in magnetic susceptibility across the section (Figs. 4b, 5b) show a notable increase in χ within paleosols compared to loess. This increase is attributed to the presence of superparamagnetic (SP) particles of ferrimagnetic minerals such as magnetite and maghemite, which form during the pedogenesis [9]. The magnetic susceptibility within the section ranges from 22.9 × 10^{-8} to 107.3 × 10^{-8} m^3/kg, with an average of 51.5 × 10^{-8} m^3/kg (Fig. 5b). The highest susceptibility values (55.6–107.3 × 10^{-8} m^3/kg) are found in the humus horizons of the paleosols, while

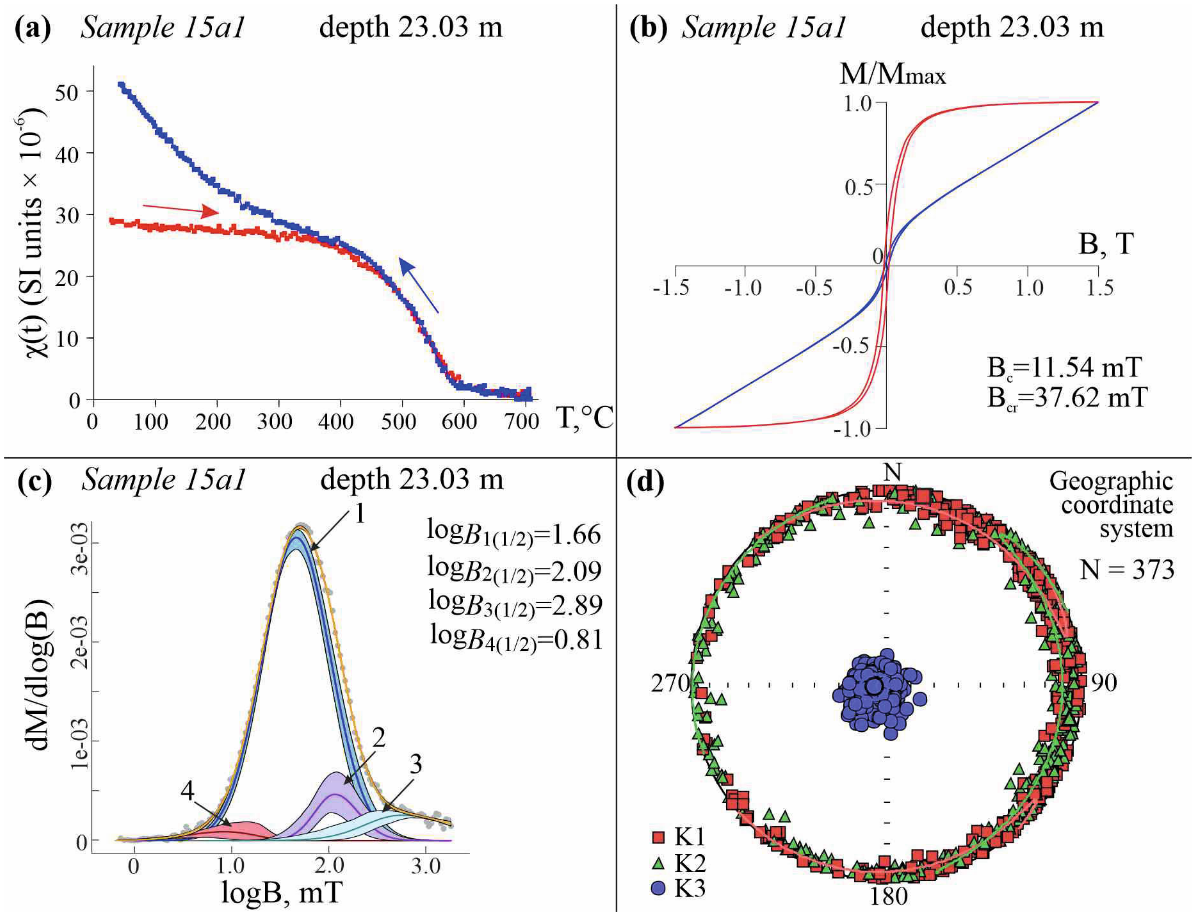

Fig. 2. Rock magnetic characteristic of loess-paleosol deposits in the Otkaznoe section: (a) temperature dependence of magnetic susceptibility (red curve—heating; blue—cooling); (b) hysteresis loops (blue—before paramagnetic correction; red—after paramagnetic correction); (c) coercivity spectrum analysis of IRM acquisition curves (1, 2, 3, 4—components of the spectrum); (d) stereogram of the distribution of the principal axes (K1, K2, K3) of the anisotropy of magnetic susceptibility (AMS) ellipsoids.

the loess horizons exhibit the lowest susceptibility values, ranging from 23.0×10^{-8} to 39.5×10^{-8} m^3/kg. These findings align well with field data regarding the structure of the loess-paleosol sequence and were used for a detailed subdivision of the LPS.

The AMS results are depicted in the stereogram showing the distribution of the main axes of the AMS ellipsoids (Fig. 2d), along with graphs illustrating the inclination of the maximum (K1-Inc) and minimum (K3-Inc) axes with depth (Figs. 4g, 4h). The results reveal that the minimum (K3) axes of the AMS ellipsoids have nearly vertical directions, while the maximum (K1) and intermediate (K2) axes are nearly horizontal and distributed around the great circle (Fig. 2d). The K1-Inc parameter ranges from 0.1° to 17.0°, with an average of 4.5°, whereas the K3-Inc values range from 63.8° to 89.8°, averaging at 82.3°.

The intensity of NRM vary from 3.8 to 31.9 × 10^{-6}A m^2/kg. A concurrent increase in both NRM and χ, particularly evident in the samples from the second trench (Figs. 4b, 4c), suggests a rise in the concentration of magnetic minerals within the paleosol.

Paleomagnetism. The NRM vector is typically represented as the sum of two components (Figs. 3a–3d): (1) a low-coercivity/low-temperature component of a viscous nature, destroyed in fields of 5–14 mT or at temperatures up to 250°C; (2) a high-coercivity/high-temperature component, which is separated between 20–110 mT or 250–590°C and is interpreted as characteristic (ChRM) and primary. Figures 4d–4f show the variations in paleomagnetic directions (declination and inclination of ChRM) and VGP latitudes.

Loess-paleosol deposits in the studied interval accumulated in the Brunhes normal polarity epoch. For the depth of 22.15–22.64 m and 22.86–24.00 m, the D and I values are comparable to modern for the study area (according to the IGRF-14 model: D = 7.7°, I = 63.2°.) and yield a mean direction of D = 357.4°, I = 63.5° (α_{95} = 1.5°, N = 58). However, a distinct zone is observed in the depth of 22.64–22.86 m, characterized by shallow inclinations (minimum I = 27.1°) and declinations near 270° (–90°). This 22 cm

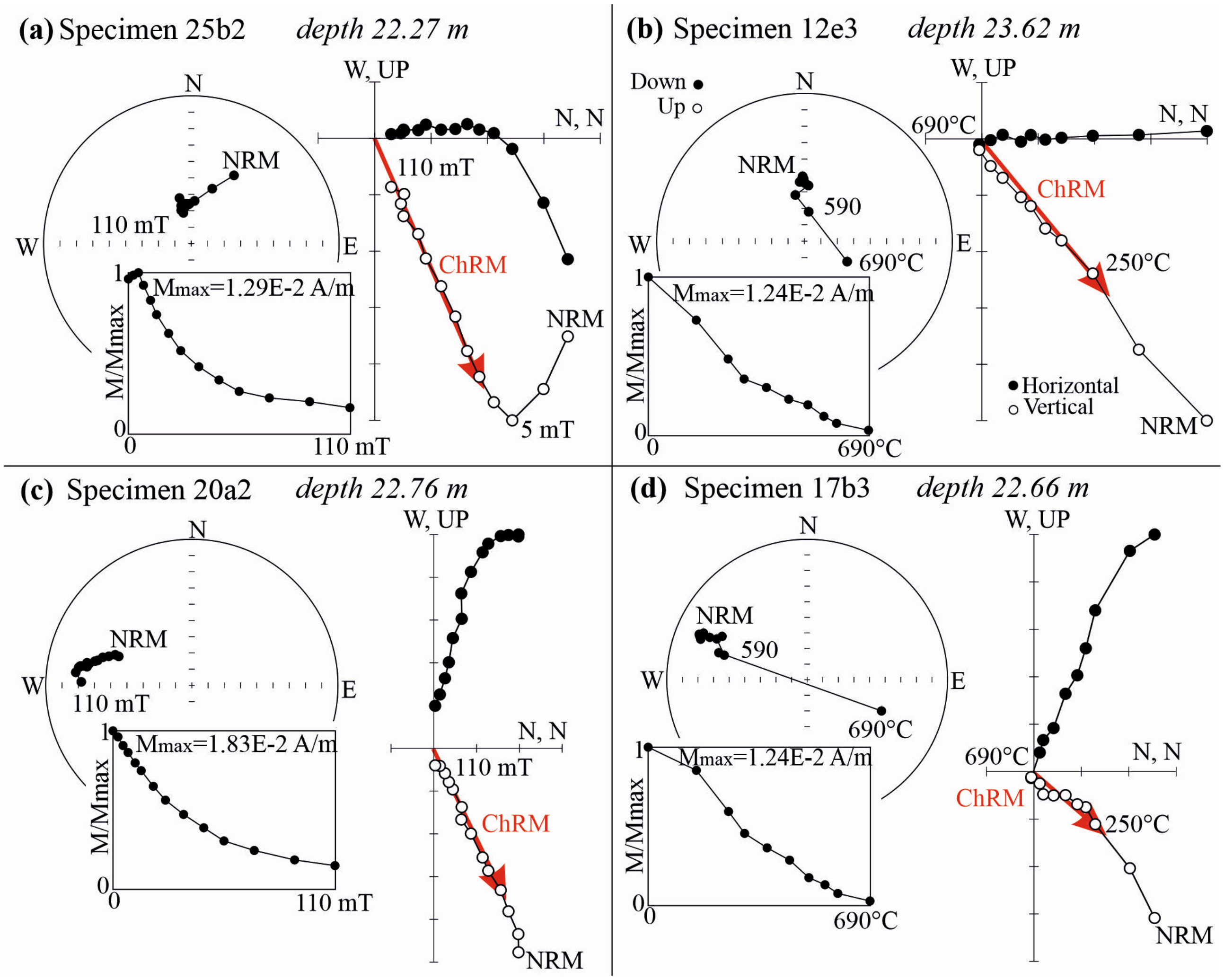

Fig. 3. Representative orthogonal (Zijderveld) vector diagrams, stereograms of component directions and intensity demagnetization plots of thermal (b, d) and alternating field (a, c) demagnetization.

zone comprises 8 stratigraphic levels from the first trench (30 samples) and 6 levels from the second trench (23 samples). The VGP latitudes in this zone vary from 19.1° to 44.1°, placing them within the range of anomalous/intermediate values (from –45° to 45°), that exceed the characteristic amplitude of paleosecular variations over the past 5 Ma [10] (Fig. 4i). Mean VGP latitude for the stable polarity intervals is 81.3°. The VGPs for the intervals exhibiting stable normal polarity are located in the Arctic latitudes of the Northern Hemisphere. In contrast, the VGPs associated with the anomalous zone demonstrate a sequential counterclockwise movement in the equatorial Atlantic (Fig. 4j).

DISCUSSION

Several factors influence paleomagnetic recording in LPSs, such as distortion, smoothing and delayed remanence acquisition caused by the lock-in processes. Distortion of the paleomagnetic record typically arises from disturbance to the primary magnetic fabric of loess, which can result in the emergence of intervals or levels exhibiting paleodirectional anomalies within the loess-paleosol sections [11]. In this context, it is essential to ensure the verifying of the paleomagnetic record by AMS measurements.

According to Zhu [11], the inclination of the maximum (K1-Inc) and minimum (K3-Inc) axes of the AMS ellipsoids serves as an indicator of post-depositional processes that may disturb the primary magnetic fabric of loess. Nearly vertical inclinations of the minimum axis (K3-Inc > 70°) and nearly horizontal distributions of the maximum axis (K1-Inc < 20°), indicate a primary eolian magnetic fabric. The results of the AMS measurements from the Otkaznoe section indicate that the sediments conform to the established criteria: all specimens exhibit K1-Inc < 20°, and 365 out of 373 specimens show K3-Inc > 70°. This data

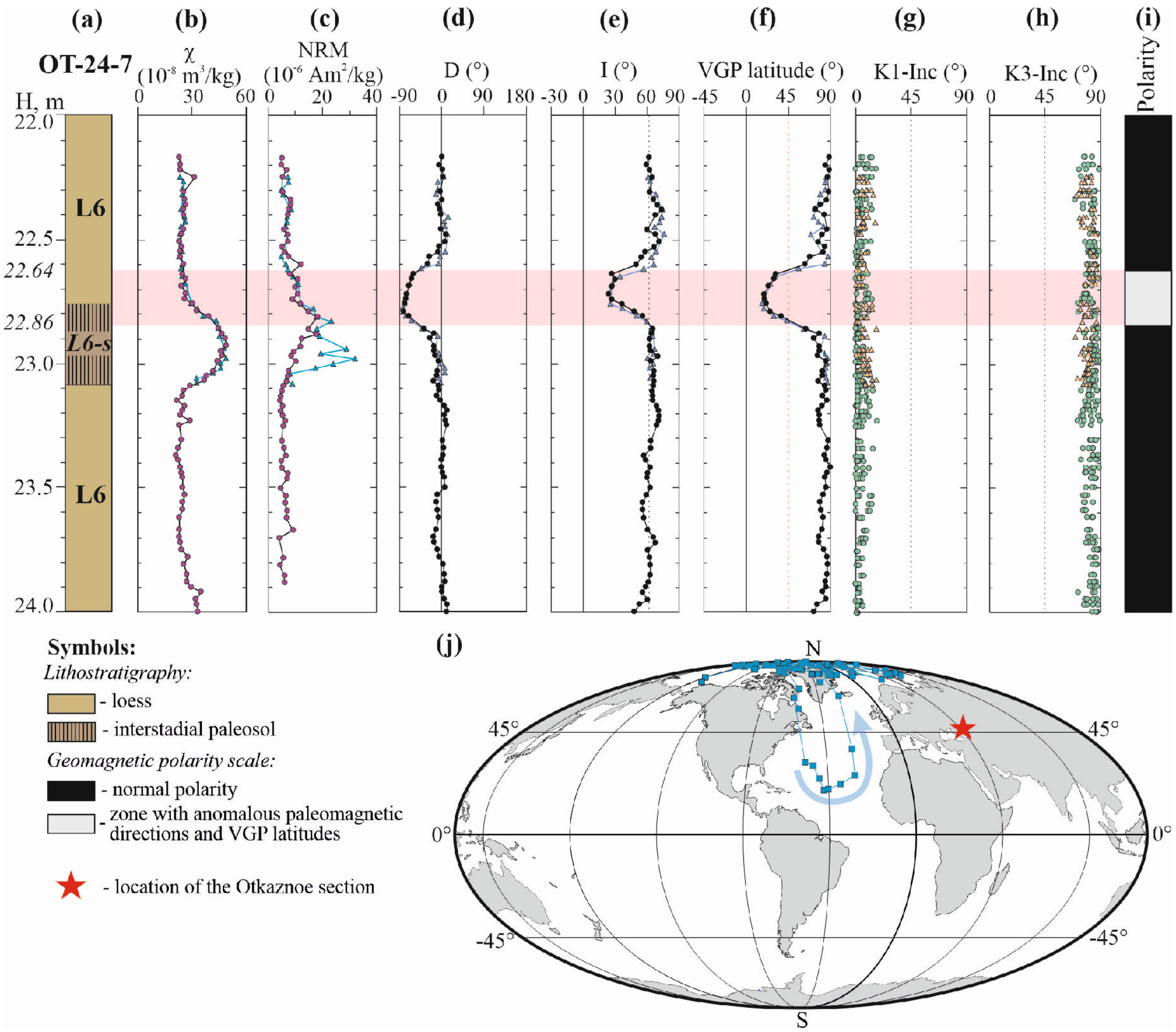

Fig. 4. (a) Lithostratigraphy of the OT-24-7 in the Otkaznoe section and its rock magnetic and paleomagnetic characteristic: (b) magnetic susceptibility; (c) natural remanent magnetization; (d) declination and (e) inclination of the characteristic component of magnetization (ChRM); (f) latitude of the virtual geomagnetic pole (VGP); (g) inclination of the maximum (K1-Inc) and (h) minimum (K3-Inc) axes of the AMS ellipsoids; (i) geomagnetic polarity scale (GPS); (j) VGP path. Circles and triangles on graphs (b–h) show the results for the first trench and for the second trench respectively. The interval corresponding to the geomagnetic excursion is highlighted in pink in the figure.

suggests a primary undisturbed magnetic fabric in the loess-paleosol deposits of the Otkaznoe section, both within the stable polarity interval and in the anomalous paleomagnetic zone. Therefore, we have substantial reason to believe that the anomalous paleomagnetic record observed in the 22.64–22.86 m interval is not attributable to lithological features, but rather reflects the behavior of the geomagnetic field and corresponds to geomagnetic excursion.

To estimate the age of the recorded geomagnetic event, we correlated variations in magnetic susceptibility from the Otkaznoe section with the LR04 oxygen isotope curve [12] (Figs. 5b, 5c). Based on our correlation, the pedocomplexes S4, S5, and S6 correspond to marine isotope stages (MIS) 11, MIS 13, and MIS 15, respectively. In addition, especially thick (up to 6 m) "Don" loess (L7) is aligned with MIS 16, while the loess horizon L6 is associated with MIS 14. These results are consistent with the regional stratigraphic scheme of the East European Plain, which indicates that the "Don" loess is part of the Don horizon, dated to MIS 16 [13, 14]. The weak developed paleosol at the depths of 22.8–23.1 m is interpreted as interstadial (L6-s) within the loess L6 (Figs. 4a, 5b).

According to the alternative stratigraphic scheme proposed by N.S. Bolikhovskaya [5], this interstadial paleosol belongs to S5, which, together with part of L6, corresponds to MIS 15 (Fig. 5a). Meanwhile, L5 correlates with MIS 12–14, S6 is associated with MIS 16, and the thick loess (L7) aligns with MIS 17. However, this interpretation disrupts the principle of correspondence between pedocomplexes and interglacials,

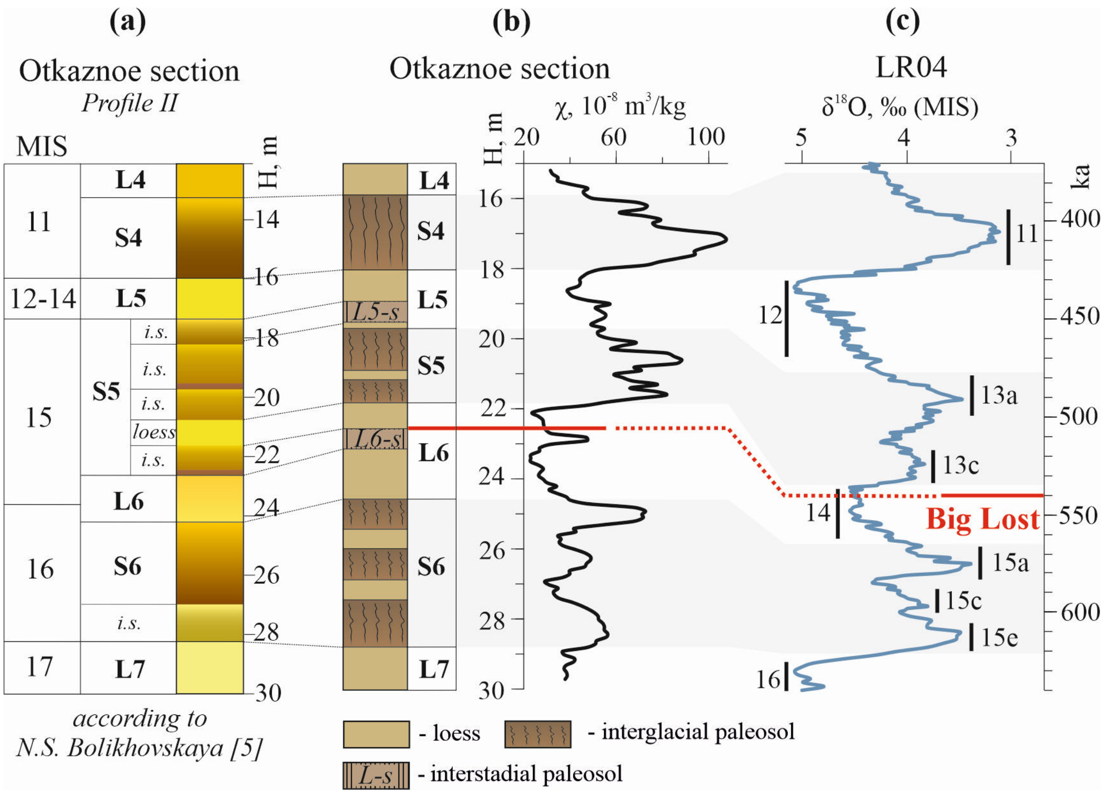

Fig. 5. Chronostratigraphy of the Otkaznoe section (a) according to N.S. Bolikhovskaya [5] and (b) our data; (b, c) correlation of variations in magnetic susceptibility in the Otkaznoe section with the LR04 oxygen isotope curve [12]. The red line shows the position in the section of the identified geomagnetic excursion, the dotted line shows its correlation with the Big Lost excursion. i.s.—initial (embryonic) soil.

loess horizons and glacial epochs. Moreover, the paleosol position of the "Don" horizon contradicts regional stratigraphy. Therefore, we consider this alternative scheme less reliable for further interpretation.

It should also be noted that our data on magnetic susceptibility variations in the Otkaznoe section exhibit a notable similarity with the results previously reported by A.O. Alekseev, which had a resolution of 0.25–2.00 m [15]. Consequently, we propose that the geomagnetic excursion identified in the upper part of L6, occurred at the end of MIS 14. The age of this geomagnetic event can be estimated at ~540 ka (Fig. 5). The estimated duration of the excursion, calculated using the average sedimentation rate for the entire section (10 cm/ka) and separately for L6 (8 cm/ka), is around 2–3 ka.

The estimated age of the excursion identified in the Otkaznoe section is older than the Orphan Knoll (~495 ka) [16] and CR2 (~515 ka) events [17], and is in excellent agreement with the age of the Big Lost geomagnetic excursion (~540–541 ka) [18]. This excursion was first identified in Idaho lavas with a $^{40}Ar/^{39}Ar$-age of 559 ± 14 ka [19, 20]. Then, it has been repeatedly documented in marine sediments, where it is characterized by not only paleodirectional anomalies but also a significant decrease in geomagnetic field intensity [18]. The age of the Big Lost event, as determined from marine sedimentary cores through orbital tuning of $\delta^{18}O$ variability in foraminifera, ranges from 536 to 543 ka [16, 18] and is dated to the end of MIS 14 (Fig. 5). Big Lost excursion in the LPSs of Europe has not been reliably recorded until now.

CONCLUSIONS

The results of detailed paleomagnetic study of the Middle Pleistocene loess-paleosol sequence in the Otkaznoe section have confidently identified a geomagnetic excursion. By correlating variations in magnetic susceptibility within the section with the oxygen isotope curve, we estimated the age of this geomagnetic event, identifying it as the Big Lost excursion (~540–541 ka). Among the loess sections in Europe, the Big Lost excursion was reliably recorded for the first time. The continuous paleomagnetic record of this event makes it possible to use it as a reliable chronostratigraphic marker for solving problems with detailed stratigraphic subdivision of the LPSs and for enabling regional and global correlations with other sedimentary archives.

SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at https://doi.org/10.1134/S1028334X25606455

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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