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Inclination Shallowing in the Permian/Triassic Boundary Sedimentary Sections of the Middle Volga Region in Light of the New Paleomagnetic Data

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Abstract—One of the key challenges which are traditionally encountered in studying the paleomagnetism of terrigenous sedimentary strata is the necessity to allow for the effect of shallowing of paleomagnetic inclinations which takes place under the compaction of the sediment at the early stages of diagenesis and most clearly manifests itself in the case of midlatitude sedimentation. Traditionally, estimating the coefficient of inclination flattening (f) implies routine re-deposition experiments and studying their magnetic anisotropy (Kodama, 2012), which is not possible in every standard paleomagnetic laboratory. The Elongation–Inclination ($E–I$) statistical method for estimating the coefficient of inclination shallowing, which was recently suggested in (Tauxe and Kent, 2004), does not require the investigation of the rock material in a specially equipped laboratory but toughens the requirements on the paleomagnetic data and, primarily, regarding the volume of the data, which significantly restricts the possibilities of the post factum estimation and correction for inclination shallowing. In this work, we present the results of the paleomagnetic reinvestigation of the Puchezh and Zhukov ravine (ravine) reference sections of the Upper Permian and Lower Triassic rocks in the Middle Volga region. The obtained paleomagnetic data allowed us to estimate the coefficient of inclination shallowing f by the $E–I$ method: for both sections, it is $f = 0.9$. This method was also used by us for the paleomagnetic data that were previously obtained for the Permian–Triassic rocks of the Monastyrskii ravine (Monastirskoje) section (Gialanella et al., 1997), where the inclination shallowing coefficient was estimated at $f = 0.6$.

Keywords: paleomagnetism, inclination shallowing, Permian, Triassic, Elongation–Inclination method, secular variations

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INTRODUCTION

The effect of paleomagnetic inclination shallowing in the sedimentary rocks has been known for a long time; however, it is most frequently thought of when something goes wrong with the interpretation of the obtained data. The situation with the global inconsistency of the paleomagnetic and geological data at the Permian–Triassic (*P-Tr*) boundary for Laurussia and Gondwana, which in its time resulted in the appearance of two alternative paleotectonic reconstructions of Pangaea (Domeier et al., 2012), is a striking example. We frequently come across the inclination shallowing effect being mentioned in the works devoted to testing the hypothesis of the central axial dipole for the Paleozoic/Mesozoic boundary, where this phenomenon is considered as one of the probable causes of the systematic difference of the coeval paleomagnetic poles of the Siberian and East European platforms (Veselovskiy and Pavlov, 2006; Bazhenov and Shatsillo, 2010).

It was recently convincingly demonstrated (Domeier et al., 2012) that the allowance for the effect of inclination shallowing in the paleomagnetic data obtained over the sedimentary rocks promotes an efficient solution of the Pangaea reconstruction problem, whereas even the presence of insignificant inclination shallowing (5–10%, $f = 0.9$) in the Permian/Triassic sediments of Europe makes the distinction between the average *P–Tr* paleomagnetic poles of Siberia and the East European platforms statistically insignificant (Veselovskiy and Pavlov, 2006; Bazhenov and Shatsillo, 2010). Thus, the allowance and subsequent correction of the paleomagnetic data for the effect of inclination shallowing is highly important for the paleotectonic reconstructions and for studying the past configuration of the Earth's magnetic field.

However, until recently the procedure of estimating the coefficient of inclination shallowing for a particular sedimentary section required lithological and rock magnetic studies, which could only be conducted with specific laboratory equipment for the experiments on the redeposition of disintegrated rocks. Certainly, this fact strongly limited the possibilities of ordinary researchers in correcting the obtained results for inclination shallowing. With the development of the *Elongation–Inclination* (*E–I*) statistical method (Tauxe and Kent, 2004), the computations of the coefficient of inclination shallowing *f* became much more available; however, currently, certain requirements on the object of study (see the Method section) and the volume of the initial paleomagnetic data set have precluded this method from being extensively used across the paleomagnetic community. At the same time, it is clear that coefficient *f*, which depends on quite a few factors (sedimentation conditions, paleolatitudinal position of the studied section, lithology), should be individually determined for each particular section because the mass routine correction of existing paleomagnetic determinations with the use of a certain average value of this coefficient cannot be considered as completely correct from the methodical standpoint.

The main purpose of our study is to estimate the coefficient of inclination shallowing *f* in the reference sections of the Permian–Triassic sections within the Russian Platform—the Puchezh and Zhukov ravine sections. For this purpose, we solved the important problem associated with obtaining new reliable paleomagnetic data meeting the requirements of the *E–I* method.

OBJECTS OF STUDY

In the course of field work in 2013–2015, we thoroughly explored the Upper Permian (P_3) and Lower Triassic (T_1) boundary terrigenous sections in the central part of the Russian Platform, which are located in the Middle Volga region. All the sections are composed of red beds and are reliably correlated to the local stratigraphic scale.

The Puchezh section (P_3–T_1) is located in the northwestern suburbs of the town of Puchezh (the coordinates are indicated in Table 1) in the Ivanovo region. The apparent thickness of the sequence is 20 m and the length of the outcrop is 100 m. At its base the sequence is composed of the Vyatkian red-brown clays, silts, sandstones; light gray, pink, and red-brown marls (upper Tatarian substage of Upper Permian). The Upper Vyatkian layers are overlain by the rocks of the Vokhmian horizon of the Induan stage of the Lower Triassic series. These rocks are represented by a unit of gray-green sands with a thickness of 2 m which is changed, further up the stratigraphy, by a layered stratum of gray brown clays, silts, and sandstones with thin intercalations of pink-brown marls. A detailed description of the section is presented in (*Granitsa*..., 1998). Hereinafter, the stratigraphic division follows Supplement no. 1 of (*Stratigraficheskii*..., 2006). The rock bedding is monocline with a dip azimuth of 100° and dip angle of 17°. The Permian/Triassic boundary in this section is lithologically indistinct and is established by a sharp change in the scalar magnetic parameters (e.g., magnetic susceptibility) in the Triassic sediments compared to the Permian layers. This phenomenon is fairly common in many *P–Tr* sections of the Russian Platform (Molostovskii, 1983). From the lower 10 m of the sequence which contain the Permian–Triassic boundary, we collected 169 samples with a step of 5 to 20 cm along the thickness of the stratum. Besides, for estimating the inclination shallowing by the site-by-site correction technique (Kodama, 2012), we took 20 samples from each of the five most distinctly tracked layers. The total number of samples in the collection is 296.

The Zhukov ravine section (P_3–T_1) located in the Klyaz'ma River valley, Vladimir region (see Table 1), is composed of subhorizontal layers of Vyatkian clays, sands, silts, pink marls, and limes. This 40-m thick stratum is overlain by similar rocks of the Vakhmian age (lower substage of the Induan stage of the Lower Triassic) with a thickness of 15 m (Minikh et al., 2011). The results of the latest paleontological studies (Molostovskaya, 2010; Minikh et al., 2011; Scholze et al., 2015) testify to the absence of a significant gap between the Permian and Triassic rocks in the sequence. The section was sampled by Yu.P. Balabanov et al. from the pits which were dug at several points across the ravine. The entire collection contains 150 oriented samples; the sampled thickness of the section is 45 m.

Besides the described sections, for estimating the coefficient of inclination shallowing, we used the results of the detailed paleomagnetic studies of the Upper Permian **Monastyrskii ravine (Monastirskoje)** reference section of the Tatarian Stage (Gialanella et al., 1997). This section is located on the right bank of Volga River (Table 1) 350 km SE from the first two sections described. The Monastyrskii ravine sequence is composed of intercalations of red silts and clays with fine seasonal layering (bandy clays); also rare interbeds of light limestones and dolomites are present. Overall, the authors of the cited work collected 300 oriented samples from a 150-m thick interval of the section. We note that since the initial data on the direction of characteristic magnetization component in the samples were absent in (Gialanella et al., 1997), the magnetization directions for the Monastyrskii ravine section were obtained by digitizing the stereogram presented in the cited paper; the accuracy of the obtained values is ±1°.

STUDY METHODS

The field and laboratory investigations, data processing, and interpretation of the results followed the standard procedure, which is widely accepted in paleomagnetic studies, with the recent methodical

Table 1. Average paleomagnetic directions and paleomagnetic inclinations corrected for inclination shallowing

Section	Sampling site		Component	N/n	Geographic coordinate system				Stratigraphic coordinate syastem				$f/I_{f\text{-corr}}$ (°)
	slat (°N)	slong (°E)			Dg(°)	Ig(°)	Kg	α95g(°)	Ds(°)	Is(°)	Ks	α95g(°)	
Puchezh	56.99420	43.15810	htc NR	269/157	36.7	43.8	19.7	2.6	**55.7**	**42.8**	**19.7**	**2.6**	**0.9/44.9**
			ltc	269/15	356.7	68.0	25.0	7.8	56.0	76.3	25.0	7.8	
Zhukov ravine	56.188	42.649	htc NR	147/106	**32.8**	**43.4**	**17.9**	**3.3**	–	–	–	–	**0.9/44.1**
			ltc	147/75	14.1	73.0	17.1	4.1	–	–	–	–	
Monastyrskii ravine (Gialanella et al., 1997)	54.80	48.82	htc NR	300/193	**22.3**	**34.9**	**11.6**	**3.1**	–	–	–	–	**0.6/49.4**

Slat, slong are sampling site latitude and longitude; htc (ltc) NR are high-temperature (low-temperature) magnetization components of normal and reversed polarity; N/n is number of specimens subjected to magnetic cleaning/used in work; Dg, Ig, Kg, α95g (Ds, Is, Ks, α95s) are declination, inclination, concentration and radius of 95%-confidence circle for average paleomagnetic direction in geographic (stratigraphic) coordinate system; $I_{f\text{-corr}}$ is paleomagnetic inclination corrected based on obtained coefficients of inclination shallowing f for each section.

and instrumental achievements taken into account (Butler, 1998; Tauxe et al., 2016; Kodama, 2012; Li and Kodama, 2016). The oriented samples were excavated by hand, with the help of a geological hammer and knife; the orientation of the samples was determined by a geological compass with allowance for local declination according to the 12th-generation IGRF model. The samples were sawn by a rock-cutting saw with a diamond cutting wheel into 2-cm cubes. The paleomagnetic collections were magnetically cleaned on modern equipment in Russian organizations. Magnetic measurements in the Laboratory of the main geomagnetic field and petromagnetism of the Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences was conducted on a SQUID magnetometer (2G Enterprises, United States) installed in the nonmagnetic room. Magnetic measurements in the Rock magnetic laboratory at the Faculty of geology of Lomonosov Moscow State University was conducted on an JR-6 spin-magnetometer (AGICO, Czech Republic). The samples were demagnetized with the use of MMTD-80 (Magnetic Measurements, England) and TD48 (ASC Scientific, USA) thermal demagnetizers. Part of the samples was demagnetized by an alternating magnetic field in an LDA-3 demagnetizer (AGICO, Czech Republic). The temperature dependence of magnetic susceptibility was determined with the use of a KLY-4S kappa-bridge with an attached CS3 furnace for high-temperature measurements. The temperature curves were measured by the Curie balance designed at Kazan Federal University, Kazan.

The coefficient of inclination shallowing f in our study was estimated by the statistical elongation–inclination (E–I) method (Tauxe and Kent, 2004), which is based on the TK03.GAD model of secular variations of the geomagnetic field (Tauxe and Kent, 2004). One of the key peculiarities of this model lies in the assumption about the circular (normal) distribution of the virtual geomagnetic poles (VGPs) caused by secular variations. In the general case, due to the nonlinear conversion of VGP coordinates into the declination and inclination of paleomagnetic direction (formula (1.5) in (Khramov et al., 1982)), the initially circular distribution of VGPs is transformed in the meridionally elongated distribution of the corresponding paleomagnetic directions. The degree of elongation of the distribution of the paleomagnetic directions (E) is maximal in the case when an object is located at the equator, where the elongation decreases polarwards with the growth in the modulus of the paleomagnetic inclination (I). This process is depicted by the curve in the graph in the E–I coordinates. If the object is located at any of the poles, then both the paleomagnetic directions and the virtual geomagnetic poles corresponding to them will have a circular distribution. The degree of elongation E is determined as the ratio of maximal to intermediate axes of the triaxial ellipsoid representing the distribution of the paleomagnetic directions.

In the case when the rocks undergo the effect of inclination shallowing, then as the coefficient f decreases from 1 (no shallowing) to 0 (complete shallowing), the meridionally elongated distribution of the paleomagnetic directions will initially tend to become circular after which they will again start stretching, but in the west–east direction, i.e., perpendicular to the meridian. According to the E–I technique, the inclination shallowing obeys King's rule (King, 1955):

$$\tan(I_0) = f\tan(I_{\text{corr}}), \tag{1}$$

where I_{corr} is the paleomagnetic inclination corrected for the effect of inclination shallowing; I_0 is the initial (measured in the rock) paleomagnetic inclination; and f is the inclination shallowing coefficient.

In the E–I method, the coefficient f for the initial sample of paleomagnetic inclinations is estimated by the following algorithm (Kodama, 2012). In the graph in E–I coordinates, a curve is drawn which corresponds to the change in the elongation E depending on the inclination I in accordance with the TK03.GAD model (the black segment of the curve in Fig. 2a). After this, the point corresponding to the initial E and I values for the considered sample of the vectors ($f = 1$) is plotted. Subsequently, each direction in the sample is recalculated by formula (1) for values of coefficient f ranging from 1 to 0 with the given step, and the points corresponding to the E and I values for each renewed sample are plotted in the graph. The resulting curve (each of the gray curves in Fig. 2a) intersects the model line at certain values of I and f which are the sought estimates of the corrected paleomagnetic direction and coefficient of inclination shallowing, respectively. The reliability of the obtained result can be estimated, e.g., by the bootstrap procedure, as it is implemented in the program package (Tauxe et al., 2016).

The practical application of the E–I method has a number of constraints. Firstly, the method works stably only with a sufficiently large set of unit vectors. The minimal required number of vectors was initially estimated at 10^3–10^4 (Tauxe and Kent, 2004); however, the further experience of using the E–I method has shown (Kodama, 2012) that the reduction of the volume of the sample to 100 vectors (but not less than 100) does not statistically significantly affect the results. Secondly, each vector in the sample should represent the record of secular variations; i.e., it should not average them. Considering the fact that it takes 10–100 kyr to average secular variations (Tauxe et al., 2016), whereas the standard cubic specimen for paleomagnetic studies has a side of 2 cm, the E–I method can only be reliably applied for sedimentary sequences that were accumulated at a rate of at least 0.2 cm/kyr. Here, it is important to remember that for satisfying the TK03.GAD model requirements about the uniform circular VGA distribution, the selected paleomagnetic samples should cover the interval of the section within which the secular variations are averaged, i.e., the rock material represented by these samples was accumulated during at least 10–100 kyr (which is the third constraint). From the practical standpoint this means that for the reliable averaging of secular variations, the sampled interval of the section should be more than 2 m, although it is also probable that the secular variations will be averaged even within a 20-cm interval.

We note that the comparison (Bilardelo et al., 2011) of the coefficient f estimated (1) by the standard procedure by redepositing the sediment and measuring the anisotropy of magnetization and (2) by the E–I method on the same objects has demonstrated the convergence of the results within the error limits provided that the number of vectors in the sample was at least 100. This example illustrates the reliability of the E–I method despite the fact that this method is statistical and that it obviously disregards the individual peculiarities of the studied rocks.

In estimating the coefficient of inclination shallowing f by the E–I method, we used the PmagPy v.3.2.1 program package (Tauxe et al., 2016).

THE RESULTS OF PALEOMAGNETIC STUDIES

All the samples were subjected to detailed thermal demagnetization, which included 8 to 16 steps. In the Puchezh section, a high-quality paleomagnetic signal is observed in 65% of the samples; in the remaining 35% of the samples, the paleomagnetic signal is noisy and uninterpretable. In most cases, the samples contain one or two magnetization components (Fig. 1a). The low-temperature component, which is removed by heating to 180–300°C, is the least stable; its direction (Table 1) is close to the present-day geomagnetic field (PDF) in the region of study ($D_{PDF} = 12.7°$, $I_{PDF} = 72.5°$). The stable high-temperature component of normal and reversed polarity is removed under heating to 580–680°C (Fig. 1e). The reversal test (McFadden and McElhinny, 1990) is positive at level C: $\gamma/\gamma_c = 3.4°/10.1°$.

The high quality of the paleomagnetic record in the rocks composing the Zhukov ravine section allows us to reliably identify up to two magnetization components in most samples (Fig. 1b): the low temperature component (20–250°C), which is close to the direction of the present geomagnetic field ($D_{PDF} = 12.1°$, $I_{PDF} = 72.0°$), and the high temperature component (300–570–680°C) of both the normal and reversed polarities (Fig. 1f). The reversal test is negative ($\gamma/\gamma_c = 13.6°/6.3°$), which is perhaps associated with the incomplete separation of the viscous and characteristic magnetization components in part of the samples. The results of the principal component analysis are presented in the Table 1.

The ancient, Permian–Triassic origin of the characteristic magnetization component is supported by (a) its bipolar distribution, (b) the positive (Puchezh section) reversal test, and (c) the closeness of the paleomagnetic pole corresponding to the average direction to the *P*–*Tr* poles of the East European Platform and its dissimilarity from the younger poles.

INCLINATION SHALLOWING ESTIMATION

The paleomagnetic data obtained in this work from two sections (Puchezh and Zhukov ravine) in the Middle Volga region meet the formal conditions of applicability of the E–I method: (1) the number of unit directions of the characteristic magnetization component in them is >100 (157 and 106, respectively), and (2) the average rate of sedimentation of these sections which were formed in the intracontinental settings of shallow lakes and periodically flooded

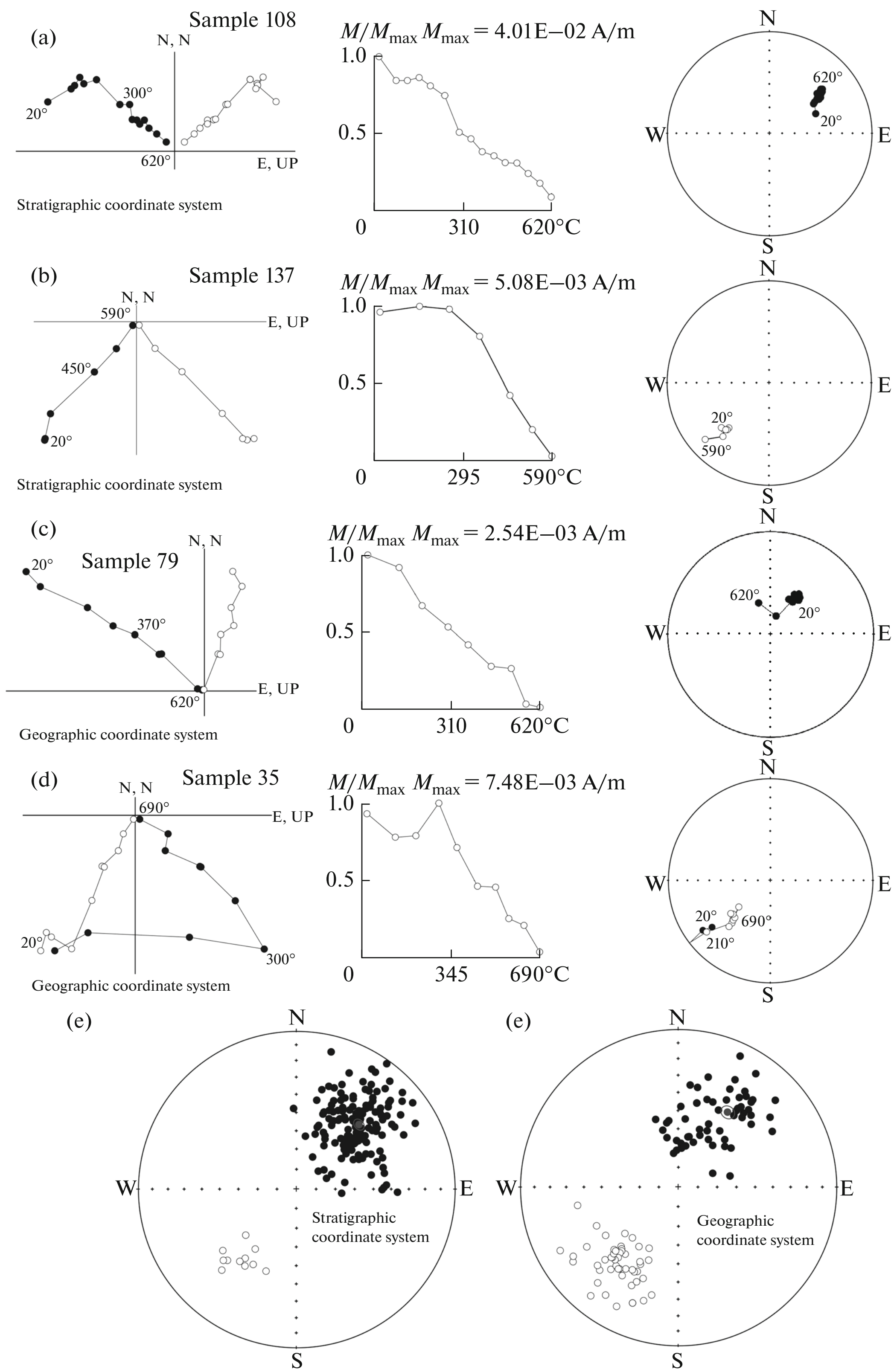

Fig. 1. Results of thermal magnetic cleaning for samples of (a), (b) Puchezh and (c), (d) Zhukov ravine sections: Zijderveld diagrams, NRM demagnetization curves, and stereograms. Filled (empty) circles in stereograms show projections of vector on lower (upper) hemisphere; filled (empty) circles in Zijderveld diagrams show projections of vectors on horizontal (vertical) plane; (e), (f) directions of characteristic magnetization components isolated in samples of studied sections ((e) Puchezh, (f) Zhukov ravine) and their average values with circles of 95% confidence.

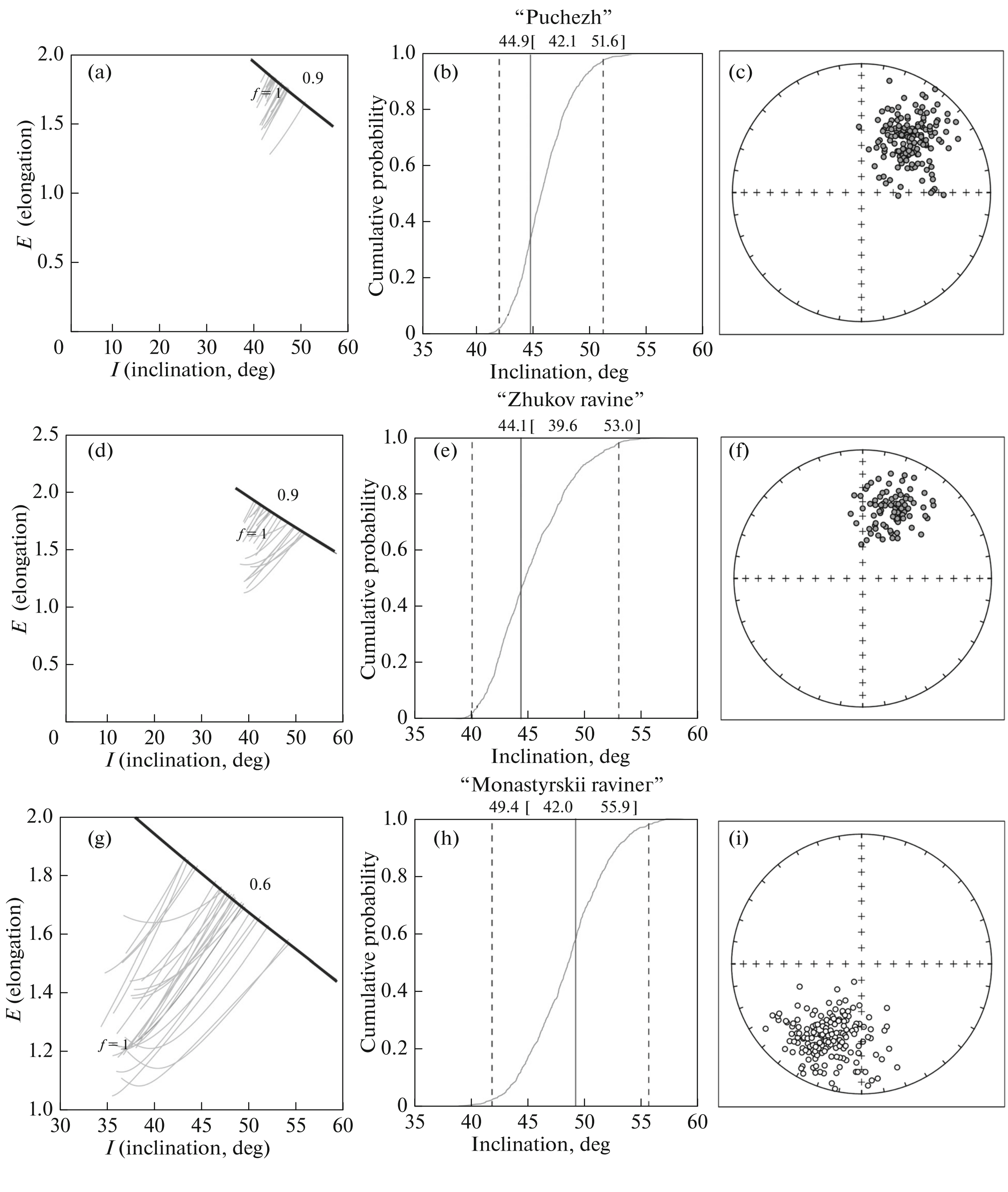

Fig. 2. Estimation of coefficient of inclination shallowing f in P–Tr sedimentary sections of Middle Volga region by E–I method: (a), (d), (g), E–I diagrams: black segment of curve is expected E/I predicted by TK03.GAD model; gray segments of curves are E/I ratios obtained by bootstrap modeling of distribution of vectors at different values of coefficient of inclination shallowing f (segments of curves corresponding to 20 bootstrap samples are shown); (b), (e), (h) are cumulative curve (gray) of points of intersection of 1000 bootstrap samples with model E/I curve; average value of calculated true inclination (vertical solid line) and its 95% confidence interval are indicated numerically and shown graphically (two vertical dashed lines); (c), (f), (i) are initial samples of directions of characteristic magnetization direction in samples.

river flood plains (Tverdokhlebov et al., 2005) can be estimated at ~0.5 cm/kyr (Kukal, 1983). Besides, our estimates obtained for the amplitude of secular variations over the sets of VGPs corresponding to the direction of the ancient magnetization component in each sample suggest that the secular variations in the sampled sections are averaged. For instance, the amplitude of secular variations (S_b, (Tauxe et al., 2016)) for the Puchezh section is 16.8° ± 1.4° (according to the TK03 model, the expected S_b value for paleolatitude 25° is ~13°), whereas for the Zhukov ravine section S_b = 16.9° ± 1.7°. The cited requirements are also met by the data presented in (Gialanella et al., 1997) for the Monastyrskii ravine section: the direction of the ancient magnetization component is obtained over 193 samples, meanwhile the presence of the bandy clays and shallow lacustrine sedimentation setting suggest that in each sample, the averaging of secular variations has not been achieved. The amplitude of secular variations recorded in the sampled interval of the section is estimated at S_b = 17.5° ± 1.3°, which points to the averaging of secular variations.

It is important that the estimates of the amplitude S_b of secular variations obtained over the samples within the small-thickness intervals of the Puchezh and Zhukov ravine sections indicates that the variations are averaged even within an interval with a thickness of ~3 m. In contrast, the amplitude of secular variations on the samples taken along the strike of the same layer in the Puchezh section are noticeably lower than the prediction by the TK03 model (S_b = 7.5° ± 1.7°), i.e., the averaging of the variations has not been achieved. These results support our previous estimate of the average rate of sedimentation in the considered sections and are an additional argument for the suitability of the analyzed paleomagnetic data for processing by the E–I method for estimating the inclination shallowing.

The obtained estimates of coefficient f for the Puchezh (Fig. 2a) and Zhukov ravine sections (Fig. 2d) are 0.9, which indicates that the effect of inclination shallowing insignificantly contributes to the paleomagnetic record of the studied sediments: its contribution is within the error limits of determination of the average paleomagnetic direction in these rocks (±3°). Coefficient f for the Monastyrskii ravine section, which is 0.6 (Fig. 2g), points to the much more intense manifestation of the effect of inclination shallowing in these sediments.

The corrected inclinations of the average paleomagnetic directions of the characteristic magnetization component for the considered sections are presented in the table and illustrated in Figs. 2b, 2d, and 2h.

DISCUSSION

The problem of the paleomagnetism of sediments, including the terrigenous red beds, is still actively discussed in the paleomagnetic community. The results of numerous studies of this problem suggest (Kodama, 2012) that natural remanent magnetization of red sedimentary rocks can be associated with three magnetic fractions: (1) clastic magnetite, (2) clastic hematite, and (3) finely dispersed specular hematite, which is formed at the late stage of diagenesis and can be significantly shifted in time (by dozens of thousands of years) from the time of sedimentation. Correspondingly, the first two magnetic fractions determining the detrital remanent magnetization of the rock can be prone to the effect of inclination shallowing, whereas pigmentary hematite, which has chemical magnetization, cannot.

For elucidating the magnetic minerals represented in the red beds of the Puchezh and Zhukov ravine sections, we conducted a series of experiments on determining the temperature dependence of magnetic susceptibility ($k(T)$) in the samples of these rocks from the discussed sections. The results have shown that the $k(T)$ curves for both sections can be classified into three groups (Figs. 3a–3c). Despite the different behavior of the heating–cooling curves (which is likely to be related to the processes of magnetite and maghemite oxidation during heating in air), it can be concluded that the main magnetic minerals in the studied rocks are magnetite, as indicated by the sharp drop in magnetic susceptibility in the temperature interval 560–580°C, and hematite, as established from the gradual decrease in magnetic susceptibility from 580 to 700°C. The results of the differential thermomagnetic analysis (Fig. 3d) support this conclusion and so does the mineral analysis of the rocks from the Zhukov ravine section, which is presented in (Minikh et al., 2011).

The further experiment was aimed at separating the magnetization associated with magnetite and hematite. Demagnetization of 20 twin samples from the Zhukov ravine section in the alternating magnetic field (AF) with the amplitude of up to 100 mT has shown that 13 samples are demagnetized by 10–70% of the value of the natural remanent magnetization, whereas the direction of the revealed magnetization component is close to the direction of the present geomagnetic field in the region of the works (Fig. 3e). Here, thermal demagnetization of the twins of the specimens that were demagnetized by the alternating field isolates the characteristic magnetization component in the temperature interval from 400 to 690°C (Fig. 3f). This observation suggests that the characteristic magnetization component is carried by hematite, whereas most of the magnetite present in the rock is viscously remagnetized by the present magnetic field. For the remaining seven samples, the magnetic cleaning by the alternating field either does not yield interpretable results or it is inefficient overall.

The measurements of the anisotropy of magnetic susceptibility (AMS) in the samples from the Puchezh and Zhukov ravine sections have shown that the AMS

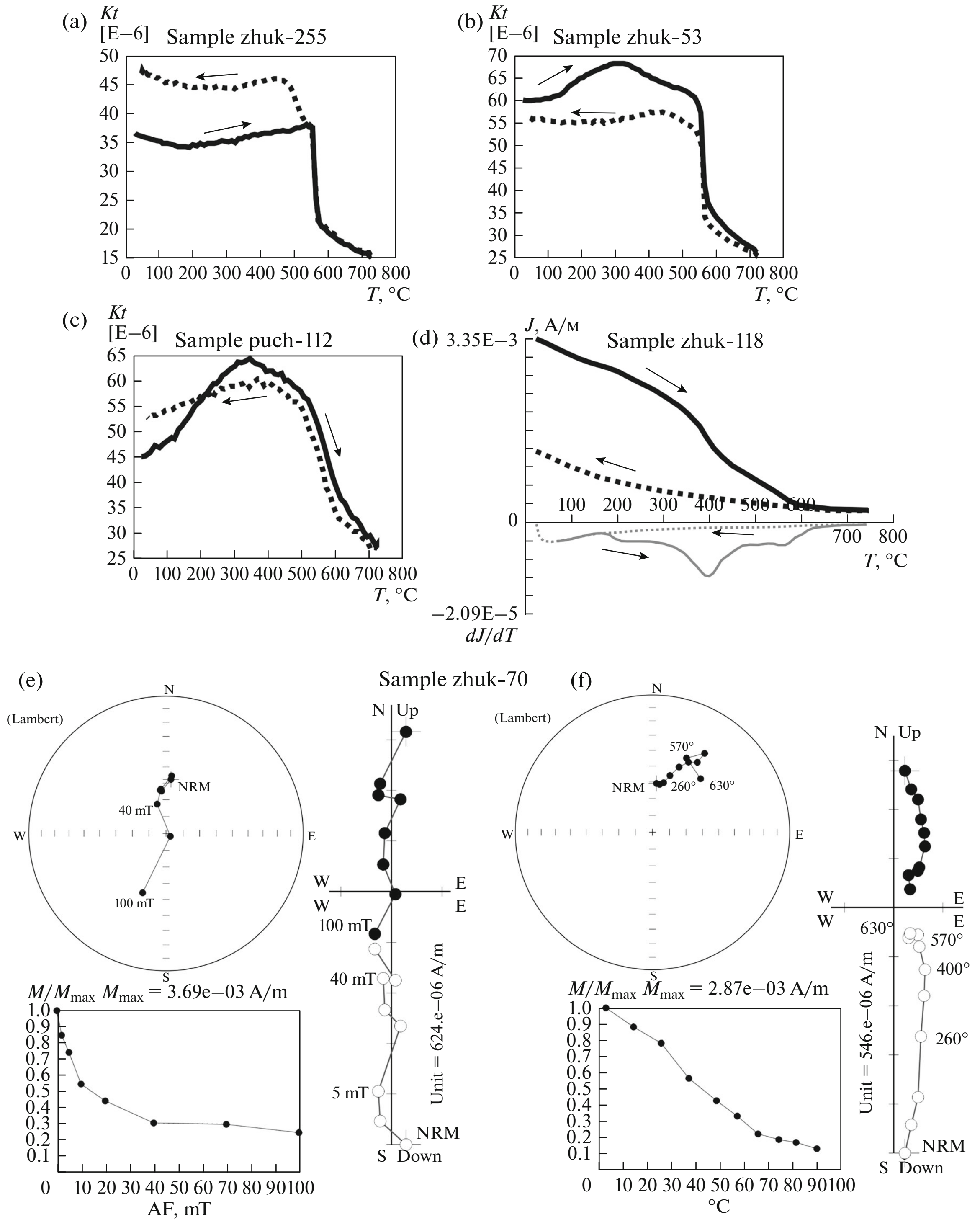

Fig. 3. Results of rock magnetic studies for samples from Puchezh and Zhukov ravine sections: (a), (b), (c) typical curves of temperature dependence of magnetic susceptibility for samples of Puchezh section (puch-112) and Zhukov ravine (zhuk-255 and zhuk-53); solid (dashed) line corresponds to heating (cooling); (d) results of differential thermomagnetic analysis for sample from Zhukov ravine section (zhuk-118): black solid curve corresponds to heating, black dashed line corresponds to cooling; gray solid curve shows first derivative of heating curves; gray dashed line is first derivative of cooling curve; (e), (f) is comparison of results of (e) demagnetization by alternating magnetic field and (f) thermal cleaning of twin specimens of zhuk-70 sample from Zhukov ravine section.

ellipsoids in all samples have an oblate shape (Figs. 4c, 4d) and in the stratigraphic coordinates they are aligned with the bedding (Figs. 4a, 4b); the degree of anisotropy (P_j, (Jelinek, 1981)) is at most 8%. The shape of the AMS ellipsoid and the degree of anisotropy in the particular samples do not demonstrate an apparent

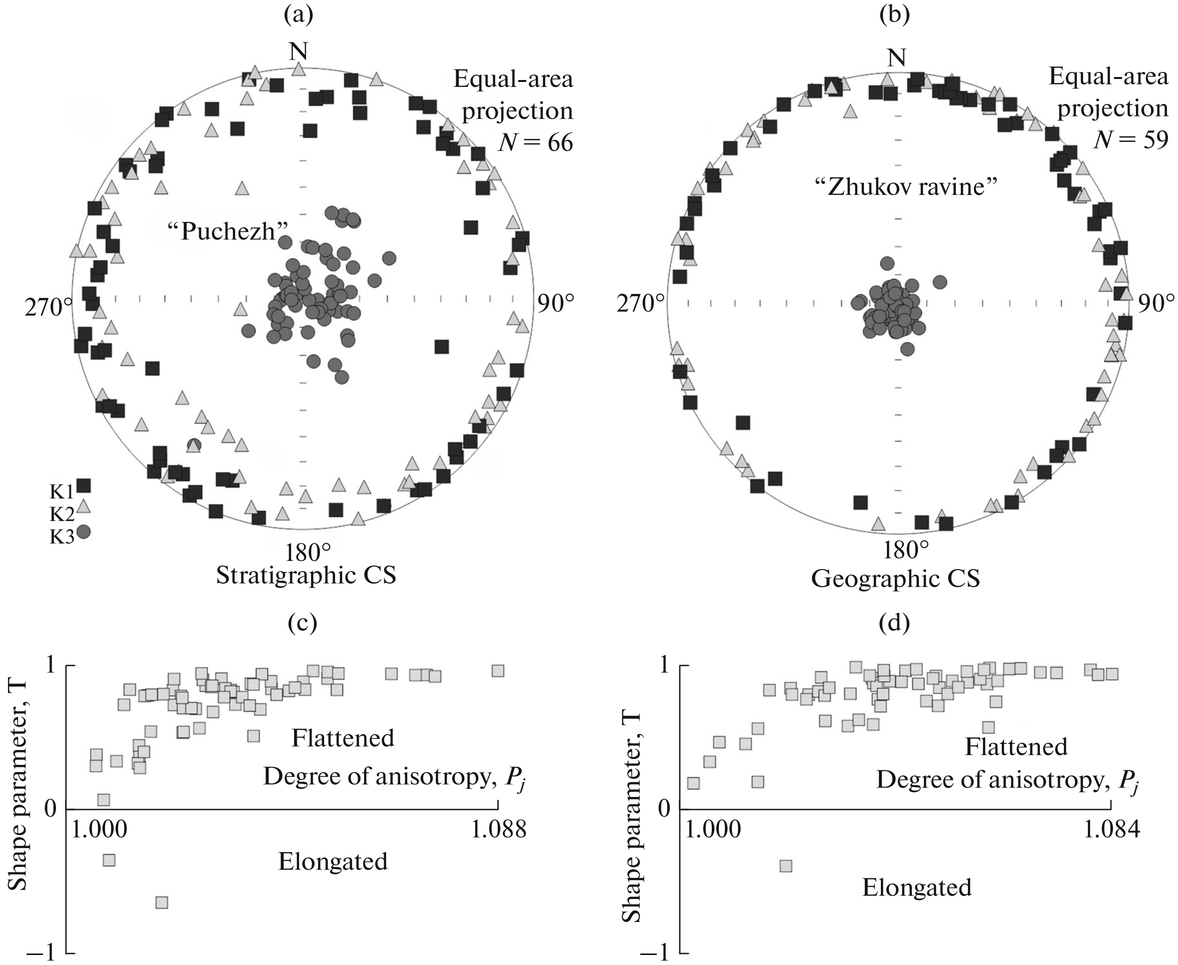

Fig. 4. Results of measurements for anisotropy of magnetic susceptibility: stereograms of distribution of semiaxes of AMS oval for samples from (a) Puchezh and (b) Zhukov ravine sections; (c), (d) Jelínek diagrams (Jelínek, 1981) illustrating dependence of shape parameter of AMS ellipsoid (*T*) (flattening/elongation) on degree of anisotropy (P_j). In stereograms, K1, K2, K3 are projections of long, intermediate, and short axes of AMS ellipsoid on lower hemisphere.

correlation to the composition of their natural remanent magnetization and are unlikely to reflect the magnetic texture of the rock. Instead, they represent the contribution of the paramagnetic minerals which suppresses the contribution of the ferromagnetic grains. It is also probable that the magnetic texture of the rock which is inferred from the distribution of the axes of the AMS ellipsoid reflects the orientation of the grains of finely dispersed hematite, whereas the remanent magnetization is associated with the larger hematite particles.

Hence, there are grounds to believe that the coefficient of inclination shallowing $f = 0.9$, which we obtained for the Puchezh and Zhukov ravine sections can be attributed to the magnetic fraction represented by clastic hematite. However, we concede that this value is somewhat smoothed due to the contribution of the magnetization of finely dispersed hematite, which is not prone to inclination shallowing; in the case of the absence of such hematite, coefficient f could be higher.

According to the results of similar rock magnetic experiments presented in (Gialanella et al., 1997) for rocks from the Monastyrskii ravine section, their magnetization is controlled by hematite and maghemite; besides, just as in the case with the Puchezh and Zhukov ravine sections, the authors of the cited work relate the characteristic magnetization component to hematite. It is most likely that the effect of inclination shallowing in the Monastyrskii ravine section is more distinctly pronounced due to the lithological peculiarities of this section: in contrast to the rocks composing the Puchezh and Zhukov ravine sections, the rocks of the Monastyrskii ravine section are represented by the finer grained fractions in which, as follows from the experience gained in experiments of this kind (Kodama, 2012), the effect of inclination shallowing manifests itself more strongly.

CONCLUSIONS

(1) Based on the extended sets of paleomagnetic determinations from the Permian–Triassic (*P–Tr*)

boundary sections of the Middle Volga region—Puchezh and Zhukov ravine, each containing more than 100 paleomagnetic directions, the estimates of the coefficient of inclination shallowing f are obtained by the E–I method. For each section, $f = 0.9$.

(2) Based on the paleomagnetic data presented in (Gialanella et al., 1997), the coefficient of inclination shallowing in the Monastyrskii ravine P–Tr section is estimated at $f = 0.6$.

(3) By the example of the samples from the Zhukov ravine section, it is shown by the rock magnetic studies that the characteristic magnetization component is carried by clastic hematite whose grains controlled the process of inclination shallowing in the course of compaction of the rock.

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