# Chapter 3
# Paleomagnetic Directions Distortion Caused by Viscous-Plastic Deformations Estimated from Anisotropy of Magnetic Susceptibility (Case Study of Berriasian Clays from East Crimea)

**V. A. Grishchenko and A. Yu. Guzhikov**

**Abstract** Deformations inside clayey strata may result in a mechanical rotation of ferromagnetic particles and of associated paleomagnetic vectors. Accordingly, restoring the orientation of magnetic susceptibility (AMS) ellipsoids to the position corresponding to the moment of magnetization fixation would be expected to improve the paleomagnetic statistics. The Upper Berriasian clays from Zavodskaya Balka section in the vicinity of Feodosiya was chosen to test this hypothesis. Paleomagnetic quality parameters in the examined rocks improved after the restoring the AMS ellipsoids into their positions at the moment of magnetization acquisition. The reversal test, negative when the original paleomagnetic directions were considered, became positive at the B level (McFadden and McElhinny 1990) after this procedure. Fold test also used to be negative, after the correction revealed a synfolding component throughout the entire section. Thus, our results validate the hypothesis on the possibility of correcting paleomagnetic data by means of the data on anisotropy of magnetic susceptibility. Nevertheless, the technique we have tested requires further elaboration and verification at other objects composed of argillaceous deposits.

**Keywords** Magnetic susceptibility · Anisotropy of magnetic susceptibility
Paleomagnetism · Berriasian · Tectonic deformations · East Crimea

Deformations inside clayey strata may result in a mechanical rotation of ferromagnetic particles and of associated paleomagnetic vectors. Accordingly, restoring the orientation of magnetic susceptibility (AMS) ellipsoids to the position corre-

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sponding to the moment of magnetization fixation would be expected to improve the paleomagnetic statistics. The Upper Berriasian clays from Zavodskaya Balka section in the vicinity of Feodosiya was chosen to test this hypothesis. Paleomagnetic quality parameters in the examined rocks improved after the restoring the AMS ellipsoids into their positions at the moment of magnetization acquisition. The reversal test, negative when the original paleomagnetic directions were considered, became positive at the B level (McFadden and McElhinny 1990) after this procedure. Fold test also used to be negative, after the correction revealed a synfolding component throughout the entire section. Thus, our results validate the hypothesis on the possibility of correcting paleomagnetic data by means of the data on anisotropy of magnetic susceptibility. Nevertheless, the technique we have tested requires further elaboration and verification at other objects composed of argillaceous deposits.

## Introduction

In thick, lithologically uniform clayey strata, visual identification of bedding elements at every section level is difficult or impossible. As a rule, one is forced to regard the levels within clay members by means of interpolating or extrapolating the bedding elements measured from the nearest hard-rock interlayers with clearly defined bedding planes. Meanwhile, the true azimuths and layer dip angles may differ substantially due to plastic deformations of diverse nature.

Errors in identifying the strata bedding elements may be important or occasionally decisive for acquiring paleomagnetic information. Disregarding the errors leads to distortions in paleomagnetic directions and, consequently, to negative results of field tests (fold test, reversal test), providing reasons for data rejection (Opdyke and Channell 1996; Supplement … 2000; Van der Voo 1993). Therefore, clays do not make favorable study objects for solving magnetotectonic problems, but are widely used in magnetostratigraphy (e.g. Arkadiev et al. 2010, 2015a, b; Bragin et al. 2013; Dzyuba et al. 2017; Grishchenko et al. 2016; Guzhikov et al. 2003, 2014).

Submicron ferromagnetic particles are as a rule aggregated on the clayey mineral scales, producing a planar anisotropy of magnetic susceptibility (AMS) with (sub) vertical arrangement of short axes of magnetic ellipsoids (K3) in the case of sediment deposition in quiet hydrodynamic settings. This fact allows to interpret deviations of the average K3 direction ($K3_{av}$) from the stereogram center (in the geographic coordinate system) as the elements of clay layer bedding that cannot be measured with a geological compass in the case of subhorizontal bedding within the platform sedimentary cover (Dzyuba et al. 2017).

Paleomagnetic data on the Tithonian-Valanginian clays from Mountainous Crimea (Arkadiev et al. 2010, 2015a, b; Grishchenko et al. 2016; Guzhikov et al. 2012, 2014) are generally peculiar for low precision parameters and negative results of the fold test. The reversal test results are positive only at low significance levels

["C" grade according to McFadden and McElhinny (1990)]; otherwise, they are negative. AMS data from these clays show numerous deviations from the ideal pattern of the sediment magnetic texture, the one with the short axes of magnetic ellipsoids tending towards vertical positions and the long (K1) and medium (K2) axes towards the stereogram equator. In Mountainous Crimea, such deviations may result from tectonic and non-tectonic deformations of both non-lithified clayey sediments and mature plastic clays.

In the course of deformations, a mechanical rotation of ferromagnetic particles and associated paleomagnetic vectors takes place. Consequently, recovering the positions acquired by ellipsoids of magnetic susceptibility at the moment of magnetization fixation would contribute to improving paleomagnetic statistics. The attempts to apply this effect while analyzing paleomagnetic data are not known to us, but there exists a significant literature on the problem of synfolding remagnetization and the paleomagnetic fold test (e.g., Borradaile 1997; Cogné and Perroud 1987; Facer 1983; Kodama 1988; Stamatakos and Kodama 1991; Van der Pluijm 1987). In each of these previous studies, reorientation of particles and their remanent vectors is considered to take place in response to tectonic stresses, and the vectors rotate away from the compression axis. In our model, the magnetic fabric forms in an incompletely lithified layer which is nevertheless tilted by tectonic compression. Within this layer particles (and hence remanence vectors and anisotropy ellipsoids) rotate in response to gravitational forces, so that vectors and long axes rotate away from the vertical and towards the tectonic compression axis. The aim of conducted study was to make an experimental examination of theoretical supposition that the restitution of ellipsoids of magnetic susceptibility to their position at the moment of acquisition of magnetization promotes the improvement of paleomagnetic statistics parameters.

## Object and Methods of Investigations

The Upper Beriasian Zavodskaya Balka section in the vicinity of Feodosiya was chosen to test this experimental statement. The section is represented by gray, massive, unstratified, unctuous, plastic, slightly silty (below 5%), slightly micaceous (less than 5% of mica scales) carbonate clays of the Sultanovka suite, with the apparent thickness over 70 m (Arkadiev et al. 2010).

Results paleomagnetic and petromagnetic examination including the data on anisotropy of magnetic susceptibility of this section have been published previously (Arkadiev et al. 2010, 2015a, b; Guzhikov et al. 2014).

Despite the good quality of Zijderveld diagrams and the presence of characteristic components (**ChRM**) of normal as well as reverse geomagnetic field polarities in the section, paleomagnetic interbed precision parameters, calculated for the directions of each polarity particularly, are not high (11.2—for N and 6.5—for R-polarity), the reversal test is negative, and the fold test is also negative. Positive reversal test at the C level (McFadden and McElhinny 1990) was obtained only with the samples composed of specimens with minimum-sized ferromagnetic grains as evaluated from the $K/J_{rs}$ ratio ($K$—magnetic susceptibility, $J_{rs}$—remanent saturation magnetization) (Guzhikov et al. 2014).

The studied clays are characterized by the orientation of long axes of magnetic ellipsoids in the NWW-SEE direction (Fig. 3.1a–c) and a planar magnetic anisotropy (Fig. 3.2a). A hypothesis that this is due to a flattened shape of clay flakes, on which the submicron ferromagnetic particles are aggregated, is confirmed by microscopic observations (Fig. 3.2b).

The method to "restore" the magnetic particles into their primary orientation corresponding to the moment of remanent magnetization fixation is based on the model of the magnetic fabric formation in the Zavodskaya balka sediments, which is illustrated in Fig. 3.3 and boils down to the following:

1. We suppose that deviations of the axes of magnetic ellipsoids from their primary positions are caused mostly by tectonic deformations of sediments during late Berriasian orogeny (Nikishin et al. 1997). These processes are reflected in the orientation of long axes of AMS ellipsoids (Fig. 3.1), perpendicular to the main direction of collision compression in the Mountain Crimea (Bagaeva and Guzhikov 2014; Guzhikov et al. 2014).
2. In the hard bed there is no rotation of ferromagnetic particles during tectonic deformations (Fig. 3.3a), and therefore there is no need to reconstruct the primary positions of magnetic ellipsoids in it. In this case the main position of short axes ($K3_{av}$) in the geographic coordinate system deviate from the vertical by the angle equal to the bedding dip ($\angle$ **1**), in the paleogeographic coordinate system the projection of ($K3_{av}$) coincide with the center of stereogram (Fig. 3.3a). The age of magnetization is prefolding. The angle between the horizontal plane and the magnetic foliation plane, where K1 and K2 are located, coincide with the dip angle of bedding ($\angle$ **1**).
3. During the synsedimentary folding deformations occur in a not completely lithified layer, within which flattened particles strive to take a horizontal position again, but because of the high viscosity of the sediment they cannot reach it. Anyway, the position of K3 deviates from the perpendicular to the underlying hard surface of bedding and on the AMS stereograms in geographic coordinate system $K3_{av}$ deviates from the vertical by the angle $\angle$ **1**, as in the case of hard layer. In the paleogeographic coordinate system $K3_{av}$ does not coincide with the center of stereogram (Fig. 3.3b).
   The direction of $K3_{av}$ corresponds to the average orientation of magnetic ellipsoids during the fixation of remanent magnetization in the rocks. For this reason to improve statistical paleomagnetic parameters it is desirable to rotate each paleomagnetic vector in such a way, that the related K3 coincide with $K3_{av}$.
4. If the final lithification of a sediment and fixation of magnetization takes place after the termination of folding, the flattened magnetic particles will strive to take a horizontal position. In this case K3 will tend to the vertical position in the geographic coordinate system, while in the paleogeographic coordinate system,

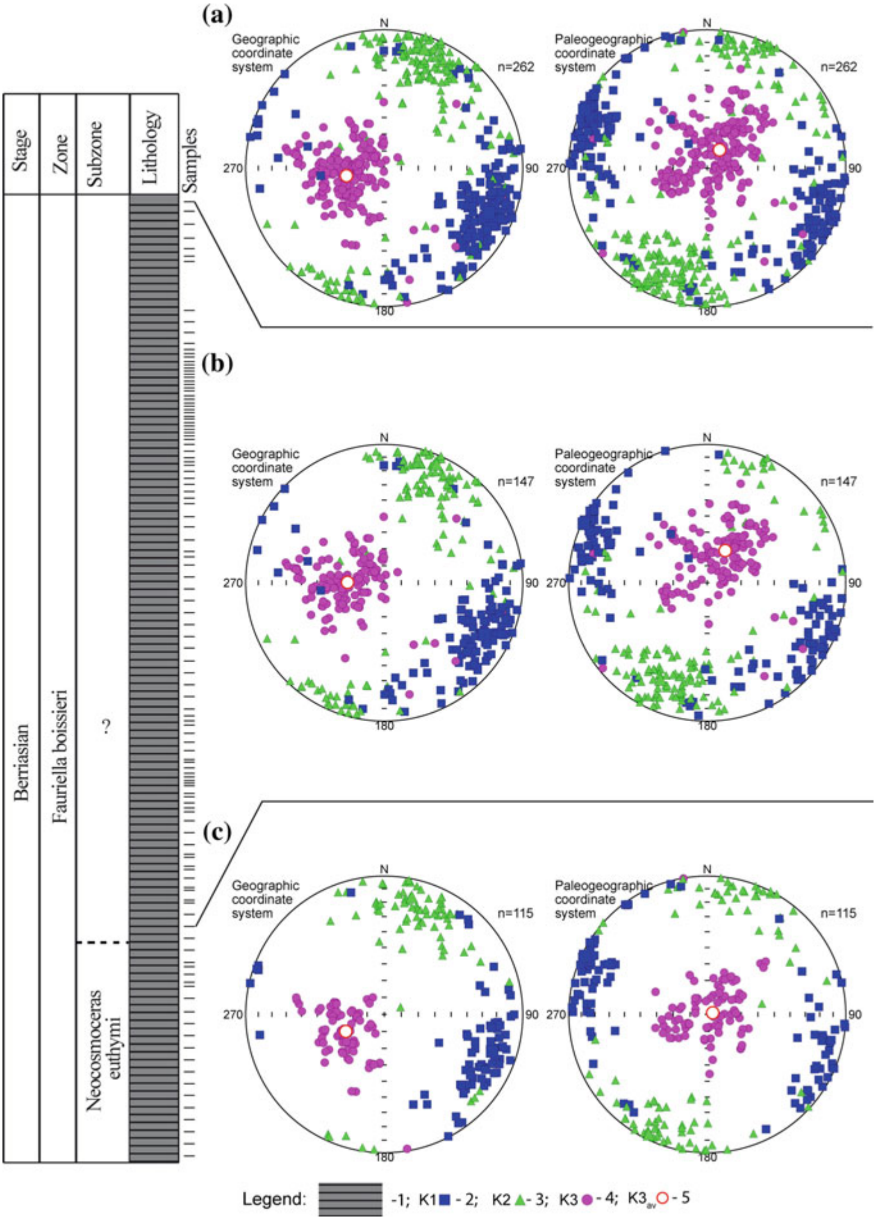


**Fig. 3.1** AMS data on the "Zavodskaya balka" section: **a** full section, **b** upper part of the section, **c** lower part of the section. Legend: 1—clay; 2, 3, 4—projections of long (K1), medium (K2), and short (K3) axes of magnetic ellipsoid, respectively; 5—projections of mean direction of short axes ($K3_{av}$) of magnetic ellipsoid

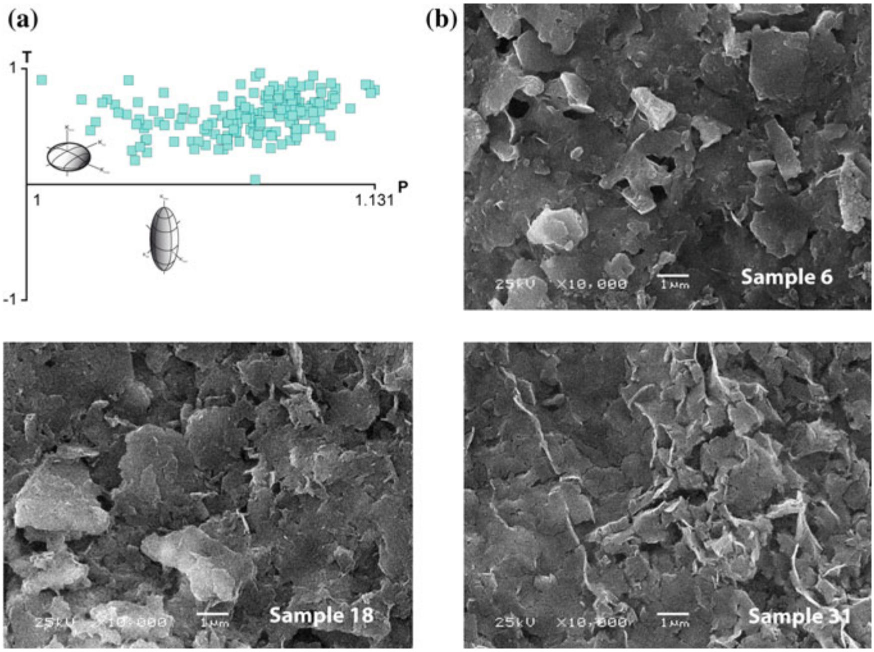


**Fig. 3.2** Diagram T-P (AMS parameters) as an indicator of magnetic ellipsoids shape (**a**) and SEM images (**b**) of studied clay

on the contrary, K3 projections will be displaced from the stereogram center (Fig. 3.3c). The results of fold test will indicate the postfolding nature of magnetization, although its age actually will not differ from the age of folding. In this case the paleomagnetic determinations reflecting most precisely the direction of geomagnetic field in which the sediment were formed will be obtained in the modern coordinate system, while the extrapolation of bed orientation from the underlying levels would introduce an error.

Therefore, the correction of paleomagnetic directions by returning AMS ellipsoids to their presumptive initial orientation is required only in the case, mentioned in the clause 3 above (Fig. 3.3b). The algorithm of **ChRM** recalculation is then the following:

1. The totality of magnetic ellipsoid axes is reduced to be arranged so that the $K3_{av}$ assumes vertical position in the paleogeographic coordinate system. For this purpose, in the Anisoft 4.2 program, designed to analyze the AMS data, in the "Edit data" regime, values $\mathbf{180° + D_{K3av}}$ and $\mathbf{90° - I_{K3av}}$ are inserted for all the samples in columns F1d and F1i, respectively. (In this case $\mathbf{D_{K3av}}$ and $\mathbf{I_{K3av}}$ are, respectively, the $K3_{av}$ declination and inclination in the geographical coordinate system.)

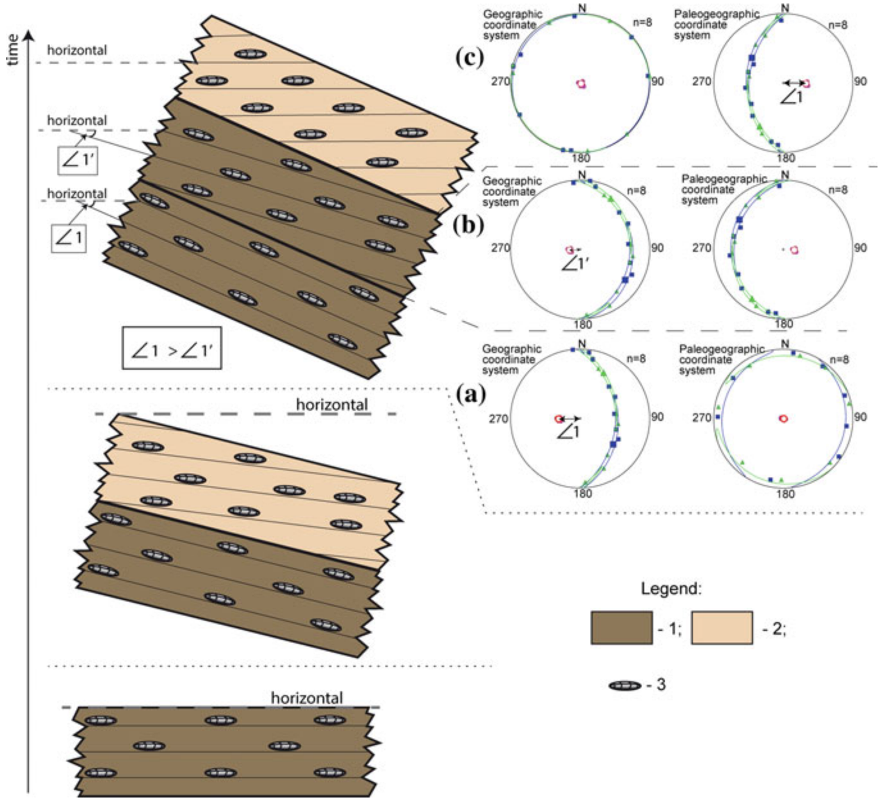


**Fig. 3.3** Models of magnetic texture (AMS) forming in rocks, affected by tectonic deformations in the hard (**a**) and viscous-plastic (**b**) state. Legend: 1, 2—Hard and viscous-plastic sediment respectively; 3—magnetic particles. Other legend symbols: see Fig. 3.1

2. Parameters $\mathbf{A_i = 180° + D_{K3i}}$ and $\mathbf{B_i = 90°} - \mathbf{I_{K3i}}$ are used as the strata dip azimuth and the strata dip angle, respectively, while converting the **ChRM** from the geographic to the stratigraphic coordinate system. (In this case, $\mathbf{D_{K3i}}$ and $\mathbf{I_{K3i}}$ are, respectively, $K3_i$ declination and inclination in the paleogeographic coordinate system, **i**–the sample number varying from 1 to n.)

To make the short axis of each magnetic ellipsoid in the set of n samples coincide with $K3_{av}$, values $\mathbf{A_i}$ and $\mathbf{B_i}$, should be inserted into the F1d and F1i columns, respectively, in the Anisoft 4.2 program in the “Edit data” regime. Therefore, use of $\mathbf{A_i}$ and $\mathbf{B_i}$ as the strata bedding elements results in the **ChRM** rotating by the angle equal to the angular distance between the short axis of the corresponding AMS ellipsoid and $K3_{av}$.

The paleomagnetic directions were analyzed by means of the Remasoft 3.0. software.

**Table 3.1** Statistic paleomagnetic characteristics of the from the Zavodskaya Balka section

| | Polarity | n | D° | I° | k | $\alpha_{95}$° | Reversal test (McFadden and McElhinny 1990) | | | Fold test (McFadden and McElhinny 1990) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | A (°) | $A_c$ (°) | Cl. | Whole section | Lower part of section | Upper part of section |
| without regard for the AMS data | N | 94 | 344 | 40.3 | 11.25 | 4.6 | 22.4 | 8.7 | – | Not correct | Pre-folding | Not correct |
| | R | 53 | 134.1 | −42.2 | 6.50 | 8.3 | | | | | | |
| with regard for the AMS data | N | 94 | 312.3 | 45.3 | 12.50 | 4.3 | 5.5 | 8.1 | B | Syn-folding | Pre-folding | Syn-folding |
| | R | 53 | 129.1 | −40.3 | 7.52 | 7.8 | | | | | | |

n—Number of samples in the selection, D and I—Average paleomagnetic declination and inclination, κ—Paleomagnetic precision parameter, $\alpha_{95}$—Radius of the vector confidence circle, A—Angle between average N and R vectors, Ac—Critical angle, Cl.—Classification after McFadden and McElhinny (1990)

## Research Results and Conclusions

In the whole Zavodskaya Balka section, $K3_{av}$ deviates from the vertical by 13°, with a substantial scatter of K3 directions relative to the mean (Fig. 3.1a). More thorough analysis of the AMS data has revealed that the distance between the $K3_{av}$ and the stereogram center is substantially larger in the upper part of the section (Fig. 3.1b) than in the lower one (Fig. 3.1c): 21.8° and 3.3°, respectively.

Thus, the AMS data from the lower half of the section (Fig. 3.1c) comply with the magnetic fabric of a hard stratum (Fig. 3.3a), while the distribution of magnetic ellipsoid axes in the upper half of the section (Fig. 3.1b) agrees with the theoretical model of synsedimentation folding (Fig. 3.3b). Therefore, the **ChRM** directions in the upper section have been recalculated with regard for the AMS data according to the procedure proposed above.

Results of statistical analyses of paleomagnetic determinations made with and without regard for the AMS data are compared in Table 3.1 and Fig. 3.4. The comparison reveals an improvement of paleomagnetic quality indicators in the examined rocks after AMS ellipsoid restoring to the position corresponding to purely depositional magnetic fabric.

Values of the interbed precision parameters have not changed appreciably within the section. But the reversal test that was negative when all samples were considered, and produced positive results of the C class only when analyzing the sample subset with minimal values of the $K/J_{rs}$ ratio (Guzhikov et al. 2014), after correcting for AMS became positive for the entire section at the B level (McFadden

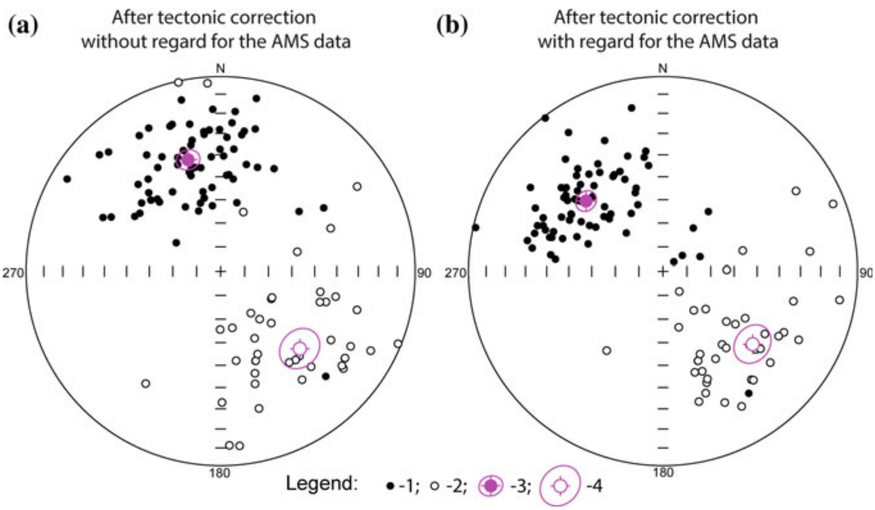


**Fig. 3.4** Summary stereograms of ChRM on the “Zavodskaya Balka” section after the tectonic correction based on the bedding elements of layers, measured with geological compass (**a**) and on the AMS data (**b**). Legend: 1, 2—stereographic projections of $\mathbf{J_n}$ directions on the lower semi-sphere and upper semi-sphere respectively; 3, 4—mean direction of $\mathbf{J_n}$ vectors

and McElhinny 1990). Furthermore, after correction of paleomagnetic directions the fold test (McFadden 1990) reveals a synfolding component both in the upper part of the section and throughout the entire section.

Thus, results of our research validate the hypothesis on the possibility of correcting paleomagnetic data by means of the data on anisotropy of magnetic susceptibility. Nevertheless, this technique requires further elaboration and verification at other objects composed of argillaceous deposits.

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