Rock-magnetic studies of the Tarkhanian sediments in Kop-Takyl section (the Kerch Peninsula)

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A detailed rock-magnetic study of the Tarkhanian sediments of the Kop-Takyl section, located on the Black Sea coast of the Kerch Peninsula, was carried out in order to verify the reliability of the obtained magnetostratigraphic data of the studied strata. It was previously shown that reverse magnetized rocks are distinguished in the upper part of the Kuvinian beds located at the base of the Tarkhanian regional stage of the Kop-Takyl section. The overlying rocks of the Terskian and Argunian Beds are characterized by normal polarity. This is inconsistent with the available magnetostratigraphic data on the same age Miocene sections. To clarify the reason for this discrepancy, a detailed magneto-mineralogical study of the composition of the ferromagnetic fraction was carried out by conducting thermomagnetic analysis according to the dependence of the saturation magnetic moment on temperature, calculating and constructing a Biplot diagram, and wavelet analysis of the coercive spectra of the saturation isothermal remanent magnetization. It was determined that the main ferromagnetic mineral in the rocks of the upper part of the section, which includes the Argunian Beds, is magnetite. In the lower part of the section, which includes the Kuvinian, Terskian and lower parts of the Argunian Beds, in addition to magnetite, greigite occurs. In the lower part of the Argunian Beds of the section, there is an increase in rock-magnetic parameters, in particular, magnetic susceptibility, due to an increase in the contribution of organic and bacteria activity. The rock-magnetic division of the deposits of the Kop-Takyl section is associated with a change in the deposition conditions that existed in the paleobasin. *KEYWORDS:* Tarkhanian; Eastern Paratethys; rock magnetic parameters; magnetostratigraphy.

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Introduction

During the study of the Kop-Takyl section located on the Black Sea coast of the Kerch Peninsula (Figure 1) [*Pilipenko et al.,* 2020], it was found that the lower part of the Kuvinian Beds of the Tarkhanian regional stage are composed of normal magnetized rocks, and in the upper part, sediments with reverse polarity magnetization are distinguished. The overlying rocks of the Terskian and Argunian Beds of the Tarkhanian regional stage are mainly characterized by normal polarity magnetization. Thus, in most of the Kop-Takyl section, the

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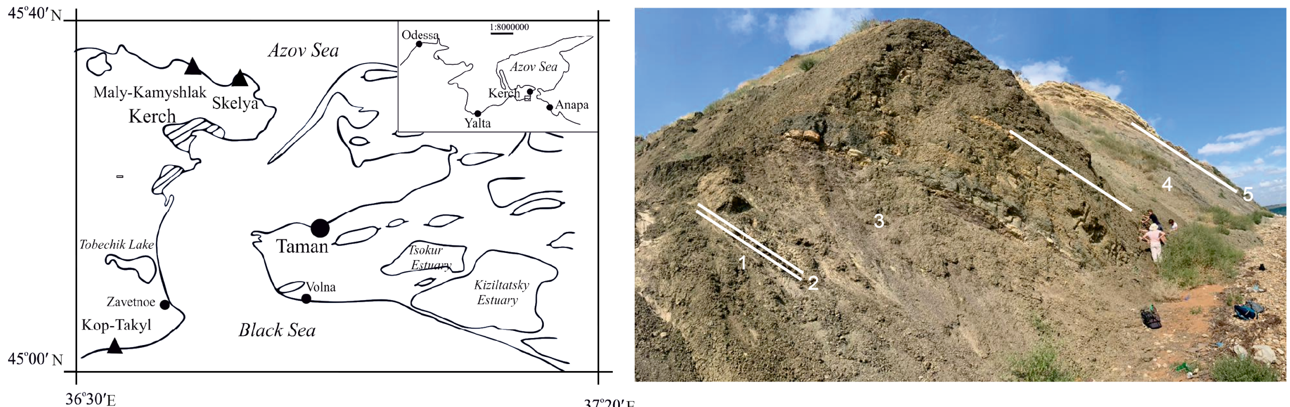


a) b)

Figure 1. Schematic map of the study area (a). In the inset, the square indicates the location of the study area on a geographical map. General view of the Tarkhanian sediments in the Kop-Takyl section (Kerch Peninsula) (b).

Tarkhanian sediments are characterized by normal polarity magnetization (Figure 2a).

These results are confirmed by studies of the Tarkhanian sediments in the sections of the Belaya and Pshekha rivers of the Western Ciscaucasia [*Palcu et al.,* 2019], (Figure 3). It was found that in these sections the Tarkhanian sediments have normal magnetization and are related to the Chron C5Bn.1n (14.870–14.775 Ma), corresponding to the middle part of the Middle Miocene Langhian of the Mediterranian.

As a result of the study of the Tarkhanian sediments in Kerch Peninsula (Skelya section) M. A. Pevzner obtained data on the normal polarity magnetization of the lower part of the Argunian Beds of the Tarkhanian (spirialis clays)) (Figure 3), which gave him reason to compare these beds with the upper part of the Chron C5Cn (16.721–16.268 Ma) and attribute them to the Lower Miocene [*Pevzner,* 1986; *Neveskaya et al.,* 2004].

According to V. M. Trubikhin [*Trubikhin,* 1998], the data obtained as a result of studying a number of sections of the Kerch Peninsula, Eastern Georgia and Turkmenistan, the lower part of the Tarkhanian-Chokrakian interval belongs to the zone of predominantly reverse polarity, the layer of normal magnetized rocks lies higher, and above there is a thin zone of reversal polarity, alternating above again with rocks with normal polarity magnetization. Moreover, the reverse polarity zone at the base of the Tarkhanian-Chokrakian interval is correlated with the lower part of the Chron C5Br (15.994–15.186 Ma) and the Lower Langhian of the Middle Miocene of the Mediterranean [*Neveskaya et al.,* 2004; *Trubikhin,* 1998]. The presence of reverse magnetized rocks at the base of the Tarhanian is also indicated in the work of E. A. Molostovsky [*Molostovsky,* 1986], (Figure 3).

To interpret the data obtained in [*Pilipenko et al.,* 2020], justify the discrepancy with the results obtained in [*Pevzner,* 1986; *Molostovsky,* 1986; *Grebenyuk,* 2004] and adequate comparison with the ATNTS 2012 magnetochronological scale additional rock-magnetic studies were required, including a detailed thermomagnetic analysis of the rocks under consideration to determine ferromagnetic minerals – carriers of natural remanent magnetization and changes in the composition of ferromagnetic minerals along the section. This work is devoted to the detail rock-magnetic study of the Middle Miocene sediments in the Kop-Takyl section in order to verify and substantiate the previously obtained magnetostratigraphic data for the Tarkhanian regional stage [*Pilipenko et al.,* 2020].

Object of Research

The Kop-Takyl section is located on the Black Sea coast of Kerch Peninsula (45°10′ N, 36°44′ E), (Figure 1a), south to Zavetnoe settlement and composed mainly of Tarkhanian clays containing carbonate layers. The Tarkhanian sediments of the Kop-Takyl section form the northern flank of the anticline, Figure 1b.

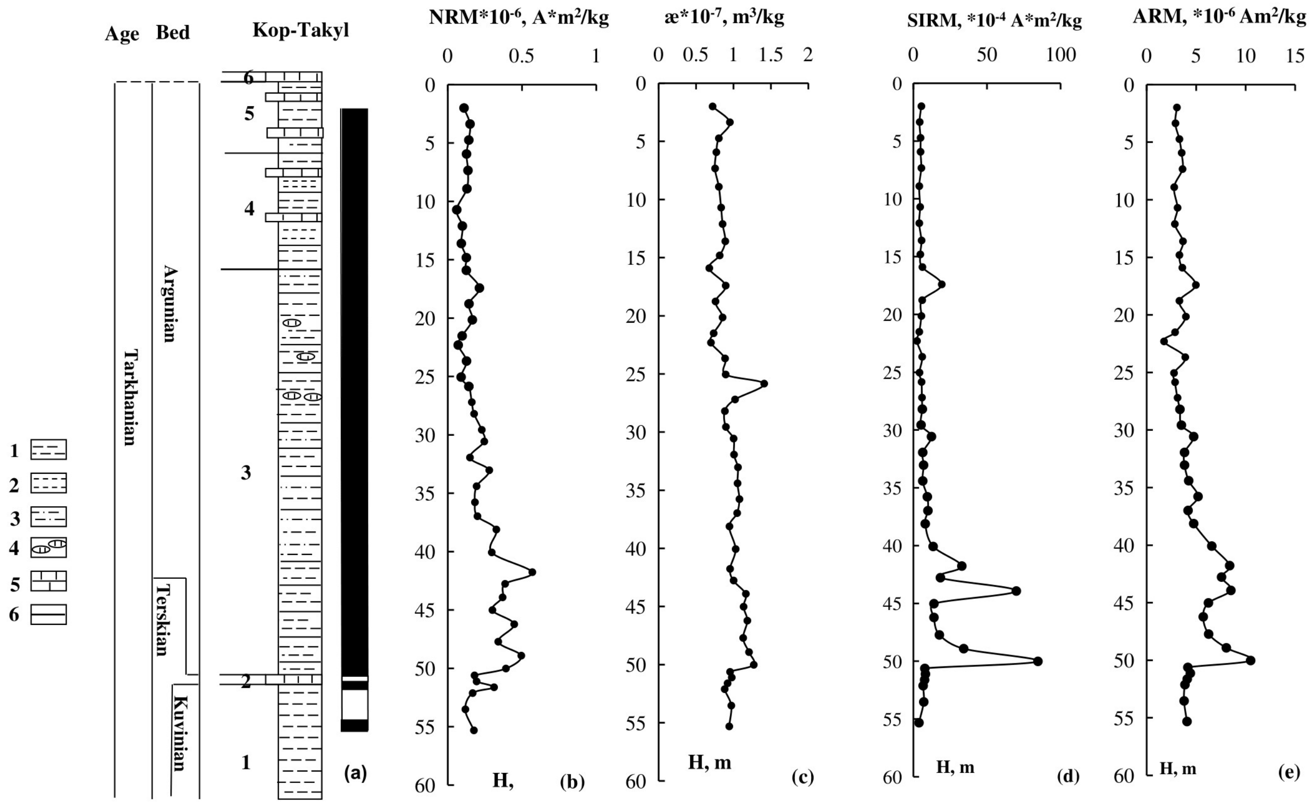


Figure 2. Lithological column of the Kop-Takyl section (a). Legend: 1 – clay, 2 – calcareous clay, 3 – clay with thin sandy layers, 4 – carbonate nodules, 5 – carbonate layers, 6 – layer boundaries. Variations curves of the magnetic characteristics versus section depth H: natural remanent magnetization NRM (b), mass magnetic susceptibility æ – (c), saturation isothermal remanent magnetization SIRM – (d), anhysteresis remanent magnetization ARM – (e).

The studied sediments of the Tarkhanian regiostage of the Kop-Takyl section are subdivided on next layer upwards (Figure 2a):

1. The lower part of the studied section is represented by slightly calcareous, dark gray (up to black), laminated clays with secondary jarosite, with exposed thickness of ~ 4 m (Figure 1b, layer 1). In the lower part, the sediments are covered by a landslide. Clays are characterized by the presence of marine fauna [*Neveskaya et al.,* 2004]. Their accumulation took place in relatively deep-water conditions during the period of connection between the Black Sea-Caspian basin and open sea waters [*Rostovtseva,* 2012]. These sediments belong to the lower part of the Tarkhanian regiostage, corresponding to the Kuvinian Beds.
2. Above the slightly calcareous clays lies a light gray, fine-grained, with mollusks shells *Lentipecten corneus denudatus*, layer of carbonate rock ~ 0.2 m thick, which corresponds to the middle part of the Tarkhanian regiostage, corresponding to the Terskian Beds and known in literature as the “Tarkhanian marlstone” [*Neveskaya et al.,* 2004]. This layer is a reliable lithological marker (Figure 1b, layer 2) and contains a marine fauna: *Abra parabilis, Lentipecten corneus denudatus, Abra alba* etc. [*Golovina and Goncharova,* 2004]. The sediments were accumulated at a sufficient saturation of the bottom waters with oxygen and low rates of sedimentation with a wide development of bottom macrofauna [*Rostovtseva,* 2012]. The primary high calcareous content of the sediments and the subsequent sec-

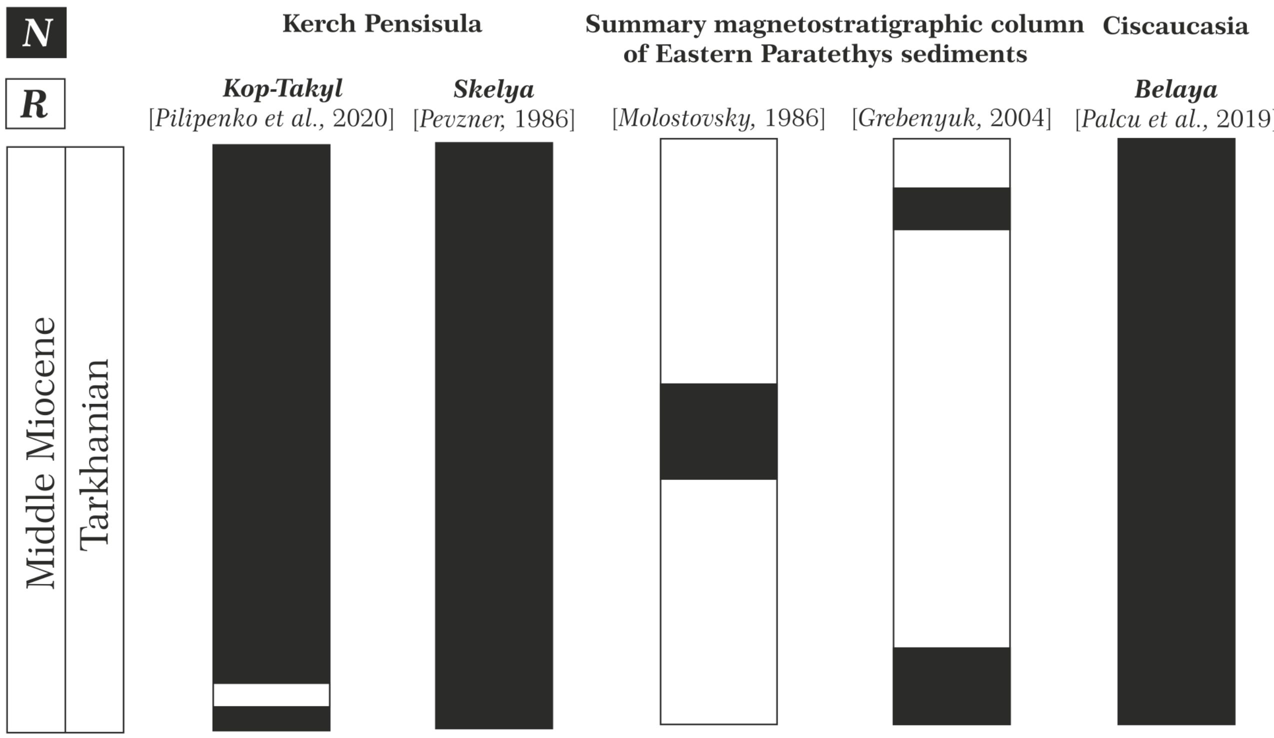


Figure 3. The correlation of magnetostratigraphic column of this work with magnetostratigraphic columns from works [*Pevzner,* 1986; *Molostovsky,* 1986; *Grebenyuk,* 2004; *Palcu et al.,* 2019.

ondary carbonatization of the sediments led to the formation of dense horizon in the section. Possibly, the decrease in sedimentation rates was associated with the beginning of the structural transformation of the basin [*Rostovtseva,* 2012].

The rocks identified in layers 3 and 4 correspond to the upper part of the Tarkhanian regiostage and belong to the Argunian Beds (Figure 1b, Figure 2a). Among them are observed:

3. Dark grey clays, laminated, with local pyritization, calcareous at the base, with thin sandy interlayers in the middle part, with separate carbonate nodules and layers in the top. The thickness of the layer is ~ 33–34 m. The deposits contain rare mollusk shells. The clays are characterized by an abundance of spiratellas (spirialis clays) and a depletion of the groups of marine fauna in the upper part [*Golovina and Goncharova,* 2004]. All this is evidence of a more difficult connection between the existing basin and open sea waters at the end of the Tarkhanian regiostage [*Goncharova,* 1989]. The marine environment of the basin is confirmed by the presence of marine species of biota: bivalve mollusks, foraminifera, sea urchins, etc. [*Goncharova,* 1989]. The accumulation of thin sandy interlayers in the middle part of the layer may have been associated with the beginning of the general shallowing of the basin, which led to a more enhanced supply of terrigenous material due to river runoff and redeposition of sediments from shallow setting [*Rostovtseva,* 2012].
4. Grey-green clays, laminated, with interlayers of carbonate rocks, also with an abundance of pteropod shells in the top (Argunian Beds) ~ 10–11 m thick.
5. Interbedding of grey-green laminated clays with carbonate rocks (Tarkhanian-Chokrakian transitional beds) ~ 5–6 m thick.
6. Interbedding of carbonate rocks, carbonates with signs of secondary dolomitization (Chokrakian regiostage) ~ 1–1.2 m thick.

The total thickness of the studied deposits is ~ 53 m.

Thus, the division into layers of the Tarkhanian sediments is associated with the variability of deposition conditions, reflecting the stages of geological development of Eastern Paratethys.

Selection of Samples for Rock-Magnetic and Paleomagnetic Research

For rock-magnetic and paleomagnetic studies, hand blocks (44 pcs.) of rocks were collected from the Lower Tarkhanian base (Kuvinian Beds) to the upper part of the Upper Tarkhanian (Argunian Beds) and the Tarkhanian-Chokrakian transition Beds with an interval of $\sim$ 1.5 m. Oriented hand blocks were taken mainly from freshly cleaned walls of section and oriented in space using a dip compass, mainly by bedding. Further, the hand blocks were sawn up into horizontal plates, from which in their turn oriented cubic samples were made with an edge of 2 cm, 2–3 samples per level. The total number of studied samples was 125. To conduct thermomagnetic analyzes, samples were cut into cubes with a 1 cm edge, two samples per level.

Equipment and Methods

On the first sister specimen of 8 cm^3 samples from all stratigraphic levels of the collection, the standard magnetic parameters were measured and investigated: the natural remanent magnetization (NRM), the mass magnetic susceptibility (æ), the bulk magnetic susceptibility (K_{lf}) at a low frequency of the magnetic field (lf = 0.46 kHz), the bulk magnetic susceptibility (K_{fd}) at a high frequency of the magnetic field (hf = 4.6 kHz), and the anisotropy of the magnetic susceptibility (AMS). On the same sample, the anhysteretic remanent magnetization (ARM), created in an alternating magnetic field of 1.2 T in the presence of a constant magnetic field of 50 µT, and an anhysteretic remanent magnetization ARM (40 mT) after 40 mT alternating magnetic field demagnetization, were measured. The same sample was used to measure the saturation isothermal remanent magnetization (SIRM), created in a constant magnetic field of 0.6 T, the isothermal remanent magnetization (IRM ($-$100 mT)), created in the opposite direction of a constant magnetic field of 100 mT, and the remanent coercive force (Bcr).

The samples collection, consisting of 8 cm^3 samples from all layers, was subjected to stepwise saturation in an impulse constant magnetic field up to 1.2 T with a variable step from 0.02 to 0.6 T, depending on the field in which the sample reached saturation. Further, the samples of the collection were subjected to stepwise thermal demagnetization.

NRM and ARM measurements were carried out with aSQUID magnetometer (2G Enterprises,USA, the sensitivity of the device is about 10^{-7} A/m) located in a non-magnetic room (Lodestar Magnetics, USA). IRM and SIRM were created on an Impulse Magnetizer IM-100 (ASC Scientific, USA). IRM and SIRM were measured with a JR-6 magnetometer (AGICO, Czech Republic, the sensitivity of the device is $2{\times}10^{-6}$ A/m). Mass magnetic susceptibility æ, bulk magnetic susceptibility at a low frequency of the magnetic field K_{lf} and at a high frequency of the magnetic field K_{fd} and an anisotropy of magnetic susceptibility AMS, were fulfilled with a Multi-Function Kappabridge MFK1-FA (AGICO, Czech Republic). All samples were weighed on a CAUY120 balance (CAS-electronic balance, Japan) before the study has started.

On samples from all selected levels, magnetic hysteresis loops were taken and the saturation magnetic moment Ms, the saturation remanent magnetic moment Mrs, Bc, Bcr were measured, and the coercive ratios Bcr/Bc and Mrs/Ms were determined with a VSM magnetometer (PMC Micro Mag 3900, USA).

The whole experiment was carried out in the Research Equipment Sharing Center "Petrophysics, geomechanics and paleomagnetizm" of Schmidt Institute of Physics of the Earth RAS.

On a collection of 2 cm^3 samples from all stratigraphic levels, the coercive spectra of normal and backfield isothermal remanent magnetization were recorded with the J-Meter coercive spectrometer [*Burov et al.,* 1986; *Nurgaliev and Yasonov,* 2009] in the Laboratory of Paleoclimatology, Paleoecology, Paleomagnetism of the Institute of Geology and Oil and Gas Technologies, the Kazan (Volga Region) Federal University. Coercive spectra were analyzed and decomposed by wavelet analysis [*Kosareva et al.,* 2015; *Utemov and Nurgaliev,* 2005], the "Mexican hat" wavelet was used as the basis decomposition function.

Magnetic Properties of Rocks

NRM was measured and normalized to sample density before demagnetization. The NRM value for the series of the first sister specimen is shown in Figure 2b. The NRM values are slightly different in the upper and lower parts of the section. In the lower part of the section at depths from 51–55 m, the NRM values vary in the range (1–3)$\times 10^{-7}$ Am^2/kg. In the middle part of the section at depths 28–50 m, the NRM values increase with depth from 2×10^{-7} Am^2/kg to 5×10^{-7} Am^2/kg. These relatively high values correspond to the interval of clays that accumulated within the shelf in relatively deep water conditions. In the upper part of the section at depths from 2–28 m, the NRM value again decreases to values (0.6–2)$\times 10^{-7}$ Am^2/kg due to low concentration of ferromagnetic particles caused by sanding of clays due to the general shallowing of the basin.

The values of magnetic susceptibility in general are low along the section: the average value of the magnetic susceptibility for the first duplicates of the samples is $\sim 1.5\times 10^{-4}$ SI, which is lower than the threshold value of 5×10^{-4} SI [*Tarling and Hrouda,* 1993]. This suggests that the paramagnetic fraction controls the susceptibility and anisotropy of the rock. The mass magnetic susceptibility æ of the first duplicates of the samples varies along the section from 0.67×10^{-7} to 1.41×10^{-7} m^3/kg, which indicates a change in the magneto-mineralogical composition or in the ratios of the contribution of magnetic minerals along the section.

Changes in æ correspond to NRM variations along the section (Figure 2b, Figure 2d). The linear correlation coefficient between the NRM and æ numerical series before demagnetization is highly significant $r = 0.63$ for the 44 pairs of points participating in the comparison [*Taylor,* 1985].

Changes in æ also correlate with changes in the saturation isothermal remanent magnetization SIRM (Figure 2b, Figure 2d), created on the same samples, along the section with a highly significant linear correlation coefficient of 0.78 for the 44 pairs of points involved in the comparison. The diagrams (Figure 2b, Figure 2c, Figure 2d, Figure 2e) demonstrate an increase in æ, NRM, SIRM, and ARM with depth in the lower part of layer 3, which reflects an increase in the concentration of magnetic minerals in sediments. An increase in the magnetic susceptibility and other concentration parameters may be associated with the growth of magnetic minerals within the sediment, as a consequence of organic activity [*Tarling and Hrouda,* 1993].

The 90% SIRM samples acquire in a field of ~ 0.2 T (Figure 4). The remanent coercive force Bcr, measured on samples with a volume of 8 cm^3, varies in the range of 35–58 mT. Thus, the main carrier of magnetization in these rocks is a low-coercive soft magnetic mineral.

To confirm the composition of the ferromagnetic fraction, stepwise thermal demagnetization of the saturation remanent magnetic moment, created in an impulse magnetic field of 1.2 T, was carried out. For this, on samples of the pilot collection (3, 7, 10, 13, 16, 19, 22, 24, 27, 30, 34, 36, 40) with an edge of 2 cm, thermal demagnetization was carried out from 100°C to 580°C with a step of 40–50°C. It is seen in Figure 5 that on all curves of stepwise demagnetization, complete demagnetization is observed at $\sim$ 580°C, which indicates the presence of magnetite. In addition to magnetite, starting from a section depth of $\sim$ 26 m and up to $\sim$ 55 m, an inflection point is observed in the thermomagnetic analysis curves in the temperature range of 300–350°C, corresponding to the unblocking temperatures of iron sulfide: monoclinic pyrrhotite or greigite.

To determine magnetite, greigite or monoclinic pyrrhotite in the composition of rocks, a biplot diagram IRM (−100 mT)/SIRM from ARM(40 mT)/ARM was constructed [*Peters and Thompson,* 1998] on a collection of samples from all stratigraphic levels, which shows the contribution of magnetic minerals in a graphic form. It can be seen from the diagram that the points separate and gravitate towards two zones: the zone of greigite and the generalized zone of magnetite, titanomagnetite and pyrrhotite, Figure 6.

The presence of greigite is also indicated by a drop in the saturation magnetic moment Ms in a field of 0.6 T upon heating to 300°C, and then a further sharp increase in the magnetic moment with temperature on the curves of thermomagnetic analysis Ms (T) [*Pilipenko et al.,* 2020].

To separate magnetic minerals by coercivity, the coercive spectra of normal and backfield isothermal remanent magnetization were measured using a J-Meter coercive spectrometer designed by P. G. Yasonov [*Burov et al.,* 1986; *Nurgaliev and*

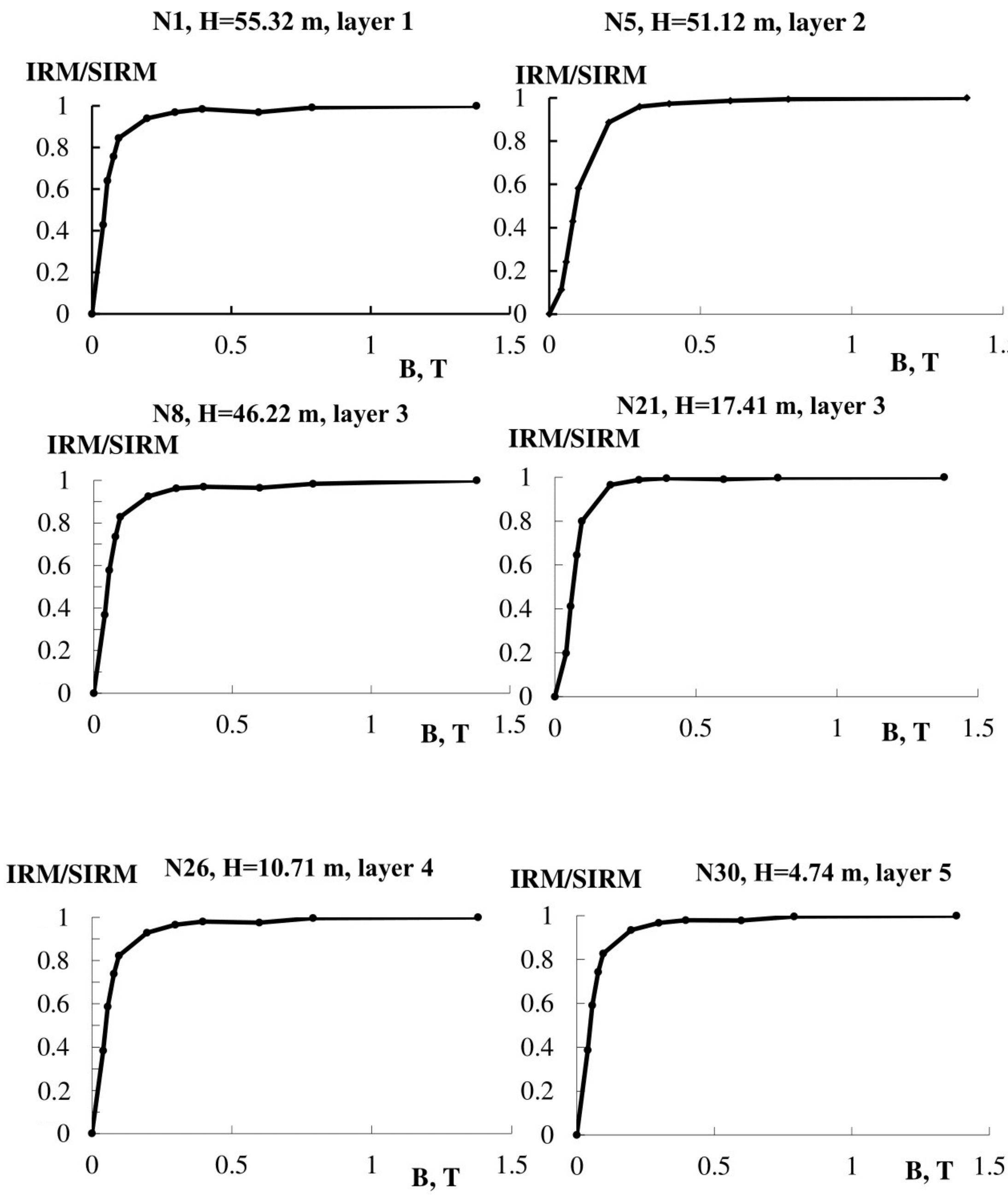


Figure 4. Saturation curves of the remanent magnetic moment in impulse constant magnetic field.

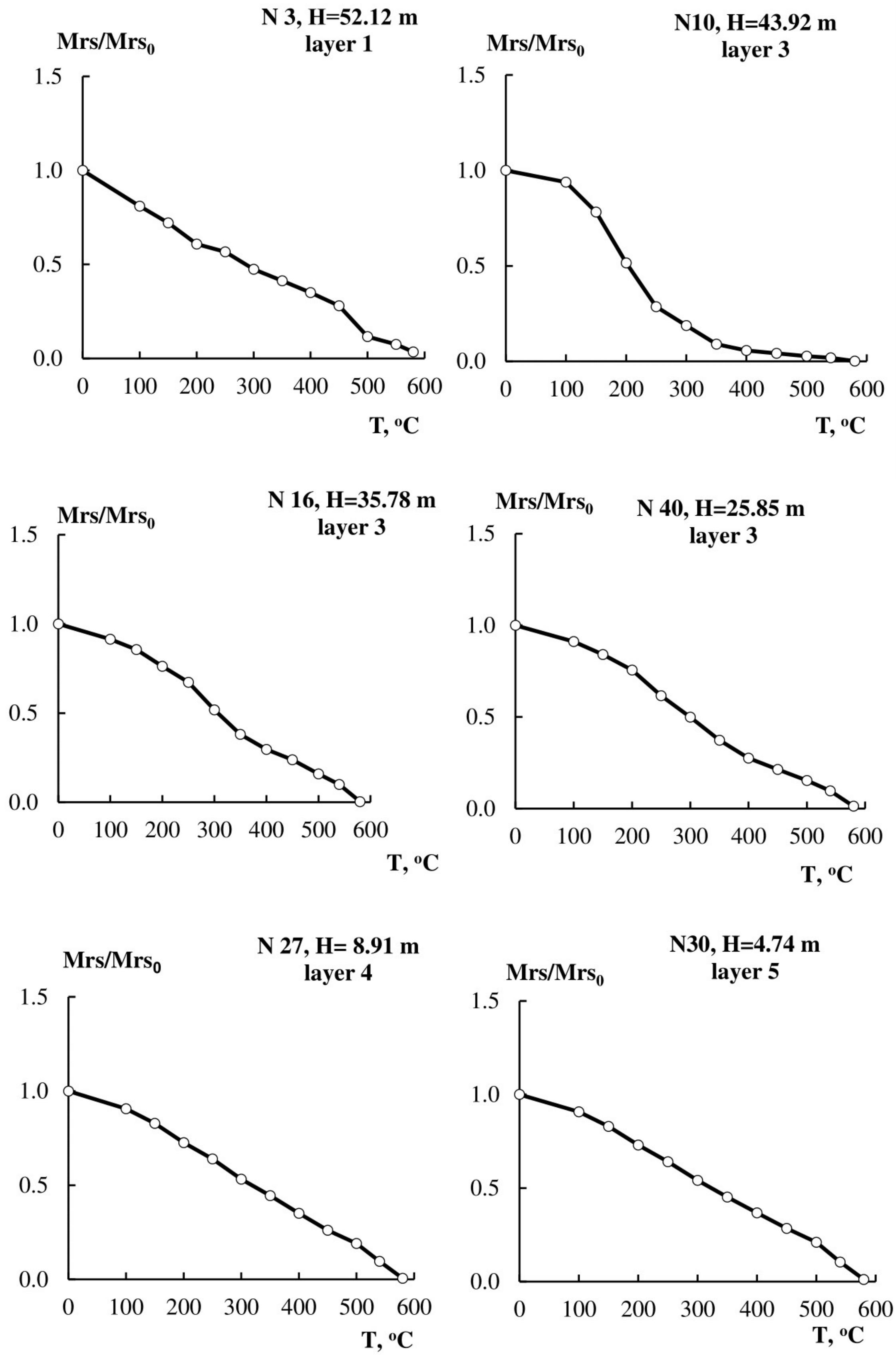


Figure 5. Thermomagnetic curves Mrs/Mrs_0 of step heating.

Yasonov, 2009] on a collection of samples, consisting of twelve samples with a volume of 2 cm^3 from different stratigraphic levels (layer 1–N 3, layer 3–NN 7, 10, 16, 20, 35, 40, layer 4–NN 23, 26, layer 5–NN 29, 30, 32). Wavelet analysis of the spectra using the "Mexican hat" wavelet showed the presence of overlapping three or four peaks corresponding to minerals of different magnetic coercivity (Figure 7). Based on the results of the wavelet analysis, histograms of the distribution of coercivity versus the value of the median magnetic field of the straight and reverse saturation remanent magnetic moment were constructed (Figure 8). The analysis of the obtained histograms was carried out on the basis of the classification of ferromagnetic minerals according to the coercivity proposed by R. Egli [*Egli,* 2003]: 0–30 mT is a mixture of detrital (D) and ferromagnetic grains of biogenic origin (EX) formed outside the cell. Minerals, whose increased values of the distribution of coercivity fall within the range of 30–60 mT, are mainly single-domain grains of biogenic origin (remnants of magnetotactic bacteria), (BS). Minerals whose values of the distribution of coercivity fall within the range of 60–90 mT are referred to magnetically hard grains of biogenic origin (BH) $>$ 90 mT – hard magnetic grains of hematite and hydroxides. As can be seen from the histograms of normal and reverse magnetic moment, the main contribution to the saturation remanent magnetic moment is made by biogenic soft magnetic grains.

Based on additional research, the main magnetic mineral in the upper part of the Kop-Takyl section is magnetite in low concentration. In the lower part of the section, which includes the Kuvinian, Terskian, and lower parts of the Argunian Beds, in addition to magnetite, iron sulfide is observed, most likely a greigite.

Granulometry

The presence of magnetite and greigite, which also has a cubic spinel structure and exhibits grain sizes similar to magnetite, made it possible to define their domain structure as a pseudo-single-domain structure (PSD) [*Pilipenko et al.,* 2020].

To determine the relative change in the grain size along the section, the ratios of the magnetic parameters SIRM/æ and ARM/æ were used. Dividing the remanent magnetizations SIRM and ARM, which depend on the grain size and the concentration of the grains- NRM carriers, by the magnetic susceptibility gives a parameter independent of the concentration. Small particles whose size lies in the SD and PSD zones will reach higher SIRM/æ and ARM/æ ratios in intervals where these particles are abundant [*Evans and Heller,* 2003]. It can be seen in Figure 9b, Figure 9c that in the lower part of layer 3 there are depth intervals (40–44 m and 48–50 m), at which an increase in the values of the SIRM/æ and ARM/æ ratios is observed. Thus, in this part of the section, there is a higher concentration of fine particles of magnetite and greigite.

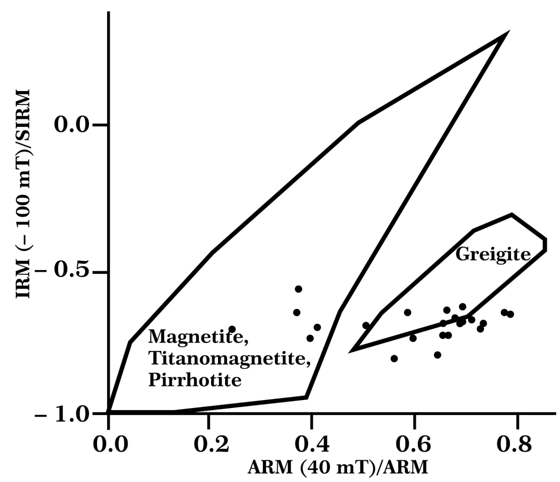


Figure 6. Biplot diagram of dependence of IRM (−100 mT)/SIRM from ARM(40 mT)/ARM.

To determine the presence of particles close to superparamagnetic (SP) in size, the bulk magnetic susceptibility was measured at two frequencies of the magnetic field and the frequency-dependent parameter $K_{fd} = (K_{lf} - K_{hf}) \times 100\%/K_{lf}$ was calculated. As can be seen from Figure 9d, except for four points, K_{fd} <2%. This suggests that the probability of having SP grains is less than 10% [*Dearing,* 1999].

Study of the Anisotropy of Magnetic Susceptibility

The magnitude of the magnetic susceptibility of rocks, measured on 8 cm^3 samples of the studied

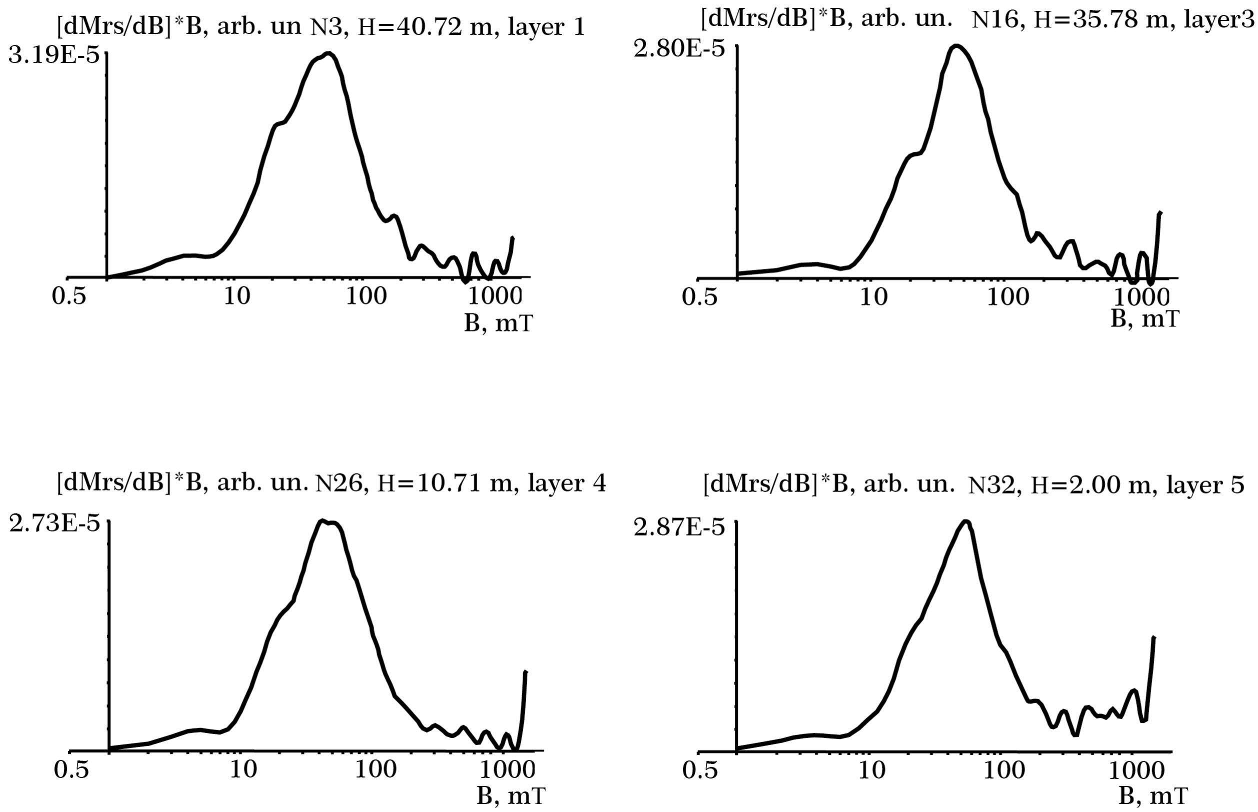


Figure 7. Coercive spectra of isothermal remanent magnetization.

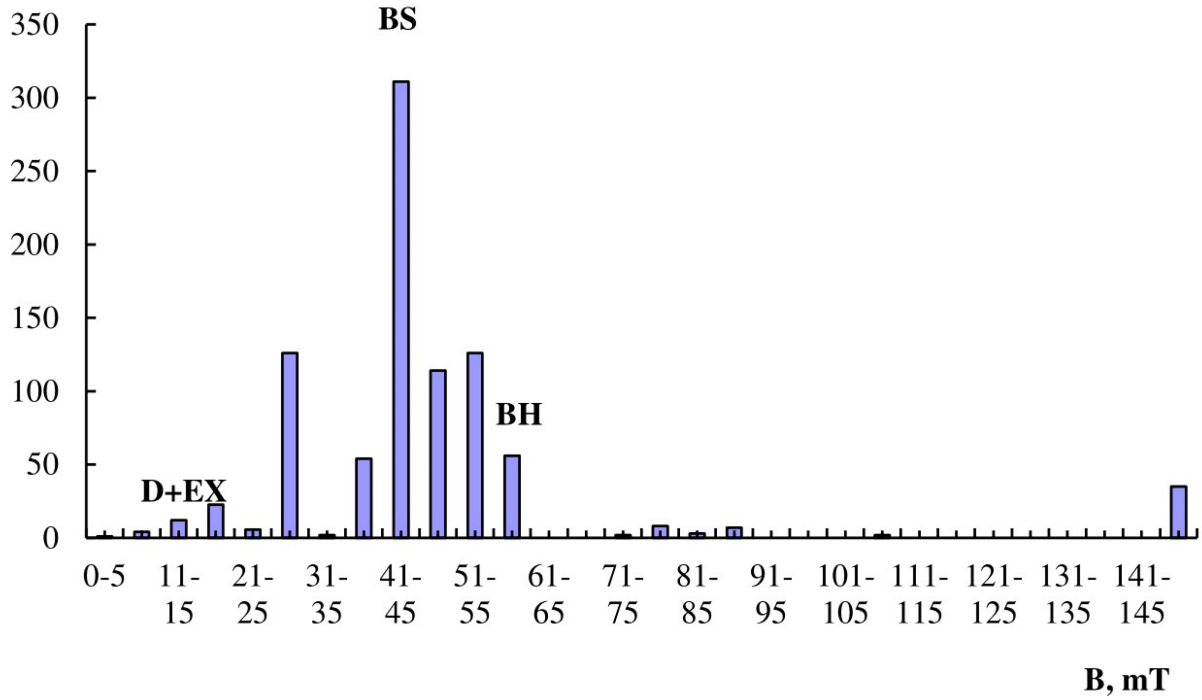
part of the Kop-Takyl section, is below the threshold value of 5×10^{-4} SI units [*Tarling and Hrouda,* 1993]. Such low values of the magnetic susceptibility indicate that the paramagnetic fraction controls the susceptibility and the anisotropy of the rocks. Previously, it was shown that most rock samples have plane type of anisotropy characteristic of sedimentary deposits [*Pilipenko et al.,* 2020].

Figure 10 shows the values of the lineation $L = K_1/K_2$, foliation $F = K_2/K_3$, the degree of anisotropy P', the parameter of the shape of the susceptibility ellipsoid T, versus the depth of the section. Average values $L = 1.003$, $F = 1.023$, degree of anisotropy $P' = 1.028$, shape parameter $T = 0.731$. Thus, the rock samples have a small degree of anisotropy ($\sim 3\%$), which is typical for undisturbed natural sediments [*Tarling and Hrouda,* 1993]. The shape parameter T is strongly positive. The depositional magnetic fabrics of deposited sediments are characterized by susceptibility ellipsoid that are clearly oblate. The obtained results indicate that the studied rocks have an invariable structure characteristic of sedimentary rocks.

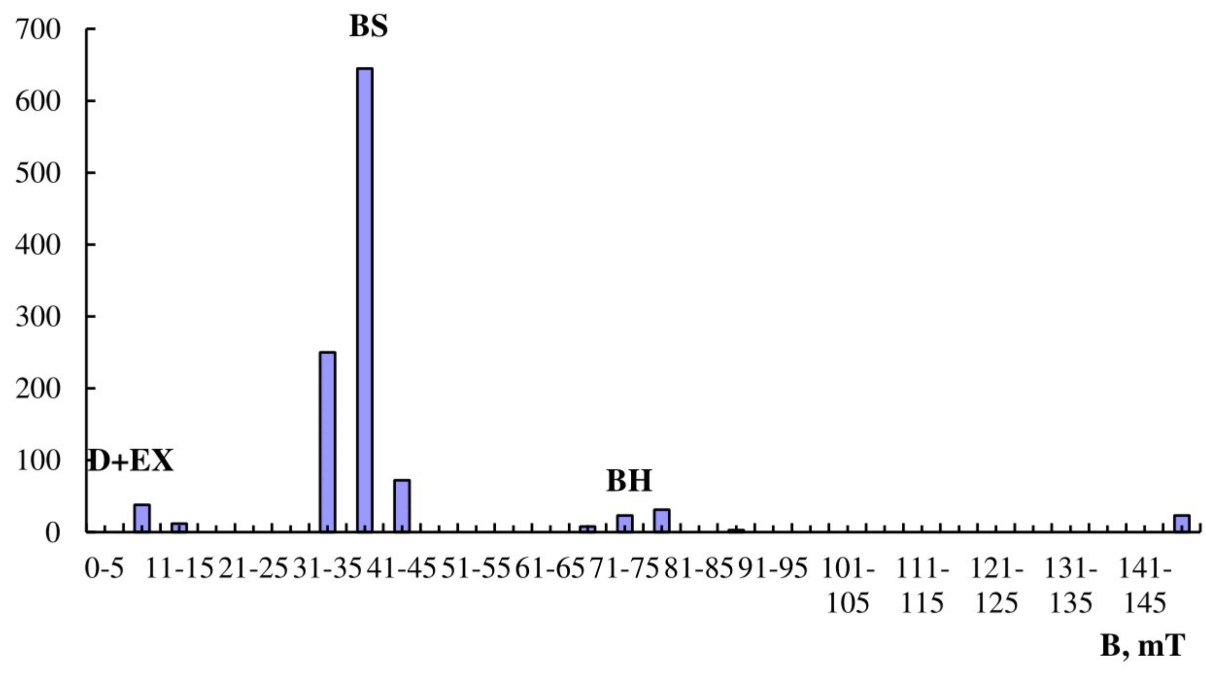
Discussion of the Results

The Tarkhanian sediments of the Kop-Takyl section are represented by relatively deep-water clays. The sediments accumulated at different rates: the lowest rate of accumulation took place during formation of the Terskian Beds (layer 2), and a higher rate of accumulation was noted for sediments of the lower part of the Argunian Beds (layer 3).

The clays of the Kop-Takyl section contain magnetic minerals: magnetite and iron sulfide, most likely greigite. According to the results of stepwise thermal demagnetization of SIRM, the section is approximately divided into two parts in terms of the magnetic mineral composition (Figure 5). The lower part of the section (depths $\sim$ 55–26 m, layers 1–3) contains magnetite and iron sulfide (greigite).



(a)



(b)

Figure 8. Coercivity distribution histograms of magnetic minerals in sediments of the Kop-Takyl section after application of wavelet analysis for direct – (a) and backfield isothermal remanent magnetization – (b).

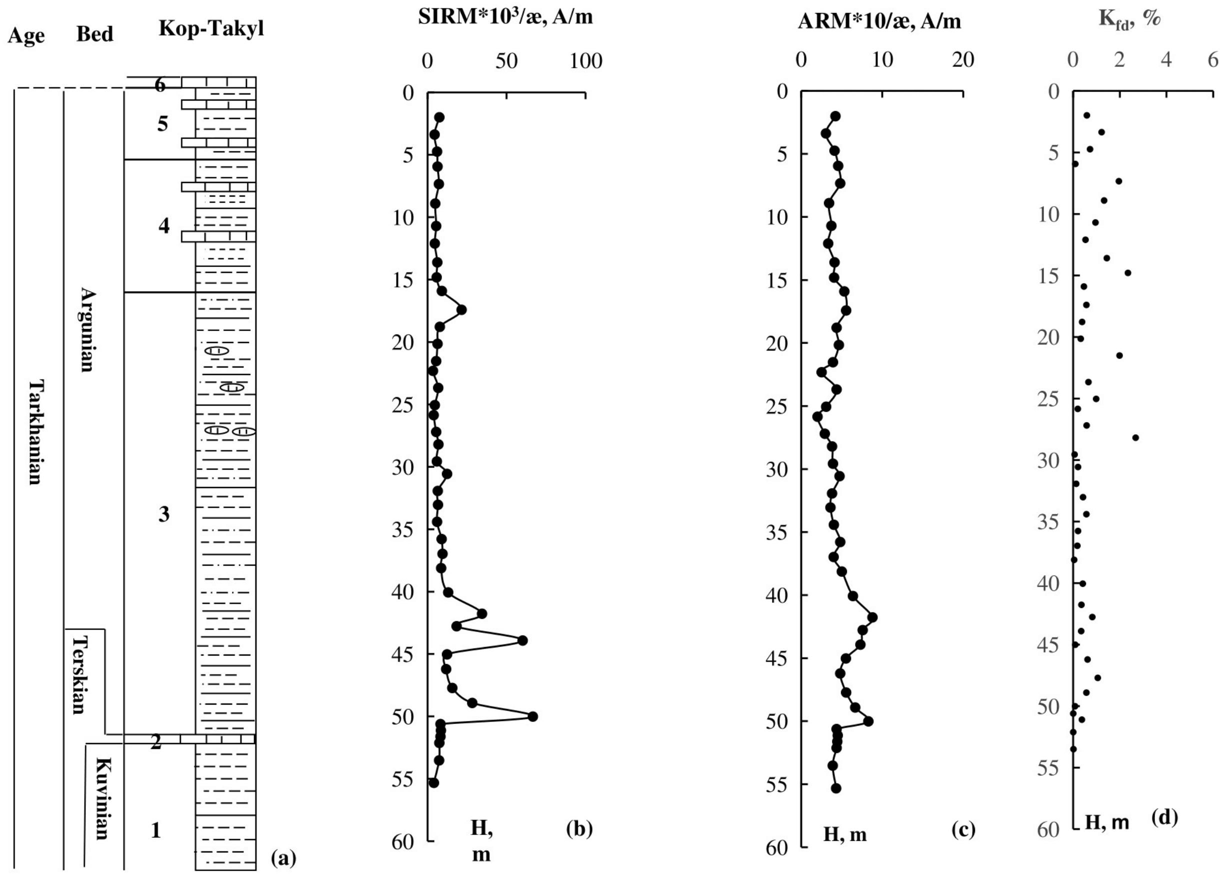


Figure 9. Lithological column of the Kop-Takyl section – (a). Curves of changes in grain size ratios versus section depth H: SIRM/æ – (b), ARM/æ – (c), frequency-dependent parameter $K_{fd} = (K_{lf} - K_{hf}) * 100\%/K_{hf}$ – (d).

In the upper part of the section (depths ∼ 25–2 m, upper part of layer 3–layer 5), represented by Argunian Beds, magnetite is mainly found.

The presence of magnetite in sediments usually indicates the terrigenous drift from land during their accumulation. Layers 4 and 5, in which magnetite is the main carrier of magnetization, accumulated in shallower water conditions than the underlying sediments. Their sedimentation took place against the background of the shallowing of the basin, into which clastic material entered with river runoff.

The sediments of the lower part of layer 3 were formed in relatively deep-water conditions characterized by low oxygen saturation of the bottom waters. An increase in the values of petromagnetic parameters (æ, NRM, SIRM, ARM) (Figure 2) in the lower part of the Argunian Beds is possibly related to the peculiarities of the transformation of organic matter and the activity of bacterial communities, which led to a decrease in the number of detrital grains of magnetite and enhanced formation of greigite. This confirms an increase in the values of the SIRM/æ and ARM/æ ratios, which indicates a high concentration of fine particles in the lower part of layer 3 at the depth intervals (50–58 m and 44–40 m), Figure 9.

Greigite can exist in biogenic form in sediments. Some types of bacteria use ferric iron as an energy source, reducing iron to a ferrous state [*Tarling and Hrouda,* 1993; *Mann et al.,* 1990]. This leads to a decrease in the content of detrital grains of magnetite and increased formation of greigite. The formation of greigite in the sediments under consideration could occur both immediately after the accumulation of the sediment, i.e. to be syngenetic and with a time delay, lagging behind sedimentation of strata by thousands – hundreds of thousands of years.

The "fold" test for Argunian Beds (layers 3+4+5) by PMGSC program (Paleomagnetic Data Analysis, version 4.2) [*Enkin,* 2003], show a negative re-

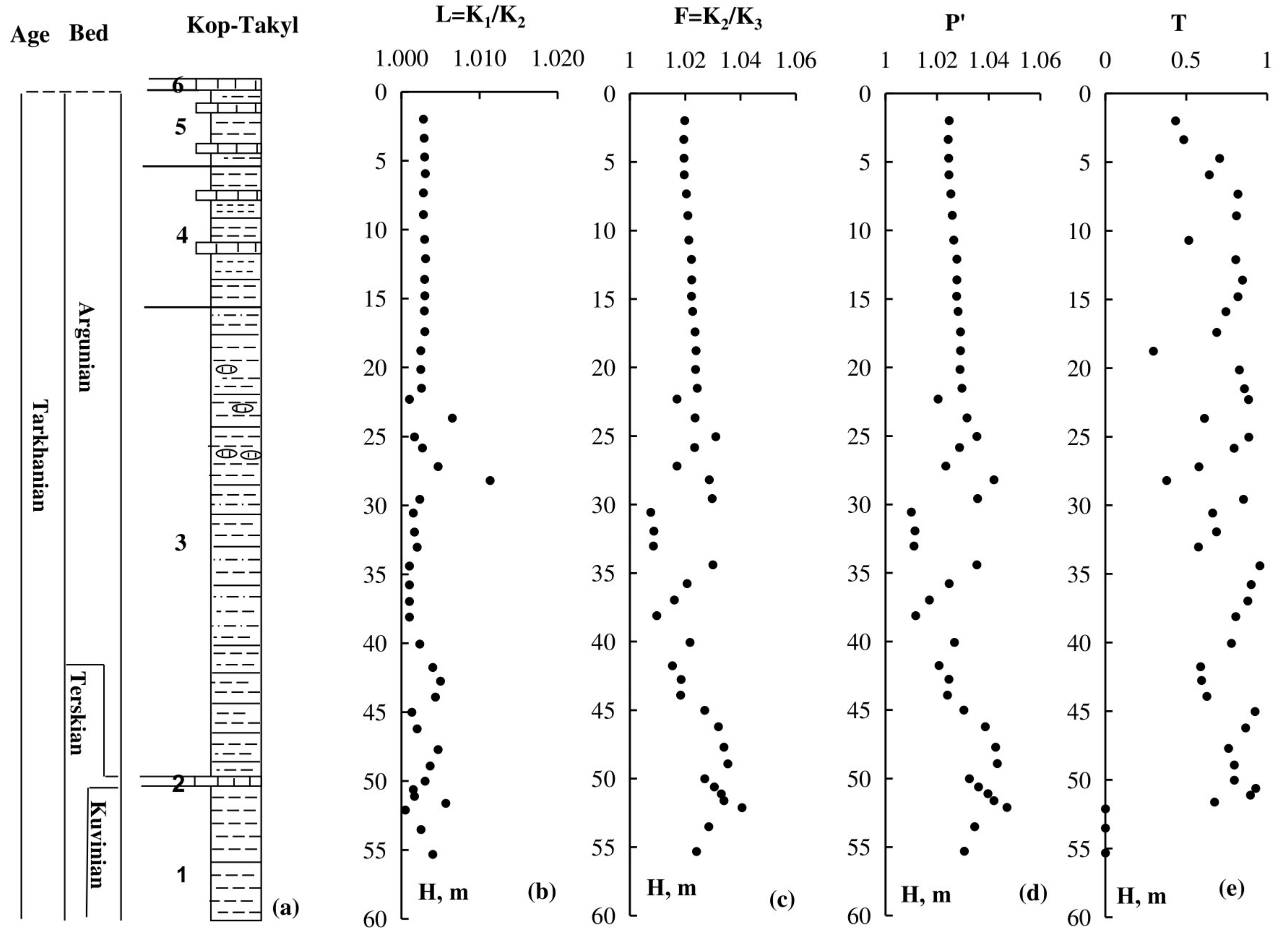


Figure 10. Lithological column of the Kop-Takyl section – (a). Dependence of AMS parameters versus section depth H: L – (b), F– (c) , P' – (d), T – (e).

sult (Optimal untilting at 4.7 ± 78.2 % untilting, test negative), which testifies in favor of the remagnetization of this part of the section.

The Kop-Takyl section rocks have an unchanged sedimentary structure, retaining the general shape and orientation of the grains of magnetic minerals due to the sufficient content of original detrital grains. Despite the fact that newly formed greigite grains retain their primary magnetic structure, the enhanced formation of greigite could lead to the destruction of the primary NRM and the formation of secondary CRM magnetization. As a result a complete or remagnetization interval of the studied rocks of the Kop-Takyl section could occur.

Conclusions

During a detailed petromagnetic study of the Tarkhanian sediments (the Middle Miocene) of the Kop-Takyl section, it was found that magnetite and, most likely, greigite are the main ferromagnetic minerals in the rocks of the Kuvinian, Terskian, and lower parts of the Argunian Beds. The main magnetic mineral in the upper part of the Argunian Beds is magnetite.

The rock-magnetic division of the sediments of Kop-Takyl section is associated with a change in the depositional environments of the paleobasin. The upper part of the Argunian Beds (layers 4 and 5) was formed during shallowing and the increased influence of the influx of clastic material due to river runoff. Detrital magnetite is the main carrier of natural remanent magnetization in this part of the section.

Most of the Argunian Beds were formed in relatively deep-water conditions. Sediments of the lower part of the Argunian Beds were formed mainly with weak aeration of the bottom waters, which led to the growth of anaerobic forms of bacteria. The increase in the values of petromagnetic parameters in the lower part of the Argunian Beds corresponds to the interval of intense accumulation of homogeneous clays and, possibly, is associated with the vital activity of bacteria, which led to a decrease in the number of detrital magnetite grains and increased formation of biogenic greigite. Despite the fact that greigite grains retained their primary magnetic structure, the enhanced formation of greigite could lead to the destruction of the primary NRM. Due to the delay between the time of sediment accumulation and the time of formation of greigite, secondary chemical magnetization CRM could have formed, in a direction not coinciding with the primary magnetization, which led to partial or complete remagnetization of rocks.

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