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Katav Limestones: A Unique Example of Remagnetization or an Ideal Recorder of the Neoproterozoic Geomagnetic Field

V. E. Pavlov[a] and Y. Gallet[b]

[a] *Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Bol'shaya Gruzinskaya ul. 10, Moscow, 123810 (123995) Russia*

[b] *Institut de Physique du Globe de Paris, UMR 7154, France*

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Abstract—The Neoproterozoic Katav Formation, participating in the composition of the Urals stratotype top section, includes a magnetostratigraphic record that can be the source of unique information on geomagnetic field behavior 800–900 Ma ago. For many years, it has been considered that the characteristic magnetization of this formation is metachronous and was formed in the course of the Late Paleozoic diastrophism. New data, obtained during the performed studies, indicate that the characteristic magnetization of the formation is primary, and the formation itself is an ideal recorder of the Neoproterozoic geomagnetic field.

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INTRODUCTION

The Late Riphean Katav Formation of the Riphean Urals stratotype (Fig. 1) is a vivid stratigraphic level, which is of great importance in correlating the Riphean rocks in the Urals and adjacent regions of the East European Platform. According to recent detailed magnetostratigraphic studies [Pavlov and Gallet, 2006], this formation includes several tens of magnetic zones of direct and reversed polarity (Fig. 1), which can indicate that the geomagnetic field inversion frequency was extremely high during the generation of this formation. If this assumption is confirmed, the Katav interval of increased inversion frequency can be considered and used as an important geophysical time benchmark in the Neoproterozoic history of the Earth. In addition, evidence that the magnetostratigraphic record detected in the Katav Formation is primary would be of great importance in understanding the character of the reversal in polarity of the geomagnetic field in the Late Precambrian, which in turn would be of extreme importance in developing geomagnetism physical theory and in understanding the evolution of the Earth's inner shells and the entire planet.

However, beginning from the pioneering works by R.A. Komissarova [Komissarova, 1970], it was customary to consider that ancient highly stable magnetization of the Late Riphean Katav limestones of the Riphean Urals stratotype is metachronous. Meanwhile, Shipunov [1991, 1993] indicated that regional magnetization of the Katav rocks can result from the superposition of at least two components, one of which (similar to such a component previously determined by Komissarova) is prefold and can in principle be primary. Not only the prefold magnetization character, but also the directions of direct and reversed polarity with almost antipodal averages, indicated that this magnetization is primary. There is only one, but rather forcible, argument for the metachronous character of magnetization: the magnetization direction is close to that of the regional Carbonaceous–Permian geomagnetic field, i.e., to the direction of the field during the period when intense tectonic deformations took place in the southern Urals and remagnetization of ancient rocks was most probable. This work presents new indications that magnetization of the Katav Formation is primary.

FOLD TEST AND MAGNETIC MINERALOGY

First of all, we mention that by magnetization we will subsequently mean the most stable magnetization component detected in the reference section near Min'yar (Fig. 1), which has declinations and inclinations of $D \sim 50°$ (230°) and $I \sim 35°$ (–35°), respectively. This component is present in many sections, located at considerable distances from one another (near Volkovo and Tolparovo [Shipunov, 1991, 1993] and in the sections of the Zilim and Shishenyak rivers [Komissarova, 1970]), and is characteristic of the Katav Formation [Zijderveld, 1967]. In individual sections (near Katav–Ivanovsk, in the region of the earlier settlement of Chernoe pleso, and in other regions), different authors (see, e.g. [Shipunov, 1991]) determined other paleomagnetic directions. At this stage of studies, we will not consider these directions, preliminarily assuming that

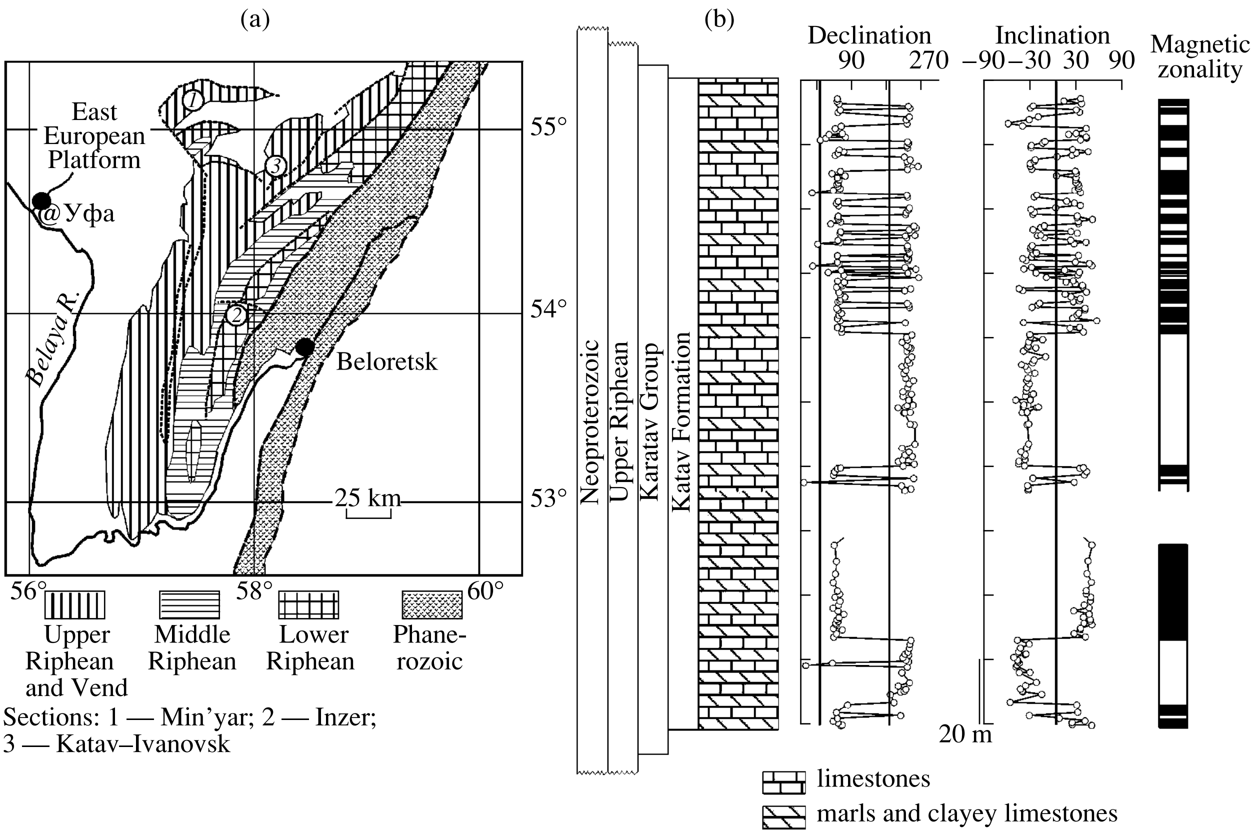

Fig. 1. (a) Geographic position and scheme of the working region; (b) magnetostratigraphic record in the Min'yar section (according to [Pavlov and Gallet, 2005]).

they result from the superposition of several magnetization components that were not separated during magnetic cleaning.

The prefold age of the Katav rock magnetization was determined at the early stage of studies [Komissarova, 1970] and was subsequently confirmed by rigorous statistical methods [Shipunov, 1991, 1993]. In 2006, we took more than 200 paleomagnetic samples from the Min'yar section during detailed paleomagnetic sampling. The number of samples was by a factor of 5–6 as large as the volume of the earlier studied collections. Another difference of our studies from the earlier ones was that we used the state-of-the-art procedure of magnetic cleaning in a paleomagnetic analysis (see, e.g. [Butter, 1992]) according to which studied samples were completely and thoroughly demagnetized.

Analysis **of of** the magnetic cleaning results has indicated that many samples consist of two magnetization components (Fig. 2). The least stable (sometimes very weak) component is usually destroyed at 300°; however, in certain samples, this component exists at temperatures of 400° and even higher. The direction of this component is close to that of the present-day magnetic field, which indicates that the component is relatively young. The only high-temperature component usually remains in samples after cleaning at higher temperatures. The maximal unlocking temperatures of this high-temperature (characteristic) component are close to 680°, which indicates (and this was also referred to in the earlier studies) that it is carried by hematite. However, our analysis also indicates that in certain samples, the characteristic component is completely or partially destroyed near the Curie point of magnetite (Fig. 3). This evidently indicates that magnetite often carries characteristic magnetization in Katav limestones. Moreover, magnetization of many samples is caused by both these minerals judging by the character of the temperature distribution of unlocking (Fig. 3). In this case, it is important to note that the directions of magnetization related to magnetite and hematite coincide.

In spite of the fact that the elements of rock occurrence vary rather insignificantly within the Min'yar exposure, the large number of samples affords a quite definite fold test result. This test, performed in the modification [Enknin, 2003], gives a confidently positive result.

Not far from the Min'yar exposure on the opposite (left) bank of the Sim River near Pervomayskii, we found a supposedly consedimentation–slide fold. This assumption has been confirmed by the fact that only the layers within a short stratigraphic interval with a thick-

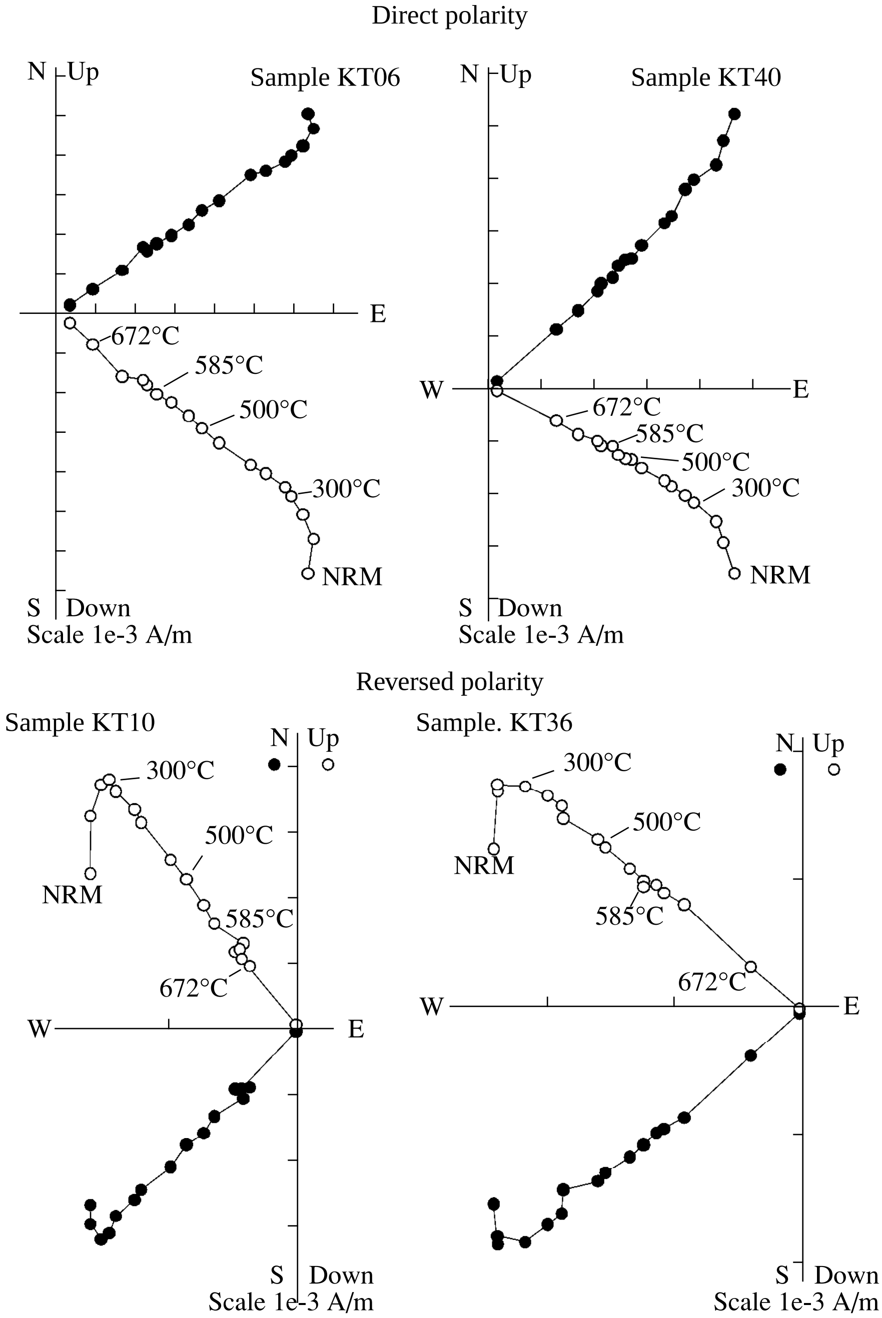

Fig. 2. Zijderveld diagrams for Katav samples; projections on the horizontal and vertical planes (filled and open circles, respectively).

ness of 1–1.5 m participate in the formation of this fold (of a rather complex structure). The overlying layers, as well as underlying ones, are regular and monoclinal. The test for a fold, performed for deformed layers, gives a confidently positive result (Table 1), which quite definitely indicates that the characteristic magnetization is primary. Unfortunately, these observations are apparently insufficient for us to be absolutely sure that the studied fold was actually formed during the Katav sedimentation.

COMPARISON WITH PALEOMAGNETIC DIRECTIONS OF THE OVERLYING AND UNDERLYING FORMATIONS

If the characteristic component of Katav rock magnetization originated as a result of recent remagnetization, the process that led to such remagnetization had to be regional. This results from the fact that the considered component is observed in different sections located at distances of many tens of kilometers [Komis-

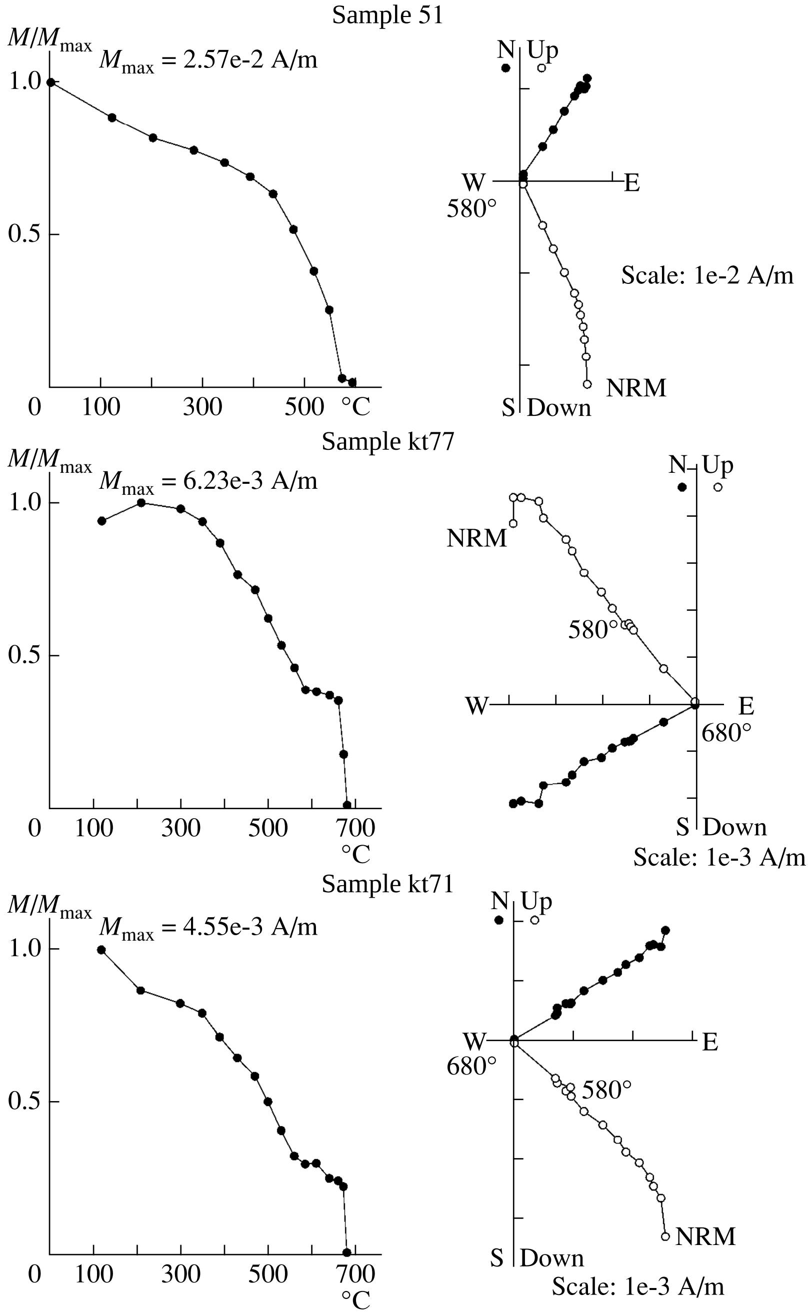

Fig. 3. Katav sample behavior during demagnetization, indicating that magnetite is one of the main magnetization carriers in the formation.

sarova, 1970; Shipunov, 1991, 1993; Pavlov and Krupenin, 2008].

If this is the case, we could naturally anticipate that this process will affect the rocks of the overlying and underlying formations (Inzer and Zil'merdak, respectively), which are rather widespread in the studied region. On the contrary, if the paleomagnetic directions of the overlying and underlying formations differ significantly from the corresponding direction of the Katav Formation, this will be a forcible argument for the absence of regional remagnetization.

Thus, a comparison of the paleomagnetic directions of the Katav, Inzer, and Zil'merdak formations can be considered as a test for the presence of post-Inzer (i.e., Late Riphean, Vendian, or Phanerozoic) regional remagnetization.

To perform this test, we sampled two exposures of the Inzer Formation (east of a pond near the mouth of Maloyuz Creek) and one exposure of the Zil'merdak

Table 1. Paleomagnetic directions of the Katav and Inzer formations

Formation	Exposure	*N*	Geographic coordinate system				Stratigraphic coordinate system				Reversal test
			D (°)	*I* (°)	*K*	α95 (°)	*D* (°)	*I* (°)	*K*	α95 (°)	γ/γ_c (°)
Katav Formation	**Min'yar** 55.06° N; 57.52° E										
	Entire section										
	Direct polarity	94	58.2	42.6	37.1	2.4	52.0	32.2	38.8	2.4	
	Reversed polarity	110	242.0	–45.3	32.7	2.4	233.6	–34.7	34.3	2.3	2.8/3.3
	Total	202	60.3	44.2	34.6	1.7	52.9	33.7	36.5	1.7	
	Min'yar bottom section (samples k1–k64, 79.9 m)										
	Direct polarity	32					50.1	37.7	44.7	3.8	
	Reversed polarity	23					228.5	–42.4	42.6	4.7	4.9/5.9
	Total	55					49.5	39.7	42.9	3.0	
	Min'yar top section (samples k104–kt105, 72.9 m)										
	Direct polarity	57					52.7	29.1	42.0	2.9	
	Reversed polarity	42					237.5	–29.0	43.4	3.4	4.2/4.5
	Total	99					51.2	29.1	41.8	2.2	
	Pervomaiskii 55.05° N; 57.54° E										Only three samples of reversed polarity
	Total	23	42.6	39.5	5.2	14.7	59.2	33.3	29.7	5.6	
Inzer Formation	**Pond** (φ = 55.08°; λ = 57.56°)	14	50.8	5.7	45.8	5.9	50.8	6.2	45.6	5.9	
	Maloyuz R. (φ = 55.06°; λ = 57.59°)	11	40.6	45.3	10.9	14.5	34.1	26.1	14.3	12.5	
	Mean	25	47.4	22.4	9.1	10.2	44.1	7.6	11.2	9.1	
Paleomagnetic pole of the Katav Formation Φ = 35.9° Λ = 168.4° *dp*/*dm* = 1.5°/1.9° A95 = 1.5°											
Paleomagnetic pole of the Inzer Formation Φ = 27.7° Λ = 185.9° *dp*/*dm* = 4.6°/9.2° A95 = 6.5°											

Note: (*N*) the number of samples; (*D*) declination; (*I*) inclination; (*K*) concentration; (α95) confidence circle radius (for directions); (γ/γ_c) angular distance and critical angle [McFadden and McElhinny, 1990]; Φ and Λ are paleomagnetic pole latitude and longitude, respectively; *dp*/*dm* confidence oval semiaxes; and (A95) confidence circle radius (for poles).

Formation (on the right bank of the Chernaya River near the bridge to Volkovo) in the vicinity of Min'yar. Figure 4 shows the distribution of the characteristic vectors of the magnetization component distinguished in the studied exposures.

In both studied exposures of the Inzer Formation, the characteristic component vectors form more or less compact clusters, which are located in the same part of the stereogram as the corresponding Katav vectors but have substantially lower deviations. The total average direction for the Inzer Formation (as well as the average directions calculated for either exposure independently) significantly differs from such a direction for the Katav Formation (see Fig. 4, Table 1).

The vector distribution in the studied exposure of the Zil'merdak Formation is more complex; however, only extremely sparse vectors in the entire, very scattered, distribution are located near the average Katav direction on the stereogram (Fig. 5). According to the preliminary data obtained during the studies in the region of Inzer (about 80 km south of Min'yar), the average directions of the characteristic components of the Zil'merdak and Katav formations differ significantly [Pavlov and Krupenin, 2008].

Finally, we can remind the reader that the directions of ancient magnetization of the Basinsk Vendian Formation, studied by Komissarova [1970] in the exposures located not far from Min'yar, also differ substantially from the Katav directions.

TEST OF REVERSAL AND TREND OF PALEOMAGNETIC DIRECTIONS ALONG THE SECTION

The relatively large volume of the collection made it possible to consider in detail the change in the average

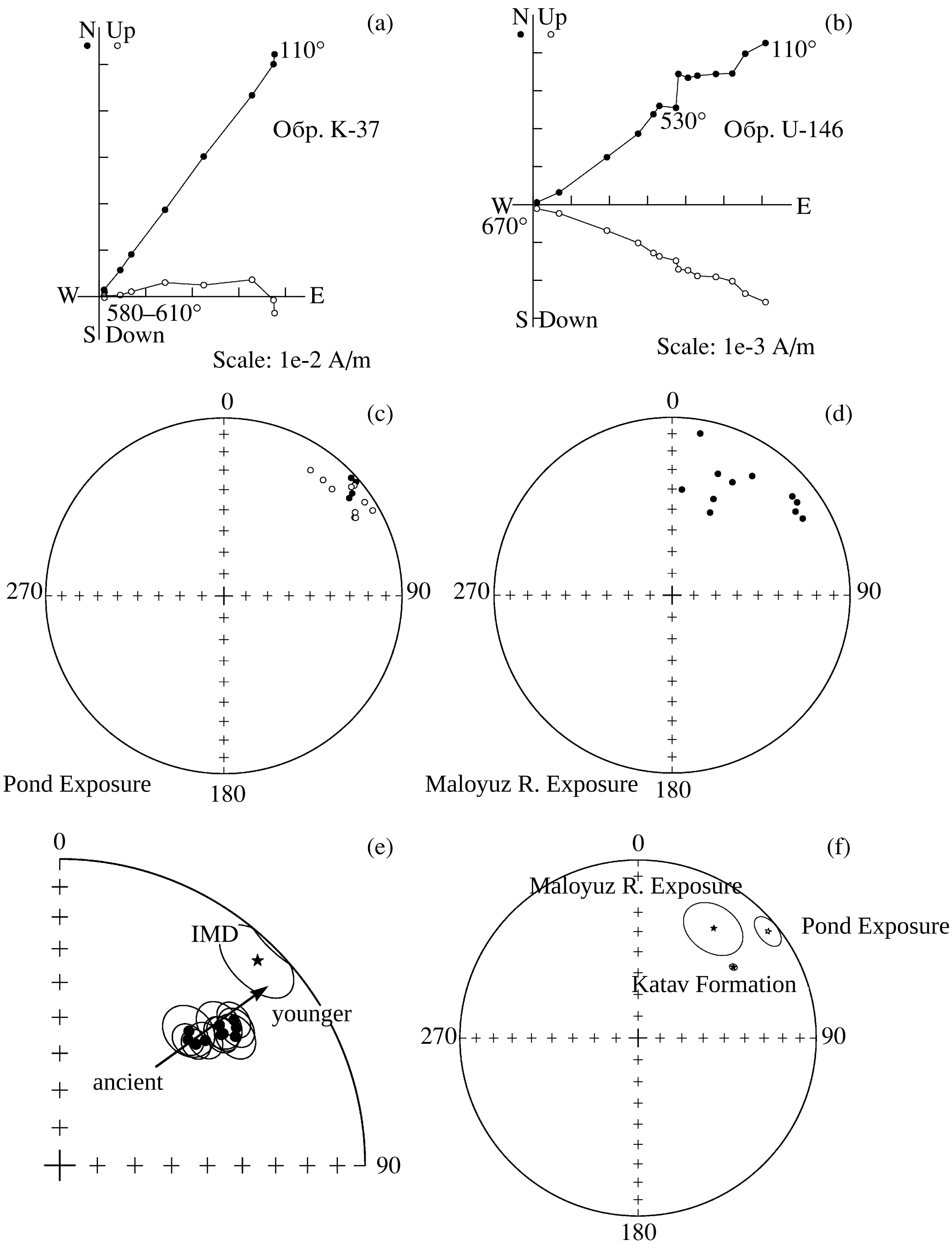

Fig. 4. (a), (b) The Zijderveld diagrams illustrating the character of the paleomagnetic record in Inzer samples; (c), (d) the distribution of the characteristic magnetization vectors in the studied Inzer exposures; (e) evolution of the average paleomagnetic directions from bottom to top in the Min'yar section and their comparison with the average paleomagnetic direction calculated for the Inzer rocks (IMD); (f) comparison of the average paleomagnetic directions of the Katav and Inzer formations; projections on the lower and upper hemispheres for stereograms (filled and open circles, respectively).

paleomagnetic direction along the Min'yar section. Table 2 presents the average directions calculated for each group of the next 20 samples from bottom to top of the section. The same data are indicated in Fig. 4e, which evidently demonstrates that the average direction quite regularly shifts from higher to lower deviations from bottom to top of the section. The total value of this shift is approximately 10°, and the general trend of this shift is directed toward the average paleomagnetic direction of the overlying Inzer Formation. It is important to note that the trend of directions is evident not only in the average values for the section intervals but

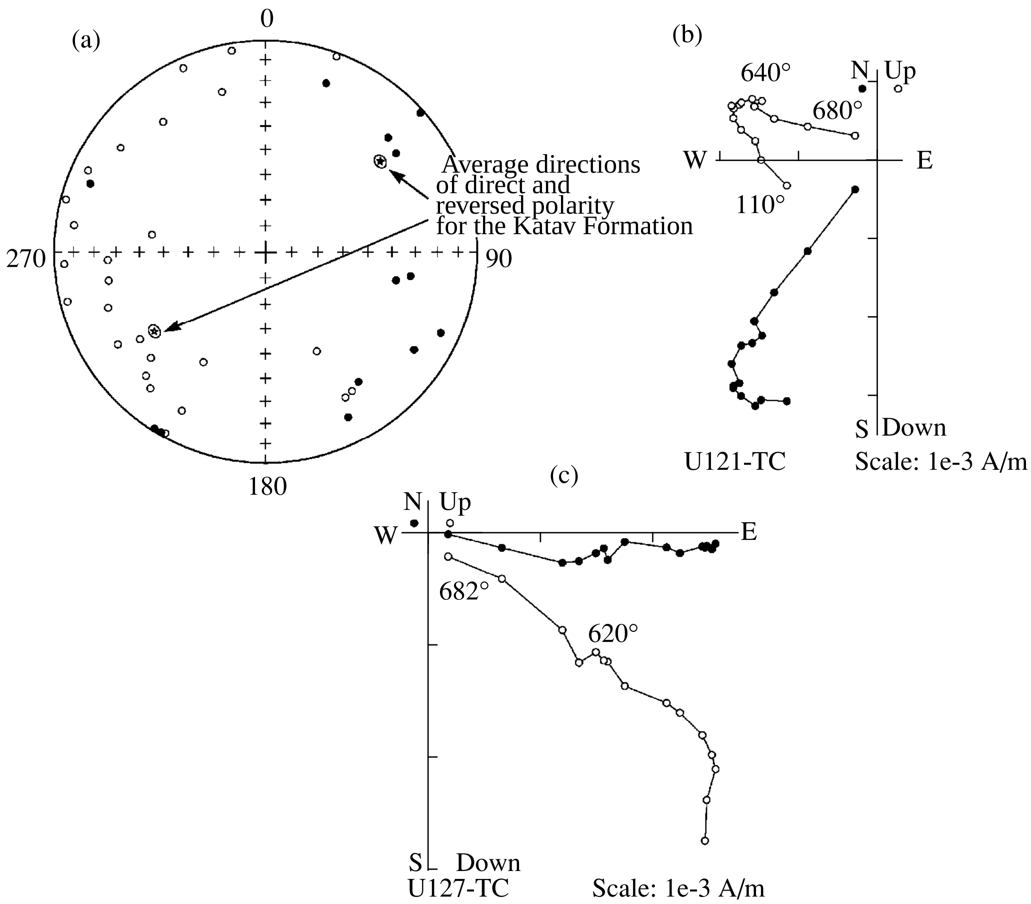

Fig. 5. (a) Distribution of the high-temperature magnetization component in the studied Zil'merdak section and (b) the behavior of natural remanent magnetization of the Zil'merdak samples during temperature demagnetization. The denotations are the same as in Figs. 2 and 4.

also in the averages calculated independently for the vectors of direct and reversed polarity (see Table 1).

Table 2. Variation in the average paleomagnetic direction from bottom to top along the Min'yar section

Sample ser. no. from bottom to top	*N*	*D*	*I*	*K*	α95
1–20	20	47.5	39.0	23.9	6.8
21–40	20	51.9	40.1	71.6	3.9
41–60	20	49.1	40.9	63.3	4.1
61–80	20	53.0	37.3	49.6	4.7
81–100	20	54.7	31.9	57.2	4.4
101–120	20	54.6	32.6	51.4	4.6
121–140	20	57.3	29.5	35.2	5.6
141–160	20	55.6	27.6	45.7	4.9
161–180	20	53.7	26.7	53.7	4.5
181–200	20	52.3	31.1	29.9	6.1

Note: (*N*) the number of samples; (*D*) declination; (*I*) inclination; (*K*) concentration; and (α95) confidence circle radius (for directions).

The test for reversal gives a positive result not only for the entire section but also for individual section intervals. It is important that the average values differ significantly for the upper and lower section intervals.

This means that, if remagnetization actually took place, the process of this remagnetization was not random. The remagnetization front had to move slowly along the section and remagnetize isolated layers, following the geomagnetic field polarity reversal.

These data (from the standpoint of the remagnetization hypothesis) indicate that the observed paleomagnetic record did not originate as a result of two adjacent remagnetization episodes (which could be confirmed by the presence of two antipolar directions) but was formed during the period necessary for the magnetic field to change its polarity at least several times and for the platform, including the considered section, to shift over a distance of about 600–700 km. Thus, according to the up-to-date concepts of a drift of lithospheric platforms in the Late Precambrian, this process had to proceed over the course of not less than several million years.

COMPARISON WITH RIPHEAN POLES OF THE EAST EUROPEAN PLATFORM

To date the characteristic magnetization of the Katav Formation, it would be of great importance to compare magnetization poles with paleomagnetic poles of the East European Platform rocks of a close age, obtained for regions located at considerable distances from the southern Urals. If these poles were close to the Katav pole, this could be considered an important argument for the primary character of Katav Formation magnetization.

Unfortunately, several circumstances hinder such a comparison.

First, the age range of the formation is insufficiently finite. The upper age boundary of this formation relatively distinctly corresponds to a Pb–Pb dating of 836 ± 25 Ma [Ovchinnikova et al., 1998] for the lower Inzer Formation and 780 ± 85 Ma for the overlying Min'yar Formation [Ovchinnikova et al., 2000], whereas the lower age boundary (1000 Ma) is drawn only based on more or less reliable transregional geological correlations.

Second, the Bashkir anticlinorium, within which the Katav Formation outcrops, experienced several stages of fold–thrust-fault deformations during its evolution; therefore, specific blocks could undoubtedly turn relative to their initial positions, and paleomagnetic poles obtained based on these blocks cannot be directly related to the East European Platform. When analyzing the paleomagnetic directions obtained based on the Katav Formation exposures, located at considerable distances from one another in different regions of the Bashkir anticlinorium, we can solve this problem. Such an analysis, performed in [Pavlov and Krupenin, 2007] based on the consideration of the available [Komissarova, 1970; Shipunov, 1991, 1993] and newly obtained data, indicated that the main elements of the anticlinorium structure (including the elements with the Min'yar section) generally did not exert any pronounced displacements relative to one another and to the East European Platform despite the fact that this anticlinorium includes isolated rotated blocks. This result makes it possible to compare Katav poles with platform ones.

Finally, it is very difficult to compare Katav and platform poles because the number of the latter poles is extremely small. Walderhaug et al. [2007] pointed out that only three groups of undoubtedly reliable paleomagnetic poles are available for the Baltic (East European Platform) Neoproterozoic: (1) 970–1100 Ma old Sweconorwegian poles, (2) Egersund anorthosite poles [Brown and McEnroe] (869 ± 14 Ma) and Hunnedalen dykes [Walderhaug et al., 1999] (848 ± 27 Ma), and (3) poles obtained based on the Late Riphean sedimentary formations in northern Norway and on the Kola Peninsula [Shipunov and Chumakov, 1991; Meert and Torsvik, 2003] (700–800 Ma).

In Fig. 6, the first group (following [Walderhaug et al., 2007]) is represented by the middle pole of Bamble intrusions; the second group, by the most exactly determined poles of this group from [Meert and Torsvik, 2003; Walderhaug et al., 1999]; the third group, by

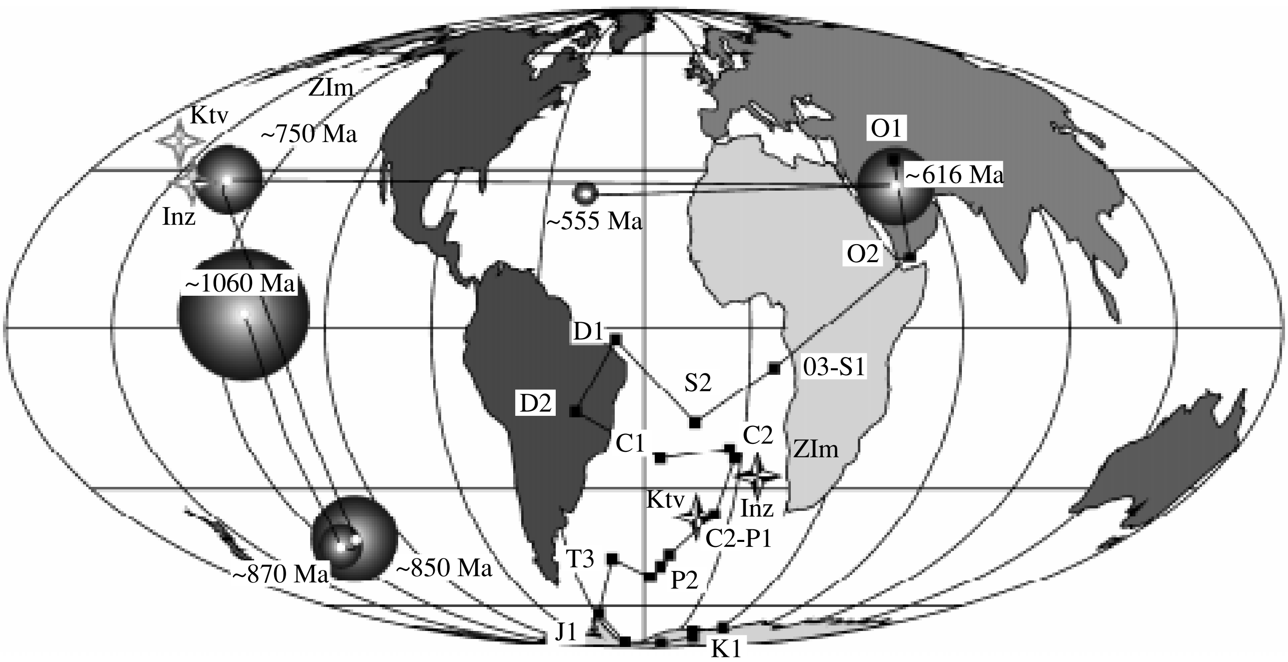

Fig. 6. Comparison of the Katav and Inzer poles with the known Neoproterozoic and Phanerozoic poles in the East European Platform (for details, see the text); four-point asterisks denote southern and northern poles of the Katav and Inzer formations; open (filled) circles correspond to Neoproterozoic (Phanerozoic) poles in the East European Platform.

the middle pole for this group [Meert and Torsvik, 2003].

Figure 6 indicates that the Inzer pole is in immediate proximity to the Kola–Norwegian third-group pole of the similar age, as should take place in the primary magnetization in Inzer rocks. The Katav pole is located only 15° from this pole. This is quite probable if the age difference between these poles is taken into account. Thus, the closeness of the Katav pole to the Early Permian platform pole can be easily explained by the fact that the Late Paleozoic segment of the East European curve of apparent pole migration (APM) is located in the same region of the Earth's surface as the inverted segment of the APM curve for the Late Neoproterozoic.

DISCUSSION OF RESULTS

This work presents a number of new facts n that the characteristic magnetization of the Katav rocks is primary. The main of these facts are as follows:

(1) an independent direction of the magnetic mineralogy characteristic component;

(2) different directions of the characteristic components of the Katav and overlying and underlying rocks;

(3) a trend of paleomagnetic directions from bottom to top of the Katav Formation;

(4) closeness of the Katav paleomagnetic pole to the Late Riphean paleomagnetic poles in the northwestern East European Platform.

Together with the positive results of the fold and reversal tests, obtained previously and confirmed at the new level in the present work, these arguments make it possible to state that ancient magnetization of the Katav rocks is primary. The main and the only argument against the statement that this magnetization is primary is rejected because the Late Proterozoic poles in the East European Platform are located near the Early Permian poles, which is not surprising if the geological time and limitedness of the Earth's surface are taken into account. Thus, the Katav paleomagnetic pole not only can but also should lie in the same (or antipodal, depending on selected polarity) region as the Early Permian poles.

Together with the facts considered above, certain additional considerations confirm the conclusion that magnetization is primary or contradict the remagnetization hypothesis.

Specifically, from the standpoint of the hypothesis on remagnetization, it is extremely difficult to explain the existence of at least several episodes of remagnetization by the field of direct and reversed polarity during the period (Late Carbonaceous–Early Permian) when the geomagnetic field exerted several inversions (the Kiam superchron). In the overwhelming majority of cases, Late Paleozoic remagnetization (really widespread within and near the Ural–Mongolian belt) forms a unipolar magnetic component in rocks.

We can try to explain the observed trend of paleomagnetic directions by the gradual motion of the remagnetization front from top to bottom or from bottom to top of the section. Such a remagnetization could be related to slow motion of fluids or to the same slow cooling of rocks at least from temperatures of about 700°C. The possibility of such a cooling is directly eliminated by the mineralogical observations and determinations of the microfossil color index (V. Sergeev, private communication). Fluids move at a fantastically low velocity (less than 1 mm per 10 years). Even if we ignore this fact, it remains unclear why fluids moved across, rather than along, stratification.

In addition, both discussed mechanisms cannot explain why the process of remagnetization stopped in the previous zone of polarity when the next zone was formed due to remagnetization (otherwise we would everywhere observe the presence of several opposite components or a quasi-chaotic distribution of vectors).

Thus, the hypothesis of remagnetization confronted with serious problems that seem difficult to solve.

A paleomagnetic study of flat-pebble conglomerates, which are observed in the Katav section near Katav–Ivanovsk (we do not know other locations of these conglomerates), could allow us to eliminate this problem. However, it is extremely difficult to separate pebble from the matrix in these conglomerates. Therefore, it seems promising to study polished sections of these conglomerates using a special magnetoscope, which should become a topic of further study.

A detailed study of at least several zones of magnetic polarity reversal in the Katav sections could become one more extremely important argument. A statistically confirmed regular replacement of the component of previous polarity by that of the subsequent polarity would be yet another argument for primary magnetization.

Unfortunately, the study of one such zone [Komissarova et al., 1997] seems insufficient for one to draw a certain conclusion. However, the data obtained in this work can be used to preliminarily estimate the total duration of the Katav inversion of the geomagnetic field and the time of blocking of primary (post-detrital or early diagenetic) magnetization in a sediment. According to [Komissarova et al., 1997], the thickness of two studied transition zones is about 20 cm. The viewpoints of the geodynamic conditions of the generation of Katav limestones (passive continental margin [Puchkov, 2000], intracontinental drift [Maslov et al., 1997]) are different; nevertheless, all researchers assume that limestones accumulated in a shallow sea basin at the margin of the East European Platform. According to numerous researchers (see, e.g. [Bosscher and Schlager, 1993; Altermann and Nelson, 1998; Satolli et al., 2007]), the average rate of such rock accumulation is usually 10–30 m per 1 Myr. If we accept such an accumulation rate for the Katav Formation, the total duration of generation of the studied 200-m interval should be about 10–20 Myr. Such a duration is very close to the estimate that can be obtained if we take a usual Phanerozoic rate of 1° per 1 Myr [Torsvik et al., 1996] as a paleomagnetic pole drift velocity and remember that the shift of the average paleomagnetic direction from the section bottom to its top is about 10°.

As a result, assuming that the probable accumulation rate of the Katav rocks is 10 m per 1 Myr, we obtain a value (20 ka) that can be considered as the probable (but still preliminary) upper estimate of the duration of inversion and the time of magnetization blocking in Katav sediments.

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SPELL: 1. marls, 2. clayey