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Magnetic Stratigraphy of the Permian–Triassic Traps in the Kotui River Valley (Siberian Platform): New Paleomagnetic Data

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Abstract—The Permian–Triassic effusive traps in the Kotui River valley (Siberian Platform) were studied in detail by a paleomagnetic method, resulting in a summarized magnetic stratigraphic section of the studied sequence. The presence of the reversed polarity zone corresponding to the Khardakh Formation was argued for the section basement. Inside the Kogotok Group, the boundary between the direct and reversed polarity zones occurs in the lower part of the Onkuchak Formation and mismatches the boundary between the formations of the Kogotok Group, as was accepted before. These results contradict the presence of the transition record between the direct and reversed polarity zones in basalts of the lower part of the Onkuhcak Formation. The strong transitional interval between the Ivakinsk Formation and the upper parts of the Nadezhda Formation of the Norilsk section has no analogs in the Kotui section. This means the absence of any significant volcanic activity in the Maimecha–Kotui province during the intense eruptions in the Norilsk region resulting in origination of the greater part of the lower formations of the trap sequence. These data and possible correlations of the traps of the Kotui River valley and Norilsk region indicate that the Norilsk and Maimecha–Kotui sections were temporally overlapped.

Keywords: magnetic stratigraphy, Siberian traps, correlation, Permian–Triassic boundary

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INTRODUCTION

In spite of numerous studies of correlation of the effusive sequences from the Norilsk and Maimecha–Kotui regions of the Siberian trap province, this problem is still open. Its solution is important for both the regional geology and assessment of the duration of formation of the thick trap sections of these regions, which is necessary to verify the relation of the greatest mass extinction on the Earth at the end of the Permian to eruption of Permian–Triassic traps of the Siberian Platform (see, for example, Courtillot and Renne, 2003).

The present correlation scheme of the effusive trap complexes of the Norilsk and Maimecha–Kotui regions is based on the geochemical, geochronological, paleontological, and paleomagnetic (magnetostratigrpahic) data (Kamo et al., 2003). The quality and reliability of the paleomagnetic data differ significantly. For example, the results of recent magnetostratigraphic studies of traps from the Norilsk region completely correspond to the modern requirements of reliability and quality (Gurevitch et al., 2004; Heunemann et al., 2004). At the same time, the data from (Gusev et al., 1967; Sidoras, 1984), which are the base for the magnetostratigraphic scheme of effusive traps of the Maimecha–Kotui region, were obtained more than 25 years ago and need confirmation.

This work presents the results of the detailed magnetostratigraphic studies of traps of the Kotui River valley conducted in 2007–2009 and reviews the correlation of the Maimecha–Kotui and Norilsk trap sections.

OBJECTS OF STUDY

The lower part of the effusive trap sequence of the Maimecha–Kotui region is the most completely present in the lower reaches of the Kotui River as a series of coastal outcrops extending for more than 40 km from the mouth of the Potokoi River to the mouth of the Eriechka River (Fig. 1). The studied stratigraphic sequence includes the Khardakh and Ary-Dzhang formations and also the Onkuchak Formation of the Kogotok Group.

The Khardakh Formation was studied in the outcrop on the right bank of the Kotui River, 20 km upstream from the mouth of the Medvezh'ya River, opposite the mouth of the Potokoi River (Fig. 1, point 1). This formation was distinguished by Egorov (1995) as

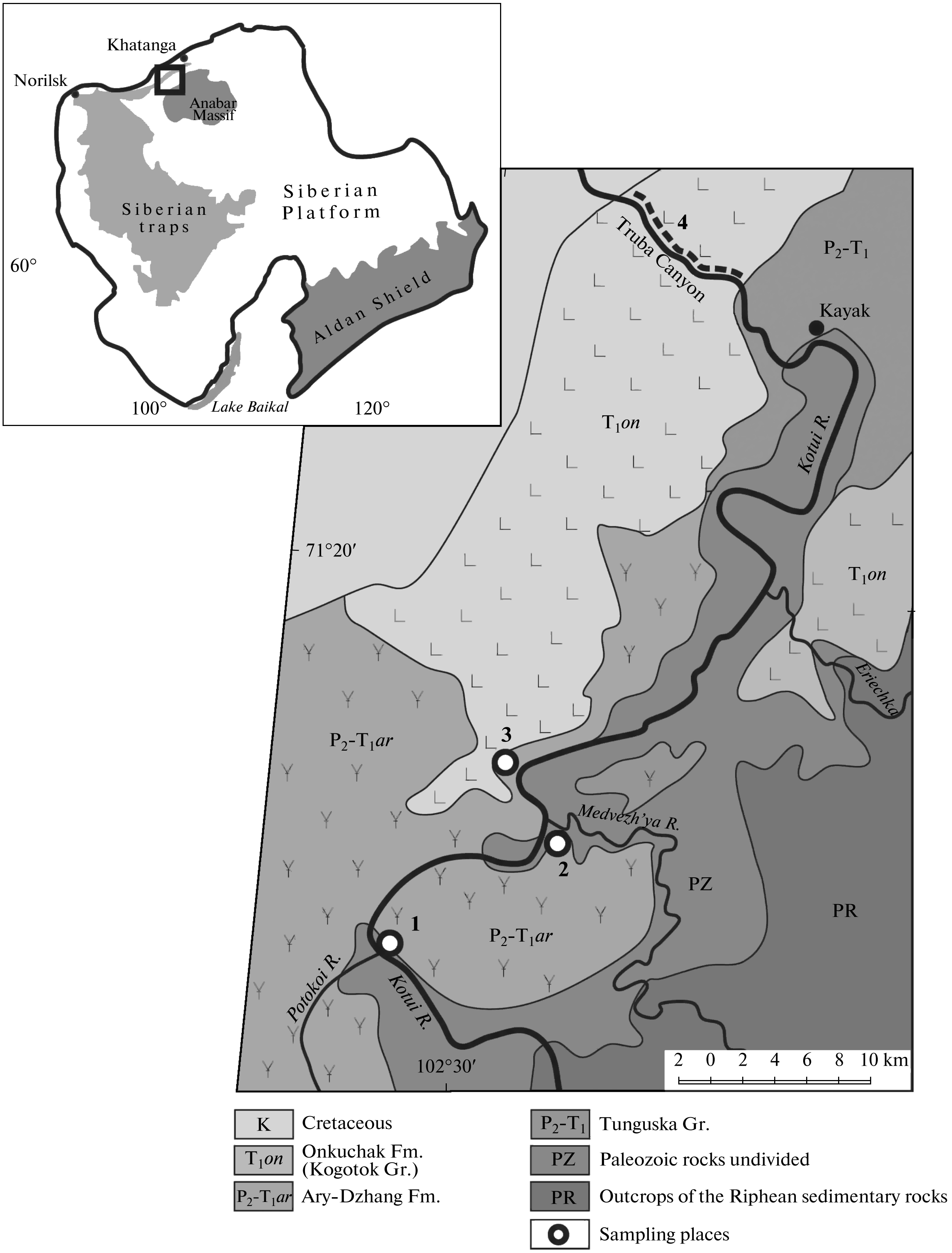


Fig. 1. Geographical location of the studied sections and geological scheme of the area of works. Points 1–4 are location of the sampled sections.

a facial analog of the Pravaya Boyarka Formation, widespread in the Maimecha River basin. Following other researchers (see references in Egorov, 1995), he emphasized a stratigraphically lower position of the Khardakh Formation relative to the lava sequence of the Ary-Dzhang Formation. The poorly exposed subordinate Khardakh Formation is characterized by a low variable thickness and is ascribed to the lower parts of the Ary-Dzhang Formation by some researchers (e.g., Fedorenko et al., 1996).

The visible thickness of the studied outcrop is 32 m (Fig. 2b). A top of flow 1 of alkali basaltic rocks at the basement of the section (at the low water level in the Kotui River) is overlapped by alkali–ultramafic tuff lavas. The greenish brown and cherry-colored tuff lavas contain angular clasts (lithoclasts) of igneous rocks of similar composition 1–20 mm in size. This member is confidently subdivided into four horizons according to the color of the rocks and contacts between them. The section is crowned by flows 2 and 3 of alkali basalts 5 and 7 m thick, respectively. The rocks lie horizontally on sandstones of the Upper Permian Tunguska Group and their contact is traced along the riverside outcrops. A vertical trachidoleritic dike 2 m thick cuts the lower and medium parts of the section (flow 1 and four tuff horizons); up the section, the dike is poorly exposed and its relation to stratified rocks is uncertain. No geochronological data are known for the Khardakh Formation and its Late Permian age is based on the paleontological findings (Ivanov and Pirozhnikov, 1959).

The Ary-Dzhang Formation occurs above the rocks of the Khardakh Formation, but we failed to find the contact between them. The rocks of the formation were studied in two outcrops. One of them is located near the mouth of the Medvezh'ya River (Fig. 1, point 2) at the height of 60 m over the riverbed, where the lavas of alkali basalts have contacts with underlying Permian sandstones. The uneven boundary of the contact is characterized by depressions with volcanic material; the lavas have locally unclear pillow structure and red crusts. Four lava flows 8–15 m thick were sampled.

The second outcrop is located on the left bank of the Kotui River 5 km downstream from the mouth of the Medvezh'ya River (Fig. 1, point 3) and is composed of flows 3–8 m thick of picrites, melilitic melanephelinites, and melanephelinites or augitites according to Fedorenko et al. (2000) and Latyshev et al. (2010), respectively (Fig. 2a). Thin (a few meters) tuff members occur in the section. The total thickness of the studied section with 27 horizontal lava flows is ~280 m. According to the scheme of the outcrop (Fedorenko et al., 2000), we ascribe the uppermost basaltic flow to the Onkuchak Formation (see below). On the basis of relics of phillopods, the age of the Ary-Dzhang Formation is estimated as Early Triassic (Ivanov and Pirozhnikov, 1959). The U–Pb age of perovskite from the lower part of formation is 251.7 ± 0.4 Ma (Kamo et al., 2003). Many researchers consider the Ary-Dzhang Formation as a facial analog of the Pravaya Boyarka Formation, widespread in the Maimecha River valley and westward (*Gosudarstvennaya...*, 1978).

The Onkuchak Formation represents the lower part of the Kogotok Group and is exclusively composed of the flows of tholeiitic olivine and olivine-free dark gray small-grained basalts with rare interlayers of mafic tuffs (Fedorenko et al., 2000; Latyshev et al., 2010). No contact with underlying alkali basalts of the Ary-Dzhang Formation was found in the outcrops. The volcanic sequence 350 m thick of the Onkuchak Formation (Fig. 2a) was studied on the right bank of the Kotui River along the valley area known as Truba (*tube*), located 5–15 km downstream from the settlement of Kayak (Fig. 1, point 4). The formation consists of 44 lava flows 3 to 10 m thick, which dip to the northwest at an angle no greater than 6°. We consider that this reflects the paleorelief rather than further tectonic deformations because of the horizontal bedding of the nearby sedimentary rocks of the Tunguska Group.

METHODS OF STUDY

The paleomagnetic collection of traps (8–20 samples from each flow) of the Kotui River valley consists of more than 1200 samples, whose orientation was identified with a mining compass under constant control of possible influence of strongly magnetic rocks. The rocks were sampled mostly from the lower parts of the lava flows in order to decrease the involvement of the rocks overmagnetized by the overlapping flow. The value of the local magnetic declination was calculated by the IGRF model (11th generation, http://www.geomag.bgs.ac.uk/data_service/models_compass/igrf_form.shtml). The results of the laboratory paleomagnetic studies and magnetic cleaning were processed in the Petromagnetic Laboratory of the Faculty of Geology of Moscow State University, the Laboratory of the Main Geomagnetic Field and Petromagnetism of the Institute of the Physics of Earth of the Russian Academy of Sciences, and the paleomagnetic laboratories of the Institute of the Physics of Earth (Paris, France) and the Massachusetts Institute of Technology (USA) according to the standard method (Zijderveld, 1967; Khramov et al., 1982; Shipunov et al., 1999).

All samples were thoroughly cleaned 10–12 times and more, if needed, at a temperature of 560–580°C. Nonmagnetic ovens with an uncompensated field value less than 5–10 T were used to demagnetize the sample. The remanent magnetization was measured on JR-6 (AGICO) spin magnetometers and on cryogenic magnetometers from 2G Enterprises. These results were processed using a software package by Enkin (1994) and Remasoft (Chadima and Hrouda, 2006), which use the RSA method for distinguishing the magnetization components (Kirschvink, 1980).

The data on magnetic minerals of the Ary-Dzhang and Onkuchak formations are based on thermomag-

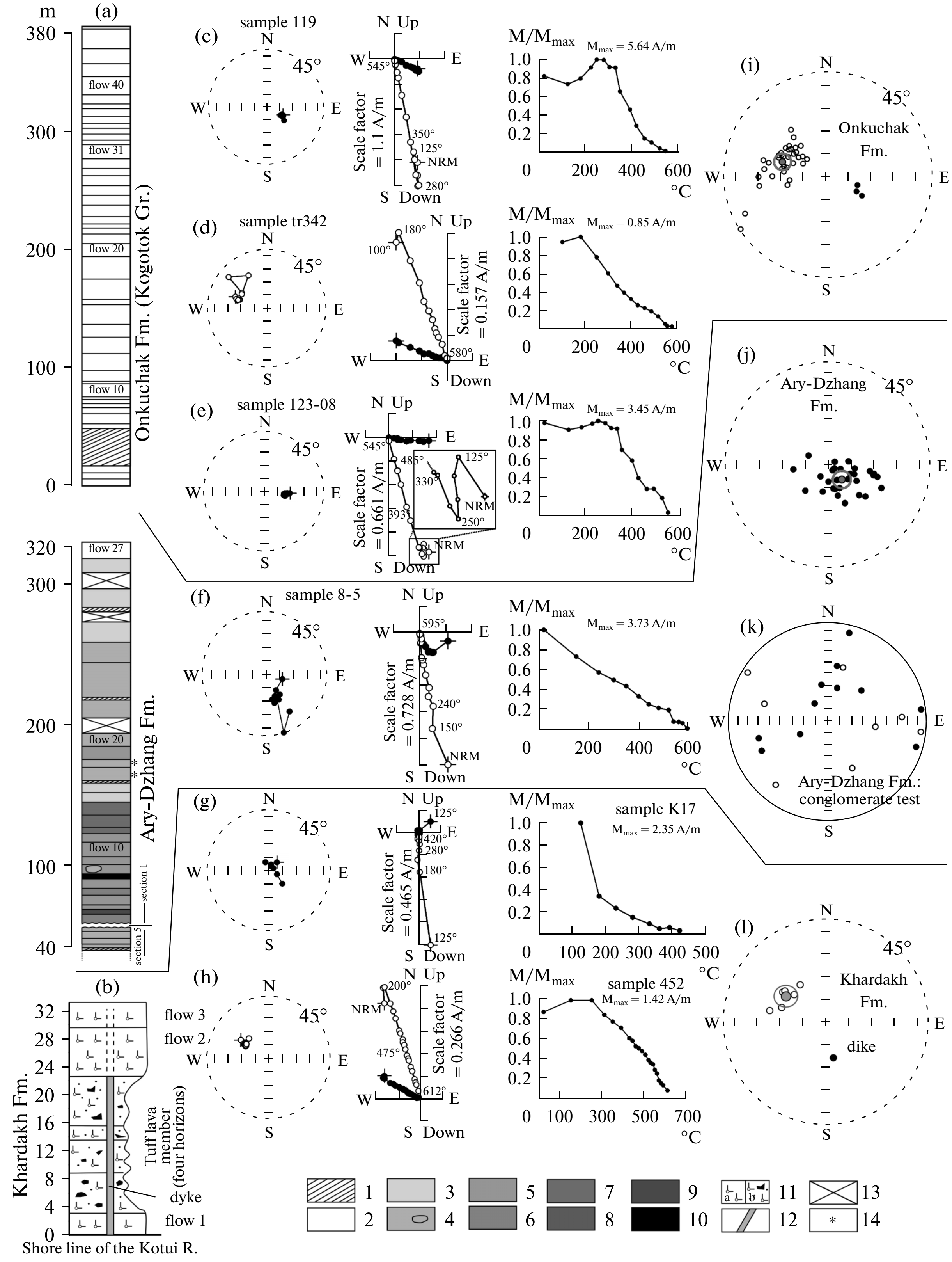

m
(a)
380
300
200
100
0
flow 40
flow 31
flow 20
flow 10
Onkuchak Fm. (Kogotok Gr.)
320
300
200
100
40
flow 27
flow 20
flow 10
Ary-Dzhang Fm.
section 1
section 5
(b)
32
28
24
20
16
12
8
4
0
Khardakh Fm.
flow 3
flow 2
Tuff lava member (four horizons)
dyke
flow 1
Shore line of the Kotui R.
(c)
sample 119
N
S
W
E
45°
N Up
S Down
545°
350°
125°
NRM
280°
Scale factor = 1.1 A/m
M/Mmax
Mmax = 5.64 A/m
1.0
0.8
0.6
0.4
0.2
0
200
400
600
°C
(d)
sample tr342
180°
100°
580°
Scale factor = 0.157 A/m
Mmax = 0.85 A/m
(e)
sample 123-08
545°
485°
330°
125°
NRM
250°
393°
Scale factor = 0.661 A/m
Mmax = 3.45 A/m
(f)
sample 8-5
595°
240°
150°
NRM
Scale factor = 0.728 A/m
Mmax = 3.73 A/m
(g)
125°
420°
280°
180°
125°
Scale factor = 0.465 A/m
sample K17
Mmax = 2.35 A/m
0
100
200
300
400
500
°C
(h)
200°
NRM
475°
612°
Scale factor = 0.266 A/m
sample 452
Mmax = 1.42 A/m
0
100
300
500
700
°C
(i)
Onkuchak Fm.
(j)
Ary-Dzhang Fm.
(k)
Ary-Dzhang Fm.: conglomerate test
(l)
Khardakh Fm.
dike
1
2
3
4
5
6
7
8
9
10
a
б
11
12
13
14
*

Table 1. Some petromagnetic characteristics of the rocks of the studied objects

Formation	Magnetic susceptibility, Km (10^{-3} SI units)			Natural remanent magnetization, In (A/m)			Kenigsberger factor, Q		
	Km_{min}	Km_{max}	Km_{av}	In_{min}	In_{max}	In_{av}	Q_{min}	Q_{max}	Q_{av}
Khardakh	10.4	128.4	71.5	0.18	2.38	1.24	0.04	0.7	0.2
Ary-Dzhang	1.7	111.4	43.8	0.14	6.02	2.76	0.07	13.2	2.2
Onkuchak	0.7	42.5	14.0	7.48×10^{-3}	11.7	1.64	0.08	11.9	1.9

netic and microprobe analyses (Latyshev et al., 2010) and those of the Khardakh Formation were identified only by the release temperatures. Some magnetic characteristics of the studied rocks (Kenigsberger factor, magnetic susceptibility, and the value of the natural remanent magnetization) are shown in Table 1.

RESULTS OF PALEOMAGNETIC STUDIES

Khardakh Formation

Several magnetization components may be distinguished in the composition of the natural remnant magnetization (NRM) of the rocks of the Khardakh Formation (Fig. 2f). The lowest temperature one is present almost in all samples and decays at temperatures of 125–230°C. Its average direction is close to that of the modern field in the studied region, which allows assumption of its modern age and viscous origin.

Almost all samples from the lava flows may be subdivided into three groups from the component analysis. The first group includes those samples which, in addition to the low-temperature modern component, also contain the high-temperature magnetization component with reversed polarity destroyed at 280–550°C (locally, up to 600°C) (Fig. 2h). The second group represents the samples containing, in addition to the low-temperature modern component, the medium-temperature component (280–420°C) with normal polarity (Fig. 2g). The third (conditional) group consists of several samples containing the low-temperature modern component (125–230°C), probably the medium-temperature component (280–450°C) of normal polarity, and the high-temperature component (470–550°C) of reversed polarity. The lowermost lava flow 1 contains the samples from all three groups; the samples from the first (three specimens) and second (seven specimens) groups were found in flow 2 up the section; all samples from the uppermost lava flow 3 belong to the second group.

Along with the low-temperature (20–250°C), the high-temperature component of reversed polarity is distinguished in all samples from the tuff lava member (Fig. 2h). Judging from the maximum release temperatures (560–620°C), the magnetic minerals are low-Ti titanomagnetite and, probably, oxidized magnetite.

The dike samples are characterized by the low-temperature (125–230°C) modern magnetization component and high-temperature (280–530°C) characteristic component of normal polarity.

Because the NRM component of normal polarity in samples from lava flows 1, 2, and 3 is distinguished in the lower temperature range of the blocked temperatures rather than the component of reversed polarity (i.e., it is less stable), we suggest its secondary origin. It is probably a result of complete (in some cases, partial) remagnetization of volcanic rocks of the Khardakh Formation in the Ary-Dzhang (?) time. Currently, we also cannot exclude that the medium-temperature component probably resulted from the magnetization self-reversal. This interpretation, however, does not significantly modify the total magnetic stratigraphy of the Kotui section.

The different polarity of the characteristic magnetization component of the dike and the host tuff lavas may favor the primary high-temperature magnetization components of the lower and middle section parts. Anyway, this indicates that the reviewed sequence did not undergo complete remagnetization after intrusion of the dike.

The NRM vectors of the igneous clasts from the tuff lava member are the sum of the low-temperature (20–180°C) and high-temperature (450–600°C) magnetization components; the latter is characterized by reversed polarity. The directions of the high-temperature magnetization component of the clasts make a cluster near the average direction of the characteristic component of the tuff lava (matrix). This allows us to suggest that the lithoclasts cooled together with lavas. The traces of viscous draping of the clasts by the matrix also indicate their occurrence in the hot liquid lava.

Fig. 2. Paleomagnetic characteristics of the studied formations from the Kotui section. (a, b) Schemes of sections of the studied formations (schemes of sections 1 and 5 of the Ary-Dzhang Formation are composed after Fedorenko et al., 2000). (1) Tuff of various compositions; (2) basalt of normal alkalinity; (3) limburgite; (4) melanephelinite and its pebble; (5) melilitic melanephelinite; (6) olivine melanephelinite; (7) melanephelinite, limburgite; (8) augitite; (9) melilite; (10) picrite; (11) lava (a) and tuff lava (b) of alkaline basaltic rocks with volcanic bombs; (12) dike of trachidolerite; (13) not exposed; (14) marking lava flows after (Fedorenko et al., 2000); (c–h) typical Zijderveld plots for samples from each formation; (i, j, l) distribution of average directions of the characteristic magnetization with respect to flows; (k) conglomerate test.

Table 2. Average paleomagnetic directions and virtual geomagnetic poles of the studied objects

Object	Sampling coordinates		Paleomagnetic direction					Virtual geomagnetic pole			
	slat	slong	N/n	D°	I°	K	α95°	Plat°	Plong°	dp/dm (°)	γ/γ_{cr} (°)
Khardakh Fm.	71°03′	102°22′	6/70	302.9	–69.3	121	5.2	40.4	143.9	7.6/8.9	8.9/5.9
Dike in the Khardakh Fm.	71°03′	102°22′	1/6	169.5	74.1	46	10.0	–	–	–	–
Ary-Dzhang Fm.	71°12′	102°37′	31/334	137.4	81.5	49	3.6	57.0	123.5	6.8/7.0	7.1/7.5
Onkuchak Fm.	71°33′	102°57′	39/395	289.2	–71.0	62	2.9	46.2	153.6	4.4/5.1	6.0/6.6

Slat and Slong, average coordinates of sampling place (latitude and longitude, respectively); N/n, amount of flows (samples); D and I, declination and inclination of the average vector; K and α95, parameters of the Fischer statistics (concentration and radius of the circle of 95% confidence, respectively); Plat and Plong, coordinates of the virtual geomagnetic pole (latitude and longitude, respectively); dp/dm, values of the semiaxes of the oval of 95% confidence; γ/γ_{cr}, comparison of directions for each formation with that recalculated for the average trap pole of the Siberian Platform NSP2 (Pavlov et al., 2007) to average coordinates of the region of works (slat = 71.2°, slong = 102.6°): γ, angular distance between the directions; γ_{cr}, critical angle (McFadden and McElhinny, 1990).

Thus, there are grounds to assume that the entire (or almost entire) sequence of studied volcanic rocks of the Khardakh Formation was formed in the epoch of reversed polarity. The lava flows were completely (flow 3) or partially (flows 1 and 2) remagnetized by later magmatic events, which, probably, coincide with origination of the lava flows of the Ary-Dzhang Formation.

The absence of a secondary component of normal polarity in the tuff lavas means that the remagnetization is probably related to the different magnetic mineralogy of the studied rocks rather than to any noticeable heating. This is evident from significant differences in their paleomagnetic record and corresponding ranges of the release temperatures.

An alternative hypothesis of magnetization self-reversal may be attractive to explain the component of normal polarity. In this case, the self-reversal could have occurred in some lava flows and not have affected the tuff lava horizons.

The paleomagnetic record of the reversed polarity in the rocks of the Khardakh Formation supports an opinion of Egorov (1995), who distinguished it from the Ary-Dzhang Formation on the basis of the lithological–facial peculiarities. According to (*Stratigraficheskii*..., 2006), our results provide additional grounds to distinguish the studied volcanic rocks as an individual formation because of their geophysical characteristics distinct from the above-lying rocks of the Ary-Dzhang Formation.

Ary-Dzhang Formation

Thirty-one studied flows of alkali and ultramafic lavas of the Ary-Dzhang Formation are characterized by moderate quality of the paleomagnetic record. However, owing to the increase in the amount of samples and their sampling from the lower parts of the flows most promising for the preserved signal, the average paleomagnetic directions were obtained almost for all sampled flows. The average paleomagnetic direction for the entire formation calculated at the site (flow) level is shown in Table 2.

All flows of the formation are magnetized in normal polarity (Fig. 2f). The NRM vector of most of the samples is characterized by the low-temperature (20–240°C) component, the direction of which is similar to that of the modern magnetic field, and the high-temperature component, which is destroyed at 550–600°C (Fig. 2f).

Two magnetic minerals (together or separately) with Curie temperatures near 570°C (magnetite) and 480–530°C (probably, low-Ti titanomagnetite) are typically present in the rocks of the formation (Latyshev et al., 2010).

Pebbles of igneous rocks were sampled from the conglomerate lens in the middle part of the formation. The directions of vectors of their characteristic component ($N = 19$) are chaotically distributed with concentration (c) of 1.2 (Fig. 2k). The length of the resultant vector $R = 2.33$ that is much less than the critical value (at a 95% confidence level) of Ro = 6.98 (Watson, 1956) for $N = 19$. Thus, a positive conglomerate test is suggested, indicating the primary age of the most stable magnetization component of the Ary-Dzhang samples.

Onkuchak Formation

Most samples of the Onkuchak Formation are characterized by a clear paleomagnetic signal. The NRM of the samples from three lower flows is a sum of two or three magnetization components. The low-temperature (20–180°C) modern magnetization component is probably of viscous origin. An intermediate medium-temperature (125–400°C) magnetization component of reversed polarity is confidently distinguished in a significant amount of samples from three lower flows (Fig. 2e). The high-temperature magnetization component of normal polarity, which is present in all samples, is destroyed at 350–545°C.

The presence of the medium-temperature magnetization component could be explained by the partial thermal remagnetization of rocks during eruption of the above-lying flows or by self-reversal. The experiments on the constant demagnetization of the NRM of samples with successive increase in the heating temperature following the method of (Krasa et al., 2005) yielded no self-reversal effect. Thus, a partial remagnetization of three lower flows of the formation at the expense of the heat of the above lying flows is more reasonable now, although the partial remagnetization (some samples are free of the medium-temperature component) of the flows under thermal influence remains unclear.

Up the section, the tuff member of about 30 m thick is characterized by a very noisy noninterpreted paleomagnetic signal.

The low-temperature (20–125°C) and high-temperature (180–570°C) reversed polarity magnetization components of the NRM are positively identified in the basaltic flow, which overlaps the tuff member.

The next five flows up the section are characterized by a noisy paleomagnetic signal, which prevents component analysis. The NRM of the samples from the other 35 flows is mostly a sum of the low-temperature (20–240°C) modern component and high-temperature (300–600°C) characteristic component of reversed polarity (Fig. 2d). The magnetization of samples in the course of the temperature magnetic cleaning mainly drops at 290–400°C.

The detailed magnetic mineralogical studies of the rocks of the formation (Latyshev et al., 2010) showed that titanomagnetite with a Curie temperature from 250 to 400°C is the major magnetic mineral. It occurs as small homogenous dendritic crystals resulting from fast magma cooling.

The average paleomagnetic direction of the formation calculated at the site (flow) levels is shown in Table 2.

Arguments for Primary Age of Magnetization Components

The arguments supporting the primary age of characteristic magnetization components of the studied formation are presented below.

1. Similarity of the virtual geomagnetic poles calculated (judging from the average directions of the distinguished magnetization components) for each formation to the average Permian–Triassic (trap) paleomagnetic pole of the Siberian Platform and their difference from the younger poles (Pavlov et al., 2007) (Table 2).

2. Stable components of normal and reversed polarity with almost antipodal average directions in the sections. The negative result of the reversal test ($\gamma/\gamma_{cr} = 8.5°/3.5°$ (McFadden and McElhinny, 1990), where γ/γ_{cr} are the values of the angular distance and critical angle for the comparable average directions) is related to insufficient averaging of the secular variations of the geomagnetic field in the section (Pavlov et al., 2011).

3. Positive result of the conglomerate test for the Ardygzhan Formation.

4. The primary igneous homogenous titanomagnetite in the Onkuchak Formation (Latyshev et al., 2010).

5. The presence of statistically distinct directional groups in the section (Pavlov et al., 2011).

Thus, there are strong grounds to suggest that the magnetization of the studied rocks is primary and reflects direction of the geomagnetic field in the period of their formation.

DISCUSSION

Magnetic Stratigraphy of Traps of the Kotui River

The magnetostratigraphic scheme of the traps of the Maimecha–Kotui region (see, e.g., Gurevitch et al., 2004) used until recently is based on the data of Gusev et al. (1967). According to this scheme, the lower part of the effusive trap sequence of the Kotui River valley corresponding to the Khardakh, Ary-Dzhang, and Onkuchan formations is magnetized in normal polarity.

Meanwhile, Sidoras (1984) in the 1970s–1980s revealed the period of reversed polarity in the volcanogenic sedimentary rocks of the lowermost part of the Kotui trap section, which lies directly on the coal-bearing Permian rocks and corresponds to the Khardakh Formation.

The results of Sidoras, however, are presented, as far as we know, only in his candidate's dissertation or in inaccessible theses or unpublished reports. Because of this, they were not taken into account in later works on correlation of traps of the Norilsk and Maimecha–Kotui regions (Fedorenko et al., 2000; Gurevitch et al., 2004). Our results allow identification of the period of reversed polarity in a new way on the basis of the modern methods.

Our data allow us again to return to the problem of two formations (subformations) in the structure of the Kogotok Group (Formation) important for the stratigraphy of the Maimecha–Kotui region. On the basis of petrological and geochemical characteristics (Egorov, 1995 and references therein), the Kogotok Formation was subdivided into two subformations: lower, mostly composed of the flows of tholeiitic basalts, and upper, with flows of trachibasalts, trachibasaltic andesites, and andesites. Later, the formation began to be considered as a group and the mentioned subformations became the Onkuchak (lower) and Tyvankit (upper) formations (Fedorenko and Czamanske, 1997). Gusev et al. (1967) also suggested its subdivision into two subformations exclusively from the magnetic polarity of the rocks: the normal and reversed magnetized rocks were ascribed to the lower and upper subformations, respectively. Later, these subdivisions were mixed and the Onkuchak and Tyvankit formations came to be considered as magnetized in normal and reversed polarity, respectively. This mistake is present in the widely cited work of Kamo et al. (2003) on traps of the north of the Siberian Platform. Our petrographic studies show that the Truba section contains no flows of trachibasalts, trachibasaltic andesites, or andesites, which were the base for the Tyvankit Formation (see, e.g., Egorov et al., 1995). So, the Truba section should completely be ascribed to the Onkuchak Formation.

Thus, our data indicate that inversion of the geomagnetic field was synchronous to the accumulation of the lower (Onkuchak) formation of the Kogotok Group and the change in magnetic polarity zones mismatches with the petrological–mineralogical boundary between the Onkuchak and Tyvankit formations.

A transitional paleomagnetic zone corresponding to the interval of a section ~140 m thick and considered as an important magnetostratigraphic marker for the regional correlation was distinguished in the section of the lower part of the Kogotok Group for the Kotui River (Truba section) (Gusev et al., 1967; Gusev, 1970). It should especially be noted that the confirmed transitional zone in this section could be an important limit for duration of its formation, because it was probably related to the inversion of the geomagnetic field and corresponded to the interval of the section which was formed over a period of ten thousand years (Merill et al., 1996). According to Gusev et al. (1967), the transitional zone is characterized by intercalation of normal and reversed magnetized flows and "... the vectors of the remanent magnetization have a gentle declination atypical of the Triassic rocks of the region."

Our studies contradict the presence of the paleomagnetic transition between the normal and reversed polarity zones in the rocks of the lower part of the Kogotok Group of the Truba section. Only a part of the section with a poor paleomagnetic record may be found because of the dominant multidomain titanomagnetite grains (Latyshev et al., 2010) frequently with an unstable paleomagnetic signal.

Thus, our magnetostratigraphic scheme of the traps of the Kotui River valley includes three zones of magnetic polarity. The lowermost zone of reversed polarity is formed by the rocks of the Khardakh Formation and is overlapped by the zone of normal polarity with rocks of the Ary-Dzhang Formation and the lower parts of the Onkuchak Formation. The section is crowned by the reversed polarity zone with the rocks of the upper part of the Onkuchak Formation.

Magnetic Stratigraphy of the Norilsk Tuff and Lava Sequence

It should be noted that the current data rather definitely point only to two zones of magnetic polarity in the magnetostratigraphic section of the Norilsk lava sequence. The greater part of the Ivakinsk Formation corresponds to the reversed polarity zone in the basement of the section. All above-lying formations (Syverma, Gudchikhi, Khakancha, Tuklon, Nadezhda, Morongo, Mokulai, Kharaelakh, Kumga, Samoedskaya) are magnetized in normal polarity (Gurevitch et al., 2004; Heunemann et al., 2004).

Lind et al. (1994), however, suggest the presence of short-term periods of reversed polarity in the Morongo and Samoedskaya time.

In case of the Samoedskaya Formation, this conclusion is supported by two reversely magnetized lava flows found in the section of the Verkhnyaya Talovaya River. Judging from the magnetic mineralogy of these flows, Lind et al. (1994) cast doubts that the reversed magnetization does reflect the polarity of the geomagnetic field during their eruption. The fact that the rocks underwent only limited magnetic cleaning during analysis of the reversed polarity strengthens these doubts. The absence of flows with reversed polarity in the section of the Samoedskaya Formation studied by Gurevitch et al. (2004) convinces us of a poorly substantiated period of reversed polarity in the Samoedskaya time.

The presence of the reversed polarity period in the Morongo time is based on the reversed polarity of the Lower Talnakh intrusion, which presumably has the same age as the Morongo lavas, which is deduced from their similar petrological and geochemical characteristics (Lind et al., 1994). Taking into account that such a similarity is a weak argument in favor of the same age and the further works lacked support of the presence of the reverse polarity zones in the Morongo Formation, we concluded that the periods of the reversed polarity in the Morongo time are also insignificantly substantiated.

In 2012, we sampled the rocks of the Samoedskaya Formation in the Verkhnyaya Talovaya River valley and Morongo Formation in the Mokulai Stream valley. Their analysis will allow us to test in the immediate future the presence of the reversed polarity field in the Morongo and Samoedskaya times. Currently, the data on possible reversed polarity zones in the sections of these formations are considered as unsubstantiated and are ignored from our reconstructions.

Because of the low reliability, we also ignore the data which indicate the presence of several zones of reversed polarity in the upper part of the Norilsk trap sequence (Gurevitch et al., 2004; Mikhal'tsov et al., 2012). They were distinguished from the paleomagnetic data on one or two drill core samples and, as honestly reported by Gurevitch et al. (2004), may be a consequence of error of the drill core orientation.

The results of Heunemann et al. (2004) give grounds to assume that the geomagnetic field began to modify its polarity in the Ivakinsk time; however, the data are not sufficient to confirm this. Meanwhile, the answer to this question will provide additional important limitations on duration of the formation of the section.

Correlation Scenarios of the Norilsk and Kotui Trap Sections

The possible correlation scenarios of these sections are shown in Fig. 3 and discussed below.

Scenario 1 suggests that the normal polarity zone corresponding to the entire Norilsk section (excluding

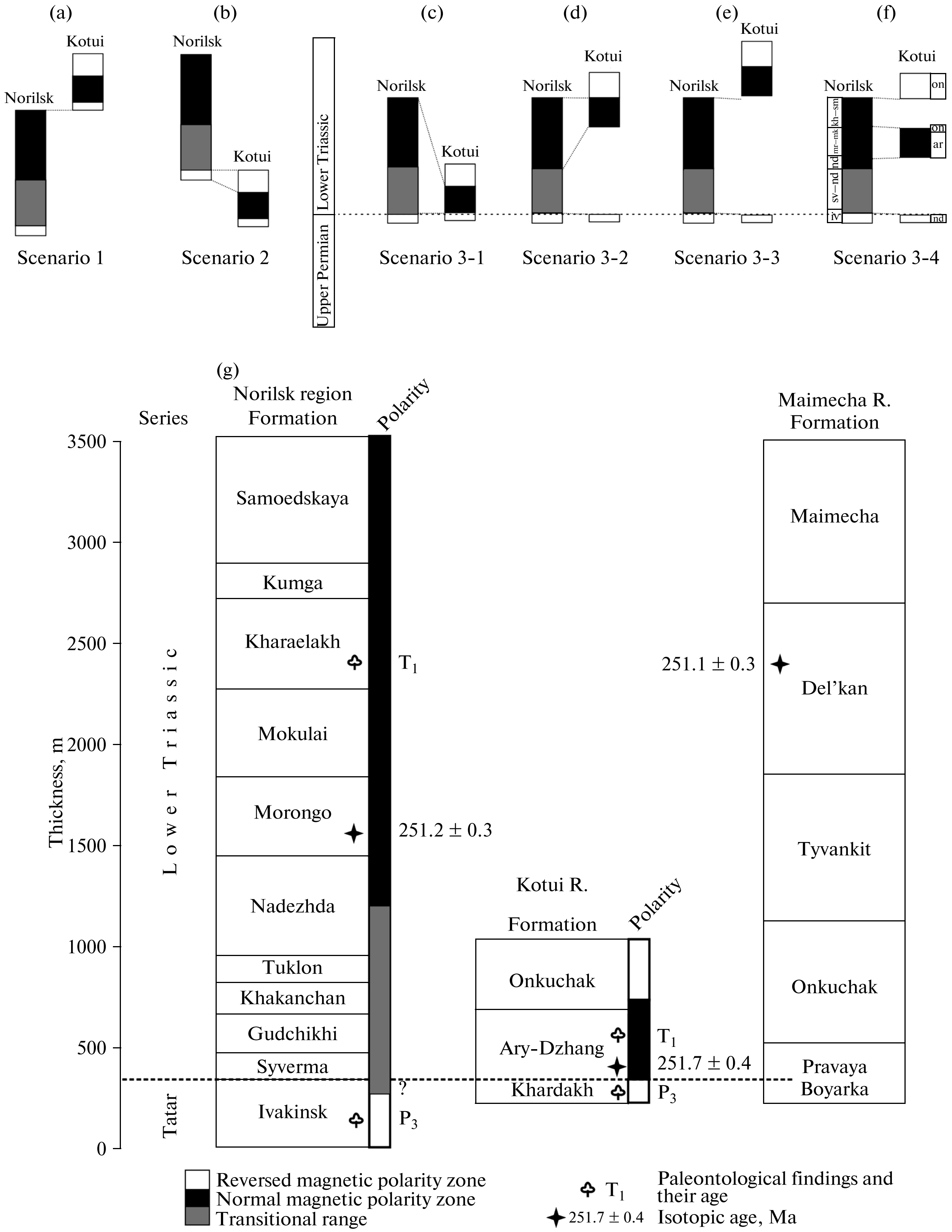


Fig. 3. Discussed correlation scenarios of the trap sections of the Norilsk and Maimecha–Kotui regions on the basis of paleomagnetic, geochronological, and paleontological data (a–f) and scheme of factual material (magnetic polarity, isotopic ages, paleontological determinations) of the reviewed sections (g).

the Ivakinsk Formation) is older than the reversed polarity zone of the Khardakh Formation of the Kotui section (Fig. 3a). The geochronological data of Kamo et al. (2003) are in agreement: varying the isotopic ages within the corresponding confidence intervals, the age of the Morongo Formation of the Norilsk region and of the Ary-Dzhang Formation of the Kotui region may be accepted as 251.5 and 251.3 Ma, respectively. The duration of the reversed polarity period corresponding to the Khardakh Formation will be a maximum of 200 k.y. (if the normally magnetized rocks of the upper parts of the Norilsk section were formed just after the Morongo Formation).

A similar correlation suggested by Steiner (2006) was based on comparison of the relative durations of magnetic zones in the Siberian trap sections and in the global Permian–Triassic scale of magnetic polarity (Fig. 4a).

This scenario, however, contradicts the paleontological data. The age of the Khardakh Formation of the Kotui section is Late Permian on the basis of the spore–pollen analysis (Ivanov and Pirozhnikov, 1959). If the entire Norilsk section is older than the Maimecha–Kotui section, then it should be completely Permian. This, however, conflicts with findings of the Lower Triassic sinapsids (theropsids) in the Kharaelakh Formation of the Norilsk section (Fedorenko et al., 1996).

Such a correlation evidently contradicts the modern determinations of the Permian–Triassic boundary (252.6 ± 0.2 Ma; Metcalfe and Isozaki, 2009).

Scenario 2 assumes that the entire Kotui section is older than Norilsk one (Fig. 3b). In this case, the upper zone of the reversed polarity of the Kotui section should be older than the reversed polarity zone of the Ivakinsk Formation of the Norilsk region or have the same age. The geochronological data make possible this correlation. In this case, the formation of the Maimecha–Kotui and Norilsk sections is separated by less than 500 k.y. if we accept (within the confidence interval of determination) the age of the Morongo Formation of 250.9 Ma and the age of the Del'kan Formation corresponding to the reversed polarity zone of the Maimecha–Kotui section of 251.4 Ma (Kamo et al., 2003). On the basis of flora and pelecypods (bivalvia), the Ivakinsk Formation of the Norilsk region, however, belongs to the Late Permian (*Ob"yasnitel'naya...*, 2000). Consequently, the entire Kotui section should be no younger than the Late Permian, which contradicts the findings of the Early Triassic phyllopods (branchiopods) in the Ary-Dzhang Formation (Ivanov et al., 1959) and also the above-given age of the Permian–Triassic boundary.

Such a correlation was previously reviewed by Gurevitch et al. (2004) (Fig. 4e, scenario B), who supported the Ar–Ar age of Basu et al. (1995) and also probably the "older" position of the Maimecha–Kotui paleomagnetic pole in comparison with Norilsk (Gurevitch et al., 2004, p. 224).

The modern U–Pb isotopic ages (Kamo et al., 2003), however, refute the arguments of the Ar–Ar age (Basu et al., 1995). The position of the paleomagnetic poles may hardly be used for determination of the relative age, because the Late Paleozoic and Early Mesozoic segments of the curve of apparent migration of the paleomagnetic pole of the Siberian Platform to date remain insufficiently elaborated.

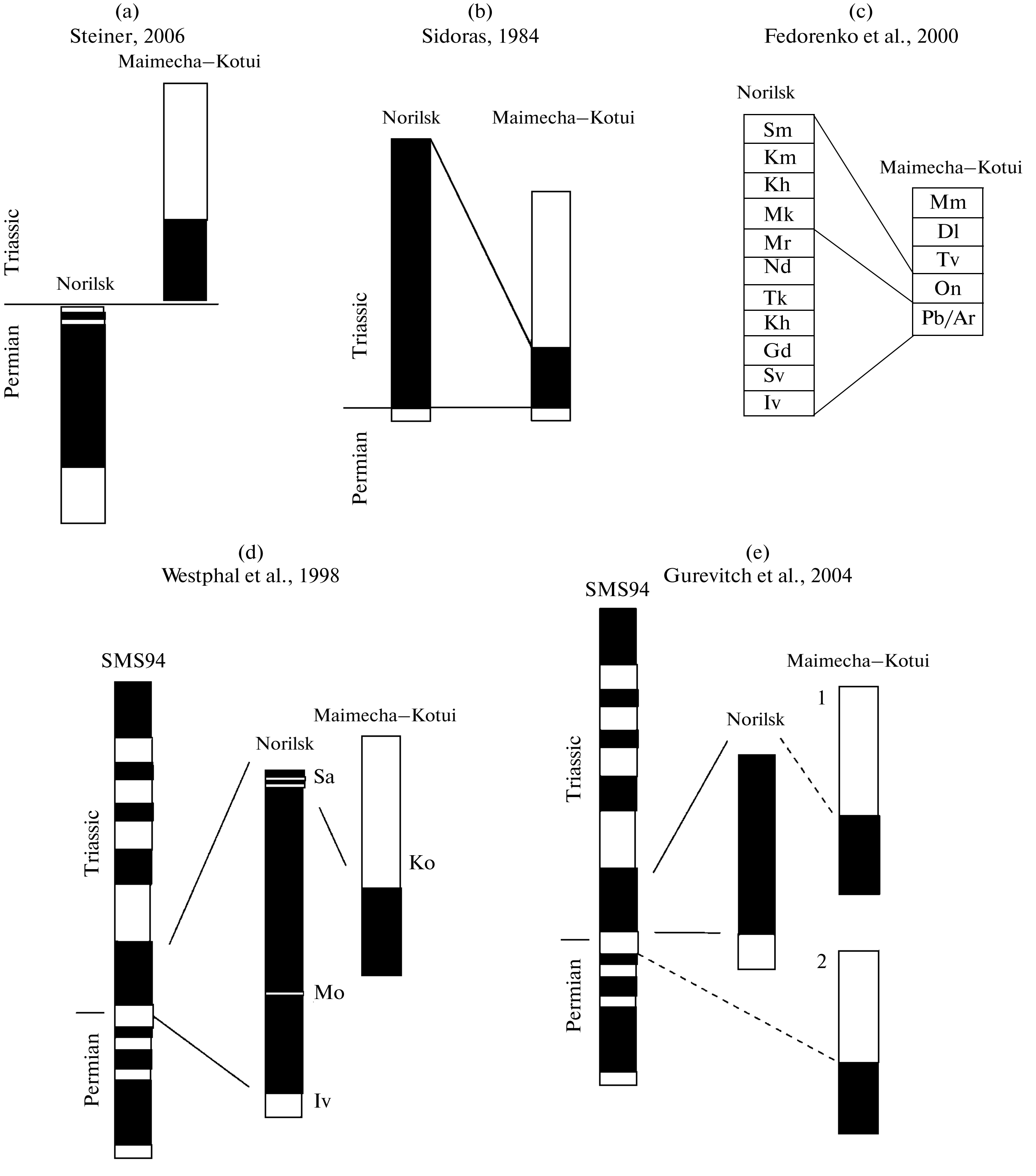
Scenario 3 assumes that formation of the Norilsk and Maimecha–Kotui sections partly overlaps. A similar correlation was reviewed by Sidoras (1984), Westphal et al. (1998), Fedorenko and Czamanske (1997), Fedorenko et al. (2000), and Gurevitch et al. (2004) (Figs. 4b–4d).

First of all, the magnetostratigraphic data do not admit a complete temporal overlapping of these sections. This is evident from two and three (at least) zones of magnetic polarities recorded in the Norilsk and Maimecha–Kotui sections, respectively (Fig. 3g). In the Talnakh, Listvyanka, and Ikon trap sections of the Norilsk region, Heunemann et al. (2004) and Gurevitch et al. (2004) distinguished a rather strong inversion–excursion period between the stable zones of reversed (greater part of the Ivakinsk Formation) and normal (section over the middle levels of the Nadezhda Formation) polarity, which corresponds to inversion and subsequent digression of the geomagnetic field (Fig. 3g). It was recently shown (Pavlov et al., in press) that this period is also present in the Sunduk and Ergalakh sections of the Norilsk region.

Our studies miss such a transition in the Kotui section. This definitely indicates that the complete temporal analogs of the upper parts of the Ivakinsk, Syverma, Gudchikhi, Khakanchan, and Tuklon formations and a significant part of the Nadezhda Formation in the Kotui section are absent or reduced to a thin interval corresponding to the poorly exposed and, thus, unstudied transition between the Khardakh and Ary-Dzhang formations. This means that, during the intense eruptions in the Norilsk region, which formed the greater part of the lower formations of the trap sequence, no significant volcanic activity is registered in the Maimecha–Kotui region.

No current data could contradict the same age of the Khardakh and Ivakinsk formations: both of them are magnetized in reversed polarity and contain the Late Permian fauna. Thus, as a working scenario, we suggest the direct age comparison of these stratigraphic subdivisions (Figs. 3c–3f). Their geochemical composition is distinct: the Ivakinsk Formation includes the normal alkaline lavas and subalkaline rocks in contrast to the alkali–ultramafic tuffs in the Khardakh Formation.

We should also pay attention to the fact that the absence of the transitional interval in the lower part of



(a) Steiner, 2006

(b) Sidoras, 1984

(c) Fedorenko et al., 2000

(d) Westphal et al., 1998

(e) Gurevitch et al., 2004

Fig. 4. Current scheme of correlation of traps of the Norilsk and Maimecha–Kotui regions. SMS94, summarized magnetostratigraphic scale (Steiner et al., 1994). Formations of the Norilsk region: Iv, Ivakinsk; Sv, Syverma, Gd, Gudchikhi; Kh, Khakanchan; Tk, Tuklon; Nd, Nadezhda; Mr, Morongo; Mk, Mokulai; Kh, Kharaelakh; Km, Kumga; Sm, Samoedskaya. Formation of the Kotui section: Pb, Pravaya Boyarka; Ar, Ary-Dzhang, On, Onkuchak; Tv, Tyvankit; Dl, Del'kan; Mm, Maimecha.

the normal magnetized Kotui section points to a break of unknown duration (longer than the time necessary for geomagnetic inversion (~10000 years)) in its basement. If this is so, then the Late Permian Khardakh Formation could be older than the Ivakinsk Formation of the Norilsk region.

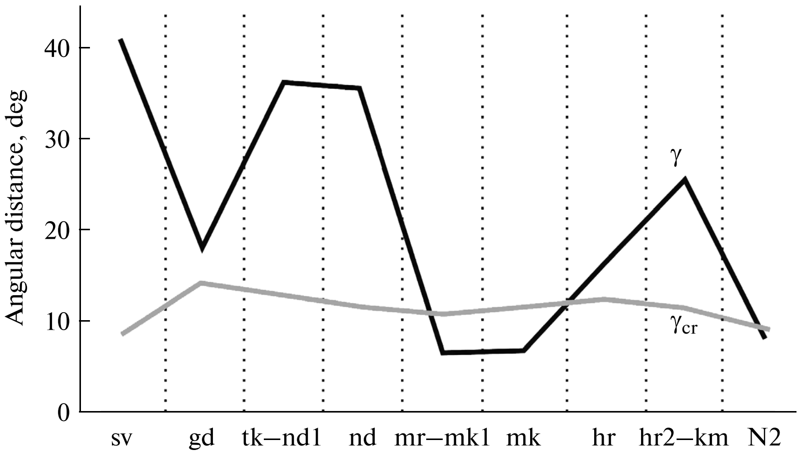


Fig. 5. Distance (γ) between virtual geomagnetic poles of formations of the Norilsk region (initial data (Gurevitch et al., 2004; Heunemann et al., 2004)) and the pole for the period of normal polarity of the Maimecha–Kotui region (Pavlov et al., 2011). γ_{cr}, critical angle (McFadden and McElhinny, 1990). Formations: sv, Syverma, gd, Gudchikhi; tk, Tuklon; nd, Nadezhda; mr, Morongo; mk, Mokulai; kh, Kharaelakh; km, Kumga; N2, normally magnetized part of the Norilsk section.

One important circumstance hampers the possibility of the older age of the Ivakinsk Formation. Judging from data of Heunemann et al. (2004) for the Talnakh section, the transitional period began at the end of the Ivakinsk time after the period of reversed polarity and continued until the stable regime of normal polarity in the middle–end of the Nadezhda time. This indicates the absence of significant breaks in the lower parts of the Norilsk section and prevents the separation of the mostly reversely magnetized Ivakinsk Formation from the above-lying normal magnetized formations. This conclusion is true if the transitional interval began in the Ivakinsk time, which requires additional verification.

It is reasonable to compare the normaly magnetized interval of the Kotui section with normaly magnetized rocks of the Norilsk region.

Fedorenko and Czamanske (1997) correlated the entire Norilsk lava section with the Ary-Dzhang (considered as an age analog of the Pravaya Boyarka Formation) and Onkuchak formations of the Maimecha–Kotui region. The latter formation corresponds to the Mokulai–Samoedskaya part of the Norilsk sequence (Fig. 4c).

Our data allow significant refinement of this scheme.

First of all, only a small (lower) part of the Onkuchak Formation is magnetized in normal polarity. So, the entire formation can be compared neither with the Mokulai–Samoedskaya level nor with any part of the Norilsk section.

We suggest correlation of the entire Ary-Dzhang Formation and the lower parts of the Onkuchak Formation with the normaly magnetized part of the Norilsk section. Taking into account the presence and the absence of the transitional period in the Norilsk and Kotui section, respectively, the Ary-Dzhang Formation and the lower part of the Onkuchak Formation should be compared with the upper part of the Norilsk section, beginning from the middle–upper parts of the Nadezhda Formation (Fig. 4d).

The average poles calculated by the directional groups and individual directions for these intervals of the Kotui and Norilsk section (Plat = 51.9°, Plong = 130.7°, $\alpha95 = 4.8°$ and Plat = 56.5°, Plong = 142.2°, $\alpha95 = 7.8°$, respectively; Pavlov et al., 2011) are relatively close ($\gamma/\gamma_{cr} = 8.1°/8.7°$) (Fig. 5). On the other hand, the comparison of the virtual geomagnetic poles of the normaly magnetized lava formations of the Kotui (Ary-Dzhang Formation and the lower part of the Onkuchak Formation) and Norilsk sections (Fig. 5) shows that the poles only of the Morongo and Mokulai formations are similar to the Kotui pole ($\gamma/\gamma_{cr} = 6.3°/10.7°$ and $6.4°/11.1°$, respectively).

This allows us to suggest the correlation of the Kotui period of normal polarity with the Morongo–Mokulai level of the Norilsk section (Fig. 3f).

The suggested correlation scheme contradicts the hypothesis that the lavas similar in chemical composition erupted synchronously. The Ary-Dzhang Formation, which is composed of ultramafic lavas and alkali basalts, in our scheme does correlate with the tholeiitic basalts of the upper part of the Norilsk section. Although the hypothesis of the close age of similar lavas is widely applied for correlation of the volcanic sections (see, e.g., Kamo et al., 2003), it continues to remain only a hypothesis, which should be verified.

The above-reviewed three scenarios do not exhaust all modifications of the correlation scheme of traps of the Norilsk and Maimecha–Kotui regions. One of the possible scenarios of the age comparison of the Norilsk and Kotui sections is that the entire section, excluding the Khardakh Formation, may be younger than the Norilsk section, taking into account the break of unknown duration in the lower parts of the Kotui section (Fig. 3e). This scheme is also in agreement with geochronological, paleontological, and magnetostratigraphic data. The only argument against such a correlation is a similarity of the Ary-Dzhang and Morongo–Mokulai poles.

Thus, several reviewed correlations, including those previously discussed in the literature, contradict the available data, and only one scenario implying partial (but probably in various modifications) overlapping in time of the discussed sections is consistent with them.

CONCLUSIONS

Below, we provide the major results of our magnetostratigraphic studies.

(1) The magnetostratigraphic section of the effusive traps of the Kotui River valley is based on the modern methods.

(2) The presence of the reversed polarity zone corresponding to the Khardakh Formation is argued for the basement of the trap section of the Kotui River valley.

(3) Inside the Kogotok Group, the boundary between the normal and reversed polarity zones occurs in the lower part of the Onkuchak Formation and mismatches the boundary between the formations of the Kogotok Group as is accepted in (Gusev et al., 1967; Fedorenko and Czamanske, 1997; Kamo et al., 2003).

(4) The record of transition between the normal and reversed polarity zones in basalts of the lower parts of the Onkuchak Formation lacks support from our study.

(5) The strong transitional period between the Ivakinsk Formation and the upper parts of the Nadezhda Formation of the Norilsk section (Heunemann et al., 2004; Pavlov et al., in press) has no analog in the Kotui section.

(6) The analysis of possible correlations of the Norilsk and Maimecha–Kotui sections indicates their partial temporal overlapping. The Ivakinsk and Khardakh formations (the lower parts of the section) are confidently correlated, whereas the upper parts of the section may be variously compared, e.g., partial overlapping (scenario 3-2, Fig. 3) or expansion of the Norilsk section by the Kotui one (scenario 3-3, Fig. 3). The available data support the correlation of the Ary-Dzhang Formation and the lower parts of the Onkuchak Formation of the Maimecha–Kotui section with the Morongo–Mokulai level of the Norilsk section (scenario 3-4, Fig. 3).

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