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Paleomagnetism of the Trap Intrusive Bodies in Arctic Siberia: Geological and Methodical Implications

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Abstract—New paleomagnetic data are reported for the dikes, sills, and lava flows in the Arctic part of the Siberian Platform, which has not been covered by previous systematical paleomagnetic investigations. The analysis of the newly obtained and previously published data provides important time constraints for the duration and character of evolution of the Permian–Triassic magmatic events in the studied regions. Our results once again illustrate the conclusion that, in order to obtain an exact estimate for the location of the paleomagnetic pole in the northern paleolatitudes, at least 30–40 rapidly cooled magmatic bodies (dikes, flows, or minor sills) should be sampled if secular variation is commensurate with the intensity of the present-day variations.

Keywords: Siberian Platform, traps, Permo–Triassic, paleomagnetism, secular variation

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INTRODUCTION

Despite more than fifty years of research, the Permo–Triassic traps of the Siberian Platform are still studied very nonuniformly. Not surprisingly, the paleomagnetic studies mainly covered the thick effusive trap formations within two major trap provinces, the Norilsk and the Maymecha–Kotuy. However, the trap magmatism in other regions was studied only occasionally, often in addition to the primary targeted survey activities. Meanwhile, the paleomagnetic information concerning the effusive and intrusive trap formations from different parts of the Siberian Platform is necessary for solving a wide range of problems, including refining the position of the Permo–Triassic paleomagnetic pole of the Siberian platform; studying the geometry of the geomagnetic field at the boundary between the Paleozoic and Mesozoic eras; exploring the possibility of spatial migration of the magmatic centers; obtaining the time constraints for the duration of Permo–Triassic magmatism in local regions and over the platform overall; and a number of problems in geological mapping.

In this paper, we present paleomagnetic data on the dikes, sills, and, to a far smaller degree, effusive trap formations of Permo–Triassic age located on the Arctic margin of the Siberian Platform, which have not been previously covered by systematic paleomagnetic investigations.

THE OBJECTS OF THE STUDY

Kotuy River Basin. The object of the paleomagnetic studies here was Permo-Triassic intrusive bodies (dikes and sills) (*Gosudarstvennaya...*, 1978) located in the basins of the Kotuy and Kotuykan rivers and left tributaries of the Kotuykan river (Dzhogdzho and Il'ya rivers) (Fig. 1a and 1b). The composition and structure of the dikes sharply differ: dolerite dikes are largely subvertical and rather thick (5–30 m), while the dikes of alkaline composition are thin (at most a few meters in thickness) and geometrically intricate, having lots of knee-like twitches. The studied dikes and sills are intruded into subhorizontal sedimentary deposits ranging from the Riphean to Upper Permian in age. The geochronological data for the studied rocks are absent. Overall, 233 samples were acquired.

In the lower reaches of the Maymecha River, in the mouth of the Delkan River (Fig. 1c), the alkali lamprophyres that compose a dike-in-dike structure were sampled. According to (*Gosudarstvennaya...*, 1996), this structure comprises more than 40 minor thin semidikes, which have baked zones (1–5 cm thick) and uniform composition. On one hand, the presence of the contact zones indicates that the earlier dike had solidified before the intrusion of the younger dike; i.e., the injections of new portions of magma were somewhat separated in time. On the other hand, the similar composition of the dikes suggests that the magma had not experienced evolution, which is most likely to

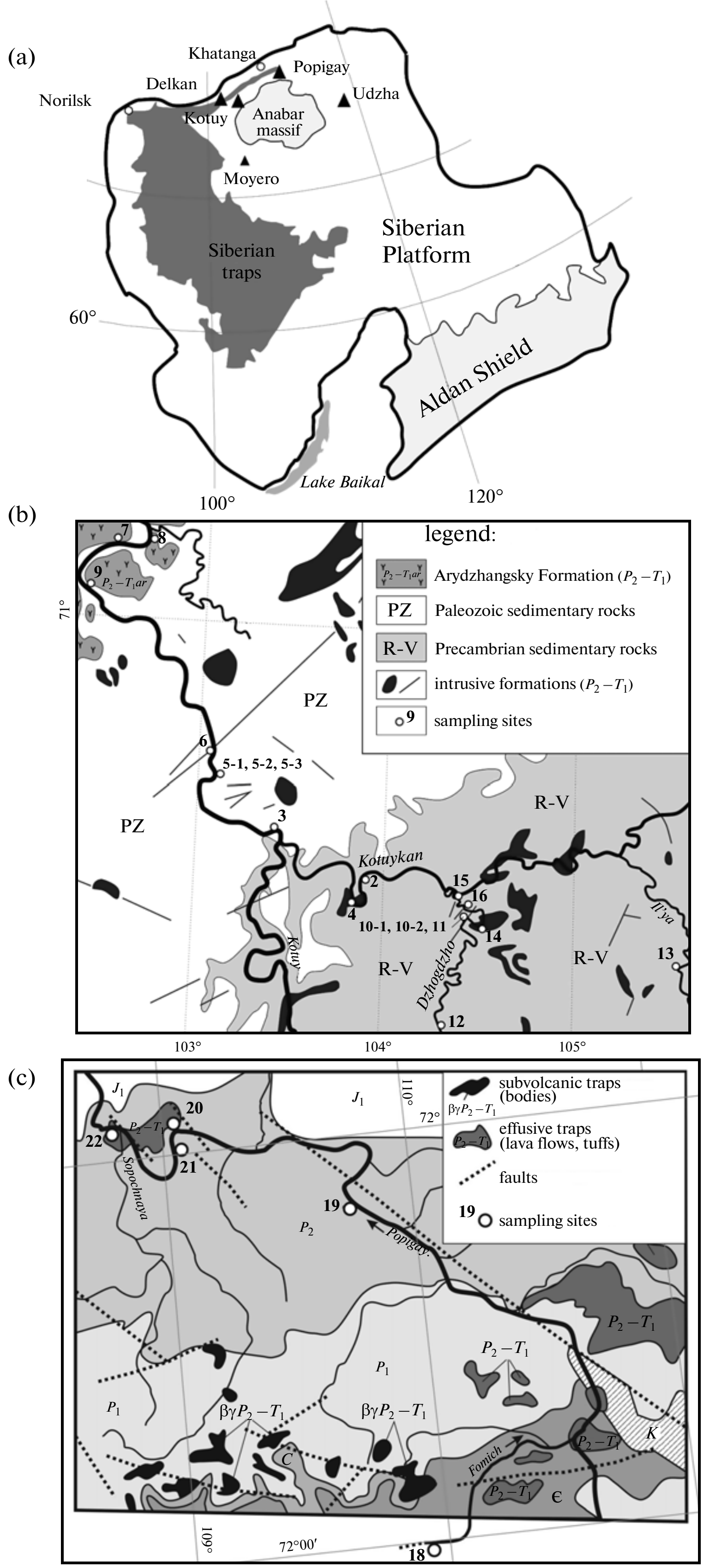


Fig. 1. The objects of the study: (a) the geographical position of the study regions (Kotuy, Delkan, Popigay, Udzha) and the region of Moyero River (Pavlov et al., 2007); (b) the location of the studied intrusive bodies in the geological scheme of the Kotuy River basin; (c) the studied intrusive bodies in the basin of Popigay and Fomich rivers.

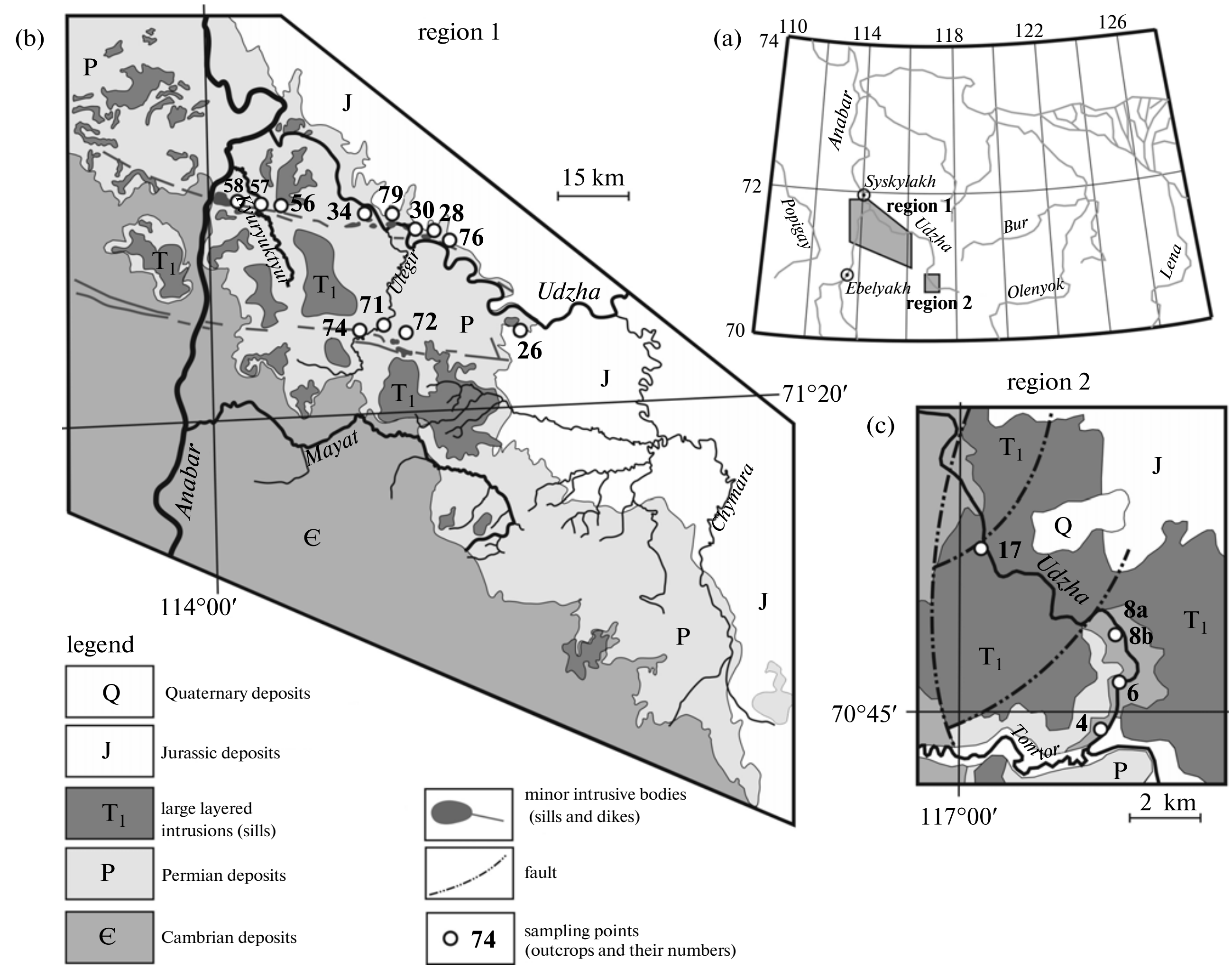


Fig. 2. The objects of the study in the basin of the Udzha River: (a) the geographical position of segments 1 and 2; (b, c) the location of the studied magmatic bodies in the geological scheme of sections 1 and 2, respectively.

show that the entire structure was formed within a short time interval.

Twenty sequentially lying semidikes, each with a thickness of at most 70 cm, were sampled for 100 oriented samples. The contact planes of the dikes are inclined: the dip azimuth is 60°NE with an average dip angle of 75°, which agrees with the bedding of the lavas of the Maymecha Formation and the underlying Delkan Formation intruded by these dikes. Assuming the dikes to be initially vertical, we used these values for recalculating the obtained paleomagnetic directions into the stratigraphic (ancient) coordinates.

The studied dikes relate to the formations of the Ust'-Delkan complex (*Gosudarstvennaya...*, 1996) and can be considered as the youngest magmatic units of Maymecha–Kotuy province as they cut through carbonates corresponding to the latest phase of intrusion of the Gulinsky pluton (*Gosudarstvennaya...*, 1996), which are dated at 250.2 ± 0.3 Ma, according to the isotopic geochronological data (Kamo et al., 2003).

Popigay River Basin. For paleomagnetic study of the rocks in the lower reaches of the Popigay River and its left tributary (Fomich River) (Figs. 1a and 1c), we sampled two dikes composed of basic rocks with a thickness of 70 cm and 5 m, which cut the horizontally bedding Cambrian carbonates. Besides, basaltic lava flows from three exposures in the region of the village of Sopochnoe were sampled. From each flow, having a thickness of at most 8 m, up to five samples were taken. Overall, 66 samples were acquired.

Udzha River Basin (Fig. 1a). We sampled the subvolcanic traps from two regions (Fig. 2a). In region 1, located on the eastern wall of the Anabar uplift in the lower reaches of Udzha River from the mouth of the Chymara River to the Anabar River (Fig. 2b), dolerites from the Udzha sill (ourcrops 26, 34, 58, 58', 72, 74, and 79) and alkaline basic rocks from the Ebekhain intrusive complex (Tomshin et al., 1997) (trachidolerites from outcrops 28, 30, 56, and 76, trachiandesites from outcrop 71, and monzonite-porphyries from outcrop 57) were studied. The field observations showed that the samples from outcrop 58' represent the contact zone of intersection of the dolerite sill by the trachidolerite dike. Region 2 within the Biliro–Udzha Uplift is located in the upper reach of the Udzha River, in the mouth of its left tributary, the Tomtor River (Fig. 2c). Here, dolerites from the Verkhne-Udzha intrusion were studied (four dikes from outcrops 4, 6, 8a, and 8b and the sill from outcrop 17, which pierce the terrigenous carbonate rocks of the Tomtor Formation of the Vendian age and are overlain with erosion by subhorizontal Pliensbachian deposits of the Upper Jurassic age. According to the Ar/Ar dating of the plagioclase monofraction, the age of the dolerites is estimated at 245–232 Ma (Konstantinov et al., 2009). Overall, 172 samples were acquired.

PALEOMAGNETIC ANALYSIS

The Procedure of Paleomagnetic Analysis

The samples for paleomagnetic collection were selected by hand, and their spatial orientation was determined with the aid of a geological compass. Each geological object (a dike, sill, or lava flow) was sampled at one site, and from each site, 10 to 25 oriented hand samples were acquired. From each hand sample, a cubic specimen with a side of 1 or 2 cm was then sawn by a rock-cutting machine.

The laboratory paleomagnetic experiments were conducted at the Institute of Physics of the Earth of the Russian Academy of Sciences in Moscow, at the Rock magnetic laboratory at the Geological faculty of Lomonosov Moscow State University, and in the Specialized geological party for petrophysical research at the ALROSA Amakinskaya exploration expedition in Aikhal settlement. The standard procedure of paleomagnetic analysis was applied (Zijderveld, 1967; Khramov et al., 1982; Shipunov, 1999; McFadden, 1988; McFadden and McElhinny, 1990; Torsvik et al., 1990). All samples were subjected to detailed thermal cleaning up to a temperature of 580–630°C. The collection of traps from the Udzha River basin was additionally subjected to demagnetization in an alternating magnetic field of up to 100 mT. During thermal cleaning, the specimens were arranged at random within the furnace chamber. The cleaning cycle normally included at least 12 steps; in some cases, the degree of the detail of the cleaning was increased. Demagnetization of the samples was carried out in nonmagnetic furnaces TD-80 (Magnetic Measurements Ltd., Great Britain) and TD-48 (ASC, USA); the alternating-current Molspin AF-Demagnetizer (Great Britain) was also used, which ensures the uncompensated field of at most 5–10 nT. The remanent magnetization of the samples was measured by the JR-4, JR-5, and JR-6 AGICO spinner magnetometers manufactured in the Czech Republic.

During the procedure of demagnetization, the samples were shielded from the external magnetic field. The measurement data were processed by the software designed by Enkin (1994), where isolation of the magnetization components is conducted by the PCA (principal component analysis) technique (Kirschvink, 1980). The parameters of secular variation were calculated using the programs developed by Tauxe (2010). The term “secular geomagnetic variation” is further understood as the changes in the direction of the geomagnetic field due to secular variation.

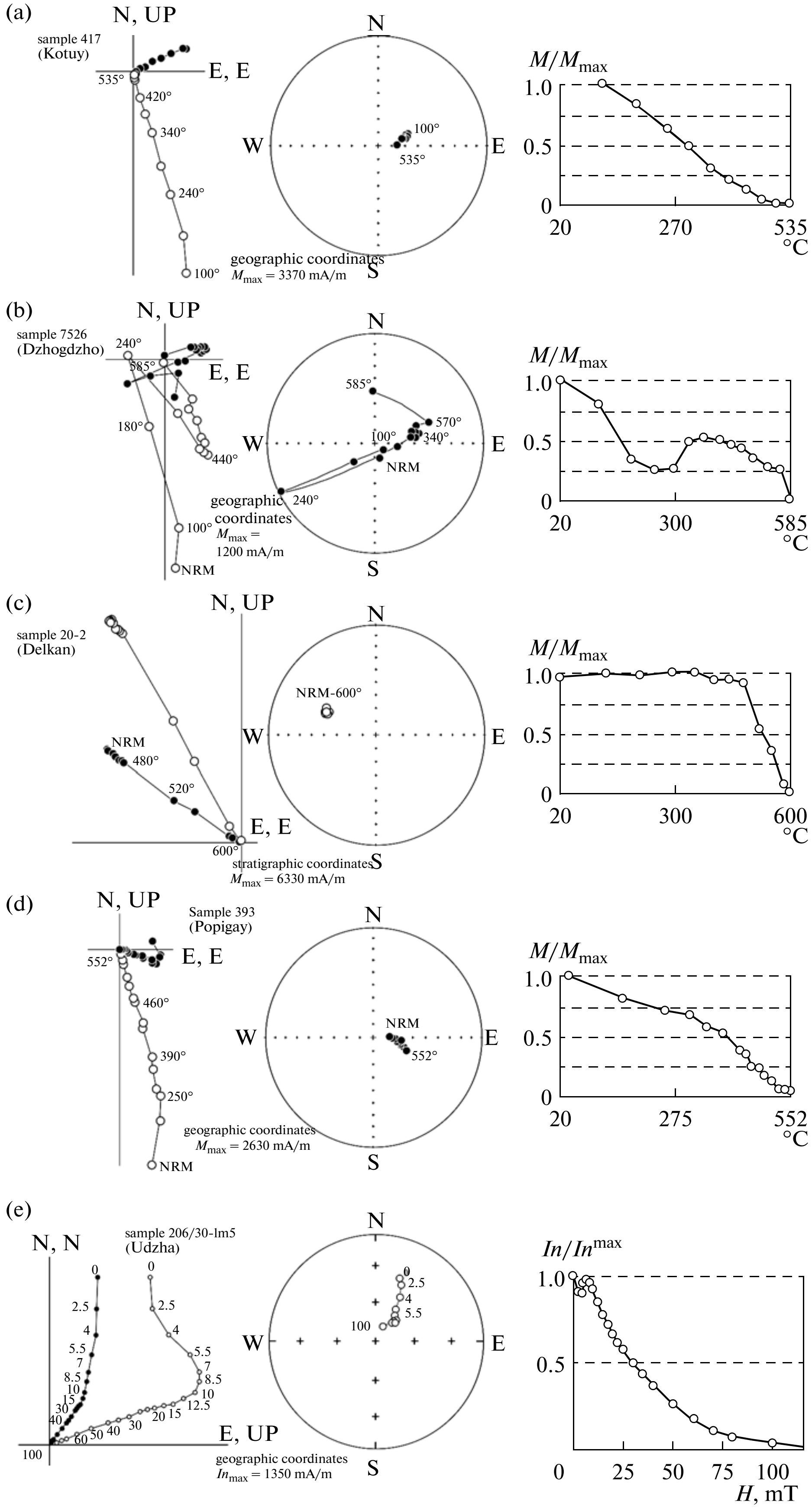
The Results of Paleomagnetic Measurements

Since the original bedding of the studied geological objects is not violated in all sampling sites except for the mouth of the Delkan River, the paleomagnetic data for these objects are presented in the geographic coordinates coinciding with the stratigraphic coordinates.

The Kotuy River Basin. The thermal demagnetization showed that a high-quality paleomagnetic signal is recorded in most of the studied samples. In addition to the recent low-temperature viscous remanent magnetization (VRM) component (20–180°C), natural remanent magnetization (NRM) also contains the high-temperature (180–600°C) characteristic component (ChRM) of normal (Fig. 3a) and reversed polarity. The high-temperature reversed-polarity component is identified in two studied objects (dike 6 and sill 11); other intrusions are found to only contain the magnetization of normal polarity. The directions of the revealed magnetization components for all the studied bodies are shown on the stereogram in Fig. 4a and presented in Table 1.

The primary character of the high-temperature magnetization component identified in the samples is testified by its positive baked contact test. In the samples from the outcrop on the left bank of the Dzhogdzho River (Fig. 1b), the NRM vector of two neighboring dikes 10-1 and 10-2, besides the high-temperature component with normal polarity typical of the most intrusive bodies across this territory, also contains the intermediate-temperature (240–440°C) component with reversed polarity (Fig. 3b). The direction of this magnetization component ($D = 283.2$, $I = -82.5$, $K = 91$, $\alpha95 = 5.8$, $N = 8$) does not statistically differ ($\gamma/\gamma_{cr} = 3.9/8.3$) from the direction of the high-temperature magnetization component of sill 11 (Table 1), which cuts these dikes.

Maymecha River Valley, the mouth of the Delkan River. The paleomagnetic record in the samples is perfectly preserved. The NRM predominantly contains a single, the most stable characteristic magnetization component of reversed polarity in the temperature interval of 20–590°C (Fig. 3c). Few samples contain overprints of recent viscous remanent magnetization component in the low-temperature interval (20–180°C). Judging by their unblocking temperatures


(a)
N, UP
sample 417
(Kotuy)
E, E
535°
420°
340°
240°
100°
N
W
E
S
100°
535°
geographic coordinates
M_{max} = 3370 mA/m
M/M_{max}
1.0
0.5
0
20
270
535
°C
(b)
N, UP
sample 7526
(Dzhogdzho)
240°
585°
E, E
180°
440°
100°
NRM
N
W
E
S
585°
570°
100°
340°
NRM
240°
geographic coordinates
M_{max} =
1200 mA/m
M/M_{max}
1.0
0.5
0
20
300
585
°C
(c)
N, UP
sample 20-2
(Delkan)
NRM
480°
520°
600°
E, E
N
W
E
S
NRM-600°
stratigraphic coordinates
M_{max} = 6330 mA/m
M/M_{max}
1.0
0.5
0
20
300
600
°C
(d)
N, UP
Sample 393
(Popigay)
E, E
552°
460°
390°
250°
NRM
N
W
E
S
NRM
552°
geographic coordinates
M_{max} = 2630 mA/m
M/M_{max}
1.0
0.5
0
20
275
552
°C
(e)
N, N
sample 206/30-lm5
(Udzha)
0
2.5
4
5.5
7
8.5
10
12.5
15
20
30
40
50
60
100
E, UP
N
W
E
S
0
2.5
4
5.5
100
geographic coordinates
In_{max} = 1350 mA/m
In/In^{max}
1.0
0.5
0
25
50
75
100
H, mT

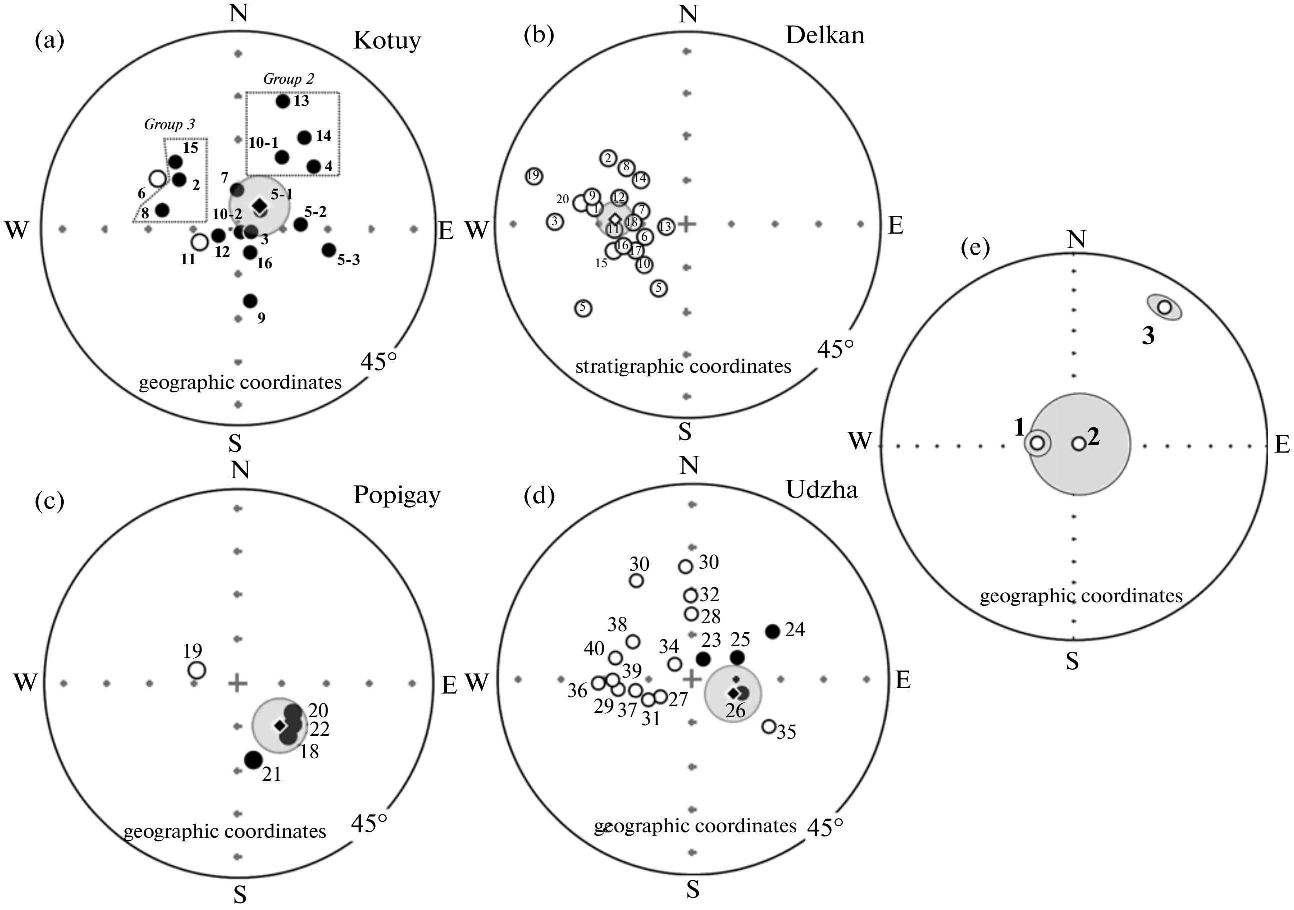


Fig. 4. The stereograms showing the distribution of average magnetization directions of the studied intrusive bodies in the basins of (a) Kotuy River; (b) Delkan River; (c) Popigay River; and (d) Udzha River. For notations, see Fig. 3. The diamond marks the position of the average paleomagnetic direction for the considered region with a circle pf 95% confidence (gray area); (e) the stereogram illustrating the positive baked contact test (average directions of magnetization for the Verkhne-Udzhinskii intrusion (**1**), exocontact (**2**), and Kotuy–Olenek sedimentary complex (**3**), see the text.)

(450–600°C), the magnetization of the studied samples is mainly carried by titanomagnetite and magnetite.

The average direction of the characteristic magnetization of the semidikes in the mouth of Delkan River has a reversed polarity and is located in the area of the expected (Pavlov et al., 2007) trap directions (Table 1, Fig. 4b) on the stereogram (in stratigraphic coordinates). The statistically significant difference in the average paleomagnetic directions of the neighboring dikes indicates that the older dikes have not been remagnetized by the younger dikes. The latest remagnetization is also unlikely, which testifies to the primary character of the high-temperature magnetization component in these objects.

Popigay River. The paleomagnetic record in the studied magmatic objects contains two components. The less stable magnetization component is removed in the temperature interval of 20–210° and is close to the direction of the present-day magnetic field, which indicates its recent formation probably due to the magneto-viscous processes; the most stable characteristic magnetization component is removed in the interval of 180–590°C (Fig. 3d). Four of the five studied bodies have a characteristic component with a steep positive inclination and one dike is characterized by negative inclination. The identified directions of normal and reversed magnetization form a compact cluster on the stereogram (Fig. 4c) (with flipped directions of reversed polarity).

Udzha River. The high-temperature and high-coercivity (characteristic) NRM vector components are identified in almost all the studied samples, starting

Fig. 3. The typical Zijderveld diagrams, stereograms, and demagnetization curves for the samples of the studied intrusive bodies. The filled circles on the Zijderveld diagrams (stereograms) show the projections of the vectors on the horizontal plane (the lower hemisphere); the open circles show the projections of the vectors on the vertical (the upper hemisphere).

Table 1. The paleomagnetic directions

Point, description	Coordinates		*N*/*n* (*S*)	Paleomagnetic direction			
	slat	slong		*D*	*I*	*K*	α95
Kotuykan and Kotuy Rivers:				Geographical coordinates**			
2 sill (Gr 3)	70.56	103.89	12/25	310.5	72.6	55.1	5.9
3 dike (Gr 1)	70.64	103.37	9/15	102.5	88.5	79.7	5.8
4 sill (Gr 2)	70.53	103.87	6/14	49.6	67.9	110.5	6.4
5-1 dike (Gr 1)	70.74	103.12	6/7	45.4	83.5	55.9	9.0
5-2 dike (Gr 1)	70.74	103.12	6/6	84.4	76.2	55.7	9.1
5-3 dike (Gr 1)	70.74	103.12	4/6	98.6	69.2	10.6	29.6
5* (average)	70.74	103.12	16/19	77.0	78.9	41.1	6.2
6 dike (Gr 1)	70.77	103.08	15/15	303.7	–68.4	87.9	4.1
7 dike (Gr 1)	71.12	102.51	9/13	358.2	81.1	25.0	10.5
8 dike (Gr 3)	71.14	102.63	6/9	280.1	73.4	16.5	17.0
9 dike (Gr 1)	71.05	102.36	6/6	171.1	73.9	46.7	9.9
Dzhogdzho and Il'ya Rivers:				Geographical coordinates**			
10-1 dike (left) (Gr 2)	70.50	104.44	7/14	30.1	71.1	34.8	10.4
10-2 dike (right) (Gr 1)	70.50	104.44	6/7	97.0	87.2	72.4	7.9
11 sill (cross-cutting) (Gr 1)	70.50	104.44	13/13	257.0	–81.2	53.1	5.7
12 dike (Gr 1)	70.31	104.31	9/15	254.8	85.2	14.7	13.9
13 dike (Gr 2)	70.42	105.56	10/15	18.8	59.4	70.3	5.8
14 sill (Gr 2)	70.50	104.50	13/13	35.1	64.6	32.3	7.4
15 dike (Gr 3)	70.54	104.39	7/8	317.3	69.2	57.9	8.0
16 dike (Gr 1)	70.53	104.46	6/13	154.7	84.4	20.4	15.2
Average over groups 1 + 2 + 3	**70.7**	**103.55**	**(16)**	**41.6**	**83.5**	**25.4**	**7.5**
Average over groups 1 + 2	**70.7**	**103.55**	**(13)**	**58.6**	**81.5**	**30.5**	**7.6**
Average over group 1	**70.7**	**103.55**	**(9)**	**118.8**	**84.6**	**64.6**	**6.5**
Maymecha River, mouth of Delkan River (dike-in-dike):				stratigraphic system			
17–1	70.9	100.6	6/6	281.8	–68.8	19.8	15.4
17–2	70.9	100.6	5/5	311.2	–66.3	15.6	20.0
17–3	70.9	100.6	3/5	271.9	–59.6	25.0	25.2
17–4	70.9	100.6	5/5	231.5	–70.4	201.0	5.4
17–5	70.9	100.6	5/5	204.3	–74.5	102.3	7.6
17–6	70.9	100.6	2/5	255.3	–80.3	7.2	115.2
17–7	70.9	100.6	3/5	286.7	–79.4	3.8	75.4
17–8	70.9	100.6	4/5	313.6	–71.0	58.1	12.2
17–9	70.9	100.6	5/5	286.9	–67.6	32.7	13.6
17–10	70.9	100.6	5/5	226.4	–77.0	45.5	11.5
17–11	70.9	100.6	5/5	266.9	–74.1	18.7	18.2
17–12	70.9	100.6	4/5	291.8	–73.5	15.3	24.2
17–13	70.9	100.6	6/6	267.4	–85.3	224.0	4.5
17–14	70.9	100.6	5/5	314.4	–75.3	28.2	14.7
17–15	70.9	100.6	5/5	251.1	–72.5	50.3	10.9
17–16	70.9	100.6	5/5	251.4	–74.7	23.4	16.1
17–17	70.9	100.6	5/5	245.1	–77.2	28.9	14.5
17–18	70.9	100.6	5/5	273.7	–78.2	46.0	11.4
17–19	70.9	100.6	5/5	288.0	–53.0	11.0	24.2
17–20	70.9	100.6	5/5	282.0	–65.5	55.1	10.4
Average:	**70.9**	**100.6**	**(20)**	**272.7**	**–73.7**	**47.6**	**4.8**

Table 1. (Contd.)

Point, description	Coordinates		*N*/*n* (*S*)	Paleomagnetic direction			
	slat	slong		*D*	*I*	*K*	α95
Popigay River:				Geographical coordinates**			
18 dike	71.99	109.80	6/12	133.8	74.1	27.0	13.1
19 dike	72.47	109.75	10/10	288.3	–80.3	24.2	10.0
20 flow	72.57	109.08	10/12	121.3	76.0	84.6	5.3
21 flow	72.53	109.00	4/11	168.6	72.5	37.1	15.3
22 flow	72.56	108.83	17/21	128.2	74.6	50.3	5.1
Average:	**72.42**	**109.29**	**(5)**	**134.8**	**76.4**	**166.2**	**6.0**
Udzha River:				Geographical coordinates**			
Outcrop 26	71.6	114.5	10	31	85	30.5	8.9
Outcrop 58	71.6	114.5	3	59	69	29.8	23.0
Outcrop 72	71.6	114.5	5	63	79	49.7	11.0
Outcrop 74	71.6	114.5	8	105	79	30.8	10.2
Outcrop 34	71.6	114.5	13	241	–82	34.3	7.2
Outcrop 58'	71.6	114.5	4	359	–75	52.8	12.8
dike 28	71.6	114.5	11	262	–73	27.8	7.0
dike 30	71.6	114.5	16	356	–64	48.0	5.4
dike 56	71.6	114.5	3	247	–79	38.5	33.5
Outcrop 57	71.6	114.5	4	359	–71	69.3	12.9
Outcrop 71	71.6	114.5	2	331	–64	29.1	48.1
dike 76	71.6	114.5	20	311	–85	38.5	5.4
paleovolcano 79	71.6	114.5	17	121	–70	6.2	15.6
dike 4	70.7	117.2	7	269	–69	19.3	14.1
dike 6	70.7	117.2	7	259	–77	11.9	18.2
dike 8a	70.7	117.2	7	303	–74	22.5	13.1
dike 8b	70.7	117.2	12	270	–72	40.8	6.9
sill 17	70.7	117.2	23	286	–72	34.6	5.2
Average:	**71.4**	**115.3**	**(18)**	**109.1**	**80.3**	**18.6**	**5.7**
Moyero River (Pavlov et al., 2007):				Geographical (synfolding) system			
dikes and sills	67.6	104.1	(11)	83.7	78.5	141	3.9
remagnetized sedimentary rocks	67.6	104.1	(13)	109.3	83.0	793	1.5
				(117.5)	(83.0)	(1327)	(1.1)

Notes: Slat, slong are the latitude and longitude of the sampled site; *N* is the number of samples used for calculations; *D*, *I* are paleomagnetic declination and inclination; *K*, α95 (°) are the parameters of the Fisher's distribution on the sphere (the concentration parameter and the radius of the circle of 95% confidence, respectively). Gr 1, Gr 2, and Gr 3 are Group 1, Group 2, and Group 3, respectively; * is the average direction for dikes 5-1 and 5-3 (see text). ** the geographic and stratigraphic coordinate systems coincide.

Table 2. Paleomagnetic poles and the amplitude of secular variation

Region/data sample	Pole					Deviation from NSP2*	Deviation of NSP4*	Estimated amplitude of secular variation			
	plat	plong	N	K	α95			N	S_f	S_{f-} S_{f+}	A
Kotuy:											
groups 1 + 2 + 3	78.9	134.7	16	10	13.7	23.6 ± 10.4	21.8 ± 10.2	16	28.6	23.3–33.7	56.5
groups 1 + 2	72.3	152.9	13	13	13.6	16.6 ± 10.4	14.2 ± 10.1	13	25.7	20.1–31.0	51.2
group 1	64.5	124.4	9	23	12.7	13.8 ± 9.7	14.0 ± 9.4	9	18.7	12.3–24.1	38.7
Delkan:	54.9	158.7	20	20	7.8	5.7 ± 6.9	4.5 ± 6.5	20	19.1	15.1–22.6	39.3
Popigay:	50.0	138.2	5	50	10.8	6.2 ± 7.9	9.7 ± 7.6	5	11.3	4.9–15.8	25.4
Udzha:	60.3	152.4	18	11	11.2	5.3 ± 8.9	3.2 ± 8.6	17	22.4	16.6–27.7	45.3
Moyero:											
sills and dikes (groups 1 + 2)	60.8	153.5	11	42	7.1	6.7 ± 9.1	3.8 ± 8.7	11	12.6	9.7–15.3	27.6
remagnetized rocks:											
geographic coordinates	60.3	130.9	13	213	2.8			13	5.6	4.3–6.7	15.0
synfolding coordinates	58.9	128.2	13	358	2.1						

Notes: Slat, slong are the latitude and longitude of the sampled site (°); N is the number of poles in the data sample; K, α95 (°) are the parameters of the Fisher's distribution on the sphere (the concentration parameter and the radius of the circle of 95% confidence, respectively). S_f is the amplitude of secular variation (°); N is the number of paleomagnetic poles used for calculations after the Vandamme cutoff; A is the cutoff angle (°) (Vandamme, 1994). S_{f-}, S_{f+} is the confidence interval (°).

* NSP2: 55.1°N, 147.0°E; $N = 8$, $K = 123$, $A95 = 5.0°$; NSP4: 57.2°N, 151.1°E; $N = 8$, $K = 192$, $A95 = 4.0°$ (Pavlov et al., 2007).

from 200–250°C, or in the alternating magnetic fields above 15–20 mT (Fig. 3d). The characteristic NRM component in the dolerites from the Verkhne-Udzhinskii sill and alkali basites from the Ebekhain intrusive complex has reversed polarity (Fig. 4d). At the same time, dolerites from the Udzha intrusion are found to have both normal (outcrops 26, 58, 72, and 74) and reversed (outcrops 79, 34, and 58') characteristic NRM components. The primary character of the characteristic magnetization component in the dolerites from the Verkhne-Udzhinskii intrusion is confirmed by the positive baked contact test (Fig. 4e) in the exocontact zone of the dikes with the Vendian limestones of the Tomptor Formation (outcrop 8). The average paleomagnetic directions for the outcrops along the Uzha River are presented in Table 1.

DISCUSSION OF THE RESULTS

The Analysis of Paleomagnetic Directions

Kotuy River. The distribution of the average paleomagnetic directions determined from the studied magmatic bodies in the Kotuy region is shown in Fig. 4a. Closely inspecting this distribution, we primarily notice the presence of three objects (intrusions 2, 8, and 15) with positive inclinations and westerly declinations (group 3 in Fig. 4a), which significantly differ from the typical trap directions expected according to the position of the "trap" pole of the Siberian Platform (NSP2 and NSP4 (Pavlov et al., 2007)). In our previous study of the Arydzhangsky volcanics outcropped in the Kotuy River's valley, we obtained very close directions, probably reflecting the geomagnetic excursion (Pavlov et al., 2011). The similar paleomagnetic directions of group 3 and the excursion directions of the Arydzhangsky Formation probably indicate that the intrusive bodies 2, 8, and 15 were formed simultaneously with the lava flows –3, –2, and –1 of the Arydzhangsky volcanics and, similar to the latter, contain the record of the geomagnetic record.

The directions that remain on the stereogram after elimination of the direction of group 3 form two clusters. One cluster (group 2) includes four directions with northwesterly declinations determined from the intrusive bodies 4, 10-1, 13, and 14. It is remarkable that all these bodies are aligned almost in a straight line and composed, according to the macroscopic description, by dolerites; therefore, they might have been formed as a result of a single common magmatic event.

We also consider the directions of group 2 as anomalous. These directions could have been formed during the geomagnetic excursion; at the same time, it cannot be ruled out that their deviation from the expected value is due to secular variation. However, as these directions are recorded in 4 of 13 bodies that remained after elimination of the dikes of group 3, these directions would assume an unduly large statistical weight after averaging, which would appreciably distort the final result. The anomality of the directions of groups 2 and 3 is supported by the fact that, when these directions are included in the common statistics, the amplitude of secular variation S_f (Table 2) becomes substantially larger than expected for these latitudes during that geological time (Pavlov et al., 2011).

On the other hand, after elimination of the directions of groups 2 and 3, the scatter of the remaining directions (group 1) agrees with the expected amplitude of secular geomagnetic variation, while the average direction becomes significantly closer to the estimated value (Table 2, Fig. 5). This indicates that, on one hand, the dikes of group 1 were formed during the period of a stable geomagnetic field (without reversals and excursions) and, on the other hand, their formation lasted for a relatively long time, sufficient for averaging the secular geomagnetic variation. At present, it is believed that secular variation is averaged over at least 10–100 thousands of years. Therefore, the formation of the intrusive bodies of group 1 (bodies 2, 5-1, 5-2, 5-3, 6, 7, 9, 10-2, 11, 12, and 16) took at least that long. The paleomagnetic results determined from the dikes pertaining to one dike cluster (5-1, 5-2, and 5-3) were averaged (result 5 in Table 1), and only this averaged value was used in the calculations. The flipped directions of reversed polarity (bodies 6 and 11) were also related to group 1.

We note that the average paleomagnetic direction of the dikes with normal polarity pertaining to group 1 does not statistically differ from the average paleomagnetic direction of the normally magnetized lava flows of the Arydzhangsky and Onkuchaksky Formations (Pavlov et al., 2011): the corresponding average directions ($D = 127.2$; $I = 87.3$; $K = 83.3$; $N = 7$ and $D = 133.7$; $I = 80.9$; $K = 53.0$; $N = 34$) differ by 6.4°, while the critical angle for them is 7.9° (McFadden and McElhinny, 1990). This indicates that the normally magnetized dikes of group 1 could have been formed simultaneously with the lava flows of the Arydzhangsky Formation and the bottom parts of the Onkuchaksky Formation; moreover, these dikes might have served as channels through which the magma outpoured and formed these lava flows.

Maymecha River, the Mouth of the Delkan River. When analyzing the distributions of the average directions of the studied Delkan dikes, we noticed a remarkable feature: the pole and the amplitude of secular variation calculated from these data are strikingly close to the expected model values (Table 2, Fig. 5). This means that the formation of the Delkan dikes lasted for a long time, measuring a few dozens or hundreds of thousands of years. On the other hand, since all the studied dikes are magnetized reversely and there are grounds to consider their magnetization as primary, it can confidently be suggested that the dikes had intruded during one epoch of magnetic polarity. In this case, taking into account the average duration of the epochs of magnetic polarity close to the Permian–Triassic boundary (Steiner, 2006), we conclude that the formation of the Delkan dikes lasted for at most 200000 years.

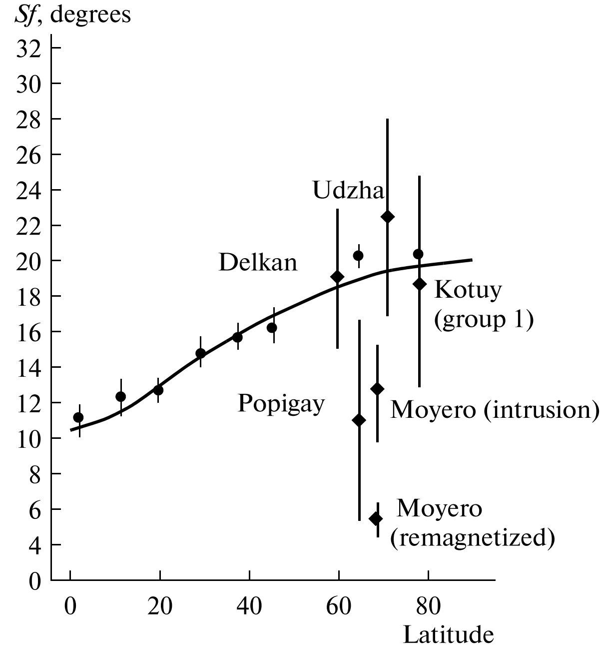


Fig. 5. Comparison of the scatter in the virtual geomagnetic poles (VGP) for the studied magmatic trap objects in the basins of the Kotuy, Delkan, Popigay, Udzha, and Moyero rivers (Pavlov et al., 2007) (Table 2) with the data for the last 5 million years. The small circles with the lines showing the confidence interval are compiled from (McElhinny and McFadden, 1997). The line on the graph is TK03 model of secular variation (Tauxe and Kent, 2004). The amplitude of secular variation S_f calculated in the present work and its confidence intervals are shown by the black diamonds and thick vertical bars, respectively.

We note that elimination of the least reliable determinations from the sample does not significantly affect the final results.

Fomich and Popigay Rivers. Although the amplitude of secular variation recorded in the studied trap formations of the Fomich and Popigay River valleys is noticeably lower than expected (Table 2, Fig. 5), the calculated pole falls quite close to the expected trap poles NSP2 (6.2 ± 7.9°) and NSP4 (9.7 ± 7.6°) (Pavlov et al., 2007), being, however, significantly different from the latter (Fig. 6). We interpret the obtained distribution as evidence of the fact that, on one hand, the magmatic activity in the region continued during at least dozens of thousands of years (as follows from the opposite polarities of the paleomagnetic directions) and, on the other hand, the studied objects were formed during 2–3 magmatic episodes (as demonstrated by the low amplitude of the variations). In our opinion, the fact that the average pole calculated from the trap objects in the Fomich and Popigay rivers are close to the expected NSP2 and NSP4 poles can only be accounted for by mere chance. We note that, with Fisher's distribution of the poles (Merrill, McFadden, and McElhinny, 1996) and with the given level of secular variation (Pavlov et al., 2011), for the average

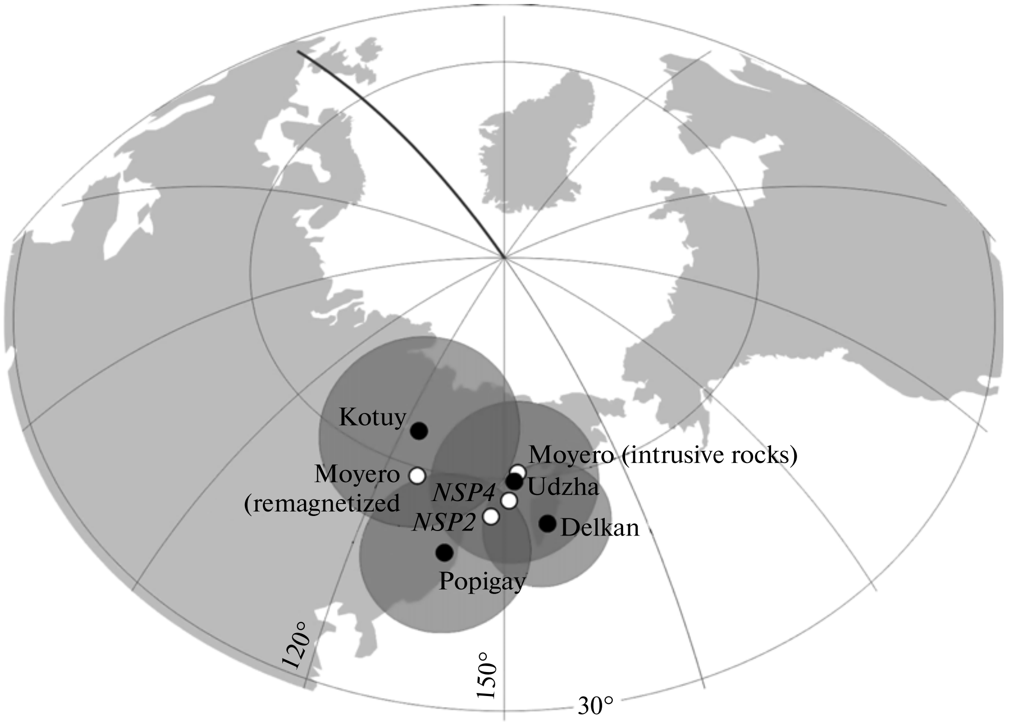


Fig. 6. The paleomagnetic poles and their 95% confidence ovals calculated in the present work (the filled circles). The open circles show the poles used in the present study (NSP2, NSP4, Moyero (Pavlov et al., 2007)).

direction to fall (with 95% confidence) within 6.2° of the true average value at a latitude of 70° (which is the paleolatitude of the region of study), at least 25 dikes representing magmatic events separated in time should be sampled.

Udzha River. The data for the Udzha River are of interest because, primarily, they provide an example of the quite complete temporal sampling of the studied magmatic object, as demonstrated by the close values of the experimental and expected paleomagnetic variations and the coordinates of the paleomagnetic poles (Table 2, Figs. 5 and 6). Although the number of the averaged (over sites) directions is still insufficient for providing the desired 5° accuracy in determining the pole locations, the average Udzha pole fell, by chance, within 2°–5° of its expected position (Fig. 6). However, normally, when the true position of the paleomagnetic pole is unknown, we cannot rely on good luck, and we can only hope (with the obtained distribution) that the calculated pole lies within 10° of its true position (Table 2).

The obtained distribution of the paleomagnetic poles indicates that the magmatic activity in the region lasted for a comparatively long time (as follows from the identified magnetization with different polarity and the expected value of the secular variation) and was most likely spread over time.

In addition to the objects studied in the present work, we also consider the data for the area of Moyero River (the southern Anabar region, Fig. 1a (Pavlov et al., 2007)).

Moyero River. In the case of subvolcanic intrusive bodies of the Moyero River valley (Pavlov et al., 2007), we observe the same situation (including the presence of bodies with a different polarity of magnetization) as in the case of the trap bodies in the basin of the Popigay River. The only difference is that secular variation is averaged somewhat better. Here, the amplitude of the recorded variations remains (statistically) significantly lower than expected (Pavlov et al., 2011) (Table 2, Fig. 5), while the calculated paleomagnetic pole is located close to the true pole (Table 2, Fig. 6). Just as for the traps in the basin of Popigay River, we interpret the obtained data as an indication that the magmatic activity in the region lasted for at least a few dozens of years, while the studied objects were formed during several magmatic episodes.

A specific feature of the data for Moyero River is the extremely sharp clustering of the paleomagnetic directions calculated for the outcrops of sedimentary rocks that were remagnetized by the traps (Table 2). This is the more surprising because the outcrops, from which the considered average directions were recorded, are spaced many dozens of kilometers apart. The clustering can be accounted for in two ways: either it reflects a very short but very intense remagnetizing event in the history of the region or it is the result of a long-term (with a characteristic time of about a million of years) averaging of the geomagnetic field in the course of slow remagnetization of sedimentary rocks. In the latter case, however, if we assume that the Permo–Triassic traps are the source of remagnetization, we should observe the calculated and expected Permo–Triassic poles to statistically coincide. However, the pole of the remagnetized rocks lies quite far from the Permo–Triassic pole and (statistically) significantly differs from the latter. Therefore, either remagnetization occurred very rapidly or its age appreciably differs from the Permian–Triassic boundary.

The hypothesis of fast trap remagnetization faces the problem of a remagnetizing source, because the average direction of remagnetization differs (and this is confirmed by the formal analysis) from the paleomagnetic directions of the studied Permo–Triassic magmatic bodies in this region considered both as a whole and individually. Therefore, the only thing that remains for us is to assume that either in the Permo–Triassic time, at a certain distance from the considered region, a short and intense event occurred which resulted in rapid remagnitization of the sedimentary rocks in the Moyero River basin, or these rocks were remagnetized at some other time.

The comparison of the paleomagnetic pole with the apparent polar wander path for the East European Platform (Torsvik et al., 2001) points to the probable Late Triassic remagnetization. According to (Torsvik and Andersen, 2002), the Late Triassic tectonomagmatic activity was widely developed in the southern Taimyr and might be considered as the probable source of remagnetization of the rocks of this age. However, the paleomagnetic studies of the Riphean and Paleozoic rocks from the western Anabar region, which are located directly between the Taimyr and the Moyero River region (Veselovskiy et al., 2009), do not show any signs of such remagnetization. Thus, the hypothesis of rapid remagnetization due to the strong Permo–Triassic event in the marginal part of the considered region is most probable. We suggest that intrusion of huge volumes of traps south of the considered region in the northern part of the Tungus syneclise in the interfluvial area of Moyero and Kochechum rivers might have been such an event.

Finally, we discuss the number of rapidly cooling subvolcanic bodies (dikes and thin sills) that need to be sampled for obtaining an exact estimate for the location of the paleomagnetic pole. Assuming (according to (Merrill, McFadden, and McElhinny, 1996)) that the distribution of the virtual poles obeys Fisher's law and knowing the expected scatter of secular variation S_f for the given latitude, we can easily calculate this value. As for the Permian–Triassic boundary, the amplitude of secular variation did not substantially differ from its Late Cenozoic values (Pavlov et al., 2011); therefore, for estimating the value of S_f for the Permo–Triassic traps, we can use the curve from (McElhinny and McFadden, 1997). For the Arctic regions of Siberia with a paleolatitude of 70° at the Permo–Triassic boundary, this curve gives $S_f \approx 18°$, which corresponds to the concentration $K \approx 20$ ($K = 6561/S_f^2$) (Khramov et al., 1982; Merrill, McFadden, and McElhinny, 1996). Therefore, in order to determine the location of the pole within 5°–6° at most, we have to sample at least 35–40 dikes or minor sills (according to the relationship for determining the radius of the 95% confidence circle: $\alpha95 = 140/(NK)^{1/2}$).

Apparently, the example of the trap objects studied in the basins of the Delkan and Udzha rivers and partly in the basins of the Popigay and Moyero rivers, where the estimated locations of the pole relatively slightly deviate from the expected trap pole (Table 2, Fig. 6), contradicts this conclusion. However, the case with intrusive traps in the valley of the Kotuy River definitely indicates that the presented examples are merely lucky, which does not guarantee that they would strike the sought pole.

CONCLUSIONS

The knowledge of the value of secular geomagnetic variation at the Permian–Triassic boundary, as well as the position of the expected (true) paleomagnetic Permo–Triassic pole of the Siberian Platform provides several additional constraints on the duration and character of the evolution of the magmatic events associated with the formation of the intrusive bodies of traps.

(1) Most of the studied dikes from the Kotuy river basin (group 3) were formed during a relatively long time (at least 10000–100000 years). Here, two rather short events (hundreds to a few thousands of years) also occurred in the region. These events resulted in the formation of the dikes related to groups 1 and 2. The dike-in-dike structure, 20 semidikes of which were studied in the mouth of the Delkan river, were also formed during a long time, which, however, did not exceed 200000–250000 years.

(2) The magmatic Permo–Triassic activity in the regions of te Popigay and Moyero river basins lasted for dozens of thousands of years; and the intrusive bodies were formed during several magmatic episodes. The intrusion of the dikes and sills in the basin of the Udzha River was a rather long process and was likely spread out in time.

(3) The analysis of the data on the remagnetized rocks from the Moyero river basin indicates that a very intense and very rapid (with a duration of up to a few thousand years) volcano–magmatic event might have occurred at the boundary of the Permian and Triassic. This event is likely to have been associated with the intrusion of large trap formations south of the Moyero river basin, in the interfluvial area of the Moyero and Kochechum rivers.

(4) Our results again show that, for obtaining an exact estimate for the position of the paleomagnetic pole, it is necessary to sample at least 35–40 dikes (thin sills) in the Arctic paleolatitudes if the level of

secular variation is commensurate with the present-day geomagnetic variations.

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