ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2011, Vol. 47, No. 5, pp. 402–417. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © V.E. Pavlov, F. Fluteau, R.V. Veselovskiy, A.M. Fetisova, A.V. Latyshev, 2011, published in Fizika Zemli, 2011, No. 5, pp. 35–50.

Secular Geomagnetic Variations and Volcanic Pulses in the Permian–Triassic Traps of the Norilsk and Maimecha–Kotui Provinces

V. E. Pavlov[a], F. Fluteau[b], R. V. Veselovskiy[a,c], A. M. Fetisova[c], and A. V. Latyshev[a,c]

[a] *Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Bol'shaya Gruzinskaya ul. 10, Moscow, 123996 Russia*

[b] *Institute of Earth Physics of Paris (IPGP), France*

[c] *Faculty of Geology, Moscow State University, Moscow, 119991 Russia*

Received May 24, 2010; in final form, October 06, 2010

Abstract—Detailed paleomagnetic studies have shown that the effusive Permian–Triassic traps in the Kotui River valley were formed as the result of volcanic activity, which occurred in the form of volcanic pulses and individual eruptions with net duration of at most 7000–8000 years, excluding the periods of volcanic quiescence. According to the analysis of the paleomagnetic data earlier obtained by Heunemann and his coauthors [2004b] on the Abagalakh and Listvyanka sections in the Norilsk region, those geological units were formed during 25 volcanic pulses and separate eruptions, which all lasted up to 8000 years altogether, whereas the total time of formation (including the periods of volcanic quiescence) exceeded 10000–100000 years for the Norilsk section and was probably a bit shorter for the Kotui section. Comparison of the positions of virtual geomagnetic poles calculated for the Norilsk and the Kotui sections provides no grounds to suggest that these sections were formed at different geological times.The scatter in the positions of the virtual geomagnetic poles (VGP) for the directional groups and individual directions (58 altogether) jointly for the two sections (more than 160 lava flows) indicates that the secular geomagnetic variations at the Permian–Triassic boundary had similar amplitudes to those that occurred in the past 5 Ma.

DOI: 10.1134/S1069351311040070

INTRODUCTION

About 250 Ma ago, the strongest Permian–Triassic Mass Extinction happened at the boundary of the Permian and the Triassic [Sepkovski, 1982]. Many researchers (e.g., [Courtillot and Olson, 2007]) associate this catastrophic event with the practically simultaneous formation of the Siberian traps, which entailed the rapid outpouring of vast amounts of volcanic material.

However, if the outpouring of Permian–Triassic volcanic rocks of the Siberian trap formation was uniform, then, taking into account the estimates concerning their volume (2–5 million km^3) [Fedorenko et al., 1996; Vasil'ev, 2000] and duration (~1 Ma) [Fedorenko et al., 1996; Renne and Basu, 1991], the average rate of their eruption should have been 2–5 km^3 per year. Being commensurable with (or even several times smaller than) the annual volumes of basalts formed at the present-day mid-oceanic ridges and also with the estimates obtained for the known historical eruptions [Davies, 1999; Thordarson and Self, 2003], this value seems thus to be strictly insufficient to give rise to catastrophic changes in climate and biosphere.

On the other hand, there is no reason to believe that the formation of traps was uniform. Moreover, the latest studies of the Deccan traps [Chenet et al., 2008] suggest that the volcanic eruptions occurred in pulses during relatively short time intervals within a much narrower timeframe than that which modern isotopic analysis is capable of accurately estimating.

The purpose of the present work is to examine whether such pulses have really occurred during the formation of the Siberian traps and to obtain the constraints regarding their volume and duration.

THE METHOD

Following Chenet and her coauthors [2008], we applied the method based on the analysis of secular geomagnetic variations recorded in the lava flows. While cooling, the volcanic flows acquire thermal remanent magnetization, which stores the current direction of the geomagnetic field at the site of the eruption. However, the variations in the geomagnetic field are rather fast on the geological time scale. According to the estimates in [Gallet et al., 2002], the direction of the geomagnetic field, on average, changes by 2° and more per century. With the determination accuracy of the mean paleomagnetic direction being 4°–6°, this means that the volcanic flows that were outpoured with a gap exceeding 300–400 years will normally have statistically different mean paleomagnetic directions. In contrast, the flows that were formed within such a time interval will be characterized by statistically undistinguishable directions.

Hence, if the average directions of the neighboring flows are statistically indiscernible (e.g., at the 95% confidence level), these flows can be organized in directional groups, each corresponding to a given individual volcanic pulse. Hereinafter, volcanic pulses will be understood as the short bursts of volcanic activity (and corresponding series of flows) separated by relatively longer quiet periods.

The number of directional groups and individual directions (the latter correspond to the individual flows that statistically differ in their average directions from the neighboring flows) in this case will be equal to the number of volcanic bursts during which the geological section of interest was formed. Here, it is assumed that each volcanic pulse lasted at most 300–400 years, while each individual flow corresponded to a time interval of at most 10–100 years [Thordarson and Self, 2003; Chenet et al., 2009].

The statistical procedure that we applied to identify the directional groups and individual directions is described in [Chenet et al., 2009].

We note that the geomagnetic variations are not unidirectional and thus the D–I (declination–inclination) diagram may contain overlaps (see, e.g., [Gallet et al., 2002]). However, in our opinion, such overlaps are unlikely for the neighboring pulses. If such a situation still occurs, this event will be recognized as a single pulse instead of being identified as two separate pulses, which will result in an insignificant underestimation of the number of pulses in the section.

Another paleomagnetic constraint, which we used while studying the lava flows, is based on the hypothesis of geocentric axial dipole [Khramov et al., 1982], widely adopted in the paleomagnetic community. According to this hypothesis, the geomagnetic field, which is time-averaged over rather long interval, coincides with the field of the magnetic dipole placed in the center of the Earth and aligned with the Earth's rotational axis. The length of the interval of time averaging should be sufficiently large to annihilate the geomagnetic variations; to date, this interval is commonly assumed by most researchers [Tauxe, 2010] to be 10^4–10^5 years. If this hypothesis is valid (which is indeed supported by numerous investigations, see, e.g., [McElhinny, 2004]), the mean paleomagnetic direction, determined for the stratigraphic interval formed within 10^4–10^5 years and longer, will correspond to the dipole's pole that coincides with the pole of the Earth's rotation. (Evidently, here, the considered time interval should be sufficiently short to allow one to disregard the plate motion, which must be taken into account on time scales of more than 5 Ma.) Such a pole, which averages the secular variations, is referred to as the paleomagnetic pole.

Correspondingly, if the pole calculated for some stratigraphic interval with an unknown duration statistically significantly differs from the known paleomagnetic pole (for the given time and given tectonic block), we should suspect that the secular variations in this interval have not been completely averaged. This, in turn, suggests that the formation of the considered stratigraphic unit took less than 10^5 years. As a result, we obtain the second paleomagnetic constraint, which can be used for estimating the duration of the formation of trap volcanic sequences.

The third and the fourth paleomagnetic constraints are applicable if the section under study contains intervals corresponding to the geomagnetic reversals or geomagnetic excursions. Since, according to the current estimates [Merrill et al., 1996], the duration of the reversals and the excursions does not usually exceed 10000 years and 2000–3000 years, respectively, we may conclude that the duration of the formation of the corresponding intervals of the geological section also does not exceed these values.

It is worth noting that caution should be exercised when applying each of the mentioned paleomagnetic constraints, since all of them are based on certain assumptions. On the other hand, it should also be recognized that these assumptions are often very well substantiated and they rely on generally used paleomagnetic research practice.

THE OBJECT OF THE STUDY

The field works of 2008–2009 were focused on the magnetostratigraphic study of the lower part of the volcanic trap section of the Maimecha–Kotui region (Fig. 1). During these expeditions, we have described and sampled several exposures outcropping along the Kotui River valley in the region of the Medvezhya River mouth and 10 km downstream of the Kayak village (Fig. 1). Stratigraphically, the studied segment of the section corresponds to the Arydzhang suite and to a considerable portion of the Onkuchak suite of the Kogotok series. Following [Fedorenko et al., 2000], it is assumed in the present work that the youngest flows and tuffs, which are underlain by the terrigenous sequences of the Tungusskaya series (C_2-P_2) and regarded by several authors as members of the Khardakhskaya or Potokoiskaya suite [Yegorov, 1995], refer to the bottom of the Arydzhang suite.

The Arydzhang suite is predominantly composed of the volcanic flows of alkaline ultramafic and mafic rocks (melanephilinites, melilites, limburgites, and picrites) with separate thin tuff interbeds. The overall

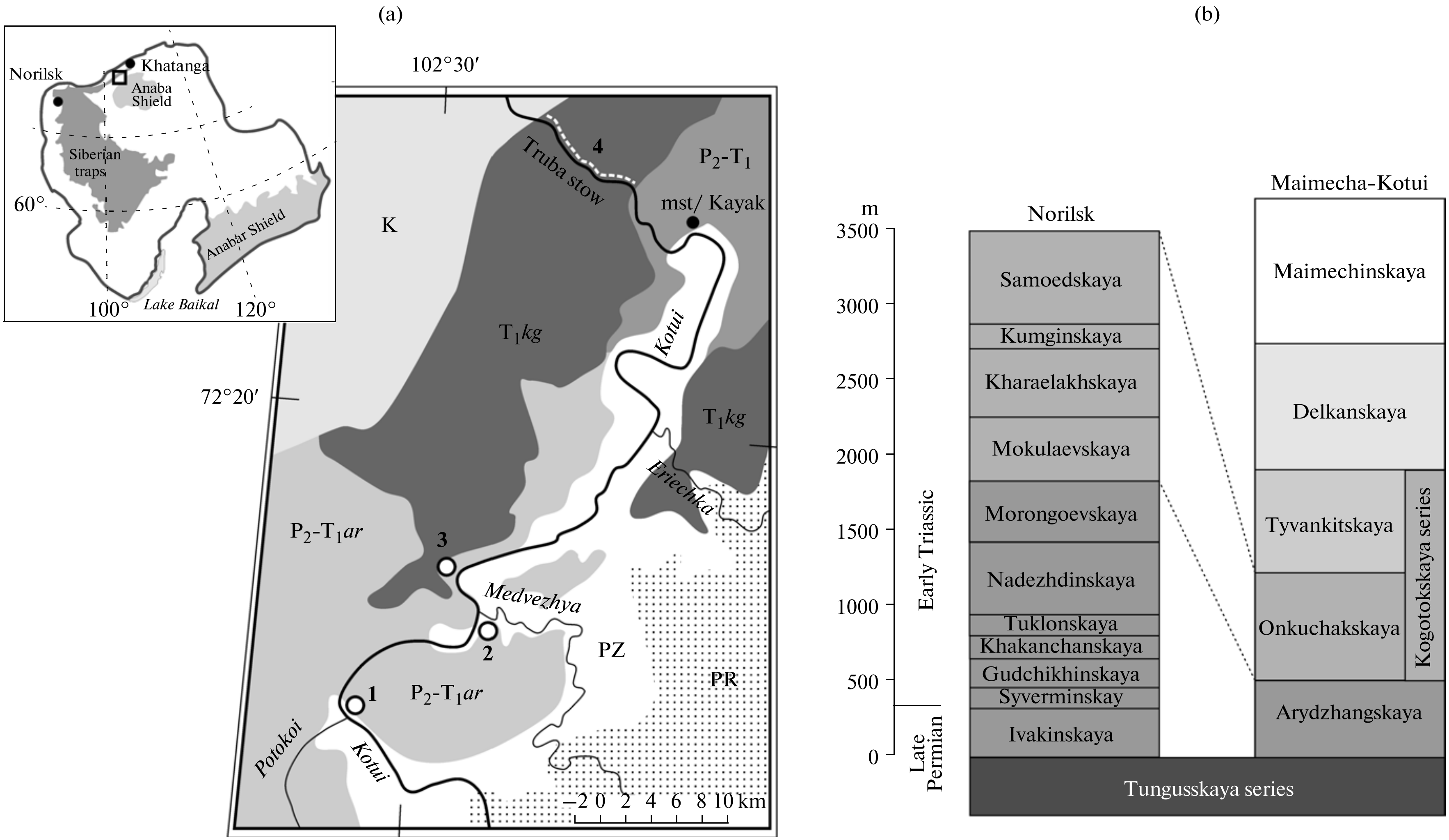

Fig. 1. (a) The geographic positions of the studied sections and the geological layout of the region; (b) the stratigraphy and correlation of traps of the Maimecha–Kotui and Norilsk regions, according to [Fedorenko, 2000], simplified. The black square in Fig. 1a shows the geographical position of the study region; the black circles and numerals 1, 2 and 3 indicate the locations of the studied exposures of the Arydzhangskaya suite; the white dashed line and numeral 4 mark the position of the studied series of outcropped Onkuchak suite (the Truba stow). T_1kg is the Kogotokskaya series; P_2–T_1ar is the Arydzhangskaya suite. PR, PZ, P_2–T_1 and K are the Proterozoic, Paleozoic, the Late Permian–Early Triassic and Cretaceous deposits, respectively.

thickness of the suite in the region under study is about 340 m. In the studied exposures, the rock bedding is nearly horizontal. From the bottom throughout the top of the Arydzhang suite, overall 37 flows have been sampled. In exposure 1 (Fig. 1, Table 1), flows hard1 through hard6 were sampled; in exposure 2, flows medv1 through medv4, and the exposure 3, flows flow0 through flow26 were sampled, with a possible narrow gap between flow10 and flow-3.

The Onkuchakskaya suite corresponds to the lower part of the Kogotokskaya series [Fedorenko, 2000] and is mainly composed of the tholeiitic basalts. In the studied series of the exposures (the Truba stow), we have sampled a continuous sequence of 43 flows of the Onkuchakskaya suite (containing a 20-meter-thick interbed of tuffs between flow3 and flow4) with a total thickness of 360 m. The flows forming the suite are gently dipping (at 3°–5°) northwestwards. Since the outcropping rocks of the Tungusskaya series lie practically horizontally, we regard the tilt of the flows as reflecting the paleotopography rather than the subsequent tectonic deformations.

PALEOMAGNETIZM

From each flow, 8 to 20 samples were taken, whose orientation was determined using the magnetic compass. No effect of the rocks on the compass readings was noticed, which agrees with the information from our German colleagues who worked earlier on these exposures and used solar and magnetic compasses in their work [Heunemann, 2004a]. The laboratory tests were carried out in the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences (RAS) in Moscow; in the Laboratory of Rock Magnetism at the Faculty of Geology, Moscow State University; and in the Institut de Physique du Globe de Paris. The tests were conducted according to the standard technique [Zijderveld, 1967; Khramov et al., 1982; Shipunov, 1999; Collinson, 1980; Kirschvink, 1980; McFadden, 1988; McFadden and McElhinny, 1990; Enkin, 1994; Torsvik et al., 1990].

All specimens were subjected to detailed thermal cleaning with heating up to 580–680°C. The number of progressive thermal demagnetization steps was normally at least 15; in some cases, the number of steps was greater. The thermal demagnetization of the specimens was carried out using thermal demagnetizers (including TD-80 furnaces designed by Magnetic Measurements Ltd., UK), providing values of the uncompensated field as low as at most 5–10 nT. The remanent magnetization of the specimens was measured using the SQUID magnetometer designed by 2-G Enterprices and using the JR-6 spinner magnetometer. During the measurements of the magnetization, the specimens were shielded from the external magnetic field. The measurement data were processed using the Enkin [1994] computer program package, where the PCA (Principal Component Analysis) method [Kirschvink, 1980] is applied for the identification of the components of magnetization. The parameters of secular variations were calculated using the program package developed by Tauxe [2010].

The quality of the paleomagnetic record in different flows is different. The paleomagnetic signal is most distinctly identified in the samples of the Onkuchakskaya suite. In most of the samples of this suite, two components of magnetization are reliably revealed.

The relatively less stable component of magnetization, which has an orientation close to the direction of the present geomagnetic field, is removed at temperatures of 200–250°C. After the removal of this component, the specimen preserves one (characteristic) component of magnetization, which is destroyed in the temperature interval 200–600°C (Fig. 2a and 2b). The paleomagnetic record in six flows from the lower part of the suite (flow6–flow11) was strongly noised, which prevented us from identifying the characteristic magnetization in these samples.

The overall Arydzhangskaya suite exhibits a poor paleomagnetic record, which is inferior to that of the Onkuchakskaya suite. Nevertheless, by taking a greater number of samples and by targeting those segments of flows that are the most promising for signal retention, we managed to obtain the average paleomagnetic directions for practically all sampled stratigraphic units. Unfortunately, for some flows (see Table 1) we were not able to achieve the desired accuracy of determination of the average direction (characterized by the value of the radius of the circle of confidence, alfa95). The magnetization of rocks of the Arydzhangskaya suite has the same component content as the rocks of the Onkuchakskaya suite (Figs. 2a and 2b): there are two components, the less stable one, being directed close to the present geomagnetic direction, and the more stable ancient characteristic component. The less stable component is removed by heating up to 200–250°C, while the range of unblocking temperatures for the characteristic component of magnetization spans 550–600°C and sometimes higher.

The distributions of the flow-mean geomagnetic directions of the characteristic component for both suites are presented in Figs. 2c and 2d. As seen from this figure and Table 1, the specimens have both the normal and the reversed polarity of magnetization. The mean directions of the normal and the reversed polarity are almost antipodal; nevertheless, the reversal test [McFadden and McElhinny, 1990] is negative for the whole set of vectors and for the Arydzhangskaya suite alone. The probable reasons for this are the insufficient averaging of secular geomagnetic variations or the presence of some relatively small contribution of the present geomagnetic field component, which has

Table 1. Mean paleomagnetic directions for the studied flows and the identified directional groups of the Kotui section

Pulse	*N*	D	I	alfa95	Pulse/*N*	Individual direction	D	I	alfa95
Arydzhangskaya suite									
hard 1	5	281.3	–65.3	16.1		E1			
hard 2	7	308.5	–67.4	9.3	P1		308.3	–68.9	4.2
hard 3	7	305.6	–67.4	7.5	P1				
hard 4	5	311.3	–71.8	14.2	P1				
hard 5	5	326	–70.1	6.2	P2		307.5	–71.0	
hard 6	3	289	–70	24.6	P2				
medv 1	6	134.7	71.1	9	P3		132.5	70	
medv 2	10	130.6	68.9	8.2	P3				
medv 3	9	81.9	81.2	8	P4		129.4	85.1	4.3
medv 4	7	68.5	86.9	8.3	P4				
flow 0	7	167.6	79.5	9.3	P4				
flow 1	14	141.5	86.8	5.1	P4				
flow 2	12	149.4	82.4	8.2	P4				
flow 3	13	119.6	86.7	5.6	P4				
flow 4	17	113.1	79.7	4.4	P5		107.1	76.7	4.9
flow 5	13	120.3	75.8	5	P5				
flow 6	11	98.2	78.6	6.2	P5				
flow 6b	8	99.1	71.8	4.3	P5				
flow 7	12	178.8	82.6	4.9	P6		173.0	79.1	4.4
flow 8	14	162.8	76	4.9	P6				
flow 9	15	162.6	78.8	4.7	P6				
flow 10	8	191.2	78.1	4.6	P6				
flow-3	10	262.1	75	9.6		E2			
flow-2	15	294	80.9	3.1		E3			
flow-1	7	268.3	71	7.4		E4			
flow 13	7	109.8	84.3	10.9		E5			
flow 14	13	101.7	69.9	10.1	P7		104.3	72.7	7.3
flow 15	15	103.2	70.1	5.5	P7				
flow 16	17	110.6	78	4.1	P7				
flow 1718	15	211.9	83.9	8.8	P8		174.1	82.3	
flow 19	7	154.5	78.8	6.5	P8				
flow 20	13	220.7	75.2	5.2		E6			
flow 21	13	156.9	79.5	9.4		E7			
flow 22	12	126	79.5	10		E8			
flow 23	6	113.9	64.8	9.9		E9			
flow 25	8	156.6	72	5.6		E10			
flow 26	9	104.2	68.1	4.3		E11			
Onkuchakskaya suite									
fl 1	16	117.6	71.8	4.5	P9		112.6	74.0	4.1
flow 2	21	114.6	74.8	3.6	P9				
flow 3	20	104.5	75.3	3	P9				
flow 4	15	292.6	–75.4	5	P10		297.1	–70.9	8.1
flow 5	7	285.1	–62.2	10.7	P10				
flow 12	10	309.1	–71.2	11.3	P10				
flow 13	5	307	–73.5	9.2	P10				
flow 14	7	270.1	–60.8	20.8		E12			
flow 15	7	283.7	–64.9	7.5	P11		277	–65.3	5.2
15crust	11	269.8	–67.3	8.3	P11				
fl 16	9	276.8	–63.5	7.6	P11				
fl 17	9	261.6	–61.1	6.5	P12		268.0	–70.9	6.2
fl 18	10	256.4	–73.4	5.3	P12				
fl 19	8	283.6	–71.5	6.3	P12				
fl 20	9	263.7	–74.8	7.4	P12				
fl 21	9	276.5	–72.2	5.3	P12				
fl 21	10	313.4	–79.1	4.8	P13		309.0	–78.6	2.8
flow 22	11	300.2	–79.3	4.5	P13				
fl 23	10	312.5	–77.2	3.2	P13				

Table 1. (Contd.)

Flow	*N*	D	I	alfa95	Pulse/*N*	Individual direction	D	I	alfa95
fl 24	10	283.9	–72.4	4.6	P14		294.7	–72.2	4.8
fl 25	8	306.2	–76	5	P14				
fl 26	8	298.5	–71.8	4.8	P14				
fl 27	9	292.9	–68.1	5.3	P14				
fl 28	9	314.9	–72.2	4.4	P15		317.6	–71.9	3.3
fl 29	10	310.8	–73.4	3.4	P15				
flow 30	10	322.3	–73.3	6.5	P15				
fl 31	10	321.6	–68.4	5.5	P15				
fl 32	11	298.3	–68.6	4.6		E13			
fl 33	9	324.1	–65	6.8		E14			
fl 34	10	295.2	–69.8	2.4		E15			
fl 35	10	308.9	–70.9	7.6	P16		304.6	–69.6	2.1
flow 36	10	295.7	–68.6	5	P16				
flow 37	10	309.1	–69.2	6	P16				
fl 38	11	311.1	–69.6	4.8	P16				
fl 39	8	306.7	–70.2	5.4	P16				
fl 40	10	296.8	–68.6	4.1	P16				
fl 41	9	244.6	–51.3	6.9		E16			
fl 42	10	237.7	–46.1	8.2		E17			
Mean for Arydzhangskaya suite									
Reversed polarity	6	302.9	–69.3	5.2					
Normal polarity (all)	31	137.4	81.5	3.6					
Normal polarity (excluding anomalous directions of flows flow-3, flow-2, flow-1)	28	131.5	79.5	3.1					
			γ/γ_c = 10.4/7.1						
Mean for Onkuchakskaya suite									
Reversed polarity	35	289.1	–70.8	3.3					
Reversed polarity (excluding anomalous directions of flows fl41 and fl42)	33	294.5	71.3	2.4					
Normal polarity	3	112.6	74.0	4.1					
			g/g_c = 2.8/8.1						
Total mean for Arydzhangskaya and Onkuchakskaya suites									
Reversed polarity	41	291.3	–70.7	2.9	16		284.4	–68.9	6.1
Normal polarity	34	133.7	80.9	3.4	17		143.2	81.8	5.9
Reversed polarity (excluding anomalous directions of flows fl41 and fl42)	39	295.9	–71.1	2.2	14		295.4	–70.0	3.7
Normal polarity (excluding anomalous directions of flows flow-3, flow-2, flow-1)	31	128.9	79.0	2.9	14		131.7	78.0	4.8
			g/g_c = 8.5/3.5					g/g_c = 9.1/5.9	
Normal + reversed polarity (excluding anomalous directions of flows fl41, fl42, flow-3, flow-2, flow-1)	70	124.7	74.7	1.9	28		121.5	74.2	3.3
Pole K1*: Plat = 48.3; Plong = 140.4 A95 = 5.7; *N* = 28									
Interval of normal polarity N located higher up in the succession than the transitional zone	15	124.8	77.3	4.7	10		130.8	77.8	6.5
Pole K2* Plat = 52.2; Plong = 130.6 A95 = 11.8; *N* = 10									

Notes: the pole is calculated as the mean VGP (over the directional groups and the individual directions) for the mean point with the coordinates 71.3°N, 102.5°E;P are the identified pulses with the corresponding numbers, counting from the bottom of the section; E are the individual directions with the corresponding numbers, counting from the bottom of the section;*N* is the number of samples used in the calculation of the mean directions of flows; D and I are, respectively, the mean declinations and inclinations of the flows and the pulses; alfa95 is the radius of the circle of confidence; γ/γ_c are the values of the angular deviation and the critical angle of deviation in the comparison of the mean geomagnetic directions [McFadden and McElhinny, 1990].

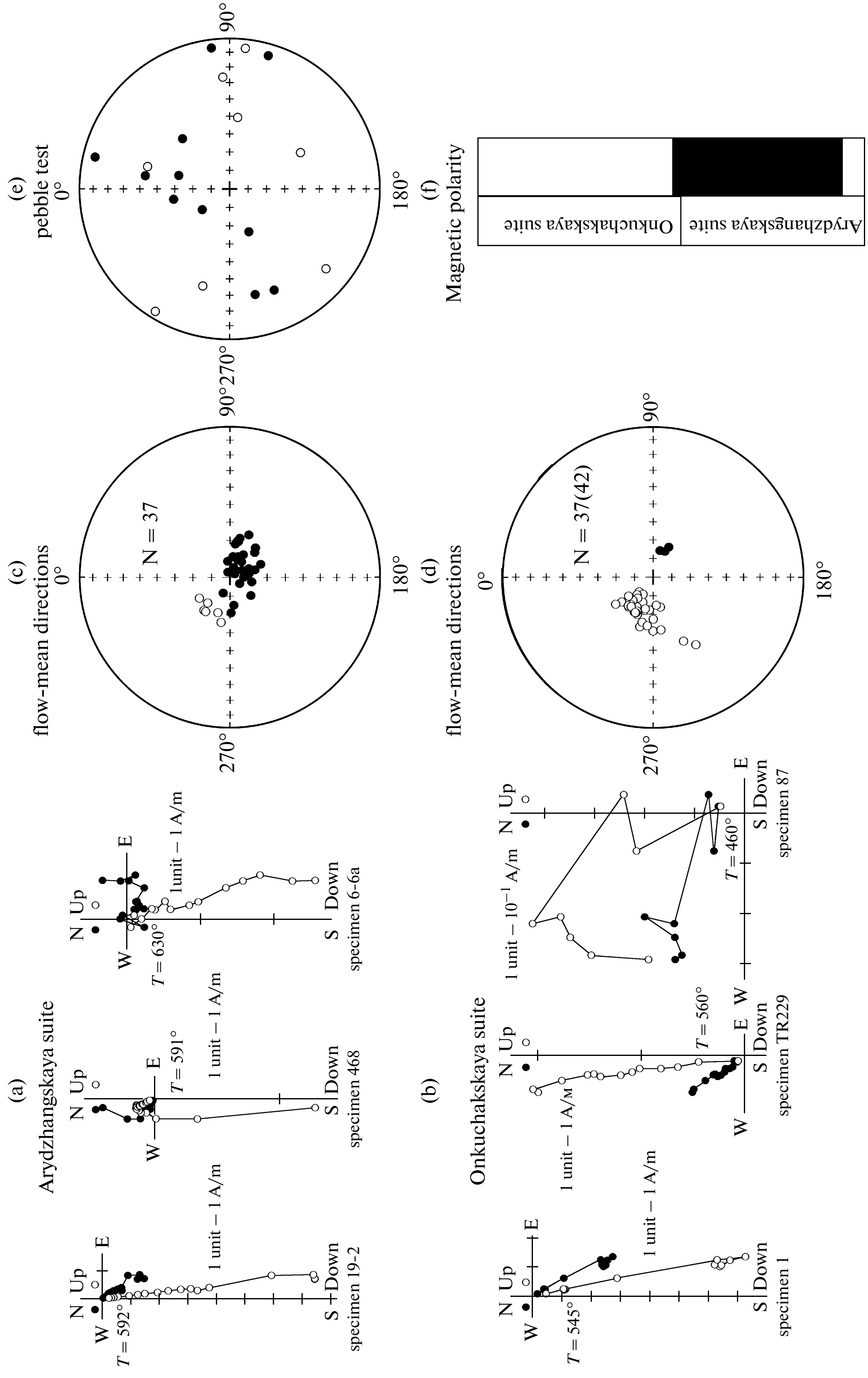

Fig. 2. The paleomagnetic characteristic of the studied suites of the Kotui section: (a), (b) the thermal demagnetization diagrams for the specimens of the Arydzhangskaya and the Onkuchakskaya suites; (c), (d) the distributions of the flow-mean directions of the characteristic magnetization; (f) the pebble test; (f) the magnetic polarity of rocks in the studied succession: the normal polarity is shown by black, and the reversed polarity, by white.

not been completely removed by thermal demagnetization. We note here that the reversal test for the Onkuchakskaya suite is formally positive (Table 1), although it covers a small number of samples of the same polarity.

In the lower part of the Arydzhangskaya suite, we have taken the volcanic pebble samples from the tuff interlayer. The distribution of the stable components of magnetization for these pebbles is shown in Fig. 2e. The length of the resultant vector R for this distribution is 2.33, which is far smaller than the critical (at the 95% confidence level) value $R_0 = 6.98$ [Watson, 1956]. Therefore, the test for the pebbles is positive, and, thus, the identified characteristic components of the pebbles' magnetization were formed before the disruption of the primary rocks.

The detailed magnetomineralogical studies of the Onkuchakskaya rock series showed that the main magnetic mineral that carries the magnetization is the primary magmatic homogeneous titanomagnetite with the Curie point at 250 to 400°C. There are also some amounts of grains of titanomagnetites that underwent heterophase oxydation and were formed during the primary melt cooling. The magnetic mineralogy of the Kotui trap sequence will be discussed in more detail in a separate paper [Latyshev et al., 2011].

The presence of magnetic minerals that have been formed at the early stages of the geological history of rocks, the positive conglomerate test, the occurrence of almost antiparallel directions of the normal and the reversed polarity, and the closeness of the calculated geomagnetic directions to the trap directions estimated for other regions suggest that the identified characteristic magnetization is the primary (or close to the primary) magnetization. That the magnetization is the primary magnetization is also supported by the presence of the directional groups in the sections that are statistically significantly different from each other.

DISSCUSSION OF THE RESULTS

Directional Groups and Individual Directions

Overall, we have studied 80 flows of the Arydzhangskaya and Onkuchakskaya suites. The mean paleomagnetic directions were determined for 75 flows (Table 1). According to the analysis based on the technique described in [Chenet et al., 2008], there are 16 directional groups and 17 individual directions in the rocks of the Kotui section. The number of flows for which the directional groups were determined was 2 to 10 (Fig. 3b). The largest volcanic pulses (which we determine from the directional groups) are the P12 (5 flows), P8 (3 flows) and P10 (10 flows) pulses, which have thicknesses of 57, 50, and 49 m, respectively.

We applied the same method to analyze the data obtained by Heunemann and his coauthors [2004b] for the Norilsk section, which they have studied on the Abagalakh and Listvyanka exposures. The analysis showed that there are 16 directional groups and 9 individual directions in this section (Table 2, Fig. 3a). The P1 (12 flows) and P16 (8 flows) are the largest pulses here, each corresponding to a stratigraphic interval with a thickness noticeably in excess of 100 m.

The Virtual Geomagnetic Poles of the Kotui and the Norilsk Sections

Many authors (see the discussion in [Gurevitch et al., 2004]) correlate the stratigraphic intervals of the Kotui and the Norilsk sections, which have the normal geomagnetic polarity (Figs. 4a and 4e). In this connection, it is instructive to compare the succession of the positions of the virtual geomagnetic poles (VGP) obtained in the present work for the Kotui section with a similar succession for the Norilsk section [Heunemann, 2004b] for the mentioned and the adjacent stratigraphic intervals. In the lowermost part of the Norilsk sequence, Heunemann with his coauthors recognizes the flows corresponding to the geomagnetic reversal followed by the geomagnetic excursion that occurred soon after the reversal (see Table 2). This part of the section together with several subjacent reversely magnetized flows of the Ivakinskaya suite will be further conventionally referred to as the transitional interval (TR). The transition interval is followed by the interval of normal polarity (N), which corresponds to the normal field.

In the Kotui section, soon after the reversed polarity changes into the normal polarity, we observe three consecutive flows with the anomalous paleomagnetic directions (flow-3–flow1). Following Heunemann and his coauthors [2004b], we supposedly correlate these directions with the geomagnetic excursion. Correspondingly, for the convenience of comparison, here we also define the transitional interval (the hard1–flow1 flows) and the normal (the flow13–fl42 flows) intervals (TR and N).

The succession of the transitional VGP of the Kotui section, unlike the corresponding Norilsk succession, does not contain any record of the reversal; however, as in the Norilsk succession, it includes anomalous poles (poles 8, 9, and 10 in Fig. 4g supposedly corresponding to the excursion) preceded by the normal northern virtual poles (poles 4, 5, 6, and 7 in Fig. 4g). Since the number of the latter is small and their clustering is relatively weak, one cannot make any sound inferences regarding their statistical coincidence or difference from the corresponding poles of the Norilsk section (poles 5, 6, 7 in Fig. 4c) because the parameter γ_c for them [McFadden and McElhinny, 1990] is greater than 25°. It may only be noted that they are

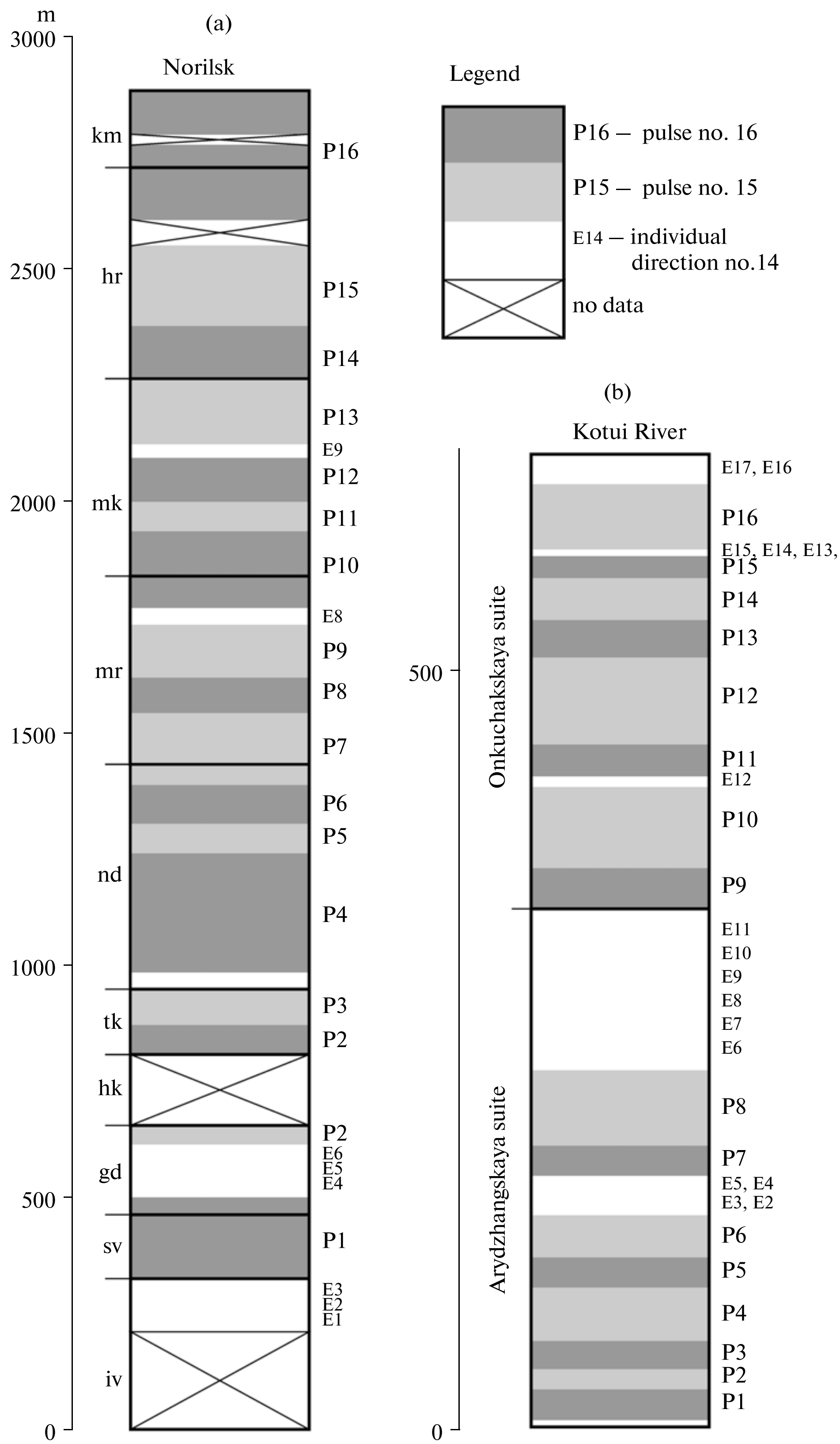

Fig. 3. The sketch of the identified pulses of magmatic activity in the trap sections of the Norilsk (a) (according to the data of [Heunemann et al., 2004b]) and the Kotui (b) regions. In panel (a), the thickness of the pulses is relative; in panel (b), the thickness of the pulses is in scale. Abbreviations of the rock suites of the Norilsk regions are as follows: iv ivakinskaya; sv syverminskaya; gd gudchikhinskaya; hk khakanchanskaya; tk tuklonskaya; n nadezhdinskaya; mr morongovskaya; mkmokulaevskaya; hr kharaelakhskaya; km kumginskaya.

Table 2. Mean paleomagnetic directions for the identified directional groups and the individual directions of the Norilsk section (according to the data of [Heunemann et al., 2004b])

No.	Pulse	Number of flows	Nomenclature of flows, according to [Heunemann et al., 2004b]	Individual directions	D	I	alfa95
1	P16	8	hr 8-km 7		61.4	74.9	3.3
2	P15	3	hr 3-hr 5		104.2	67.7	8.1
3	P14	2	hr 1-hr 2		89.0	57.1	
4	P13	4	mk 10-mk 13		93.5	70.8	5.1
5			mk 9	E9	68	67	
6	P12	3	mk 6-mk 8		105.8	79.5	5.4
7	P11	2	mk 4-mk 5		75.5	73.2	
8	P10	5	mr 10-mk 3		128.9	77.4	5.0
9			mr 9	E8	73	76	3.6
10	P9	2	mr 7-mr 8		92.5	75.5	
11	P8	2	mr 5-mr 6		159.9	82.3	
12	P7	5	nd 1-mr 4		91.9	77.1	3.1
13	P6	3	nd 5-nd 3		57.4	76.3	8.8
14	P5**	2	nd 7-nd 6		9.4	70.6	
15	P4**	8	nd 25-nd 8		20.4	67.2	3.0
16			nd 26	E7**	38	62	
17	P3**	3	tk 3-tk 5		28.4	71.4	5.7
18	P2	3	gd 5-tk 7-tk 6		79.8	75.3	6.3
19			gd 4	E6	82	51	
20			gd 3	E5	114	58	
21			gd 2	E4	127	69	
22	P1**	12	sv 1-sv 11+gd 1		151.3	54.4	2.1
23			iv 3	E3	258	–70	
24			iv 2	E2	236	–62	
25			iv 1	E1	261	–65	
		Number of directional groups (pulses) and individual directions					
	Mean for the directional groups and individual directions, without the reversal and the transitional zones	20			88.1	71.6	4.5
		Pole *N*1*: Plat = 53.0; Plong = 146.9 A95 = 7.1					
	Mean paleomagnetic direction for the segment of the section located shallower than the reversal and the excursion zones	13			88.2	74.6	4.7
		Pole *N*2*: Plat = 56.5; Plong = 142.2 A95 = 7.8					

Notes: the pole is calculated as the mean VGP for the mean point with the coordinates 70.0°N, 89.3°E; Intervals corresponding to the zones of the geomagnetic reversal (P1) and the excursion (P2, P3, E7, P4, P5) (according to [Heunemann et al., 2004b]) are marked by color; The numbering of pulses (P) and individual directions (E) starts from the bottom of the sequence. All designations are the same as in Table 1.

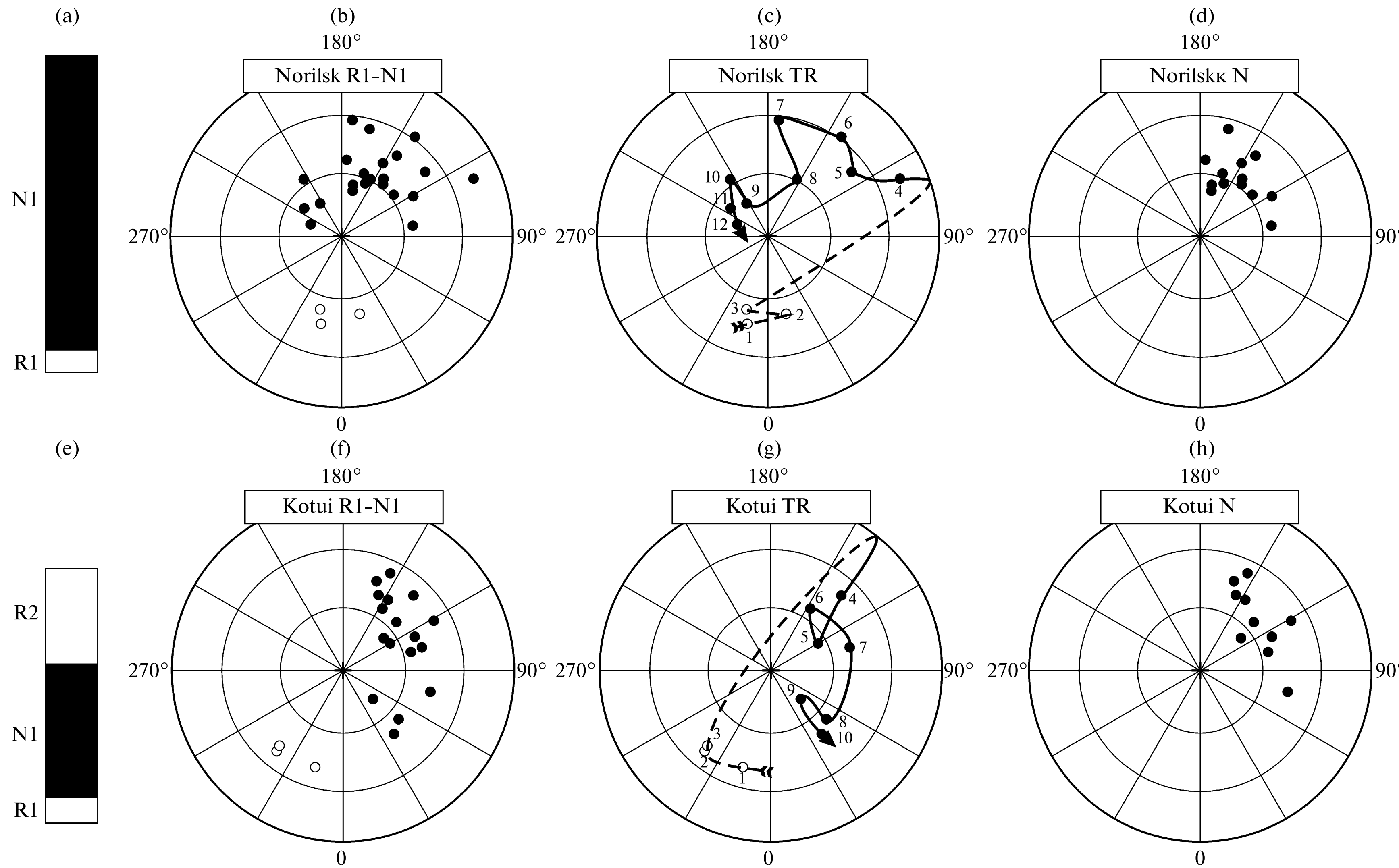

Fig. 4. The comparison of virtual geomagnetic poles for the intervals R1–N1 of the Kotui and Norilsk sections. The poles located in the southern hemisphere are shown in white, and the poles in the northern hemisphere, in black. (a), (e) the magnetostratigraphy of the Norilsk and the Kotui sections, respectively. Designations of the polarity the same as in Fig. 2; (b), (f) the locations of all virtual poles calculated from the identified pulses and individual directions of the Norilsk and the Kotui sections, respectively; (c), (g) the locations of the virtual poles calculated in a similar way for the transitional zones (TR) of the Norilsk and the Kotui sections, respectively. The numerals indicate the serial number in the succession of pulses and individual directions, beginning from the bottom of the section; (e), (h) the locations of the virtual poles calculated in a similar way for the normal zones (N).

located approximately in the same area of the stereographic projection (Figs. 4c and 4g).

On the other hand, the anomalous poles for these sections are different (Figs. 4c, 4g, poles 9–12 and 8–10, respectively). However, since as of today there are no reasonable grounds to believe that the geomagnetic field during the excursions is a dipole field, the difference in the positions of the corresponding poles for the considered regions, which are spaced apart by more than 500 km, cannot be regarded as a sure indication of different geomagnetic excursions.

Therefore, the attempt to verify the identity of R–N transitions of the Kotui and the Norilsk sections by comparing the virtual geomagnetic poles of their transitional intervals proved to be a failure.

The comparison of the average poles of the normal intervals of the Kotui and the Norilsk sections (Figs. 4d, 4h, Tables 1, 2, poles N2, K2) shows that they are statistically undistinguishable (γ/γ_c = 8.0°/10.9°). The same holds true also for the poles obtained from all directional groups and the individual directions, except for the anomalous poles (poles N1 and K1, γ/γ_c = 6.9°/7.6°). Poles N1 and K1 are also very close to the Triassic paleomagnetic poles NSP2 and NSP4 of the Siberian platform [Pavlov et al., 2004].

The geological data and the isotopic datings [Fedorenko et al., 2000; Kamo et al., 2003] unambiguously indicate that the both sections were formed within a relatively short geological time of at most a few Ma. This means that if the secular geomagnetic variations in both sections relating to the same rigid plate are completely removed by averaging, the corresponding paleomagnetic poles should coincide, just as we actually observe in our studies.

Thus, the statistical indiscernibility of the Norilsk and the Kotui mean poles can be regarded as an indication of the secular variations having been completely averaged in the discussed sections; the sections themselves were formed (see the second paleomagnetic constraint discussed above) within a time interval that is in excess of 10^4–10^5 years.

The Amplitude of the Secular Geomagnetic Variations Recorded in the Kotui and the Norilsk Sections

Based on the obtained data, we may estimate the amplitude of secular variations during the formation of the studied geological sections. The amplitude of secular variations is usually estimated by the scatter of the virtual poles S_p calculated according to the formula [Cox, 1969]

$$S_p^2 = (N-1)^{-1}\sum_{i=1}^{N}(\Delta i)^2.$$

Here, N is the number of the virtual geomagnetic poles used in the calculations, and Δ_i is the angle of deviation of the ith VGP from the rotation axis (the mean point of the VGP distribution).

According to McElhinny and McFadden [1997], one should use the S_f parameters, which allows for the scatter of the directions within the sites (flows)

$$S_f^2 = S_p^2 - \left(S_w^2/\overline{n}\right),$$

where

$$\frac{S_w^2}{\overline{n}} = 0.335\alpha_{95}^2\frac{2\left(1+3\sin^2\lambda\right)^2}{\left(5+3\sin^2\lambda\right)}.$$

Here, α_{95} is the mean radius of the circle of confidence and λ is the latitude (or the paleolatitude, if rocks older than 5 Ma are considered) of the sampling site.

In order to eliminate the effects of the anomalous states of the field (reversals and excursions), the critical angles of deviation of VGP from the mean direction are introduced: if the given VGP deviation exceeds the critical angle, this VGP is excluded from the considered distribution. The critical angles (A) are either chosen to be constant and equal for all distributions, for example 35° or 40° (see [McElhinny and McFadden, 1997] for the review), or they are calculated separately for each distribution, according to Vandamme's iterative method [Vandamme, 1994]:

$$A = 1.85S' + 5°,$$

where S' is equal to S_p for the initial and each subsequent distribution obtained at the current rejection of the anomalous VGP.

Applying this approach to the combined sample of the virtual poles, calculated for the directional groups and individual paleomagnetic directions of Kotui and Norilsk, we obtain the value $S_f = 17.7^{+2.3}_{-2.4}$ (degrees), the critical angle being 36.9° (Table 3). The paleolatitude is assumed to be 58°, which corresponds to the averaged value of the paleolatitudes of the Kotui and the Norilsk sections.

Let us now compare the derived estimate with the value of the secular variations determined for the past 5 Ma. As seen from Fig. 5, the VGP scatter, which we calculated for the rocks of the Kotui and the Norilsk sequences together, agrees with the scatter for the past 5 Ma [McElhinny and McFadden, 1997; Tauxe, 2004]. This means that the amplitude of the secular geomagnetic variations at the Permian–Triassic boundary was close to the amplitudes of the geomagnetic variations in the Late Cenozoic.

This result has important implications for understanding the evolution of the geomagnetic field and, at the same time, it provides us with a versatile tool for estimating the duration of the formation of the Per-

Table 3. Estimation of the amplitude of secular geomagnetic variations recorded in the Norilsk and the Kotui sections

Sample (directional groups and individual directions)	Number of VGP whose data were used in calculations before/after the rejection according to the Vandamme's method	Critical angle (A) calculated according to the Vandamme's method	Amplitude of secular variations (degree)	Confidence interval (degree)
	Norilsk and Kotui sections			
Overall data	58/49	36.9	17.7	15.3–20.0
	Kotui section			
Overall data	33/27	32.4	15.2	12.8–17.4
Zone N1 without anomalous directions of flows flow-3, flow-2, flow-1	14/14	36.4	17.4	13.3–22.4
Zones R1 and R2	16/14	28.3	12.9	9.8–16.1
Zone R2	13/11	30.5	14.2	9.9–18.1
	Norilsk section			
Overall data	25/24	43.1	21.2	16.7–25.0
The same, without the zones of the reversal and the excursion	20/20	36.1	17.3	13.6–20.6
Zone N1 located higher up in the section than the transitional zone	13/13	32.3	15.2	11.0–19.3

mian–Triassic sections. Indeed, if the amplitude of the geomagnetic variations recorded in a particular geological section is smaller than the amplitude of variations established for the corresponding geological time interval, one may speak about the relatively short time of formation of the given rock sequence (the case of remagnetization is not considered here).

Let us analyze the Norilsk section in this context. From Table 3 it is seen that the mean amplitude of the secular geomagnetic variations in the Norilsk sequence $\left(21.2^{+3.8}_{-3.5}\right)$, is somewhat greater than the mean value established above for this geological time. However, the increased scatter in the VGP positions is probably due to the fact that the analysis invoked the virtual poles corresponding to the geomagnetic reversal and the excursion. Indeed, if we exclude the reversal and the excursion zones from the considered sample, the calculated amplitude of secular variations for the Norilsk section will be $17.3^{+3.3}_{-3.7}$ (Table 3, Fig. 5). If we consider only that part of the section, which lies above the zone of excursion (Table 2, interval D [Heunemann et al., 2004b]), we will obtain the estimate $15.2^{+4.1}_{-4.2}$, which is close to the value $15.4^{+2.7}_{-2.0}$ earlier obtained by Heunemann and his colleagues for this interval. We recall however that, as opposed to Heunemann and his colleagues, in our calculations we use the VGP determined from the directional groups and the individual directions rather than from the separate flows.

The value we obtained is very close to that expected for the Permian–Triassic; this fact suggests that the secular variations in the Norilsk section have been sufficiently well averaged. Therefore, the overall Norilsk section was formed not faster than 10^4–10^5 years. Here, it should be noted that the value S_f calculated for the interval D likely indicates the insufficient averaging of the variations in this segment of the geological section (Fig. 5). However, we cannot verify this assumption because the confidence interval is excessively wide (Table 3).

As regards the Kotui section (Table 3, Fig. 5), here the amplitude of the recorded variations (the confidence interval taken into account) is somewhat lower than expected, which probably indicates that the total duration of the volcanic activity during the formation of the Kotui section was relatively short (at most 10^4–10^5 years), and that the episodes of volcanism were nonuniformly distributed over time.

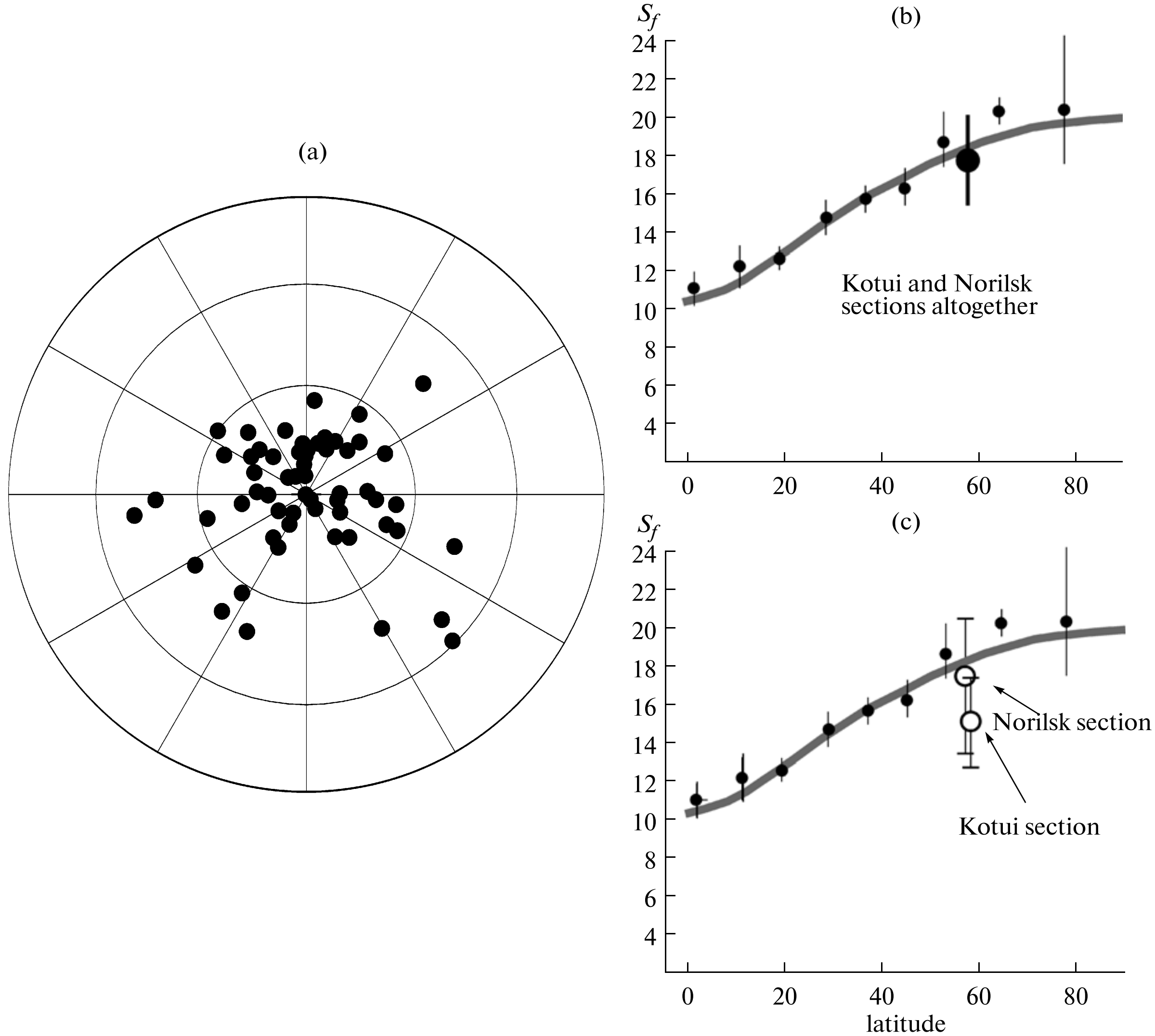

Fig. 5. (a) the virtual geomagnetic poles (VGP) calculated from the pulses and individual directions of the Kotui and Norilsk sections and centered with respect to the mean direction; (b), (c) the comparison of the VGP scatter for the Kotui and Norilsk sections altogether (b) and individually (c) with the data for the past 5 Ma. The small black circles with the vertical bars indicating the interval of confidence are the compilation by McElhinny and McFadden [1997]; the gray line in the graph is the model of secular variations [Tauxe, 2004]. The scatters of VGP together with their confidence intervals calculated in the present work are shown by large circles and vertical bars.

CONCLUSIONS

Let us summarize the above discussion. According to [Heunemann et al., 2004b], the lower part of the Norilsk section bears the records of the reversed geomagnetic field and the field at the time of the geomagnetic excursion, while in other parts of the section the secular geomagnetic variations are rather well averaged. Thus, based on these data, we may assert that, although the individual members of the section were formed within a rather short time (flows vs1–gd1 in less than 10 000 years, flows tk3–nd6 in less than 2000–3000 years), the overall duration of the formation of the Norilsk section was more than 10000–100000 years.

In the course of the formation of this section, the eruptive activity occurred in the form of either volcanic pulses or single eruptions. Overall, 25 pulses and single eruptions took place during the geological history of the Norilsk section, whose net duration (excluding periods of quiescence) did not exceed 7000–8000 years (see the discussion of the first paleomagnetic constraint in the section The Method).

The number of pulses and single eruptions (16 and 17, respectively) established for the Arydzhangskaya and Onkuchakskaya suites shows that the net eruptive activity during the deposition of the Kotui section (excluding the quiescence periods) also lasted about 7000–8000 years. The total time of the Kotui section's formation was probably a bit shorter than 10–100 thousand years.

In addition,

(1) The comparison of the virtual geomagnetic poles calculated for the Norilsk and the Kotui sections provides no grounds to suggest that these sections were formed at different time intervals;

(2) The amplitude level of the secular geomagnetic variations at the Permian–Triassic boundary was close to that for the past 5 Ma.

ACKNOWLEDGMENTS

We are grateful to G.Z. Gurariy for reviewing the manuscript and his valuable comments. The work was supported by the Russian Foundation for Basic Research (grants nos. 10-05-00557a, 09-05-01180-a) and RFBR-PICS project (grant no. 09-05-91056-NTsNI_a).

REFERENCES

Chenet, A.L., Fluteau, F., Courtillot, V., et al., Determination of Rapid Deccan Eruptions across the Cretaceous-Tertiary Boundary Using Paleomagnetic Secular Variation: Results from a 1200-m-Thick Section in the Mahabaleshwar Escarpment, *J. Geophys. Res.*, 2008, vol. 113, p. B04101.

Chenet, A.L., Courtillot, V., Fluteau, F., et al., Determination of Rapid Deccan Eruptions across the Cretaceous-Tertiary Boundary Using Paleomagnetic Secular Variation: 2. Constraints from Analysis of Eight New Sections and Synthesis for a 3500-M-Thick Composite Section, *J. Geophys. Res.*, 2009, vol. 114, p. B06103.

Collinson, D., *Paleomagnetism*, Cambridge: Cambridge Univ. Press, 1980.

Courtillot, V. and Olson, P., Mantle Plumes Link Magnetic Superchrons To Phanerozoic Mass Depletion Events, *Earth Planet. Sci. Lett.*, 2007, vol. 260, nos. 3–4, pp. 495–504.

Cox, A., Research Note: Confidence Limits for the Precision Parameter, *Geophys. J. Roy. Astron. Soc*, 1969, vol. 17, pp. 545–549.

Davies, G.F., *Dynamic Earth: Plates, Plumes, Mantle Convection*, Cambridge: Cambridge Univ. Press, 1999.

Enkin, R.J., *A computer Program Package for Analysis and Presentation of Paleomagnetic Data*, Sidney, B.C.: Pacific Geoscience Centre, Geological Survey of Canada, 1994, p. 16.

Fedorenko, V.A., Lightfoot, P.C., Naldrett, A.J., et al., Petrogenesis of the Flood-Basalt Sequence at Noril'sk, North Central Siberia, *Inter. Geol. Rev,* 1996, vol. 38, pp. 99–135.

Fedorenko, V., Czamanske, G., Zen'ko, T., et al., Field and Geochemical Studies of the Melilite-Bearing Arydzhangsky Suite, and An Overall Perspective on the Siberian Alkaline-Ultramafic Flood-Volcanic Rocks, *Int. Geol. Rev*, 2000, vol. 42, no. 9, pp. 769–804.

Gallet, Y., Genevey, A., and Le Goff, M., Three Millennia of Directional Variation of the Earth'S Magnetic Field in Western Europe As Revealed by Archeological Artefacts, *Phys. Earth Planet*, 2002, vol. 131, no. 1, pp. 81–89.

Gurevitch, E.L., Heunemann, C., Rad'ko, V., et al., Palaeomagnetism and Magnetostratigraphy of the Permian–Triassic Northwest Central Siberian Trap Basalts, *Tectonophysics*, 2004, vol. 379, pp. 211–226.

Heunemann, C., Ludwig-Maximilians University at Munchen, personal communication, 2004a.

Heunemann, C., Krasa, D., Soffel, H., et al., Directions and Intensities of the Earth's Magnetic Field during a Reversal: Results from the Permo-Triassic Siberian Trap Basalts, Russia, *Earth Planet. Sci. Lett.*, 2004b, vol. 218, pp. 197–213.

Kamo, S.L., Czamanske, G.K., Amelin, Yu., et al., Rapid Eruption of Siberian Flood-Volcanic Rocks and Evidence for Coincidence with the Permian–Triassic Boundary and Mass Extinction at 251 Ma, *Earth Planet. Sci. Lett.*, 2003, vol. 214, pp. 75–91.

Khramov, A.N., Goncharov, G.I., Komissarova, R.A., et al., *Paleomagnitologiya* (Paleomagnetology), Leningrad: Nedra, 1982.

Kirschvink, J.L., The Least-Square Line and Plane and the Analysis of Paleomagnetic Data, *Geophys. J. R. Astr. Soc.*, 1980, vol. 62, pp. 699–718.

Latyshev et al., in *Moscow University Geology Bulletin*, 2011, in press.

McElhinny, M.W. and McFadden, P.L., Palaeosecular Variation Over the Past 5 Myr Based on a New Generalized Database, *Geophys. J. Int.*, 1997, vol. 131, no. 2, pp. 240–252.

McElhinny, M.W., Geocentric Axial Dipole Hypothesis: A Least Squares Perspective, in *Timescales of the Paleomagnetic Field*, Channell, J.E.T., Kent, D.V., Lowrie, W., and Meert. J.G., Eds., AGU Geophysical Monograph Series, Washington D.C., 2004, vol. 145, pp. 1–12.

McFadden, P.L., The Combined Analyses of Remagnetization Circles and Direct Observations in Paleomagnetism, *Earth Planet. Sci. Lett.*, 1988, vol. 87, pp. 53–58.

McFadden, P.L. and McElhinny, M.W., Classification of the Reversal Test in Palaeomagnetism, *Geophys. J. Int.*, 1990, vol. 103, pp. 725–729.

Merrill, R., McFadden, P., and McElhinny, M., *The Magnetic Field of the Earth: Paleomagnetism, the Core, and the Deep Mantle*, San Diego: Academic Press, 1996.

Pavlov, V., Courtillot, V., Bazhenov, M., and Veselovsky, R., Paleomagnetism of the Siberian Traps: New Data and a New Overall 250 Ma Pole for Siberia, *Tectonophys.,* 2007, vol. 443, pp. 72–92.

Renne, P.R. and Basu, A.R., Rapid Eruption of the Siberian Traps Flood Basalts at the Permo-Triassic Boundary, *Science*, 1991, vol. 253, pp. 176–179.

Sepkoski, J.J., A Compendium of Fossil Marine Families, *Milwaukee Public Museum. Contributions to Biology and Geology*, 1982, vol. 51, p. 125.

Shipunov, S.V., Tests of Significance in Paleomagnetism, *Fiz. Zemli*, 1999, no. 6, pp. 89–92 [*Izv. Phys. Earth* (Engl. Transl.), 1999, vol. 35, no. 6, pp. 518–521].

Tauxe, L. and Kent, D.V., A Simplified Statistical Model for the Geomagnetic Field and the Detection of Shallow Bias in Paleomagnetic Inclinations: Was the Ancient Magnetic Field Dipolar?, *Timescales of the Paleomagnetic Field*, Channell, J.E.T., Kent, D.V., Lowrie, W., and Meert. J.G., Eds., AGU Geophysical Monograph Series, Washington D.C., 2004, vol. 145, pp. 101–116.

Thordarson, T. and Self, S., Atmospheric and Environmental Effects of the 1783–1784 Laki Eruption: a Review and Reassessment, *J. Geophys. Res.*, 2003, vol. 108, no. D1, p. 4011.

Torsvik, T.H., Smethurst, M.A., and Pesonen, L.J., GMAP—Geographic Mapping and Paleoreconstruction Package, *Norv. Geol. Serv. Rep*, 1990, no. 90019, p. 64.

Vandamme, D., A New Method To Determine Paleosecular Variation, *Phys. Earth Planets*, 1994, vol. 85, pp. 131–142.

Vasil'ev, Yu.R., Zolotukhin, V.V., Feoktistov, G.D., and Prusskaya, S.N., Estimation of Volumes and the Problem of Genesis of the Permian–Triassic Trap Magmatism of the Siberian Plarform, Geol. Geofiz., 2000, vol. 41, no. 12, pp. 1696–1705.

Watson, G.S., A Test for Randomness of Directions, Mon. Not. Roy. Astron. Soc., Geophys. Suppl., 1956, vol. 7, pp. 160–161.

Yegorov, V.N., Stratification and Correlation of the Triassic Volcanic Sequences of the Maimecha–Kotui Province, in *Nedra Taimyra* (Taimyr Interiors), Samoilov, A.G. and Malich, N.S., Eds., St. Petersburg: VSEGEI, 1995, Issue 1, pp. 141–154.

Zijderveld, J.D.A., A.C. Demagnetization of Rocks: Analysis of Results, *Methods in Paleomagnetism*, Collinson, D.W. and Creer, K.M, Eds., Amsterdam: Elsevier, 1967, pp. 254–286.