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New Paleomagnetic Data on Late Cretaceous Chukotka Volcanics: the Chukotka Block Probably Underwent Displacements Relative to the North American and Eurasian Plates after the Formation of the Okhotsk-Chukotka Volcanic Belt?

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Abstract—Paleomagnetic studies of several Late Cretaceous volcanic sections of the Okhotsk–Chukotka volcanic belt have been carried out in the Bilibino region of the Chukotka Autonomous Okrug and along the Pevek–Egvekenot road. Extensive collections have been acquired and analyzed. The laboratory experiments isolated the ancient characteristic magnetization component reflecting the direction of the geomagnetic field at the time of formation of the studied rocks (~85 Ma ago). The primary character of the revealed characteristic magnetization component is supported by the positive regional fold test and by the coincidence of the paleomagnetic pole calculated from this component with that previously obtained for Chukotka from the rocks of similar age (Stone et al., 2009). The paleomagnetic pole calculated from the combination of the previous and our newly obtained data (Plat = 69.3°, Plong = 180.7°, N = 99, A95 = 5.1°) indicates that the sampled rocks were formed in the immediate vicinity of the geographic pole. The reliability of the existing Late Cretaceous paleomagnetic poles for Eurasia and North America is analyzed, and the refined poles are calculated for these plates for the time of ~85 Ma. The reconstruction of the Chukotka–Kolyma–Omolon block's position relative to Eurasia and North America allowing for the paleomagnetic poles calculated for that time is proposed. The reconstruction implies that from the formation time of the studied rocks up to the present, the Chukotka–Kolyma–Omolon block has undergone relatively small (tens to first hundreds of km) southward movements relative to the North American plate and has been noticeably shifted (by a few hundred km) relative to the Eurasian plate. Our reconstruction is close to that proposed in (Otofuji et al., 2015) but, in contrast to the latter, it does not require a collision between the Chukotka–Kolyma–Omolon block and Eurasia after 80 Ma ago.

Keywords: paleomagnetism, Chukotka, volcanics, Late Cretaceous, paleoreconstructions
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INTRODUCTION

Understanding the geological evolution of Northeast Eurasia, eastern Arctic and the North Pacific is impossible without unraveling the tectonic history of the Chukotka Peninsula (hereinafter Chukotka) which is also important for solving a number of the applied problems associated with mineral prospecting in the continental part of the region and adjacent Arctic shelf. An important element in the general problem of reconstructing the Mesozoic and Cenozoic tectonic history of Chukotka is elucidating its relationship with the rest of Eurasia, Alaska microcontinent, and North American tectonic plate.

This issue is largely but, of course, not fully reduced to ascertaining the possibility of mutual displacements of the host tectonic blocks of these territories on the different intervals of geological history.

The paleomagnetic method has been traditionally an efficient instrument in solving such problems providing, subject to the appropriate conditions, important constraints on the age and scale of the tectonic movements. Despite this, only one paleomagnetic study over the entire period of geological exploration of Chukotka has been followed through completely (with publishing the results in a peer-reviewed journal) (Stone et al., 2009). The authors of the cited work studied the paleomagnetism of the volcanics of the

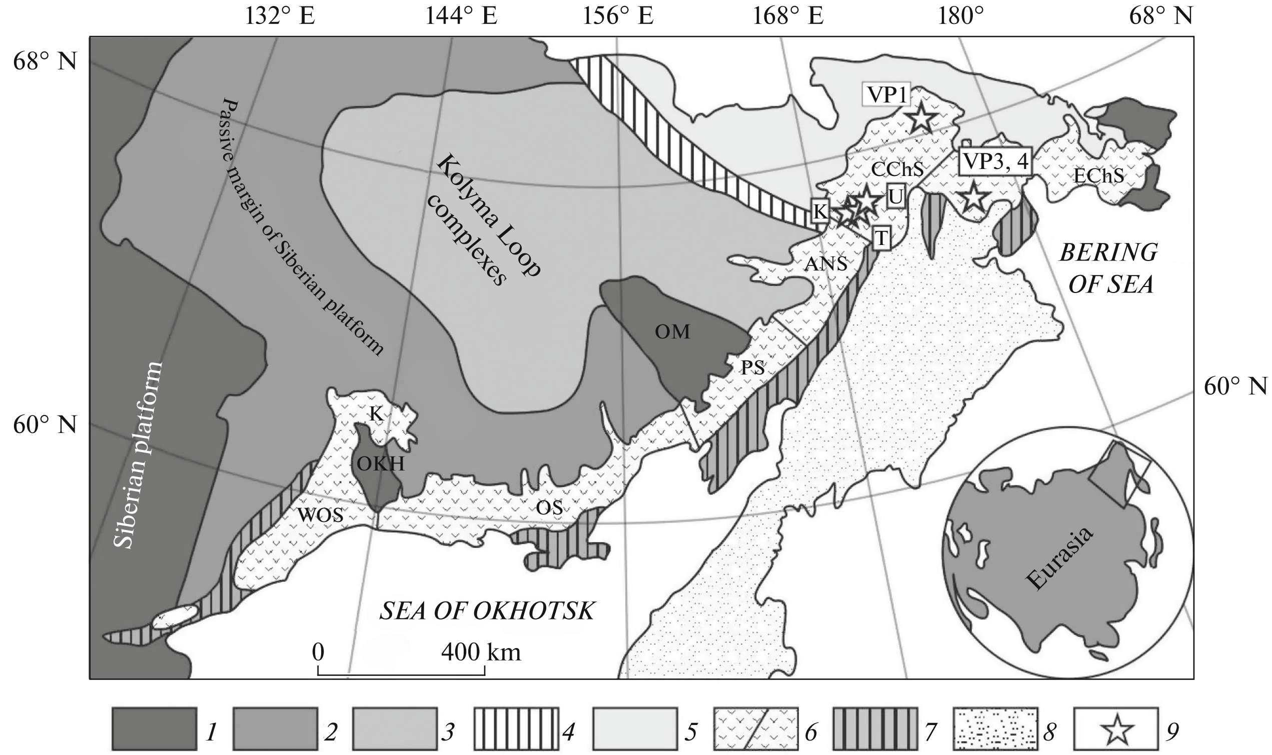

Fig. 1. Tectonic scheme of Northeast Asia (based on (Tikhomirov, 2018) with simplifications). (*1*) Siberian platform and cratonic blocks (OKH, Okhotsk massif, OM, Omolon massif); (*2*) passive margin of Siberian platform; (*3*) Kolyma loop complexes—tectonic collage of diverse terranes including blocks of ancient continental crust, complexes of various continent-ocean transition zones and fragments of ophiolitic sections; (*4*) South Anyui suture zone (SAS); (*5*) passive margin of Chukotka-Alaska microcontinent; (*6*) Okhotsk–Chukotka volcanic belt with boundaries of segments: EChS, East Chukotka Segment; CChS, Central Chukotka; ANS, Anadyr; PS, Penzhina; OS, Okhotsk; WOS, West Okhotsk; PD, Pre-Dzhugdzhur depression; K, Kuidusun depression; (*7*) magmatic complexes of Late Jurassic–Early Cretaceous (pre-Albian) volcanic arcs; (*8*) Koryak-Kamchatka fold region; (*9*) location of study objects: K, Kupol; T, Timofeevka; U, Ugatkyn; P, Palyavaam; V, Valunistyi; M, Matachingai, E, Egvekinot.

Okhotsk-Chukotka volcanic belt (OChVB) outcropping in the region of Lake Elgygytgyn. With all the importance of the paleomagnetic data obtained so far, their quantity and accuracy are however apparently insufficient for reliable tectonic interpretations. The latter require an extensive paleomagnetic database and, in turn, new paleomagnetic studies for its creation.

In this work, we present the data of paleomagnetic studies of the Late Cretaceous Chukotka volcanics carried out in 2019–2020. These data contain new important information concerning the possibility of displacements of the Chukotka block relative to the North American and Eurasian plates since the time of formation of the studied objects in Late Cretaceous.

STUDY OBJECTS AND SAMPLING PROCEDURE

Over the field season of summer 2019 in the Bilibino, Chaun, Iultin and Anadyr districts of the Chukotka Autonomous Okrug, we have picked extensive collections of oriented samples of the volcanic rocks participating in the structures of the Okhotsk–Chukotka volcanic belt. The geographic locations of the sampled sections (Timofeevka, Kupol, Ugatkyn, VP-1, VP-3, and VP-4) are shown in Fig. 1.

The Cretaceous Okhotsk-Chukotka volcanic belt (OChVB) is one of the world's largest provinces of magmatism spatially related to the continental margins (Belyi, 1977; Tikhomirov, 2012; Khanchuk et al., 2019). Having a width of 100–300 km, it stretches for more than 3000 km along the Pacific Ocean margin of Asia from the western coast of the Sea of Okhotsk to the east of the Chukchi (Chukotka) Peninsula. Within the territory of Chukotka, OChVB is largely superimposed on the structures of the Chukotka block (or the Chukotka-Alaska microcontinent according to (Miller et al., 2017)) whose boundary with the rest of Eurasia (except for Koryakia and northern part of Kamchatka) follows along the South Anyui zone (Fig. 1). In many works (Miller et al., 2018; Sokolov et al., 2015; Kuzmichev, 2009), this zone is considered as a suture formed in the second half of the Mesozoic due to the closure of the South Anyui Ocean which separated the Chukotka block and the Kolyma-Omolon superterrane.

The Chukotka block is a unit of the continental crust which currently composes most of the Chukotka Peninsula. In the tectonic zoning scheme (Bogdanov et al., 1992) this block comprises the Anyui and Chaun Mesozoic folded zones and the East Chukotka cratonic block. According to the accepted paleotectonic reconstructions (Parfenov et al., 2009; Grantz et al., 2011; Shepherd et al., 2013), in the Early Mesozoic the Chukotka (Chukotka-Alaska) block was separated from the North American and Siberian continents by the basins with oceanic crust. The boundary between the Chukotka block and the Late Mesozoic and Cenozoic Koryakia and northern Kamchatka accreted complexes is drawn along the outlines of the southeastern outcrops of the Okhotsk-Chukotka belt structures.

In this paper, as well as in many other works, the Kolyma-Omolon superterrane is understood as a collage of diverse terranes that were amalgamated into a single block of the continental crust in the Jurassic. In the west and in the north (in the present-day coordinates), this block was bounded by the relics of the Oymyakon and South Anyui oceanic basins, and in east, by the Paleo-Pacific (e.g., (Shepherd et al., 2013)). The Late Jurassic closure of the Oymyakon basin resulted in the accretion of the Kolyma-Omolon block to the margin of the Siberian continent (e.g., (Didenko et al., 2002; Laverov et al., 2013)). The boundary of the block is traced by the relics of the Uyandina-Yasachnen volcanic belt and the coeval Main batholith belt (Akinin et al., 2009); however, the position of the respective suture zone has remained debatable.

In the geological literature it is almost universally accepted (Otofuji et al., 2015; Parfenov et al., 2009; Sokolov, 2010) that after the closure of the South Anyui Ocean, the Chukotka block has got amalgamated with the Kolyma-Omolon superterrane. This resulted in the formation of a tectonic that we will hereinafter refer to as the Chukotka-Kolyma-Omolon block.

It is believed that the formation of OChVB began after the termination of compressional activity in the region which, in particular, resulted in the fact that the signs of significant deformations in the volcanics of the belt are, as a rule, absent (Sokolov et al., 2010; Miller et al., 2018). The bedding of the volcanic flows is typically controlled by the paleorelief and by the elements of the structures of compensatory subsidence—calderas and volcanotectonic depressions (Tikhomirov, 2018). According to the zoning scheme proposed in (Bely, 1977), the objects studied in this paper pertain to the Central Chukotka and East Chukotka segments of OChVB.

Currently, the age determinations of the sampled sections are based on the data obtained from the rocks which (1) are more or less reliably correlated with the rocks studied in our work; (2) pertain to the same stratons, and (3) outcrop relatively close to the regions of our field studies.

The existing isotope dating data (see Table 1) constrain the age of the studied strata with an error of at most ± 5 Ma. However, the significant lateral variability of the OChVB sections limits the possibilities of lithological correlation of the strata (Tikhomirov, 2018). If a sample for dating was picked beyond a studied section, the obtained age can only conditionally be applied to the section.

We note that the age determination accuracy within 5 Ma is fairly sufficient for our study because of the smallness of plate displacement over this time interval and the known fact of long standstills of Late Cretaceous paleomagnetic poles for North America and Eurasia (Besse et al., 2003; Kent et al., 2010; Torsvik et al., 2012).

Samples for paleomagnetic studies were collected by the site method (Butler, 1998); most sites correspond to the individual lava flows, some sites are outcrops of tuffs, ignimbrites, and other volcanics. The belonging of the rocks of the studied sites to a particular formation and the number of the samples collected from each site are presented in Table 1. Overall, during our field studies of 2019, we sampled six spatially separated sections and collected 963 oriented samples from 68 sites. The studied outcrops mostly lack any signs of significant secondary transformations; the rock bedding is horizontal or monocline with a gentle slope at an angle of 12°–16° at most. The orientation of the samples was measured by a magnetic compass and corrected for declination based on the 12th-generation IGRF model (Thébault et al., 2015). Each sample was picked with checking the effect of the rocks on the readings of the magnetic needle.

PALEOMAGNETISM

The laboratory paleomagnetic studies were conducted by standard technique (Khramov et al., 1982; Butler, 1998; Tauxe, 2010) in the paleomagnetic laboratories of the Schmidt Institute of Physics o the Earth of the Russian Academy of Sciences (IPE RAS) in Moscow and in the Ludwig Maximilian University in Munich. The alternating-magnetic-field demagnetization (AF demagnetization) was carried out at the Paleomagnetic laboratory of IPE RAS. The instruments in this laboratory allow for AF demagnetization in the automated mode which substantially increases the efficiency of laboratory measurements and significantly reduces the effect of the probable human errors.

Demagnetization of the samples from the Kupol and Ugatkyn sections was carried out at the Paleomagnetic laboratory of the University of Munich. The component composition of magnetization in these samples was established using thermal demagnetization.

Table 1. Paleomagnetic directions isolated in studied rocks

Site no.	Formation and lithology data according to (Imaeva et al., 2016b)	Isotope age	*N*	*n*	Dg	Ig	Ds	Is	K	alfa95	*Km*, × 10^{-3} SI units
Kupol 66°51′ N, 169°51′ E											
1	Emuneret Formation, predominantly tuffs and ignimbrites of acidic composition, at places interbeds of basic and intermediate lavas	Sample 3 km west of study region, close to section top: 86.8 ± 2.7 Ma, Ar–Ar dating of plagioclase (Tikhomirov, 2006)	14	11	47.1	83.5	47.1	83.5	544	2	5.29
2			13	10	26	78.3	26	78.3	302.2	2.8	5.37
3			13	9	9.3	79.9	9.3	79.9	153	4.2	3.17
4			13	7	34.2	64.5	34.2	64.5	274.7	3.6	15
5	Koekvun Formation, predominantly basic and intermediate lavas, tuffs of same composition	Sample 4 km west of study region, approximately at section middle: 93.7 ± 1.2 Ma, Ar–Ar dating of amphibole; 91.8 ± 1.6 Ma, Ar–Ar dating of plagioclase (Tikhomirov, 2006)	16	14	327.2	84.8	327.2	84.8	97.9	4	23.2
6			14	13	85	85.2	85	85.2	77.6	4.7	19.6
7			12	13	356.1	72	356.1	72	73.3	4.9	23
8			14	9	316.2	67.8	316.2	67.8	167	4	22.3
Timofeevka 66°56′ N, 170°15′ E											
1	Koekvun Formation, predominantly basic and intermediate lavas, tuffs of same composition	Rocks pertain to the same structure as Ugatkyn and Kupol rocks and are close to them in age	15	12	252.2	80.9	162.7	78.1	90.4	4.6	4.44
2			8	4	289.2	74.1	219.4	85.7	65.7	11.4	3.62
2			5	4	265.3	70.3	217.2	77.5	129.3	8.1	0.56
3			12								0.14
4			13	11	332.1	70.2	8.2	75.1	225.5	3	16.3
5			15	14	328	70.8	5.4	76.4	98.8	4	28.6
6			13	13	316.9	67.9	339.7	77.9	82.6	4.6	18.1
7			13	13	317	73.2	0.7	80.5	242.2	2.7	23.5
8			13								23.4
9			13	13	294.4	76.1	342.3	86.8	385.5	2.1	24.1
10			13	10	10.3	80.7	63.8	75.2	44.4	7.3	20.1
11			13	13	321.6	62.7	314.8	79.6	195.6	3	24.3
12			14	12	333.4	76.1	117.1	86.3	102.4	4.3	19.4
13			15	15	340.8	57.8	355	73.7	160	3	13.1
14			14	14	273	74	206	81.5	100.7	4	20
15			10	6	251.5	82.4	172.5	73.4	173.5	5.1	17.8
17			12	8	283.4	77.2	195.3	78.6	144	4.6	18.1
18			14	12	258	79.4	183.6	73.8	87.2	4.7	34.2
19			13	13	341.2	76.7	106.1	84.6	127.4	3.7	17.6
20			16	11	5.1	78	101.1	79.3	173.8	3.5	19
Ugatkyn 67°14′ N, 170°59′ E											
1	Pykarvaam Formation, predominantly acidic lavas, ignimbrites, tuffs	Sample 13 km east of study region, approximately corresponds to overlying complexes: 85.4 ± 1.2 Ma, U-Pb zircon dating (Tikhomirov, 2012)	13	9	50.6	62.8	71.7	59.4	140.8	4.4	11.1
3			12	12	247.7	84.2	163.9	78.9	80.8	4.9	12.7
4			15	14	329.6	86.2	128.4	81.6	103.6	3.9	22.7
5			13	11	257.7	72	217.5	74.8	87.8	4.9	6.35
6			13	10	342.9	80	78.9	84.4	89.5	5.1	7.09
7			14	13	279.1	75.5	223.9	81.6	93.9	4.3	12.8
8			23	19	346.8	59.5	2.8	68.8	53.7	4.6	6.5

Table 1. (Contd.)

Site no.	Formation and lithology data according to (Imaeva et al., 2016b)	Isotope age	*N*	*n*	Dg	Ig	Ds	Is	K	alfa95	*Km*, $\times 10^{-3}$ SI units
VP1 (Palavaam) 68°28′ N, 174°32′ E											
1	Alkakvun Formation, predominantly acidic lavas, tuffs, ignimbrites	Alkakvun Formation, 20 km north of study region, approximately corresponds to section base: 88.6 ± 2.1 Ma, U-Pb zircon dating (Tikhomirov, 2012)	15	12	260.1	61.1	260.1	61.1	95.1	4.5	0.29
2			15	13	227.7	72.1	227.7	72.1	41.4	6.5	3.58
3			15	12	251.4	77.7	251.4	77.7	89.6	4.6	2.77
4			15	12	302.4	75.6	302.4	75.6	66.3	5.4	4.97
5	Kalenmuvaam Formation, predominantly lavas, tuffs, ignimbrites of intermediate composition		15	14	231.5	77.5	231.5	77.5	05.4	3.9	7.93
6-1			8	7	101.7	76.9	101.7/121.8	76.9/65.6		7.3	10.7
6-2			15	12	81.9	80.9	81.9/118	80.9/70.9	1	6.2	5.79
8			15	8	40.9	79.4	40.9/96.4	79.4/82.1	186.1	4.1	3.94
9			16	11	46.1	76.9	46.1/77.8	76.9/78.3	130.1	4	6.8
10			16	6	43.2	82	43.2/157.4	82.0/85.1	244.4	4.3	6
11			14	12	29.9	77.3	29.9/77.2	77.3/87.2	80.8	4.9	5.45
VP4 (Valunistyi) 66°26′ N, 177°37′ E											
1	Nunligran Formation, predominantly lavas and tuffs of basic and intermediate composition	Leurvaam Formation, 12 km southeast from study region, corresponds to approximately underlying complexes: 80.6 ± 1.3 Ma, U-Pb zircon dating (Sakhno, 2010)	13	10	109.6	–35.7	109.6	–35.7	41.3	7.6	21.9
2			12	11	316.8	–9.5	316.8	–9.5	49.3	6.6	31.2
3			15	14	299.2	–30.9	299.2	–30.9	41.8	6.2	29.5
4			15	12	62.4	76.7	62.4	76.7	82.3	4.8	27.8
5			17	13	284.4	76	284.4	76	116.6	3.9	28.2
6			16	12	215.9	82.5	215.9	82.5	54.8	5.9	37.6
7			16	13	46.9	62.4	46.9	62.4	128.4	3.7	27.1
8			17	9	196.5	81.4	196.5	81.4	24.1	10.7	39.1
9			16	15	119.1	85.8	119.1	85.8	99.1	3.9	31.3
10			16	15	26.1	69.1	26.1	69.1	46.3	5.7	23.7
11			15	12	64.8	73.9	64.8	73.9	44	6.6	37.2
12			15	14	62.1	80	62.1	80	62	5.1	26
13			15	11	63.5	74.6	63.5	74.6	48.5	6.6	30.1
VP3 (Valunistyi) 66°21′ N, 177°31′ E											
1	Ekitykin Formation, predominantly basic or intermediate lavas, tuffs of same composition	Leurvaam Formation, 20 km northeast of study region, approximately corresponds to complexes overlying the Ekitykin Formation: 80.6 ± 1.3 Ma, UPb zircon dating (Sakhno, 2010). As the studied flows of sections VP3 and VP4 comprise a single structure and have similar composition, they are assumed to have a close age	15	13	109.6	80.2	109.6	80.2	48.6	6	9.67
3			16	13	51.4	81.4	51.4	81.4	109.5	4	11.8
4			16	12	139.2	64.2	139.2	64.2	98.1	4.4	15.4
4-1			13	9	106.3	79.1	106.3	79.1	121.8	4.7	24.4
5			16	12	156.4	69.3	156.4	69.3	234.2	2.8	22.5
6 +7			30	25	70.4	74.8	70.4	74.8	52.5	4	21.4

N is the number of samples picked from a site; *n* is the number of samples used for calculating paleomagnetic directions; Dg (Ds), Ig (Is) are declinations and inclinations in the geographic (stratigraphic) coordinate system; K is precision parameter, alfa95 is the radius of the confidence circle; *Km* is the magnetic susceptibility.

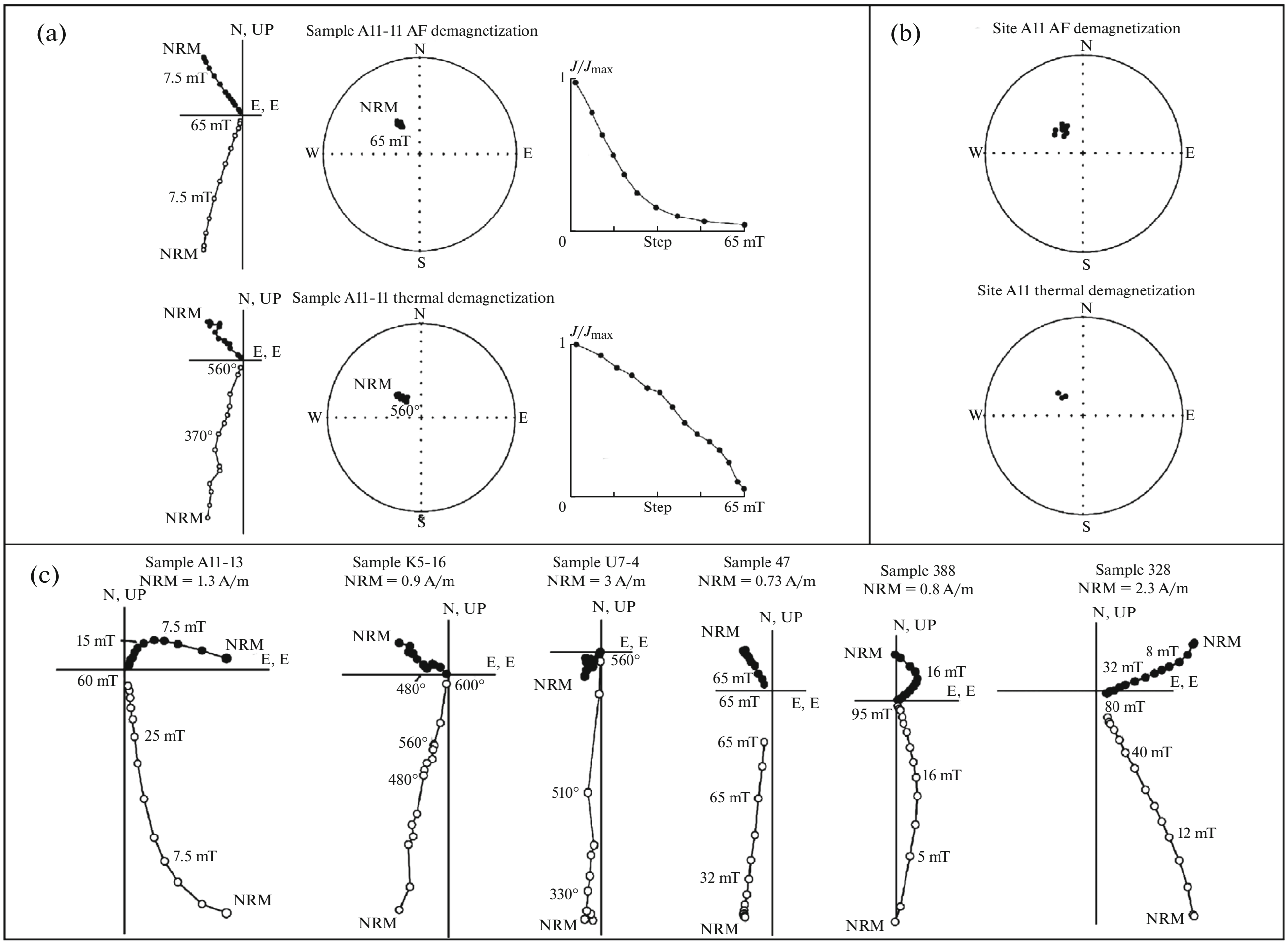

Fig. 2. (a), (b) Comparison of results of thermal and AF demagnetization: (a) examples of Zijderveld diagrams for duplicate specimens from one sample subjected to thermal and AF demagnetization; (b) examples of comparison of magnetization directions within one site based on results of thermal and AF demagnetization; (c) examples of Zijderveld diagrams based on demagnetization results for rocks from Timofeevka (sample A11-13), Kupol (sample K5-16), Ugatkyn (sample U7-4), VP1 (sample 47), VP3 (sample 328), and VP4 sections (sample 388). Filled (open) circles are projections of natural remanent magnetization vector on horizontal (vertical) plane.

At the first stage of the laboratory studies, we compared the results of thermal and AF demagnetization on duplicate specimens cut from 2–3 samples from each site. This comparison has shown that these two types of demagnetization give statistically indistinguishable results therefore demagnetization of samples from the Timofeevka, VP1, VP2, and VP3 sections was carried out using the alternating magnetic field.

A significant part of the studied samples (sites) contain a paleomagnetic record of good and acceptable quality (Fig. 2).

In these samples, demagnetization typically isolates two magnetization components: the first, low-stable low-coercive or low-temperature component with extremely irregular magnetization directions and the second, stable high-coercive or high-temperature characteristic component with positive steep inclinations and declinations spread over all quadrants of the stereogram (Figs. 2 and 3). The low-stability low-coercive component is most likely to be due to the superimposition of recent viscous in situ remagnetization, viscous laboratory remagnetization, and the remagnetization induced by lightning, which are present in different proportions in different samples. The characteristic component apparently corresponds to the direction of the magnetic field at the time of formation of the studied rocks. Some arguments in favor of the primary origin of this component will be discussed below.

The site distribution of the directions of the characteristic component and the corresponding statistical characteristics are presented in Table 1 and illustrated in Fig. 3. Within a number of sites, there have been sharp deviations of some individual directions from the general distribution. These outliers were neglected and considered as sample's orientation errors during

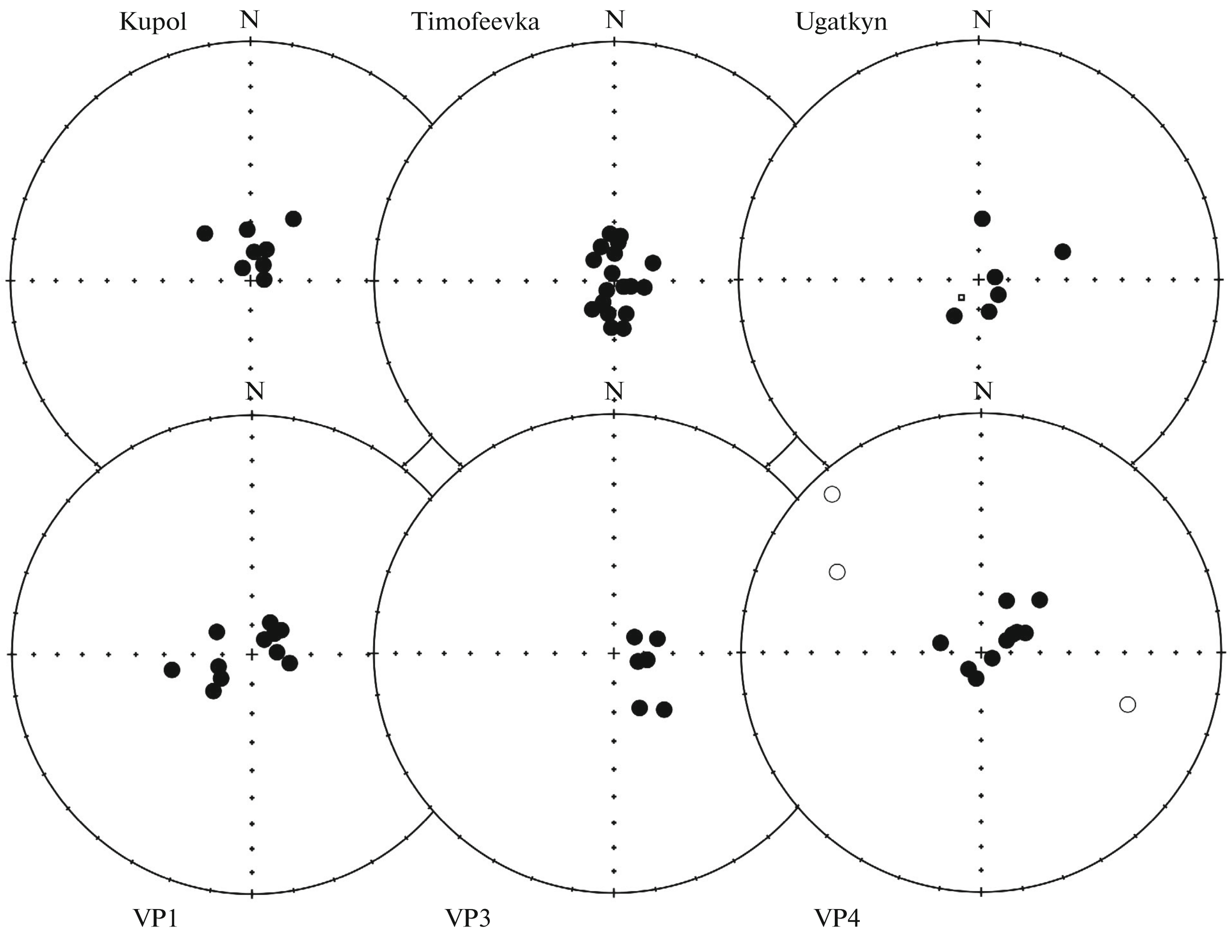

Fig. 3. Distribution of directions of characteristic magnetization components in studied sections: circles are site mean directions; filled and open circles show lower- and upper-hemisphere projections, respectively.

its picking or sawing. The vast majority site-mean directions correspond to normal polarity of the field; however, in three sites from the lower part of the VP4 section, these directions have low and moderate negative inclinations. We consider these directions as reflecting the direction of the transition field (i.e., geomagnetic field during a reversal) and, therefore, exclude them from our calculations.

In the VP1 section, the upper six flows are gently sloping at an angle from 7° to 13° whereas the lower five ones are horizontal (Fig. 4). The field observations indicate that the sloping of the upper six lava flows is primary and associated with the underlying slope topography. Therefore, for these six upper flows we used site-mean directions of characteristic magnetization calculated in the present-day coordinates.

The site-mean directions of characteristic magnetization obtained from all the studied sections were converted into virtual geomagnetic poles. The coordinates (latitude and longitude) of the average pole are Plat = 69.4° N, Plong = 183.7° E with the radius of the confidence circle A95 = 6.1° and the number of sites used for calculations $N = 60$. It is this pole that is discussed hereinafter. If we exclude the data for the tilted flows of the VP1 section, the coordinates of the average pole will differ from the above figure by 1.7° and will be Plat = 70.2° N, Plong = 188.2° E with A95 = 6.7° and $N = 54$.

As of now, we may present two we believe strong arguments in favor of the primary origin of the isolated characteristic magnetization component.

The first argument follows from the comparison of mean directions of characteristic magnetization component calculated for the sites with undisturbed bedding (Kupol, VP1, VP3, VP4 sections) and for the sites where rocks underwent tilting after their formation (Timofeevka and Ugatkyn sections). This comparison is in fact a fold test (Butler, 1998; Khramov et al., 1982). Figure 5 shows that the test (carried out by the procedure described in (McFadden et al., 1990)) is positive: the directions under comparison are statistically indistinguishable in the stratigraphic (ancient) coordinate system and apparently diverge in the geographic (present-day) coordinate system. Since the

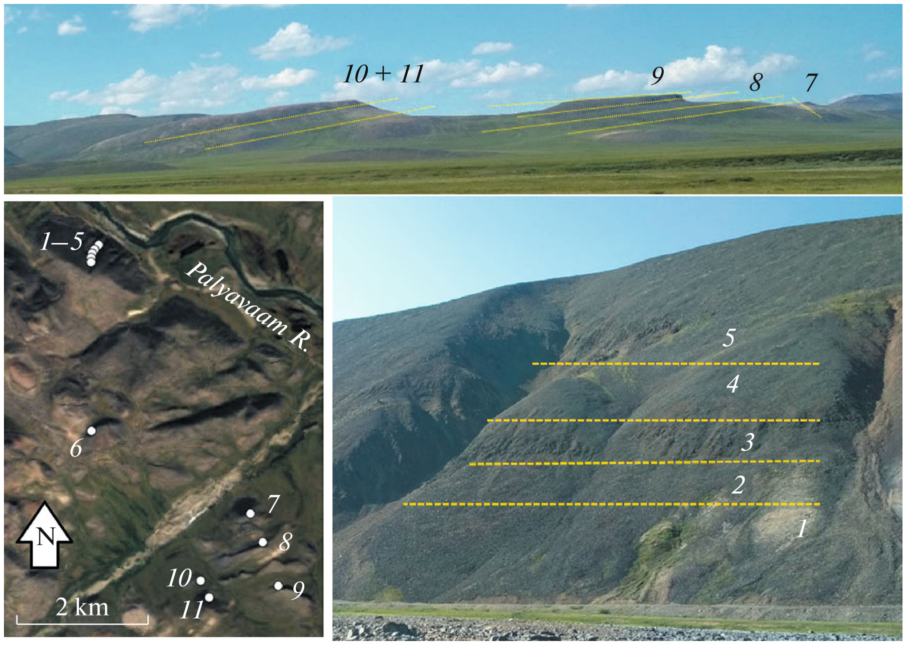

Fig. 4. Lava flow attitude in VP1 sampling region. Top: upper part of section; bottom: lower part of section (right) and layout of lava outcrops in study region (left).

original bedding of the rocks at the studied sites was deformed apparently during compensatory subsidence immediately after the formation of the volcanic sequences, the positive fold test definitely indicates that the isolated characteristic magnetization component was formed at the time of or shortly after the outpouring of lava flows.

The second argument suggesting the primary origin of the isolated characteristic magnetization component is the statistical coincidence of the position of the average pole obtained in this work with that presented in (Stone et al., 2009) for the OChVB volcanics of close age from a relatively nearby site (Plat = 67.0° N, Plong = 171.0° E with A95 = 9.8° and N = 40). The angular distance between these poles is 5.6° with a determination error (calculated according to (Debiche et al., 1995)) of 8.4°.

DISCUSSION

The average pole calculated in our work for the Chukotka block is based on the data from 60 sites. These sites are mainly lava flows studied in five sections located dozens and hundreds km away from each other. The isotope datings (Table 1) indicate that the age of the rocks from the Timofeevka, Kupol, Ugatkyn, and VP1 sections can be several million years larger than that for the VP3 and VP4 sections.

This result together with the fact that the number of the studied flows is quite significant gives ground to believe that the geomagnetic secular variation in this pole has got averaged and the pole can thus be considered paleomagnetic. Based on the existing data, we estimate the age of this pole at ~85 Ma.

The calculated coordinates of the pole (see above) indicate that the studied rocks were formed in very high latitudes in the immediate vicinity of the geographic pole. For the conditional midpoint of the study region with the coordinates 67° N and 173° E, the calculated paleolatitude for the time of ~85 Ma is 83.6° ± 5.1°.

Considering the fact that the paleomagnetic results presented in (Stone et al., 2009) are obtained from the OChVB rocks having a close age, we can combine our data with those of D. Stone et al. and calculate a somewhat more accurate pole. The joint mean pole was calculated by averaging the virtual geomagnetic poles obtained from our sites and those calculated from the volcanic sites in (Stone et al., 2009). The coordinates of the joint pole are Plat = 69.3°, Plat = 180.7° with A95 = 5.1° and N = 99. Using this pole, we estimated the paleolatitude of the conditional midpoint more accurately and obtained it at 86.3° ± 5.1°.

For a long time, information on the position of the Mesozoic paleomagnetic poles in North America and Eurasia has been drawn from (Besse et al., 2003). However, two new recent-decade works (Kent et al., 2010; Torsvik et al., 2012) propose the updated poles for these plates which somewhat differ from the previous ones. We note that if the "new" poles for North America fall in the immediate vicinity of the previous poles, then the "old" and "new" poles for Eurasia differ substantially. Thus, the estimate of the Chukotka block displacement relative to the Eurasian plate will

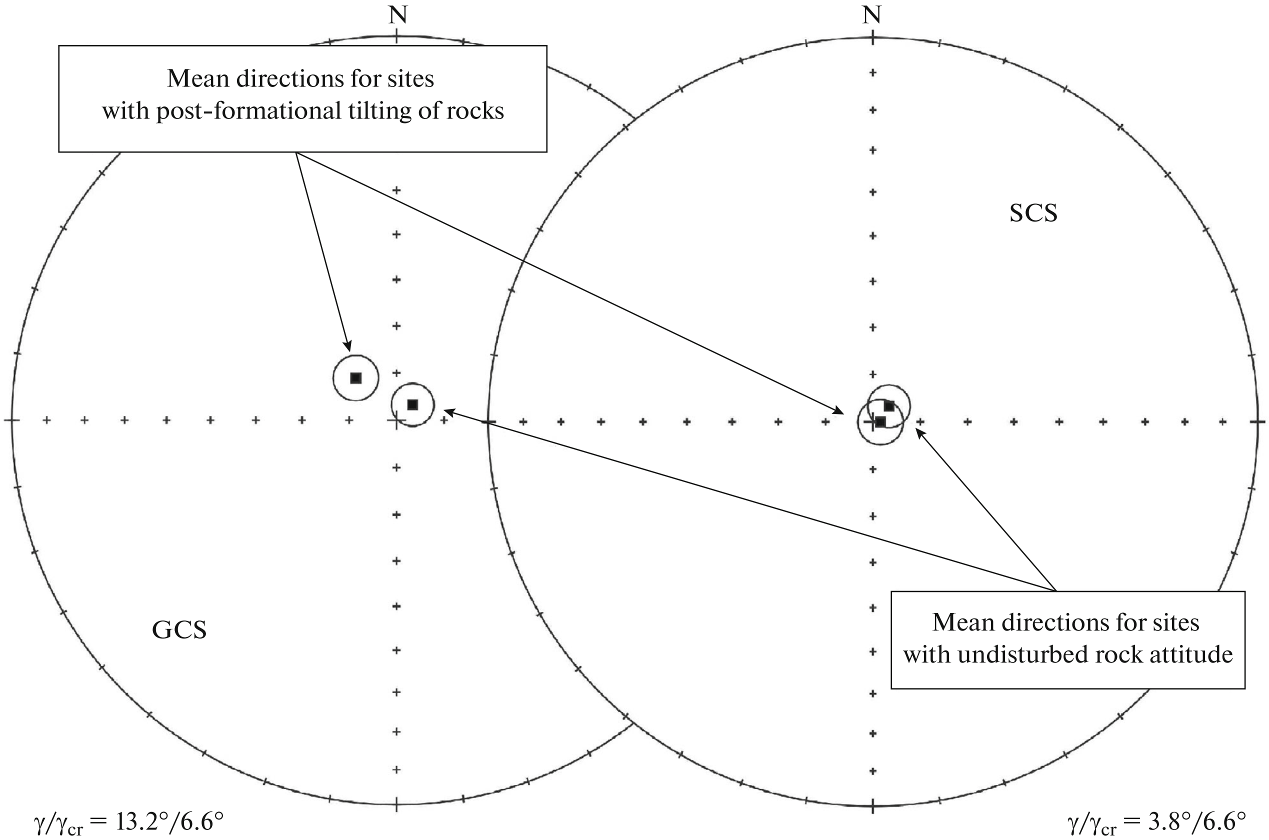

Fig. 5. Comparison of site mean directions calculated for sites with undisturbed rock attitude and with post-formational tilting of rocks. Mean directions are shown by filled squares. Left and right stereograms show directions in geographic (GCS) and stratigraphic coordinate system (SCS), respectively. γ/γ_{cr} is angular distance between compared directions and corresponding critical angle (McFadden and McElhinny, 1990).

vitally depend on which poles we select as reference for Eurasia. Hence, it would be reasonable to compare the reliability of the estimated positions of the paleomagnetic poles proposed by the cited authors for Eurasia for the time level of 80–90 Ma.

The apparent polar wander path (APWP) tracks used by Besse and Courtillot (2003) for determining the poles were obtained by the following algorithm. The paleomagnetic poles of different plates chosen in accordance with the selection results are recalculated into one plate (South Africa) based on kinematic models. Then, these poles are averaged in a moving window with a length of 20 Myr and a synthetic APWP curve (a track) is calculated as a sequence of average poles determined for different time levels. Finally, the obtained APWP curve is recalculated with the use of the selected kinematic models for specific plates.

The same algorithm was employed for calculating the poles by Kent and Irving (Kent et al., 2010) with the only difference that these authors considered a somewhat more extensive set of the initial poles compared to Besse and Courtillot (2003), all the poles were recalculated for the North American plate, and the APWP curve was only constructed for the North American plate.

In contrast to the cited works, Torsvik et al. (2012) constructed the APWP curve for North America and Eurasia only using the data obtained from these plates. This approach has the advantage that the final result is free of the errors associated with kinematic models; however, it relies on substantially fewer initial poles which entails a corresponding loss in accuracy. Given the fact that the number of initial poles for North America and Eurasia is especially small for the considered time interval, this disadvantage can seriously undermine the robustness of the resulting average poles. Correspondingly, the latter challenges the reliability of the North American and Eurasian poles for 80–90 Ma obtained in (Torsvik et al., 2012).

The results for the North American poles obtained by Torsvik et al. (2012) are, however, supported by their closeness to the poles of the same age obtained by a different method and from other initial data (Besse et al., 2003; Kent et al., 2010). At the same time, as noted above, the Eurasian poles from (Torsvik et al., 2012) markedly differ from their counterparts pro-

Table 2. Angular distance between paleomagnetic poles of Chukotka block, Eurasia, and North America

Pole age	Pole coordinates	Angular distance to ~85-Ma paleomagnetic pole of the Chukotka (paleo) microcontinent (Plat = 69.3°, Plong = 180.7° with A95 = 5.1° and *N* = 99, this work)	Paleolatitudes calculated for the conditional mid-point of study region with coordinates 67° N, 173° E
Paleomagnetic poles of Eurasia (Besse and Courtillot, 2003)			
80 Ma	Plong = 206.1°; Plat = 81.4°; A95 = 5.9°; *N* = 14	13.1° ± 5.8°	73.6° ± 5.9°
90 Ma	Plong = 202.1°; Plat = 82.2°; A95 = 5.1°; *N* = 13	13.4° ± 5.4°	73.4° ± 5.1°
Paleomagnetic poles of Eurasia (Torsvik et al., 2012)			
80 Ma	Plong = 156.7°; Plat = 73.5°; A95 = 3.9°; *N* = 4	8.3° ± 4.5°	81.5° ± 3.9°
90 Ma	Plong = 159.0°; Plat = 74.2°; A95 = 6.2°; *N* = 4	7.8° ± 5.4°	81.5° ± 6.2°
Paleomagnetic poles of Eurasia (this work)			
85 Ma	Plong = 176.4°; Plat = 80.4°; A95 = 2.7°; *N* = 27	10.9° ± 4.4°	76.6° ± 2.7°
Paleomagnetic poles of North America (Besse and Courtillot, 2003)			
80 Ma	Plong = 207.4°; Plat = 74.7°; A95 = 5.9°; *N* = 14	9.3° ± 5.8°	76.6° ± 5.9°
90 Ma	Plong = 207.4°; Plat = 75.5°; A95 = 5.1°; *N*= 13	9.7° ± 5.4°	76.4° ± 5.1°
Paleomagnetic poles of North America (Torsvik et al., 2012)			
80 Ma	Plong = 202.8°; Plat = 75.9°; A95 = 7.9°; *N* = 4	8.6° ± 6.7°	77.3° ± 7.9°
90 Ma	Plong = 197.2°; Plat = 75.7°; A95 = 6.3°; *N* = 4	7.6° ± 5.4°	78.5° ± 6.3°
Paleomagnetic poles of North America (Kent and Irving, 2010)			
80 Ma	Plong = 195.0°; Plat = 75.2°; A95 = 4.5°; *N* = 6	8.6° ± 6.7°	79.3° ± 4.5°
90 Ma	Plong = 190.6°; Plat = 75.5°; A95 = 3.4°; *N* = 8	7.6° ± 5.4°	79.9° ± 3.4°
Paleomagnetic pole of North America (this work)			
85 Ma	Plong = 185.0°; Plat = 76.1°; A95 = 2.7°; *N* = 27	6.5° ± 4.4°	80.2° ± 2.7°

Plat, Plong, A95 are the latitude, longitude, and radius of the confidence circle of the paleomagnetic poles. *N* is the number of individual poles used for calculating the coordinates of the average pole.

posed in the other works, which raises even stronger doubts in their reliability (Table 2).

It appears that as of now, the most adequate average poles for the considered plates can be calculated by applying the method used by Besse and Courtillot to the set of the initial poles from (Torsvik et al., 2012). The latter is substantially larger than that of (Besse and Courtillot al., 2003) and, hence, other factors being equal, it is a more solid basis for determining reliable average poles. The poles calculated in this way for the North American and Eurasian plates for ~85 Ma are presented in Table 2. It is notable that the pole for Eurasia calculated in our work (Table 2) is statistically indistinguishable (γ/γ_{cr} = 2.4°/5.1° (Debiche et al., 1995)) from the well-substantiated Late Cretaceous pole for South Siberia (Plat = 82.8°, Plat = 188.5° with A95 = 6.1°) obtained independently in (Metelkin et al., 2007). We consider this fact as an additional evidence supporting the reliability of the Eurasian pole calculated in our work.

We can now focus on the displacements of the discussed tectonic blocks. We note that whichever pole of

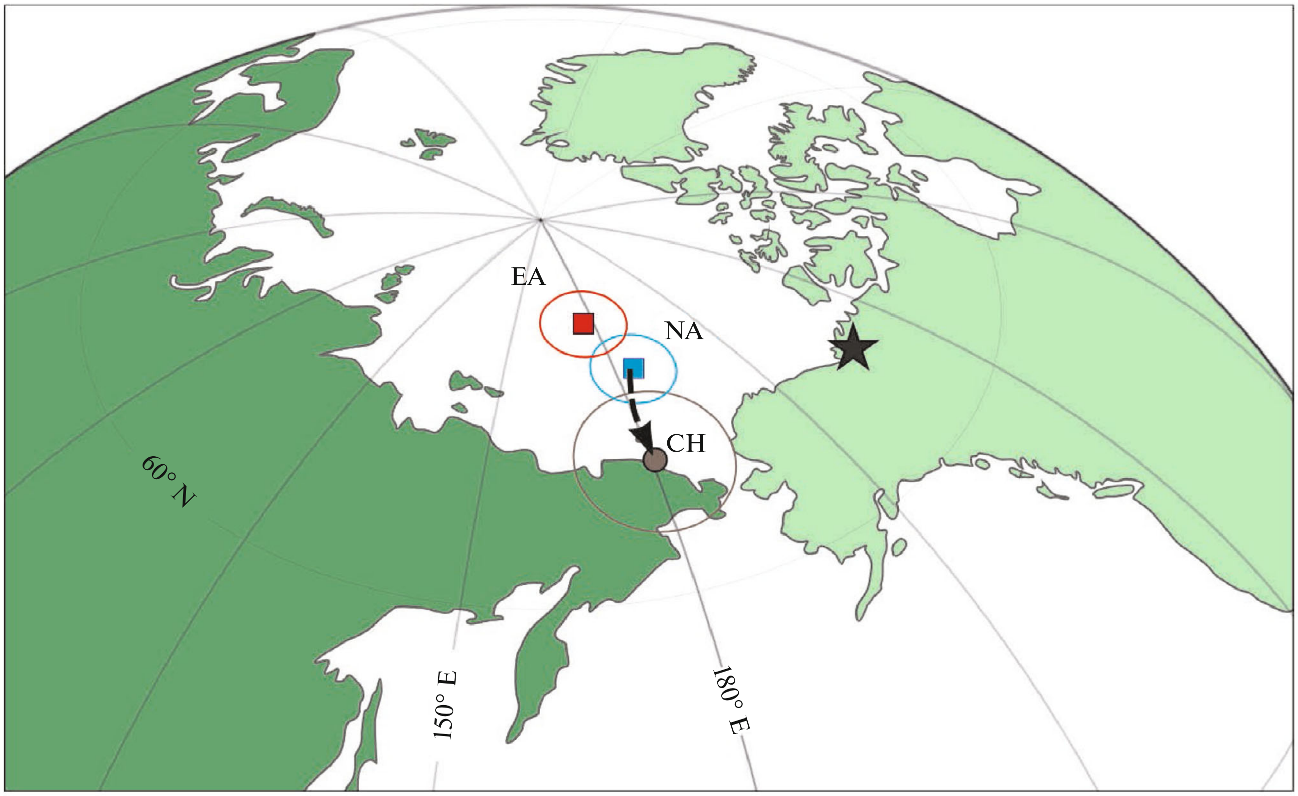

Fig. 6. Comparison of Chukotka pole with North American and Eurasian poles for time ~85 Ma. Gray circle (CH) is Chukotka pole; blue square (NA) is North American pole, red square (EA) is Eurasian pole. Poles are shown with corresponding confidence circles. Black asterisk shows estimated location of Euler pole in region of Mackenzie River mount for probable displacement (dashed arrow) of Chukotka pole relative to North American pole.

the North American Plate we compare with our Chukotka pole (Table 2), the result is the same: the paleomagnetic data definitely indicate that from 80–90 Myr ago to the present, the Chukotka block has underwent relatively small but still quite detectable displacements relative to the North American plate. Thus, our data show that for at least part of the time during the last 80–90 Myr, Chukotka had not been a constituent of the North American Plate.

It appears that the scale and the character of Chukotka displacements relative to the North American Plate can most reliably be estimated from the comparison of the Chukotka and North American poles obtained in this work. These poles are shown in Fig. 6.

Although the confidence circles of these poles overlap, the strict test in (Debiche et al., 1995) validates the statistically significant difference of these poles (see Table 2). The observed divergence of the Chukotka and North American poles could be provided by the rotation of Chukotka relative to North America around the Euler pole located in the region of the mouth of the Mackenzie River (~69° N and 135° W) by an angle of ~10°–15° clockwise (Fig. 6). A similar rotation of Chukotka within the Alaska-Chukotka microcontinent was proposed for explaining the origin of the Amerasian basin in the Eastern Arctic (rotation hypothesis of (Grantz et al., 2011)). It was hypothesized that this rotation could continue either until the Aptian–Albian (~110 Ma ago (Parfenov et al., 2009; Sokolov, 2010)), or up to the second half of Late Cretaceous (~80–70 Ma ago (Miller et al., 2018)). Our data rather agree with the second opinion.

Based on the obtained data we can estimate the relative latitudinal displacements of Chukotka (hereinafter within the Chukotka-Kolyma-Omolon block) and the North American plate over the past 80–90 Myr (Fig. 7). Had Chukotka been part of the North American Plate all this time, the latitude of the conventional midpoint at the time of the formation of the studied rocks would have been 80.2° ± 2.7° (Table 2). Our results indicate that at that time, Chukotka was located at even higher latitudes (see above). The difference between the observed and expected paleolatitudes is 6.1° ± 5.8° which, given the radii of the confidence circles A95 of the compared poles, gives a 95% confidence interval of 1300–30 km for estimating the relative latitudinal displacements.

In contrast to the relative displacements of Chukotka and North America which we are able to detect only at the limit of the achieved accuracy, the compar-

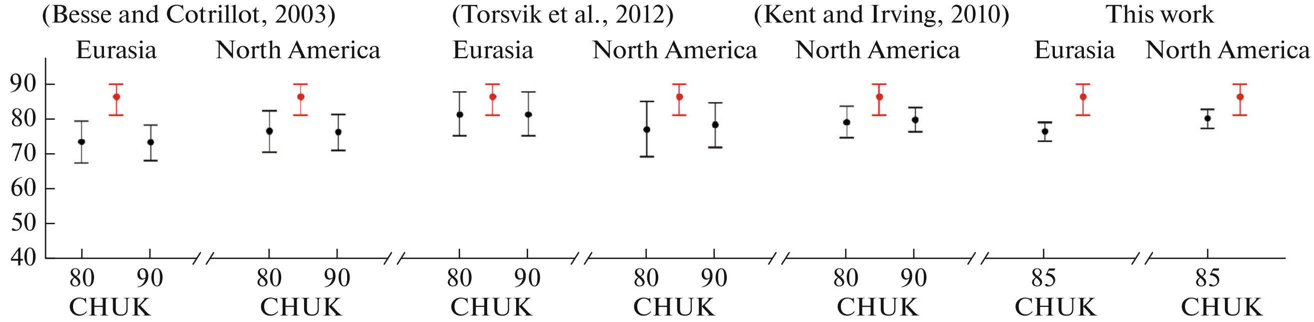

Fig. 7. Comparison of calculated and empirically estimated paleolatitudes for Chukotka (conditional midpoint with coordinates 67° N, 173° E) for ~80–90 Myr ago.

ison of the Chukotka pole with the coeval pole in Eurasia quite confidently testifies to the significant displacements of Chukotka relative to Eurasia during the past 80–90 Myr. It can be seen from the Table that the corresponding paleomagnetic poles differ by 10.9° ± 4.4° while the paleolatitudinal shift of the conditional midpoint relative to Eurasia is 9.4° ± 5.8°. On the linear scale, these figures correspond to the 95% confidence interval of 1700–400 km.

Figure 8 shows the relative positions of North America, Greenland, and Eurasia for the time level of ~85 Myr ago. This reconstruction is based on the kinematic model (Torsvik et al., 2012) and reduced to the geographic pole with the use of the paleomagnetic pole of North America calculated in this work for the considered time level.

On this reconstruction, we superimposed the Chukotka-Kolyma-Omolon block in accordance with its paleolatitudinal position determined in this work. Although the paleomagnetic method is, as known, incapable of determining the paleolongitudes, the surely known position of North America, Eurasia and the adjacent Arctic cratonic regions for 85 Myr ago constrain the position of the Chukotka–Kolyma-Omolon block to that shown in the figure practically leaving no room for the alternative layouts of the Chukotka-Kolyma-Omolon block.

The proposed reconstruction of the position of the Chukotka-Kolyma-Omolon block implies that this block had undergone relatively small (dozens to first hundreds of kilometers) but statistically significant displacements towards the south relative to the North American plate and noticeable displacements (by a few hundred km) relative to the Eurasian plate.

The proposed reconstruction is close to that presented in (Otofuji et al., 2015). However, in contrast to the latter, our reconstruction builds on a more extensive statistical base and does not require a collision of the Chukotka-Kolyma-Omolon block with Eurasia after 80 Myr ago.

The reliability of the proposed reconstruction vitally depends on the reliability of the paleomagnetic poles of North America and Eurasia for the time level of ~85 Myr ago. Each of these poles is flawed and needs further improvement. We stress, however, that these poles are consistent with the up-to-date knowledge of Late Cretaceous paleomagnetism of these and other plates and are based on the data of quite a few independent studies (e.g., (Torsvik et al., 2012)).

In the scope of this work, we do not consider geological arguments supporting or challenging the proposed reconstruction because, in our opinion, this issue merits a separate geological study.

We only note that the existence of Late Cretaceous, Paleogene, Cenozoic and recent tectonic movements (including strike-slip displacements) in the junction zone of the Chukotka-Kolyma-Omolon block and the Eurasian plate was noted, inter alia, in (Parfenov, 1991; Parfenov et al. 1995; Timofeev et al., 2012; Gaina et al., 2002; Imaeva et al., 2017). The Late Cretaceous tectonic activity within the Verkhoyansk fold-thrust complex which continued to "at least ~70 Myr ago" (Malyshev et al., 2018) could also be the reflection of these movements. The existence of tectonic movements in the contact region of the Kolyma-Omolon (Chukotka-Kolyma-Omolon) block with the rest of Eurasia by no means contradict the generally accepted opinion about the Mesozoic accretion (approximately from the terminal Jurassic to the beginning of Cretaceous) of the Kolyma-Omolon block to Eurasia.

In conclusion, we would like to emphasize that we consider the proposed reconstruction as a hypothesis, although relying on a sound basis but certainly requiring detailed geological validation. In our opinion, geological testing of this hypothesis should be a subject of special future research.

CONCLUSIONS

(1) Extensive collections of Late Cretaceous Chukotka volcanics sampled in the Bilibino region of the Chukotka Autonomous Okrug and along the Pevek–Egvekinot road have been studied paleomagnetically.

Fig. 8. Reconstruction of position of Chukotka-Kolyma-Omolon block, North American and Eurasian plates for ~85 Myr ago. Position of Chukotka-Kolyma-Omolon block at that time is shown by dark gray-green contour; position of block for same time in absence of its displacements relative to Eurasian plate is shown by light gray-green contour; yellow contour shows current position of block within Eurasian continent. Filled bubble and circle around it indicate position of paleomagnetic pole of Chukotka block for time ~85 Myr ago and 95% confidence circle for this pole, respectively.

Most of the studied rocks contain a high-quality paleomagnetic record.

(2) The positive fold test and the coincidence of the paleomagnetic poles obtained in this study with those obtained in (Stone et al., 2009) from coeval rocks in the nearby region testifies to the primary origin of the isolated characteristic magnetization component.

(3) Based on the combined set of the results obtained in this work and the data of (Stone et al., 2009), the relatively accurate coordinates of the regional paleomagnetic pole have been calculated for the age level of ~85 Ma: Plat = 69.3°, Plat = 180.7° with A95 = 5.1° and $N = 99$. The calculated latitude for the conditional midpoint of Chukotka (67° N, 173° E) is 86.3° ± 5.1°.

(4) Using the set of the poles of (Torsvik et al., 2012) and the method of (Besse et al., 2003), we calculated a new, apparently more correct paleomagnetic pole for Eurasia for ~85 Myr ago.

(5) The obtained data testify to the displacements undergone by Chukotka (Chukotka-Kolyma-Omolon block) relative to the North American and Eurasian plates during the last ~85 Myr. Over this time interval, the conditional midpoint of Chukotka has been shifted in paleolatitude by 9.4° ± 5.8° relative to Eurasia and by 6.1° ± 5.8° relative to North America. In the linear units, the above figures correspond to the 95% confidence intervals of 1700–400 and 1300–30 km, respectively.

(6) The position of the Chukotka-Kolyma-Omolon block relative to Eurasia and North America for ~85 Myr has been reconstructed based on the obtained data. The reconstruction implies that from that time to the present, the Chukotka-Kolyma-Omolon block has undergone relatively small displacements (dozens to first hundreds of km) towards the south relative to the North American plate and a noticeable displacement (by a few hundred km) relative to the Eurasian plate.

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