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Reconnaissance paleomagnetism of Late Triassic blocks, Kuyul region, Northern Kamchatka Peninsula, Russia

William Harbert[a,*], Sergei Sokolov[b], Maxim Alexutin[b], Kirill Krylov[b], Vladimir Grigoriev[b], Alexander Heiphetz[c]

[a] Department of Geology and Planetary Science, 200 SRCC, University of Pittsburgh, Pittsburgh, PA 15260, USA
[b] Geological Institute, Russian Academy of Sciences, Pyzhevsky lane 7, Moscow 109017, Russia
[c] Alex Heiphetz Group, State College, PA, USA

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Abstract

The northernmost Kamchatka Peninsula is located along the northwestern margin of the Bering Sea and consists of complexly deformed accreted terranes. Progressing inland from the northwestern Bering Sea, the Olyutorskiy, Ukelayat and Koryak superterranes (OLY, UKL and KOR) are crossed. These terranes were accreted to the backstop Okhotsk-Chukotsk volcanic-plutonic belt (OChVB) in northernmost Kamchatka. A sedimentary sequence of Albian to Maastrichtian age overlaps the terranes and units of the Koryak superterrane, and constrains their accretion time. A paleomagnetic study of blocks within the Kuyul (KUY) terrane of the Koryak superterrane was completed at two localities (Camp 2: $\lambda = 61.83°$N, $\phi = 165.83°$E and Camp 3: $\lambda = 61.67°$N, $\phi = 164.75°$E). At both localities, paleomagnetic samples were collected from Late Triassic (225–208 Ma) limestone blocks (2–10 m in outcrop height) within a melange zone. Although weak in remanent magnetization, two components of remanent magnetization were observed during stepwise thermal demagnetization at 32 sites. The A component of magnetization was observed between room temperature and approximately 250 °C. This magnetic component is always of downward directed inclination and shows the best grouping at relatively low degrees of unfolding. Using McFadden–Reid inclination-only statistics and averaging all site means, the resulting A component mean is $I_{opt} = 60.3°$, $I_{95} = 5.0°$ and $n = 36$ (sites). The B magnetic component is observed up to 565 °C, at which temperature, most samples have no measurable remanent magnetization, or growth of magnetic minerals has disrupted the thermal demagnetization process. Combining sites with Fisher estimates of kappa (k-value) ≥ 13 and n (sites) ≥ 3, where bedding orientation differs within a block, most of these sites show the best grouping of B component directions at 100% unfolding, and two of the blocks display remanent magnetizations of both upward and downward directed magnetic inclination. Combining sites with Fisher estimates of kappa (k-value) ≥ 13 and n (sites) ≥ 3, the resulting overall B component paleolatitude and associated uncertainty are $\lambda_{obs} = 30.4°$N or S, $\lambda_{95} = 8.9°$ and $n = 19$ (sites). When compared with the expected North America paleolatitude of $\lambda_{APWP\ expected} = 57.9°$N, our data support a model in which blocks within the Koryak superterrane are allochthonous and far travelled.

Keywords: Paleomagnetism; Mesozoic; Terrane accretion; Kamchatka

* Corresponding author. Fax: +1-412-624-3914.
E-mail address: bill@earth.eps.pitt.edu (W. Harbert).
URL: http://www.ahg.com.

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1. Introduction

The Koryak Highlands occupy the topographically elevated regions of the northernmost Kamchatka Peninsula in northeastern Russia. Along a region of intense study within the former Soviet Union, the formation of the Koryak superterrane (KOR) by accretion and assemblage of oceanic and island-arc terranes has been suggested in the scientific literature during the last 20 years (Aleksandrov et al., 1980; Alekseyev, 1979, 1981, 1987; Kazimirov, 1985; Nokleberg et al., 1998). However, the entire northeastern region of the Russian Republic has only recently been interpreted to consist of accreted terranes (Fujita and Newberry, 1982; Zonenshain et al., 1987, 1991; Stavsky et al., 1990; Didenko et al., 1993). Fauna described within the Koryak superterrane is anomalous for their present-day high latitudes when compared with the Boreal fauna of the neighboring regions of Siberia within similar aged terranes (Shapiro and Ganelin, 1988; Dagis, 1993). In this paper, we present new paleomagnetic data from this northernmost portion of the Kamchatka Peninsula. We interpret our data to show that this region of northeastern Russia includes tectonic units that are allochthonous and far traveled.

2. Regional geology of the Southern and Central Kamchatka Peninsula

On the basis of geological mapping, structural relationships and geochronological observations, the geographical region of the Koryak Highland has been subdivided into three first-order superterranes. While more detailed tectonostratigraphic terrane models for this region have been presented by Nokleberg et al. (1998, 2000), the regional first-order superterranes are, moving inboard from the northwestern Bering Sea toward more interior Eurasia, the Olyutorskiy superterrane (OLY), the Ukelayat superterrane (UKL) and the Koryak superterrane (KOR) (Fig. 1). The innermost terrane is the Okhotsk-Chukotsk volcanic-plutonic belt (OChVB) and its associated forearc deposits (the Udsko-Murgalsky and the Taigonosky terranes).

2.1. Olyutorskiy superterrane

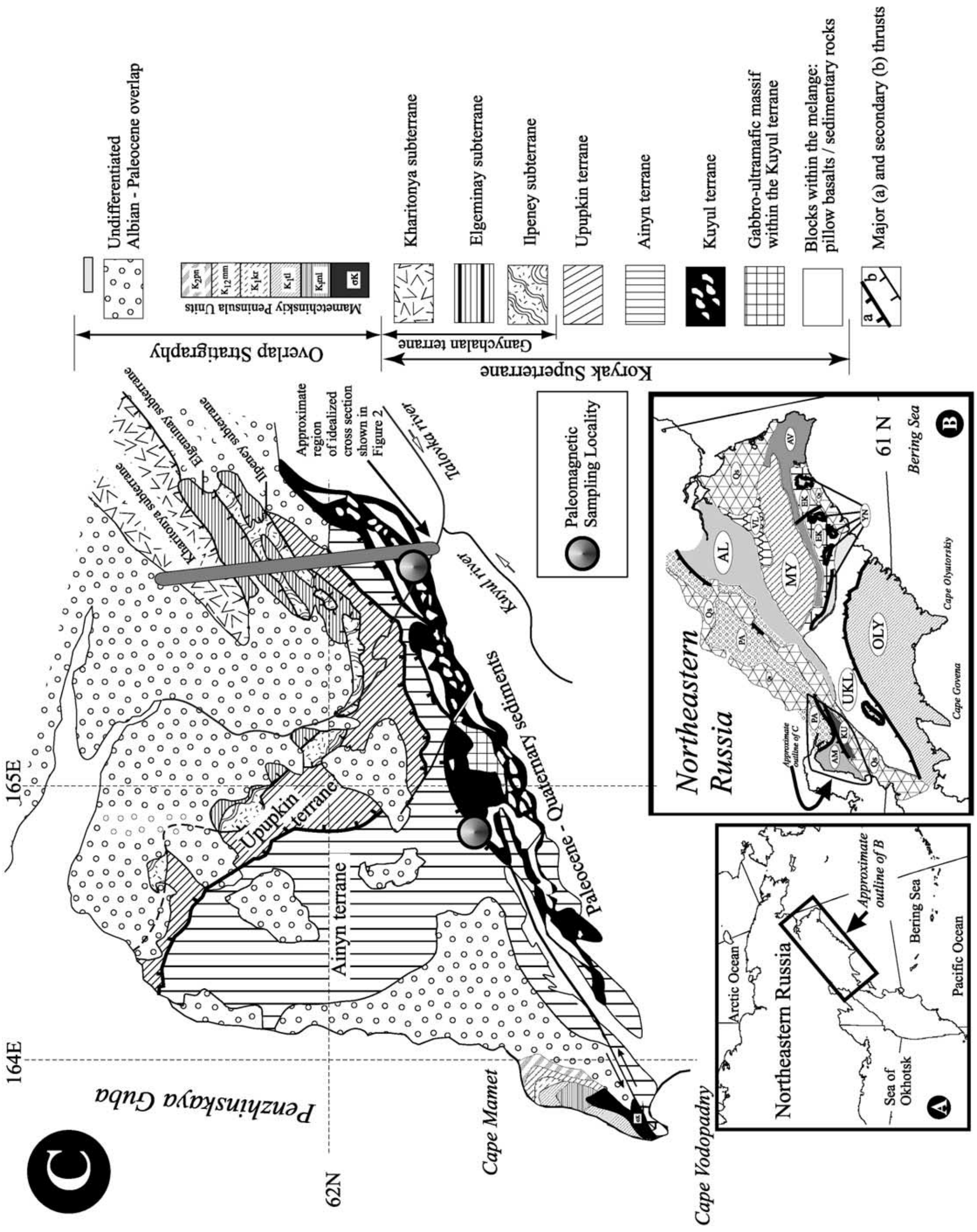
The most outboard of tectonostratigraphic superterranes have been interpreted to represent an accretionary prism composed of at least three large, thrust fault bounded terranes made of Late Albian to Campanian oceanic basalt and Late Campanian (?) Maastrichtian–Paleocene island arc sedimentary, volcanic and plutonic units (Astrahantzev et al., 1987; Kazimirov et al., 1987; Bogdanov and Fedorchuk, 1987). In the central and southern Kamchatka peninsula, corresponding terranes have been described in the Sredinny, Valaginsky, Tumrok and Kumroch mountain ranges (Shapiro, 1976; Sokolov, 1992).

The present interpretation of the Olyutorskiy superterrane is that it formed during the Late Campanian as an island arc (in the Russian-language literature, the Achaivayam terrane or Achaivayam island arc) on Albian to Early Campanian Kula plate oceanic crust (the Vatyna terrane). In this model, which has been supported by paleomagnetic studies and terrane track modeling, after northward motion on the Kula plate, this composite terrane collided with and was accreted to the North American plate during a major collision and obduction event (Kazimirov et al., 1987; Heiphetz et al., 1994b).

2.2. Ukelayat superterrane

This superterrane consists of a thick sequence of Albian–Paleocene flysch rocks (Aleksandrov et al., 1980; Mitrofanov, 1977; Alekseyev, 1987). Having a similar regional structure to the Olyutorskiy superterrane, this superterrane strikes southwestward into the Kamchatka peninsula where it is known as the West Kamchatka superterrane (West Kamchatka zone

Fig. 1. Regional terrane map of the northern Kamchatka Peninsula. (A) Regional geographic view of the region. (B) Abbreviations used in the inset figure are AL—Algan, AM—Ainyn-Main, AV—Alkatvaam, EK—Ekonai, KU—Kuyul, MY—Mainits, OLY—Olyutorskiy, PA—Penzhina-Anadyr, UKL—Ukelayat, VL—Velikorechy and YN—Yanranay. Additional information regarding the stratigraphy and geometry of these terranes can be found in Nokleberg et al. (1998, 2000). The Olyutorskiy superterrane extends southward into Kamchatka, where it is known as East Kamchatka superterrane (East Kamchatka zone in the Russian-language literature) (Sokolov, 1992); although, the outcrops of older rocks structurally located between the West and East Kamchatka superterranes are covered by Paleocene–Quaternary deposits. (C) Camp 2 and Camp 3 sampling localities and the map location of the idealized geologic cross-section are shown in Fig. 2.


Undifferentiated
Albian - Paleocene overlap
Mametchinsky Peninsula Units
Overlap Stratigraphy
Kharitonya subterrane
Elgeminay subterrane
Ilpeney subterrane
Ganychalan terrane
Upupkin terrane
Ainyn terrane
Kuyul terrane
Gabbro-ultramafic massif
within the Kuyul terrane
Blocks within the melange:
pillow basalts / sedimentary rocks
Major (a) and secondary (b) thrusts
Koryak Superterrane
Paleomagnetic
Sampling Locality
Approximate
region
of idealized
cross section
shown in
Figure 2
Talovka river
Kuyul river
Paleocene - Quaternary sediments
Ainyn terrane
Upupkin terrane
Penzhinskaya Guba
Cape Mamet
Cape Vodopadny
164E
165E
62N
Northeastern
Russia
Approximate
outline of C
Cape Olyutorskiy
Cape Govena
61 N
Bering Sea
Northeastern Russia
Approximate
outline of B
Arctic Ocean
Sea of
Okhotsk
Pacific Ocean

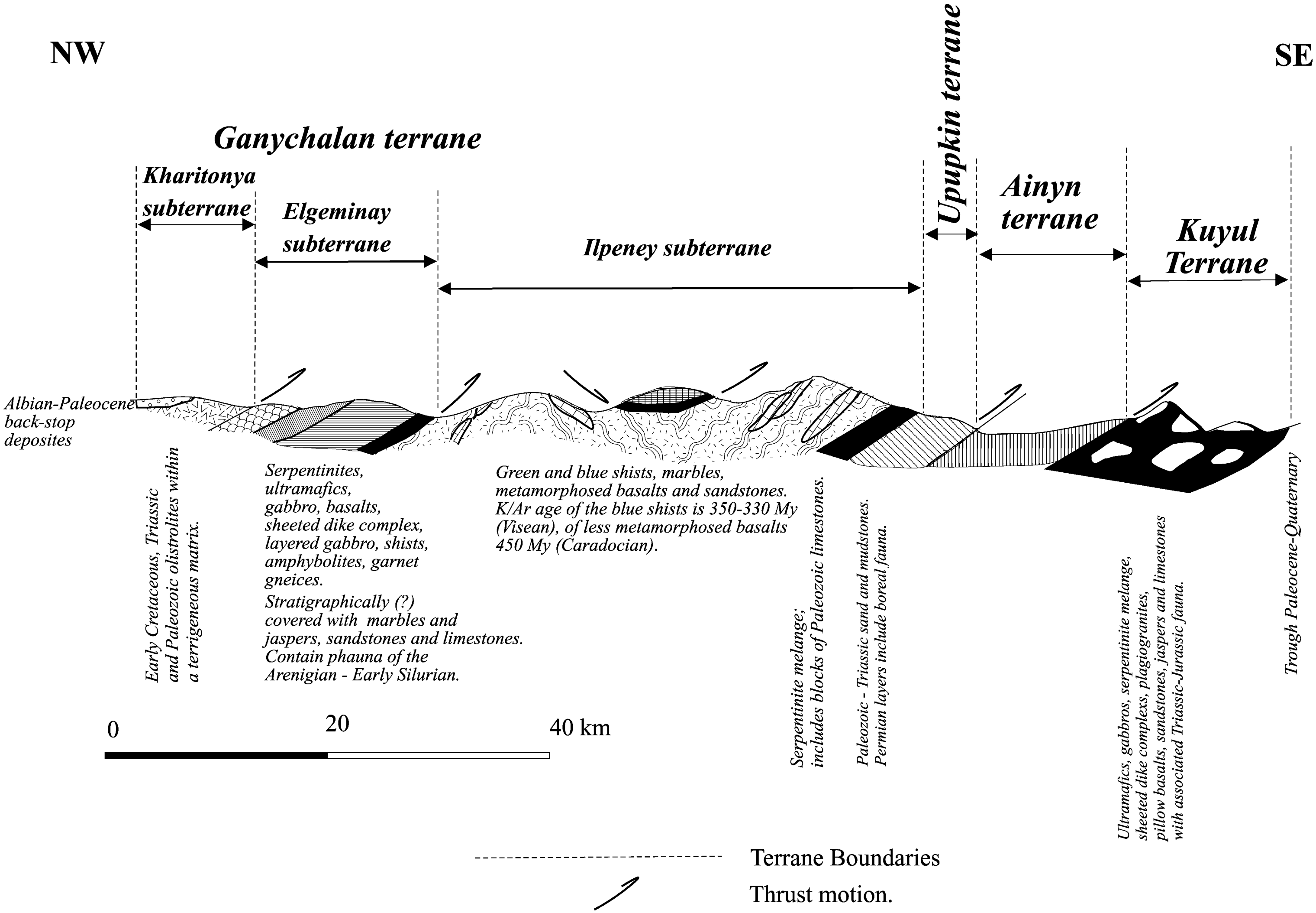


Fig. 2. A representative geological cross-section through the Koryak highlands showing the thrust relationships between the major terranes discussed in the text.

or Lesnovsky terrane in the Russian-language literature) (Shapiro and Ganelin, 1988; Sokolov, 1992). The oldest fauna, which is Albian in age, is concentrated near the northern margin of the Ukelayat superterrane (within the Koryak mountains segment of this superterrane). The lower part of the stratigraphic sequence in the central part consists of sub-arkose sandstones and mudstones that contain Santonian–Coniacian fauna (Ermakov and Souprounenko, 1975; Kazimirov et al., 1987). The Late Cretaceous rocks consist mainly of graywake and turbidites interbedded with sub-arkose contourites. These are described in earlier Russian-language literature as a "two-component flysch" (Ermakov and Souprounenko, 1975). Campanian units contain layers of jasper and chert interbedded with mudstones. The UKL superterrane has been interpreted as having been formed in a marginal, or back-arc, basin between the Achaivayam member of the Olyutorskiy superterrane and a continental plate (Kazimirov et al., 1987).

2.3. Koryak superterrane

Continuing inboard from the Ukelayat superterrane, the Koryak superterrane is thrust over the Ukelayat superterrane from the north (Aleksandrov, 1978; Ruzhentsev et al., 1982). The Koryak superterrane is a complex composite terrane, which consists of many tectonostratigraphic terranes (Fig. 1). These terranes vary in age from the Middle Paleozoic to the Early Cretaceous (Sokolov, 1992; Nokleberg et al., 1998). Thrusts within the composite superterrane appear to be overlapped by Albian to Maastrichtian and Late Maastrichtian to Paleocene sedimentary rocks (Fig. 2). In the western portion of the northern Kamchatka region, the Koryak superterrane includes (from northwest to southeast, progressing down the present-day tectonic section) the Ganychalan (GNC) terrane, Upupkin (UPU) terrane, Ainyn (AIN) terrane and Kuyul (KUY) terrane (Nekrasov, 1976; Sokolov, 1992; Grigoriev et al., 1986, 1987). Our samples were collected from the Kuyul terrane at two localities.

3. New paleomagnetic data from the Kuyul region

Two paleomagnetic studies were completed at localities Camp 2 ($\lambda = 61.83°$N, $\phi = 165.83°$E) and Camp 3 ($\lambda = 61.67°$N, $\phi = 164.75°$E). At each sampling site, a diamond-tipped, gasoline-powered core drill was used to collect samples and when possible, orientation was determined using both magnetic and solar compasses. Orientation and geological data were communicated and recorded in both Russian and English languages for maximum clarity. The samples were measured in a three-axis 2G superconducting rock magnetometer (SRM) at the University of Pittsburgh Paleomagnetic Laboratory (http://www.geology.pitt.edu). The SRM, along with both AF and thermal demagnetization equipment, is located inside a magnetically shielded room (maximum field < 300 nT). The paleomagnetic specimens were measured within the SRM in two different orientations. The second orientation was obtained by reversing the specimen's *z*-axis and rotating it 90° and data from both orientations were combined into a resulting step measurement. After each set of measurements, the samples were subjected to increasing increments of either AF (up to 95 mT) or thermal (up to 580 °C) demagnetization. Thermal cleaning was completed in an AST magnetically shielded (total field < 3–4 nT in the cooling region) large capacity furnace. Principal component analysis was applied to the resultant magnetization vectors in geographic coordinates to determine best fitting linear and planar segments to the demagnetization data.

At both localities, paleomagnetic samples were collected from Late Triassic aged variably deformed limestone blocks (2–10 m in outcrop height with visible bedding surfaces present within each block), outcropping within a sheared melange matrix. Although weak in remanent magnetization, during stepwise thermal, two components of remanent magnetization were observed at 32 sites (Fig. 3, Table 1).

4. Magnetic component A

The A component of magnetization was observed between room temperature and approximately 250 °C. Within sampled blocks, this component is always of downward directed magnetic inclination and shows the best grouping at relatively low percentages of stepwise unfolding (Fig. 4). Using McFadden–Reid (McFadden and Reid, 1982) inclination-only statistics, the resulting A component is $I_{opt} = 60.3°$, $I_{95} = 5.0°$, $n = 36$ and

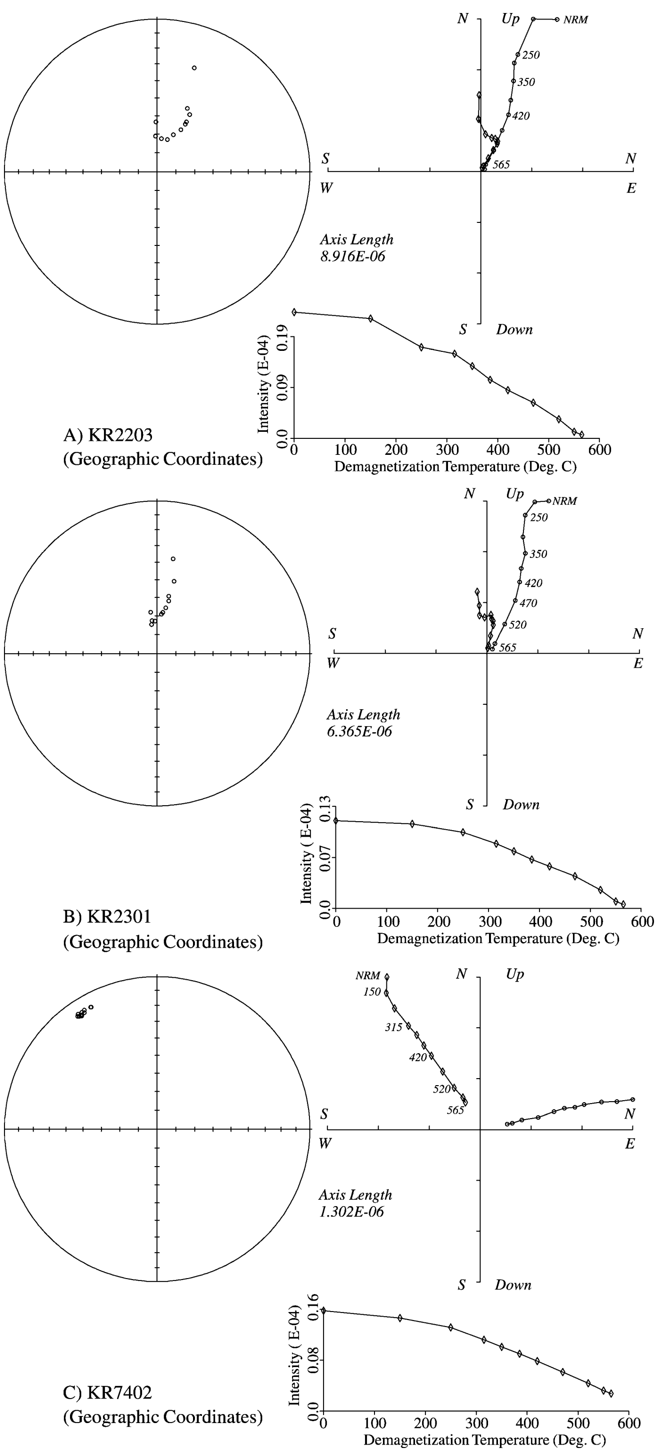

N
Up
NRM
250
350
420
565
S
N
W
E
Axis Length
8.916E-06
S
Down
Intensity (E-04)
0.19
0.09
0.0
0
100
200
300
400
500
600
Demagnetization Temperature (Deg. C)
A) KR2203
(Geographic Coordinates)
N
Up
NRM
250
350
420
470
520
565
S
N
W
E
Axis Length
6.365E-06
S
Down
Intensity (E-04)
0.13
0.07
0.0
0
100
200
300
400
500
600
Demagnetization Temperature (Deg. C)
B) KR2301
(Geographic Coordinates)
NRM
150
315
420
520
565
N
Up
S
N
W
E
Axis Length
1.302E-06
S
Down
Intensity (E-04)
0.16
0.08
0.0
0
100
200
300
400
500
600
Demagnetization Temperature (Deg. C)
C) KR7402
(Geographic Coordinates)

Table 1
New paleomagnetic data from the Kuyul region

Camp	Block	Site	Strike	Dip	Direction	Geographic component A				Geographic component B			
						I_A	D_A	n	K_g	I_B	D_B	n	K_g
2	BLK 2	KR21	83.2	71.0	N	74.7	318.4	2	54.3	− 12.8	335.7	1	–
		KR22	83.2	71.0	N	65.1	10.4	4	22.0	3.3	6.6	4	104.1
		KR23	83.2	71.0	N	71.3	7.5	2	33.7	4.4	359.9	2	747.0
		KR24	86.2	62.0	N	51.8	349.7	3	12.0	− 15.3	346.3	3	86.5
		KR25	106.2	66.0	N	74.6	351.7	3	38.1	− 34.9	312.2	3	5.8
	BLK 3	KR28	67.2	75.0	N	67.1	6.3	3	39.0	68.6	175.3	3	36.2
	BLK 4	KR31	57.2	81.0	N	74.2	9.3	3	48.9	40.3	135.7	3	76.9
		KR33	254.2	74.0	S	62.3	344.0	5	12.1	40.3	334.3	3	235.3
		KR34	40.2	77.0	N	66.8	344.9	1	–	–	–	–	–
	BLK 5	KR35	91.2	90.0		56.2	243.0	1	–	20.8	237.8	1	–
		KR36	279.2	87.0	S	74.0	354.0	1	–	36.8	28.6	1	–
		KR37	121.2	65.0	N	63.4	302.5	1	–	− 11.9	30.6	1	–
	UB	KR45	264.2	75.0	S	49.8	346.7	6	24.1	44.1	13.3	6	20.6
		KR46	271.2	74.0	S	61.5	355.4	5	11.7	45.7	8.5	4	163.5
		KR47	56.2	66.0	N	64.1	15.6	5	9.0	45.4	342.4	4	17.8
		KR51	54.2	74.0	N	63.1	345.2	4	26.0	60.6	317.6	3	16.0
		KR52	6.2	58.0	W	85.5	347.7	4	23.5	60.5	15.7	4	12.4
		KR53	6.2	58.0	W	61.5	346.5	4	15.5	60.6	11.9	3	12.6
3	1kBLK	KR58	356.8	29.0	W	64.4	167.3	5	10.0	78.5	163.3	5	215.1
		KR59	352.8	16.0	W	73.2	189.1	5	6.6	76.1	222.8	5	29.3
		KR60	5.8	34.0	W	84.8	305.6	5	9.2	–	–	–	–
		KR61	5.8	34.0	W	67.0	132.0	5	20.1	–	–	–	–
		KR62	5.8	34.0	W	54.5	145.1	5	7.2	–	–	–	–
		KR63	5.8	34.0	W	42.3	184.6	5	39.8	–	–	–	–
		KR64	5.8	34.0	W	67.4	163.3	5	5.2	–	–	–	–
	2 kBLK	KR73	36.8	69.0	W	59.3	310.8	3	13.7	65.2	293.8	4	84.6
		KR74	67.8	43.0	W	51.6	287.7	1	–	35.5	319.2	4	161.0
		KR75	86.8	30.0	N	46.5	336.5	4	8.9	37.3	326.4	5	75.5
		KR77	98.8	25.0	N	32.0	345.0	4	12.6	30.6	333.5	4	100.4
		KR78	99.8	64.0	N	68.9	300.7	2	7.8	65.0	278.9	2	729.4
	4 kBLK	KR79	117.8	40.0	E	12.5	256.1	1	–	13.1	260.0	1	–
		KR80	136.8	29.0	N	57.2	357.5	1	–	− 15.2	58.4	2	12.4
		KR81	101.8	87.0	N	74.0	311.8	4	12.8	24.7	317.4	4	13.1
		KR82	101.8	87.0	N	63.2	310.3	5	19.2	14.0	328.5	5	15.1
		KR83	83.8	19.0	N	65.5	337.7	3	33.4	38.3	318.6	3	1.9
		KR86	103.8	50.0	N	69.9	6.7	2	12.8	51.5	55.4	3	2.4
		KR87	122.8	54.0	N	–	–	–	–	65.9	6.8	2	45.8
		KR88	96.8	40.0	N	–	–	–	–	− 38.9	42.5	3	60.4

$k = 19.1$. If an incremental fold test is applied to the Fisher averaged A site mean directions, the highest k-value is observed at 4% unfolding coordinates with associated statistics of $D = 329.1°$, $I = 73.7°$, $\alpha_{95} = 8.3°$, k-value = 9.3 and $n = 36$ (sites). These results do not differ significantly from those in geographic co-

Fig. 3. Representative orthogonal vector plots, magnetic intensity decay diagrams and equal-area stereographic projects for selected stepwise thermal demagnetization data for samples (A) KR2203 (site 22), (B) KR2301 (site 23) and (C) KR7402 (site 74); all in geographic coordinates. Lower hemisphere demagnetization directions are shown by the "*" symbol, upper hemisphere directions with the "O" symbol on the equal area stereographic projections, orthogonal vector plot projections onto the vertical plane are shown by circles and onto the horizontal plane by diamonds.

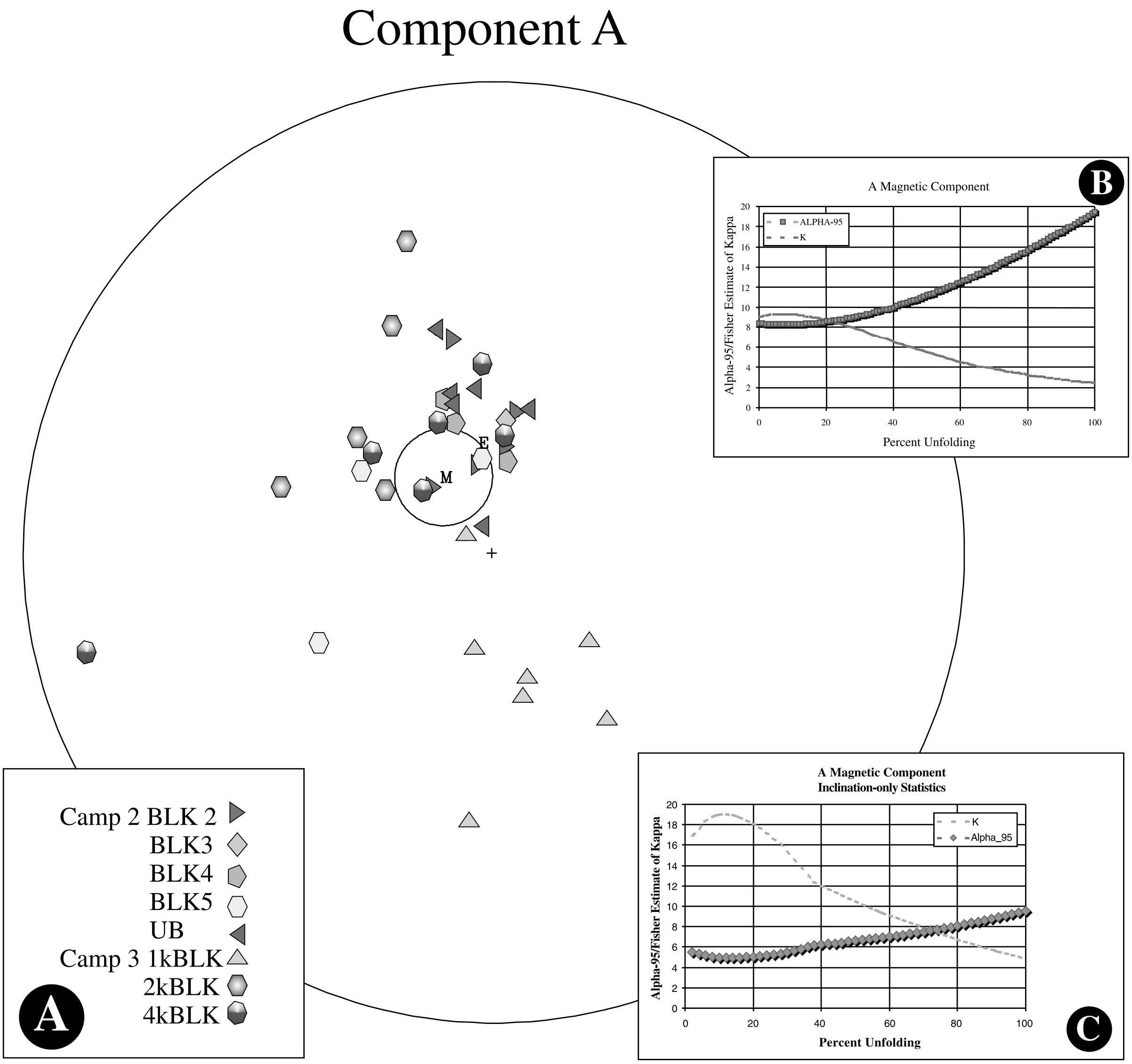


Fig. 4. (A) Equal area stereographic projections of the lower hemisphere A component group I and II site mean directions (all are lower-hemisphere directions), present-day magnetic field direction (E), component A mean direction (M) and α_{95} circle of confidence shown in geographic coordinates. Also shown is (B) stepwise unfolding statistics for the Fisherian *k*-value and α_{95} and (C) variation in the McFadden–Reid inclination-only *k*-value and α_{95} during incremental unfolding.

ordinates of $D_g = 329.0°$, $I_g = 74.8°$, $\alpha_{95} = 8.4°$, *k*-value = 9.1 and *n* = 36 (sites). This inclination is similar with that reported for Late Cretaceous age Ar^{40}/Ar^{39} dated basalt dikes within the Kuyul region (Table 2, result GA2), suggesting a possible common overprinting thermal event associated with both the observed A component and these intruding dikes.

5. Magnetic component B

The B magnetic component is observed up to 565 °C, at which temperature, most samples have lost measurable remanent magnetization or new magnetic minerals appear, making interpretation of the characteristic remanence impossible. The B magnetic com-

Table 2
Selected paleomagnetic data from the Koryak region, Northeastern Russia

Result	Age	Location (°N/°E)	N	Demagnetization/ Test/Polar	D_s	I_s	α_{95}	$\lambda_{obs} \pm \alpha_{95}$	Terrane
UB	Senonian	63.0/179.5	13	AF/?/M	263	82	13	74.3 ± 13°	Al'Katvaamsky–Koryak
PB	Cenomanian–Maastrichtian	61.5/164.0	10	AF/?/M	61	75	15	61.8 ± 15°	Ainyn–Koryak
YA	Late Jurassic–Early Cretaceous	63.2/174.3	5	TH/F/N	201.2	50.7	15.3	31.4 ± 15°	Maynitsky–Koryak
KO	Late Triassic	62.5/174.5	5	TH/F/M	186.5	41.5	15.4	23.9 ± 15°	Khatyrka–Koryak
RY	Late Jurassic	62.4/174.8	4	TH/F/N	47.9	38.7	8.8	21.8 ± 9°	Khatyrka–Koryak
SE	Senonian	62.5/174.4	5	TH/F/N	5.5	84.4	6.9	78.9 ± 7°	Overlap sequence Koryak
GA1	Late Bathonian–Early Callovian	61.5/164.6	15	TH/F/M	34.6	43.5	7.1	25.4 ± 7°	Kuyul–Koryak
GA2	93.6 ± 2.7	61.5/164.6	4	TH/F/N	273.4	87.3	23.1	84.6 ± 24°	Gankuvayamsky–Koryak
KU	Late Triassic	–	22	TH/F/M	–	–	–	30.4 ± 8.9°	Kuyul–Koryak

References: Pechersky (1970) UB and PB; Didenko et al. (1993) YA, KO, RY and SE; Heiphetz et al. (1994a) GA1 and GA2; This study KU.

ponent is observed within blocks located in both the Camp 2 and Camp 3 regions. For sites collected within deformed blocks (see Table 1 for within-block variation in measured bedding attitudes), combining sites with Fisher estimates of kappa (k-value) ≥ 13 and $n \geq 3$ (sites), most of these blocks show their best grouping of B component directions at 100% unfolding and two of the blocks display remanent magnetizations of both upward and downward directed magnetic inclination. Because of the potential for relative rotations of sampled blocks, we decided to use inclination-only statistics to calculate overall mean directions for the B component. Using McFadden–Reid statistics and combining sites with $n \geq 3$ that have associated Fisher (1953) estimates of k-value ≥ 13, the resulting overall B component paleolatitude and associated uncertainty in stratigraphic coordinates are $\lambda_{obs} = 30.4°$N or S, $\lambda_{95} = 8.9°$, $n = 19$ (sites) and k-value = 11.1 (Fig. 5). This overall study of paleolatitude result is similar to previously reported paleomagnetic studies completed within the Koryak superterrane (Table 2; results GA1, YA and KO).

6. Interpretation of paleomagnetic data

Our paleomagnetic data suggest that limestone blocks presently found within the Koryak superterrane were deposited during the Late Triassic at significantly lower than expected paleolatitudes. Our observed paleolatitude is $\lambda = 30.4°$N or S, $\lambda_{95} = 8.9°$. The expected paleolatitude for this site, calculated using the Besse and Courtillot (1991) North America Apparent Polar Wander Reference Pole (NAM APWP) for 196.2 Ma, is $\lambda_{exp} = 62.5°$ and $\lambda_{95} = 6.7°$. Using the Irving and Irving (1982) NAM APWP of 201 Ma, the expected site paleolatitude is $\lambda_{exp} = 57.9°$, $\lambda_{95} = 5.0°$, and of 224 Ma, is $\lambda_{exp} = 57.2°$, $\lambda_{95} = 5.0°$. Each of these estimates is significantly greater than our component B paleomagnetic results.

Eight previous paleomagnetic studies have been completed within this region in which sampled units range in age between Late Triassic and Late Cretaceous. Paleomagnetic data presented in these studies from units within the Koryak superterrane (see Table 2 for appropriate references) suggest low paleolatitudes of deposition. Paleomagnetic results from portions of the Koryak superterrane including the Khatyrka terrane (results KO and RY), Kuyul terrane (result GA1), Maynitsky terrane (result YA) and sedimentary overlap sequences (results SE, UB and PB) constrain the Late Paleozoic and Mesozoic paleolatitudes of these terranes. Within the Khatyrka terrane, the observed paleomagnetic paleolatitude is 24°N or S for the island arc complex of the Late Triassic aged KO locality. The observed paleomagnetic paleolatitude from the Jurassic to Cretaceous, RY locality is 22°N or S, and 25°N or S for GA1. The ophiolite rocks studied in the Maynitsky terrane also differ significantly in paleolatitude when compared with that expected for either the Eurasia or North America plates. The paleolatitude, calculated from the

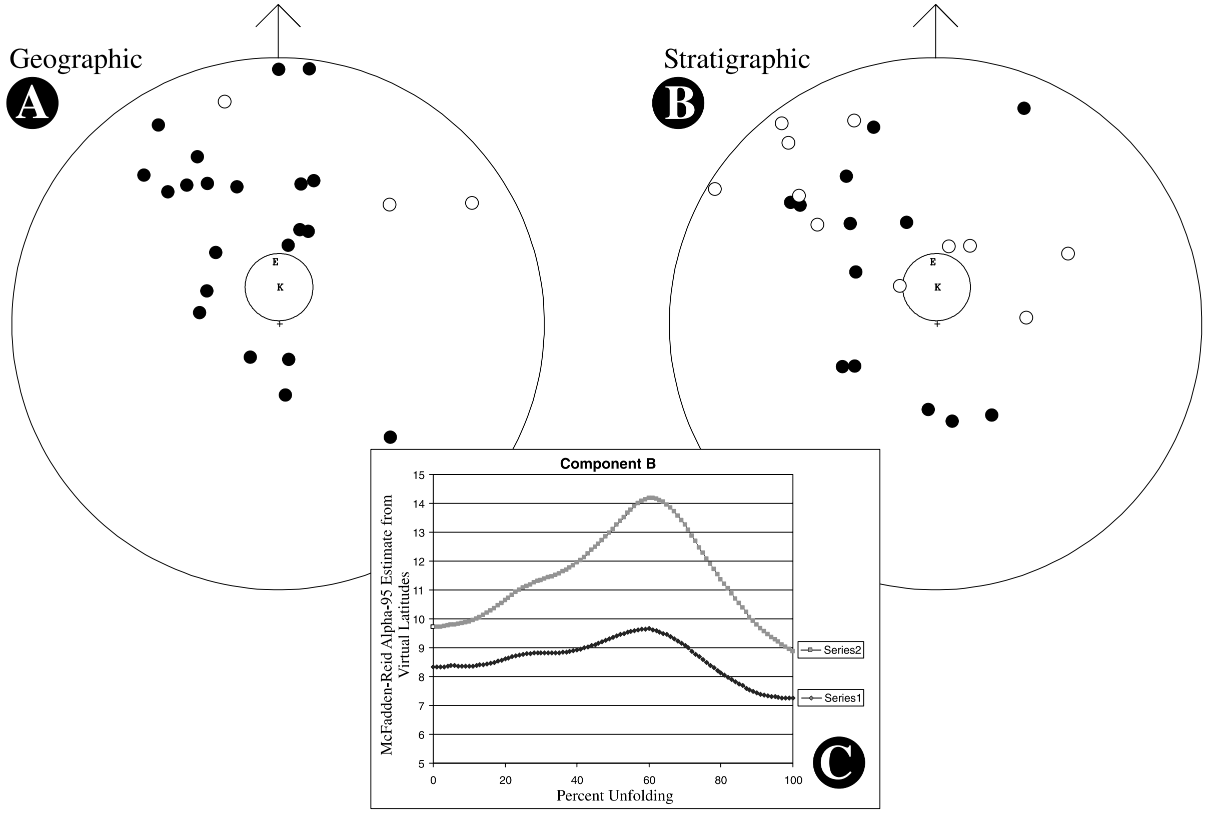


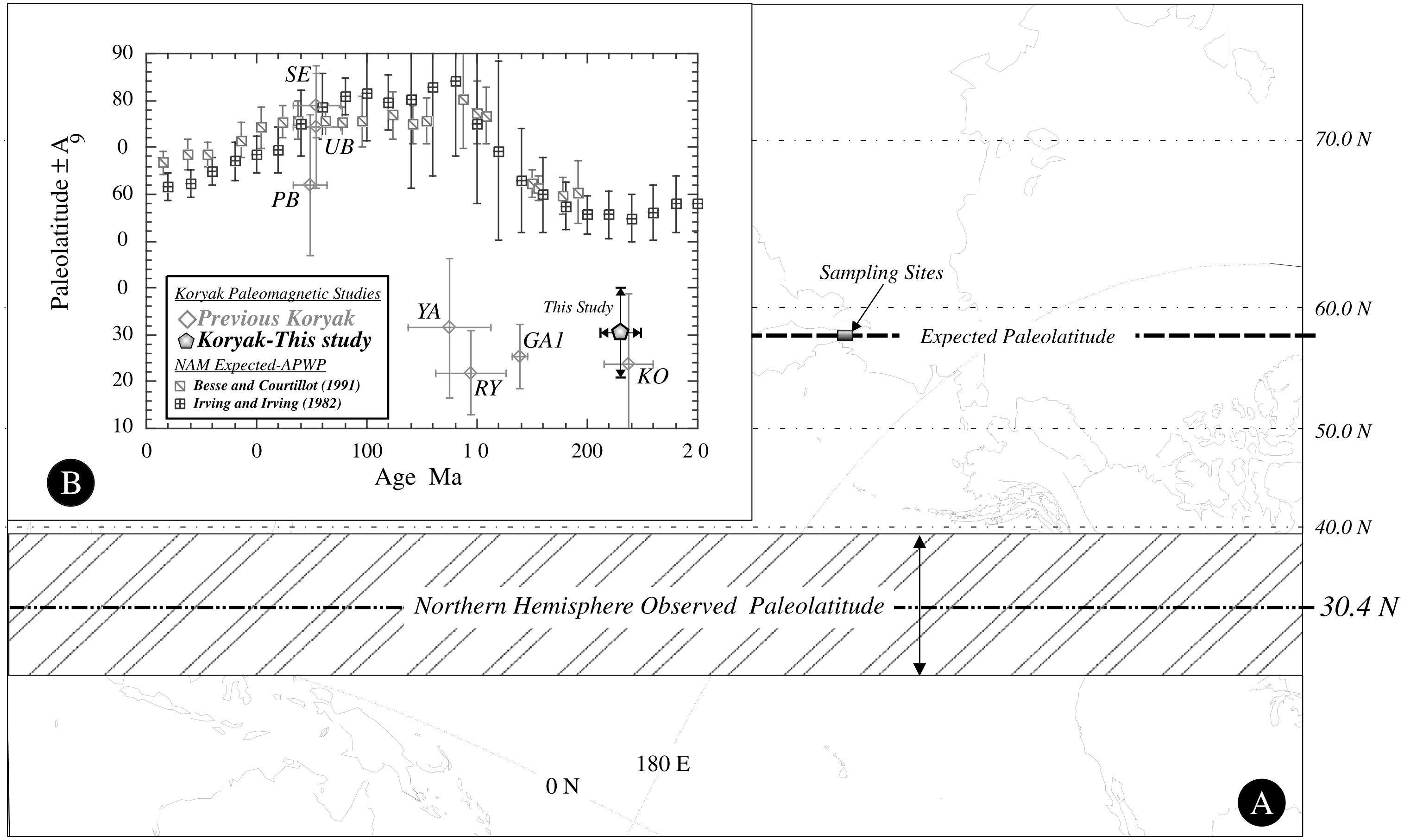
Fig. 5. Equal area stereographic projections of the B component group II site mean directions (solid circles are lower hemisphere site mean directions, open circles are upper hemisphere site mean directions), present-day magnetic field direction (E), Cretaceous expected direction (K) and α_{95} circle of confidence are shown in (A) geographic and (B) stratigraphic coordinates. In subfigure (C), the McFadden–Reid estimate of the α_{95} for virtual latitudes is shown as a function of percent unfolding. In (C), series 2 shows this statistic calculated during stepwise unfolding when applied to all sites with Fisher estimates of kappa (k-value) ≥ 13, and n (sites) ≥ 3 resulting in a study result of $\lambda_{obs} = 30.4°$N or S, $\lambda_{95} = 8.9°$ and $n = 19$ (sites). In (C), series 1 shows this statistic when applied to all sites with Fisher estimates of kappa (k-value) ≥ 12, and n (sites) ≥ 2. The resulting study result is $\lambda_{obs} = 28.0°$N or S, $\lambda_{95} = 7.3°$ and $n = 24$ (sites).

YA of the Maynitsky terrane, yields a paleolatitude of 32°N or S, significantly shallower than expected. Our study agrees with these previous studies and suggests a coherent picture of low paleolatitudes between the Late Triassic and the Early Cretaceous (Fig. 6). None of these studies uniquely determines the hemisphere of deposition of these units.

In contrast, the observed paleolatitudes for overlapping sedimentary units are well constrained by paleomagnetic results from the Senonian and Campanian–Maastrichtian sedimentary sequences (UB and PB). These units suggest expected high latitudes during the Late Cretaceous. The paleomagnetic data from the Senonian and Campanian–Maastrichtian age overlap sediments of the Al'katvaamsky terrane (UB), Penzhina Bay (PB) and Khatyrka terrane (SE) suggest that these sediments were deposited at high paleolatitude along the southeastern edge on the Eurasia plate. This suggests that accretion of the Koryak superterrane occurred prior to Senonian–Campanian–Maastrichtian time.

7. Conclusion

Our paleomagnetic study observed two components of magnetization during stepwise thermal demagnetization. The A component appears to be of



Mercator Projection about 201 Ma. NAM Reference Pole of Irving and Irving [1983]

Fig. 6. (A) Mercator projection of the northern Pacific basin using the North America Apparent Polar Wander Pole for 201 Ma of Irving and Irving (1982). Shown are thin solid lines, present day reference latitude/longitude lines and coastlines; horizontal dashed lines, 201 Ma, (Late Triassic) reference latitudes; bold horizontal dashed lines, expected and observed paleolatitudes, and the uncertainty of the observed paleolatitude calculated from the B component. Inset figure (B) shows an age versus paleolatitude plot for the study region using the NAM APWP reference data from Besse and Courtillot (1991) and Irving and Irving (1982), our study and the other paleomagnetic studies from this region summarized in Table 2.

secondary origin, is best clustered at low percentages of unfolding and is always of downward directed inclination. Using McFadden–Reid or Fisher averaging, our A component study mean paleolatitude is similar to that observed in reconnaissance paleomagnetic studies of Late Cretaceous dikes in the Koryak superterrane. In two of the paleomagnetically sampled blocks, two polarities of characteristic magnetization were observed. In most cases within-block fold tests show highest site clustering at 100% unfolding. Calculation of McFadden–Reid inclination-only statistics for the B component in stratigraphic coordinates indicates a paleolatitude of $\lambda = 30.4°$N or S, $\lambda_{95} = 8.9°$, $n = 12$ (sites) and k-value = 11.1. When combined with apparent polar wander path reference data from Besse and Courtillot (1991) and Irving and Irving (1982), our paleomagnetic data suggest significant northward latitude displacement.

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References

Aleksandrov, A.A., 1978. Thrust Faults and Imbricated Structures in Koryak Highland. Nauka Publisher, Moscow, 121 pp., in Russian.

Aleksandrov, A.A., Bogdanov, N.A., Palanjan, S.A., Chekhovich, V.D., 1980. On the tectonics of the northern part of the Olyutorsky zone of the Koryak Highland. Geotektonika 3, 111–122 (in Russian).

Alekseyev, E.S., 1979. Main features of the development and structure of the northern part of the Koryak Highland. Geotektonika 1, 85–96 (in Russian).

Alekseyev, E.S., 1981. The Kuyul Serpentinite Melange and the structure of the Talovsk–Maynska Zone (Koryak Mountains). Geotektonika 2, 68–78 (in Russian).

Alekseyev, E.S., 1987. Geodynamics of the ocean–continent transition zone on the example of Late Mesozoic and Cenozoic history of the southern part of the Koryak Highland. Geotektonica 3, 102–114 (in Russian).

Astrahantzev, O.V., Kazimirov, A.D., Heiphetz, A.M., 1987. Tectonics of the northern part of the Olyutorsky zone. In: Pusharovsky, Yu.M. (Ed.), Geology of the Northwestern Part of the Pacific Belt. Academy of Sciences of the USSR, Moscow, pp. 161–183. In Russian.

Besse, J., Courtillot, V., 1991. Revised and synthetic polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma. J. Geophys. Res. 96, 4029–4050.

Bogdanov, N.A., Fedorchuk, A.V., 1987. Geochemistry of Cretaceous oceanic basalts of the Olutorsky range (Bering Sea). Ofioliti 12 (1), 113–124.

Dagis, A.S., 1993. Geographic differentiation of Triassic brachiopods. Palaeogeogr. Palaeoclimatol. Palaeoecol. 100 (1), 79–87.

Didenko, A., Harbert, W., Stavsky, A., 1993. Paleomagnetism of the Khatyrka and Maynitsky superterranes, Koryak Highland, Far Eastern Russia. Tectonophysics 220, 141–155.

Ermakov, B.V., Souprounenko, O.I., 1975. Structure and environment of origin of the Late Cretaceous and Miocene flisch of Koryak–Kamchatka area. Sov. Geol. 12, 53–65 (in Russian).

Fisher, R.A., 1953. Dispersion on a sphere. Proc. R. Soc. Lond., A 217, 295–305.

Fujita, K., Newberry, J.T., 1982. Tectonic evolution of northeastern Siberia and adjacent regions. Tectonophysics 89, 337–357.

Grigoriev, V.N., Krylov, K.A., Sokolov, S.D., 1986. Upper Jurassic–Lower Cretaceous sediments of central part of Koryak Highland. In: Pusharovsky, Yu.M. (Ed.), Essays on Geology of Eastern USSR. Nauka Publishers, Moscow, pp. 58–80. In Russian.

Grigoriev, V.N., Krylov, K.A., Sokolov, S.D., 1987. Basic formational types of the Mesozoic sequences from Koryak Highland and their tectonic implications. In: Pusharovsky, Yu.M. (Ed.), Early Geosynclinal Formations and Structures. Trans. of Geological Institute Ac. Sci. USSR, vol. 417. Nauka Publishers, Moscow, pp. 138–145.

Heiphetz, A., Harbert, W., Layer, P., 1994a. Preliminary reconnaissance paleomagnetism of some Late Mesozoic ophiolites, Kuyul region, Koryak superterrane, Russia. Proceedings of the International Conference on Arctic Margins MMS 94-0040, pp. 229–234.

Heiphetz, A., Harbert, W., Savostin, L., 1994b. Reconnaissance paleomagnetism of the Olyutorsky superterrane, Northeast Russia. Proceedings of the International Conference on Arctic Margins MMS 94-0040, pp. 223–228.

Irving, E., Irving, G.A., 1982. Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana. Geophys. Surv. 5, 141–188.

Kazimirov, A.D., 1985. Nappes of the East Koryak Highland and their structural-formational homologues. Trans. of Geological Institute Ac. Sci. USSR, vol. 391. Nauka Publishers, Moscow. 112 pp., in Russian.

Kazimirov, A.D., Krylov, K.A., Fedorov, P.I., 1987. Tectonic evolution of the back-arc basins (using south of the Koryak Highland as an example). In: Pusharovsky, Yu.M. (Ed.), Essays of Geology of the northwestern part of the Pacific belt. Academy of Sciences of the USSR, Moscow, pp. 200–225. In Russian.

McFadden, P.L., Reid, A.B., 1982. Analysis of paleomagnetic inclination data. Geophys. J. R. Astron. Soc. 69, 307–319.

Mitrofanov, N.P., 1977. Vatyna overthrust in the central Koryak fold belt. Geol. Geofiz. 4, 144–149 (in Russian).

Nekrasov, G.E., 1976. Tectonic and Magmatism of Taygonos and North–Western Kamchatka. Nauka Publishers, Moscow. 160 pp., in Russian.

Nokleberg, W.J., et-al., 1998. Summary terrane, mineral deposit and metallogenic belt maps of the Russian far east, Alaska, and the Canadian Cordillera, US Geological Survey Open-File Report 98-136 (CDROM Media).

Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., Norton, I.O., Khanchuk, A.I., Stone, D.B., Scotese, C.R., Scholl, D.W., Fujita, K., 2000. Phanerozoic Tectonic Evolution of the Circum-North Pacific, US GS Professional Paper 1626. 122 pp.

Pechersky, D.M., 1970. Paleomagnetic study of the Mesozoic sediments from the northeastern USSR. Izv. Akad. Nauk SSSR., Fiz. Zemli 6, 69–83 (in Russian).

Ruzhentsev, S.V., Byalobzhesky, S.G., Grigoriev, V.N., Kazimirov, A.D., Peive, A.A., Sokolov, S.D., 1982. Tectonics of Koryak ridge. Essays on Tectonics of the Koryak Highland, Academy of Sciences of the USSR, Moscow. Nauka Publishers. 136–189 pp. (in Russian).

Shapiro, M.N., 1976. Tectonic Development of the Eastern Margin of Kamchatka. Nauka Publishers, Moscow. 124 pp., in Russian.

Shapiro, M.N., Ganelin, V.G., 1988. Paleogeodynamic interrelations in the large blocks of the Mesozoic of the north–eastern USSR. Geotektonika 5, 94–104 (in Russian).

Sokolov, S.D., 1992. Accretionary tectonics of the Koryak–Chukotka segment of the Pacific belt. Trans. of Geological Institute Russian Academy of Sciences, vol. 479. Nauka Publishers, Moscow. 182 pp., in Russian.

Stavsky, A.P., Chekhovich, V.D., Kononov, M.V., 1990. Plate tectonics and palinspastic reconstructions of the Anadyr Koryak region, northeast USSR. Tectonics 9, 81–101.

Zonenshain, L.P., Kononov, M.V., Savostin, L.A., 1987. Pacific and Kula/Eurasian relative motions during the last 130 Ma and their bearing on orogenesis in northeast Asia. In: Monger, J.W.H., Francheteau, J. (Eds.), Circum-Pacific Orogenic Belts and Evolution of the Pacific Ocean Basin. Geodynamics Series, vol. 18, pp. 29–47.

Zonenshain, L.P., Kuzmin, M.I., Natapov, L.M., 1991. Geology of the USSR: A Plate-Tectonic Synthesis. In: Page, B.M. (Ed.), Geodynamics Series, vol. 21. American Geophysical Union, Washington, DC, 242 pp.