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Paleomagnetism of the Cretaceous rocks from Cape Kronotskiy, East Kamchatka and reconstruction of terrane trajectories in the NE Pacific area

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Abstract. The Kamchatka Peninsula of northeastern Russia is located along the northwestern margin of the Bering Sea and consists of zones of complexly deformed accreted terranes. Paleomagnetic samples were collected for study from a Late Cretaceous aged locality at Cape Kronotskiy (λ=54°44.8′ N, ϕ=162°1.29′ E). Two components of magnetization were observed. During stepwise thermal demagnetization, the B-magnetic component was observed up to 600°C having a direction and associated uncertainty in stratigraphic coordinates of D_s=300.7°, I_s=48.7°, α_{95}=10.9°, k-value=11.8, n=17. The B component paleolatitude calculated from the Fisher mean in stratigraphic coordinates and associated statistics are λ_{obs}=30.4° N or S, λ_{95}=8.9°, n=17 (sites), k-value=11. Our overall study paleolatitude result is similar to a previously reported paleomagnetic study completed within this unit. Terrane trajectories calculated using the finite rotation poles of Engebretson et al. (1985), which are corrected for either Pacific-hotspot drift or True Polar Wander hotspot-spin axis relative motion, show that the sampled unit represents a far traveled tectonostratigraphic terrane and support a model in which accretion (docking) events of this composite or superterrane with the North America plate occur at approximately 40 Ma.

1 Introduction

The Kamchatka Peninsula of northeastern Russia consists of zones of complexly deformed accreted terranes. The formation of the Kamchatka Peninsula by accretion and assemblage of oceanic and island-arc terranes, has been suggested during the last thirty years (Aleksandrov et al., 1975, 1980; Aleksandrov, 1978; Ruzhentsev et al., 1979, 1982; Byalobzhesky, 1979; Alekseyev, 1979, 1981, 1987; Kazimirov, 1985; Khramov, 1987, 1988; Gelman and Bychkov, 1988) and has been broadly studied using seismological, structural, paleontological, and paleomagnetic methods (Fujita and Newberry,1982; Zonenshain et al., 1987, 1991; Sokolov, 1988, 1992; Stavsky et al., 1990; Astrahantzev et al., 1987; Grigoriev et al., 1986, 1987, 1990; Khanchuk et al., 1990; Krylov et al., 1989; Kazimirov et al., 1987; Didenko et al., 1993; Kovalenko, 2003). The goal of this study was to collect paleomagnetic data from an outermost tectonostratigraphic terrane of the Kamchatka Peninsula.

The Kamchatka Peninsula of northeastern Russia consists of zones of complexly deformed accreted terranes. We studied rock units at Cape Kronotskiy, which is located on the eastern side of the Kamchatka Peninsula (Fig. 1). Presently, the Cape Kronotskiy region is an area of intense tectonic activity with an unknown number of interacting lithospheric plates and/or tectonic blocks. Even the present-day regional plate tectonic configuration of this area is uncertain as models consisting of two plates (e.g. Chapman and Solomon, 1976; Cook et al., 1986; Riegel et al., 1993), three plates (Cook et al., 1986; Riegel et al., 1993; Geist and Scholl, 1994), or two plates with numerous blocks (Mackey et al.,

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1997; Gaedicke et al., 2000; Avé Lallemant and Oldow 2000; McElfesh et al., 2002) have been proposed.

Tectonic models for the evolution of this region can be broadly classified into oceanic-cratonal plate models in which only two plates interact in the Cape Kronotskiy region and multiple plate models in which a succession of oceanic plates (or blocks) interact in this region. Numerous authors have discussed the number, location, and configuration of tectonic plates in the Pacific basin in terms of seismic data, paleomagnetic data, magnetic isochrons, and fault orientation data (Chapman and Solomon, 1976; Parfenov and Na-tal'in, 1985, 1986; Natal'in et al., 1986; Engebretson et al., 1985; Watson and Fujita, 1985; Heiphetz et al., 1992a, b; Didenko et al., 1993; Riegel et al., 1993; Geist and Scholl, 1994; Mackey et al., 1997; Perchesky et al., 1997; Levashova et al., 1998; Chekhovich et al., 1999; Konstantinovskaia, 2001). By sampling paleomagnetic units from an out board terrane and then comparing these results with terrane trajec-tories calculated from finite-rotation models for known plates of the ancient pacific basin it was hoped that some insight could be gained into the past plate tectonic configuration of this complex region.

2 Regional geology of the Kamchatka Peninsula

The Kamchatka Peninsula is generally described as consist-ing of three distinct geologic regions: northern, central and southern. The northern and central regions are discussed be-low and are relevant because much of the previously col-lected paleomagnetic data comes from these geologic re-gions.

2.1 Northern region

The northern Kamchatka region, consisting mainly of the Koryak highlands, can be subdivided into three large tectonostratigraphic terranes, or superterranes, on the ba-sis of composition, internal structure, age of rocks, and the age of the fault relationships. Moving inboard from the northwestern Bering Sea toward more interior Eurasia and the Okhotsk-Chukotka volcanic plutonic belt and the associated forearc deposits (the Udsko-Murgalsky and the Taigonosky terranes), are the Olyutorskiy superterrane, Uke-layat superterrane and Koryak superterrane (Sokolov et al., 1988; Grigoriev et al., 1990; Nokleberg et al., 1997, 1998) (Fig. 1).

The most outboard of tectonostratigraphic terranes which make up the northeast Kamchatka Peninsula is the Olyu-torskiy superterrane. A major southeastward-dipping thrust fault boundary, the Vatyna thrust, juxtaposes the Olyutorskiy superterrane (sometimes referred to as "Olyutorskiy zone" or "Olyutorskiy system of nappes" in the Russian-language literature (Kazimirov et al., 1987) to the south and the late Cretaceous to Paleogene-aged Ukelayat superterrane to the

north (Ermakov and Souprounenko, 1975; Mitrofanov, 1977; Aleksandrov et al., 1980; Mitrofanov and Sheludchenko, 1981; Alekseyev, 1987; Astrahantzev et al., 1987). The Olyutorskiy superterrane extends southward into the central Kamchatka region where it was referred to as the East Kam-chatka superterrane (or the East Kamchatka zone in the ear-lier Russian-language literature) and is now referred to as the Achaivayamian–Valaginian arc (Fig. 1b) (Shapiro et al., 1984; Sokolov, 1992; Sokolov et al., 1988; Shapiro, 1995) although the outcrops of older rocks between the Koryak su-perterrane and the Achaivayamian–Valaginian arc are cov-ered by Paleocene–Quaternary deposits. However, the con-tinuity of this terrane boundary is clearly shown by regional residual magnetic anomalies (Harbert et al., 1998). A thrust, the Vatyna thrust, (Fig. 1b) extends into Kamchatka and is known in Kamchatka as the Lesnovsky thrust (Shapiro, 1976; Shapiro and Ganelin, 1988; Soloviev et al., 2002).

The Olyutorskiy superterrane in the northern-most Kam-chatka region has been interpreted to represent an ac-cretionary prism composed of at least three large, thrust fault bounded, terranes made of Late Albian to Campanian oceanic basalts and Late Campanian (?) Maastrichtian–Paleocene island arc sedimentary, volcanic and plutonic units (Astrahantzev et al., 1987; Kazimirov, 1985; Kazimirov et al., 1987; Bogdanov and Fedorchuk, 1987; Krylov et al., 1989; Garver et al., 2000; Soloviev et al., 2002). In the cen-tral and southern Kamchatka Peninsula, corresponding ter-ranes have been described in the Sredinny, Valaginsky, Tum-rok and Kumroch mountain ranges (Shapiro, 1976, 1995; Shapiro et al., 1984; Sokolov et al., 1988; Grigoriev et al., 1990; Konstantinovskaia, 2001). The present interpreta-tion of the Olyutorskiy superterrane is formation during the Late Campanian to Eocene as an island-arc (in the Russian-language literature the Achaivayam terrane or Achaivayam island-arc) on Albian to Early Campanian age Kula plate oceanic sea floor basement (the Vatyna terrane).

The Ukelayat superterrane (UKL) consists of a thick se-quence of the Albian–Paleocene sedimentary-flysch rocks (Ermakov and Souprounenko, 1975; Mitrofanov, 1977; Aleksandrov et al., 1980; Mitrofanov and Sheludchenko, 1981; Alekseyev, 1987; Astrahantzev et al., 1987; Garver et al., 2000; Shapiro et al., 2001; Soloviev et al., 2002). Fol-lowing the same general regional structure as the Olyutorskiy superterrane, this superterrane strikes southwestward into the Kamchatka Peninsula, where it is known as the West Kam-chatka superterrane (West Kamchatka zone or Lesnovsky terrane in the Russian-language literature) (Shapiro and Ganelin, 1988; Sokolov, 1992; Sokolov et al., 1988; Grig-oriev et al., 1990). Findings of the oldest fauna, Albian, are concentrated near the northern margin of the Ukelayat su-perterrane (within the Koryak mountains segment of this su-perterrane), or near western margin (within the Kamchatka Peninsula segment). The lower part of the stratigraphic sequence in the central part consists of sub-arkose sand-stones and mudstones which contain Santonian–Coniacian
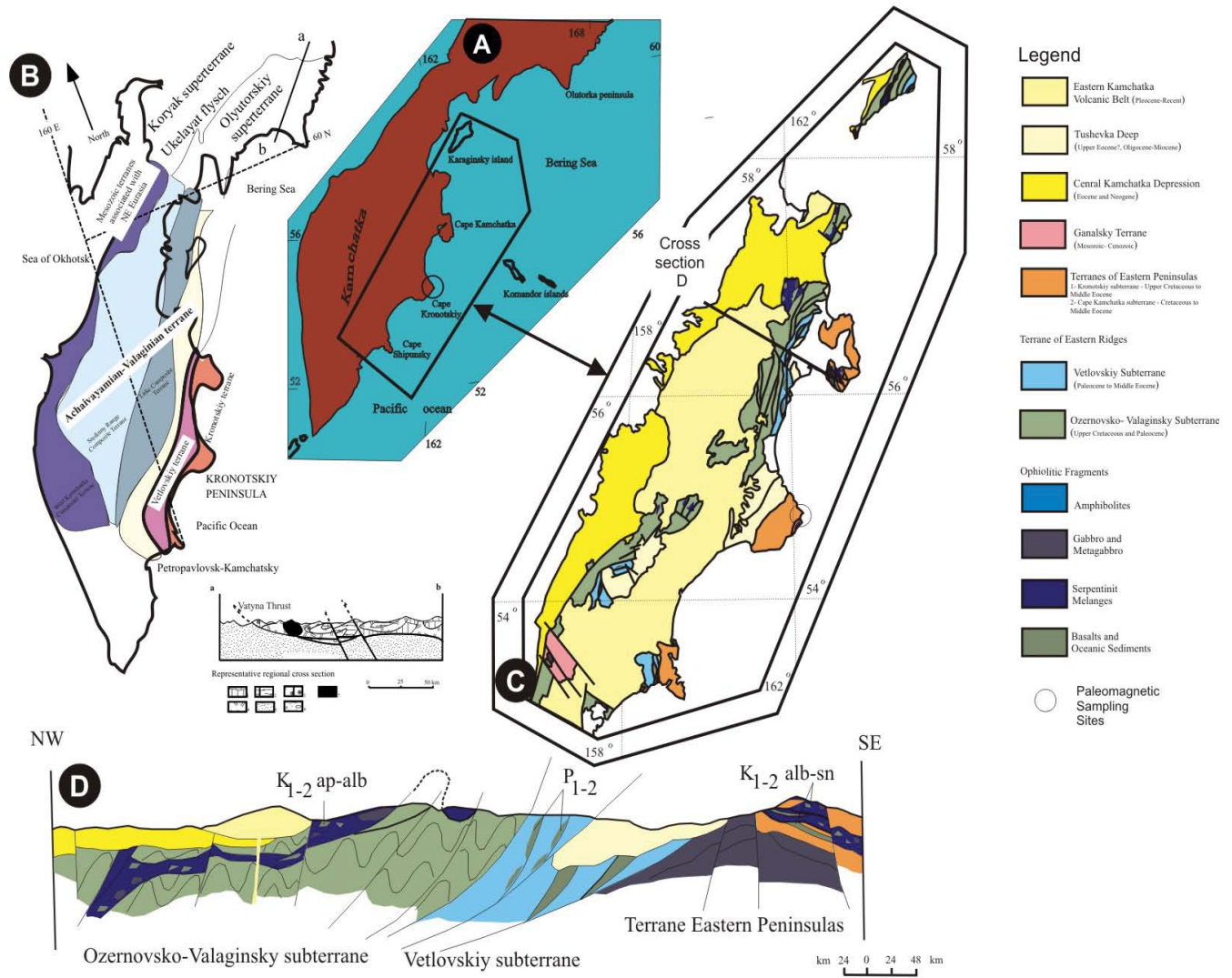
Fig. 1. A: Reference geographic map of the Kamchatka Peninsula. **B**: Simplified terrane map showing terranes associated with the margin of northeastern Eurasia (Koryak and UKL), the Olyutorskiy or Achaivayamian-Valaginian terrane, the Vetlovskiy (or Vetlovka) terrane and the Kronotskiy terrane (Alexeiev et al., 2006). The Vatyna thrust separates the Olyutorskiy superterrane and the Ukelayat flysch. and is shown on cross section a–b (symbols for this subfigure are described in Heiphetz et al., 1994) **C**: Geologic map of the eastern portion of the Kamchatka Peninsula. **D**: Reference cross section of the eastern Kamchatka Peninsula (the approximate location of this composite cross section is shown in B). Our samples were collected from the Cape Kronotskiy region. Subfigures B, C and D are taken directly from Tsukanov and Fedorchuk (2000).

fauna (Ermakov and Souprounenko, 1975; Kazimirov et al., 1987). The Late Cretaceous rocks consist mainly of gray-wake turbidites interbedded with subarkose countourites. These are described in earlier Russian-language literature as a "two-component flysh" (Ermakov and Souprounenko, 1975). Campanian units contain layers of jaspers and cherts, interbedded with mudstones. Several flows of the high-Ti MORB-like tholeiites have been identified interbedded with the Campanian sandstones (Shapiro and Fedorov, 1985; Kazimirov et al., 1987). Locally, Late Cretaceous sandstones are interbedded with coal deposits. 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). Recent fission-track grain ages from detrital zircons and sediment composition analysis have suggested that the UKL is composed of margin turbidite sequences, which formed in proximity of the Okhotsk-Chukotka volcanic plutonic arc (Garver et al., 2000; Shapiro et al., 2001; Soloviev et al., 2002).

Continuing inboard from the Ukelayat superterrane, the Koryak superterrane is thrust over the Ukelayat superterrane from the north. The Koryak superterrane is a complex composite terrane which consists of many tectonostratigraphic

terranes (Migovich 1972; Nekrasov, 1976; Sokolov, 1988; 1992; Grigoriev et al., 1990; Khanchuk et al., 1990; Nokleberg et al., 1997, 1998). These terranes vary in age from the Middle Paleozoic to Early Cretaceous (Sokolov, 1988; 1992). Thrusts within the composite superterrane appear to be overlapped by Albian to Maastrichtian and Late Albian to Paleocene age sedimentary rocks.

The terrane boundaries are well expressed by regional magnetic and gravity field anomalies. Significant magnetic and relatively high gravity (Aleksandrov, 1978) anomalies allow calculation of the thickness of the Kuyul terrane. Models vary slightly, however generally all of the models Kuyul terrane are found to be that of a slab with thickness ranging from 0.9 km (Aleksandrov, 1978) to 2.0 km (Alekseyev, 1981) dipping to northwest at 10 to 15°. A magnetotelluric profile across the southern border of the terrane suggests penetration of the terrane-bounding fault to depths up to 10 km with physical properties of the rocks differing significantly across this fault zone (Moroz, 1987).

2.2 Central region

While more complex schemes have been proposed (Watson and Fujita, 1985), the region of central Kamchatka Peninsula has been divided into two main zones, the western (WZ; Western Zone Kamchatka superterrane) and eastern (EZ, Eastern Zone; East-Kamchatka superterrane) zones (Fig. 1). The boundary between these two regions is marked by a significant magnetic anomaly and a thrust system. This regional thrust, of western vergence in the northern part of Kamchatka, continues to the northeast where it may be traced to a major thrust system which divides the Koryak and Olyutorskiy superterranes discussed in the previous paragraphs. Much of the WZ complex consists of metamorphosed and strongly deformed, poorly dated, pre-Upper Cretaceous rocks of East and Central Kamchatka (Raznitsin et al., 1985; Tsukanov and Fedorchuk 1989; Tsukanov, 1991). The EZ complex is made up of thick stratigraphic sections of Upper Cretaceous and Paleocene rocks, (Lower Eocene rocks in East Kamchatka), which have been thrust and folded. Intense deformation of this complex may be related to collision events of other terranes with the Kamchatka Peninsula. A less-deformed complex is present in eastern-most Kamchatka, bordering the Pacific Ocean and Bering Sea. Folding and thrusting of pre-Pliocene rocks in a zone between the Kamchatka Peninsula and the Kronotskiy Peninsula implies that the latter (geographically including the Kamchatka and Shipunsky Peninsulas) may be the youngest terrane accreted to the Kamchatka landmass (Fig. 1).

In the WZ, the Upper Cretaceous is represented by thick stratigraphic sections composed of turbidites. The source material for these deposits has been suggested to have been the Okhotsk-Chukotka zone and an associated fore-arc. Volcanic material in sediments is scarce (at least in the Campanian-Maastrichtian portion of the section); however blocks or lenses of basalt are present. The WZ is usually interpreted as a marginal basin not far away from the continental margin. In the eastern zone, EZ, volcanic flows (basalts, andesites, some associated sediments) are most common in the Late Cretaceous–Early Paleocene portion of the section. Some cherts and other silicious sediments are also found among volcanics (Zinkevich et al., 1990; Tsukanov, 1991; Shapiro et al., 1987; Shapiro, 1976). Sedimentary formations of considerable thickness of Paleocene and Lower Eocene, sometimes Upper Senonian, are also present in this zone. The EZ can be divided into five composite terranes, the Sredinny Range terrane, Litke terrane, East Ranges terrane, Vetlovskiy terrane, and East peninsulas or Kronotskiy terrane.

Previously the jaspers and basalts of Santonian–Campanian age are the oldest rocks found in the Sredinny Range terrane (Shapiro et al., 1987), however recent U/Pb (SHRIMP) dating of zircons from a tuff layer within the lower portions of these units suggest they are Early Eocene in age (Soloviev et al., 2004). Conformably overlying this unit are Campanian–Maastrichtian sediments, lava flows, and Upper Maastrichtian to Paleocene turbidites, ages that are now clearly inconsistent with the recent U/Pb ages. These rocks are exposed in thrust sheets of western vergence. The eastern limit of the terrane is now hidden under Late Cenozoic sedimentary cover of the Litke and Central Kamchatka basins but can be identified using regional residual magnetics. The Litke terrane is mainly covered by Late Cenozoic rocks with the exception of a limited area on a small Peninsula where the Upper Cretaceous island-arc series (flows and turbidites) outcrops (Shapiro, 1976; Kravchenko-Bereznhoy et al., 1990; Stavsky et al., 1990). The Litke subzone can be traced northward from Kamchatka into the Ilpinsky Peninsula of Koryak region, where tuffaceous Maastrichtian rocks are overlain without angular unconformity by a thick Paleocene sequence.

Within the Eastern Ranges terrane the Upper Santonian to Maastrichtian interval is represented by volcanic flows, mainly basalts, and turbidites which are conformably overlain by Paleocene flysch. These rocks are deformed into folds and thrusts of western vergence and unconformably overlain by Middle Eocene sediments.

The Vetlovskiy terrane is a narrow band of Paleocene–Eocene sediments and oceanic basalts deformed into thrusts of eastern vergence and unconformably overlain by Middle Eocene sediments. The entire subzone has been interpreted to represent an ancient accretionary complex. As presented in Alexeiev et al. (2006) and Freitag et al. (2001) these volcanic and chert blocks immersed in a sheared terrigenous matrix may differ both in age and place of origin from the matrix. The zone is bounded on the east and west by large-magnitude trusts of eastern vergence.

The Eocene volcanic flow-sedimentary rocks of the Eastern Peninsulas, or Kronotskiy terrane, are similar in Cape

Kamchatka, Cape Kronotskiy and Cape Shipunsky, whereas older rocks on each peninsula are very different. Post Coniacian time there was an active Kronotskiy arc, which was located to the outboard away from the continental plate margin of the Olyutorskiy arc. In this geodynamic model the Kula plate subducted under the Kronotskiy arc (Alexeiev et al., 2006). The Olyutorskiy and Kronotskiy arcs were separated by a back arc-basin (the Vetlovka basin during Paleocene and Eocene time). These arcs have been interpreted to have been located on a smaller scale plate (the "Vetlovka plate" suggested in Konstantinovskaia, 2001; see also Alexeiev et al., 2006). In this model, after northward motion on the Kula and Vetlovka plates, at about 50 Ma, this composite terrane collides with, and is accreted to the Eurasia plate (Astrahantzev et al., 1987; Kazimirov et al., 1987; Heiphetz et al., 1994; Shapiro, 1995).

At the Kronotskiy Peninsula locality paleomagnetic samples were collected from Late Cretaceous basaltic flows and interbedded fine grained sediments with visible bedding surfaces present within each sampled unit, outcropping within tidal coastal exposures. Paleomagnetic sites KRON01 to KRON18, with each site being represented by a collection of between 5 to 7 individually samples, were collected. During step-wise thermal demagnetization two components of remanent magnetization were observed at 18 sites (Fig. 2, Table 2). Previous paleomagnetic data show consistently lower than expected paleolatitudes from sampling sites throughout the Kamchatka region (Table 1).

3 New paleomagnetic data

Paleomagnetic samples were collected for study from the North Cape (λ=54°44.8′ N, ϕ=162°1.29′ E) locality (Fig. 2) on the Kronotskiy Peninsula. At each of 18 sampling localities 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 3-Axis 2-G 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 are 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 600°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.

3.1 Magnetic component A

The A component of magnetization was observed between room temperature and approximately 250°C in many of the sites. Within the sampled units, the A component was not well grouped within sampling sites or between spatially adjacent units. Two polarities of A component were observed widely varying in declination. The Fisher estimate of kappa within sites where this component was observed varied between 170.1 to 2.2, with only three sites having a Fisher estimate of kappa (Fisher, 1953) greater than 15, reflecting the scatter of this lower temperature of unblocking magnetic component. The site mean A component directions define a great circle with pole at λ= − 2.3°, ϕ=59.7°. If an incremental fold-test is applied to the Fisher averaged A site mean directions the highest k-value is observed at 0% unfolding coordinates with associated statistics of D=171.6°, I=84.8°, α_{95}=27.1°, k-value=3.3, n=13 (sites), although the site mean directions clearly do not have a Fisher distribution. If Bingham statistics are applied a resulting overall mean of D=26.4°, I=86.3°, α_{95-1}=30.5°, α_{95-2}=67.8°, ϕ=53.7°, n=13 (sites) is observed. This inclination is similar with that expected from the present day dipole magnetic field at the study location.

3.2 Magnetic component B

The B-magnetic component was observed up to 600°C at which thermal demagnetization temperature most samples have lost measurable remanent magnetization or new magnetic minerals appeared making interpretation of the characteristic remanence impossible (Fig. 3). The B magnetic component was observed within all sampled paleomagnetic sites at this locality. For our sites (see Table 2 for measured bedding attitudes and B component site level statistics), combining sites show the best grouping of B component was observed at 100% unfolding. Using Fisher (1953) statistics the resulting overall study B component and its associated uncertainty in geographic and stratigraphic coordinates are D_g=288.3°, I_g=57.9°, α_{95}=24.4°, k-value=3.1; D_s=300.7°, I_s=48.7°, α_{95}=10.9°, k-value=11.8, n=17 (sites). If Bingham statistics (Bingham, 1974) are applied a resulting overall mean of D_g=285.6°, I_g=81.2°, β_{95-1}=12.6°, β_{95-2}=63.4°, ϕ=172.1°; D_s=302.4°, I_s=48.3°, β_{95-1}=9.1°, β_{95-2}=10.7°, ϕ=104.7°, n=17 (sites) is observed (Fig. 4). The B component paleolatitude calculated from the Fisher mean in stratigraphic coordinates and associated statistics are λ_{obs}=30.4° N or S, λ_{95}=8.9°, n=17 (sites), k-value=11.1 (Fig. 5). The paleolatitude derived from this overall study is similar to those obtained from

Table 1. Selected Paleomagnetic data from the Kamchatka region, northeastern Russia.

Locality	Age	Loc ° N/° E	N	Demag/Test/Pol	D_s	I_s	α_{95}	$\lambda_{obs} \pm A_{95}$	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
UA	66±4 (K/Ar)	61.5/170.5	15	TH/F/R	321.4	70.8	10.8	55.1°±11°	Olyutorskiy
MB	66±4 (K/Ar)	60.8/171.6	16	AF+TH/F/N	336.0	66.5	10.5	49.0°±11°	Olyutorskiy
JB	Campanian	60.2/170.4	17	AF+TH/F/N	297.6	49.9	12.9	30.7°±13°	Olyutorskiy
VIII	K_2cp-m	60.3/170.6	??	TH/F/M	97	68	5	51.1°±8°	Olyutorskiy
VII	K_2cp-m	60.8/170.0	??	TH/F/M	88	65	5	47.0°±8°	Olyutorskiy
VI	K_2cp-m	61.6/171.2	??	TH/M	80	67	8	49.7°±13°	Olyutorskiy
XIII	P_2	60.7/168.0	??	TH/F/M	348	74	4	60.2°±8°	Olyutorskiy
YA	L. Jur–E. Cret	63.2/174.3	5	TH/F/N	201.2	50.7	15.3	31.4°±15°	Mainitsky-Koryak
KO	L. Triassic	62.5/174.5	5	TH/F/M	186.5	41.5	15.4	23.9°±15°	Khatyrsky-Koryak
RY	L. Jurassic	62.4/174.8	4	TH/F/N	47.9	38.7	8.8	21.8°±9°	Khatyrsky-Koryak
SE	Senonian	62.5/174.4	5	TH/F/N	5.5	84.4	6.9	78.9°±7°	Overlap Sequence Koryak
GA1	L. Bathonian–E. 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
KMP	63.5±2.5	56.3/163.3	5	TH/F/M	28.0	60.2	12	41°±.18°	Kronotskiy
KME1	44.5±1.5	56.5/163.3	7	TH/F/M	18.8	64.5	5.3	46°±.49°	Kronotskiy
KME2	38±2	56.5/163.3	1	TH	359.4	66.9	11.2	49.5°±19°	Kronotskiy
KMR	Campanion–L. Paleocene	56.6/162.3	5	TH/F/R	337.5	67.4	7	50.2°±12°	Vetlovskiy
KMR1	Oligocene–Miocene	56.2/162.2	21[+]	TH/R	310	54	7	34.5°±10°	Post-accretionary Complex
KP1	Eocene	56.5/163.3	31[+]	TH/N	18	66	10	48.3°±16°	Kronotskiy
KRP	Eocene	54.8/162.1	4	TH/F/M	310	59	9	39.8°±13°	Kronotskiy
IXX	K_2m-d	59.0/164.5	??	TH/F/M	332	62	5	43.2°±6°	Eastern Ranges
XV	P_2^3–P_3^1	60.0/165.0	??	TH/F	338	80	9	70.6°±17°	Litke
XVII	P_2^2	59.8/164.9	??	TH/F	299	73	10	58.6°±18°	Litke
XIV	P_2^1	60.0/165.2	??	TH/F/M	321	76	6	63.6°±11°	Litke
XVIII	P_1^2	59.8/164.8	??	TH/F/M	285	75	8	61.8°±15°	Litke
XVI	K_2cp-d	60.0/164.9	??	TH/F/M	299	61	6	42.1°±9°	Litke
KA	66±4 (K/Ar)	59.0/164.2	3	TH/F/M	330.3	64.8	15.0	46.7°±15°	East Kamchatka**
MA	L. Paleocene–Oligocene	60.4/167.1	5	TH/F/M	353.6	77.4	12.7	65.9°±13°	East Kamchatka*
IL	Paleogene	59.8/164.9	10	TH/F/M	307.3	72.9	8.8	58.4°±9°	East Kamchatka*

References: Pechersky (1970) UB, PB; Bazhenov et al. (1992a, b), KMR, KP1, KRP; Heiphetz et al. (1993b) UA, MB, and JB; Didenko et al. (1993) YA, KO, RY, and SE; KA, MA, and IL; Heiphetz et al. (1993a) GA1 and GA2; Pechersky et al. (1997) KMP, KME1, KME2; Levashova et al. (1997), KMR; D. V. Kovalenko (personal communication, 1998), Kovalenko (1992, 1996), and Kovalenko and Kravchenko-Berezhnoy (1999) VIII, VII, VI, XIII, IXX, XV, XVII, XIV, XVII, XVI.

[+] Statistics calculated using N=number of samples.

* East Kamchatka superterrane can be correlated with the Olyutorskiy superterrane.
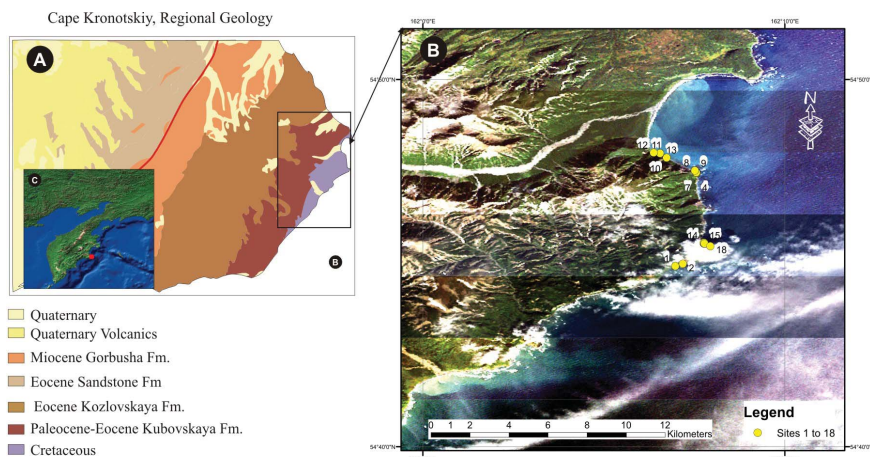

Fig. 2. A: Simplified geology and local stratigraphy of the units on Cape Kronotskiy **B**: A regional LANDSAT 7 image showing the sampling sites and **C**: A geographic reference map showing the location of the Kamchatka Peninsula in the northeastern Pacific basin.

Table 2. Northwestern Cape Kronotskiy region component B site mean directions and associated site statistics.

Site	Latitude (N)	Longitude (E)	Strike	Dip	Dir	Inc_g	Dec_g	N	$Kappa_g$
KRON01	54.7488	162.1163	48.95	20.0	S	38.3	325.3	7	13.3
KRON02	54.7499	162.1198	338.95	9.0	N	42.2	297.7	3	6.1
KRON03	54.7911	162.1261	21.95	38.5	S	−0.4	266.1	6	147.0
KRON04	54.7910	162.1260	21.95	38.5	S	−17.3	277.1	2	85.3
KRON05	54.7913	162.1259	21.95	38.5	S	−8.6	295.0	5	123.0
KRON06	54.7913	162.1259	18.95	47.0	S	−6.0	303.0	4	6.2
KRON08	54.7913	162.1259	42.95	22.0	S	41.8	290.1	6	45.0
KRON09	54.7922	162.1253	39.95	33.0	S	33.0	257.8	5	52.3
KRON10	54.7922	162.1253	236.94	25.5	N	84.2	161.9	6	963.0
KRON11	54.7999	162.1093	229.94	48.0	N	78.4	86.3	6	334.8
KRON12	54.7999	162.1093	236.94	25.5	N	66.6	174.0	3	712.5
KRON13	54.8003	162.1063	236.94	85.0	N	63.8	143.4	4	89.3
KRON14	54.8003	162.1063	214.96	52.0	W	83.6	71.5	6	453.6
KRON15	54.7980	162.1123	214.96	52.0	W	86.7	219.8	6	1757.6
KRON16	54.7593	162.1294	214.96	52.0	W	83.4	152.3	6	324.6
KRON17	54.7593	162.1294	214.96	52.0	W	76.8	70.4	3	427.6
KRON18	54.7593	162.1294	54.96	21.0	S	−20.4	144.3	2	5.1

Study mean direction D_s=300.7, I_s=48.7, α_{95}=10.9, Fisher estimate of kappa=11.8, N (sites)=17, percent unfolding=100%.

previously reported paleomagnetic studies from this sampling region (Table 1; result KMR; Levoshova and Bazhenov, 1997).

3.3 Interpretation of previous and new paleomagnetic data

Our results from the Kronotskiy region of the eastern Kamchatka Peninsula are consistent with a regional dataset showing that the terranes presently making up the peninsula are far traveled. Data from the Khatyrka terrane (KO and RY), Kuyul (GA1), Maynitsky terrane (YA), and sedimentary overlap sequences (SE, UB and PB) from the Koryak superterrane of northern Kamchatka constrain the Late Paleozoic and Mesozoic paleolatitudes of these terranes (Table 1). The paleolatitudes from the Khatyrka and Maynitsky terranes are anomalously low, while the paleomagnetic pole from the Senonian and Cenomanian-Maastrichtian sedimentary sequences suggests deposition of these units at the expected paleolatitudes with respect to either North American or Eurasian Apparent Polar Wander Paths (APWP), thus providing a minimum estimated accretion age for the overlapped terranes.

Paleomagnetic data collected from sedimentary rocks of Senonian and Cenomanian–Maastrichtian age, which overlap those from Al'katvaamsky terrane (UB), Penzhina Bay (PB) and Khatyrka terrane (SE) suggest that these sediments were all deposited at high paleolatitude, along the southeastern edge on the Eurasia plate. There is no significant difference between the expected and observed paleolatitudes (Table 1). This suggests that accretion of the Koryak superterrane occurred prior to Senonian–Cenomanian–Maastrichtian time.

Outboard of the Koryak superterrane paleomagnetic data show that the Olyutorskiy superterrane also consists of far traveled tectonostratigraphic terranes. The difference between the Olyutorskiy (UA, MB, and KA) terrane localities paleolatitudes for the Late Cretaceous-Paleocene are insignificant at the 95% confidence limits and consistent with paleomagnetic results VIII, VII, and VI (Table 1). Studies from Upper Apuka (UA) shows a latitudinal anomaly of 23.0°±18.0° and 28.3°±17.0° for the Machevna Bay (MB) localities, suggesting that Maastrichtian tuffs and tuffaceous

sandstones originated significantly to the south of either reference plate. Rotational and flattening statistics (Demarest, 1983) calculated with respect to the 67 Ma North America paleomagnetic reference pole (Irving and Irving, 1982) shows that these rocks formed at a significant distance from the North America continent. Calculated latitudinal anomalies are 20.5°±14.7° for the Upper Apuka and 26.2°±13.4° for the Machevna Bay localities. The choice of the paleomagnetic reference pole (reference continent) does not effect to the interpretation of the displacement: the Maastrichtian island-arc where these rocks originated was situated 20°–30° south from both North America and Eurasia continents. The Olyutorskiy (JB) result is significantly shallower than expected from either APWP, with an observed paleolatitude of 32° and a difference between expected and observed paleolatitudes of 42.6°±21.8° (Table 1).

In order to model these observed paleolatitudes we have used plate kinematic models of the past motions of oceanic and continental plates in the Northern Pacific Basin (Engebretson et al., 1985) and the modeling techniques described in Debiche et al. (1987).
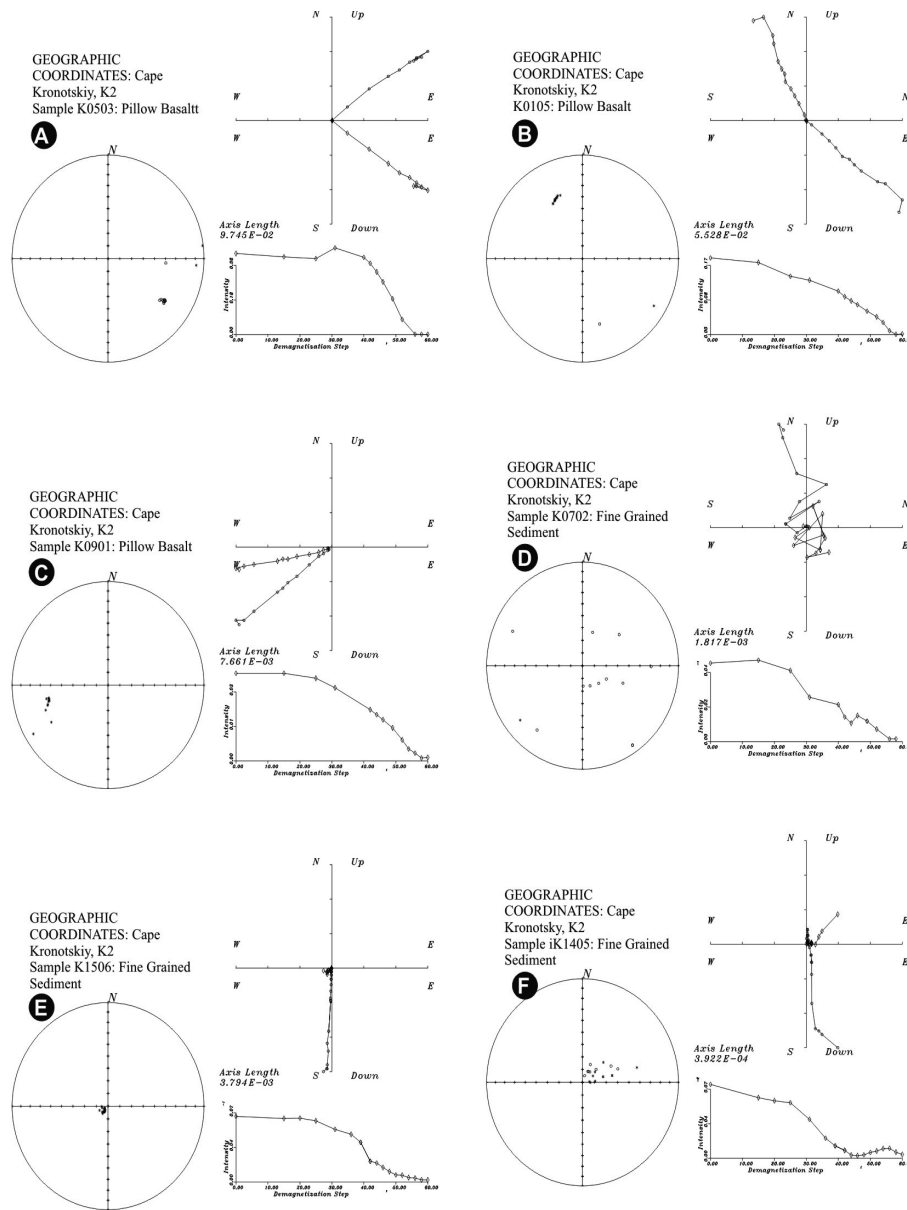
Fig. 3. Representative orthogonal vector plots, magnetic intensity decay diagrams and equal-area stereographic projects for selected stepwise thermal demagnetization data for samples **A** K0503, **B** K0105, **C** K0901, **D** K0702, **E** K1506 and **F** K1405. Lower hemisphere demagnetization directions are shown by the "*" 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.

4 Modeled accretionary terrane trajectories

To model the paleomagnetic results and the associated paleolatitudes we constructed model apparent polar wander paths (MAPWP) and terrane trajectories (Debiche et al., 1987; Cox and Hart, 1986). This method consists of rotating APWP reference points into a terrane frame of reference using finite rotations between the Eurasian and the ancient Izanagi and Farallon oceanic plates. Recently, data supporting a

modification to this analysis, true polar wander and/or relative displacement of regional hotspot reference frames, have been presented (Tarduno and Gee, 1995; Torsvik et al., 2002; Courtillot et al., 2003; Tarduno et al., 2003). In this section terrane trajectory analysis, which incorporates these two modifications, will be presented. The construction of terrane trajectories is based upon the application of finite plate rotations to paleomagnetic results and details of our models and their calculation are given in Appendix A.
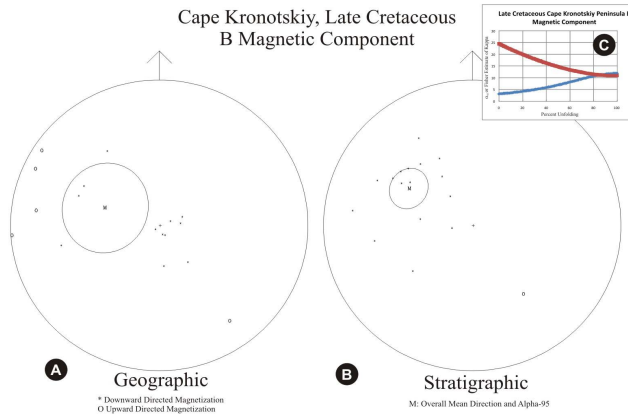
Fig. 4. Equal area site mean stereographic projection plots of the B magnetic component in **A** geographic coordinates, **B** stratigraphic coordinates, and **C** the Fisher estimate of Kappa and Fisher estimate α_{95} during stepwise unfolding. On these plots (X), present-day magnetic field direction (P), component B mean direction (M) and α_{95} circle of confidence shown in geographic and 100% unfolding coordinates. Upper hemisphere directions are shown with "O" symbols. Site mean B component numerical data are presented in Table 2.

Fig. 5. The paleolatitude and uncertainty calculated from the observed magnetic component B are shown in a Mercator projection about the 89 Ma NAM Reference pole of Besse and Courtillot (1991).

We find that after these modifications the expected paleo-latitude corresponding to this displacement history is shallower than paleomagnetic results (in the 30 Ma accretion model) but better agrees with our paleomagnetic results in the 40 Ma accretion model. Assuming the later displacement history and collision to North American plate we expect a paleolatitude of between 45° and 25° N between 60 to 80 Ma matching our observation of λ_{obs}=30.4° N or S, λ_{95}=8.9°, n=17 (sites). Our paleomagnetic data was collected from the Kronotskiy arc, which is a distinct terrane from the Olyu-torskiy, however, our paleomagnetic results are compatible with an earlier accretion for this terrane than previously interpreted. We interpret our paleomagnetic data and revised terrane trajectory models to show that fragments of an island arc are present in the East Kamchatka superterrane that accreted to a cratonal plate in this region during the Eocene.

5 Conclusions

We have observed a characteristic B component in Late Cretaceous aged geologic units at Cape Kronotskiy. The resulting paleolatitude and associated uncertainty in stratigraphic coordinates are D_s=300.7°, I_s=48.7°, α_{95} = 10.9°, k-value = 11.8, n = 17 (sites). The B component paleolatitude calculated from the Fisher mean in stratigraphic coordinates and associated statistics are λ_{obs} =30.4° N or S, λ_{95}=8.9°, n=17 (sites), k-value=11. Our paleomagnetic data from the Kronotskiy Peninsula in eastern Kamchatka agree well with the highest unblocking temperature direction presented in study
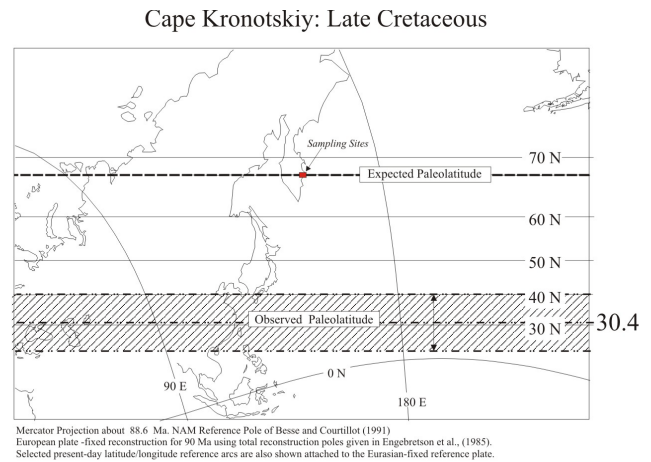
KMR (Levashova and Bazhenov, 1997). These paleomagnetic data are consistent with a terrane trajectory model of the Kronotskiy superterrane, in which relative displacement of the Hawaii hotspot, or True Polar Wander, are incorporated.

Appendix A

Modeling finite rotation trajectories

An efficient notation for finite rotations has been developed and well described so that relative motion of the Pacific hotspot framework can be incorporated into terrane analysis of the Kronotskiy B component paleomagnetic result. Understanding of the basics of finite pole rotations is useful in understanding this analysis and its inherent assumptions; this summary is based upon presentations in Engebretson et al. (1985), Debiche et al. (1987) and Cox and Hart (1986).

Total reconstruction poles (TRP) represent the pole, which rotates points on the earth's surface from their present location to an ancient location, in a particular plate reference frame between two time intervals. For example, the TRP, which rotates the Kula plate from its present position to its position at 73 Ma with respect to the Pacific plate is shown as ${}^{0}_{PAC}\Re^{73}_{KUL}$. In this notation the fixed plate is the Pacific plate, while the mobile plate, the Kula in this example moves from a present to a past, 73 Ma, position. The TRP pole, which spatially displaces surface points from ancient to present positions, is shown as ${}^{73}_{KUL}\Re^{0}_{PAC}$. The Euler pole in computations is either expressed by a rotation matrix or quaternion. TRPs can be combined, however, because there is not a commutative property in TRP finite rotations, the order of rotations is critical. Notation showing the proper combination of

TRPs resulting in a description of motion of the Kula (KUL) plate in a North America plate (NAM) fixed reference frame, in which a matrix operation is shown with the circle/plus symbol, is shown in (1)

$$^0_{NAM}\Re^{70}_{KUL}=^0_{NAM}\Re^{70}_{PAC} \oplus^0_{PAC}\Re^{70}_{KUL} \qquad (A1)$$

Or in the hotspot fixed reference frame,

$$^0_{HSP}\Re^{70}_{KUL}=^0_{HSP}\Re^{70}_{PAC} \oplus^0_{PAC}\Re^{60}_{KUL} \oplus^{60}_{PAC}\Re^{70}_{KUL} \qquad (A2)$$

In (2) the finite rotation pole is of a different type and defined as a stage pole, $^{60}_{PAC}\Re^{70}_{KUL}$. A stage pole represents the finite rotation, which moves features on one plate with respect to another plate, between two intervals of time t_1 and t_2: An assumption is made that the Euler pole for a plate pair remains fixed during stages and changes locations, or "jumps" between stages. This assumption is supported by detailed analysis of oceanic magnetic isochrones (Engebretson et al., 1985). TRPs can easily be converted to stage poles and stage poles to TRPs. Associated with the concept of stage poles is an important property of finite rotation algebra,

$$^{T2}_{A}\Re^{T1}_{B} \neq (-(^{T2}_{B}\Re^{T1}_{A})) \qquad (A3)$$

This algebraic property at first glance seems violated by the algebraic identify

$$A^T\Re^0_B=(-^0_A\Re^T_B) \qquad (A4)$$

However, it is not inconsistent with Eq. (3) because total reconstruction poles all share the same present-day reference system at $t=0$ (present day) time (Cox and Hart, 1986).

In our analysis we first convert TRPs to Stage Poles. The TRPs are taken directly from the magnetic isochron analysis of Pacific basin oceanic plate kinematics published by Engebretson et al. (1985). For each plate pair these stage poles are then interpolated to a series of stage poles, each 0.1 Ma in duration by combining discrete position and negative signed finite rotations. The specific plate kinematic history of the displaced terrane is then used to guide the editing and then combination of 0.1 Ma duration stage poles into a file which is then used to calculate total reconstruction poles at 0.1 Ma time steps. These TRPs now describe the displacement history of the terranes in eastern Kamchatka with respect to translation on specific oceanic plates. From the TRPs and assuming a point of beginning the terrane trajectory is calculated (Debiche et al., 1987). The expected paleomagnetic inclination, declination and paleolatitude can be easily calculated for the modeled displacement history.

As seen earlier there are assumptions, such as the "jumping" nature of stage poles, in this methodology. A key assumption in the analysis of Engebretson et al. (1985) was the fixed nature of the hotspot coordinate framework for the Africa and Pacific plates. If the Atlantic/Africa region hotspot frame is noted as HS_1 and the Pacific region hotspot finite rotation frame as HS_2, the hotspot fixed finite rotation poles were calculated as:

$$^0_{NAM}\Re^{T1}_{KUL}=^0_{NAM}\Re^{T1}_{AFR} \oplus (-(^0_{HS1}\Re^{T1}_{AFR})) \oplus^0_{HS2}\Re^{T1}_{PAC} \oplus^0_{PAC}\Re^{T1}_{KUL} \quad (A5)$$

The fixed hotspot assumption is inherent in this analysis:

$$0=^0_{HS1}\Re^{T1}_{HS2} \qquad (A6)$$

Models of hotspot–spin axis relative motion have been published (Tarduno and Gee, 1995; Torsvik et al., 2002; Courtillot et al., 2003; Tarduno et al., 2003). The results of Torsvik et al. (2002), does not alter terrane trajectories although the predicted paleolatitudes are shifted. Terrane trajectories modified to include the TRP presented in Torsvik et al. (2002) are shown in Fig. A1.

Recently new paleomagnetic data from the Hawaiian hotspot, innovatively collected, analyzed and interpreted by Tarduno et al. (2003), have been presented and interpreted to show the relative displacement of the Hawaii hotspot with respect to the geographic axis (GXS). These data only constrain latitudinal displacement and have been interpreted to show motion of the Hawaiian hotspot (the HS2 finite rotation pole framework) with respect to the geographic axis. A finite-rotation based model of this displacement can be incorporated into terrane trajectory analysis. A model of $^0_{GXS}\Re^{T1}_{HS2}$ finite rotation poles is used and terrane trajectories are then calculated with respect to each of these finite rotation pole models. Earlier finite rotation pole models incorporated the explicit assumption of

$$0=^0_{GXS}\Re^{T1}_{HS1} \qquad (A7)$$

It is straightforward to incorporate this simple modification of the finite rotation pole analysis by adding the additional finite rotation stage pole describing this rotation given by

$$^{T1}_{GXS}\Re^{T2}_{HS2} \qquad (A8)$$

The unit vector Euler pole is calculated from the cross product of $\hat{A}_1 \times \hat{A}_2=\boldsymbol{C}$, where c represents the unit vector Euler pole. The finite rotation stage pole is determined by combining with the Euler pole the rotation angle defining $^{T1}_{GXS}\Re^{T2}_{HS2}$. In this stage pole calculation $\hat{A}_1$ and $\hat{A}_2$ represent the present day and interpreted positions of the Hawaii hotspot, where $\hat{A}_2$ satisfies the latitude displacement presented in Tarduno et al. (2003). Using this $^{45}_{GXS}\Re^{85}_{HS2}$ model as the stage pole describing geographic axis – Hawaii hotspot displacement this new term may be incorporated in our analysis as shown by,

$$^{T1}_{NAM}\Re^{T2}_{KUL}= ^{T1}_{NAM}\Re^{T2}_{AFR} \oplus (-(^{T1}_{HS1}\Re^{T2}_{AFR})) \oplus^{T1}_{HS1}\Re^{T2}_{GXS}$$
$$\oplus^{T1}_{GXS}\Re^{T2}_{HS2} \oplus^{T1}_{HS2}\Re^{T2}_{PAC} \oplus^{T1}_{PAC}\Re^{T2}_{KUL} \qquad (A9)$$

Equation (9) incorporates within the North America fixed terrane trajectories an estimate of geographic axis-Hawaii hotspot relative motion. This analysis can be extended to include Atlantic/Africa region hotspot absolute motion where

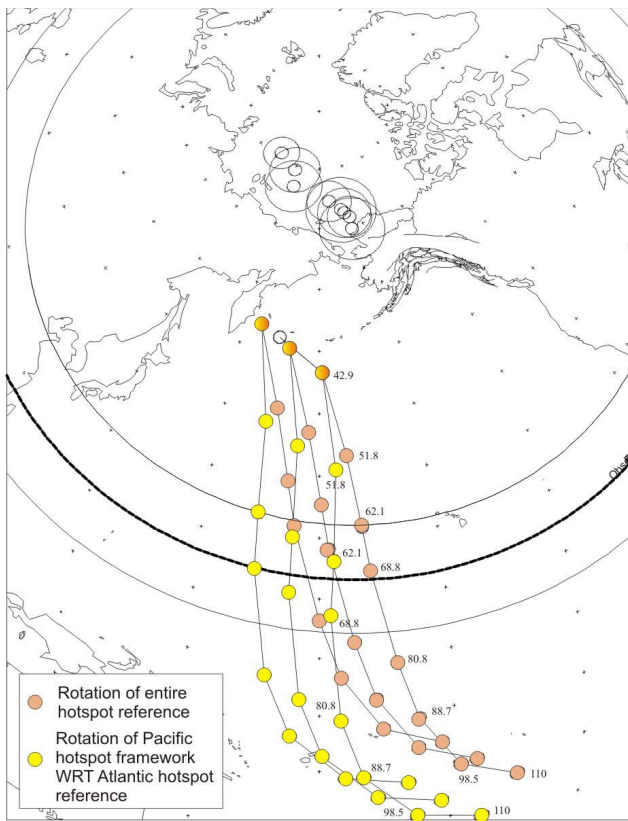$$0 \neq^0_{GXS}\Re^{T1}_{HS1} \qquad (A10)$$

Fig. A1. The APWP for North America and associated 95% confidences from Besse and Courtillot (1991) are compared with the observed B component paleolatitude and uncertainty compared with a series of terrane trajectories. Yellow circles are calculated assuming the TPW presented in Torsvik et al. (2002) and docking with the North America plate at 20, 30 or 40 Ma. Orange circles lay along terrane trajectories calculated assuming a relative rotation of the Pacific Hotspots with respect to other hotspots as suggested by Tarduno et al. (2003). The plate trajectories only involve recalculated finite rotations for the Pacific, Kula and Izanagi plates. Other plates, such as the proposed Vetlovka (Konstantinovskaia, 2001) are not modeled because of a lack of magnetic isochron derived finite rotations for this particular plate. Most reconstructions involving other oceanic plates in the northwest Pacific basin do not show major relative motion between such smaller oceanic plates and the modeled oceanic plates; therefore the terrane trajectories shown in this figure would be similar to those calculated for terrane migration including plates such as the Vetlovka.

and

$$
\begin{aligned}
{}_{\mathrm{NAM}}^{T1}\Re_{\mathrm{KUL}}^{T2} = {}_{\mathrm{NAM}}^{T1}\Re_{\mathrm{AFR}}^{T2} \oplus (-({}_{\mathrm{HS1}}^{T1}\Re_{\mathrm{AFR}}^{T2})) \oplus {}_{\mathrm{HS1}}^{T1}\Re_{\mathrm{GXS}}^{T2} \\
\oplus {}_{\mathrm{GXS}}^{T1}\Re_{\mathrm{HS2}}^{T2} \oplus {}_{\mathrm{HS2}}^{T1}\Re_{\mathrm{PAC}}^{T2} \oplus {}_{\mathrm{PAC}}^{T1}\Re_{\mathrm{KUL}}^{T2}
\end{aligned}
\tag{A11}
$$

The predicted terrane trajectories from this modified analysis are shown in Fig. A1.

An additional key assumption in constructing a terrane trajectory is the location and age of accretion (Debiche et al., 1987). Presently the most accurately constrained age of accretion has been determined for the Olyutorskiy on the basis of single zircon crystal fission-track analysis. The age of accretion of the Olyutorskiy terrane is estimated now as middle Eocene based on new ages determined for the rocks in the terrane thrust sheets and age of intrusions which suture the thrust (Soloviev et al., 2002; Garver et al., 2000; Alexeiev et al., 2006). We constructed three terrane trajectory models each assuming the age of accretion to be 20, 30 or 40 Ma. To model the paleomagnetic result we assumed a displacement history for the terrane that consists of being transported with the Izanagi plate between 110.1 and 85 Ma followed by Kula plate motion between the beginning of Campanian (∼85 Ma) and the time of accretion. In each accretion model, motion with the Pacific plate occurs between 43 and the age of docking.

A brief personal memory of Dr. Parfenov

(WH) I had the pleasure to initially correspond with Dr. Parfenov while completing my Ph.D. at Stanford University during the early 1980's. During that time, after reviewing the literature describing the geology, geophysics and tectonics of the northeastern USSR I had written Dr. Parfenov a letter, somewhat unfocused, but full of idealism and interest in his research. It was my pleasure to receive a very thoughtful reply to my initial correspondence and a thick collection of Russian language articles written by Dr. Parfenov and his colleagues. These articles were enormously useful to my understanding the geological history of this large region of Eurasia, and are carefully preserved today. After several earlier visits to the USSR, in 1987 I met Dr. Parfenov for the first time while attended the first plate tectonics conference held in the USSR, at Yuzhno-Sakhalinsk on Sakhalin Island. It was a pleasure to meet and talk with Dr. Parfenov about his ideas regarding the plate tectonic history of the USSR. At that time a number of research teams in the USSR were actively, and somewhat discretely, applying plate tectonics to the geodynamics of this vast region. I remember accompanying my Russian colleagues on a pleasant picnic and swim held

in an Elysian pastoral scene near a local river. A group broke away to enjoy swimming in the wonderful blue cool river on this warm afternoon. It was a joke for our group, called back and forth numerous times in Russian, that the "Mobilists" would float, but the "Fixists" should beware, they would no doubt immediately sink to the bottom of the river! Dr. Parfenov continued to aid my research with thoughtful discussions at international meetings and by generously providing copies of his significant and important publications, such as his geodynamic reconstructions of northeastern Russia. His presentations were "must-attend" events for me and my graduate students at geoscience meetings in Anchorage, San Francisco or international locations. My coauthors and I are honored to contribute to this volume in Dr. Parfenov's honor. A scholar and gentleman, Dr. Parfenov is fondly remembered and greatly missed.

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