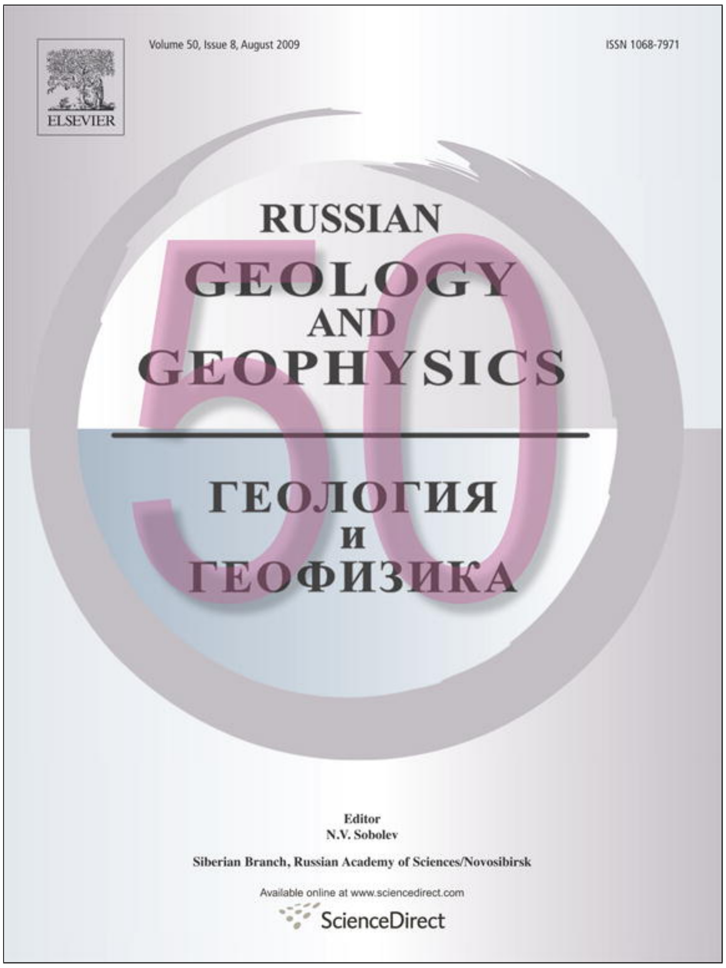
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Formation of the Olyutorsky–Kamchatka foldbelt: a kinematic model

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Abstract

The Olyutorsky–Kamchatka foldbelt formed as a result of two successive collisions of the Achaivayam–Valaginsky and Kronotsky–Commander island arcs with the Eurasian margin where the two terranes docked after a long NW transport. We model their motion history from the Middle Campanian to Present and illustrate the respective plate margin evolution with ten reconstructions. In this modeling the arcs are assumed to travel on the periphery of the large plates of Eurasia, North America, Pacific, and Kula, for which the velocities and directions of motion are known from published data. The model predicts that the Achaivayam–Valaginsky arc was the leading edge of the Kula plate from the Middle Campanian to the Middle Paleocene and then moved slowly with the Pacific plate as long as the Middle Eocene when it accreted to Eurasia. The Kronotsky arc initiated in the Middle Campanian on the margin of North America and was its part till the latest Paleocene when the terrane changed polarity to move northwestward with the Pacific plate and eventually to collide with Eurasia in the Late Miocene. The predicted paleolatitudes of the Achaivayam–Valaginsky and Kronotsky–Commander island arcs for the latest Cretaceous and Paleogene are consistent with nine (out of eleven) reliable paleomagnetic determinations for samples from the two arcs. Additional changes imposed on the initial model parameters (kinematics of the large plates, relative position of the Kula–Pacific Ridge and the Emperor seamount chain, or time of active volcanism within the arcs) worsen the fit of the final reconstructions to available geological and paleomagnetic data. Therefore, the suggested model appears to be the most consistent one at this stage of knowledge.

Keywords: Late Mesozoic–Cenozoic; plate kinematics; northwestern Pacific; Olyutorsky–Kamchatka foldbelt

Introduction

The history of orogenic areas of different ages has been interpreted since recently in the context of accretionary tectonics. According to this theory, which stems from plate tectonics and proceeds from data on dynamics of active margins and detailed reconstructions, most of orogenic areas formed at active continental margins as a result of subduction and collision.

Long-lasting subduction of oceanic lithosphere beneath a continent, one of the two basic processes, goes by steady counter motion of oceanic and continental plates**, and is attendant with formation of accretionary prisms and volcanic arcs over the subduction zones. Accretionary prisms and suprasubduction magmatic arcs are thought to contribute to continental growth, though the increment is actually not very large as they result from recycling of continental lithosphere.

Collision, the other basic process, takes place when subduction ceases as ocean islands (seamounts), being too large and light to submerge into the mantle, accrete to the continent (or to an island arc). As a consequence, the subduction boundary moves offshore while the accreted lithosphere most often deforms and becomes part of the continental plate whereby the latter grows notably in surface area and in volume.

With this approach, kinematic modeling of a foldbelt's evolution reduces to deciphering the paths of all its major constituents prior to their amalgamation into the existing

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** Hereafter the concept of a continental plate includes the entire collage of relatively small plates in the space between a trench and a craton rather than being restricted to the craton proper or to continental lithosphere. In the case of today's northeastern Asia, the Eurasian continental plate is meant to encompass areas of definitely oceanic crust, such as the basins of the Bering, Okhotsk, and Japan seas. The velocities of these small plates with respect to the flanking continent are most often unknown but are presumably negligible for our consideration.

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intricate system, under the assumption that they traveled as parts of large continental or oceanic plates. This kind of modeling is discussed, for instance, in (Debiche et al., 1987) for the case of western North America. All available kinematic models for the Olyutorsky–Kamchatka area (Kononov, 1989; Konstantinovskaya, 2003; Kovalenko, 2003; Levashova, 1999; Parfenov et al., 1999; Savel'ev, 2004; Scotese et al., 2001; Seliverstov, 1998; Stavskii et al., 1988; Verzhbitskii et al., 2006) agree about the northwestward direction of island arc terranes prior to their collision with Eurasia but differ in details of the motion histories. The controversy is largely due to insufficiently formalized definition of plate boundaries in the part of the Pacific that has already been consumed in subduction zones having left a few isolated island arc blocks. This study is an attempt to formalize the reconstruction for the position of these blocks and, correspondingly, the plate boundaries since the latest Cretaceous.

We describe the evolution of the study area as motion histories of its several elements (terranes) assumed to travel as parts of four large plates with known velocities and directions of motion. The latest event in the evolution of each terrane is motion with the plate the foldbelt currently belongs to. According to the model, at least two terranes underwent quite a long transport before they collided with Eurasia. The model is tested by checking the predicted paleolatitudes against published paleomagnetic data for samples of Late Cretaceous and Paleocene–Eocene island arc rocks from Kamchatka and southern Koryakia. Note that this modeling approach was summarized in (Levashova, 1999), with reference to (Debiche et al., 1987), but has never been applied to model the history of the Olyutorsky–Kamchatka area.

Terranes in the basement of the Olyutorsky–Kamchatka area

The basement structure of the Olyutorsky–Kamchatka area has been interpreted using the terrane analysis. This analysis consists in distinguishing fault-bounded regional-scale geological bodies with their specific lithology and structure different from those in coeval rocks on the other side of the faults. This terrane concept appeared in the middle 1980s, mainly for circum-Pacific foldbelts (e.g., Howell et al., 1985; Parfenov et al., 1999; Sokolov, 1992). The term *terrane* is especially good for the cases when the origin and paths of large constituents of an area are unknown or, at least, not obvious.

The basement of the Olyutorsky–Kamchatka foldbelt is roughly divided into four terranes: Omgon–Ukelayat, Achaivayam–Valaginsky, Vetlovaya–Govena, and Kronotsky–Commander (Fig. 1).

The **Omgon–Ukelayat terrane** consists of strongly deformed (tightly folded) Upper Cretaceous–Middle Eocene sand-silt flysch-like sediments barren of macrofossils. These terrigenous rocks are mapped on the western slopes of the southern Malka uplift (Khanchuk, 1985; Litvinov et al., 1999), in some basement uplifts in the West Kamchatka basin (Grechin, 1979; Solov'ev, 2005), over a great part of the Lesnaya uplift (Shantser et al., 1985; Shapiro et al., 1992), and north of the Vetveisky and Olyutorsky ranges (Central Koryak or Ukelayat basin) (Ermakov and Suprunenko, 1975; Solov'ev, 1998). There are also small exposures of Cretaceous and Early Paleogene terrigenous sequences that have a similar lithology but originate from shallower marine environments and bear macrofossils and even plant remnants (Gladenkov et al., 1997). Transition from relatively deep-sea Late Cretaceous flysch in the south to shallower facies in the north is traceable in the Central Koryak basin as well (Chekhovich et al., 2008; Sokolov, 1992).

Terrigenous deposition in the Omgon–Ukelayat terrane presumably began in the Middle Campanian after the cessation of subduction beneath the Okhotsk–Chukchi volcanic belt, when this part of Asian margin became relatively passive (Filatova, 1979, 1987). The sediments were deformed in the Eocene (52–46 Ma) (Solov'ev, 2008), possibly as a result of collision between the Achaivayam–Valaginsky terrane and northwestern Asia. The Omgon–Ukelayat terrane was interpreted as the submarine terrigenous apron of the Asian continent (Ermakov and Suprunenko, 1975; Grechin, 1979; Sokolov, 1992; Solov'ev, 2005).

The rocks of the Omgon–Ukelayat terrane lie under volcanic and sedimentary rocks of the Achaivayam–Valaginsky terrane along the Middle Eocene (~46 Ma, Shapiro et al., 2001) Vatyna–Lesnaya thrust in the Kamchatka isthmus and in the Olyutorsky zone (Bogdanov et al., 1987; Mitrofanov, 1977; Solov'ev, 1998). In the south, in the Malka uplift, the tectonic contact of the two terranes is obscured by high-grade metamorphism and later deformation (Kirmasov et al., 2004; Solov'ev and Palechek, 2004). Motions at the terrane boundaries had ended mainly by ~52–50 Ma or the latest Early Eocene (Hourigan et al., 2009; Solov'ev et al., 2004a).

The **Achaivayam–Valaginsky terrane** is composed of Late Cretaceous and Early Paleocene volcanic (basaltic andesites and less abundant more felsic varieties) and sedimentary rocks of diverse but mostly submarine facies, with older Mesozoic volcanosedimentary blocks and imbrices and ophiolite fragments. The Cretaceous–Paleocene volcanosedimentary strata build a great part of uplifts in the Olyutorsky zone (Astrakhantsev et al., 1987; Bogdanov et al., 1987; Kazimirov et al., 1987), are widespread in the northern and southern Sredinny Range (Avdeiko et al., 1974; Flerov and Koloskov, 1976), and predominate in uplifts of the Vostochny Range (Tsukanov, 1991; Zinkevich et al., 1993). According to recent data (Kirmasov et al., 2004; Solov'ev and Palechek, 2004), some metamorphic complexes of the Malka uplift (Andrianovka and, possibly, Khimka Formations) are equivalent to nonmetamorphosed Cretaceous–Paleocene sequences on the terrane periphery and must belong to the terrane as well. The metamorphic rocks of the Ganaly Range may be tentatively assigned to the Achaivayam–Valaginsky terrane, but the origin and age of their protolith remain uncertain (Bindeman et al., 2002; German, 1978; Zinkevich et al., 1993).

Volcanics are of island arc affinity and, on this basis, we interpret them as subprasubduction rocks and apply this interpretation to the kinematic reconstructions.

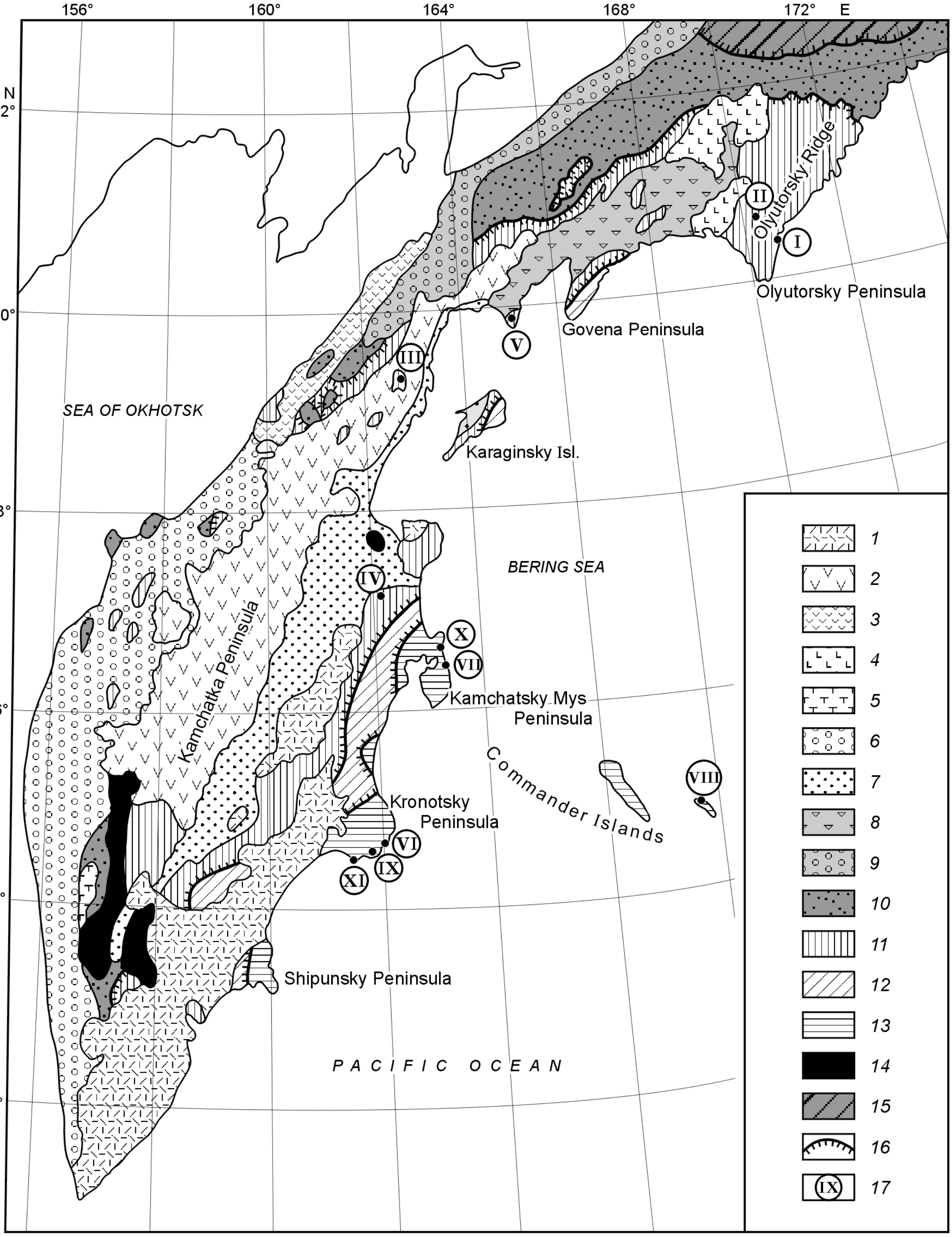


Fig. 1. Tectonic framework of Kamchatka and South Koryakia. *1–8*, volcanic and sedimentary rocks: *1–5*, subaerial volcanic belts and fields: East Kamchatka belt, N_2 to Present (*1*), Central Kamchatka, Ᵽ$_3$(?) to Present (*2*), Kinkil (West Kamchatka–Koryak), Ᵽ$_{2-3}$ (*3*), Apuk–Vyvenka, N_2–Q (*4*), Cherepanov, Ᵽ$_{1-2}$ (*5*); *6–9*, sedimentation basins: West Kamchatka basin, Ᵽ$_2$–N_2 (*6*), Central Kamchatka basin, N_2–Q (*7*), Ilpinsky–Pakhachi basin, Ᵽ$_2$–N_1 (*8*), Pustoretsky–Parapol basin, N–Q (*9*); *10–15*, basement terranes: Omgon–Ukelayat terrane, continental rise terrigenous rocks, K_2–Ᵽ$_2$ (*10*), Achaivayam–Valaginsky terrane, paleo-island arc, K_2–Ᵽ$_1$ (*11*), Vetlovaya–Govena terrane, accretionary prism, Ᵽ$_2$–N_1 (*12*), Kronotsky–Commander (Kronotsky) terrane, paleo-island arc, K_2–Ᵽ$_3$ (*13*), metamorphics after rocks of Omgon–Ukelayat and Achaivayam–Valaginsky terranes (*14*), terranes of northern Koryakia (*15*); *16*, tectonic sutures (thrusts); *17*, sampling sites for paleomagnetism mentioned in text.

In the southeast of the terrane, the Cretaceous–Paleocene volcanosedimentary strata are conformably overlain by Late Paleocene–Early Eocene sand-clay flysch of the Drozdovka and Talnikovaya Formations (Belousov, 1987; Tsukanov, 1991). Sandstone in these formations is compositionally close to that in the Omgon–Ukelayat terrane and must likewise have a continental provenance (northeastern Asia) (Solov'ev et al., 2004b).

The **Kronotsky–Commander (Kronotsky) terrane**, another island arc terrane, includes peninsulas of eastern Kamchatka (Shipunsky, Kronotsky, Kamchatsky Mys) and the Commander Islands (Bazhenov et al., 1992; Tsukanov, 1991; Zinkevich et al., 1993). The area is remarkable by broad occurrence of Late Paleocene and Eocene submarine suprasubduction volcanics which are absent from adjacent western Kamchatka (Khubunaya, 1987).

The boundary between the Achaivayam–Valaginsky and Kronotsky terranes is a band of thrusts and SE recumbent folds (Alexeiev et al., 2006; Belousov, 1987; Solov'ev et al., 2004b; Tsukanov, 1991; Zinkevich et al., 1993) involving Late Paleocene to Oligocene and, possibly, up to Middle Miocene terrigenous, tuffaceous- and siliceous-terrigenous rocks of the Vetlovaya Group. The Group often looks like sedimentary melange with blocks of chert, jasper, and pelitic limestone coexisting with low-K and high-Ti basaltic pillow lavas (Tsukanov, 1991).

There is a system of thrusts and SE folds in Late Eocene–Early Miocene terrigenous strata on the northeastern extension of the Vostochny range (in Karaginsky Island, southeast of the exposed Cretaceous and Early Paleogene volcanics of the Achaivayam–Valaginsky terrane) which continues along the southeastern shore of the Govena Peninsula almost as far as the Pakhachi River mouth (Chekhovich et al., 1990; Ledneva et al., 2004). We suggest to call this zone the **Vetlovaya–Govena terrane** and to classify it as an accretionary prism following Chekhovich et al. (1990), Tsukanov (1991), and Sokolov (1992).

The four strongly deformed terranes in the basement of the Olyutorsky–Kamchatka area and the fault sutures between them are overlain, with a sharp unconformity, by relatively flat layers of volcanics that make up three volcanic belts and several isometric fields. Together with sediments of a few large Cenozoic basins, they form a discontinuous cover of a variable thickness (Fig. 1). The most active East Kamchatka belt is related to the modern Kuriles–Kamchatka subduction zone (Avdeiko et al., 2002). The older belts and fields of postorogenic volcanics are presumed to be of a suprasubduction origin as well. Therefore, although remaining fixed with respect to the continent, they are important elements in our modeling as tracers of old subduction zones at the ocean–continent boundary.

Basic postulates of the model

The available paleomagnetic data from Upper Cretaceous and Lower Paleogene rocks (Table 1) show that the island arc terranes (Achaivayam–Valaginsky and Kronotsky–Commander) of the Olyutorsky–Kamchatka area underwent quite a long northward transport before docking at Eurasia (Bazhenov et al., 1992; Kovalenko, 2003; Levashova, 1999; Levashova et al., 1998, 2000), but there has been no reliable paleolatitudes for the two other terranes (Omgon–Ukelayat and Vetlovaya–Govena). We assume the Omgon–Ukelayat terrane to be part of Eurasia and thus may neglect its motion relative to the latter. The Vetlovaya–Govena terrane may be an accretionary prism, and if this interpretation is right, most of its rocks likewise formed on the Eurasian margin after accretion of the Achaivayam–Valaginsky island arc.

Thus, the Olyutorsky–Kamchatka foldbelt and the zone of the Koryak Plateau formed as a result of two successive accretion events in which the Achaivayam–Valaginsky and Kronotsky island arcs accreted to the submerged margin of northeastern Asia after a long transport. We obtained a kinematic model of the foldbelt formation assuming that the arcs traveled together with large plates (Kula, Pacific, Eurasia, North America) while the role of small plates was minor. Therefore, the motion history of each island arc terrane was reduced to a series of rotation events about the poles of the large plates known from published global plate motion reconstructions (Engebretson et al., 1985; Kraus and Scotese, 1993; Norton, 1995; Petronotis and Jurdy, 1990). Deformation inside the terranes was neglected.

The **Achaivayam–Valaginsky terrane** originated at about 90–85 Ma (Coniacian–Santonian) as an island arc upon oceanic crust (Bogdanov et al., 1987; Sokolov, 1992) but island arc volcanism was especially active in the Campanian, about the time when suprasubduction volcanism ceased in the Okhotsk–Chukchi belt (Filatova, 1987). Paleomagnetic data indicate an about 2000 km northward transport of the terrane from its formative paleolatitude to the modern position at the Eurasian margin (Kovalenko, 2003; Levashova, 1999), at a mean velocity of 7–8 cm/year between the Campanian (75 Ma) and the Middle Eocene (45–50 Ma), which is approximately the velocity of the Pacific plate. On the other hand, the Eurasian provenance of Paleocene flysch (Drozdovka and Talnikovaya Formations) in the Vostochny Range of Kamchatka (Solov'ev et al., 2004b) indicates that already at 60 Ma the Achaivayam–Valaginsky arc must have been no farther than 500 km from the continent. This idea is consistent with generally proximal paleolatitudes of Late Paleocene tuff in the Ilpinsky Peninsula and those expected for the area assumed to be part of Eurasia (Kovalenko, 2003). Therefore, in the latest Cretaceous and in the Early Paleocene (75–60 Ma) the arc apparently moved faster than the Pacific plate, at ~10 cm/year. That is why we believe that it formed upon the Kula plate which moved rapidly because of fast Kula–Pacific spreading in the W–E ridge segment (Engebretson et al., 1985). Then the arc slowed down abruptly to 3.5 cm/year in the second half of the Paleocene, possibly as a result of accretion of the western Kula (together with the arc) to the Pacific plate.

The Achaivayam–Valaginsky subduction was to southeast toward the ocean and the zone apparently consisted of two segments (southwestern and northeastern ones) separated by a transform (Kovalenko, 2003; Levashova, 1999), with an amount of displacement up to 300–500 km. That was, possibly, the reason why the northeastern arc flank accreted to the continent 5–7 Ma later than the southwestern flank (Solov'ev, 2008). Taking this into account, we predict that the

Table 1
Most reliable paleolatitudes of Achaivayam–Valaginsky arc and all paleolatitudes of Kronotsky–Commander arc

Determination (Figs. 1–5)	Sampling area	Age, Ma	Number of samples	Thickness of sampled section, m	Paleomagnetic latitude, deg N	Reference
I	Olyutorsky Ridge (AVA)	83–65 (Campanian–Maastrichtian)	68	No data	51.1 ± 7	(Kovalenko, 2003)
II	Olyutorsky Ridge (AVA)	83–65 (Campanian–Maastrichtian)	64	No data	47 ± 6.5	(Kovalenko, 2003)
III	Kamchatka isthmus (AVA)	83–71 (Campanian)	74	385	48.5 ± 8.4	(Levashova et al., 1998)
IV	Kumroch Ridge (AVA)	83–65 (Campanian–Maastrichtian)	71	260	48.7 ± 5	(Levashova et al., 1997)
V	Ilpinsky Peninsula (AVA)	55–45 (Lower–Middle Eocene)	44	No data	63.5 ± 10	(Kovalenko, 2003)
VI	Kronotsky Peninsula (KA)	83–65 (Campanian–Maastrichtian)	78	215	44.8 ± 8	(Levashova et al., 2000)
VII	Kamchatsky Mys Peninsula (KA)	65–60 (Lower Paleocene)	78	288	38.1 ± 4.1	(Pecherscky et al., 1997)
VIII	Mednyi Island (KA)	65–35 (Paleocene–Eocene)	31	No data	45 ± 8	(Bazhenov et al., 1992)
IX	Kronotsky Peninsula (KA)	55–50 (Lower Eocene)	24	90	38.6 ± 3.5	(Levashova et al., 2000)
X	Kamchatsky Mys Peninsula (KA)	49–40 (Lutetian)	54	194	47 ± 6.5	(Pecherscky et al., 1997)
XI	Kronotsky Peninsula (KA)	40–37 (Bartonian)	76	120	45.1 ± 7	(Levashova et al., 2000)

Note. AVA is Achaivayam–Valaginsky arc, KA is Kronotsky–Commander arc. For stability criteria see (Shapiro, 2005).

southwestern segment of the terrane moved with the Kula plate between ~75 and 56 Ma (since the Middle Campanian), then with the Pacific plate until its collision with Eurasia at ~52 Ma, and since then it has been part of Eurasia (52–0 Ma). Its trajectory can be backward modeled as motion with Eurasia from 0 to 52 Ma, with Pacific from 52 to 56 Ma, and with Kula between 56 and 75 Ma. The motion of the northeastern segment differs in a shorter stay with Eurasia (0–45 Ma) and, correspondingly, a longer travel with Pacific (from 45 to 56 Ma).

The **Kronotsky–Commander terrane**, like the Achaivayam–Valaginsky one, is interpreted as an oceanic island arc that originated in the middle Late Cretaceous (e.g., Khubunaya, 1987). Its motion history ended with Miocene–Pliocene docking and formation of the Grechishkin thrust (Shapiro, 1980).

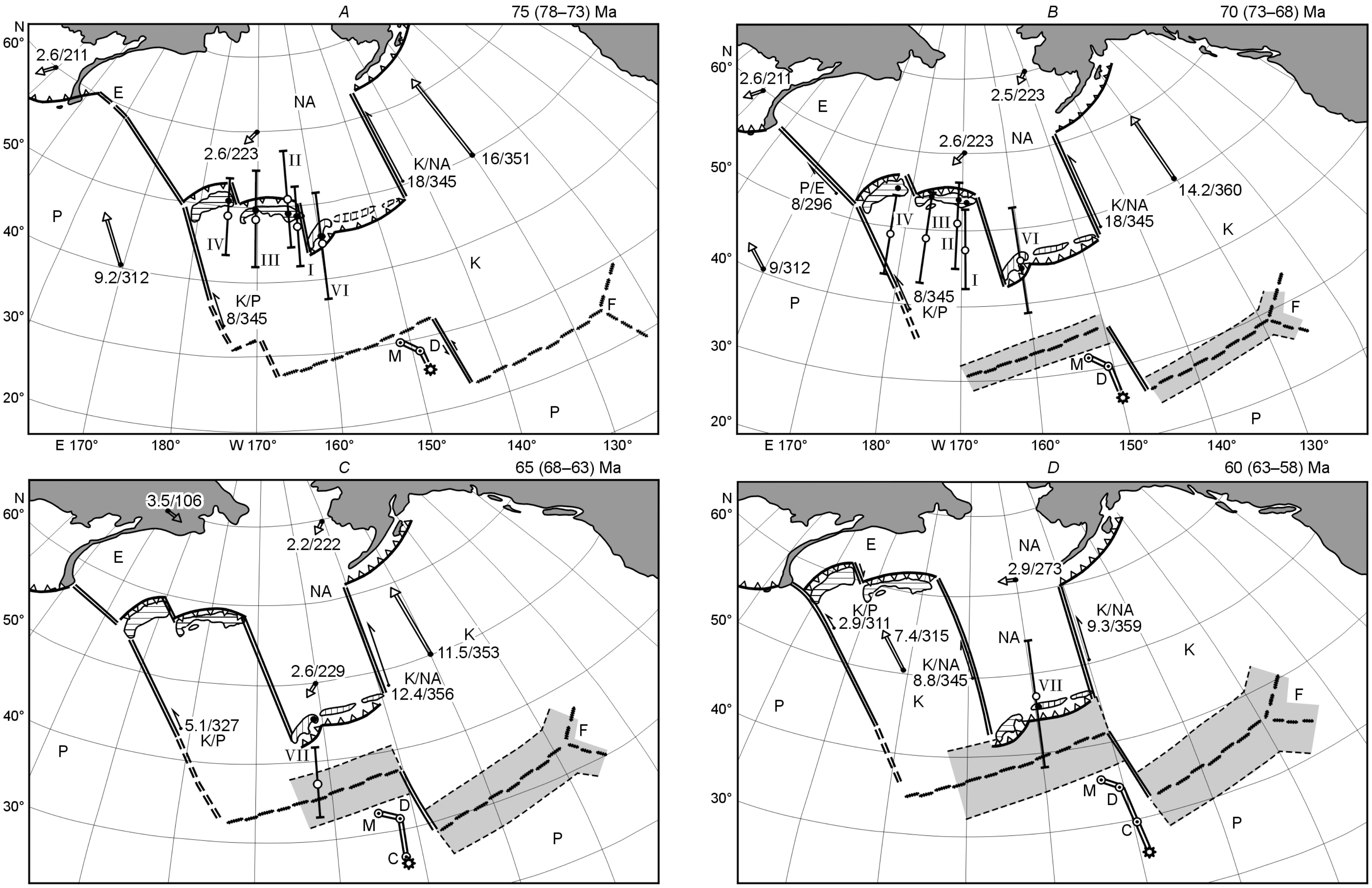
The history of the Kronotsky arc includes three main stages in which it was an active suprasubduction structure (Campanian through latest Middle Eocene, 75–40 Ma), a relict within-plate seamount (an aseismic ridge) in the Pacific plate (Late Eocene through Middle Miocene, 40–10 Ma), and a terrane as part of Eurasia (past 5–10 Ma).

According to paleomagnetic evidence, the Kronotsky–Commander arc may have moved southward from the Campanian through Early Eocene (Levashova, 1999), and this transport was possible in no way but with North America or with a kinematically similar small plate. Thus, we assume that a small part of the northern Pacific south of the present Aleutian islands belonged to North America (or to a smaller plate) in the latest Cretaceous.

In the Middle Eocene, the southward arc transport gave way to northward motion, possibly because the older subduction zone south of the arc had died out and a new zone appeared in the north. However, there is no enough geological evidence of that dramatic change which may have been responsible for abundant ophiolite clastics in the Middle Eocene section of Cape Kamchatka (Shapiro et al., 1997). The end of suprasubduction volcanism at about 40 Ma marks the cessation of subduction and conversion of the arc into a relict seamount within the Pacific plate. After having traveled northward with the latter, the Kronotsky–Commander seamount collided with Eurasia at 5 to 10 Ma. Thus, the motion history of the Kronotsky–Commander arc was different from that of the Achaivayam–Valaginsky arc: it moved with Eurasia from 0 to 7 Ma, with the Pacific plate from 7 to 56 Ma, and with North America between 56 and 75 Ma.

The reconstructions may be problematic because of ambiguity in the pre-Late Eocene kinematics of the Pacific and Kula, two major plates in the northern Pacific, namely the reasonable doubt of whether the Hawaii hotspot was fixed before 43 Ma (Norton, 1995; Tarduno et al., 2003). Therefore, we chose the model by Petronotis and Jurdy (1990) of global plate circuit with respect to African hotspot frame.

The motion histories of the two island arc terranes as part of large plates with known velocities and directions (borrowed from published data, see Table 1) were simulated using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50°
40°
30°
20°
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E
NA
2.6/223
II
K/NA
18/345
16/351
P
IV
III
I
VI
9.2/312
K
K/P
8/345
F
M
D
P
E 170°
180°
W 170°
160°
150°
140°
130°
B
70 (73–68) Ma
2.6/211
E
2.5/223
2.6/223
NA
P/E
8/296
IV
III
II
VI
I
K/NA
18/345
14.2/360
K
9/312
8/345
K/P
P
F
M
D
C
65 (68–63) Ma
3.5/106
E
2.2/222
NA
K
11.5/353
2.6/229
K/NA
12.4/356
5.1/327
K/P
VII
P
F
D
M
C
D
60 (63–58) Ma
E
NA
2.9/273
K/P
2.9/311
7.4/315
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K/NA
8.8/345
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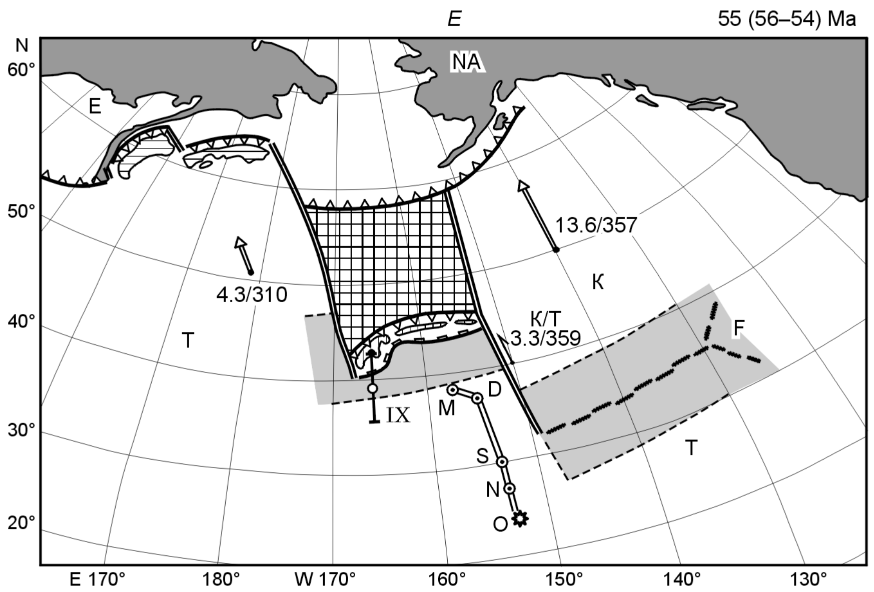
E
55 (56–54) Ma
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E
T
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4.3/310
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K/T
3.3/359
IX
M
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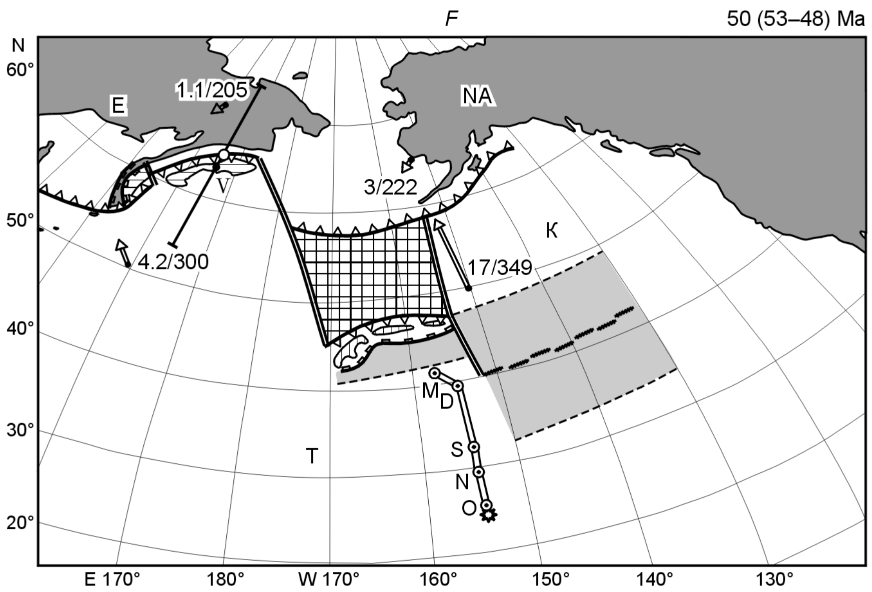
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1.1/205
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V
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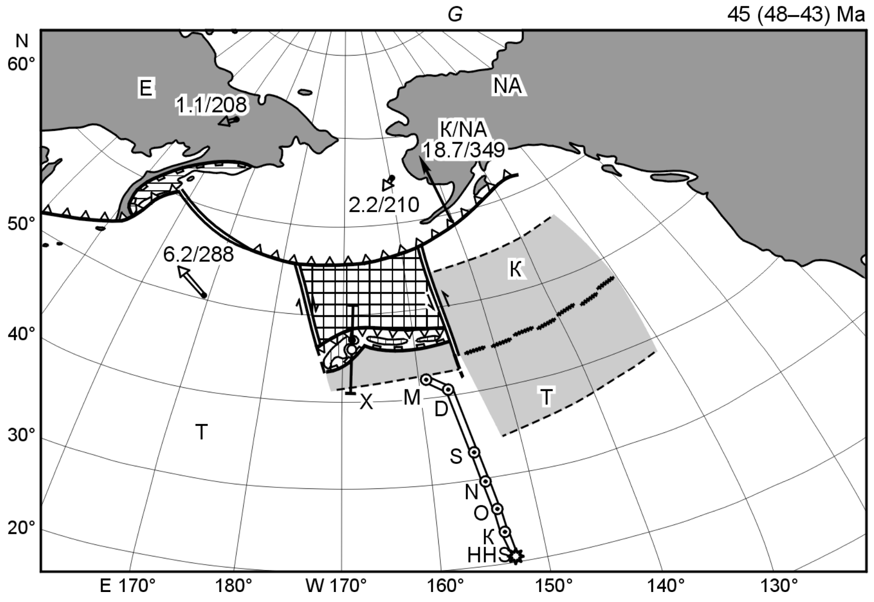
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6.2/288
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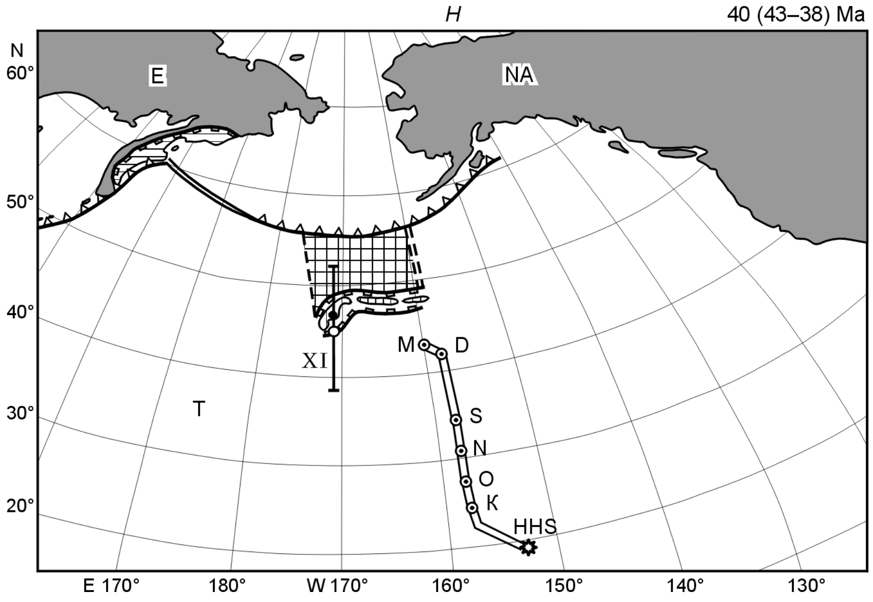
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130°

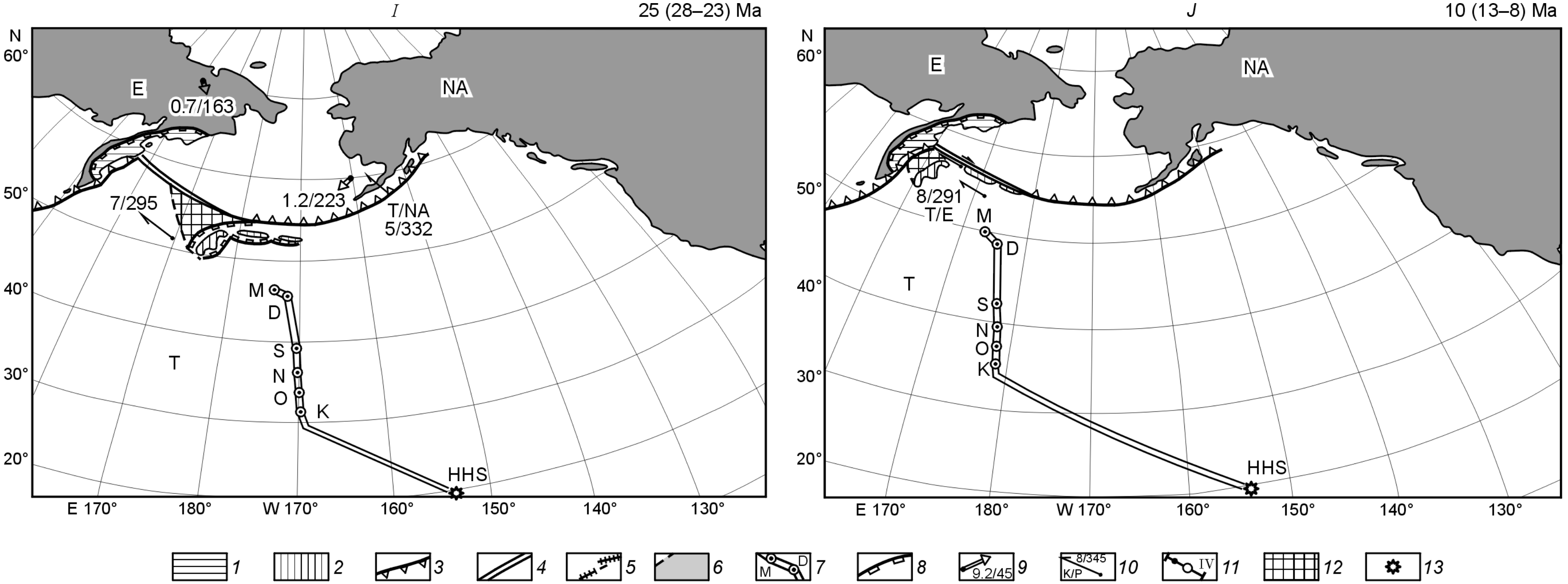

Fig. 2. Plates of northern Pacific and island arc terranes of Olyutorsky–Kamchatka foldbelt, from Campanian to Pliocene. Figures in right top corner of each panel show time of reconstruction and averaging interval. Reconstructions generated by using *Handrot* software (by A.V. Lander) with reference to published global kinematic models of continental and oceanic plates (Engebretson et al., 1985; Petronotis and Jurdy, 1990). *A–J* are explained in text. Plates: Eurasia (E), North America (NA), Pacific (P), Kula (K), Farallon (F). *1*, *2*, Achaivayam–Valaginsky (*1*) and Kronotsky–Commander (*2*) island arcs; *3*, trenches and subduction zones; *4*, transform faults; *5*, spreading centers; *6*, oceanic lithosphere younger than 75 Ma; *7*, Emperor-Hawaii chain of seamounts (M, D, S, N, O, K stand for names of seamounts Meiji, Detroit, Suiko, Nintoku, Ojin, and Koko, respectively; HHS is Hawaii hotspot); *8*, collisional sutures; *9*, vectors of absolute plate motion (numerator is velocity, in cm/year, and denominator is direction in present frame of reference); *10*, directions and velocities of relative plate motion (letters label plates, with letter in denominator indicating reference frame (e.g., K/P for Kula with respect to Pacific); numerals show respective velocity (numerator, in cm/year), and azimuth (denominator, in degrees) relative to presumably fixed frame; *11*, paleomagnetic determinations, with error bars (bold circle is position of section with respect to arc contours; open circle is mean paleolatitude); Roman numerals correspond to Table 1 and Fig. 1; *12*, hypothetical plate between Kronotsky and Aleutian arcs, 60 to 45 Ma; *13*, Hawaii hotspot.

Handrot software by A. Lander. The code calculates the directions of absolute motion at each point of a large plate and the vectors of relative motion for any two plates with known kinematics at any point of their boundary, which is essential for the choice of displacement vectors in inferred transforms. The resulting reconstructions are shown in Fig. 2.

The paleolatitudes we used (Table 1) are not very precise, with a variance of 10–15°. The ages of the sampled rocks are reported at the level of stages, but, nevertheless, the predicted values fit the observed mean paleomagnetic latitudes to an error of 2–3° in nine out of eleven cases.

Reconstructions of northern Pacific plate boundaries and paths of island arc terranes

The **~75 Ma** reconstruction (Fig. 2, *A*), second half of Campanian, depicts cessation of volcanism in the Okhotsk–Chukchi volcanic belt, onset of voluminous suprasubduction volcanism in the Achaivayam–Valaginsky and Kronotsky–Commander arcs, and formation of the northern Emperor chain of seamounts corresponding to magnetic anomaly 33. According to this reconstruction, the Achaivayam–Valaginsky arc, assumed to have a motion history as mentioned above, was W–E trending and located about 50° N and right east of 180° E. The two arc segments appear to have experienced no significant deformation in the plan view, while the declination difference in most of Cretaceous sections relative to the Present is defined by general counterclockwise rotation of the terrane through ~45°.

The W–E Kronotsky–Commander arc, with a different motion history, was located slightly south and east of the Achaivayam–Valaginsky arc. Had the two arcs had the same subduction polarity, the former would appear to be an extension of the latter. Unlike the Achaivayam–Valaginsky arc, blocks in the Kronotsky arc experienced differential rotations, mainly during the arc collision with the Aleutian Islands and Kamchatka. The position of the eastern end of the Kronotsky–Commander arc is highly problematic. Most likely it met the Alaska subduction zone via a long N–S transform.

Large transform faults along which the Kronotsky–Commander and Achaivayam–Valaginsky arcs are juxtaposed with the Alaska and southern Kamchatka continental-margin subduction zones are an essential though putative element of the reconstructions. Their trends approximately follow the "parallels" to the Pacific and Kula rotation poles relative to North America and Eurasia. It is hard to draw these "parallels" precisely for two reasons. First the true plate boundary remains poorly constrained (where exactly North America ended and Eurasia began) and, second, the Euler poles were also moving, which would require splitting the model into shorter time intervals to make the "parallels" appropriate. The ambiguity in the position of the Eurasia–North America boundary may cause an additional error to the reconstruction for the Kronotsky–Commander arc, but the effect cannot be too large because the two plates moved rather slowly (3.5–2.2 cm/year) and in similar directions in the latest Cretaceous.

There is no explicit evidence of pre-Middle Campanian structures in the western Kula which were the foundation of the Achaivayam–Valaginsky arc and then submerged in the Kronotsky–Commander subduction zone. However, one may assume that the Late Jurassic–Early Cretaceous oceanic lithosphere represented by the Olenegorsky ophiolite (Khotin and Shapiro, 2006) coexisted with a small Albian–Cenomanian oceanic plateau which was an area of pelagic deposition and volcanism (basalts of the Smagin Formation) (Savel'ev, 2004). The plateau may have undergone dispersal with formation of a segment of the Kula–Pacific Ridge. Later the ridge moved north off the hotspot that continued to extend the plateau southward producing the Emperor seamount chain.

The **~70 Ma** or Maastrichtian (Fig. 2, *B*) and **~65 Ma** or earliest Paleocene (Fig. 2, *C*) reconstructions are generally similar to that of 75 Ma (Fig. 2, *A*) and predict northward motion of the Achaivayam–Valaginsky arc and the Kula–Pacific Ridge, and a minor southward displacement of the Kronotsky–Commander arc.

We fitted the three reconstructions (Fig. 2, *A–C*) to paleomagnetic latitudes determined in Campanian–Maastrichtian samples from the Achaivayam–Valaginsky and Kronotsky–Commander arcs, and obtained the best fit for the Late Campanian but higher computed paleolatitudes for the later times. This appears reasonable because the reconstructions assumed rapid northward motion of the former arc with the Kula plate. Or, one may draw another conclusion that the paleomagnetic determinations used to check our model, if the latter is correct, refer to the Upper Campanian interval of the Achaivayam–Valaginsky section. The good fit of latest Cretaceous paleolatitudes for the Kronotsky terrane is due to slow southward motion of the Kronotsky–Commander arc.

The paleolatitudes predicted by the 65 Ma reconstruction (Fig. 2, *C*) were compared with paleomagnetic determinations (mean latitudes and confidence interval) in Danian tuff of the Tarkhovka Formation (Cape Kamchatka Peninsula) and turned out to be 8° higher, i.e., showed the worst fit. The question is whether the misfit may result from the drawbacks of the model that assumes a rapid southward motion from 75 through 65 Ma. In this case the Kronotsky–Commander arc cannot have been part of North America and a center of rapid spreading should have existed at its back. We discuss this hypothesis below in more detail, while at this point we only note that tuff was sampled at strongly deformed sites and the paleomagnetic directions with respect to present frame of reference varied broadly, the declinations being ambiguous though the inclinations were rather reliable. Furthermore, no test (fold, conglomerate, or reversal) was possible to check the data.

The **~60 Ma** (Middle Paleocene) reconstruction (Fig. 2, *D*) shows all pre-Middle Campanian lithosphere of the Kula plate between the Kronotsky–Commander arc and the Kula–Pacific Ridge to have been consumed in the subduction zone, i.e., the arc and the ridge already began colliding. In the north, the Achaivayam–Valaginsky arc approached the continent and the strait between its segments received terrigenous material of the Drozdovka and Talnikovaya Formations (Solov'ev, 2008).

Note that although the arc had not docked yet, volcanism within its limits stopped or, at least, was restricted to the southern end of the northern segment (Govena arc).

The paleolatitudes of Fig. 2, *D* fit well the available paleomagnetic data for Mednyi Island samples, which are, however, of a limited number and from a poorly constrained section (Paleocene–Eocene).

The **~55 Ma** (Paleocene–Eocene boundary) reconstruction (Fig. 2, *E*) differs notably from the previous ones. According to this reconstruction, the Kronotsky–Commander arc collided with the Kula–Pacific ridge whereby spreading and subduction south of the arc had stopped and the arc accreted to the Pacific plate. Thus, the arc began to move northward, at a similar velocity and in the same direction as the Achaivayam–Valaginsky arc, which was about docking and, together with a part of the Kula plate at its back, accreted to the Pacific plate.

Most of models (Creager and Scholl, 1973; Geist et al., 1994; Scholl et al., 1989) predict that the central part of the Aleutian arc initiated about that very time. A small plate which appeared between the two new subduction zones (Aleutian in the north and Kronotsky–Commander in the south) must have experienced extension as it was subducting in two opposite directions. Its kinematics remains unknown but most likely the plate moved to the north at a velocity slower than 4 cm/year and thus might subduct either under slow Eurasia or fast Pacific. However, the uncertainty in the velocity and direction of motion of this small plate does not preclude reconstructing the position of the island arcs.

The paleolatitudes (Fig. 2, *E*) estimated for the Ypresian basalt and tuff of the Kronotsky Peninsula, like those for samples of Danian rocks (Fig. 2, *C*) are notably lower than the computed latitudes. The reason of the poor fit may be that there were less than 30 samples, most of them being from a poorly constrained pillow lava section.

The **~50 Ma** reconstruction (Fig. 2, *F*) for the Early–Middle Eocene boundary corresponds to the time when the southern segment of the Achaivayam–Valaginsky arc had already accreted to Eurasia while the northern segment kept moving with the Pacific plate to close the relict Lesnaya–Ukelayat basin (Kovalenko, 2003; Levashova, 1999; Solov'ev, 2008). The southern Vetlovaya–Govena accretionary prism apparently initiated then over the subduction zone but, surprisingly, the corresponding volcanic belt appeared neither in the Eocene nor in the Oligocene (50–25 Ma). The predicted paleolatitude shown in this panel fits well the paleomagnetic determination for Early–Middle Eocene rocks from the Ilpinsky Peninsula.

The **~45 Ma** (Lutetian) reconstruction (Fig. 2, *G*) shows the Achaivayam–Valaginsky arc having docked, the Aleutian arc approaching its today's contours, and the Emperor Ridge having completed its formation. Since that time, the activity of Kamchatka, including the formation of the northern Vetlovaya–Govena accretionary prism, has been controlled by events in the Bering Sea and by Eurasia–North America interaction rather than being related directly to processes in the ocean. The computed Kamchatsky Mys Peninsula paleolatitude of that time fits well the determination for the Lutetian Baklan Formation (Kamchatsky Mys Peninsula).

The **~40 Ma** (Bartonian) reconstruction (Fig. 2, *H*) corresponds to the time when the plate contours approached their today's geometry; the remaining part of Kula had accreted to the Pacific plate; the Kronotsky–Commander subduction zone was no longer active, though weak volcanism continued in the arc; the western Aleutian arc turned into a transform fault as the Pacific plate had changed its direction; the Pacific plate was subducting beneath southern Kamchatka but volcanism in that part of the peninsula was very low. A single paleomagnetic determination for Bartonian samples from the Kronotsky Peninsula is in agreement with the model.

Two latest reconstructions (**~25 Ma**, Late Oligocene, Fig. 2, *I* and **~10 Ma**, Middle Miocene, Fig. 2, *J*) image the final stages of motion of the already inactive Kronotsky–Commander arc and the onset of its collision with Eurasia. For more details see (Shapiro and Lander, 2001) where we showed that the collision began in the area of the Shipunsky block and propagated northeastward as far as Kamchatsky Mys Peninsula, provided the Kronotsky arc segment was W–E trending prior to the collision. The blocks of the Kronotsky segment were subject to counterclockwise rotation while the Commander segment underwent dextral strike-slip faulting and clockwise rotation.

Discussion

We obtained a more or less consistent kinematic model for the motion of island arc terranes in the Olyutorsky–Kamchatka foldbelt as parts of large plates with known velocities and directions. In the reconstructions we used the geological ages of suprasubduction volcanism and collisional events, as well as the predicted velocities and directions of the island arc terranes which guided the choice of carrier plates at any time since the Middle Campanian. Most of the predicted mean paleolatitudes showed a good fit to reliable paleomagnetic determinations, notable misfit being restricted to two out of eleven latitudes (Table 1)*. Below we are trying to check the stability of our basic model by imposing changes to the initial parameters in order to see whether other models implying different motion history details can be as consistent with the geological and paleomagnetic data. In this respect, we discuss the following essential points of the kinematic model we suggest.

1. It is assumed that the island arc terranes of the Olyutorsky–Kamchatka foldbelt moved in no way but with large plates for which the velocities and directions of Late Cretaceous and Cenozoic motion are known. Although there are small oceanic and continental plates (e.g., Sea of Okhotsk and Bering) between the modern western Pacific plate and the flanking large continental plates, their rotation parameters are

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* We used only the paleomagnetic data that were checked by fold, conglomerate, or reversal tests and based on at least 50 analyses (Shapiro et. al., 2005) for the Achaivayam–Valaginsky arc and all available determinations for the Kronotsky arc.

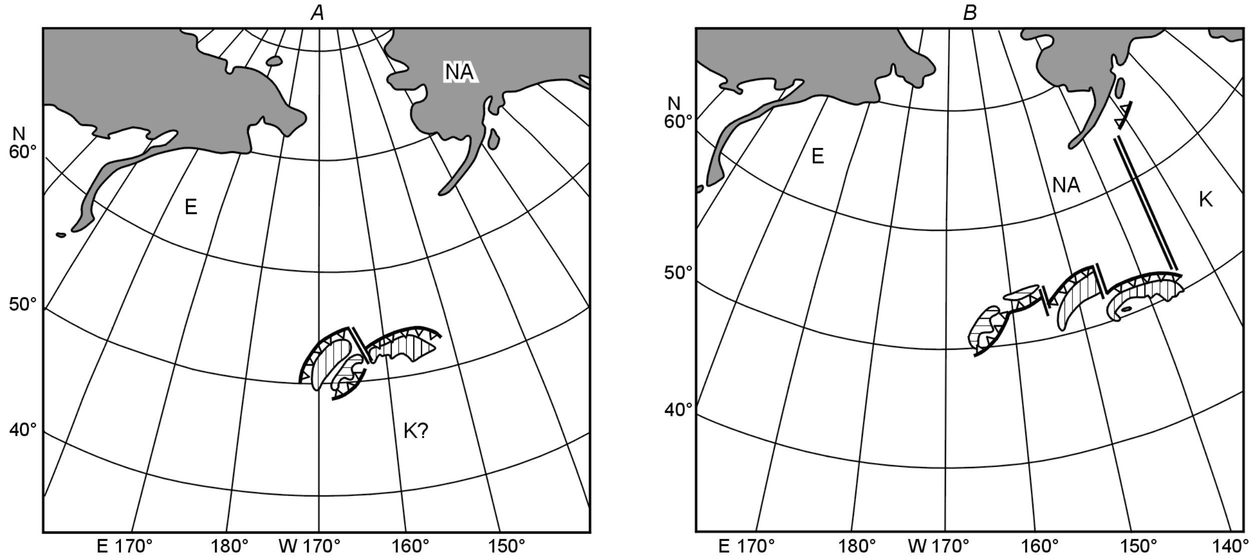

Fig. 3. 75 Ma reconstructions, based on moving-hotspot frame: (Norton, 1995) (*A*) and (Engebretson et al., 1985, model 2) (*B*). Reconstructions give the same sequence of plates that transport the arcs and the same motion history as in Fig. 2 but contradict available geological and paleomagnetic data.

generally similar to those of the latter, the difference being negligible for regional kinematic modeling.

2. The model includes the kinematics of the Pacific and Kula plates which is a key element of plate motion in the northwestern Pacific. We simulated the Pacific and Kula kinematics (Fig. 2) with reference to the model by Petronotis and Jurdy (1990) which was advantageous over other models as it provided better consistency with geological and paleomagnetic data. The published kinematic models for the absolute motion of the Pacific and Kula plates use a reference frame of the Hawaii hotspot assumed to be either fixed (Engebretson et al., 1985; Kononov, 1989) or moving before 43 Ma (Engebretson et al., 1985; Norton, 1995; Petronotis and Jurdy, 1990). Our 75 Ma reconstructions based on the moving-hotspot models of Norton (1995) and Engebretson et al. (1985) (Fig. 3, *A* and *B*, respectively) turned out to be unrealistic though gave a motion history similar to that of Fig. 2. In those reconstructions, the Kronotsky–Commander arc either coincided with (Fig. 3, *A*) or was west of (Fig. 3, *B*) the Achaivayam–Valaginsky arc, which contradicts the geological evidence of an earlier collision of the Achaivayam–Valaginsky arc.

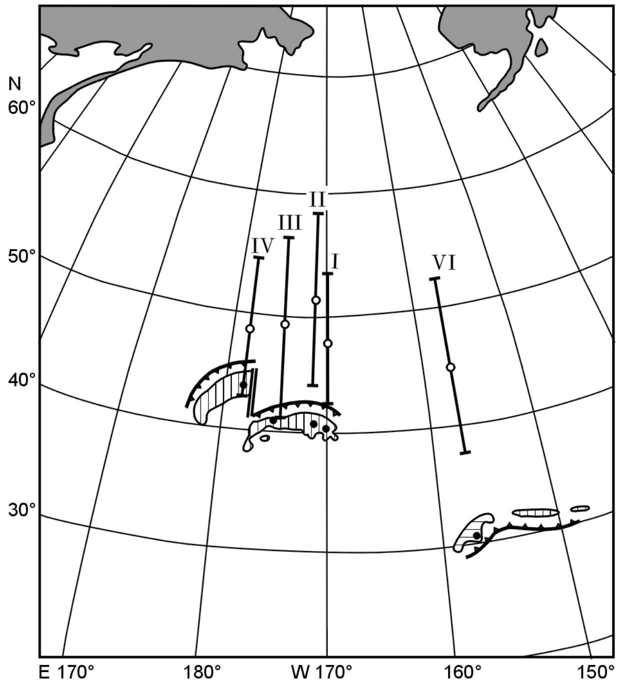

Fig. 4. 75 Ma reconstruction, based on fixed-hotspot frame (Engebretson et al., 1985, model 1). Reconstruction contradicts available geological and paleomagnetic data.

The Late Campanian reconstruction based on the fixed-hotspot frame before 43 Ma (Engebretson et al., 1985) looked realistic and akin to that of Fig. 2 (Fig. 4), but the computed paleolatitudes of the two arcs (especially, the Kronotsky–Commander one) were much lower than the paleomagnetically constrained ones.

3. Another important point in geodynamic history of the northern Pacific area is the Pacific–Kula plate boundary in the latest Cretaceous–earliest Paleogene (Fig. 2, *A*–*D*). Magnetic anomaly 33 in the Kula–Pacific Ridge, the oldest one in the W–E series of northern Pacific anomalies, provides reliable constraints on the latest Campanian position of the eastern Kula–Pacific segment from the Pacific–Kula–Farallon triple junction to the modern Emperor seamount chain, which at that time included the Meiji and Detroit seamounts. The today's structure of the Emperor Ridge leaves no doubt that it evolved upon the Pacific plate from its very inception. Therefore, the western extension of the W–E trending Kula–Pacific Ridge, if any, should be located north of Meiji and Detroit. Yet, all the terranes that existed northwest of Meiji either had accreted to the continent (island arc terranes) or submerged in the subduction zones. This fact makes all reconstructions putative. One might assume, for instance, that there was no continuation of the Pacific–Kula boundary north of the Emeperor seamount

chain but the western end of the latter joined the eastern end of the Kronotsky–Commander arc via an N–S transform. This pattern would mean a different kinematics of the Achaivayam–Valaginsky arc which then must have moved northward on the edge of the slower Pacific plate. Then, the arc's formative latitudes would be higher than those according to paleomagnetic data and to our reconstruction. Furthermore, there is evidence that the Kula plate and the Kula–Pacific Ridge extended southwestward as far as the modern Philippine Sea in pre-Middle Eocene time (Lewis et al., 2002).

Thus, the existence of a W–E trending western extension of the Kula–Pacific Ridge appears quite realistic. This is an essential point of reconstruction because the northward motion of the ridge in this case inevitably leads to its collision with the Kronotsky–Commander arc moving to the south on the edge of North America. Interaction of the two structures brings about important changes in the arcs' kinematics at the Paleocene–Eocene boundary.

4. One more essential element of the model is the northward transport of the active Achaivayam–Valaginsky arc in the latest Cretaceous and Early–Middle Paleocene when the oceanward subduction was responsible for both the arc's fast motion and the intense volcanism (Shapiro, 1995). This point is worth a more thorough consideration. Okhotsk–Chukchi was a very active suprasubduction volcanic belt in the northwestern circum-Pacific area, along the Pacific margin of northeastern Asia, from the Middle Cretaceous till the Middle Campanian when volcanism ceased there (Filatova, 1979, 1987) but intense eruptions began in the Achaivayam–Valaginsky arc. Therefore, the convergence of Pacific plates with northeastern Asia became accommodated mainly in the Achaivayam–Valaginsky subduction zone at some distance off the continent. Active suprasubduction volcanism went on at least for 15 Ma till the Middle Paleocene and then had decayed abruptly before the arc collided with Asia in the Eocene. There arises the question when did the Achaivayam–Valaginsky arc traveled 12–15° to the north: either simultaneously with (~75 to 60 Ma) or after (~60–45 Ma) the volcanic activity.

In the former case, the Achaivayam–Valaginsky arc would be located at the edge of an oceanic plate, the trench being in its north, and subduction being oceanward, with the subduction zone rapidly migrating to the north, together with the arc, and consuming oceanic lithosphere between the arc and the continent. Suprasubduction volcanism (Late Campanian–Early Paleocene) and the arc-continent collision were the natural consequences of this kinematics, which is consistent with geological and paleomagnetic signatures of arc-continent convergence already in the Late Paleocene.

In the other case, the Achaivayam–Valaginsky arc (like the Kronotsky–Commander arc) would be located on the edge of a large continental plate (Eurasia or North America) in Campanian, Maastrichtian, and Early Paleocene time, with the trench south of the arc, and subduction toward the continent, propagating slowly to the south. The subduction zone would consume the lithosphere of the Pacific and Kula plates but without causing arc-continent convergence and the ensuing collision. Thus we have to assume that the Achaivayam–Valaginsky subduction zone became extinct in the Middle Paleocene, and a new subduction zone initiated on the continental margin and was looking northwestward where the lithosphere between the arc and the continent was submerging.

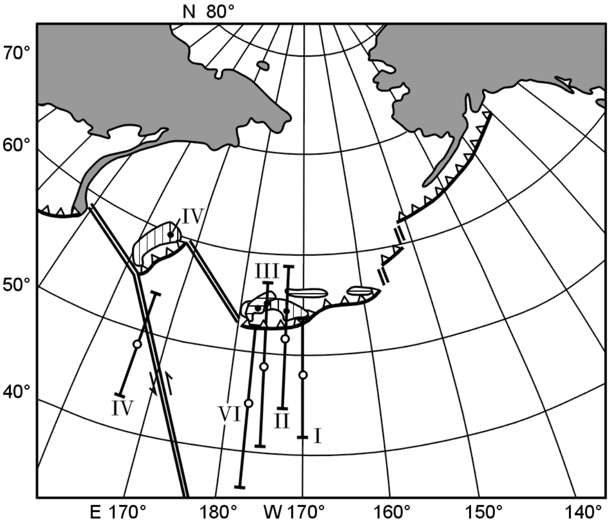

Fig. 5. 75 Ma reconstruction, based on assumption that fast motion of Achaivayam arc began as late as 60 Ma ago when intense volcanism stopped, and northward motion of Kronotsky arc began in Bartonian. Reconstruction contradicts available geological and paleomagnetic data.

For the lack of explicit geological evidence for the polarity of the Achaivayam–Valaginsky arc and reliably dated paleomagnetic determinations that would allow a better resolution of paleolatitude changes, the choice between the two alternatives can base on implicit evidence only. Specifically, the Paleocene–Eocene subduction zone at the continental edge, where all oceanic lithosphere between the arc and the continent was consumed according to the second hypothesis, would have been attendant with volcanism from 60 Ma (cessation of intense volcanism in the Achaivayam–Valaginsky arc) to 45 Ma (formation of the collisional suture at the Kamchatka isthmus). Yet, Paleocene–Early Eocene volcanics with an island arc affinity, though known in West Kamchatka (Gladenkov et al., 1997), are of a very limited amount.

The latter hypothesis causes another problem, that of explaining the origin of the Drozdovka and Talnikovaya Formations which were deposited over island arc volcanics in the time when the arc was the farthest off the continent. Although the former hypothesis appeared more preferable, we computed the reconstructions for the second hypothesis as well (Fig. 5). They were inconsistent with most of paleomagnetic data, which made us turning back to the idea of synchronicity of suprasubduction volcanism and northward motion of the Achaivayam–Valaginsky arc.

Conclusions

The available ages of key regional events and data on velocities and directions of four large plates in northeastern Asia and the northwestern Pacific were used to model the latest Cretaceous and Cenozoic (75 Ma to Present) motion histories of two paleo-island arc terranes of the Olyutorsky–Kamchatka foldbelt. The results highlight the leading role of large plates in the kinematics of continental margins.

The predicted latest Cretaceous and Paleogene paleolatitudes of the Achaivayam–Valaginsky and Kronotsky–Commander island arc terranes agree with nine out of eleven formally reliable paleomagnetic determinations for samples from the respective arcs. This is another proof for importance of paleomagnetic data for estimating the amount of terrane transport during formation of orogenic areas.

Additional changes imposed on the initial model parameters (kinematics of the large plates, relative position of the Kula–Pacific Ridge and the Emperor seamount chain, or time relationship of arc motion with active volcanism within it) worsen the fit of the final reconstructions to available geological and paleomagnetic data. Therefore, the suggested model appears to be the most consistent one at this stage of knowledge.

We wish to thank A.V. Lander for having kindly offered the *Handrot* software we used to generate the reported reconstructions and for related discussions.

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