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Paleomagnetism of a Late Cretaceous island arc complex from South Sakhalin, East Asia: Convergent boundaries far away from the Asian continental margin?

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Abstract. The Hokkaido-Sakhalin fold system stretches for ~1500 km along the eastern coast of Asia and consists of several N-S trending tectonic belts. Studies in South Sakhalin show that the northern part of the Tonino-Aniva Peninsula (Ozersk unit) is a counterpart of the Tokoro belt on Hokkaido, Japan. In the eastern part of the Ozersk unit, 195 hand samples were sampled at 20 sites from Campanian-Maastrichtian tuffaceous siltstones and sandstones of the Chayka Formation of island arc affinity. Stepwise thermal demagnetization isolates a postfolding low- to intermediate-temperature component (B) of normal polarity. A high-temperature component (A) is isolated from about half the samples. Because of strong overlap of unblocking temperature spectra of these two components in other samples, direct observations and remagnetization circles were combined for calculation of site-mean directions. Component A is mostly of reversed polarity: a few samples of normal polarity are found at three sites. The presence of two polarities with approximately antipodal directions and the positive fold test imply a prefolding, and most probably primary, origin of component A. A formation-mean inclination of 45.0° ± 6.4° calculated with the aid of inclination-only statistics corresponds to a latitude of 26.6° ± 5.2°N. A similar inclination is derived from a late Cretaceous island arc complex from the Tokoro belt on Hokkaido. Since both mean inclinations are ~30° lower than the coeval Eurasian reference value, a large-scale northward transport of the entire Tokoro island arc is inferred. We exclude the possibility of displacement with the Kula plate and coast-parallel transport; instead, intra-oceanic motion with the Pacific plate and docking at the Eurasian margin at circa 30 Ma are inferred. Combined paleomagnetic data from the Tokoro belt, the Nemuro belt and Kamchatka region imply that a system of intra-oceanic island arcs existed in the northwest Pacific in Late Cretaceous time.

1. Introduction

A wide diversity of tectonic settings in East Asia presents a unique opportunity to get a clearer insight into processes at convergent boundaries of oceanic and continental plates. A part of East Asia comprising the Japanese Islands, Sakhalin Island, and adjacent regions (Korean Peninsula, Maritime Province of Russia) is rather well studied, and most authors agree that considerable horizontal movements of various tectonic units occurred prior to amalgamation. The accord, apparently, ends here. Some authors claim that the Japanese Islands were attached to Asia from the Permian-Triassic boundary until the late Miocene [*Maruyama et al.*, 1997], whereas *Sengor and Natal'in* [1996] place the convergent boundary more oceanward and allow for a complicated kinematics of Japanese tectonic units before formation of the present-day framework.

Despite many differences most proposed tectonic scenarios agree that the convergent boundary of continental and oceanic plates has always been close to the continent and that continuing accretion and docking of small blocks has led to eastward growth of Asia. This view has some support as many Andean-type subduction-related volcanic belts are well documented along the eastern margin of Asia. Examples include the late Cretaceous-Paleogene Sikhote-Alin and "Middle" Cretaceous Okhotsk-Chukotka volcanic belts (Figure 1a).

Even a cursory look at a geographic map, however, shows that modern convergent boundaries in the west Pacific are usually more than a thousand kilometers away from the continent. There is no reason to believe that this pattern is a recent feature; for instance, island arc complexes on Alaska and hence the related convergent boundaries were shown to have formed far away from North America [e.g., *Harbert*, 1990]. Paleomagnetic studies of late Cretaceous to Paleogene island arc complexes of Kamchatka also show that the convergent boundaries were originally far away from the Asian continental margin [*Levashova et al.*, 1998, 2000]. The pericontinental position of the East Asian convergent boundaries on many reconstructions may be dictated by the lack of information on their original whereabouts which are difficult to derive solely from geological data. Attempts to correlate geological records with kinematic events such as the passage and subduction of ancient spreading centers [*Maruyama et al.*, 1997] indicate that the exact positioning of convergent boundaries at various times is important.

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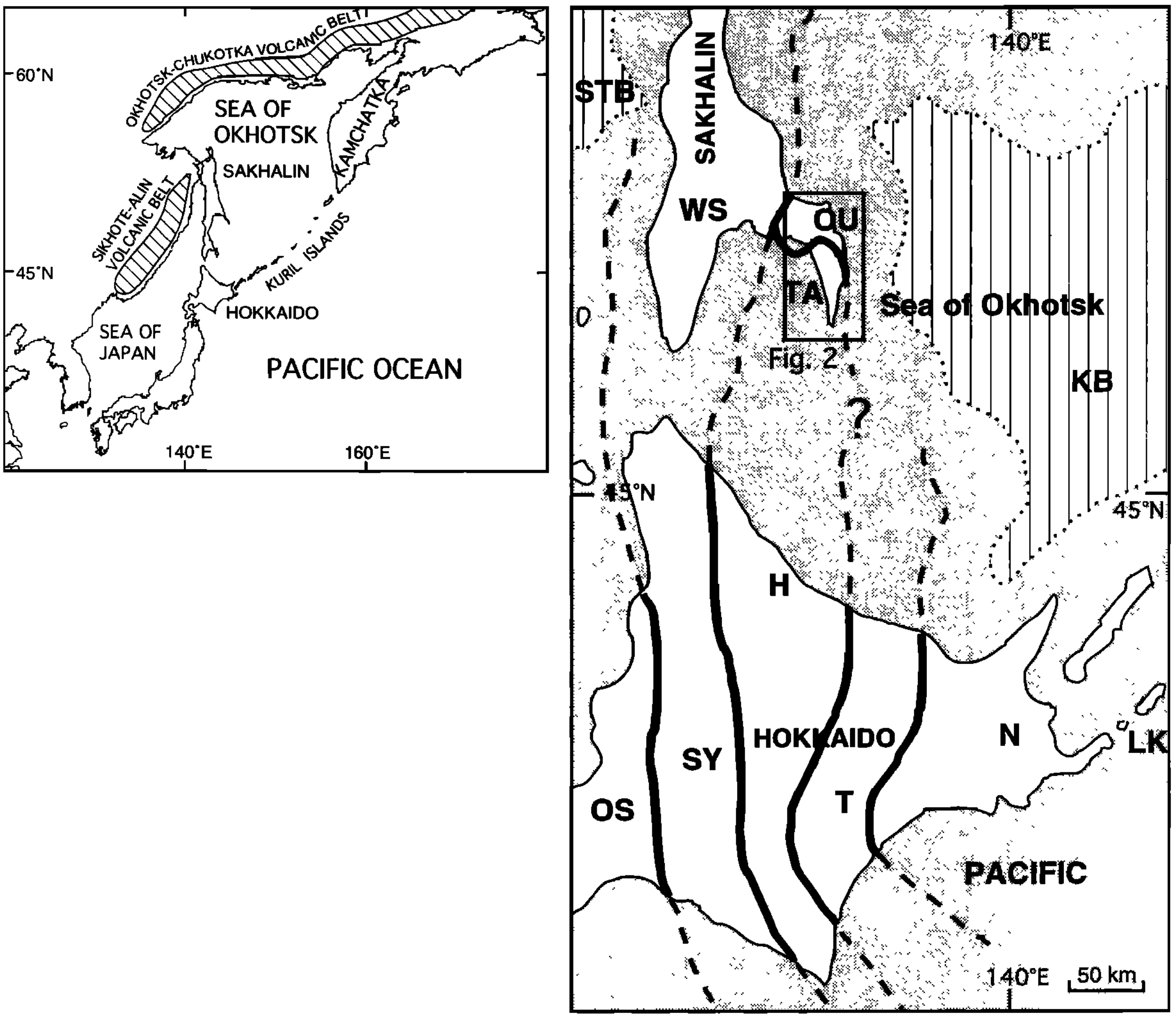

Figure 1. (a) Location map and (b) major tectonic units of the Hokkaido-Sakhalin fold system and adjacent areas Major units of Hokkaido· OS, Oshima belt, SY, Sorach.-Yezo belt; H, Hidaka belt; T, Tokoro belt; N, Nemuro belt. Major units of Sakhalin: WS, West Sakhalin Zone; TA, Tonino-Aniva Zone; OU, Ozersk Unit. KB and STB, late Cenozoic South Kuril and South Tartar Basins, respectively (hatched); LK, Lesser Kuril Islands.

Paleomagnetism can resolve these problems, but the results on ancient island arc complexes are scarce We performed mapping (A Zharov), stratigraphic (N. Bragin and L Bragina), paleomagnetic (M Bazhenov, N. Levashova and K. Kodama), and petrographic and geochemical (A Zharov, P. Fedorov, and S Lyapunov) studies of the southeastern part of Sakhalin in an attempt to better understand the evolution of the Hokkaido-Sakhalin fold system The main purpose of this paper is to present the first late Cretaceous paleomagnetic data on island arc complexes from South Sakhalin and to reconstruct the positions of different island arcs in the northwest Pacific using paleomagnetic and geological data from Kamchatka, Sakhalin, and Hokkaido

2. Geological Setting and Sampling

The Hokkaido-Sakhalin fold belt stretches for ~1500 km along the eastern coast of Asia (Figure 1b). On Hokkaido, five major late Mesozoic-early Cenozoic tectonic zones are the Oshima, Sorachi-Yezo, Hidaka, Tokoro, and Nemuro belts with prominent faults between them [e g, *Kimura et al*, 1983; *Kiminami et al*. 1986; *Niida and Kito*, 1986]. Most authors agree that the Oshima, Sorachi-Yezo, and Hidaka resided on the continental margin and are related to westward subduction under the continent The Tokoro belt comprises late Jurassic to Early Cretaceous pillow lava with a minor amount of chert, limestone, volcanoclastic sediments, and red shale (Nikoro group), latest Cretaceous to Paleocene flysch-type sediment and pelagic or hemipelagic red and green shales (Yubetsu Group) and more coarse-grained sediments of the Saroma Group of similar age. On the whole, this belt is regarded as a trench-filling accretionary complex The Nemuro belt together with the Lesser Kuril Islands is composed of Upper Cretaceous to early Eocene volcanics and volcanoclastics (Nemuro Group) which accumulated in a forearc basin [*Kiminami*, 1986, *Kiminami et al*, 1992] The Tokoro and Nemuro belts are often regarded as two parallel zones of the same island arc [e.g *Kanamatsu et al.*, 1992]. The West Sakhalin and Tonino-Aniva tectonic zones on South Sakhalin are commonly correlated with the Sorachi-Yezo and Hidaka belts, respectively, while the Tokoro and Nemuro belts have not been traced here [*Rikhter*, 1986, *Dobretsov et al*, 1994].

The tectonic evolution of South Sakhalin is controversial. Some researchers consider that a single subduction zone has permanently existed along the coast of Asia, and the present-day

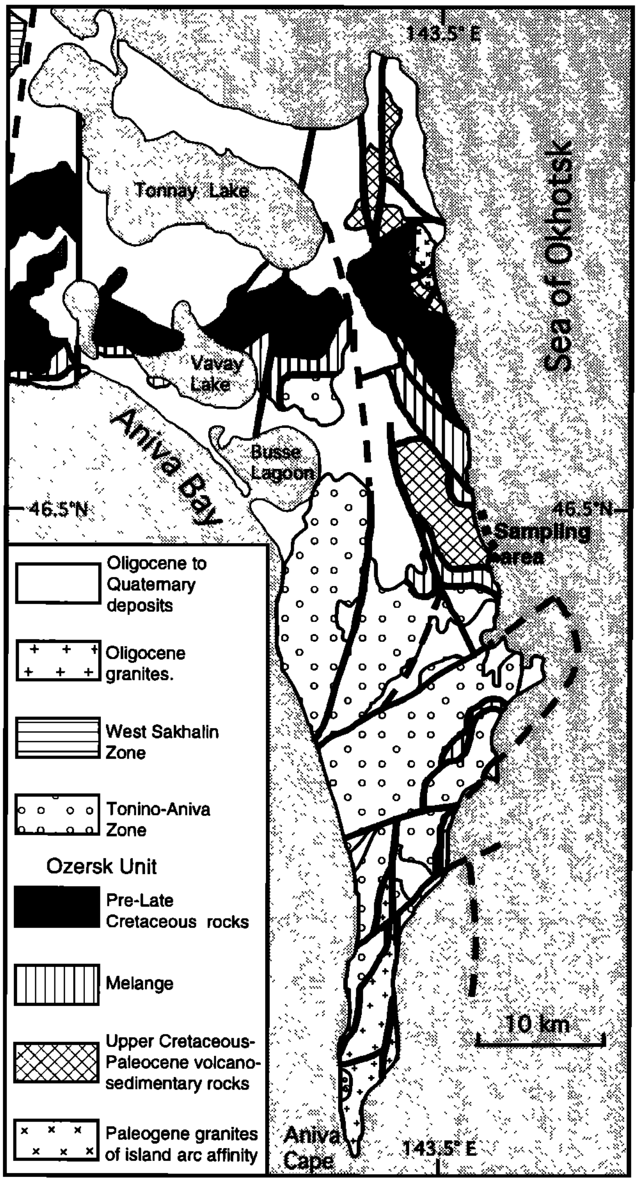

Figure 2. Schematic geological map of the Tonino-Aniva Peninsula Faults are shown as thick lines (dashed when inferred)

pattern is due to later deformation involving relatively small, a few hundred kilometers at most, horizontal displacements [*Rozhdestvensky*, 1982, 1993]. Multiple collisions of wandering terranes, including the remnants of island arcs, with the Asian margin were proposed by others [*Rikhter*, 1986; *Khanchuk et al.*, 1989. *Zonenshain et al*, 1990] Still others [*Parfenov*, 1984; *Kiminami et al.*, 1986] are of the opinion that the East Sakhalin composite block is part of the Okhotia microcontinent which moved with the Kula plate and collided with Asia by the end of Cretaceous None of the scenarios gives definite information on the original positions and kinematics of the Sakhalin units.

Geological studies. including our own, on the Tonino-Aniva Peninsula in South Sakhalin (Figure 2) reveal that its northern part consists of late Permian(?) to Early Cretaceous oceanic basalts and sediments, late Cretaceous to Paleocene tuffaceous sediments with a few basalts of island arc affinity [*Kimura et al.*, 1992], and numerous melange blocks (Ozersk unit, [*Zharov*, 1998]) A melange band includes blocks of oceanic and island arc rocks with granite debris of island arc affinity and hemipelagic sediments. This band is recognized in the central part of the study area (Figure 2); melange units farther to the north are of similar composition. In the north, late Cretaceous to Paleocene tuffaceous sediments are intruded by a granite body and dikes of island arc affinity, as indicated by the relationships between Nb, Y, and Rb (our data). The granite is of early Tertiary age as indicated by fission track results on zircons (63 Ma (I Gonzava, unpublished data, 1996)) and K-Ar results on hornblende and biotite (57-45 Ma (D.I Golovin, unpublished data, 1997)) Melange units, tuffaceous blocks, and intrusions are unconformably overlain by upper Eocene-lowermost Miocene terrigenous sediments [Serova et al, 2001] The Tunaicha Formation of South Sakhalin (foraminifera, flora, age, and correlation), *Stratigraphy and Geological Correlation*, 2000), which are in turn covered with a major angular unconformity by coal-bearing upper lower Miocene deposits.

Volcano-sedimentary rocks form isolated blocks; the largest of them on the east coast of the Tonino-Aniva Peninsula (Figure 2) consists of (from bottom to top) strongly deformed brown-red to greenish-red to dark green siliceous tuffaceous siltstones, light gray to gray tuffaceous sandstones with some acidic tuffs, conglomerate, and olistostromes of the Chayka (Seagull) Formation Conglomerates contain basalt debris of various origins, from typical mid-ocean ridge basalts to seamounts to island arcs (our data); continent-derived debris is absent altogether The conglomerates of this composition are found only in the Chayka Formation in South Sakhalin and in the Saroma Group of the Tokoro belt in Hokkaido [*Sakakibara et al.*, 1986]. The composition of the melange and the coexistence of oceanic and island arc complexes also resembles the Tokoro belt but differs from the Hidaka belt and the Tonino-Aniva zone to the south of the melange band (Figures 1b and 2).

Sandstones of the Chayka Formation and its counterparts in the other blocks in the northern part of the Tonino-Aniva Peninsula consist mainly of basalt and andesite clastics with negligible amounts of quartz (Figure 3a) and fall into the undissected island arc field on the ternary diagram of sandstone compositions [*Dickinson et al*, 1983] (Figure 3b). We have compiled published data on sandstone composition from different tectonic zones of Hokkaido [*Kanamatsu et al*, 1992; *Kiminami et al*. 1992. *Nanayama*, 1992] and South Sakhalin and find that the Chayka sandstones and island arc-derived sandstones of the Tokoro belt are similar and differ from coeval sandstones of the Hidaka and Sorachi-Yezo belts and the Tonino-Aniva zone (Figure 3)

Brown-red to greenish-red to dark green siliceous tuffaceous siltstones of the Chayka Formation closely match hemipelagic sediments of the Yubetsu Group and Yosenkyo Formation from the Tokoro belt on Hokkaido [*Sakakibara et al.*, 1986; *Tajika*, 1988, *Kiminami et al.*, 1992] but are not reported from coeval formations in other tectonic units of Hokkaido or South Sakhalin. Note also that hemipelagic sediments are overlain by coarser-grained rocks, including conglomerates, in both the Tokoro belt [*Sakakibara et al.*, 1986] and the Ozersk unit

These observations lead us to conclude that (1) the northern part of the Tonino-Aniva Peninsula is a separate tectonic unit (Ozersk unit) which is a counterpart of the Tokoro belt, and (2) the melange band is a suture between this unit and the Tonino-Aniva zone (Figure 2). This is in contrast to an earlier view that the entire Tonino-Aniva Peninsula belongs to the same accretionary complex [e g., *Kimura et al*, 1992]. It is also reasonable to assume that island arc complexes of the Tokoro

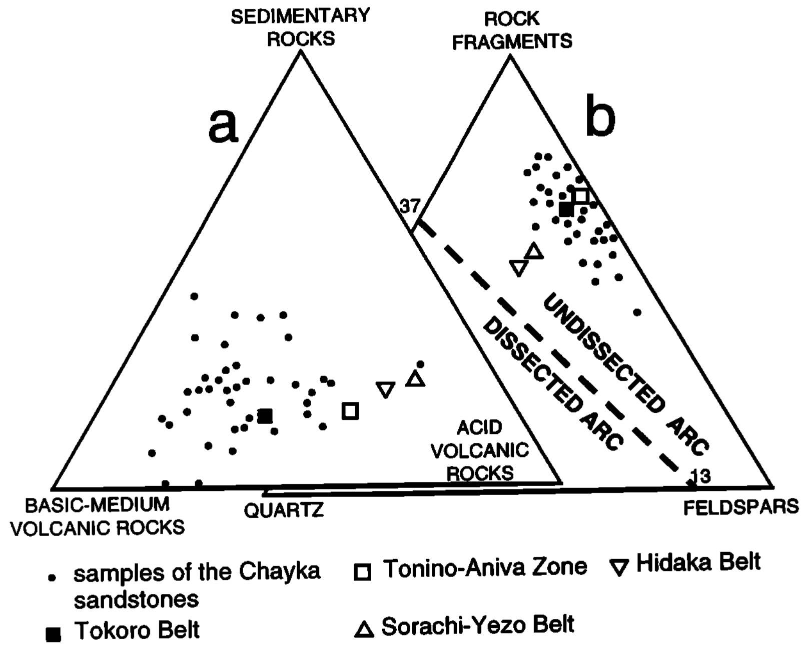

Figure 3. Ternary diagrams of sandstone compositions from Hokkaido and South Sakhalin. Overall means only are given for sandstones from the Tokoro, Sorachi-Yezo, and Hidaka belts [*Kanamatsu et al.*, 1992; *Kiminami et al.*, 1992; *Nanayama*, 1992] and the Tonino-Aniva Zone. Discriminating fields on the right diagram are from *Dickinson et al.* [1983]

belt and the Ozersk unit originally belonged to the same island arc (Tokoro arc). This assumption can be verified with the aid of paleomagnetic data on coeval island arc complexes of both tectonic units. Such data are available on late Campanian-early Maastrichtian rocks of the Tokoro belt [*Kanamatsu et al.*, 1992], but they are absent from South Sakhalin.

A well-exposed section of the Chayka Formation on the eastern coast of the Tonino-Aniva Peninsula was chosen for our studies (Figure 2). This coastal section is cut by numerous steep thrusts of western vergence; locally, a weak to moderate cleavage is present. Thrust sheets are deformed into folds of north to NNW strike; some folds are either established (or suspected) to be isoclinal. In the brown-red siltstones from the lower part of the Chayka Formation, we found the following radiolaria: *Amphypyndax stocki Campbell et Clark, A. mediocris Tan Sin Hok, Alievium gallowayi White, A. sp. aff. A. praegallowayi Pessagno, Archaeodictyomitra regina Campbell et Clark, Dictyomitra koslovae Foreman, D. densicostata Pessagno, D. multicostata Zittel, Hemicryptocaspa conara Foreman, Phaseliforma sp., Pseudoaulophacus praefloresensis Pessagno, Stichomitra livermorensis Campbell et Clark, Xitus asymbatos Foreman*. The complex was found in California [*Pessagno*, 1976] and Japan [*Taketani*, 1982] and indicates a Campanian-Maastrichtian age of the Chayka Formation. Unfortunately, more precise age determination is not possible, and we assign a Campanian-Maastrichtian age (75 ± 9 Ma) to the rocks studied. Note that all radiolarians and paleomagnetic samples are from the lower half of the formation, and the age of its upper half is unknown.

A total of 195 hand samples were taken at twenty sites from beds of various attitudes in the coastal section. Preferably, red, green, and gray siltstones were taken; gray tuffaceous sandstones were avoided because of indistinct stratification. One hand sample per stratigraphic level was oriented with a magnetic compass, samples being spaced approximately uniformly across the sampled outcrops. The true thickness studied at each site varied from 3 to 10 meters. Most sites are from homoclines, and a few are from both limbs of small open folds.

3. Treatment

Hand samples were cut into cubic specimens with a diamond saw, and 189 samples from 20 sites were treated in the Paleomagnetic Laboratory in Moscow. The collection was thermally demagnetized in 12 to 16 steps in ovens with internal residual fields of ~10 nT. All measurements of natural remanent magnetization (NRM) were made on a JR-4 spinner magnetometer with a noise level of 0.05 mA/m. The magnetometer was placed into large Helmholtz coils which reduce the ambient geomagnetic field by a factor of ~100. Demagnetization results were plotted on orthogonal vector diagrams [*Zijderveld*, 1967], and linear trajectories and remagnetization circles were used to determine directions of magnetic components by a least squares fit [*Kirschvink*, 1980]. Anisotropy of magnetic susceptibility was measured on a kappa-bridge KLY-3 in the Paleomagnetic Laboratory of Kyoto University, Japan. Paleomagnetic software for IBM PC by R. Enkin, A. Lander, and S. Shipunov and for Macintosh by J.-P. Cogné was used for analysis.

4. Results

NRM intensities in tuffaceous rocks of the Chayka Formation vary from more than 100 mA/m to less than 1 mA/m. Red and brown varieties are more strongly magnetized than green and gray ones though intensity variations are large within each group. Also very variable are demagnetization characteristics: some gray and greenish-gray siltstones and fine-grained sandstones showed erratic behavior above 200°C or were completely demagnetized by 300°C to 350°C (not shown). A single component of reversed polarity is present in some samples (Figure 4a), whereas curved

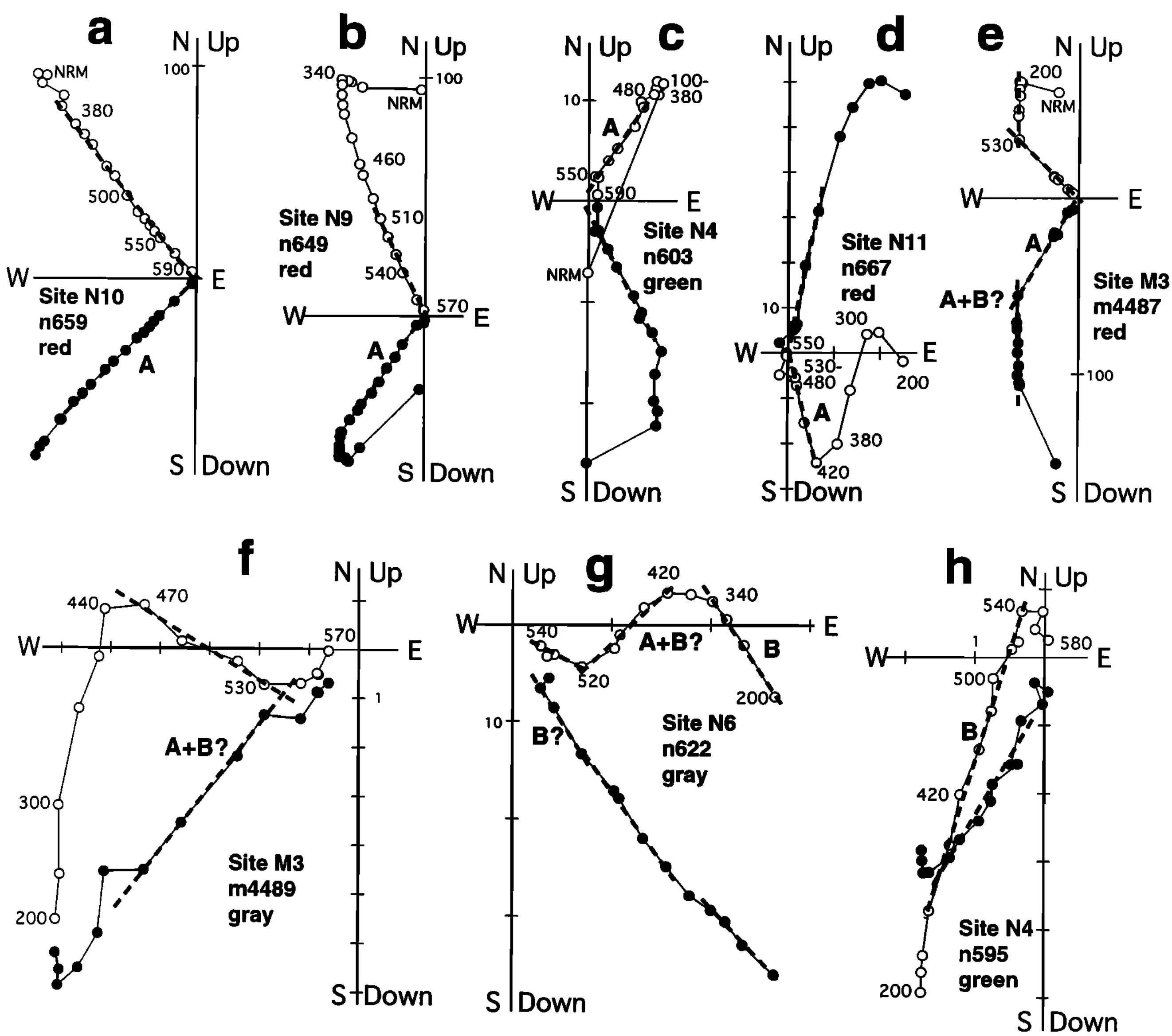

Figure 4. Representative thermal demagnetization plots of volcano-sedimentary rocks in stratigraphic coordinates. Solid (open) dots represent vector endpoints projected onto the horizontal (vertical) plane. Temperature steps are in degrees Celsius. Magnetization intensities are in mA/m. Thick dashed lines denote isolated components labeled as in the text. For clarity, NRM points are omitted from some plots.

(Figure 4b) or linear (Figures 4c-4e) segments at low to intermediate temperatures in others indicate the presence of another component with lower unblocking temperatures. In still other samples, three linear segments can be recognized (Figures 4f and 4g), note that the first and third segments correspond to components with similar directions. Finally, NRM in a few samples is mostly accounted for by a single component which does not decay to the origin and has moderate to steep positive inclination in situ (Figure 4h)

With the exception of an unstable remanence removed at 100° to 200°C, the NRM consists of two components, A and B, which interact in a complex manner. As a rule, component A has higher unblocking temperatures than component B. The latter, however, has very variable unblocking spectra as evidenced by zigzag (Figures 4f and 4g) or hooked-at-the-end (Figure 4h) demagnetization plots In many samples, strong overlapping of the spectra of these components may be suspected from a high scatter of component directions isolated in the final steps of cleaning Well-defined great circles for many samples also indicate that unblocking spectra of the components strongly overlap Irrespective of their color, all samples are completely demagnetized by 560° to 600°C, and magnetite is likely to be the main NRM carrier.

Component B of normal polarity in situ was isolated from more than three samples at seven sites (Table 1). Its directions are much better grouped in situ than after tilt correction, and the fold test [*McElhinny*, 1964] is negative for sites N1 and N3 at the within-site level; this test is also negative for seven site means (Table 1 and Figures 5c and 5d). The best site-mean grouping, though statistically insignificant, is observed at 15% incremental unfolding for five homoclinal sites. Thus component B is postfolding All site means and the overall mean are significantly different from the present-day dipole field (PDF) and indicate that component B is not a present-day overprint (Figure 5c) We

Table 1. Paleomagnetic Results for Component B[a]

			In Situ				Tilt-Corrected			
Site	*N*	BED	*D*, deg	*I*, deg	*k*	a_{95}, deg	*D*, deg	*I*, deg	*k*	a_{95}, deg
M1	9/7	20/71	246.7	68.3	45	9.1	1.9	32.5	6	26 0
M5	9/5	25/51	259 7	65.8	17	19.0	354.4	49.6	11	24 0
N1	9/5	fold	271.5	67.0	9	27.9	13.8	70.5	<3	>90
N2	9/8	67/59	257.8	75.1	74	6.5	49.5	44.9	44	8.4
N3	8/6	fold	242.9	64.1	25	13.6	126.2	-19.7	<3	>90
N4	12/8	242/37	131.8	83.9	7	22.3	232.4	54.3	4	31.6
N8	10/4	182/25	262.6	78.5	21	20.5	205.8	60.8	19	21.8
Mean	(20/7)		263 5	73.4	55	8.2	52.8	75.6	<3	50.9

[a] *N*. number of samples studied/used; number of sites is in parentheses, BED, mean azimuth of dip/dip angle; *D*, declination; *I*. inclination. *k*. precision parameter [*Fisher*. 1953]; a_{95}, radii of cone of confidence. Only sites where component B is isolated from more than 3 samples are presented

attribute the deviating mean direction of component B to tilting of the Chayka rocks during Neogene faulting of the area.

Component A is rather scattered at most sites in both geographic and stratigraphic coordinates, but directions derived from the longest linear segments (Figures 4a and 4b) are much better grouped It was suspected that unblocking spectra of components A and B overlap even more than appears from orthogonal plots. and hence directly isolated components and remagnetization circles were combined for computation of component A site means [*McFadden and McElhinny*, 1988]. After tilt correction, this component is reversed in most samples (Figures 4a-4c and 4e) and of normal polarity in a few from the upper parts of sections at sites M6, M7, and N11 (Figure 4d). Reversed and normal vectors are approximately antipodal, and the reversal test is positive at the within-site level

At site N3. component A directions form two dense clusters with different means in both coordinate systems While the mean direction of four consecutive samples closely matches the other data (subsite N3a), that of the other four consecutive samples (subsite N3b) is anomalous (Table 2) Although the N3 outcrop is like a homocline we assume that an isoclinal fold passes unrecognized at this site When bedding attitudes are changed accordingly. both means are in agreement in stratigraphic coordinates (Table 2)

Sites M2 and N6 were rejected because of high data scatter. Site means with a_{95} > 20° after tilt correction (sites M4, M5, and M9). and a site mean based only on three remagnetization circles (site M6) were omitted from further analysis despite their general agreement with the other data (Table 3). The remaining 14 site means are more tightly clustered after tilt correction (Figures 5a and 5b), and the best data grouping is achieved at 100% unfolding. The scatter of site means, however, is rather high. and site means form a banana-type distribution cocentric with the stereoplot pole (Figure 5b) We attribute this pattern to local rotations which are quite likely in the strongly deformed Chayka Formation The inclination-only fold test [*McFadden and Reid*. 1982] is positive and yields a well-defined mean inclination of 45 0° ± 6.4°.

Anisotropy of magnetic susceptibility (AMS) (K_{max}/K_{min} - 1) on 39 samples varies from 0 7% to 10 2%, 5.2% on average. For further analysis. we selected 24 samples exemplified in Figures 4a and 4b. where component A is reliably isolated and accounts for more than 50% of the NRM. For this subset the mean inclination of 45.2° is very close to the overall mean inclination of 45.0°, and the mean magnetic susceptibility is 900 x 10^{-6} SI units. which is much more than any possible contribution of paramagnetic minerals These observations indicate that AMS is dominated by ferromagnetic minerals which carry the ChRM Principal anisotropy axes are scattered in situ (Figure 6a); after tilt correction. K_{max} and K_{int} axes are nearly uniformly distributed close to the stereonet equator, while most K_{min} axes are nearly orthogonal to bedding planes (Figure 6b). These results indicate that a primary sedimentary fabric is preserved in the Chayka rocks despite rather strong deformation.

AMS was shown to be a good proxy for deep-sea sediments to evaluate inclination error and even to find the true inclination, I_H. corrected for this bias [*Hodych et al*, 1999]. In our case, the correlation of tan *I* and AMS (*R* = -0.25) is well below the 95% confidence level of ±0 41 (Figure 6c). This insignificant correlation mainly relies on the single highest tan *I* value (circled symbol in Figure 6c). without it, the correlation drops to a still smaller value of 0 17. We thus assume that no statistically significant inclination shallowing has affected component A directions in the Chayka rocks

Thus the bipolar component A isolated from Campanian-Maastrichtian volcano-sedimentary rocks of South Sakhalin passes the fold test and is most probably primary. The sufficient number of sites and the presence of both polarities indicate an

Table 2. Paleomagnetic Results for Component A at Site N3[a]

			In Situ				Tilt-Corrected			
Site	*N*	BED	*D*, deg	*I*, deg	*k*	a_{95}, deg	*D*, deg	*I*, deg	*k*	a_{95}, deg
N3a	4/3/1	73/63	111.2	-17.3	22	21.2	156.3	-53.3	30	17.9
N3b	4/3/1	70/79	210.8	11.6	31	17.7	155.2	51.7	31	17.7
N3b	4/3/1	250/101	210.8	11.6	31	17.7	164.8	-51.7	31	17.7
N3	8/6/2	fold	162.5	-3 7	2	52.0	160.4	-52.6	35	9.6

[a] *N*. number of samples studied/isolated components used/remagnetization circles used. Other notation as in Table 1.

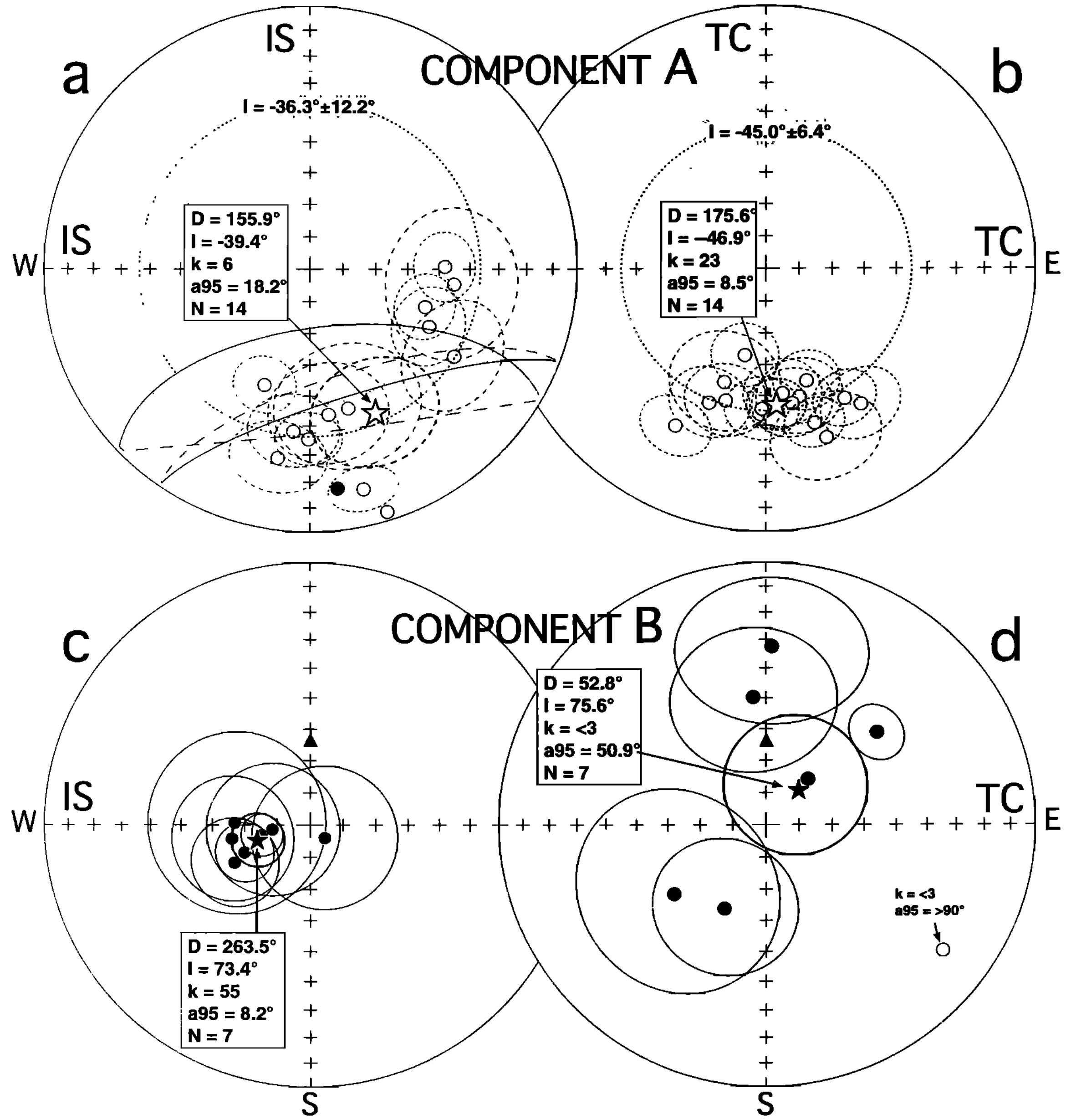

Figure 5. Equal-area projection of site-mean directions (dots) of components (a-b) A and (c-d) B together with associated confidence circles (thin lines) and overall means (stars) with associated confidence circles (thick dashed line) in situ (Figures 5a and 5c) and after tilt correction (Figures 5b and 5d). Thick and thin dotted lines are mean inclinations obtained by the inclination-only statistics and their confidence limits, respectively (for component A only). Open (solid) symbols and dashed and dotted (solid) lines are projected onto upper (lower) hemisphere.

adequate averaging of secular variation. These fine-grained rocks of submarine origin display distinct stratification, and their accumulation on a tilted surface is unlikely. AMS data reveal no significant inclination shallowing. Thus the overall-mean inclination of component A obtained with the aid of inclination-only statistics appears to be unbiased.

5. Paleomagnetic Data on Island Arc Complexes of Hokkaido-Sakhalin Fold Belt

The Ozersk unit in South Sakhalin has been shown to be a counterpart of the Tokoro belt on Hokkaido, which also includes rocks of island arc affinity such as the Late Campanian-Early Maastrichtian Yosenkyo Formation. The mean inclination of 43° ± 14° obtained from ten sites in this formation [*Kanamatsu et al.*, 1992] corresponds to a latitude of 25° ± 11°N. The mean inclination of 45.0° ± 6.4° in the Chayka Formation of this study corresponds to a latitude of 26.6° ± 5.2°N (Table 4). Thus island arc complexes of the Tokoro belt on Hokkaido and the Chayka Formation, which are approximately coeval (Campanian-Maastrichtian), were formed at similar latitudes. We therefore assume that the Yosenkyo Formation on Hokkaido and the Chayka Formation on Sakhalin originally belonged to the same island arc (Tokoro arc).

The Campanian-Maastrichtian to Eocene island arc complexes are known in the Nemuro belt on Hokkaido and its northeastward

Table 3. Site-Mean Paleomagnetic Results for Component A[a]

			In Situ				Tilt-Corrected			
Site	*N*	BED	*D*, deg	*I*, deg	*k*	a_{95}, deg	*D*, deg	*I*, deg	*k*	a_{95}, deg
M1	9/3/4	31/68	96.2	-44.8	10	21.8	160.6	-32.4	19	15.1
M2	12/0	fold				scattered				
M3	7/5/1	52/21	200.9	-51.0	56	9.2	209.4	-31.7	47	10.0
M4[b]	5/2/3	62/46	112.4	-52.8	12	25.6	185.2	-56.2	12	25.6
M5[b]	9/1/4	29/54	67.1	-76.9	20	22.0	197.1	-46.0	10	31.1
M6[b]	8/0/3	89/43	129.4	-37.8	-	>90	177.2	-59.2	-	12.4
M7	9/6/2	fold	164.8	-44.3	8	21.0	165.5	-48.3	22	12.4
M8	12/4/4	49/56	116.1	-48.8	25	11.7	181.6	-45.5	31	10.5
M9[b]	10/1/2	124/41	154.5	-40.8	7	84.6	203.7	-66.8	30	38.1
N1	9/2/3	fold	172.9	17.0	3	54.9	145.5	-37.5	52	11.5
N2	8/2/4	49/58	89.0	-48.1	57	10.0	193.2	-62.3	57	10.0
N3	8/6/2	fold	162.5	-3.7	2	52.0	160.4	-52.6	35	9.6
N4	12/5/6	234/31	189.4	-28.0	14	12.9	169.1	-46.6	18	11.4
N5	13/9/4	246/37	180.4	-35.5	22	9.1	149.3	-42.0	22	9.1
N6	8/0	312/20				scattered				
N7	7/2/3	80/66	121.7	-36.7	30	16.2	199.6	-52.1	30	16.2
N8	10/4/4	181/24	166.4	-14.9	47	8.6	162.8	-38.4	49	8.4
N9	13/5/3	48/46	108.4	-52.4	36	9.7	172.5	-50.4	27	11.2
N10	10/4/2	121/20	185.6	-37.9	32	12.6	202.5	-44.0	37	11.6
N11	10/5/3	102/23	172.7	-43.5	12	17.0	196.5	-46.5	24	11.9
Mean	(20/14)		155.9	-39.4	6	18.2	175.6	-46.9	23	8.5
Incl	(20/14)		-	36.3	-	12.2	-	45.0	-	6.4

[a] Incl. inclination-only statistics [*McFadden and Reid*, 1982]. Other notation as in Tables 1 and 2.
[b] Omitted from computation of the formation mean (see text for explanations).

continuation on the Lesser Kuril islands (Figure 1b). Paleomagnetic data on Santonian (84-88 Ma) dikes from the Nemuro Peninsula [*Fujiwara and Ontake*, 1974] imply a latitude of 34.5° ± 5.9°N for the Nemuro arc at that time (Table 4). According to *Bazhenov and Burtman* [1994] the Maastrichtian (circa 70 Ma) island arc complex of the Lesser Kuril islands was formed at a latitude of 36.5° ± 4.0°N (Table 4). These results imply that the Nemuro arc was 12° ± 7° to the north of the Tokoro arc in the Late Cretaceous. Hence the island arc complexes of the Nemuro and Tokoro belts most probably originally belonged to different island arcs. This does not support the view that these belts belonged to the same island arc [e.g., *Kanamatsu et al.*, 1992].

All paleolatitudes derived from the Tokoro and Nemuro belts are much lower than the coeval Eurasian reference values (Table 4) calculated from the kinematics of this plate [*Engebretson et al.*, 1985]. Large differences between the observed and predicted latitudes indicate considerable northward transport of these island arc complexes.

6. Kinematics of the Tokoro Arc

Kinematics of the Chayka terrane and the entire Tokoro paleoarc can be reconstructed if the following are known: (1) the kinematic parameters of the main continental and oceanic plates for the Late Cretaceous-Cenozoic, (2) the original paleolatitudes of the island arc complexes, (3) the interval of arc volcanic activity, and (4) the age of collision between the continental margin and the island arc. Kinematic parameters of the main plates in the hot spot reference frame are taken from *Engebretson et al.* [1985], whereas paleolatitudes are from paleomagnetic data. Other information is derived from analysis of geological data.

East Sakhalin belongs now to the rather recent Okhotsk plate that is slowly moving southward [*Riegel et al.*, 1993]; total displacement of this plate accumulated to-date is negligible with respect to error limits of the other data used in our analysis. The Tartar Strait between Sakhalin and Eurasia (Figure 1) is an arm of the Japan Sea rift system [*Jolivet et al.*, 1992], the opening of which could have resulted in a few degrees counterclockwise rotation and minor eastward displacement of entire Sakhalin. On the other hand, the opening of the Japan Sea could have been accommodated by Neogene folding and thrusting which are well developed on Sakhalin. N-S trending dextral strike-slip faults of late Cenozoic age are documented on Sakhalin [*Rozhdestvensky*, 1982]; however, several hundred kilometers of displacement along these faults [*Fournier et al.*, 1994] appears to be model-dependent and is not confirmed by geological data. In view of these ambiguities, we do not take into account any Neogene motion of Sakhalin and perform kinematic analysis for the present-day position of the study area (46.8°N, 143.0°E) with Eurasia as the docking plate.

The modern convergent boundary in the northwest Pacific passes along the Kuril-Kamchatka and Japanese trenches, thus completely isolating Sakhalin from oceanic plates. This configuration was created after the opening of the Japan Sea in the south and the South Kuril basin in the north (Figure 1b). Most authors agree that the opening of the former occurred between 20 and 14 Ma and led to eastward extrusion of the Japanese Islands [*Tamaki*, 1988; *Otofuji*, 1996]. The age of the South Kuril basin is less certain but generally interpreted to be close to that of the Japan Sea [*Tamaki*, 1988; *Takeuchi*, 1997]. Therefore northward motion of the Chayka block had to occur before 20 Ma. This is in accord with the geology of the Tonino-Aniva Peninsula, where continent-derived coal-bearing terrigenous rocks of early Miocene age (circa 20-16 Ma) unconformably overlap older complexes.

By about 43 Ma the Kula-Pacific spreading center had become extinct, and the Chayka terrane could have subsequently been transported only with the Pacific plate. Before 43 Ma, the

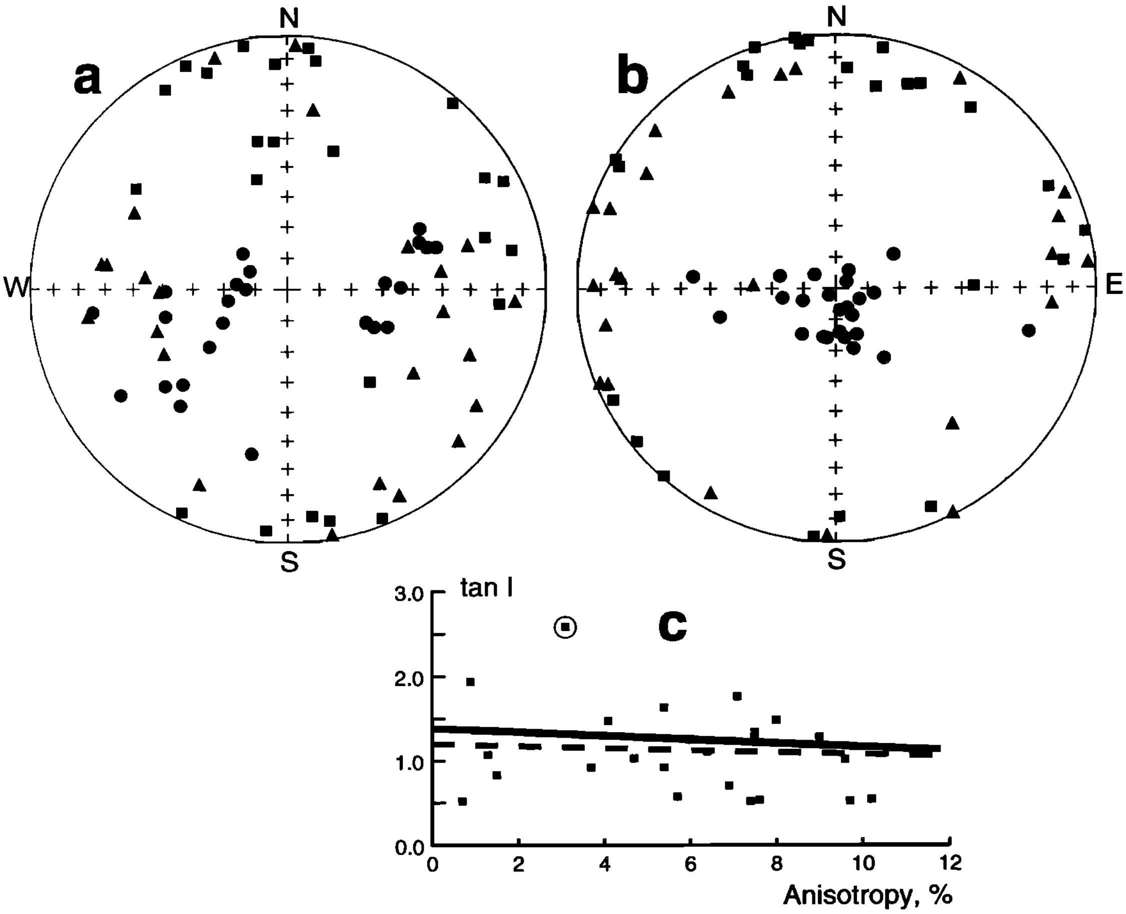

Figure 6. (a-b) Stereoplots of K_{max} (squares), K_{int} (triangles), and K_{min} (dots) axes of AMS ellipsoids in 24 samples of the Chayka rocks in situ (Figure 6a) and after tilt correction (Figure 6b); all symbols are projected onto lower hemisphere (c) Plot of tan I versus anisotropy (K_{max}/K_{min} -1) for the same samples, where I is inclination of component A. the largest value of tan I is circled (see text). Thick solid (dashed) line, regression line of these two parameters all (without encircled entry) samples after *Hodych et al.* [1999].

Chayka terrane could move either with the Pacific or with the Kula plates However, the position of the Kula-Pacific boundary, though not well constrained, was shifting eastward between the Campanian and Middle Eocene [*Engebretson et al.*, 1985] and was to the east of Sakhalin in the Maastrichtian-Paleogene. Paleocene to middle Eocene paleolatitudes from island arc complexes of east Kamchatka fit well with a permanent motion on the Pacific plate and disagree with motion on the Kula plate, thus placing the Kula-Pacific boundary to the east of Kamchatka during the entire Cenozoic [*Levashova et al*, 2000]. Therefore motion of the Chayka terrane and the entire Tokoro arc was most probably driven by the Pacific plate.

Paleo-orientation of the Eurasian convergent margin did not change appreciably during the Cenozoic [*Engebretson et al*, 1985], and the Pacific plate moved subnormal to this margin after 43 Ma thus precluding large coastwise translation. Before 43 Ma the convergence of these plates was oblique enough to allow for a coast-parallel transport. However, we estimate that the latitudinal component of such transport from the Campanian-Maastrichtian till 43 Ma did not exceed 4°-6°, while the

Table 4. Summary of Late Cretaceous Paleomagnetic Data from Hokkaido and Sakhalin[a]

Location (°N; °E)	Age	Expected plat ± Δplat, deg	Observed plat ± Δplat, deg	F ± ΔF, deg	References
Chayka (46 8; 143 0)	C-M	53.9 ± 5.9	26.6 ± 5.2	27.7 ± 6.3	1
Yosenkyo (43 2, 143 8)	C_l-M_e	51.1 ± 5.6	25.0 ± 11.0	26.1 ± 9.9	2
Shikotan (43 5, 146 5)	M	51.5 ± 6.3	36.5 ± 4.0	15.0 ± 6.0	3
Nemuro (43 0, 145.0)	S	49.7 ± 4.8	34.5 ± 5.9	15.2 ± 6.1	4

[a] Location, localities with coordinates in parentheses labeled as in the text. Age, age of rocks studied: M, Maastrichtian; C, Campanian; S, Santonian: subscripts e and l stand for early and late subperiods, respectively; plat ± Δplat, paleolatitudes with 95% confidence limits; F ± ΔF, flattening with 95% confidence limits calculated as suggested by *Demarest* [1983]. References are 1, this paper; 2; *Kanamatsu et al* [1992]. 3. *Bazhenov and Burtman* [1994]; 4, *Fujiwara and Ontake*, [1974].

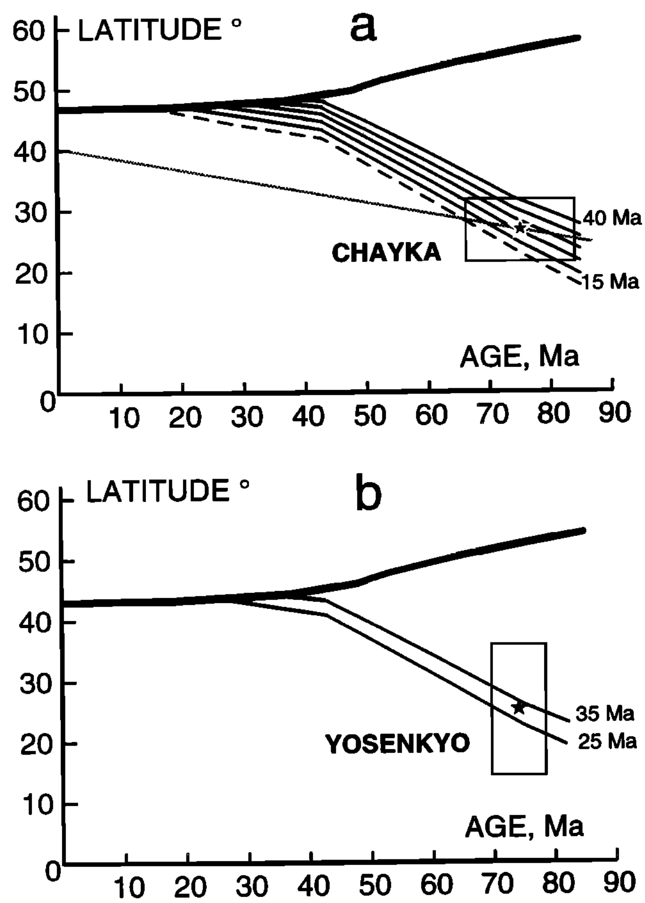

Figure 7. Latitude versus age plots for different docking times for the (a) Chayka and (b) Yosenkyo [*Kanamatsu et al.*, 1992] results Stars, observed latitudes; rectangles, confidence limits on rock age and observed latitude; thick solid lines, reference plots assuming no relative motion of a terrane with respect to the Eurasian plate, thin solid lines, plots for motion of the terranes with the Pacific plate for different docking times (either labeled or with 5 Myr decrements for other trajectories in Figure 7a); thin dashed line, a trajectory for 15 Ma docking time which is unacceptable on geological grounds. Shaded line denotes a trajectory calculated as suggested by *Norton* [1995].

difference between the predicted and observed paleolatitudes of the Chayka terrane is ~30°. Thus the coastwise translation could play only a minor role in motion of the Chayka terrane, and intraoceanic northward drift on the Pacific plate is strongly indicated

The Chayka terrane docked with the continental margin not later than 20 Ma, but we do not know when this northward motion started. As the polarity of subduction under the Tokoro arc is also unknown, two kinematic scenarios are possible. If subduction was directed oceanward, as has already been suggested by some studies [*Tajika*, 1988], the Tokoro paleoarc had to reside on the leading edge of the Pacific plate and move with it both during the Campanian-Maastrichtian while it was active and after cessation of activity until the docking with the continental margin Otherwise, if the Pacific plate was subducted under the Tokoro arc while it was active, northward drift of the paleoarc could start only after the cessation of subduction. In this model the Tokoro arc could have been passively carried on the Pacific plate while it was subducting somewhere to the north, most probably under the Sikhote-Alin volcanic belt.

Kinematic analysis for various docking times shows (Figure 7) that the Chayka terrane had to start moving northward in the late Maastrichtian otherwise docking would have had to occur after 20 Ma For both Chayka and Yosenkyo results the trajectories for docking times at 25-30 Ma fit the paleomagnetic data better than for older docking times. This means that the Chayka terrane started moving northward at about 74-78 Ma (Late Campanian) and, in turn, means that either subduction under the Tokoro paleoarc ceased at the end of the Campanian or that both the Chayka and Yosenkyo rocks are purely of Campanian age. We consider that it is more possible that the Tokoro arc resided on the leading edge of the Pacific plate and the polarity of subduction was oceanward

7. Late Cretaceous Convergent Boundaries in the Northwest Pacific

We have compiled paleomagnetic data on Campanian-Maastrichtian and Paleogene island arc complexes from Hokkaido to Kamchatka and attempted to fit them into a reconstruction of convergent boundaries in the northwest Pacific The remnants of the Campanian-Maastrichtian to early Eocene Nemuro island arc on Hokkaido and the Lesser Kuril Islands (Figure 1b) are on the external (oceanic) side of the Kuril and Japanese island arcs The Nemuro arc was at a latitude of 34.5° ± 5.9°N in the Santonian [*Fujiwara and Ontake*, 1974] and at a latitude of 36.5° ± 4.0°N in the Maastrichtian [*Bazhenov and Burtman*, 1994], therefore this island arc stayed at similar latitudes during the Late Cretaceous. This observation indicates that the Nemuro arc did not permanently move on a quickly moving oceanic plate, as a point on the Pacific plate would have moved northward by ~15° from the Santonian to the Maastrichtian, motion on the Kula plate would have resulted in a still larger displacement At the same time, two Late Cretaceous paleolatitudes from the Nemuro belt are significantly lower than the Eurasian reference values (Table 4); hence the Nemuro island arc could not permanently reside on the Eurasian plate.

Using paleomagnetic data on Maastrichtian rocks from the Lesser Kuril Islands, *Bazhenov and Burtman* [1994] concluded that the Nemuro arc moved on the Pacific plate from the Maastrichtian and docked with the Kuril subduction zone at ~15 Ma. Our analysis shows that this kinematic scenario is in error because permanent motion with the Pacific plate since the Maastrichtian predicts a docking time of ~50 Ma, which is much older than the age of the Kuril island arc and also predates docking of the Tokoro arc Here we assume that the Nemuro arc separated a backarc basin from the oceanic plates which subducted under this arc thus resembling, for instance, the Mariana arc and the Philippine Sea plate. A thick sequence of lava and volcano-sedimentary rocks of island arc affinity (Nemuro Group) encompasses an interval from Campanian, probably Santonian, to early Eocene [*Okada et al.*, 1987]; hence the Nemuro arc was active during this interval This arc became inactive by the end of the early Eocene (circa 50 Ma) and started moving passively northward on the Pacific plate to dock with the Kuril arc at ~15 Ma (Figure 8) in agreement with the age of collisional events on Hokkaido [*Kimura et al.*, 1983, *Celaya and McCabe*, 1987]. The convergence of the Nemuro arc with the Eurasian plate was rather oblique (Figure 8), and their collision is likely to lead to large clockwise rotations in the Tokoro belt and the western part of the Nemuro belt, as evidenced by paleomagnetic declinations, whereas the eastern part of the Nemuro belt remained weakly deformed [*Kanamatsu et al.*, 1992] A more thorough discussion of postaccretion tectonics of

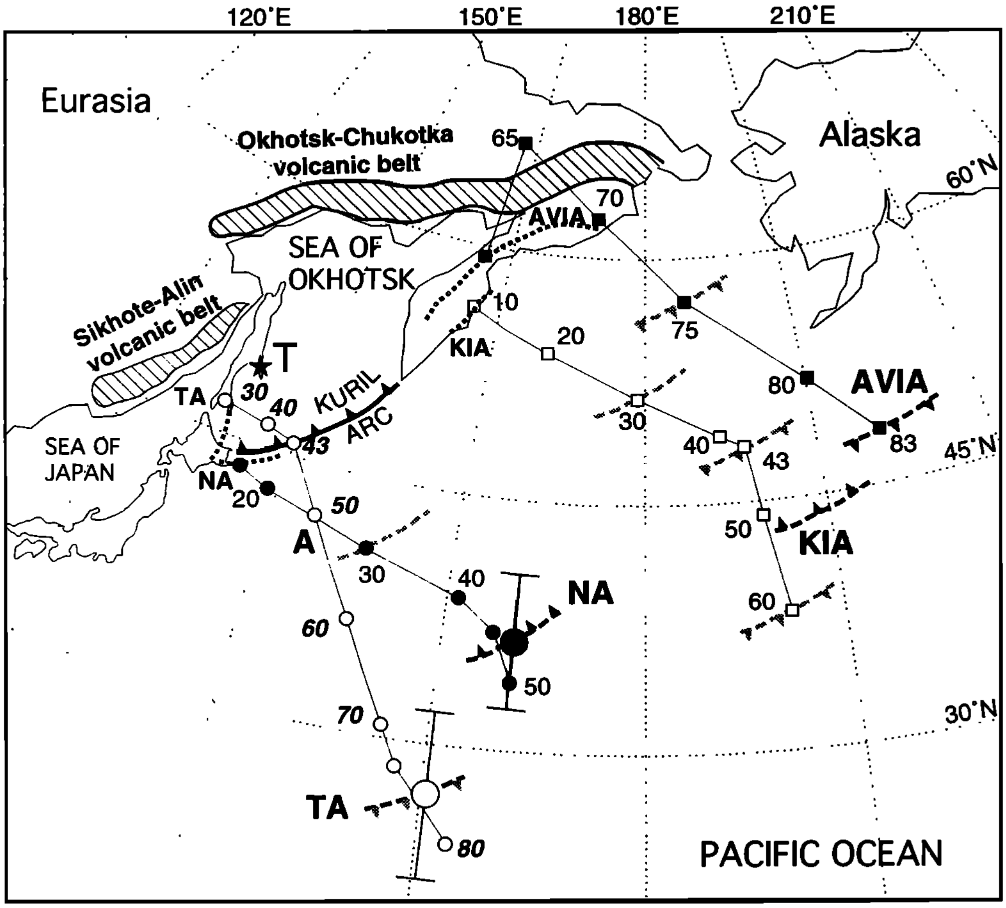

Figure 8. Reconstruction of convergent boundaries in the Northwest Pacific. Island arcs: TA, Tokoro arc; NA, Nemuro arc. KIA. Kronotsky arc; AVIA, Achayvayam-Valagina arc (KIA and AVIA are described in more detail by *Levashova et al* [2000]) Thick dashed (dotted) lines and larger (smaller) characters denote Late Cretaceous inferred (present-day) locations of these arcs. Shaded dashed lines denote the island arcs at intermediate positions during their intraoceanic transport. Toothed lines are for active arcs; by lines without the teeth are for extinct arcs The teeth denote the subduction direction; note that subduction polarity is arbitrary for the TA (see text). Trajectories are computed in the hot spot reference frame using kinematic parameters of *Engebretson et al* [1985] for the following docking times: TA, 30 Ma, NA, 15 Ma, KIA, 10 Ma; AVIA, 65 Ma; the postdocking parts of the trajectories are simplified. Trajectories are dated in Ma; those for TA are in bold italics for clarity. Star indicates a completely remagnetized island arc complex on the Terpenia Peninsula (T) in central East Sakhalin (see text). Note that the trajectory for the Tokoro arc passes through point A at 50 Ma, while the trajectory for the Nemuro arc passes through the same point at ~25 Ma.

the Hokkaido-Sakhalin fold system, however, is beyond the scope of this paper. Note only that most authors assume a few hundred kilometers of postaccretion movements at the stage [e.g., *Takeuchi*, 1999, and references therein], which is much less than the error limits of paleomagnetic data used and many times less than intra-oceanic motion Hence taking postaccretion movements into account does not affect the above conclusions.

Campanian-Maastrichtian to middle Eocene complexes of the Kronotsky island arc have been studied in the East Peninsulas tectonic zone of Kamchatka [*Levashova et al.*, 2000], where it was shown that the Eocene Kronotsky island arc originated in the Late Cretaceous at a latitude of ~45°N and moved slowly southward with the continental plate until the beginning of Paleocene, when subduction under this paleoarc changed polarity Since the beginning of the Paleocene until docking in late Miocene-Pliocene time, the Kronotsky island arc moved with the Pacific plate.

Widespread Upper Cretaceous island arc complexes of the Achayvayam-Valagina zone of Kamchatka, the Olutor zone of the Koryak Highland and the Karaginsky island are regarded as the remnants of a single Achayvayam-Valagina island arc (AVIA). *Levashova et al.* [1998] synthesized all paleomagnetic data available on these rocks and showed that the AVIA was 20°-25° south of the continental margin in the Campanian and was later transported northward on the leading edge of either the Kula or the Pacific plate until emplacement at 65-50 Ma.

When the above results are combined, a system of island arcs extending across the northwest Pacific appears (Figure 8). The segments of this system differ in subduction polarity and subsequent kinematics This pattern is in drastic contrast to the present-day "emptiness" of the northwest Pacific but resembles the tectonic pattern in Polynesia where multiple microplates and subduction zones of different polarity coexist.

A convergent boundary of the Andean type (Okhotsk-Chukotka and Sikhote-Alin volcanic belts, Figure 8) was active along the Asian margin in the early Late Cretaceous [*Bazhenov et al.* 1999, and references therein]; the subduction-related volcanic activity in the former ceased in the Campanian

[*Filatova*, 1988]. Our results imply that a Polynesian-type plate boundary existed in the northwest Pacific in the Campanian-Maastrichtian, thus a drastic change in subduction pattern took place during Santonian-Campanian time. During the Cenozoic the system of intra-oceanic island arcs was gradually replaced by the late Cenozoic "condensed" convergent boundaries with marginal seas. Thus convergent boundaries of different types replaced each other in the northwest Pacific. Discussion of processes governing the evolution of convergent boundaries is beyond the scope of this paper.

The proposed model relies on paleomagnetically derived paleolatitudes and kinematic trajectories in the hot spot reference frame. Unless one assumes a new source of inclination shallowing over the entire region from Hokkaido to well north of Kamchatka and time interval from the Late Cretaceous to the end of Eocene or an unknown mechanism of extremely high coast-parallel transport, this pattern appears to be generally robust. According to this reconstruction, drowned subducted slabs should exist in the Pacific basin as they exist under Siberia [*Van der Voo et al.*, 1999], if such slabs are found far away from the continental margins, it will strongly support the suggested model. Just a few island arc complexes are so far characterized by reliable paleomagnetic results, and new paleomagnetic and geological data are needed. Unfortunately, another Campanian-Maastrichtian island arc complex in central East Sakhalin (locality T in Figure 8) appears to be completely remagnetized: all ChRM directions isolated after stepwise thermal cleaning up to 600°C in a collection of ~400 samples are of normal polarity and show distinct maximum grouping at 80% unfolding (N.M. Levashova, unpublished data, 1999): the mean direction of this remanence is very close to the present-day field. More valuable would be a time sequence of paleomagnetic directions from the island arc complexes. So far, such a set of reliable paleomagnetic data is only available from the East Peninsulas zone in east Kamchatka [*Levashova et al.*, 2000]. Another attempt of this kind was undertaken in the eastern part of the Nemuro belt [*Tanaka and Uchimura*, 1989], but the limited number of sites of each age and the lack of numerical data (mean directions and statistics) do not allow to incorporate these results into our analysis.

Finally, we note that the validity of the hot spot reference frame, which our interpretation is based on, is now hotly debated [e.g., *DiVenere and Kent*, 1999, and references therein]. We refrain from thorough discussion of this subject but note in defense of this frame and our use of it that no consistent interpretation of the Chayka and Yosenkyo data can be obtained for limiting case of hot spot motion [*Norton*, 1995]. According to Norton's kinematics, the Chayka and Yosenkyo terranes are still moving somewhere nearby the Kuril-Kamchatka trench (Figure 7a). Less extreme versions of the hot spot mobility [*DiVenere and Kent*, 1999] can be matched with the observed paleolatitudes but require either younger docking times or large inclination shallowing or both, in contrast to above presented geological and AMS data. May it be that, ultimately, the hot spot reference frame is not so much in error as is sometimes suggested?

8. Conclusion

The Hokkaido-Sakhalin fold system is usually regarded as a juxtaposition of several island arc complexes of different polarity [e.g., *Kanamatsu et al.*, 1992]. A geological study of the Tonino-Aniva Peninsula on South Sakhalin shows that its northern part (Ozersk unit) correlates with the Tokoro belt on Hokkaido, and not with the Hidaka belt as suggested earlier [*Kimura et al.*, 1992]. In the eastern part of the Ozersk unit, 195 hand samples were taken at 20 sites from Campanian-Maastrichtian tuffaceous siltstones and sandstones of the Chayka Formation of island arc affinity. Stepwise thermal demagnetization of the collection reveals two NRM components. A low- to intermediate-temperature component B is ubiquitously of normal polarity and postdates folding, its mean direction deviates from the present-day field or any late Cenozoic expected direction supposedly because of Neogene tilting. Component A is reliably isolated from less than a half of samples; strong overlapping of unblocking spectra of components A and B in the other samples leads us to combine direct observation and remagnetization circles for calculation of component A site-mean directions [*McFadden and McElhinny*, 1988]. Component A is mostly of reversed polarity, with a few antipodal normal polarity vectors. This and the positive fold test imply a prefolding, and most probably primary origin, of component A. AMS data reveal a well-preserved syndepositional pattern and indicate no significant inclination shallowing. The overall mean inclination of 45.0° ± 6.4° calculated with the aid of inclination-only statistics [*McFadden and Reid*, 1982] corresponds to a latitude of 26.6° ± 5.2°N, which is ~30° lower than the coeval Eurasian reference value. This finding is in accord with paleomagnetic data on Late Cretaceous rocks from the Tokoro belt on Hokkaido [*Kanamatsu* et al., 1992].

We infer a large-scale northward translation of the entire Tokoro belt, and hence an ancient Tokoro island arc, which predated the opening of the Japan Sea (i.e., is older than 20 Ma). Kinematic analysis excludes motion with the Kula plate as well as a considerable coast-parallel transport and infers motion of the Tokoro arc with the Pacific plate until docking to the Eurasian margin at ~30 Ma. The original position of the Tokoro arc far from its present-day position indicates that the Pacific and Eurasian plates could not have continuously interacted in the late Cretaceous and Early Tertiary while this arc was active. Hence a direct connection of geological events on the Eurasian periphery with the kinematics of oceanic plates is not evident at certain times.

An analysis of paleomagnetic data from late Cretaceous island arc complexes from Hokkaido to Kamchatka indicates that a system of island arcs obliquely crossed the northwest Pacific. This system appeared in the Santonian-Campanian and replaced the Andean-type volcanic activity which had existed along the Asian continental margin in the Early and early Late Cretaceous. Segments of this system had different kinematics and activity intervals and docked to the Eurasian landmass at different times. In particular, docking of the Nemuro island arc with the Kuril Trench resulted in deformation and rotations in east Hokkaido.

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