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Paleomagnetism of Paleogene rocks of the Central–East Kamchatka and Komanorsky Islands: tectonic implications

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ABSTRACT

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Paleomagnetic investigation of Paleocene–Eocene to Miocene rocks has been carried out at five localities in the Eastern Kamchatka and Komandorsky Islands. After thermal and af cleanings, consistent paleomagnetic directions were isolated for a number of formations. Data from the Kronotsky Peninsula and Medny Island passed both the fold and reversal tests and thus can be considered as reliable; other results are of lower quality. All the results were derived from sedimentary rocks, and thus the corresponding paleolatitudes may be biased due to inclination errors. A limited collection of basalts yielded inclination values systematically lower than those in sediments; this anomaly was tentatively explained by shape anisotropy. The correctness of paleolatitude estimations was thus left unproved. Several models of the Northern Pacific tectonic evolution were suggested and analyzed, but the authors failed to find a model that was fully compatible with paleomagnetic, kinematic and geological data.

Introduction

The tectonic evolution of the Aleutian arc–Kamchatka juncture has been attracting much attention, but it is still a matter of controversy (Bogdanov, 1988; Kononov, 1989; Savostin et al., 1986; Schmidt, 1978; Scholl et al., 1975; Stavsky et al., 1988; and others). According to the kinematic analysis the Pacific plate is moving parallel to the western flank of the Aleutian arc along the strike-slip fault and is being subducted in the Kuril–Kamchatka trough. Such a pattern is thought to have persisted for the past 42 Ma. Before that, from 42 to 55 Ma, the Kula plate had been moving northward in respect to North America, and had been subducted under it along the Kamchatka–Chukotka–Alaska continental margin (Kononov, 1989; Lonsdale, 1988). The dying-out of that subduction zone is usually thought to have resulted in the formation of the Aleutian arc. In order to clarify the tectonic evolution of this region, we undertook a paleomagnetic investigation of the Paleogene island arc complexes in the Central–East Kamchatka and the western-

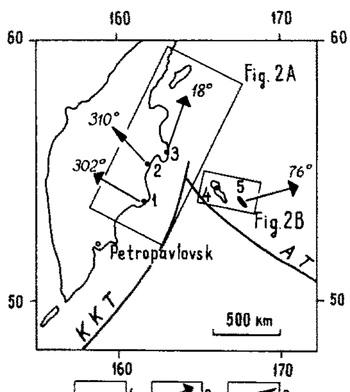

Fig. 1. General outline of investigation area. *1* = sampling localities; *2*, *3* = paleomagnetic directions in Eocene and Oligocene–Miocene rocks, respectively; *KKT* = Kuril–Kamchatka Trench; *AT* = Aleutian Trench. Areas in rectangles are presented in more detail in Fig. 2.

most part of the Aleutian arc, the Komandorsky Islands (Fig. 1).

Tectonic relationship of Eastern Kamchatka and the Aleutian island arc

Paleocene–Eocene volcanosedimentary rocks of the island-arc affinity (Khubunaya, 1987) are widespread on three peninsulas of easternmost Kamchatka; from south to north they are the Shipunsky, Kronotsky and Kamchatsky Mys Peninsular (Fig. 2). These peninsulas are usually regarded as a single tectonic zone, the Zone of Eastern Peninsulas, ZEP, which is separated from the Kamchatka mainland by the Tushev basin. The basin is filled by thick Oligocene–Miocene sediments, overlying with slight angular unconformity the Eocene volcanics in the Kronotsky Peninsula. Sediments on the eastern and western slopes of the basin are rather different and are cut by a number of thrusts. Thus, it is probable that these two slopes were originally wide apart. It should be stressed that ZEP cannot be traced northward beyond the Kamchatsky Mys Peninsula (Fig. 2).

The Kamchatsky Mys Peninsula is situated at the westward continuation of the Aleutian arc, and tectonic structures here have "Aleutian" NW strikes, quite anomalous for Kamchatka. That is why this peninsula was sometimes regarded as part of the Aleutian arc, although they are now separated by an appendage of the Kuril–Kamchatka trench. There are many similarities in the geological setting of the Eocene sections on the Kamchatsky Mys Peninsula and Komandorsky Islands. However, there are also noticeable differences; for example, rhyolites, which occur abundantly on the Komandorsky and Near Islands, are absent on the peninsula. On the other hand, rhyolites are also absent among the paleogene volcanics in the eastern part of the Aleutian arc. In general, the variability of the Eocene sections along the island arc appears to be comparable to that between the Komandorsky Island and ZEP and, therefore, the latter may be traced from the Kronotsky Peninsula via Kamchatsky Mys to the Aleutians.

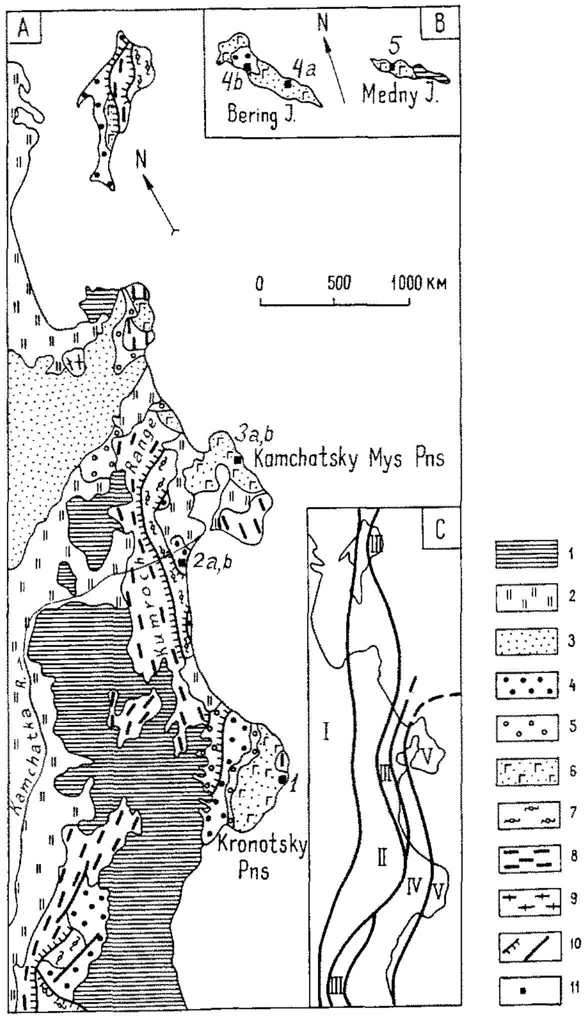

Fig. 2. Figure 2. simplified geological map of Eastern Kamchatka (A) and the Komandorsky Islands (B). *1* = Pliocene–Quarternary volcanics; *2* = Upper Pliocene–Quaternary sediments; *3* = Miocene–Lower Pliocene rocks; *4* = Oligocene–Miocene rocks; *5* = Oligocene rocks; *6* = Paleocene–Eocene rocks; *7* = Paleocene rocks; *8* = Upper Cretaceous rocks; *9* = pre-Cretaceous metamorphic rocks; *10* = faults; *11* = sampling localities. Also shown (C) is the tectonic zonation of the pre-Pliocene series of the Eastern Kamchatka. *I* = Central Kamchatka basin; *II* = Eastern Range uplift; *III* = Vetlov zone; *IV* = Tushev basin; *V* = Eastern Peninsula zone.

We hypothesize that in Paleogene time the Kronotsky–Komandorsky Island arc had already existed and was later fragmented. In turn, it seems possible that this Paleogene arc had inherited an older island arc, as the Paleocene–Eocene complex overlies the Cretaceous island-arc sequence on the Kronotsky Peninsula (Khubunaya, 1987), while Upper Eocene terrigenous rocks in the Komandorsky Islands contain much debris from some deeply eroded landmass (Shapiro, 1976).

Geological setting and sampling

Kronotsky Peninsula

The oldest rocks exposed are Upper Cretaceous basalts and volcanosedimentary rocks in the eastern part of the peninsula. They were dissected by thrusts, and nappes were "sealed" by the Paleogene–Middle Miocene sequence (Raznitsyn et al., 1985). The lowermost part of this neoautochthon consists of interbedding volcanogenic sandstones, siltstones and diatomaceous mudstones with some pillow basalts. Benthic and planktonic foraminiferas of Paleocene age were found at the base of the neoautochthon (Serova, 1966); the sampled part of this formation is of Middle Eocene age (Yu.B. Gladenkov, pers. comm., 1990). Up-section, these rocks are conformably overlain by a thick pile of Upper Eocene volcanics. They contain basalts of island-arc affinity, similar to those of Cretaceous age (Khubunaya, 1987). The Eocene rocks are overlain with slight angular unconformity by fossiliferous Oligocene–Middle Miocene shallow-water clastic sediments (Arsanov, 1978). This unconformity implies some weak pre-Oligocene deformations but most probably, the main folding here took place during the Late Miocene–Pliocene.

The Middle Eocene volcanogenic siltstones, fine-grained sandstones and one flow of pillow lava were sampled from coastal exposures in the eastern part of the peninsula (54.8°N, 162.1°E). Samples were taken on both limbs of a gentle syncline; the true thickness studied is about 100 m (locality *1*, Figs. 1 and 2).

Kumroch Range

On the southeastern slopes of the Kumroch Range, conglomerates at the section base are overlain, presumably without a large time gap, by fossiliferous Oligocene–Miocene siltstones and terrigenous flysch. The siltstones sampled (56.2°N, 162.2°E, locality *2*, Figs. 1 and 2) dip very gently westward in the Gorbusha River valley (site 2a) and southward along its tributary Burny Creek about 2 km to the north (site 2b). The true thicknesses studied are about 40 m and 60 m, respectively.

Kamchatsky Mys Peninsula

Two structural zones separated by a young basin are recognized here. Basalts, silicic–tuffaceous and terrigenous sediments as well as gabbroic and ultramafic ophiolitic bodies are widespread in the southern zone (Zinkevich et al., 1987). In the northern zone, an up to 5000 m thick sedimentary pile is distributed; its base may be Late Cretaceous in age but the main part is Paleocene–Eocene (Borzunova et al., 1969). In the northeastern part of this zone there are some basalt flows and diabase sills that are geochemically similar to those in the Kronotsky Peninsula (Khubunaya, 1987). The sedimentary rocks of the two peninsulas are also rather similar.

In the Kamchatsky Mys Peninsula, the Paleogene rocks were deformed into large NW–SE-striking folds. The age of folding is constrained only as Oligocene–Pliocene. Intercalating tuffaceous siltstones, sandstones and marls with Eocene foraminiferas and gastropods were sampled on the both limbs of a syncline (56.5°N, 163.3°E, locality *3*, Figs. 1 and 2). Its northeastern limb is gentle, and the other one is overturned (sites 3*a* and 3*b* about 6 km apart, respectively). The total stratigraphic interval studied is about 500 m.

Komandorsky Islands

A small collection of Paleogene sedimentary rocks was sampled along the eastern coast of Bering Island (site 4a); (55.2°N, 166.0°E, locality *4*, Figs. 1 and 2). A trachydolerite extrusion with a potassium–argon whole-rock age of 21–25 Ma (Borsuk and Tsvetkov, 1980) crops out on the southwest coast of the island. Samples were taken along its southern semi-perimeter from coastal exposures, at intervals of from several tens to several hundred meters from each other (site 4b; see also Fig. 6B).

At the base of the Paleogene section of Medny Island (54.8°N, 167,6°E), acid lavas and tuffs (Medny Formation) crop out as small patches on the northeastern coast. These rocks, mainly of green color due to propilitization, are cut by numerous diabase dikes and sills. This formation is overlain by a volcanoclastic sequence more than 1000 m thick (Komandorsky Formation). Both formations, although separated by a gap in volcanic activity, are considered as a series of island-arc affinity. Higher still, the Komandorsky Formation is comformably overlain by turbidites of the Pribrezhny Formation, about 1200 m thick. In the northern part of Medny Island, the Paleogene rocks dip 25–50° to southwest, with some short-wave fault-conjugated folds.

In the lower part of the Komandorsky Formation, planktonic foraminiferas, presumably of Paleocene age, were found (Schmidt, 1978). The younger rocks and their counterparts on Bering Island contain Eocene benthic foraminiferas, mollusks and flora. On the other hand, the whole-rock potassium–argon determinations on rhyolites and basalts of the Medny Formation yielded ages not exceeding 34 ± 4 Ma (Borsuk et al., 1984). As radiometric data could be biased because of hydrothermal reworking of these rocks, we consider the stratigraphic ages to be more reliable.

Pelitic tuffs, tuffaceous siltstones and rhyolites of the Paleocene Medny Formation were sampled, as well as five sills of basalts. One of the sills folded comformably with host rocks was studied in more detail: both basalts and heated host rocks were sampled along its strike. Fine-grained sediments, mostly siltstones and pelitic tuffs, were taken from the Eocene Komandorsky and Pribrezhny formations (locality 5, Figs. 1 and 2).

Some concluding remarks on the sampling policy adopted seem to be required. For the peculiar cases only (the trachydolerite extrusion, the folded sill), one hand-sample was taken, i.e., from a lava flow, from a sill, or from a layer of sediment. The total number of samples and the true thicknesses studied were chosen in such a way as to achieve adequate averaging of all kinds of paleomagnetic noise, including secular variations. Each hand-sample was oriented with a magnetic compass. When working with basalts, it was checked whether compass readings had been distorted by these strongly magnetized rocks.

Methods and procedures

Three to four specimens were cut from each sample. All measurements were made with a Czechoslovakian JR-4 spinner magnetometer. Two specimens per sample were subjected to stepwise thermal cleaning. At the first stage, the whole collection was heated in four steps up to 350°C, and then the representative pilot samples were cleaned stepwise up to 560° or 580°C. According to the results for pilot samples, the remaining parts of the collections were either stepwise demagnetized or heated at an optimal temperature. The mutual orientation of the specimens was changed after each heating in order to detect any laboratory-induced components. If an acquisition of such components prevented further cleaning and twin-vectors (that is, directions for two specimens from a sample) had been well clustered before, the "unspoiled" directions obtained at the previous steps were used for analysis. Some samples were also subjected to stepwise AF cleaning up to 800 Oe. Results after treatments were analyzed using stereonets and orthogonal diagrams.

Wherever possible, reversal and fold tests were applied. Several modifications of the latter were used. A test based on precision parameters before (K_b) and after (K_a) tilt correction (McElhinny, 1964) was utilized for small data sets only. If two or more monoclines were sampled, the mean vectors for each limb calculated before and after tilt correction were compared with the statistical F distribution (McFadden and Jones, 1981); the same procedure (the mean test) was used when performing the reversal test. If bedding attitudes at sampling points varied considerably, the distribution of bedding poles on the stereonet was divided into a number of approximately isometrical non-overlapping groups, irrespective of the sample position within a locality, and then the corresponding paleomagnetic group means were analyzed as in the previous case (the group test). The mean and group test are very similar but for the origin of bedding pole groups, either natural or artificial. In order to underline this difference, two terms will be used is what follows. Finally, if bedding attitudes were variable, another approach was used (the correlation test). This is based on the comparison of intercorrelation coefficients between two sets of unit vectors, the bedding poles and the corresponding paleomagnetic directions (for details, see Bazhenov and Shipunov, 1991).

If unit magnetization vectors shifted along great circle segments in the process of cleaning, converging remagnetization circles (after Halls, 1976) were used. This approach was always applied at specimen level. As a data fitness criterion, the orthogonal distance of a unit normal to the best-fitting plane was calculated for each entry. If this distance exceeded 20° such a normal was omitted and the best-fitting plane was recomputed. The confidence limit of the least-dispersed component was calculated as the mean of two semiaxes of the confidence oval.

Results

Kronotsky Peninsula (locality 1)

Paleogene sedimentary rocks responded quite well to thermal cleaning. The characteristic magnetization (ChRM) was isolated in pilot samples after heating above 250° or 300°C (Fig. 3A), and so the results beyond 350° were used for interpretation. The bedding poles, although not widely dispersed, were divided into four groups (Fig. 3B) and group and correlation tests were applied. Both unequivocally point to the prefolding age of the ChRM (Table 1). One of the bedding pole groups consists of only three entries, but after its omission the group test led to the same conclusion (Table 1). Reversed polarity predominates here, but directions of normal polarity are clearly antipodal to those of the other sign (Fig. 3C).

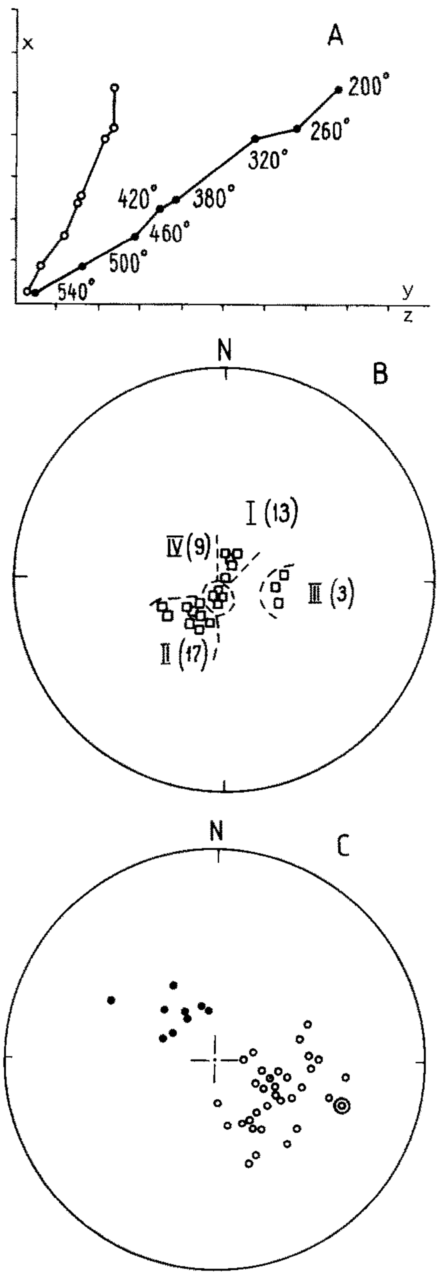

Fig. 3. Paleomagnetic and structural data for Eocene rocks from the Kronotsky peninsula (locality 1). (A) Thermal demagnetization of a representative sample; open (closed) dots denote projection on the horizontal (vertical) plane (the same convention is preserved later). (B) Distribution of bedding poles (squares) for the whole collection. Roman numbers on the stereonet denote group numbers corresponding to those in Table 1. The number of normals in each group (given in brackets) can exceed that shown on the stereonet, as unit bedding poles were often quite similar. Dashed lines denote between-group boundaries. (C) Distribution of the sample mean ChRM directions for the whole collection after tilt correction: dots = sediments; encircled dot = basalt flow. Solid (open) symbols are plotted on lower (upper) hemispheres (the same convention is preserved later).

The only sample of basalt from a single flow yielded a ChRM direction of $D = 105°$, $I = -38°$. While the declination is in agreement with those for sediments, the inclination is the lowest (Fig. 3C). This direction was excluded from calculation of the locality mean.

Kumroch Range (locality 2)

The NRM intensities of the Oligocene siltstones were rather low and dropped ten-fold at 350°C. Above this temperature, magnetization proceeded to decrease quickly and noticeable spurious components appeared, resulting in a sharp increase of the within-sample scatter. The cleaning had to be terminated, and we had to use the results after heating to a temperature when twin-vectors were less dispersed. All of the samples accepted for analysis are of reversed polarity (Fig. 4). As two monoclinal sections had been studied, the mean test was used: but the difference in bedding attitudes is very small and the test proved to be inconclusive (Table 2).

Kamchatsky Mys Peninsula (locality 3)

When heated above 480°C, a few samples from the overturned fold limb (site 3a) revealed univectoral decay to the origin, although most did not. At lower temperatures, the within-sample scatter was small as a rule, but sample means were almost chaotic.

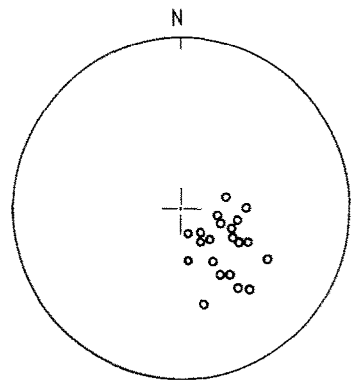

Fig. 4. Distribution of magnetization directions after cleaning for sediments from the Kumroch Range (locality 2). All vectors are tilt corrected.

Samples from the gentle limb showed univectoral behavior from 200° or 250°C on (Fig. 5A), but many of them acquired spurious laboratory-induced components above 480°C, thus preventing complete demagnetization. Complete demagnetization was possible in only about one-quarter of the collection. Irrespective of the quality of demagnetization, sample-means are distributed in a similar way (Fig. 5B), and the mean directions

TABLE 1

Paleomagnetic results on the Eocene rocks from the Kronotsky Peninsula (locality 1)

Group [a]	N_s/N_a	In situ				Tilt corrected			
		$D°$	$I°$	K	α_{95}°	$D°$	$I°$	K	α_{95}°
I	14/13	286	61	18	9.2	301	60	18	9.2
II	22/17	332	61	16	8.6	292	61	19	7.8
III	3/3	316	34	90	8.6	331	52	66	10.0
IV	10/9	324	54	32	8.2	312	60	29	8.6
Mean (samples)	49/42	315	59	16	5.3	*302*	*60*	*20*	*4.9*
Mean (groups)	4	313	56	43	10.8	310	59	62	8.9
Mean (groups)	3	314	60	44	12.2	301	61	278	4.9
Group-test (4 groups)		$F_b = 4.56$			$F_a = 1.75$		$F_c(6,76) = 2.23$		
Group-test (3 groups)		$F_b = 5.60$			$F_a = 0.82$		$F_c(4,72) = 2.24$		
Correlation-test (42 samples)		$R_b = 0.51$			$R_a = 0.28$		$R_c = 0.38$		

[a] Bedding pole groups as shown in Fig. 3. N—number of samples: N_s—studied, N_a—accepted; D, I—declination and inclination of paleomagnetic vector (all data are presented as normal polarity directions); K—precision parameter; α_{95}—semi-angle of confidence at 95 percent confidence level; F—statistics based on F-distribution; R—rank correlation coefficients. Subscripts a, b and c refer to data before tilt correction, after tilt correction and the corresponding critical value, respectively; degrees of freedom are given in brackets. Data used for tectonic interpretation are in italics.

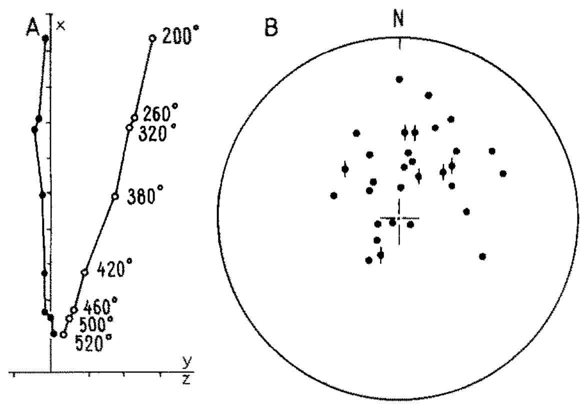

Fig. 5. Paleomagnetic data for the Kamchatsky Mys Peninsula (locality 3). (A) Thermal demagnetization of a representative sample. (B) Sample mean distribution for the whole collection after tilt correction; crossed dots represent samples where univectorial decay to the origin was observed (see text for explanation).

for "good" samples and those affected by spurious remagnetization are statistically indistinguishable (Table 2). The whole collection is of normal polarity. Before tilt correction, the overall mean is rather far away from the modern dipole field direction ($D = 0°$, $I = 71°$), although the latter does fall within the unit vector distribution, which is quite diffuse. All the modifications of the fold test were inconclusive due to very limited dispersion of bedding attitudes.

At first, converging remagnetization circles were analyzed for each site separately. The scatter of normals to remagnetization circles was very high and some 30 percent of them had to be rejected according to the fitness criteria. When two sets of normals purified in this way were combined it resulted in a considerable growth of dispersion, both before and after tilt correction. The repeated application of the fitness criteria did not seem sensible and thus no result was obtained in this way. We also failed to find a reasonable explanation for such a pattern.

Bering Island (locality 4)

Paleogene rocks from site 4a were subjected to thermocleaning. The dispersion was very high both on the within- and between-sample levels and the whole collection was discarded.

The Neogene trachydolerites (site 4b) responded quite well both to thermal and af cleaning yielding similar results (Fig. 6A). Twin-vectors are well clustered and sample means are distributed both systematically and enigmatically.

TABLE 2

Paleomagnetic data on the Oligocene rocks from the Kumroch Range (locality 2) and the Eocene rocks from the Kamchatsky Mys Peninsula (locality 3)

Site	N_s/N_a	In situ				Tilt corrected			
		$D°$	$I°$	K	$\alpha_{95}°$	$D°$	$I°$	K	$\alpha_{95}°$
Kumroch Range									
2a	14/11	334	69	24	8.7	305	54	24	8.7
2b	16/10	331	58	17	10.7	318	64	17	10.7
Mean	30/21	332	64	19	7.0	*310*	*59*	*19*	*7.0*
Mean test		$F_b = 1.80$			$F_a = 2.80$		$F_c(2,40) = 3.23$		
Kamchatsky Mys Peninsula									
36 [a]	7					14	65	9	17.6
3b [b]	24					19	66	6	11.4
3b	35/31	168	87	7	9.4	*18*	*66*	*7*	*9.5*
Group test (2 groups)			$F_b = 0.65$			$F_a = 0.45$		$F_c(2,58) = 3.16$	
Correlation test (31 samples)			$R_b = 0.25$			$R_a = 0.21$		$R_c = 0.43$	

[a] The mean direction for the samples where univectorial decay to the origin was observed.
[b] The same for the samples where complete demagnetization was prevented by acquisition of spurious components.
Notation is the same as used in Table 1.

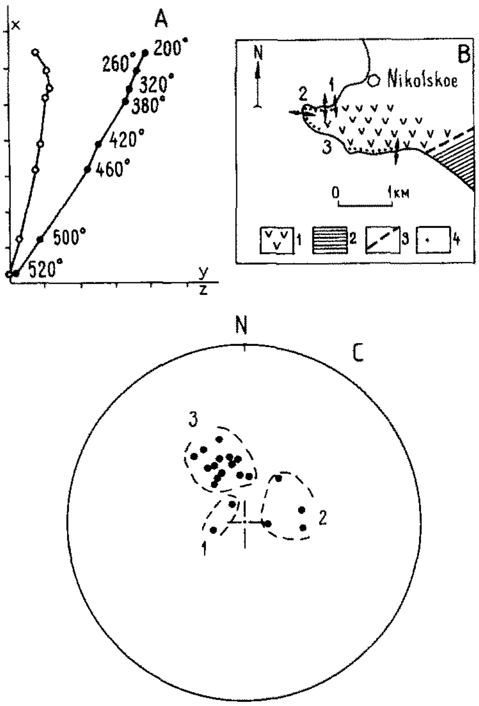

Fig. 6. Paleomagnetic results for the Neogene trachydolerite extrusion on the Bering Island (locality 4, site 4b). (A) Thermal demagnetization of a representative sample. (B) Schematic geological map of the area studied. *1* = Trachydolerites; *2* = host rocks; *3* = extrusion boundary; *4* = sampling points; double-pointed arrows represent boundaries of the differently magnetized parts of the body. (C) ChRM directions grouped as described in the text; group boundaries are shown as dashed lines and their numbers correspond to those in the Fig. 6B.

This collection was taken along the southern semi-perimeter of the extrusion, and paleomagnetic directions seem to correlate with the positions of sampling points (Figs. 6B and C). Several explanations for this correlation have been considered. (i) An assumption that the correlation resulted from a partial remagnetization of the trachydolerites can hardly be accepted, as paleomagnetic characteristics of these rocks are very uniform and the ChRM was isolated everywhere. (2) Each cluster on the stereonet may represent a spot-reading of the ancient geomagnetic field. If so, there are only three independent readings, which is too little for averaging of secular variations. (3) As all the samples were taken in the peripheral parts of the extrusion this clustering might result from their differentiated tilts, due either to the mode of emplacement or to later deformations. As there is no way to take these tilts into account the mean vector for the extrusion does not seem suitable for tectonic interpretation.

Medny Island (locality 5)

Of the three formations studied, no interpretable data were obtained for the Pribrezhny Formation: paleomagnetic directions were inconsistent both at the within- and between-sample level during the thermal cleaning.

On the contrary, the middle member of the succession (Komandorsky Formation) proved to be suitable for paleomagnetic study. When heated stepwise up to 560°C, univectorial decay to the origin was observed in quite a number of cases

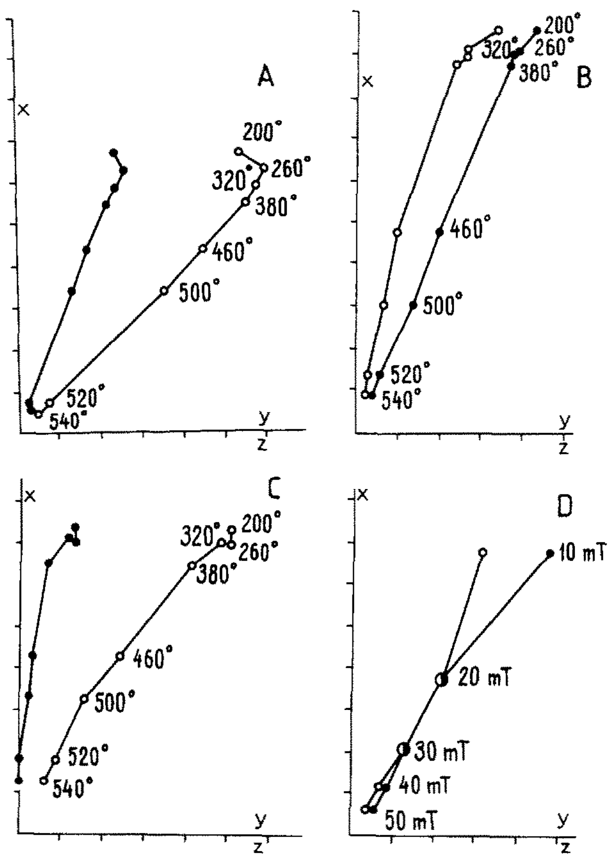

Fig. 7. Thermal (A,B,C) and af (D) demagnetization of representative samples from Medny Island (locality 5); (A) sedimentary rock of the Komandorsky Formation; (B) heated host rock from the folded sill of the Medny Formation; (C, D) basalt from the same sill.

(Fig. 7A), but the majority of samples acquired spurious components of magnetization above 450°C but sometimes as low as 350°C. However, the two mean directions, those for the completely demagnetized samples and those affected by laboratory-induced remagnetization, are in good agreement (Table 3).

Of 33 samples accepted, 27 are normally and 6 reversedly magnetized (Fig. 8B), and the reversal test is positive after tilt correction. The group and correlation tests were applied and both point unambiguously to the prefolding age of magnetization (Table 3, Fig. 8A). In addition, paleomagnetic directions for 27 specimens from 18 samples had been shifting along great circles during the cleaning. The direction of the least-dispersed component is quite similar to the formation mean (Table 3, Fig. 8C).

Twin-vectors for volcanosedimentary rocks and rhyolites of the Medny Formation were consistent during thermocleaning, but sample means were distributed chaotically and we failed to obtain any meaningful result here. It may be hypothesized that such a unfavorable situation had resulted

TABLE 3

Paleomagnetic results on the Paleogene rocks from Medny Island (locality 5)

Data	N_s/N_a	In situ				Tilt corrected			
		$D°$	$I°$	K	$a_{95}°$	$D°$	$I°$	K	$a_{95}°$
Komandorsky Formation									
Group I	21/15	52	28	16	8.9	63	60	16	9.0
Group II	8/6	89	56	16	14.3	81	60	14	15.4
Group III	8/5	169	63	9	21.3	83	63	12	15.1
Group IV	5/5	24	−14	13	17.5	59	79	26	12.4
Mean (samples)	42/33 [a]	55	35	4	14.4	68	63	15	6.3
Mean [b]	10					73	66	12	12.9
Mean [c]	23					66	62	16	7.2
CRC	27/23					67	58		9.3
Group-test (4 groups)			$F_b = 25.1$		$F_a = 1.62$		$F_c(6,54) = 2.28$		
Correlation test (33 samples)			$R_b = 0.89$		$R_a = 0.35$		$R_c = 0.42$		
Reversal test					$F_a = 0.52$		$F_c(2,62) = 3.15$		
Basalts of Medny Formation									
FSHR	4/4	71	13	12	20.6	106	57	115	6.5
FSB(350)	4/3	82	−4	17	19.6	92	39	47	11.8
FSB(EP)	4/3	72	15	41	12.6	100	49	497	3.6
Sills	4/3	80	20	9	26.8	94	32	29	15.0
Overall mean (samples) [d]	50/40	59	31	4	10.8	*76*	*62*	*15*	*5.7*
Group test (5 groups) [e]		$F_b = 20.1$			$F_a = 1.17$		$F_c(8,70) = 2.07$		
Correlation test		$R_b = 0.83$			$R_a = 0.31$		$R_c = 0.39$		

[a] Two samples only are included in Group V; they were not used for the group test but were used for calculation of the mean direction of the formation.

[b] The mean direction for the samples where univectorial decay to the origin was observed.

[c] The same, but for the samples where complete demagnetization was prevented by acquisition of spurious components.

[d] For computation of the overall mean, FSHR and FSB(EP) were added to data on the Komandorsky Formation.

[e] All 40 bedding poles were used.

Data: CRC, FSHR, FSB(350), FSB(EP) and Sills are converging remagnetization circles, heated host rocks from the folded sill, basalts from the same sill after treatment at 350°C, and end-points for the same basalts and other three sills, respectively.

The other notation is the same as used in Table 1.

from the above-mentioned propilitization of these rocks.

On the other hand, basalts and heated host rocks of the same formation responded well to thermal and af cleaning and the normal polarity ChRM was readily isolated (Figs. 7B, C and D). The fold test (after McElhinny, 1964) was applied to paleomagnetic directions from the folded sill, to the basalts and host rocks separately. The ratio of precision parameters after and before tilt correction is about 12 for basalts and 10 for host rocks, while the critical values are 6.4 and 4.3, respectively. Thus, the prefolding component prevails here.

As the number of spot-readings of the ancient geomagnetic field is clearly too low for the Medny Formation, it was decided to combine these data with those for the Komandorsky Formation. After doing so, it became clear that while the host-rock vectors fell within the "Komandorsky" distribution, those for the basalts from the folded sill were on its periphery and the directions for other three sills were outliers (Figs. 8B and D). The difference is mainly in inclination. Two facts should be mentioned. First, the magnetization intensity of the basalts from the folded sill is about 10^{-2} e.m.u., which is weaker than that for the other three sills by roughly a factor of ten.

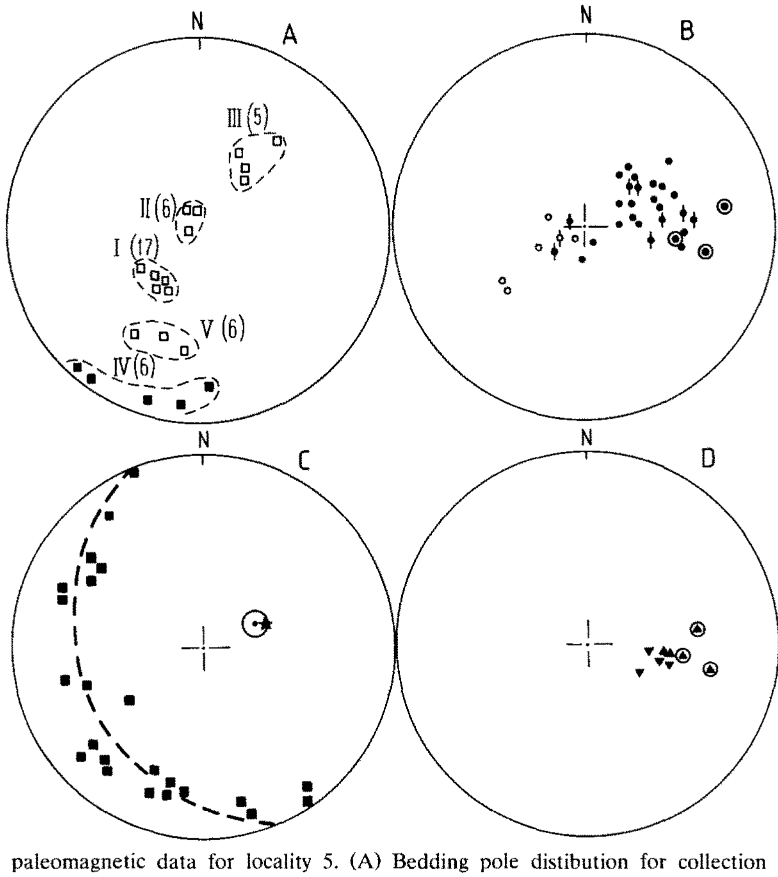

Fig. 8. Structural and paleomagnetic data for locality 5. (A) Bedding pole distibution for collection from the Komandorsky Formation (the same notation as in Figure 3B; the roman numerals correspond to those in Table 3). (B) Sample mean distribution for sediments of the Komandorsky Formation (dots) and three sills with anomalously low inclinations from the Medny Formation (encirled dots). Crossed dots represent samples where univectorial decay to the origin was observed. (C) Results of the remagnetization circles method: squares = normals to unit remagnetization circles; dashed line = best fitting plane; asterisk = mean direction of the least dispersed component; dot = mean vector with its confidence circle for the samples of the Komandorsky Formation after thermal cleaning. (D) Data for the folded sill: triangles = ChRM directions for basalts; inverted triangles = the same for heated host rocks; encircled triangles = magnetization directions in basalts after cleaning at 350°C. All data in (B), (C) and (D) are in stratigraphic coordinates.

Second, the mean vectors for the basalts, from the folded sill and the other three, are very similar throughout the greater part of the cleaning range (Table 3). The first vector approached the main data set above 500°C, only while the other directions remained stable. We decided to exclude the data from the strongly magnetized sills from computation of the overall mean. The group and correlation tests, re-applied to the combined data set, point to a prefolding age of magnetization (Table 3).

Analysis of paleomagnetic data

Our data

The unicomponent magnetization in the Eocene sediments of the Kronotsky peninsula (locality *1*) was reliably isolated. Both of the polarities are present and the reversal test is positive. Two modifications of the fold test point to the predeformational age of ChRM here. Although the main folding took place in Neogene, some less pronounced deformations also occurred during the Oligocene. The group and correlation tests are very sensitive (Bazhenov and Shipunov, 1991) and if these rocks had been remagnetized at some time between the two foldings the tests would most probably detect it. Thus, the age of ChRM in these rocks is certainly pre-Oligocene and most probably primary, and the result is reliable.

At locality 2, the result is of dubious quality; no end-points were reached, and the fold test is inconclusive. However, the exclusively reversed magnetization of the sediments points to a pre-Bruhnes or older age.

The result for the Eocene sediments from locality 3 is also doubtful: end-points were reached in a very limited number of samples, and the fold test is inconclusive. In addition, the whole collecton from site 3a was discarded. The only evidence for an old age of magnetization here is the fact that the mean vector before tilt correction deviates considerably from the modern field direction, as well as from any Cenozoic reference direction for the North American or Eurasian plates. It is out of the question to assume a complete postfolding remagnetization in the vicinity of the North Pole (the mean inclination in geographic coordinates is 87°).

The result on the Paleogene rocks from Medny Island (locality *5*) seems to be reliable, although complete demagnetization was possible in the limited part of the collection. Both the reversal and fold tests are positive, thus pointing to prefolding and most probably a primary age of the bipolar magnetization. Converging remagnetization circles yielded a direction that was very similar to the mean vector.

In general, the number of samples and the stratigraphic intervals at all localities are large enough to average out all kinds of paleomagnetic noise, including secular variations. We see no reason why declinations could be distorted or biased, for the most reliable results at least (locality *1* and *3*). However, the situation for inclinations is not that clear. All the data are from sedimentary rocks where inclinations might be shallowed, due either to inclination error or to compaction. The most common way to evaluate this effect is to study volcanics, which should yield an unbiased direction. This had been foreseen during the sampling, but we failed with rhyolites from Medny Island. As for basalts, they gave inclinations which are systematically shallower than those in sediments, both at the Kronotsky Peninsula and Medny Island. In all the cases, the inclinations in basalts before tilt correction are shallower than after it, so this phenomenon cannot be attributed to a postfolding remagnetization. If one assumes that the basalts only preserved the primary magnetization, and that all sediments had been remagnetized later but before folding, these volcanics should have been originally at 15–20°N, which is hardly possible. Of course, the data set is limited—one flow from locality *1* and four sills from locality *5*—but the pattern is too systematic to be put down to chance. Therefore, secular variations or incorrect compass readings can also be discarded.

As an explanation of the basalt anomaly we propose the following hypothesis, but do not insist on it. The shallow inclinations in basalts are due to the shape anisotropy (e.g., Abrahamsen, 1986). This effect should be more pronounced for strongly magnetized rocks—as is the case for the sills from Medny Island. It may decrease or be completely absent near to the Curie point, which conforms with the data from the folded sill (locality 5) but not with the basalts from the Kronotsky peninsula. The latter preserved an inclination of about 35° up to 560°C, while magnetization dropped by a factor of roughly 1000. One may say that such strongly magnetized rocks should be discarded on the spot, but this was not detected in the field and, its addition, lavas with similar magnetization intensities, e.g. from the Caucasus, yielded undistorted directions (Bazhenov and Burtman, 1990). Such an effect may be less pronounced, say 10°, and it will still affect tectonic interpretation. Moreover, if a lava flow did record a shallowed inclination and its magnetization was diminished afterwards, e.g. due to secondary alterations, such an object would be treated without any suspicion. It seems that volcanics as recorders of the ancient field, cannot be considered to be as reliable as was stated by Coe et al. (1985). Moreover, shallower inclinations in pillow lavas have already been reported (Osete et al., 1988). To finish this short discussion, it should be stressed that no definite conclusions have been reached on the inclination bias in sediments and the origin of anomaly in basalts.

Published data

There are two Miocene paleomagnetic results from Eastern Kamchatka presented as catalogue entries only (entries 02030 and 02085; Paleomagnetic Directions and Pole Positions, 1984). They were obtained without any cleaning at all and will not be used later. No data exist for the Komandorsky Islands.

There are a number of paleomagnetic results from the Aleutians to the west of the Amlia Island (for a review, see Harbert, 1987). However, all of the data on Paleogene rocks are of rather low precision, their confidence circles varying from 11° to 21°, and do not seem suitable for tectonic interpretation.

At Amlia Island, it was stated that the unicomponent magnetization in these rocks was prefolding, as $K_a/K_b = 2.23$ (Harbert, 1987). However, this conclusion is stipulated by the only site of reversed polarity the mean vector of which deviates noticeably from eight site means of normal polarity both before and after tilt correction. If the latter are treated separately, the relation is reversed; $K_b/K_a = 1.58$. Both values are statistically insignificant at the 95 percent confidence level, although the first one is only marginally so, but their "trends" are opposite. In addition, the mean for eight sites of normal polarity before tilt correction differs by less than 10° from the modern dipole field direction. Thus, the magnetization age here does not seem to be reliably established and we prefer to exclude this result from our interpretation.

Discussion

Paleomagnetic directions for Eastern Kamchatka and the Komandosky Islands were compared to reference mean poles for the North America plate, NAP (Harrison and Lindh, 1982).

TABLE 4

Kinematic parameters, as deduced separately for each locality

Locality	D_m°	D_r°	R°	dR°	I_m°	I_r°	F°	dF°	Pl_m°	SH°	dPL°
1	302	9	−67	12	60	76	16	5	41	23	6
2	310	359	−49	13	59	75	16	6	40	22	7
3	18	8	10	21	66	77	11	8	48	17	11
5	76	6	70	14	62	77	15	5	43	19	7

D, *I*—declination and inclination; *R*—rotation angle (positive and negative values represent clockwise and anticlockwise rotations, respectively); *dR*—semi-interval of confidence; *F*—flattening; *dF*—semi-interval of confidence; *PL*—paleolatitude, *SH*—northward movement of locality, calculated as $(PL_m - PL_r)$; *dPL*—semi-interval of confidence (this semi-interval is recalculated to symmetrical form with respect to point estimation of *SH*). Subscripts m and r denote measured and reference data, respectively.

Due to age differences of the rocks studied, the NAP Paleocene–Eocene pole was used for localities 1, 3 and 5, and the NAP Oligocene one for locality 2. These poles were converted separately into reference declinations and inclinations for each locality. After that, rotations and flattenings were calculated (Table 4), together with their error limits (corrected after Demarest, 1983).

It is easy to see that both declinations and inclinations deviate significantly from the reference data (Table 4). From our point of view, declination anomalies, especially for the most reliable data (localities 1 and 5), can only be explained by tectonic movements. We also tried to give tectonic interpretation to inclination anomalies, despite some possible bias in these data, as discussed in the previous section. The problem, as we see it, is to find a geodynamic model compatible with various geological, paleomagnetic and geophysical data.

The first model is based on some very simple and almost self-evident relations. If we fix the easternmost end of the Aleutians, that is the Alaska Peninsula, and straighten up this arcuate island arc parallel to this peninsula, its western end will be placed just at a latitude coinciding with our results, thus suggesting no shallowing of inclination here. Paleomagnetic data from the Alaska Peninsula (Coe et al., 1985), pointing to no detectable transport of this area in relation to the NAP, are compatible with this model. The consequent bending of this rectilinear structure with its eastern end fixed will result in clockwise rotation of its western "Komandorsky" part through an angle of about 70°, which is again in good agreement with the result from Medny Island. The small rotation of the Kamchatcky Mys (locality 3) and larger anticlockwise rotations of localities 1 and 2, as well as the folding in the Tushev basin can easily be explained by an oblique collision with the main Kamchatka landmass. Such a collision could most probably lead to the rupture of the continuous tectonic zone—as is the situation now. This model predicts gradually diminishing magnitudes both of clockwise rotations and inclination discrepancies along the Aleutians eastward.

It may be hypothesized that a primary Benioff zone of the rectilinear proto-Aleutians become extinct and that the corresponding island arc had been bent and translated northward to its present-day position, where a new subduction zone had been created in the Neogene. Such a hiatus in volcanic activity from the Late Eocene up to the Late Oligocene does exist, at least at the Komandosky Islands. The hypothesized primary island-arc complex had to be tectonically juxtaposed with the Neogene island arc. However, this model is vulnerable, as there are no traces of such suturing in the Aleutians.

According to another model (Stavsky et al., 1988; Kononov, 1989), both the Komandorsky Islands and Eastern Peninsules tectonic zones originally occupied a position more to the south in relation to the present-day Aleutians and were later translated to the northwest. This translation ceased in Miocene time. The trajectory of movement depends on their belonging either to the Pacific or Kula plates. If we use the kinematics of the Pacific plate ([Kononov, 1989; Lonsdale, 1988), it can be estimated that the Eocene rocks studied had been accumulated on the Pacific plate near to a point with coordinates 38°N, 186°E. Within the error limits, this agrees with the paleomagnetic data (Table 4). The kinematics of the Kronotsky–Komandorsky Island arc (*KKA*) from the Paleocene to the Miocene are shown on Fig. 9.

The formation of the island arc complex most probably took place at the boundary between the NAP and Pacific plate (Fig. 9). The active KKA moved northward prior to 42 Ma. At that time, the lithosperic plate pattern in the North Pacific was re-organized: the Kula Ridge became extinct, the direction of the Pacific plate movement changed, and the KKA stopped being active and started moving northwestward. However, it is not quite clear how to explain the sharp knee-like bend of the KKA, and to relate it to the modern kinematics in this region. Presumably, at a certain epoch some northward movement of the Pacific plate might have occurred after the collision of the KKA with the Kamchatka landmass. During this epoch, the Kronotsky Peninsula had been torn apart from the island arc and rotated anticlockwise, while the Kamchatsky Mys Peninsula and Komandorsky Islands had been incorporated into the Aleutians. The deep-sea trench in front of the Komandorsky Islands and some traces of the island-arc volcanism beyond them may be regarded as evidence that the Pliocene–Quaternary kinematics were somewhat different from the modern kinematics. This model is rather artificial, and as such is not very satisfying.

So far, paleomagnetic inclinations have been taken at their face value. Below, two models (model 3 and 4) will be discussed in which some shallowing of inclinations is assumed.

Model 3 is based on a hypothesis that KKA had initially been a part of the Kula plate, and was linked to the Aleutian arc near the southern end of the Bowers Ridge (Fig. 10). It is possible to reconstruct the primary structural trend in the western part of the KKA using paleomagnetic declinations and working on the assumption that primary strikes of the Eocene and Oligocene–Miocene zonations had been similar to each other. Taking into account the modern strike of about NE30° and the anticlockwise rotation of the Kronotsky Pns through 67°, the primary trend was directed about SE100°. The modern strike of the Komandorsky part of the arc is about SE130°. If the KKA had initially been rectilinear, then it as a whole had been rotated by about 30° (130–100°) clockwise since the Eocene. The relation of this general rotation to those of each locality is shown in Table 5. The local movements in the west of the KKA have resulted from its oblique collision with the Kamchatka landmass, while the clockwise rotation of Medny Island is connected with the dextral strike-slip fault directed along Komandorsky Island.

The general rotation could be compensated both by subduction of oceanic crust beneath the Shirshov Ridge and by its thrusting and piling-up at the Bowers Ridge. Thus, it is assumed that an independent Komandorsky plate had existed and been rotated since the Eocene; the corresponding

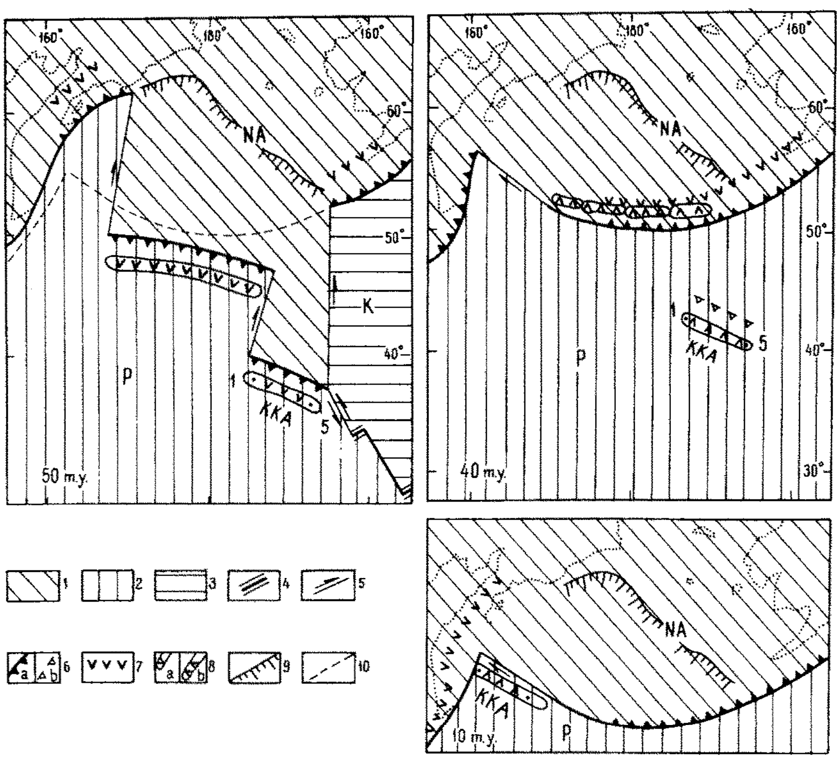

Fig. 9. Kinematics of the Kronotsky–Komandorsky Island arc (*KKA*), after data from Kononov (1989). *1*, *2*, *3* = main lithospheric plates (*1* = North American (*NA*), *2* = Pacific (*P*), *3* = Kula (*K*); *4*, *5*, *6* = plate boundaries (*4* = divergent, *5* = transform, *6* = convergent (*a* = active, *b* = extinct)); *7* = active volcanic zone; *8* = island arcs (*a* = active, *b* = extinct); *9* = passive oceanic margins; *10* = modern deep-sea troughs. Numbers *1* and *5* on the figures are paleomagnetic localities.

TABLE 5

Post-Eocene deformation of the Kronotsky—Komandorsky island arc, as deduced from paleomagnetic data (model 3)

Locality	D°_m	D°_r	R°	R°_i	R°_b
1	302	9	−67	30	−97
3	18	8	10	30	−20
5	76	6	70	30	40

D—declination (subscripts m and r denote measured and reference values, respectively); *R*—total rotation of paleomagnetic vector as the sum of Island arc rotation (R_i) and rotation of a separate block (R_b). A positive (negative) sign represents clockwise (anticlockwise) rotation.

Eulerian pole should be placed at the Aleutian arc–Bowers Ridge junction (Fig. 10). The strike-slip component of movement prevailed along the Kamchatka–Komandorsky plate boundary, while underthrusting of a generally lesser magnitude increased from north to south. This stipulated the northward decrease of the Oligocene–Early Miocene volcanic activity at Kamchatka. By the Eocene–Oligocene boundary, volcanic activity in the Kronotsky Peninsula ceased. Presumably, by this time the linear velocity of the Komandorsky plate in relation to Kamchatka became equal to that of the Pacific plate. Eastward, near to the Komandorsky and Near Islands, such a change in volcanic activity did not take place. As this area was nearer to the Eulerian pole, the linear velocity of the microplate was lower, and subduction of the Pacific plate continued here.

The rotation of the Komandorsky plate, subduction under the Shirshov Ridge and thrusting at the Bowers Ridge went on during the Miocene. The Miocene andesite volcanism of the Shirshov Ridge (Scholl et al, 1975) provides evidence for such subduction. The oblique collision of the western KKA with the Kamchatka landmass

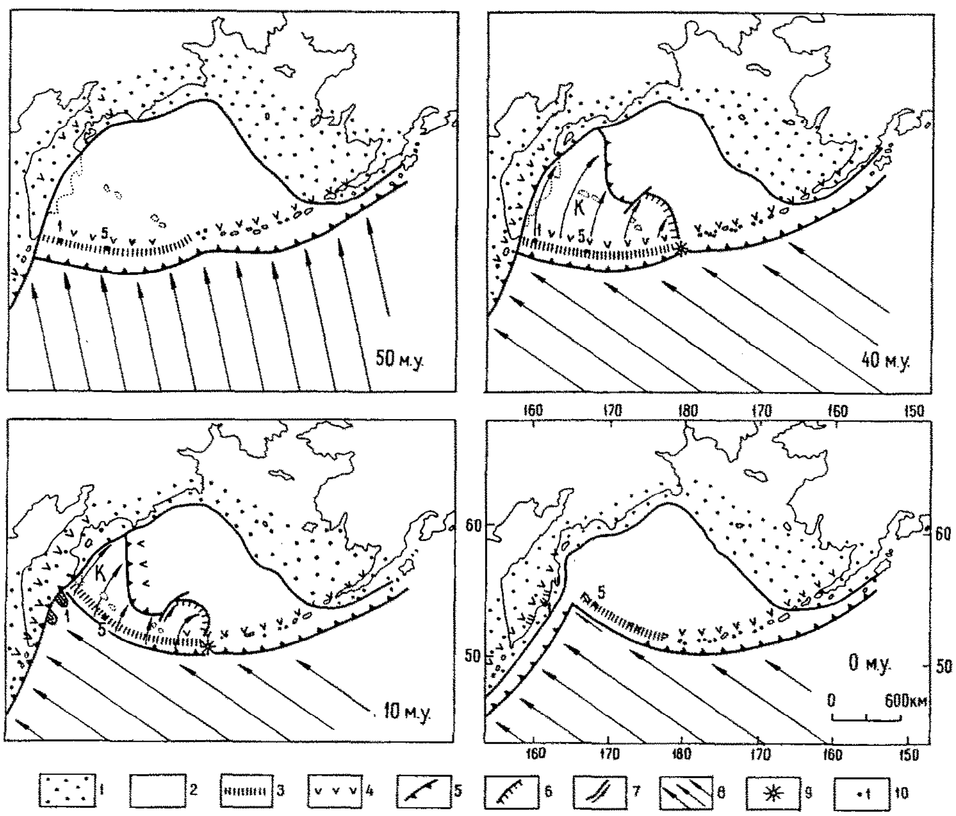

Fig. 10. Kinematic schemes with the Komandorsky plates (*K*). *1* = Continental crust; *2* = oceanic crust; *3* = the Kronotsky–Komandorsky Island arc and its fragments; *4* = active island-arc volcanism; *5* = subduction zones; *6* = zones of thrusting and piling-up of oceanic crust; *7* = strike-slip faults; *8* = direction of movement of the Pacific plate in relation to North America; *9* = Eulerian pole of the Komandorsky plate.

started by this time, and led to its rupture into a number of terranes. Having been welded to Kamchatka, these terranes then rotated anticlockwise and led to deformation of flysch sequences on the continental slope. This model agrees with the modern geomorphology, because the Eastern Peninsula is now separated by bays of considerable depth. The rotation of the Komandorsky microplate continual until the eastern segment of the KKA had been aligned parallel to the direction of the Pacific plate movement. After that, the subduction under the microplate ceased and it became a part of the NAP (Fig. 10). This model seems to be successful in explaining many data of different types. However, some characteristics of this model, namely, an assumption about a certain partial shallowing of inclinations, the very existence of the Komandorsky plate and its kinematics, are ad hoc hypotheses and have not been confirmed independently.

In model 4, no northward movement is assumed and inclination data are not taken into account, the difference between measured and reference values thus being attributed to shallowing. Declination anomalies are correlated with independent local rotations. In particular, the clockwise rotation of Medny Island appears to be a logical way in which to explain the dextral strike-slip motion of the Pacific plate along the western Aleutians. This rotation must have occurred before folding, i.e. during the Oligocene or Miocene: otherwise, tectonic structures here would have been oriented cross-arc, which is unlikely. Rotations of the Eastern Peninsulas could be stipulated by a sinistral strike-slip at any other time interval.

Conclusions

Paleomagnetic investigations have been carried out on Paleogene rocks from three localities in Eastern Kamchatka and two localities on the Komandorsky Islands. With the aid of stepwise thermocleaning, consistent paleomagnetic directions were obtained for all localities sampled. With the exception of data from the trachydolerite extrusion (locality 4), all of the other results were considered suitable for tectonic interpretation. However, the main body of data were obtained on sedimentary rocks, where a certain shallowing of inclinations may be present. No method of estimating such an effect was found, and therefore the paleolatitudes obtained may be biased. Thus, the most crucial question to be answered is the reliable determination of paleolatitudes.

The very diversity of tectonic models described in the previous section proves that we failed to invent any unique interpretation fully compatible with the paleomagnetic, kinematic and geological data. Moreover, the authors themselves could not reach an agreement as to which model to prefer. As we see it, the way to resolve these problems is to obtain paleomagnetic data from the western part of the Aleutians and the Kamchatka inland tectonic zones.

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