New Paleomagnetic Data From the Central Aleutian Arc: Evidence and Implications for Block Rotations

Lena Krutikov

Department of Geology and Geophysics, University of Alaska, Fairbanks, Alaska, USA

David B. Stone

Geophysical Institute, University of Alaska, Fairbanks, Alaska, USA

Pavel Minyuk

Northeast Interdisciplinary Research Institute, Magadan, Russia

Early paleomagnetic measurements (late 1960s and early 1970s) from the central Aleutian Island Arc produced both scattered and internally consistent results based solely on alternating field demagnetization. Archived core samples collected from Amchitka and Adak islands for these previous paleomagnetic studies were reanalyzed for this study using modern thermal demagnetization techniques. The new measurements from Amchitka Island indicate significant clockwise rotation ($R = 54.7 \pm 8.0°$) between 14 Ma and the present. Adak Island showed no rotation for volcanic rocks of Quaternary age associated with the present volcanic arc, which is consistent with the lack of rotation seen in other young volcanic rocks (<2 Ma) sampled at localities from Unalaska Island in the east to Kanaga Island in the west. The Eocene Andrew Lake Formation shows a clear magnetic overprint that completely masks any information about possible rotations. Other published studies show rotations similar to those seen for Amchitka Island on Umnak, Amlia, Bering, and Medny islands. Models predicting clockwise rotations involve breaking the forearc into discrete blocks and slivers that rotate and/or travel westward along the curve of the arc in response to the arc-parallel component of the Pacific Plate motion. These models have difficulty explaining the large rotations seen in the easternmost islands sampled, where the relative motion of the Pacific Plate is more or less perpendicular to the arc. The data are insufficient to resolve the mechanism involved in rotations, but it seems likely that any or all of the possible mechanisms could have played a role.

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1. INTRODUCTION

The Aleutian Arc is an intraoceanic arc, where the obliquity of subduction increases to the west (Figure 1). Relative motion between North America and the Bering Block is small, thus present-day motion of the Pacific plate relative to the North American plate is a good approximation for the Aleutian Arc–Pacific plate interaction. Changes along the length of the arc vary from normal convergence in the east through oblique motion to essentially arc-parallel motion in the west. *Geist et al*. [1988] postulated that strain partitioning could result in tectonic segmentation of the lithosphere, caused by increasing obliquity of plate convergence and characterized by clockwise rotation and westward translation of discrete blocks in the Aleutian forearc (Figure 1). Their analysis of the present-day morphology and tectonic location of the arc, and particularly the 5- to 10-Ma-old summit basins, suggests the presence of rotated blocks, and implies that the rotation is ongoing. Subsequent geologic and geophysical investigations yield some data to support this model, but the paucity of such data makes it difficult to constrain the dynamics and kinematics of forearc deformation.

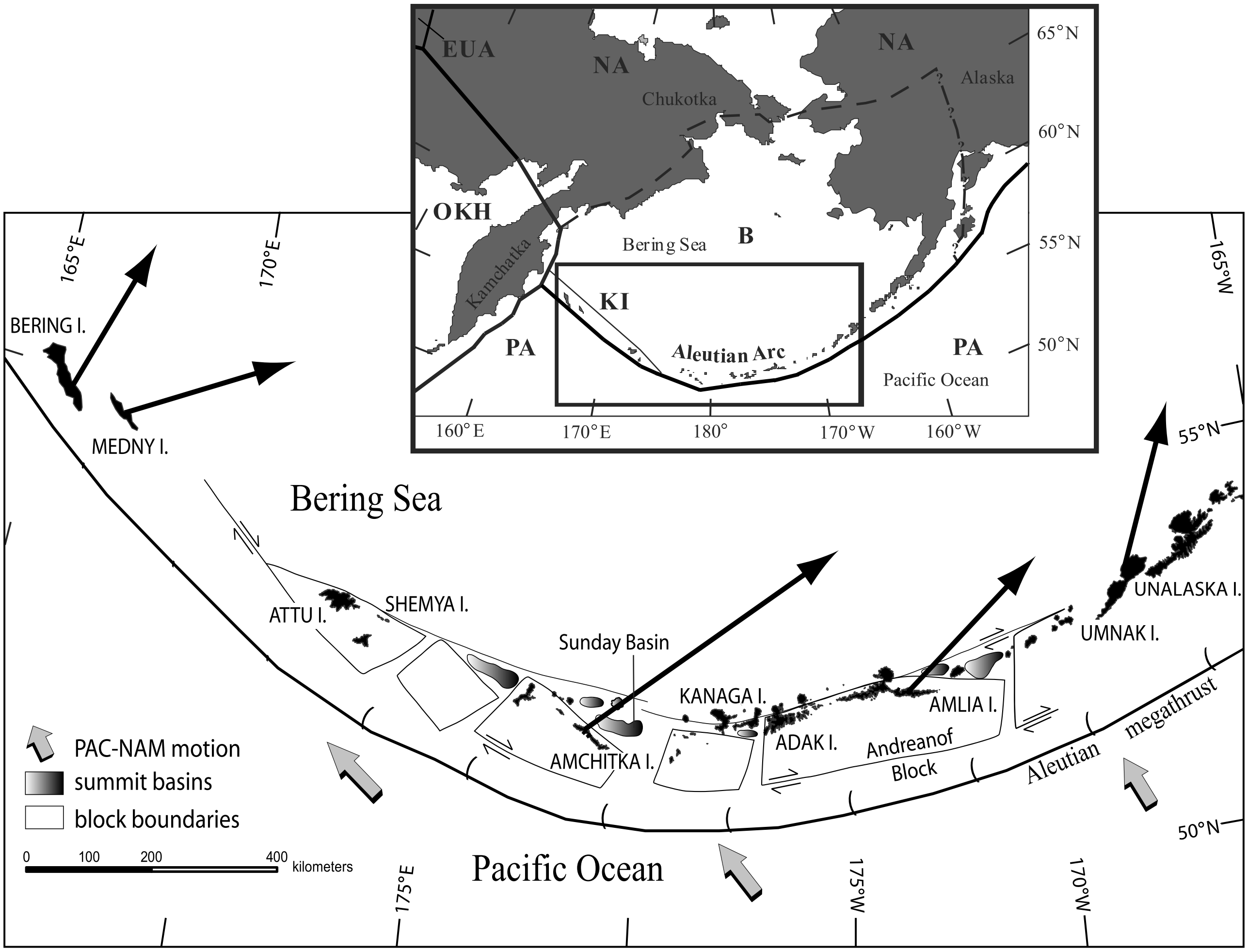

Figure 1. Location map for the Aleutian Islands. The outline blocks and shaded summit basins are from *Geist et al.* [1988], showing a possible rotation mechanism. The heavy arrows show the mean rotations with respect to North America indicated by paleomagnetic data, the lighter arrows the motion of the Pacific plate with respect to North America. (inset) General location map modified from *Chapman and Solomon* [1976], *Mackey et al.* [1997], and *Pedoja et al.* [2006]. Solid lines show boundaries of plates and blocks: NA, North American Plate; B, Bering Block; PA, Pacific Plate; OKH, Okhotsk Plate; KI, Komandorsky Island Block; EUA, Eurasian Plate.

1.1. Tectonic Evolution

It is widely believed that the Aleutian Arc originated in the early Tertiary period, although the precise date has come under considerable debate. It had been assumed that the Aleutian Arc initiated in 55–50 Ma [*Scholl et al*., 1987]. This was based on a poorly constrained ^{40}Ar/^{39}Ar date of 55–50 Ma for a basalt sample from Adak Island [*Jicha et al*., 2006] and was thought to be associated with extensive volcanism and magmatic growth, possibly associated with a change in Pacific–Farallon plate motion ~49–53 Ma [*Norton*, 1995]. However, recent dating of the oldest-known material sampled from the Aleutian Arc, from Murray Canyon, yielded an ^{40}Ar/^{39}Ar isochron age of 46.3 ± 0.9 Ma [*Jicha et al.*, 2006], which constrains arc magmatism to at least the last 47 Ma.

Increased obliquity of subduction and decreased magma generation have been linked to a change in Pacific plate motion at 47 Ma, as recorded by the bend in the Hawaiian–Emperor Seamount chain [*Jicha et al*., 2006]. This has now been challenged by data from deep-sea drilling cores strongly suggesting that the Emperor Seamount Chain is the result of motion of the hot spot in addition to the Pacific plate motion [*Tarduno et al.*, 2003]. There is also little evidence from marine magnetic anomalies to confirm a change in Pacific plate motion at that time [*Norton*, 1995]. Regional subsidence and extensional deformation of the Aleutian platform, as well as an acceleration in block-style deformation of the Aleutian forearc, have been attributed to another shift in Pacific plate motion in the late Cenozoic at ~5 Ma [e.g., *Harbert et al*., 1986; *Scholl et al*., 1987].

Structural evolution of the Aleutian forearc is poorly understood, since it is difficult to constrain rates and geometry of slip, because extensive deformation and erosion have obscured much of the geologic history and because there is such a scarcity of both subaerial rock exposure and submarine data.

2. PREVIOUS WORK

Early paleomagnetic studies on the Aleutian Arc yielded somewhat ambiguous results. In general, paleomagnetic data from the Aleutian Islands have been considered too sparse to contribute significantly to a model of the arc's tectonic history. However, most of these earlier paleomagnetic data indicate little or no displacement of the Aleutian Arc with respect to North America. A review of all available paleomagnetic data from the arc indicates that only a few high-quality paleomagnetic studies exist (Table 1). Work completed in the 1980s found significant clockwise rotations in Eocene and Lower Oligocene sedimentary rocks on Umnak and Amlia islands [*Harbert*, 1987]. More recent data from the Komandorsky islands showed evidence of large clockwise rotations in Middle and Upper Eocene rocks on Medny Island [*Bazhenov et al*., 1992]. *Minyuk* [2004] found a similar rotation on Bering Island. In contrast to these measurements, samples from the present volcanic arc (also collected on the 1970s) have been remeasured and show no rotations over the last 2 Ma [*Stone and Layer*, 2006]. The young volcanic rocks sampled come from Unalaska (DFB), Umnak (CCR, NJC, ASH), and Kanaga (RDH, KAN). The original data were published by *Bingham and Stone* [1972]. One other data set of interest is from Shemya Island [*Stone*, 1975]. This study is also from the 1960s, and shows evidence of little or no rotation.

In contrast to the clockwise rotations found in the Aleutian Arc, it is notable that data from southwest Alaska, behind the arc, give counterclockwise rotations. These were determined for volcanic sequences that erupted before the formation of the present arc [*Coe et al*., 1985; *Thrupp and Coe*, 1986].

For this study, we elected to measure archived samples selected from paleomagnetic core samples from Amchitka [*Stone*, 1972] and Adak [*Cameron and Stone*, 1970] islands. These were originally collected and measured at the University of Alaska at Fairbanks (UAF) paleomagnetic laboratory in the 1960s. The results presented here are from samples remeasured with modern equipment and protocols.

3. PALEOMAGNETIC STUDIES

3.1. Sample Selection

Samples for remeasurement were selected from unmeasured slices of cores that were collected on Adak and Amchitka islands (Figure 1) in 1967 and 1968 [*Cameron and Stone*, 1970; *Stone*, 1972]. Samples chosen from Adak Island were taken from the Adagdak volcanics (<500 ka), which form part of the active volcanic arc, and from the Andrew Lake Formation (late Eocene) [*Scholl et al*., 1970]. Andrew Lake Formation was selected for remeasurement because of its close association with the underlying Finger Bay Volcanics, which appear to represent the oldest magmatic event in the whole arc.

Amchitka Island samples were chosen from the Chitka Point Formation, based on their age of 14 Ma [*Carr et al*., 1970; Layer, personal communication, 2006] intermediate between the Andrew Lake formation and the Quaternary volcanics, and the fact that original measurements showed a reasonable grouping of the magnetic vector directions. Amchitka Island was an obvious choice for the current study as well, because it is located within the boundaries of the rotating Rat Island block proposed by *Geist et al*. [1988].

Table 1. Paleomagnetic Vector Directions for Samples From the Aleutian Islands

Island	Approximate Location (Lat., Long.)	Rock Type	Age	Dating Method	*N*	*D*	*I*	*k*
Unalaska	53.97, 193.27	Driftwood Bay, volcanic flows DFB	400–800 ka	Ar/Ar	11 F	1.4	68.4	95.8
Umnak	53.53, 193.27	Ashishik volcanic flows ASH	1.9 Ma	Ar/Ar	6 F	196.3	-81.3	14.5
	53.53, 191.92	New Jersey Creek volcanic flows NJC	1.9 Ma	Ar/Ar	10 F	342.5	66.9	247.0
	53.47, 191.92	Crater Creek volcanic flows CCR	50(?) ka	Ar/Ar	11 F	356.2	68.7	71.5
	52.92, 191.97	Starr Pt., Driftwood Bay sediments	~35 Ma	Microfossils	29 Sm	35.4	72.3	42.2
Amlia	52.10, 186.08	Sediments	~35 Ma	Microfossils, K–Ar	9 Sm	37.7	74.3	60.5
Adak	51.96, 183.4	Adagdak and Andrew volcanics combined	<500 ka	K–Ar, Geomorphology and setting	61 Sm	352.2	69.7	31.6
	51.95, 183.4	Adagdak volcanics ADK	<500 ka	K–Ar	11 F	10.0	71.3	95.2
Kanaga	51.9, 182.95	Round Head volcanics RDH	120 ka	Ar/Ar	8 F	7.5	71.7	379.8
	51.9, 182.9	Mt. Kanaton volcanics KAN	200 ka	Ar/Ar	5 F	355.5	65.7	298.9
Amchitka	51.5, 179.2	Banjo Point volcanics	35 Ma	As below	8 Sm	23.0	49.0	8.0
	51.6, 178.75	Chitka Point volcanics	14 Ma	Forams, spores, and K–Ar [*Carr et al.*, 1969]	19 Sm	39.7	59.3	17.8
	51.6, 178.75	Chitka Point volcanics	14 Ma	Forams, spores, and K–Ar [*Carr et al.*, 1969]	19 Sm	52.3	67.3	85.4
Shemya	52.73, 174.13	Intrusives, samples	12 Ma	K–Ar	56 Sm	13.1	80.6	39.8
		Intrusives, sites	12 Ma	K–Ar	7 Ste	11.2	78.8	146.8
Medny	57.2, 167.52	Komandorsky	38–54 Ma	Forams, mollusks, and flora	10 Ste	73.0	66.0	12.0
	57.2, 167.52	Medny Fm. basalts	34(?) Ma	K–Ar	40 Sm	76.0	62.0	15.0
Bering	57.2, 166.56	Sediments	38–54 Ma	Fossils and magnetostratigraphy	11 Ste	26.0	67.5	139.1

Table 1. (continued)

Island	α_{95}	Displacement	*dP*	Rotation	*dR*	Demag	Reference
Unalaska	3.9	−1.5	5.1	+1.6	8.5	AF + T	*Stone and Layer* [2006]
Umnak	18.2	21.9	4.3	+21.8	16.1	AF + T	*Stone and Layer* [2006]
	3.1	1.4	4.0	−6.1	6.9	AF + T	*Stone and Layer* [2006]
	5.4	1.1	7.0	−3.3	12.0	AF + T	*Stone and Layer* [2006]
	4.0	0.3	5.4	+32.8	12.0	AF + T	*Harbert* [1987]
Amlia	6.0	2.7	12.3	+49.5	28.9	AF + T	*Harbert* [1987]
Adak	3.3	1.6	4.9	±7.8	8.2	AF	*Cameron* [1970], *Cameron and Stone* [1970]
	4.7	3.2	6.2	−10.7	10.9	AF + T	This study
Kanaga	2.9	3.0	3.7	+7.9	6.4	AF + T	*Bingham and Stone* [1972], *Stone and Layer* [2006]
	4.4	−3.5	5.7	−4.6	8.7	AF + T	*Bingham and Stone* [1972], *Stone and Layer* [2006]
Amchitka	17.0	−28.3	17.1	+29.7	20.8	AF	*Stone* [1972]
	8.2	−17.2	8.8	+42.2	11.9	AF at 200 Oe	*Stone* [1972]
	4.1	−7.0	4.9	+54.7	8.0	AF + T	This study
Shemya	3.1	13.0	5.2	+14.4	15.6	AF	*Cameron and Stone* [1970], *Stone* [1975]
	5.0	10.2	7.6	+12.9	21.0	AF	*Cameron and Stone* [1970], *Stone* [1975]
Medny	12.9	−21.3	7.2	+65.0	11.3	AF + T	*Bazhenov et al.* [1992]
	5.7	−22.5	6.1	+73.0	9.8	AF + T	*Bazhenov et al.* [1992]
Bering	3.9	−16.2	5.4	+20.9	9.1	AF + T	*Minyuk* [2004]

N = the number of: volcanic flows F, samples Sm or sites Ste, used to calculate mean paleomagnetic vector direction; D = mean declination, I = mean inclination in selected coordinates; k = Fisher precision parameter [Fisher, 1963]; α_{95} = radius of circle of confidence at 95% level; Displacement = latitudinal difference between observed paleolatitude and that expected if fixed with respect to N. America, *dP*, the related error bar; Rotation = rotation with respect to N. America with related error bar, *dR*; Demagnetization method, AF = alternating magnetic field, T = thermal.

3.2. Sample Collection

Samples were collected with nonmagnetic core barrels tipped with diamond in phosphor-bronze cutting edges. Orientations in the field were determined by using a combination of map bearings, a sun compass, and a magnetic compass. The 2.4-cm-diameter cores were sliced into 2-cm-tall right cylinders. Each cylindrical core sample was originally sliced into three specimens—a, b, c—from the surface down, respectively. Specimen b had been used for most of the original measurements. For this study, we used specimen c whenever possible to minimize the effects of surface weathering. In a few cases where specimen c was not available, specimen a was measured.

3.3. Demagnetization Techniques

The original or primary magnetization of rock samples, acquired at the time of cooling in igneous rocks or dewatering or cementing in sediments, is often overprinted by later magnetizations. To erase overprinted magnetizations and isolate the original magnetization, samples must be demagnetized, or "cleaned." The two most common methods for cleaning a sample are alternating field (AF) demagnetization and thermal demagnetization.

AF demagnetization destroys the alignment of less stable magnetic domains by subjecting them to successively stronger AFs that are then slowly reduced to zero while the sample remains in a zero field environment. This randomizes the magnetization of the magnetic material susceptible to the peak field applied. Demagnetizing the samples by applying successively higher peak AFs allows the magnetization carried by minerals with various magnetic stabilities to be determined. This is intended to demagnetize the sample until only the characteristic, or most stable, component of magnetization remains.

Thermal demagnetization involves heating samples to a given temperature and cooling them in a zero magnetic field environment. This enables the removal of magnetizations carried by successively higher blocking temperatures. Samples from the Aleutian Islands may well have been heated after formation, since proximal plutons and volcanic activity are common. Provided the heating was insufficient to completely remagnetize the sample, thermal demagnetization will commonly remove less stable magnetic overprints and systematically remove magnetizations carried by minerals with low blocking temperatures, thereby revealing the magnetization acquired at the time of origin in igneous rocks. Demagnetization behavior can be tracked between heating steps so that the temperature increment can be adjusted accordingly. Previous paleomagnetic studies were conducted using AF demagnetization alone; thus, remeasuring available samples with thermal demagnetization steps can produce significantly better estimates of the original magnetization.

3.4. Instrumentation

Instruments and equipment used for this study are located in the Paleomagnetic Laboratory at the UAF. A 2-G Enterprises superconducting cryogenic magnetometer, Schonstedt thermal demagnetizer (model TSD-1) and Schonstedt AF demagnetizer (model GSD-1) are housed in a Lodestar Magnetics shielded room, which blocks about 99% of the ambient field and reduces the internal field to between 200 and 800 nT. Nested magnetic shields around the thermal and AF demagnetizers reduce the field within these instruments to near zero.

3.5. Measurement Protocols

A total of 105 specimens from oriented core samples were remeasured. Each sample was first demagnetized in a 400-Hz AF of 2 Am^{-1} at a decay rate of 4 mAm^{-1}/cycle to remove any magnetization acquired during storage. Complete thermal demagnetization protocols were then applied to the samples, which were incrementally heated beginning at 150°–200°C through 575°–600°C. Heating steps were conducted at 50°C increments for temperatures below 300°–350°C, and at 25°C increments at higher temperatures. Magnetic susceptibility of all specimens was measured before and after each heating step to monitor whether the most recent heating step had altered the magnetic minerals present.

3.6. Data Analysis

Demagnetization results from each specimen were plotted on an orthogonal vector diagram [*Zijderveld*, 1967] to determine the characteristic magnetization direction (e.g., Figure 2). By applying principal component analysis [*Kirschvink*, 1980] to the demagnetization results, a least-squares line was fit to straight segments of the demagnetization curve. Line fits that trend to the origin give the characteristic magnetization of the specimen, which can then be tested with fold and reversal tests to see if they represent the original magnetization. In determining a best-fit line to the demagnetization curve, secondary components of magnetization (usually lower temperature components) were recorded separately.

Samples showing significant increases in magnetic intensities and susceptibilities at high demagnetization temperatures, usually indicative of changes in the magnetic minerals, were excluded from the analysis. Error limits for the line fits were represented by the maximum angular deviation. Strike and dip measurements and other archived field observations were used to convert the paleomagnetic vector from specimen coordinates to a geographic reference frame of present north and horizontal (D_g, I_g), and then to a stratigraphic reference frame using north and ancient horizontal (D_s, I_s). Following the statistical analysis methods developed by *Fisher* [1953], we calculated the precision parameter (k) and the radius (in degrees) of a circle for 95% level of confidence (α_{95}) for the means of the paleomagnetic vectors. From these vector directions the equivalent virtual geomagnetic poles (VGP) are easily calculated. The rotations were calculated using the VGP data and the equivalent reference pole for North America as determined by *Besse and Courtillot* [2003]. The error bars on the rotations were determined using the method of *Demarest* [1983].

3.7. Adak Island Study

Centrally located along the Aleutian Island Arc, Adak Island (~179°E) is a prime location to investigate the deformation history of the arc because much of the island is within the proposed boundaries of the Andreanof block [*Geist et al*., 1988]. The north end of Adak Island, which is ostensibly outside the Andreanof block boundary (Figure 1), is dominated by three young (<500 kA) volcanic centers: Mt. Moffett, Mt. Adagdak, and a subsidiary vent complex known as Mt. Andrew. Selected samples from Mt. Adagdak, referred to here as the Adagdak volcanics, were remeasured for this study.

The rest of the island is mostly mapped as "Finger Bay Volcanics" [*Coats*, 1956], which are part of the Eocene Lower Series seen throughout the arc [e.g., *Vallier et al*., 1994]. A high-precision age of 37.4 ± 0.6 Ma for the Finger Bay volcanics on the southern end of the island was recently obtained using $^{40}Ar/^{39}Ar$ dating [*Jicha et al*., 2006]. Rocks associated with the Finger Bay volcanics, the Andrew Lake Formation [*Scholl et al*., 1970], were sampled for paleomagnetic studies in 1967 and 1968 from the northern edge of the block.

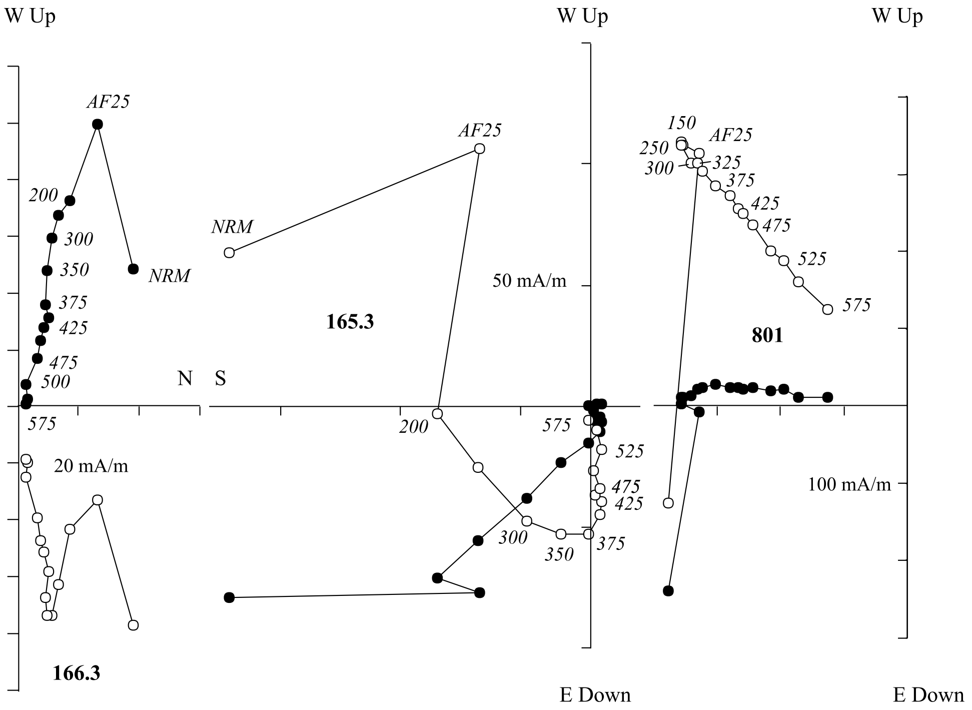

Figure 2. Zidjerveld (orthogonal) demagnetization plots for selected samples. Demagnetization levels include 2.5 mT AF plus multiple levels of thermal demagnetization (°C). The dots represent the declination of the vectors with respect to N–S–E–W (north to the right) and the open circles the inclination as projected onto a N–S plane. Line-fit directions were obtained for the high-temperature results that trend towards the origin. Samples 165 and 166 are from the Finger Bay Formation and show a clear near-vertical secondary magnetization in geographic coordinates. Sample 801 is from the reversely magnetized section in the Chitka Point Formation, also in geographic coordinates.

3.8. Adagdak Volcanics

Adagdak specimens were sampled from horizontal flows of olivine basalt and hornblende-bearing basaltic andesite on the north end of Adak Island [*Cameron and Stone*, 1970]. The Adagdak volcanics are younger than 0.5 Ma, although the exact age has not been determined because they are younger than the limits of resolution of the K–Ar dating technique in use when the samples were first analyzed [*Stone*, 1975].

The original paleomagnetic measurements showed no significant rotation or latitudinal translation [*Cameron and Stone*, 1970] with respect to present-day geographic coordinates. Because the original measurement protocols used single-level "blanket" AF demagnetization, the Adagdak duplicate samples were remeasured using complete thermal and AF protocols. The Adagdak samples were chosen because the early measurements exhibit very stable original magnetization and good grouping of measurements, and thus acted as a control group in comparing new results with original results obtained with previous protocols. Declinations and inclinations from the best line-fit data obtained during this study are listed in Tables 2a and 2b. No regional or local tilting was observed for the Adagdak flows; thus, the measured paleomagnetic vectors do not require a tectonic correction.

Two samples from each of the five flows in the Adagdak volcanics were collected at site 1 (Table 2a). Two well-defined flows, each several meters thick and separated by several meters of sediment, were sampled at site 2 (Table 2a). The paleomagnetic measurements were then combined as flow means for each site and as combined flow means for the whole section (Table 2b). The mean of all samples is also listed in Table 2b. The combined Adagdak volcanic flow means generate a small circle of confidence (Figure 3), which suggests a relatively stable magnetization and a reliable result. The mean paleomagnetic vector for all seven flows includes the present axial dipole within its 95% circle of confidence, indicating no measurable deformation of these rocks since the time of their formation. This new result overlaps the original measurements, and suggests that the other original measurements can be used with confidence.

Table 2a. Paleomagnetic Results for Adagdak Volcanics[a]

Locality	Sample	D_g	I_g	D_s	I_s	MAD	Temp, °C
Site 1 (Lat. 51.95, Long. 183.4), Flows 1–5							
Flow 1	140.3	31.6	70.4	31.6	70.4	1.31	350–575
	141.3	351.4	66.5	351.4	66.5	2.64	250–525
Flow 2	142.3	29.4	80.0	29.4	80.0	0.93	425–575
	143.3	11.0	77.2	11.0	77.2	1.41	350–525
Flow 3	144.3	29.4	77.5	29.4	77.5	0.99	350–500
	145.3	23.7	65.3	23.7	65.3	0.92	375–475
Flow 4	146.3	1.2	71.5	1.2	71.5	1.10	350–525
	147.3	6.8	63.8	6.8	63.8	1.72	350–500
Flow 5	148.3	20.5	74.4	20.5	74.4	0.76	300–550
	149.3	13.8	66.7	13.8	66.7	0.85	350–475
Site 2 (Lat. 51.95, Long. 183.4), Flows 6–7							
Flow 6	150.3	353.5	61.8	353.5	61.8	1.37	350–575
	151.3	351.9	63.1	351.9	63.1	1.00	300–575
	152.3	343.2	59.8	343.2	59.8	1.45	350–525
	153.3	352.1	65.3	352.1	65.3	0.91	350–575
	154.3	342.4	62.4	342.4	62.4	1.38	350–550
	155.3	349.3	60.1	349.3	60.1	1.45	350–550
	157.3	328.2	62.4	328.2	62.4	0.28	475–575
Flow 7	158.3	326.9	63.2	326.9	63.2	0.95	350–575
	159.3	341.3	62.7	341.3	62.7	0.82	350–575

[a]Paleomagnetic directions and associated statistics after thermal demagnetization of samples from the Adagdak volcanics on Adak Island. *Dg*/*Ds*, mean declination in geographic/stratigraphic coordinates; *Ig*/*Is*, mean inclination in geographic/stratigraphic coordinates; MAD, mean angular deviation; temp, the temperature range for the points in the line fit [*Kirschvink*, 1980]. Flows 1 to 7 are in stratigraphic order from top to bottom.

3.9. Finger Bay Volcanics–Andrew Lake Formation

The Finger Bay volcanics consist of metabasalts, lithic tuff breccia, palagonitic tuff breccia, as well as rhyodacite, andesite, and andesitic basalt flows. Three localities were sampled near Andrew Lake at the north end of Adak Island [*Cameron and Stone*, 1970]. At the time of sampling these units were labeled as Finger Bay Volcanics, but later redefined as the Andrew Lake Formation [*Scholl et al.*, 1970]. Since that time the upper and lower boundaries of the Andrew Lake Formation have been modified [*Hein and MccLean*, 1980]. All of the samples collected were within the Andrew Lake Formation, which overlies the true Finger Bay volcanics. These sediments represent deposition in a marine environment with probable water depths between 200 and 500 m, and the section is cut by numerous dikes and sills [*Hein and McLean*, 1980]. The age of the sediments, based on numerous microfossils, is late Eocene [*Scholl et al.*, 1970]. A K–Ar age of 14.4 ± 3.5 Ma was determined from fresh plagioclase from a sill within the section. Original paleomagnetic results for the Andrew Bay Formation were very scattered [*Cameron*, 1970; *Cameron and Stone*, 1970]. Because the original study only used blanket AF demagnetization, duplicate samples of the Andrew Lake Formation were remeasured.

Table 2b. Means for Paleomagnetic Results for the Adagdak Volcanics[a]

ADK	D_{mean}	I_{mean}	N	k	R	α_{95}	VGP_{Lat}	VGP_{Long}	d_m	d_p
Flows 1–7	0.9	70	7	73.06	6.92	7.1	87.9	198.2	12.2	10.5
Flows 1–5	14.3	71.7	5	265.2	4.98	4.7	80.5	239.1	8.3	7.3
Flows 6–7	337.7	62.5	2	127.43	1.99	22.2	73.1	73.6	34.7	27.1
All samples	353.7	68	20	58.88	19.68	4.30	86.0	83.1	7.2	6.1

[a] *N*, number of flows or samples; *k*, Fisher precision parameter; *R*, the vector sum of N unit vectors; α_{95} = radius of circle of confidence at 95% level for *D* and *I*; VGP_{Lat}, VGP_{Long}, coordinates of VGP; d_m, d_p, and N–S and E–W 95% error bars (in degrees).

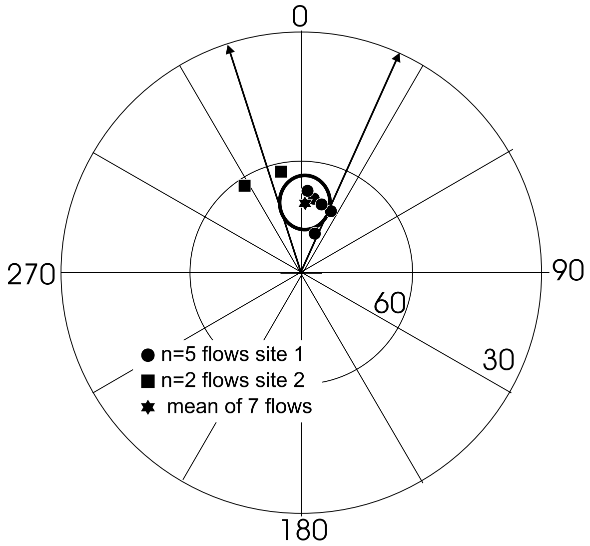

Figure 3. Paleomagnetic vector directions for seven flows from two locations on Adagdak volcano. The final mean direction (star) and α_{95} circle of confidence is based on flow means from five sequential flows plus the mean for two flows from site 2. The arrows are tangential to the α_{95} circle of confidence about the overall mean, thus indicating the overall declination range. Note the 30–90° inclination scale.

New measurements of the Andrew Lake Formation show that the characteristic magnetization is highly contaminated by an overprint, and we were not able to isolate the characteristic magnetization. The samples produce scattered directions of both reversed and normal polarities. The reversed directions are roughly antiparallel to the normal ones in both geographic and stratigraphic coordinates, but overall the directions fail the fold test (k_{geog}/k_{strat} = 1.53). In geographic coordinates, the mean direction is steep and directed southward, which can be interpreted as a result of postmagnetization tilting. Because the Finger Bay samples were collected from outcrops adjacent to two young volcanic centers, Moffett and Adagdak volcanoes, they are prone to both thermal and chemical remagnetization. Thus, the variable magnetization probably reflects the fact that these rocks are highly chemically, physically, and thermally altered. *Hein and McLean* [1980] suggest that the secondary minerals found in the Andrew Lake Formation "reflect a complex history of alteration involving burial diagenesis, migration of hydrothermal solutions associated with granodiorite plutons and local metamorphism caused by intrusion of dikes and sills." The paleomagnetic results from these rocks do not appear to carry any information concerning rotation or translation, and they will not be considered further.

3.10. Amchitka Island

Amchitka Island lies on the southern margin of the Aleutian Arc, just west of the 180° meridian (Figure 4). Three main rock units are identified on Amchitka Island. The oldest is the Amchitka Formation, consisting mainly of pillow lavas and breccias, which are older than 35 Ma [*Carr et al.*, 1970]. The Amchitka Formation is overlain by the Banjo Point Formation, which is dominated by basaltic breccias and minor pillow basalts and sedimentary rocks [*Bath et al.*, 1972]. This is overlain by the youngest of the extrusive rocks, the Chitka Point Formation, which is dominated by hornblende and pyroxene andesite lava flows and breccias with subsidiary sedimentary beds. For the Chitka Point Formation, three K–Ar measurements give an age of 14.1 ± 1.1 Ma [*Carr et al.*, 1970], which is consistent with the mid-Miocene age estimate based on pollen and spores from a coal sample [*Carr et al.*, 1970] and is backed up by a new ^{40}Ar/^{39}Ar age of 13.8 ± 0.2 Ma (Layer, personal communication, 2006).

All three of these units were sampled for paleomagnetic studies in 1967 and 1968. Paleomagnetic results commonly exhibited unacceptable scatter of the magnetic vectors, with the exception of the Chitka Point Formation, which showed signs of good grouping [Stone, 1972]. However, the groupings were not distinct enough to draw any significant conclusions in the original study, so these samples were selected for remeasurement. Samples remeasured for this study were all from the Chitka Point Formation from four locations on Amchitka Island (Figure 4). Samples 24–32 were obtained from near the Atomic Energy drill site Uae3. These are slightly porphyritic altered andesites from a road material quarry (24–27, 31) and adjacent hill (28–30). The exposures were not sufficient to allow investigators to distinguish flow units, but the separation of the sampled areas suggests that at least three flows were cored. Samples were taken at the Bird Cape (samples 800–805) and from andesite lavas with one clear lava–lava boundary; thus, at least two flows were sampled. Samples 821–823 were collected from a small exposure adjacent to the NW road, and it is assumed that only one flow was present. Windy Island samples (829–836) are divided into two groups: 829–834, which are from an apparently disturbed location, and 835–836, from a columnar jointed flow. Because of the sparse information regarding the distribution of flows, the paleomagnetic data from individual core samples have been treated as semi-independent measurements.

3.11. Chitka Point Formation

Results show two groups of clustered vectors: one normal and the other reversely magnetized (Figure 5). Not shown in

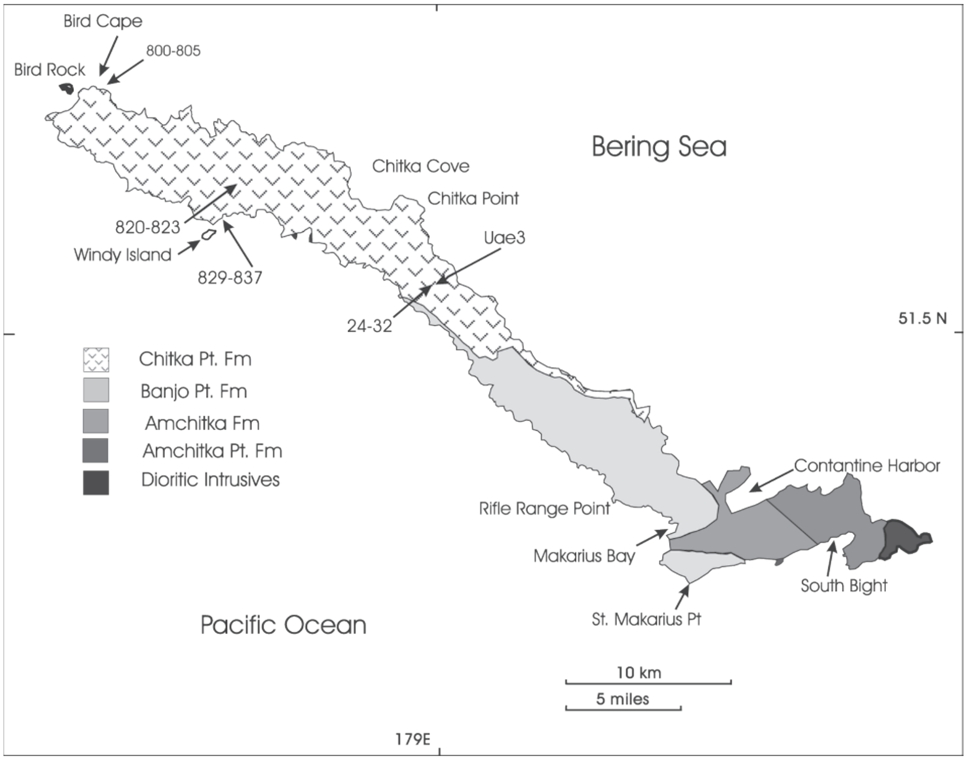

Figure 4. Outline geology of Amchitka Island showing the locations and sample numbers within the Chitka Point Formation (base map from *Bath et al.* [1972]).

this figure is a group of divergent vectors, all from a small area at the Windy Island locality (samples 829–834; Table 3a). Original field notes reveal that surfaces near these samples were interpreted as flow tops and bottoms. The notes also called this interpretation into question since the “flows” had both very steep and internally inconsistent attitudes. This suggests that the local area had been disturbed. Therefore, these discordant measurements were not included in the final means. Sample 32.3 was also omitted due to divergent vectors that were probably measurement or orientation errors.

The remaining 19 samples consist of 3 reversed and 16 normal polarities (Table 3a, b). In geographic coordinates, the reversed samples give very similar directions to the normal polarity samples, with overlapping circles of confidence when inverted through the origin. In stratigraphic coordinates, the reversed and normal vectors are widely separated (Figure 5). In contrast, the dispersion of the combined magnetic vectors increases when they are corrected for the measured tilts of the flows ($k_g/k_s = 2.4$). Normally, this would indicate that they fail the fold test; however, the Chitka Point flows appear to be essentially horizontal over the entire western part of the island. The local attitude measurements almost certainly reflect primary dips that result from lava flowing over varying topography rather than tectonic disruption after emplacement, thus we did not correct for local tilt variations measured in the field.

3.12. Rotation

New paleomagnetic results from the Adagdak volcanics on Adak Island indicate no rotation and corroborate the previous findings of *Cameron and Stone* [1970]. This means that either there has been little or no rotation over the last 0.5 Ma, or any rotation of the Andreanof block has caused little tectonic disturbance north of its boundary. These results are consistent with paleomagnetic measurements from young volcanics along the arc that span the last 2 Ma [*Bingham and Stone*, 1972; *Stone and Layer*, 2006] (Figure 6). Volcanoes on Kanaga and Adak islands show no sign of rotation, which indicates that the northern bounding fault defining the region undergoing transpression is south of the present volcano line. East of the Andreanof block, volcanoes on Unalaska and Umnak islands with ages younger than 2 Ma also show no rotations (Figure 6) [*Stone and Layer*, 2006]. The above

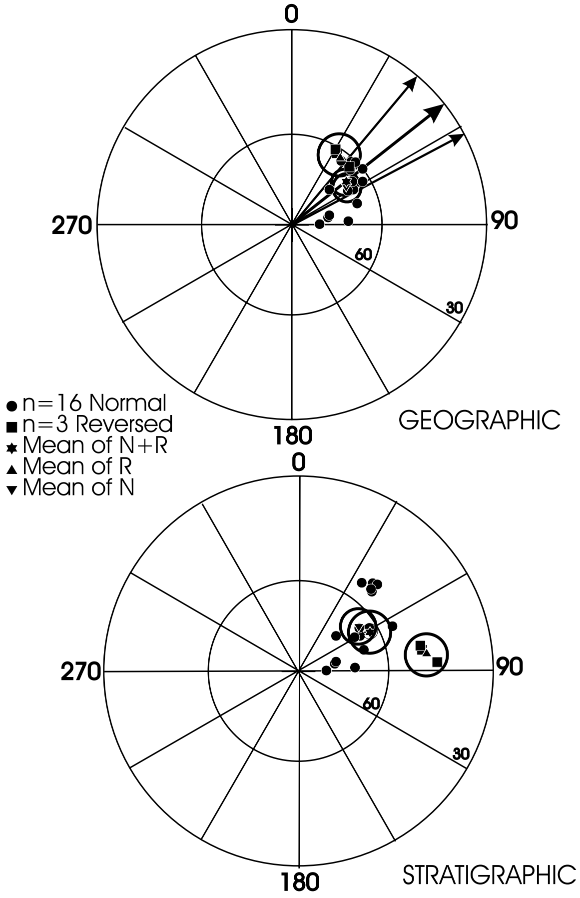

Figure 5. Paleomagnetic vector directions for the Chitka Point Formation. The squares and dots represent the line-fit results from each of the samples. The dots are normal directions and the squares are reversed directions inverted through the origin. The means of the normal, reversed, and combined directions are also shown together with their α_{95} circles of confidence. Data are shown in both geographic and stratigraphic (tilt corrected) coordinates. The increased scatter in stratigraphic coordinates is interpreted in terms of the measured tilts being primary (see text). The arrows tangential to the α_{95} circle of confidence about the overall mean indicate the range of possible declinations. Note the 30–90° inclination scale.

rotations cover a short time span relative to any motions of the geomagnetic poles of the major plates, and are thus calculated with respect to today's axial dipole field. For the older formations described below, the declination is listed with respect to the appropriate paleomagnetic pole for North America for the age of the formation sampled (Table 1). The *Besse and Courtillot* [2003] Apparent Polar Wander path for North America was used to determine the appropriate pole for each formation. This latter rotation describes the vertical axis rotation relative to North America needed to explain the observed declination.

In contrast to the data for the 2 Ma and younger volcanoes described above, the new paleomagnetic measurements from Amchitka Island not only confirm clockwise rotation, but indicate a much greater rotation than was estimated in previous studies (~+20°) and with smaller error (55 ± 9°; Figures 1 and 5). Existing data from other parts of the arc also indicate substantial clockwise rotations. Paleomagnetic measurements of Oligocene/Eocene-aged rocks from the eastern arc show clockwise rotations of 33 ± 12° for Umnak and 50 ± 30° for Amlia Island [*Harbert*, 1987]. Shemya Island, located on the Near Island Block in the far western part of the arc, exhibits paleomagnetic directions that indicate no rotation within the error limits [*Stone*, 1975]. This result appears to be anomalous in both rotation and paleolatitude, and a review of the original field data shows that the assumption that the rocks were flat-lying is poorly constrained. Therefore, these data have not been included in our final analysis.

From the Komandorsky Island Block, paleomagnetic data from Medny Island yield a clockwise rotation of 70 ± 12° [*Bazhenov et al*., 1992], and those from Bering Island give a clockwise rotation of 26 ± 9° [*Minyuk*, 2004].

3.13. Translation

Some of the clockwise rotations observed in the paleomagnetic data can be explained by westward translation along the curved Pacific–Aleutian (North American) plate boundary. According to *Avé Lallement* [1996] and *Avé Lallement and Oldow* [2000], the westward migration of Attu Island from a location near the present-day central Aleutians can account for about 50° of clockwise rotation, which is consistent with paleomagnetic observations from the Komandorsky Islands to the west [*Bazhenov et al*., 1992; *Minyuk*, 2004].

Westward translation along the curved Aleutian Arc would also be recorded as a change in latitude indicated by the inclination of the paleomagnetic vector. *Harbert* [1987] found no statistically significant latitudinal translation of the eastern Aleutian Arc with respect to the North American plate. This conclusion is supported by results from Umnak, Amlia, and Amchitka, which all show no latitudinal motion within their error bars.

In the case of Amchitka, westward translation of the island along the arc would show little or no clockwise rotation owing to the curvature of the arc. Therefore, the majority of the measured 55 ± 9° of Amchitka Island rotation can be attributed to the clockwise rotation of a discrete block as suggested by *Geist et al*. [1988]. However, the rotation indicated by Sunday Basin, an extensional feature northeast

Table 3a. Paleomagnetic Results for the Chitka Point Formation Measured in 2006[a]

Locality	Sample	D_g	I_g	D_s	I_s	MAD	Temp, ºC
UAe-3	24.3	47.18	72.73	47.18	72.73	1.61	300–450
Lat. 51.54	25.3	78.60	77.53	78.60	77.53	3.28	300–450
Long. 179.01	26.3	76.01	76.92	76.01	76.92	1.64	300–500
	27.3	89.44	80.58	89.44	80.58	2.77	300–500
	28.3	72.04	66.98	72.04	66.98	0.61	300–450
	29.3	60.15	66.28	60.15	66.28	2.56	300–400
	30.3	59.02	68.04	59.02	68.04	3.44	300–500
	31.3	86.55	70.87	86.55	70.87	1.96	300–450
Bird Cape	800	45.22	62.81	41.57	54.09	1.21	150–575
Lat. 51.66	801	43.26	61.22	40.22	52.44	0.59	325–550
Long. 178.66	802	52.00	60.10	64.56	55.67	1.50	300–575
	803	46.85	63.21	42.78	54.54	1.29	150–575
	804	45.71	60.35	42.25	51.65	1.12	300–550
	805	37.65	63.20	35.67	54.28	1.46	350–550
NW Road	821R	32.34	62.03	80.25	49.20	1.15	150–575
Lat. 51.60	822R	44.70	62.94	86.36	45.19	0.99	150–575
Long. 178.77	823R	30.29	61.14	78.29	49.52	1.14	150–575
Windy	835	58.66	62.44	58.66	62.44	1.08	150–575
Columnar	836	54.79	65.10	54.79	65.10	1.80	150–575
Windy	*829*	*152.39*	*46.99*	*123.53*	*57.58*	*0.82*	*200–600*
disrupted units[b]	*830*	*173.13*	*41.50*	*153.96*	*60.40*	*0.95*	*325–475*
Lat. 51.57	*831R*	*273.52*	*47.37*	*301.28*	*49.82*	*3.37*	*300–500*
Long. 178.73	*832*	*219.04*	*52.98*	*242.20*	*74.74*	*0.78*	*300–500*
	833	*263.70*	*48.62*	*293.96*	*54.79*	*1.18*	*375–575*
	834	*227.68*	*61.28*	*281.11*	*78.17*	*1.43*	*300–525*

[a] Paleomagnetic directions, mean paleomagnetic vector, and associated statistics after thermal demagnetization of samples from the Chitka Point Formation on Amchitka Island. R designates reversed magnetization (see Figure 2a for further explanation).

[b] Disrupted units in italics are not included in means.

of Amchitka Island, can only account for <20°; thus, earlier rotations must have involved other mechanisms or block geometries (Figure 1).

In contrast, Bering Island shows significant northward motion (16.6 ± 5.4°), which is compatible with, but greater than, the displacement from the present latitude of Amchitka Island. The rotation measured at Amchitka is far greater than that measured in older rocks on Bering Island [*Minyuk*, 2004]. This suggests that the latitudinal transport of Bering Island was accomplished at least in part by lateral migration along the arc rather than by block rotation. In this scenario, the lateral migration of Bering Island was initiated by the arc-parallel component of strain and facilitated by the arc-parallel Beringia and Steller strike-slip fault systems. The angle around the section of the arc from Amchitka to the strike-slip faults is approximately 30°, which is consistent with the rate of rotation (26 ± 9°) measured for Bering Island. Therefore, it is possible that Bering Island was transported westward as a forearc sliver [*Jarrard*, 1986] rather than rotated as a forearc block.

Medny Island shows a rotation of 70 ± 12° and 23 ± 7° of northward latitudinal displacement [*Bazehnov et al.*, 1992],

Table 3b. Means for Paleomagnetic Results for the Chitka Point Formation (see Table 2b for Explanation)

CHK	D_{mean}	I_{mean}	N	R	k	α_{95}	VGP_{Lat}	VGP_{Long}	D_m	D_p
D_g, I_g	52.3	67.3	19	18.79	85.41	3.7	57.7	250.3	6.2	5.1
D_s, I_s	60.8	62.90	19	18.49	35.14	5.70	51.4	239.5	8.90	7.00
D_g, I_g, R	35.6	62.2	3	3.00	470.76	5.70	64.9	273.5	8.90	6.90
D_g, I_g, N	56.1	68	16	15.83	90.57	3.90	55.8	247.1	6.50	5.50

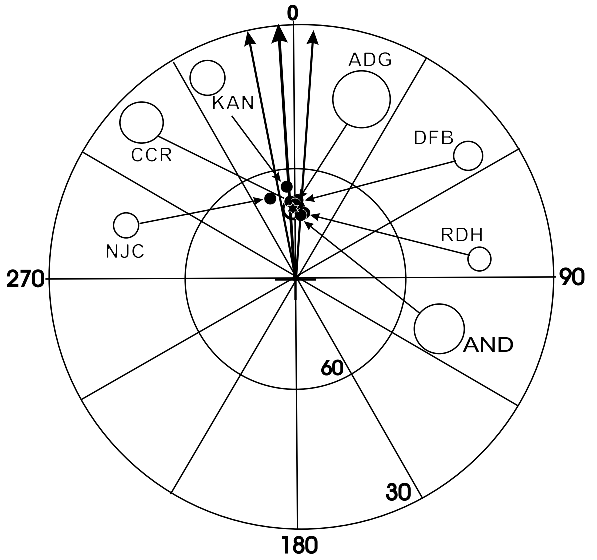

Figure 6. The dots represent the mean paleomagnetic vectors from <2 Ma flow sequences from New Jersey Creek (NJC), Crater Creek (CCR), Mt. Kanaton (KAN), Adagdak (ADK), Driftwood Bay (DFB), Round Head (RDH), and Andrew (AND). For clarity the circles of confidence for the individual data points are shown adjacent to the identifier. The star is the mean of all locations and the heavy circle the α_{95} circle of confidence about the mean. The tangential arrows represent the range of declinations within the 95% confidence limits. Note the 30–90° inclination scale.

which are both larger than expected. The rotation might be due to a combination of translation and block rotation. The latitudinal displacement, although similar within the error bars to that determined for Bering Island, points to the possibility that Medny Island may have formed as part of a rotating forearc block further east and south than Amchitka Island.

3.14. Too Much Rotation?

The block rotation model [*Geist et al*., 1988] is not consistent with the large rotations recorded in rocks from Umnak (33°) and Amlia (50°) islands in the eastern arc and Amchitka (55°) in the central arc. Within the constraints of the block model, Umnak Island should not have rotated and Amlia and Amchitka islands should show less than ~20° of clockwise rotation, based on the nearby extensional basins. However, the paleomagnetic data indicate far larger clockwise rotations [*Harbert*, 1987; this study]. This indicates a greater degree of complexity to the model and suggests that the western end of the arc may have behaved very differently from the central and eastern regions. An alternative explanation of the observations is to consider the entire Aleutian Arc pivoting about a point near the transition of the subduction zone from ocean–continent to ocean–ocean near Unalaska Island. A clockwise rotation of about 30° would account for the majority of the paleomagnetic data. However, this would require significant modifications to the current models for the plate geometries of the Bering Sea and the northwestern corner of the Pacific.

4. CONCLUSIONS

Results from this study provide short-term constraints and longer-term rates of rotation and translation of blocks in the Aleutian Arc. New paleomagnetic measurements of rocks north of the proposed zone of deformation confirm no significant rotation or translation, which is in accord with the Andreanof block boundary as defined by *Geist et al*. [1988]. It also predicts that ongoing seismicity and faulting associated with the development of summit basins is the result of continuing block rotation. New measurements on paleomagnetic samples from Amchitka indicate ~55° of clockwise rotation, part of which can be attributed to block rotation. The resolution of the paleomagnetic data can also be improved upon by resampling using multiple samples for all the flows and other units.

Archived paleomagnetic samples remeasured for this study with modern equipment and protocols produced measurements with smaller error bars, but similar mean vector directions to the original findings. Consistency in the original and new data demonstrates that measurements from other previous studies along the arc may be valid, but still need to be resampled with a much higher sample density.

The most recently published paleomagnetic data from the Aleutian Arc suggest that the eastern and western ends of the arc behave quite differently. Therefore, it may be necessary to consider separate models to describe the origin and kinematics of deformation in the eastern Fox Islands, Amchitka Island, and the western Komandorsky Islands. A possible alternative is to consider the whole Aleutian Arc having pivoted about 30° about an axis near Umnak Island. This could account for the majority of all the observed latitudinal and rotational changes.

Although the paleomagnetic data set from the Aleutian Arc is far from complete, existing data provide insights into the tectonic development of the arc. They demonstrate that where subduction is oblique, rotations develop in the expected fashion. However, rotations are also seen at the eastern end of the arc where oblique subduction has not been recognized, indicating that there may be several different mechanisms driving block rotations.

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L. Krutikov, Department of Geology and Geophysics, University of Alaska, Fairbanks, AK, 99775, USA. (lkrutikov@co.fairbanks.ak.us)

P. Minyuk, Northeast Interdisciplinary Research Institute, 16 Portavaya Street, Magadan, Russia.

D. B. Stone, Geophysical Institute, University of Alaska, Fairbanks, AK 99775-0800, USA.