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NEW PALEOMAGNETIC DATA FROM THE ALEUTIAN ISLANDS: IMPLICATIONS FOR TERRANE MIGRATION AND DEPOSITION OF THE ZODIAC FAN

William Harbert

Department of Geophysics, Stanford University, Stanford, California

Abstract. Sedimentary rocks of late Eocene to early Oligocene age from the Aleutian Islands, have been paleomagnetically studied to determine the paleolatitude of this island arc. Samples were collected from gently dipping, thin-bedded, laminated siltstone, mudstone, and very fine grained sandstone of marine origin. After demagnetization, samples from each locality showed both polarities of a remanent magnetization that thermal, isothermal remanent magnetization, and J_s-T experiments suggest is carried by magnetite. After tectonic correction, the α_{95} decreases in both localities, suggesting magnetization was acquired before folding of the beds. The characteristic magnetization shows that no significant poleward motion of the Aleutian arc has occurred with respect to the North American plate since the early Oligocene (Amlia, F=-4°, ΔF=5°; Umnak, F=0.8°, ΔF=3.5°), but the declinations are rotated significantly clockwise (Amlia, R=70°, ΔR=23°; Umnak, R=36.7°, ΔR=11.2°). Using these paleomagnetic data, relevant Euler poles, and hotspot locations, we propose a new model for the formation of the Zodiac fan. In this model, the start of Zodiac fan deposition corresponds to accretionary, igneous, and erosional events in the Pacific Northwest and fragmentation of the Farallon plate along the margin of the North American plate into small plates. Fan deposition on the Pacific plate was controlled by the geometry of the Bowie and Cobb seamount chains, which prevented sediment from being dispersed over the bathymetrically lower oceanic crust to the west, and by the bathymetry of the Pacific plate, which focused sedimentation in the magnetic bight region of the plate. Our model suggests that the present-day Zodiac fan is only a remnant of a much larger fan system.

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INTRODUCTION

It is now recognized that southern Alaska is a collage of tectonostratigraphic, accreted terranes. At least 50 terranes, blocks, and fragments make up central and southern Alaska [Berg et al., 1978; Jones and Silberling, 1979; Coney et al., 1980]. Recent paleomagnetic studies of samples from the Aleutian arc have suggested poleward translation of between 0 and 1440 km (Figure 1, Table 1) since the middle Tertiary [Stone, 1972, 1975; Hillhouse and Gromme, 1977; Panuska, 1980; Stone et al., 1982a, b; Harbert et al., 1984]. This early paleomagnetic data from the Peninsular and Prince William terranes in southern Alaska (Figure 1) suggested that these terranes may not have accreted to the North American plate until the middle or late Tertiary [Stone and Packer, 1977, 1979; Stone et al., 1982a]. However, thermal alteration of sampled units, complex geological structure, and demagnetization of only a small number of samples made tectonic interpretation of many of the previous paleomagnetic studies difficult [Coe et al., 1985]. In addition, the geometry of the large Zodiac sediment fan in the northeast Pacific basin suggests poleward transport of the Aleutian arc [Scholl et al., 1977; Byrne, 1979; Stevenson et al., 1983; Moore et al., 1983]. Previous models describing the formation of the Zodiac fan have required a source region terrane, consisting of southern Alaska and Aleutian arc terranes. This model was supported by preliminary Aleutian arc paleomagnetic data. In this paper two questions are addressed. The first question is simply, at what paleolatitude was this

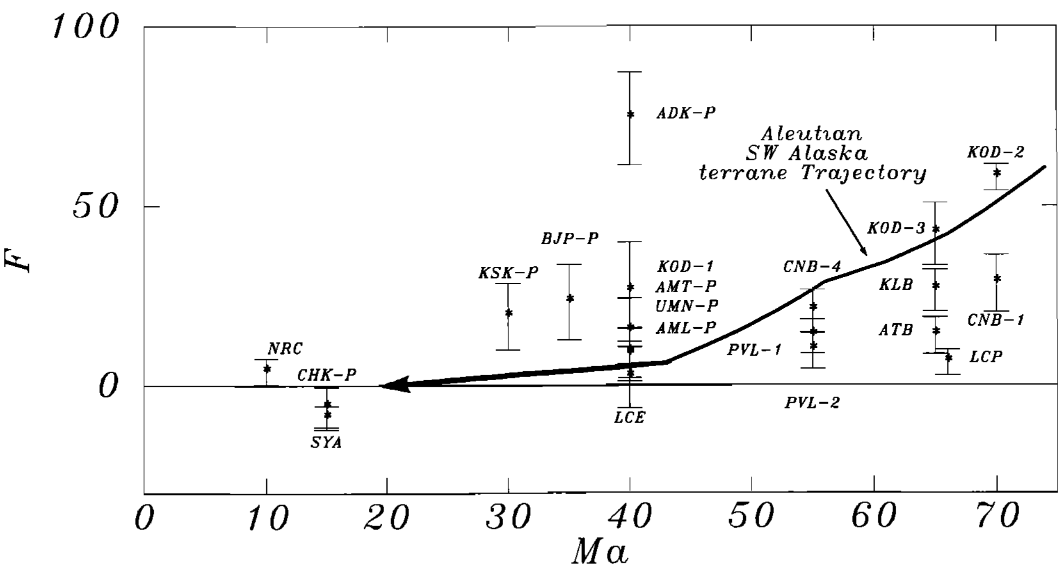


Fig. 1. Previous paleomagnetic results from the Aleutian Islands, southern Alaska, and Kodiak Island. Shown is the difference between observed and expected inclinations and the corresponding ΔF statistic. Locality and study parameters are given in Table 1. This data set as a whole suggests docking of an Aleutian arc–Peninsular terrane to the North American plate between 10 and 30 Ma.

zone of subduction in the northern Pacific basin during the early Oligocene? To test the hypothesis of poleward motion of the Aleutian arc–southern Alaska source terrane, we have sampled a sequence of gently folded marine siltstones, mudstones, and very fine grained sandstones on Amlia and Umnak islands in the central and eastern Aleutians. The continuity of the middle Tertiary Aleutian–Alaska Peninsula plutonic belt also allows paleomagnetic studies along the Aleutian arc to place limits on the motion of the Peninsular and Prince William terranes in southern Alaska [Vallier et al., 1987] and constrain the age of accretion of these terranes. We will show that no motion of the Aleutian arc is suggested since the late Eocene and that the southern Alaska terranes could not have been the primary source region for sediment deposited in the Zodiac fan. The second question is, then, without a nearby source terrane how did the Zodiac fan form? Our model will show that hotspot tracks, the Farallon–Pacific spreading center and oceanic transform faults funnelled sediment from the Pacific Northwest region of the North American plate towards the magnetic bight region of the Pacific plate and resulted in deposition of the Zodiac fan.

GEOLOGY OF EARLY OLIGOCENE TO LATE EOCENE ROCKS ON AMLIA AND UMNAK ISLANDS

We chose Hungry Bay on Amlia Island (186.08° E, 52.10° N) and Starr Point and Driftwood Bay on Umnak Island (191.17° E, 52.92° N) as sampling localities because the late Eocene to early Oligocene marine sediments there had recently been geologically studied [McLean et al., 1982; Hein et al., 1984; McLean and Hein, 1984], and the outcrops from which the samples came were only slightly altered, well exposed, and gently deformed. Judging by the results of thermal and alternating field (AF) demagnetization of pilot samples, sediments exposed at both localities appeared to possess a stable characteristic remanent magnetization [Stone et al., 1982a, b].

Amlia Island (Figure 2a) consists of a series of diverse volcaniclastic sedimentary rocks interfingered with volcanic flows and breccia. The sediments show weak to strong alteration depending on their proximity to igneous dikes, shallow plutons, or plugs [McLean et al., 1982]. The strata sampled on the east shore of Hungry Bay consist of a gently folded, thin-bedded sequence of laminated siltstone and very fine grained sandstone. The section is only mildly deformed; dips are 10° to 15° to the south with some variation in strike. Samples from one site located near a small pyroxene basaltic andesite dike contained extensively mottled, albitized, and slightly sericitized and chloritized plagioclase, with secondary minerals including chlorite and prehnite. This composition suggests local metamorphism related to intrusion of the dike. However, most samples are only slightly altered, containing authigenic zeolite minerals, rare laths of twinned plagioclase, and no high-temperature metamorphic minerals. The sampled units are of middle Eocene to early Oligocene age as shown by calcareous nannofossils found in sediment near Hungry Bay. McLean et al. [1982] also collected gabbro float that presumably came from a nearby outcrop that was covered by alluvium on the east shore of inner

Hungry Bay. A whole rock K/Ar age of 39.8 ± 1.2 Ma was determined from this sample, substantiating the fossil age for the sampled section [McLean et al., 1982].

The exposed sedimentary rocks of southern Umnak Island (Figure 2b) consist of about 300 m of thin-bedded laminated siltstone, mudstone, and very fine grained sandstone of mainly volcaniclastic composition. Strata are gently folded and dips rarely exceed 10°. The thickest, most continuous exposures are along Driftwood Bay and Starr Point where palynomorphs and dinoflagellates suggest a late Eocene to early Oligocene age of deposition [McLean and Hein, 1984]. Siltstone and mudstone consist of varying proportions of tuff (glassy volcanic debris) and angular grains of calcic plagioclase, rare quartz, augite, and opaque minerals. In most rocks the tuffaceous component is altered to smectite and more rarely to zeolite minerals, while calcic plagioclase and augite remain unaltered. A low-temperature diagenesis of the sediments is suggested by preservation of calcic plagioclase, the presence of low-temperature zeolites (heulandite and analcime), and light-colored palynomorphs. A quartz diorite stock is present along the south shore of Driftwood Bay at Cape Udak, (U/Pb age, 30.4 ± 1.5 Ma), and 13 m.y. old dikes of dark gray pyroxene basaltic andesite and pyroxene andesite cut the sedimentary rocks of Driftwood Bay and Starr Point [McLean and Hein, 1984]. In the central and northern portions of the island, Quaternary andesitic volcanics of Mt. Vsevidof, Mt. Recheshnoi, and Okmak volcano cover the older marine rocks. No Quaternary volcanoes are present in the southern third of the island.

PALEOMAGNETISM OF EARLY OLIGOCENE-LATE EOCENE SEDIMENTS OF AMLIA AND UMNAK ISLANDS

We collected the paleomagnetic samples from thin-bedded laminated siltstone, mudstone, and very fine grained sandstone. Each turbidite bed sampled was treated as a site. We collected 10 cores from each site with a stratigraphic site spacing of approximately 1-2 m. Each core was cut into 1 to 3 specimens which were subjected to a stepwise alternating field or thermal demagnetization. For the sedimentary units, in each case attitude control was excellent; errors in core orientation are probably less then 2°. Demagnetization data for each specimen were analyzed using principle component analysis [Kirshvink, 1980] to determine best fitting lines (if one magnetic component was present) or planes (if two magnetic components were present). Using the statistics of Fisher [1953] we averaged these directions for each site (Tables 2, 3, and 4), converted the average directions to paleomagnetic poles, and combined them into overall study averages for each island (Table 4).

Alternating Field Demagnetization

In most cases a single magnetic component was present after 10-mT demagnetization and remained stable during AF demagnetization to 70 mT. Orthogonal vectors plots showing representative demagnetization behavior are shown in Figure 3. The median destructive field (MDF) for samples of normal (present-day) polarity was 20 mT; reversely magnetized samples had a MDF of 50 mT. In some specimens two magnetic components were observed and a remagnetization plane was calculated for each of these samples. A best fitting pole to all the poles of the respective remagnetization planes was then calculated. The poles to the remagnetization planes were fit with a great circle that minimized the quantity

$$\chi^2 = \sum_{i=0}^{N} \left[\frac{c_i - r}{\sigma_i} \right]^2$$

$$c_i = \cos^{-1} \left[\hat{t} \cdot \hat{p}_i \right]$$

where c_i is the angular distance of a trial pole to a remagnetization plane pole (p_i), r is the expected angular distance (90°), and σ_i is the angular misfit in fitting a great circle to the demagnetization data of the specimen i. In this algorithm, one hemisphere was tested in a 1° by 1° grid to find the minimum of χ^2 (Figure 4). This estimate of the direction of the characteristic remanent magnetization closely matches that calculated directly by fitting line segments to the demagnetization data. The close match suggests the presence of only one magnetic vector after AF demagnetization. We defined the error distribution for each trial pole as $E(\hat{p}_i, \theta)$, where the variable θ is the cone angle away the trial pole $\hat{p}_i$. The misfit of data with respect to each trial pole, $E(\hat{p}_i)$, is the integral of this function.

$$E(\hat{p}_i) = \int E(\hat{p}_i, \theta)\, d\theta$$

We assumed that any nonlinearities are weak and that $E(\hat{p}_i, \theta)$ is normally distributed. We define the difference between the integrals of trial and best fit error distributions $S(\hat{p}_i, \hat{p}^*)$ as

$$S(\hat{p}_i, \hat{p}^*) = \int \left[E(\hat{p}_i, \theta) - E(\hat{p}^*, \theta) \right] d\theta$$

$S(\hat{p}_i, \hat{p}^*)$ should be χ^2 distributed with 2 degrees of freedom. To obtain the 95% confidence limit, we drew on the surface of the sphere a contour of the $S(\hat{p}_i, \hat{p}^*)$ function at the critical chi-squared value with two degrees of freedom. The actual mean is within this contour at 95% certainity.

We performed thermal demagnetization experiments on selected samples to check the results of AF demagnetization. These experiments showed single component behavior to thermal steps of 500°, although in some samples from Umnak Island magnetic intensity increased at higher thermal steps. Thermal demagnetization of selected samples from Amlia Island showed a single magnetic vector with a Curie temperature of 575°.

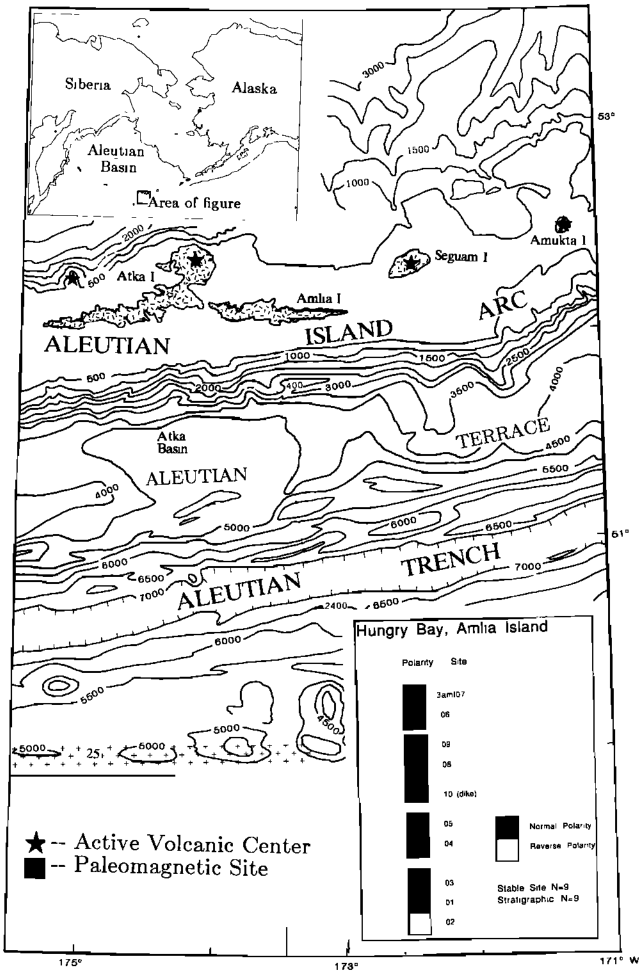


Fig. 2a

Fig. 2. Locality maps of (a) Amlia and (b) Umnak Islands. One locality in Hungry Bay on Amlia Island and two localities at Starr Point and Driftwood Bay on Umnak Island were sampled.

Rock Magnetism

To identify the magnetic mineral responsible for the characteristic remanent magnetization identified in thermal and AF demagnetization, we performed isothermal remanent magnetization (IRM) and magnetization–temperature (J_s-T) experiments. In the samples collected from Amlia and Umnak Islands, IRM experiments showed rapid saturation at field strengths of < 1 KG, suggesting the presence of magnetite (Figure 5). Thermomagnetic experiments on a magnetic separate in air and argon atmospheres identified the Curie temperatures of magnetic minerals in the samples collected from Umnak Island. The reversible nature of the J_s-T curve in both air and argon atmospheres suggests that the samples did not contain lower–temperature magnetic minerals ($T_c < 500°$ C), which invert to magnetite or hematite during heating, or high–temperature magnetic minerals such as hematite ($T_c > 580°$ C). The high–temperature inflection point in the J_s-T curves shows the presence of a titanomagnetite with Curie temperature of approximately 540° C (Figure 6). This magnetic phase could be either a primary low–Ti titanomagnetite or a high–temperature deuteric oxidation of a primary Ti–rich titanomagnetite to a Ti–poor titanomagnetite containing ilmenite lamellae.

In reflected light, two thin sections from samples collected from Umnak Island showed fresh unoxidized euhedral pyrite of approximately 10 μm size but no identifiable magnetite. A microprobe scan for the elements Ti and Fe showed 2 to 5 μm sized grains distributed throughout the thin section, but these sizes were just at the resolving power of the instrument, and the grains could not be carefully examined. Some of the

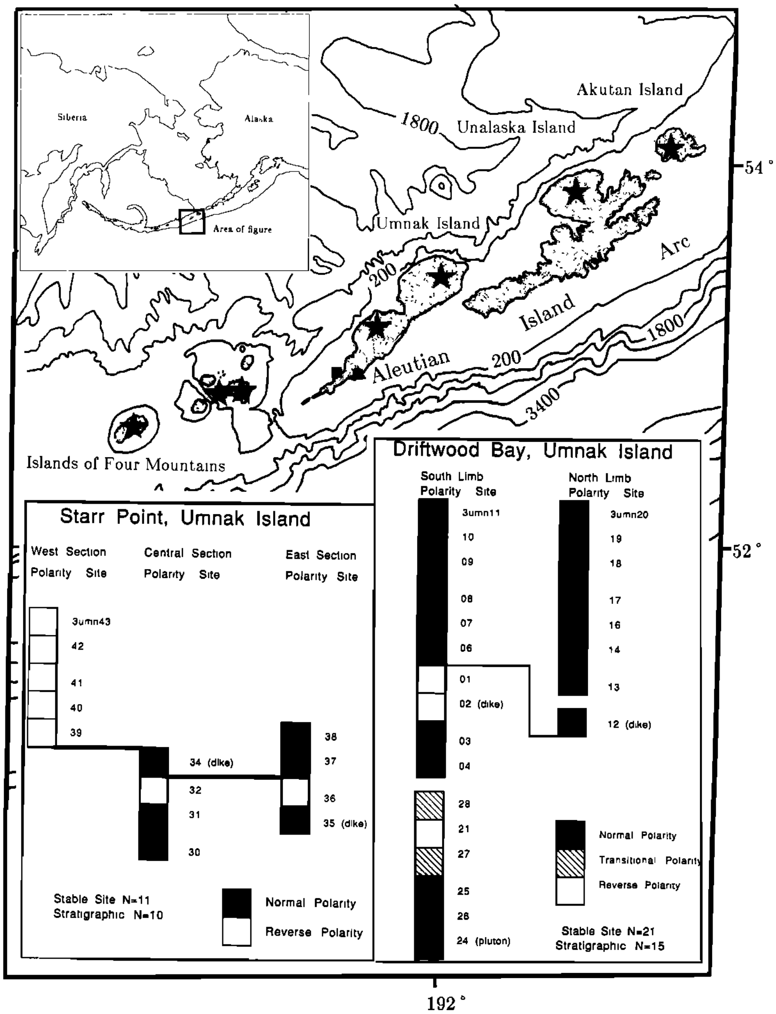


Fig. 2b

2 to 5 μm sized minerals showed both elemental Ti and Fe, suggesting that these may be the magnetic mineral carrying the characteristic remanent magnetization.

Paleomagnetism

To assess the significance of the characteristic remanence, further tests, such as the fold test, reversal test, and the NRM (natural remanent magnetization) present-day magnetic field discordance test were applied to both localities. These tests support the conclusion that the characteristic magnetic direction isolated from the sediments was acquired during or shortly after deposition of the units in the early Oligocene.

The Amlia Island sites were found to have a mean NRM direction of declination 31.5°, inclination 76.1°, which contrasts with the present magnetic field of declination 9.9°, inclination 63.4°, or dipole-only inclination 68.7°. This difference suggests that these sites have not been remagnetized in the direction of the earth's present-day magnetic field. The stratigraphically lowest site, 83aml02, is of reversed polarity (Figure 7). After tectonic correction this reversed direction becomes more antipodal to the other eight normally magnetized sites, unfortunately no units were sampled stratigraphically below this site (Figure 8). The ratio of the estimate of the dispersion parameter κ [Fisher, 1953], before and after unfolding (κ_s/κ_g=2.23), reflects the better grouping of the magnetic vectors after correction for the tilt of the beds. We interpret the observed Amlia magnetization to be the characteristic remanent magnetization acquired during or shortly after deposition of the sediments during the late Eocene or early Oligocene. This conclusion is supported by the presence of relatively unaltered calcic plagioclase, lack of high-temperature metamorphic minerals in samples, observation of two polarities of a single magnetic component stable during AF and thermal

TABLE 1. Previous Aleutian, Kodiak and Alaska Peninsula Paleomagnetic Studies

Locality	Age, Ma	N	K	α_{95}	Λ	Φ	D_s	I_s	Site
Shemya Island	Middle Miocene (10)	7	147	5	52.8	174	11	79	SYA
Adak Island	Eocene (40)	5	14	21	54.8	183.5	318	53	ADK-P
Amchitka Island	Early Oligocene (35)	8	8	17	51.4	179	23	49	BJP-P
Amchitka Island	Middle Miocene (10)	20	12	9	51.4	179	44	75	CHK-P
Kiska Island	Eocene Oligocene (30)	7	12	15	52.0	178	327	52	KSK-P
Amatignak Island	Late Eocene (40)	6	22	15	51.2	181	53	57	AMT-P
Umnak Island	Late Eocene (40)	9	23	11	53.0	191	67	64	UMN-P
Amlia Island	Late Eocene (40)	7	27	12	52.2	186	---	64	AML-P
Pavlov Bay	Paleocene-Eocene (55)	23	15.2	7.5	55.5	198.6	230	-62	PVL.1
Pavlov Bay	Paleocene-Eocene (55)	17	17.2	8.2	55.5	198.6	197	-66	PVL 2
Canoe Bay	Paleocene-Eocene (55)	18	11.8	9.6	55.5	198.7	195	-55	CNB.4
Canoe Bay	Late Cretaceous (70)	22	7.1	12.5	55.5	198.1	316	52	CNB.1
Lake Clark	66 (70)	30	32.8	4.7	60.3	205.3	298.4	74.4	LCP
Lake Clark	44 (45)	6	24.1	13.9	60.6	205.7	341.6	74.8	LCE
Kodiak Island	Late Cretaceous (70)	12	81.4	4.8	57.5	207.7	118	-23	KOD.2
Kodiak Island	62 (60)	8	17.0	13.8	57.5	207.7	136	-37	KOD.3
Kodiak Island	Eocene-Oligocene (40)	8	6.9	22.6	57.5	207.7	140	-49	KOD.1
Kodiak Island	Late Miocene (10)	73	8.8	5.9	57.5	207.7	170	-68	NRC
Kodiak Island	62 (60)	11	29.4	8.6	57.3	207.1	320.1	52.6	KLB
Kodiak Island	62 (60)	16	25.8	7.4	56.9	206.1	82.1	65.0	ATB

Previous paleomagnetic studies from the Aleutian Islands are listed above. For the appropriate reference, the age, number of sites (N), dispersion parameter (κ), uncertainty α_{95}, site latitude (Λ, degrees north) and site longitude (Φ, degrees east), study declination and inclination (D_S, I_S) after bedding correction are given. Abbreviations used for the site locations are SYA, Shemya; ADK, Andrews Lake formation, Adak; BJP, Banjo Point formation, Amchitka; CHK, Chitka formation, Amchitka; KSK, Vega Bay formation, Kiska; AMT, Amatignak; UMN, Umnak; AML Amlia. Studies KSK, AMT, UMN, and AML were preliminary studies using oriented hand samples. References cited are the following: for KSK, Panuska [1980]; for SYA, ADK, BJP, and CHK, Beck [1980], Stone [1972, 1975]; for PVL.1, PVL.2, CNB.4, CNB.1, KOD.1, KOD.2, KOD.3, and NRC, Stone et al., [1982a]; for AMT, UMN, and AML, Stone et al., [1982b]; for KLB and ATB, Plumley et al., [1984]; for LCP and LCE, Thrupp and Coe [1986].

TABLE 2. Summary of Paleomagnetic Directions of Sites Collected From the Late Eocene-Early Oligocene Units of Hungry Bay on Amlia Island in the Central Aleutian Islands

Site	D_g	I_g	D_s	I_s	α_{95}	κ	N	Polarity
3aml01	28.7	65.0	32.9	69.7	15.0	8.7	10	N
3aml02	83.8	44.7	108.0	67.2	8.8	21.1	12	R
3aml03	349.2	78.0	319.0	81.6	23.2	4.1	9	N
3aml04	351.1	77.6	55.8	80.7	2.0	456.8	11	N
3aml05	14.8	78.4	71.0	76.6	9.2	29.2	8	N
3aml06	19.7	68.4	76.8	74.3	4.9	205.1	4	N
3aml07	19.0	71.2	57.7	76.5	7.2	74.9	5	N
3aml08	30.4	77.7	63.2	85.6	2.9	324.7	7	N
3aml09	1.0	72.6	32.8	73.2	6.1	48.1	11	N
3aml10	10.9	68.0	----	----	8.9	25.0	10	N

D_g, I_g, refer to the declination and inclination of the magnetic vector for the appropriate site in geographic coordinates, or before correction for the tilt of the beds. D_s, I_s refer to this vector in stratigraphic coordinates, after correction of the beds to ancient horizontal; α_{95} is the angle of 95% certainty about the mean; and κ is the associated estimate of the dispersion parameter using the statistics of Fisher [1953]. N refers to the number of samples used to calculate each site direction of polarity R (reversed) or N (normal).

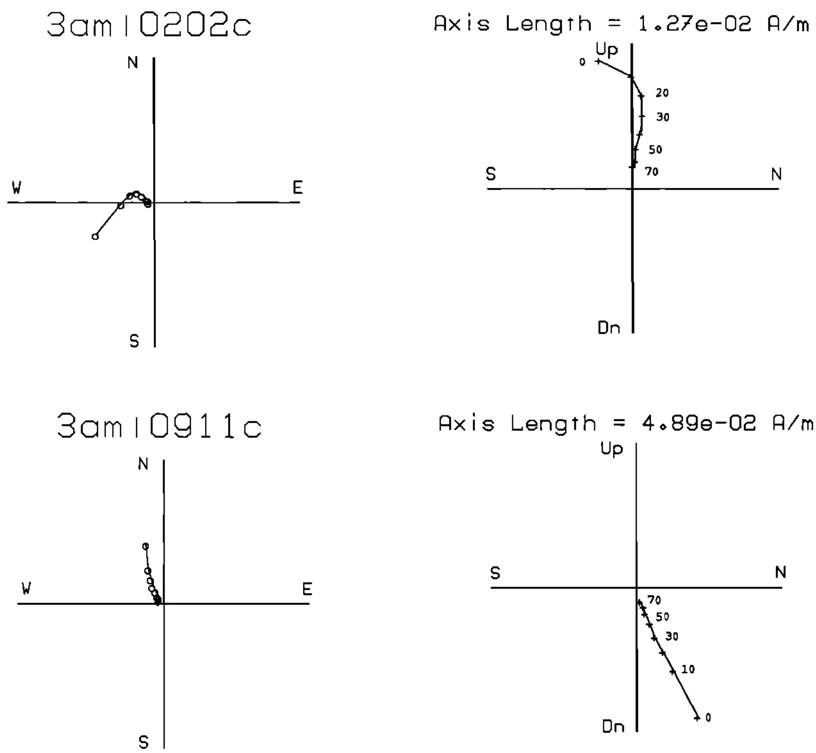
TABLE 3. Summary of Paleomagnetic Directions of Sites Collected From the Late Eocene-Early Oligocene Units of Driftwood Bay and Starr Point on Southern Umnak Island in the Eastern Aleutian Islands

Site	D_g	I_g	D_s	I_s	α_{95}	κ	N	Polarity
83umn01	199.7	-70.3	203.2	-75.2	34.1	8.4	2	R
83umn02	200.4	-58.7	-----	-----	9.9	28.4	7	R
83umn03	325.6	+68.4	333.1	+79.2	11.5	29.5	5	N
83umn04	56.5	+74.5	66.1	+80.1	27 6	8.5	3	N
83umn06	12.6	+48.8	14.1	+57.7	5.4	170.8	4	N
83umn07	30.3	+66.6	26.3	+75.5	7.5	57.8	6	N
83umn08	16.9	+62.2	30.2	+70.4	16.3	8.2	9	N
83umn09	29.3	+51.0	40.6	+56.8	19.2	13.3	4	N
83umn10	16.6	+32.8	21.6	+45.3	23.4	17.8	2	N
83umn11	7.1	+79.7	64.8	+82.4	7.9	31.1	10	N
83umn12	24.6	+60.1	-----	-----	3.8	113.1	12	N
83umn13	11.2	+68.9	36.9	+64.1	4.4	112.8	9	N
83umn14	329.0	+59.8	344.4	+68.0	10.6	58.6	3	N
83umn16	6.3	+68.6	24.5	+70.9	1.7	966.8	7	N
83umn17	47.5	+70.0	59.9	+66.6	6.1	75.1	7	N
83umn18	15.6	+82.2	54.4	+80.5	6.0	50.2	11	N
83umn19	354.6	+72.5	16.2	+76.2	5.3	98.1	7	N
83umn20	47.7	+68.5	69.5	+67.0	4.8	119.8	7	N
83umn21	197.8	-69.3	228.4	-74.1	2.8	837.0	3	R
83umn24	5.7	+64.4	-----	-----	7.0	50.4	8	N
83umn25	337.4	+87.2	86.3	+85.5	9.2	46.2	5	N
83umn26	330.6	+71.7	6.4	+80.4	17.8	6.2	10	N
83umn27	275.4	+75.2	212.7	+76.6	13.7	13.1	8	T
83umn28	211.4	+31.7	204.7	+23.8	26.4	7.1	4	T
83umn30	19.4	+60.8	38.7	+66.6	4.0	132.8	9	N
83umn31	14.0	+47.8	20.3	+56.6	6.8	42.9	10	N
83umn32	179.9	-69.9	187.6	-75.5	7.2	42.4	9	R
83umn34	51.2	+64.8	-----	-----	16.8	13.9	5	N
83umn35	227.4	+57.8	209.3	+55.2	8.8	25.5	10	T
83umn36	216.4	-75.2	208.4	-78.8	7.3	41.2	9	R
83umn37	16.5	+59.3	12.1	+64.9	12.1	33.6	4	N
83umn38	62.9	+51.1	65.6	+58.9	12.2	65.7	2	N
83umn39	215.4	-70.7	224.0	-70.7	5.0	155.7	5	R
83umn40	193.6	-71.9	222.5	-73.8	1.3	1368.4	8	R
83umn41	190.6	-68.9	213.2	-74.0	2.8	279.5	9	R
83umn42	187.3	-70.9	213.3	-75.6	0.9	2408.1	10	R
83umn43	185.2	-73.3	-----	-----	1.4	849.4	12	R

Notation is the same as is used in Table 2.

demagnetization, and better grouping of magnetic vectors after unfolding.

For Umnak Island, the Fisher average of NRM directions is D=359.9°, I=75.6°, and κ=6.4°. This average of NRM directions is rotated counterclockwise and is steeper than the earth's present-day magnetic field of D=13.3° and I=64.8° (dipole-only I_d=69.4°) at the sampling sites. Before tectonic correction the mean of the characteristic magnetization of all the sites (D_g=18.1°, I_g=68.2°) lies relatively close to the present-day magnetic field direction (Figure 8). However, the two polarities of the NRM directions suggest that the sampled units do not represent a present-day magnetic field direction. The α_{95} decreases after tectonic correction from 4.6° to 3.7° (κ_s/κ_g=1.52), showing improved grouping of the magnetic vectors after the beds are unfolded (Figure 8). We interpret the Umnak magnetization to be the characteristic remanent magnetization acquired during or shortly after deposition of the sampled units in the early Oligocene. This interpretation is supported by the consistency of magnetic directions between the localities at Starr Point and Driftwood Bay, better grouping of the paleomagnetic vectors after unfolding of the beds, two polarities of characteristic magnetization, simple magnetic mineralogy seen in J_s-T and IRM experiments, single component demagnetization in both thermal and AF experiments, and the presence of fresh unaltered calcic-plagioclase, low-temperature zeolites, and light-colored palynomorphs within the sampled sediment.



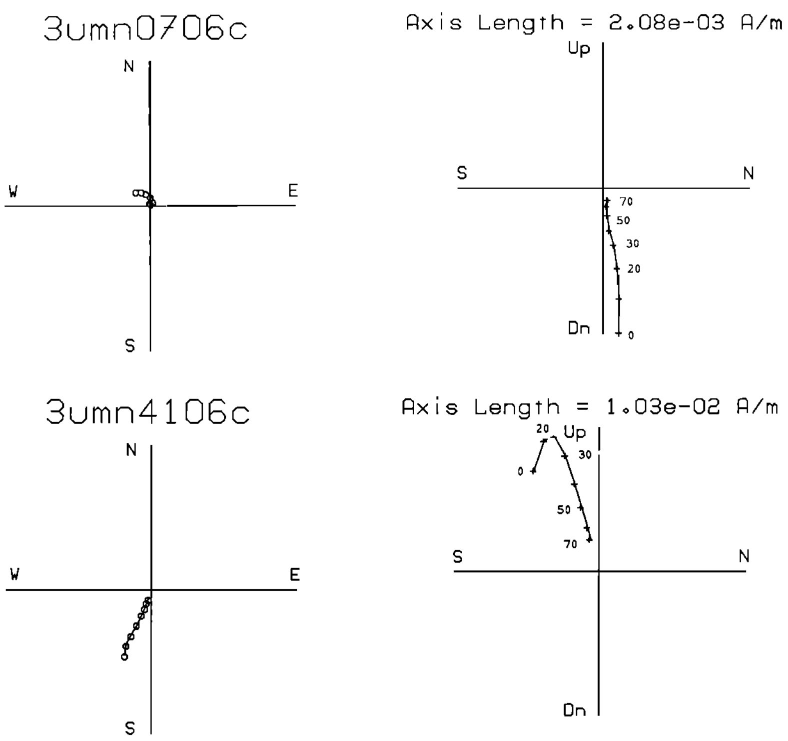
Amlia AF Demagnetization

Fig. 3a

Fig. 3. Representative orthogonal vector plots of AF demagnetization of (a) Amlia samples (0202 and 0911) and (b) Umnak samples (0706 and 4106). Simple magnetic behavior and a linear characteristic magnetic vector were observed during demagnetization with peak fields of >15 mT. The intensity of the characteristic component varied with the composition of the rocks sampled. For Umnak Island, Miocene dikes had a mean intensity of I= 8.2e-04 emu/cm^3, σ=5.4e-04. For the Cape Udak pluton, I= 7.0e-04 emu/cm^3, σ=2.0e-07, and for the rest of the sites collected from turbidites, I=7.3e-06 emu/cm^3, σ=6.73e-05. The average NRM intensity of the Amlia Island sediments was, 2.2e-04 emu/cm^3, σ=3.0e-04, and for the basaltic andesitic dike, 2.9e-03 emu/cm^3, σ=8.2e-04.

Interpretation

Pole positions for the Amlia and Umnak island localities were calculated by converting the site directions to virtual geomagnetic pole positions and then averaging these points using the statistics of Fisher [1953]. Using these results and the reference pole position of Coe et al. [1985] for the North American plate, rotation and flattening statistics (defined by Beck [1980]; corrected by the factor suggested by Demarest [1983]) for Umnak Island are the following: R=37°, ΔR=11.2°, F=0.8°, and ΔF=3.5°. When compared with the 30 m.y. reference pole Amlia Island rotation and flattening statistics are R=70°, ΔR=23°, F=-5°, and ΔF=5°. When compared with the 49 m.y. reference pole R=66°, ΔR=22°, F=-4°, and ΔF=5°, these statistics show that significant clockwise has occurred since deposition of these units in the early Oligocene, but there has been no significant latitudinal displacement with respect to the North American plate. Thus the conclusion of this paleomagnetic study is that no significant poleward latitudinal motion of the central and eastern Aleutian arc with respect to the North American plate has occurred since the early Oligocene. Figure 9 shows the difference and associated uncertainities between the observed inclinations and inclinations expected from the apparent polar wander path (APWP [Coe et al., 1985]) for the North American plate for sites in southern Alaska and the Aleutian Islands. When the results of studies calculated from a large number of sites [Coe et al., 1985] are plotted with the results of this study, the data are coherent and suggest that docking of the Peninsular terrane occurred before 45 Ma (Figure 9). In Figure 9, the study labelled LCP was interpreted by Thrupp and



Umnak AF Demagnetization

Fig. 3b

Coe [1986] to show Tertiary shortening and not northward migration of a terrane.

The paleomagnetic azimuths found in our study are rotated clockwise. Amlia and Umnak islands (separated by 320 km) probably rotated independently in response to the tangential component of Pacific–North American plate convergence [Spence, 1977; Geist et al., 1985]. This clockwise rotation differs from the generally counterclockwise rotations observed in paleomagnetic studies completed in western Alaska and the Alaska Peninsula. This counterclockwise rotation probably reflects Late Cretaceous oroclinal bending of western Alaska due to the convergence of the North American and Eurasian plates in the Bering Sea region [Globerman and Coe, 1984; Coe et al., 1985]. This style of North American-Eurasian plate convergence ended before formation of the Aleutian arc in the early Tertiary [Harbert et al., 1987].

The paleomagnetic study of Plumley et al. [1983] of the Ghost Rocks of the Prince William terrane show significant northward displacement of this terrane since the early Tertiary. To model these displacements, we have constructed a series of terrane trajectories using the plate model of Engebretson et al. [1984], and the apparent polar wander path of Coe et al. [1985]. We constructed a series of curves that show the expected flattening as a function of age for terranes on the Kula plate that accrete to southern Alaska between 45 and 60 Ma. These calculations show that the Ghost Rocks probably accreted to the North American plate near their present location, between 45 and 55 Ma, before the deposition of the Zodiac fan. Previous explanations of the formation of the Zodiac fan have required the northward transport of either the Aleutian arc or a large source terrane during the middle Tertiary [Scholl et al., 1977; Byrne, 1979; Stevenson et al., 1983]. Our paleomagnetic result indicates that no statistically significant latitudinal translation of the Aleutian arc with respect to the North American plate has occurred and that accretion of the Ghost Rocks of the Prince William terrane occurred before formation of the Zodiac fan; hence a new model is required.

FORMATION OF THE ZODIAC FAN

The Zodiac fan consists of four major channels that become younger west to east. The youngest and largest channel, the Taurus, has a late Oligocene age, while the age of the oldest channel is between middle Eocene to early Oligocene age according to core data from Deep Sea Drilling Project (DSDP) hole 183 [Scholl and Creager, 1973]. After deposition of Zodiac fan turbidites stopped, turbidite deposition on the neighboring Alaska Abyssal Plain to the east of the Zodiac fan began at approximately 24 Ma. Stevenson et al. [1983] interpret the age of youngest Zodiac sedimentation to be either 32

TABLE 4. Summary of Paleomagnetic Results From the Localities at Starr Point and Driftwood Bay Located in Southern Umnak Island in the Eastern Aleutian Islands and From the Localities at Hungry Bay in the Central Aleutian Islands

Location	Age	N	D_g	I_g	α_{95}	κ	D_s	I_s	α_{95}	κ
UMN sediments	38	29	16.7	67.9	4.6	31.6	32.2	72.1	3.7	48.1
UMN dikes	15	4	15.7	70.6	10.7	43.0				
AML sediments	40	9	29.3	73.2	8.7	28.8	58.7	78.6	5.9	63.2
AML dike	15	1	10.9	68.0	8.9	25.0				
Location	Age	N	ϕ_g	λ_g	A_{95}	K	ϕ_s	λ_s	A_{95}	K
UMN sediments	38	29	275.5	80.1	6.4	16.3	233.9	73.0	6.3	17.2
AML sediments	40	9	236.7	74.1	12.3	14.4	229.2	63.7	14.9	9.8

D_g, I_g, refer to the direction of the average magnetic direction for Umnak and Amlia Island before correction of the vector for the tilt of the strata from which they were collected; α_{95} is the cone angle of 95% confidence about the mean; and κ is the associated estimate of the dispersion parameter using the statistics of Fisher [1953]. N refers to the number of sites used to calculate each direction; D_s and I_s refer to the position of the magnetic vector after restoration of the beds to ancient horizontal. Using the result from the sampled sediments and the reference pole position of Coe et al., [1985] for the North American plate, Umnak rotation and flattening statistics are the following: R=37°, ΔR=11.2°, F=0.8°, and ΔF=3.5°. When compared with the 30 Ma reference pole Amlia Island rotation and flattening statistics are, R=70°, ΔR=23°, F=-5°, and ΔF=5°. When compared with the 49 Ma reference pole R=66°, ΔR=22°, F=-4°, and ΔF=5°, these statistics show that significant clockwise rotation has occurred since deposition of these units in the early Oligocene, but there has been no significant latitudinal displacement with respect to the North American plate. All rotation and flattening statistics are calculated using the method presented by Beck [1980] and corrected by the factor suggested by Demarest [1983]. Pole positions for the Amlia and Umnak Island localities were calculated by converting the site directions to pole positions and then averaging these points using the statistics of Fisher [1953].

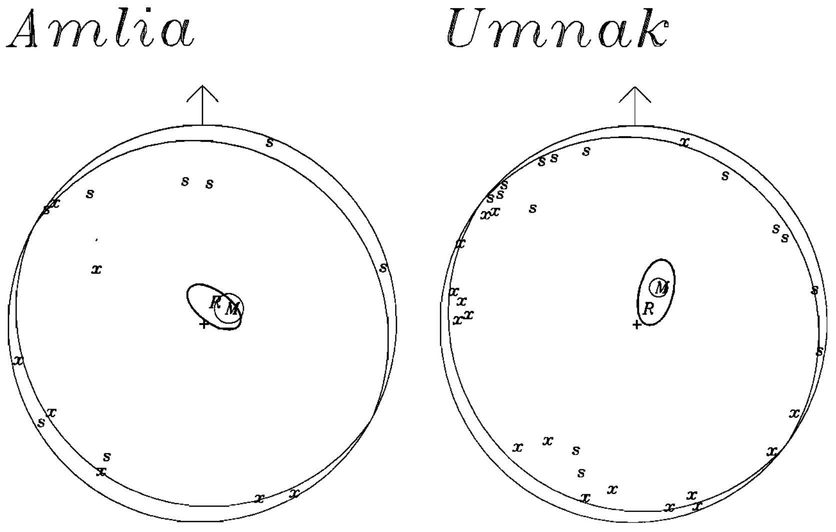


Fig. 4. Estimation of the higher coercivity characteristic magnetization of Amlia and Umnak islands using remagnetization circles. R is the best fit pole to the poles of sample demagnetization great circles. The circle of confidence about R is the parametric estimate of the uncertainty. M is the mean direction found using best fit line segments for all sites to demagnetization data, surrounded by the corresponding α_{95}. This agreement between remagnetization circles and line segments suggests AF demagnetization isolated a characteristic magnetization.

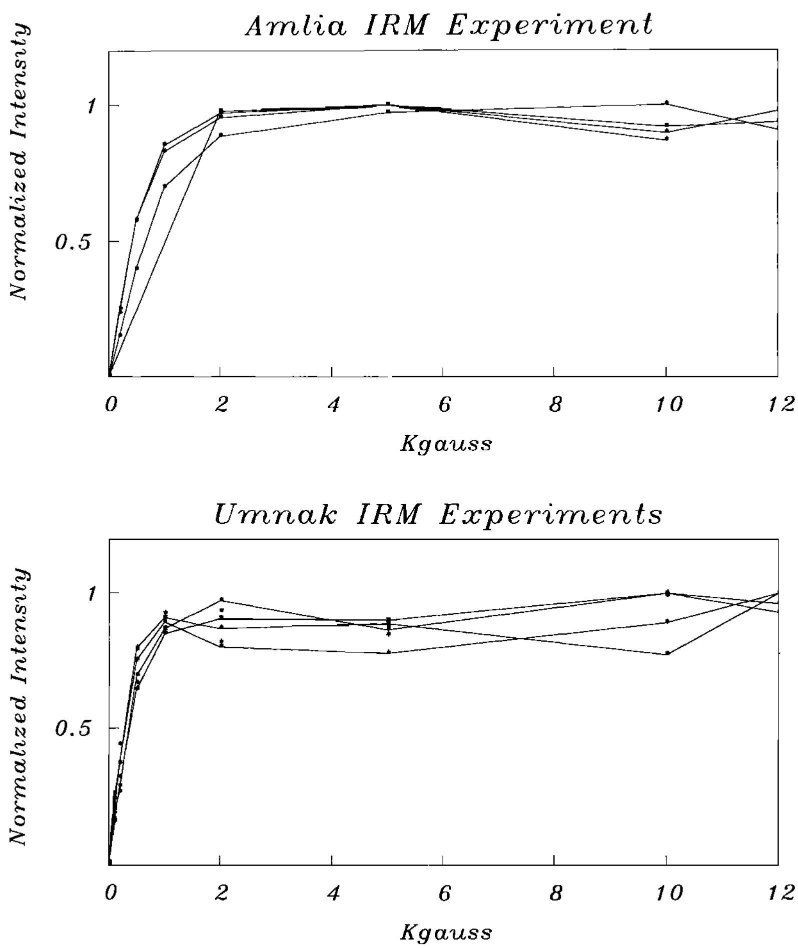


Fig. 5. Isothermal remanent magnetization (IRM) experiments for selected samples from Amlia and Umnak islands. Low-field saturation with applied field suggests the presence of magnetite as a magnetic phase.

or 24 Ma, depending on the age and stratigraphic relationship of two channels; they favor the later age as representing the actual age of cessation of sedimentation. Any model of the formation of the Zodiac fan must satisfy the constraints presented by the sediment age (40–32, or 40–24 Ma), the age of the oceanic crust on which the fan sits (74–44 Ma), and relative motion Euler poles between the Pacific and North American plates that restore the fan to a middle Eocene position. The present interaction of oceanic ridges, transform faults, hotspot tracks, and sedimentary systems in the northeastern Pacific basin suggests that these tectonic features may have been important in controlling the timing of sedimentation and geometry of the Zodiac fan in the Oligocene.

The locations of subducted seamounts generated by the Bowie (53.5° N, 224.0° E) and Cobb (46.5° N, 230.0° E) hotspots may be determined in a hotspot-fixed reconstruction of the Pacific basin at 40, 32, and 24 Ma (Figures 10a, 10b, and 10c). In addition, the geometry of the Kula–Pacific ridge and Farallon–Pacific ridge west and south of the Kula–Farallon–Pacific triple junction may be accurately determined because these features are recorded by magnetic isochrons and transform faults on the Pacific plate. Unfortunately, the geometry of the Kula–Farallon ridge cannot be reconstructed with a high degree of certainity north of this point because of the subduction of both the Kula and Farallon oceanic crust that recorded the geometry of the ridge. The presence of northwest trending faults with large amounts of Cretaceous dextral motion in northern Washington [Tabor et al., 1984; Trexler and Bourgeois, 1985] and British Columbia [Pacht, 1984; Gabrielse, 1985] suggest a tectonic driving force with a significant northward component. To reconstruct the Kula–Farallon spreading center at 65 Ma, Engebretson et al. [1984] connected the Pacific–Farallon–Kula triple junction to a point along the southern Washington continental margin with a single

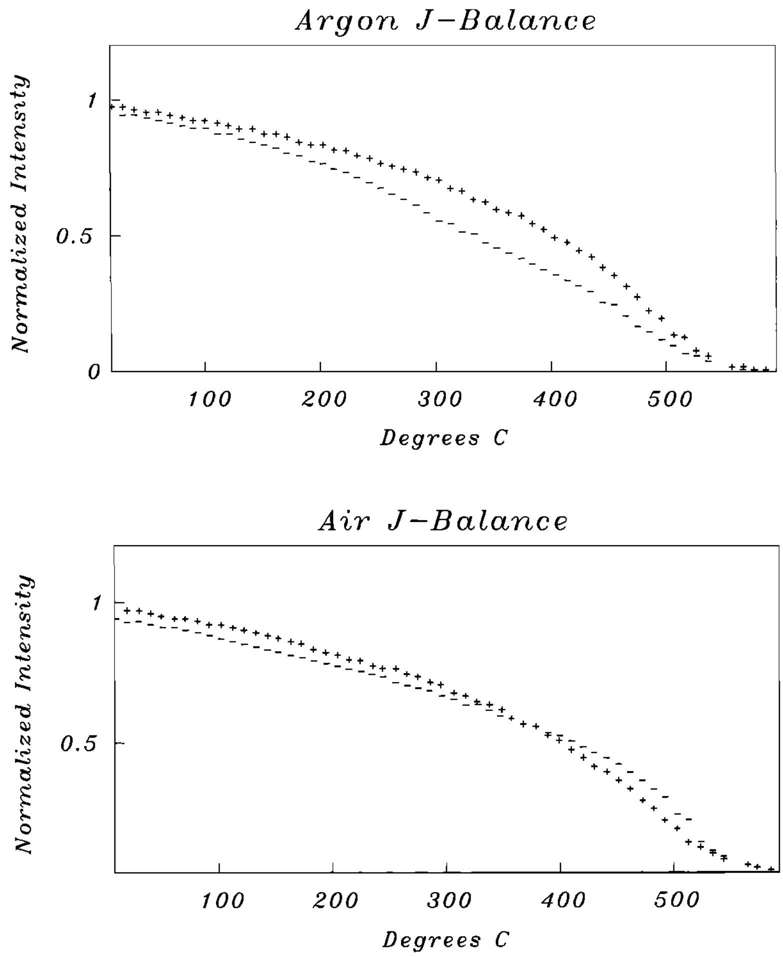


Fig. 6. J_s-T experiments for magnetic separates made from Umnak Island sediment samples. Plus symbols show behavior during heating, minus symbols show behavior during cooling. The reversible nature of this curve and the high temperature inflection point suggest titanomagnetite of T_c=540° is the magnetic mineral carrying the characteristic magnetization for Umnak Island turbidite samples.

great circle. In our model for the formation of the Zodiac fan we have used their Kula–Farallon ridge geometry.

A tectonic map of the present–day Pacific basin shows small oceanic plates along the northwestern margin of the North American plate. The geometry of the Juan de Fuca and Gorda ridges and transform faults control the geometry of sediment channels carrying sediment from western Oregon and Washington to the Pacific plate. Sediment that is deposited beyond the Juan de Fuca–Pacific ridge on the Pacific plate is channeled through the spreading center along transform faults [Stevenson et al., 1983]. Similarly, in our model, the Zodiac fan is formed by sediment channeled along transform faults through the bathymetrically high Farallon–Pacific spreading center to the Pacific plate. However, in our model both the seamount tracks of the Cobb and Bowie hotspots and the Farallon–Pacific ridge direct sediment from the Pacific Northwest region of the North American plate onto the magnetic bight region of the Pacific plate (Figures 10a, 10b, and 10c). Composition of sediment from this source region matches that of the Zodiac fan. Sediment from DSDP site 183 showed that Zodiac fan turbidites probably originated from a plutonic or metamorphic source provenance [Creager et al., 1973]. Moore et al. [1983] concluded on the basis of QFL (proportion of quartz to feldspar to lithic fragments) and V/L (proportion of volcanic to lithic fragments) criterion that Eocene and Oligocene rocks from the Olympic Peninsula region of Washington state matched those of the Zodiac fan, suggesting that this region may preserve proximal Zodiac fan deposites. In our model, the start of Zodiac fan deposition corresponds to the fragmentation of the Farallon plate into small plates [Menard, 1978]. In the Pacific Northwest, several tectonics events correspond in time with late Eocene to Oligocene Zodiac fan deposition; these events include

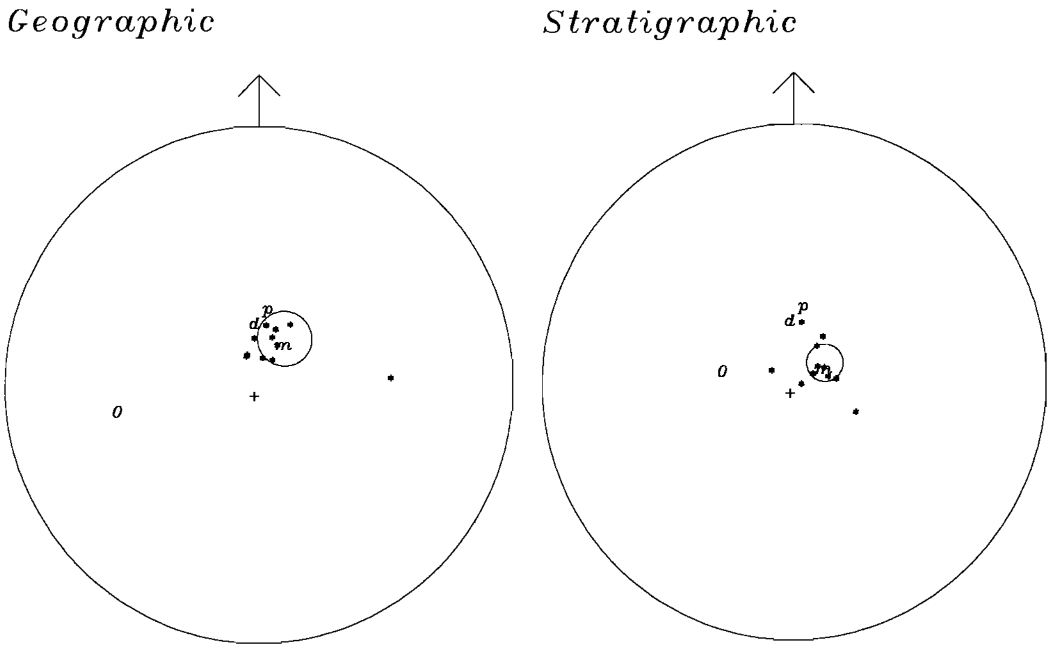


Fig. 7. Equal area stereographic projections of site means from Amlia Island. Crosses correspond to lower hemisphere (normal polarity), and circles correspond to upper hemisphere (reversed polarity). The mean direction (M) and α_{95} before and after unfolding is compared with the present–day (P) and dipole only (D) magnetic direction at Amlia Island. Numeric data are given in tables 2 and 4.

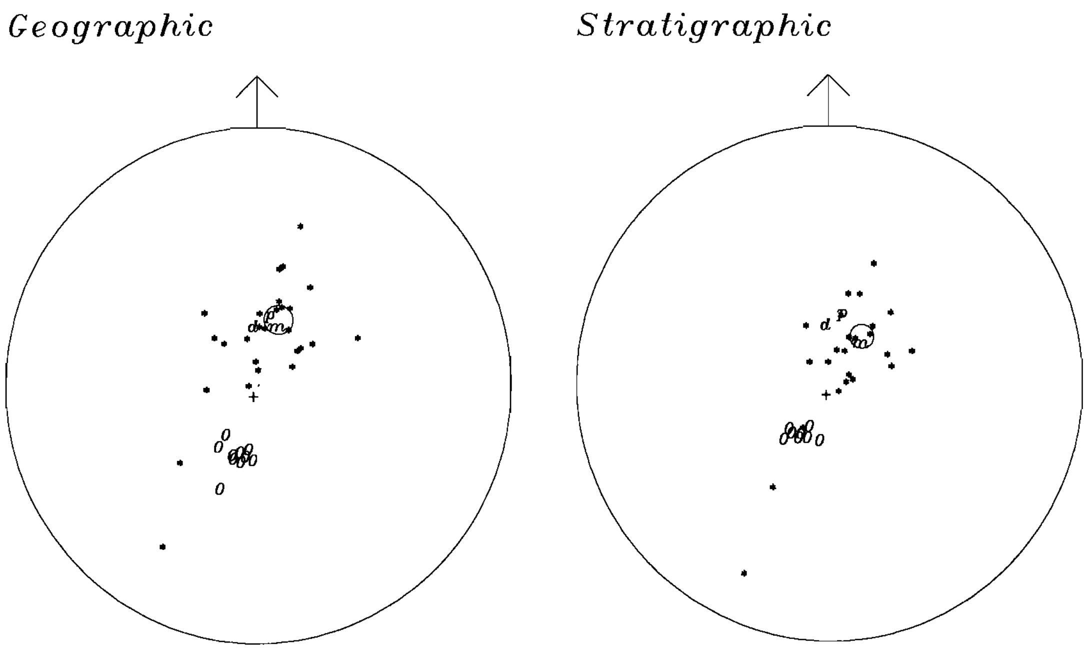


Fig. 8. Equal area stereographic projection of site means from Umnak Island. Symbols are the same as those used in Figure 7. Numeric data are given in Table 3. Hillhouse [1975] defined paleomagnetic directions greater than 30° away from either a lower or upper hemisphere average as transitional in polarity. Sites 28, 27, and 35 represent transitional polarities using the criteria of Hillhouse [1975] and were not used in calculating the average magnetic direction for Umnak Island given in Table 4.

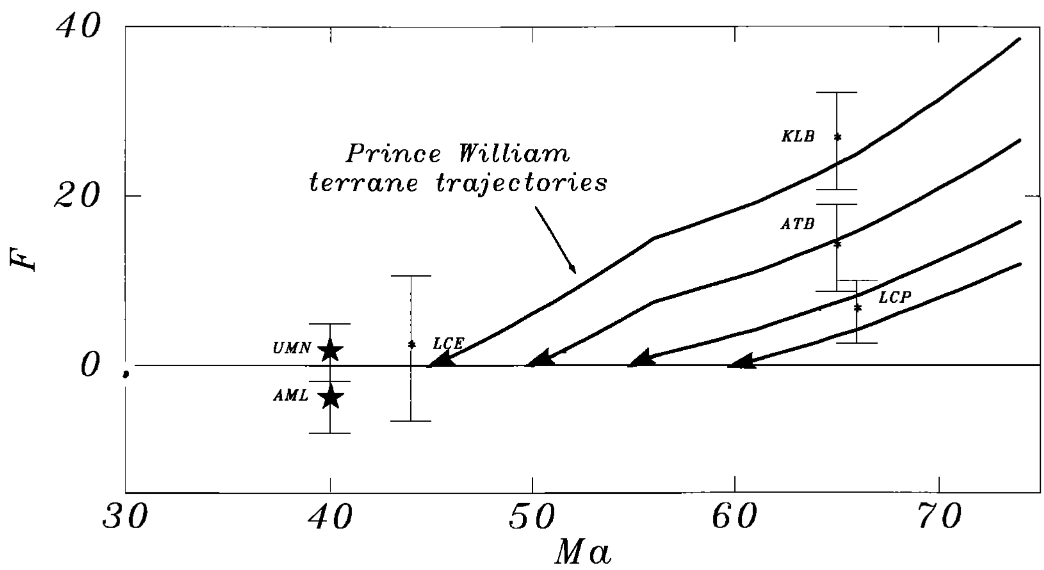


Fig. 9. Paleomagnetic results from Amlia and Umnak islands are compared with those of high quality studies recently completed on the Alaska Peninsula and Kodiak Island. These results suggest no movement of the Aleutian arc since the early Oligocene and accretion of the Peninsular terrane during the early Tertiary. Shallow results from Kodiak Island (KLB and ATB) suggest that the Ghost Rocks may not yet have accreted to North America in the early Tertiary. The dark lines show a series of terrane trajectories with different ages of accretion to the North American plate. These lines show the expected flattening for a terrance riding on the Kula plate and accreting to the North American plate at the age where the terrane trajectory intersects the ordinate corresponding to zero flattening (45, 50, 55, and 60 Ma). In each trajectory, no younger change in flattening would be expected because the terrane has accreted to the North American plate.

TABLE 5. Outline of the Model Proposed in This Paper to Explain the Formation of the Zodiac Fan

Observation	Explanation
Initiation of sedimentation of Zodiac fan.	Fragmentation of Farallon plate along west coast of NAM plate. Accretionary, igneous, and erosional events in Pacific Northwest.
Location of fan on Pacific plate.	Transform systems associated with Farallon plate fragments. Cobb and Bowie hotspot tracks. Bathymetrically low magnetic bight region of Pacific plate.
West to east decrease in age of Zodiac fan channels.	West to east disruption of Zodiac sediment channel by Cobb and Bowie hotspot tracks.
Cessation of Zodiac sedimentation.	Subduction of Farallon plate fragments in NE Pacific.
Initiation of Alaska Abyssal plain deposition.	Blocking of Zodiac sediment channel by Cobb and Bowie hotspot tracks. NW movement of Zodiac fan away from source regions in the Pacific Northwest.

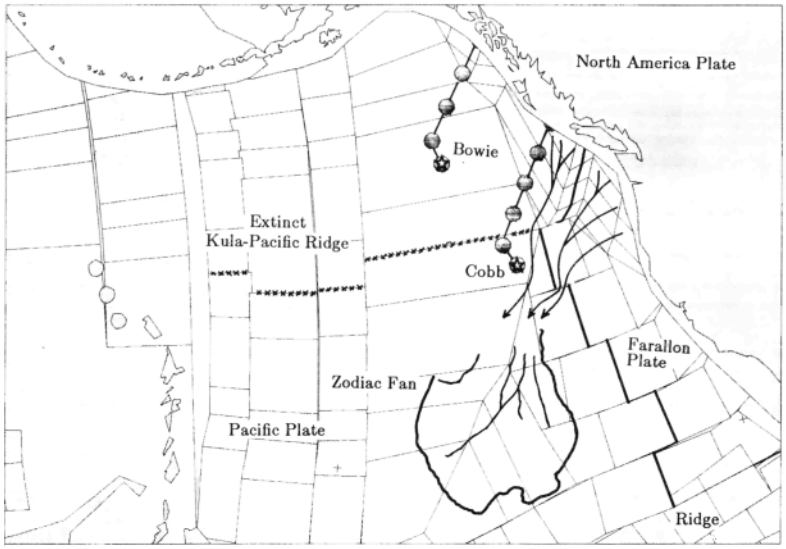


Fig. 10a

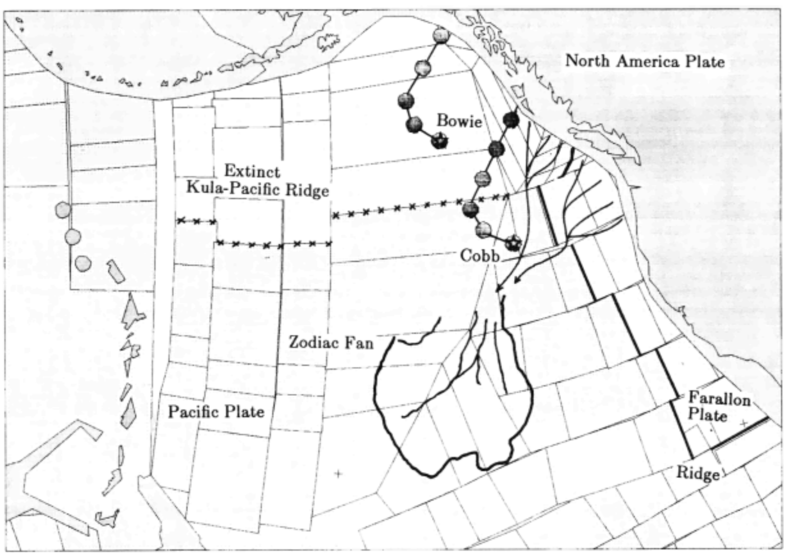


Fig. 10b

Fig. 10. Plate reconstruction in hotspot–fixed coordinates of the Pacific basin at (a) 40, (b) 32, and (c) 24 Ma. At 40 and 32 Ma, sediment is channeled by the Farallon-Pacific ridge and Bowie and Cobb seamounts over the then extinct Kula-Pacific ridge and onto the Pacific plate, forming the Zodiac fan. Sedimentation of the fan stops after subduction of the Farallon-Pacific ridge, formation of seamounts across the principle channel of the Zodiac fan and migration of the fan to the NW, away from sediment source regions in the pacific northwest region of the North American plate. The motion of the hotspot tracks from west to east agrees with the older ages of the western with respect to the eastern channels of the Zodiac fan.

accretion of tectonostratigraphic terranes to the North American plate, volcanic and igneous episodes, and periods of erosion.

The Metchosin volcanics of Vancouver Island accreted between 40 and 36 Ma, and the larger Oregon Coast Range terrane accreted between 57 and 36 Ma [Muller, 1980; Armstrong, 1985; Wells and Coe, 1985]. Both of these terranes probably represent seamounts or tracks of hotspots on the Farallon plate that collided with the North American plate [Wells and Coe, 1985] near the

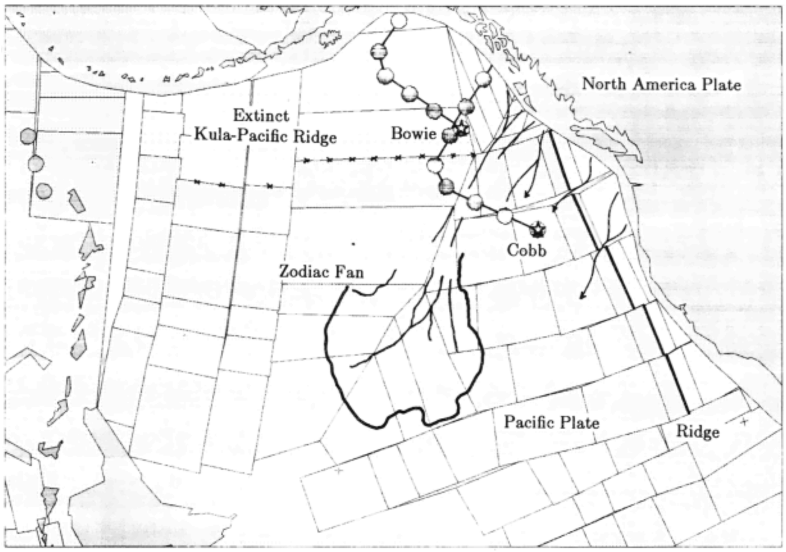


Fig. 10c

time of initial deposition of Zodiac fan sediment. In addition, the beginning of Cascade volcanism occurred about this time, between 42 and 35 Ma, as did the Catface magmatic episode on Vancouver Island between 45 and 36 Ma [Wells et al., 1984; Armstrong, 1985]. Igneous activity also occurred in the southwest Washington Coast Range and Cascade arc during the time of Zodiac fan deposition, with a major episode of Coast Range basaltic and alkalic volcanism between 44 and 30 Ma and deposition of thick ashflow tuffs and ignimbrites in the Cascade arc between 34 and 18 Ma [Wells et al., 1984; Wells and Coe, 1985]. During the interval of Zodiac fan deposition, erosion in the Pacific Northwest is suggested by a regional unconformity between 42 and 35 Ma and rapid erosion and subsidence of the Oregon Coast Range between 44–36 Ma [Wells et al., 1984]. The superposition in time of accretion of tectonostratigraphic terranes, igneous activity, and erosion in the Pacific Northwest region of the North American plate and the geometry of seamount tracks and spreading centers in the Pacific basin were probably responsible for formation of the Zodiac fan. Fan deposition on the Pacific plate was controlled by the geometry of the Bowie and Cobb seamount chains, which blocked sediment from being dispersed over the bathymetrically lower oceanic crust to the west, and the bathymetry of the Pacific plate, which focused sedimentation in the magnetic bight region of the plate (Figures 10a, 10b, and 10c; Table 5).

Reconstructions for the age when Zodiac fan deposition stopped (between 32 and 24 Ma, Figures 10b and 10c) show the subduction of the Farallon–Pacific ridge system along western edge of the North American plate and the obstruction of the main Zodiac fan sedimentation channel by the tracks of the Bowie and Cobb seamounts. The formation of seamounts in the main sediment channel of the Zodiac fan and the migration of the Zodiac fan to the northwest, away from western North American sediment source regions, caused sedimentation on the Zodiac fan to stop and turbidite deposition in the neighboring Alaska Abyssal Plain (Figure 10) to begin. Without focusing of turbidite sedimentation by the hotspot tracks and ridge systems associated with small plates along the western edge of the North American plate, sedimentation was dispersed over the larger Alaska Abyssal Plain. Our model suggests that the present-day Zodiac fan is only a remnant of a much larger fan system and that a large volume of Zodiac fan sediment deposited northeast of the present-day Zodiac fan has been subducted in trench systems bordering the Gulf of Alaska. Subduction of portions of the Zodiac fan may be related to the landward verging thrust systems, vertical uplift and erosion of the accretionary complex on Kodiak Island [Byrne, 1986; Sample and Moore, 1987] and by thick repeated sections of low velocity material at a depth of 12 to 25 km, seen in recent refraction experiments over the Chugach terrane [Page et al., 1986].

SUMMARY

Paleomagnetic data from the Aleutian islands suggests no significant poleward displacement of the Aleutian arc with respect to the North American plate since the early Oligocene. The magnetic directions found in our study are rotated clockwise. Amlia and Umnak islands (separated by 320 km) probably rotated independently in response to the tangential component of Pacific–North American plate convergence since 40 Ma. The formation of the Zodiac fan may be understood by reconstructing the Farallon–Pacific ridge system and the tracks of the Bowie and Cobb hotspots. These reconstructions of the northeast Pacific basin suggest that the interaction of

tectonic events occurring in the Pacific Northwest region of the North American plate and the geometry of the Farallon–Pacific ridge, fragments of the Farallon plate along the northwest margin of the North American plate, hotspot tracks in the northeast Pacific basin, and the absolute motion of the Pacific plate to the northwest, away from sediment source regions in the Pacific Northwest, controlled the timing and geometry of sedimentation in the Zodiac fan.

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William Harbert, Department of Geophysics, Stanford University, Stanford, CA., 94305-2171.

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