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Keck Geology Consortium: Projects 2009-2010
Short Contributions – UNALASKA

LATE CENOZOIC VOLCANISM IN THE ALEUTIAN ARC: EXAMINING THE PRE-HOLOCENE RECORD ON UNALASKA ISLAND

Project Faculty: ***KIRSTEN NICOLAYSEN***: Whitman College
RICHARD HAZLETT: Pomona College

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ADAM CURRY: Pomona College
Research Advisors: Jade Star Lackey and Richard Hazlett

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ALLISON R. GOLDBERG: Williams College
Research Advisor: Reinhard A. Wobus

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Research Advisor: Peter D. Crowley, Amherst College

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Research Advisor: Jim Rougvie

PALEOMAGNETIC EVIDENCE AND IMPLICATIONS FOR STRUCTURAL BLOCK ROTATION ON UNALASKA ISLAND

CLARE TOCHILIN: Whitman College
Research Advisors: Kirsten Nicolaysen and Robert Varga

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Whitman College
Research Advisors: Kirsten Nicolaysen and Robert Varga

INTRODUCTION

The nature of subduction in the Aleutian Arc is unusual compared with that of most other island arcs. Because of the highly arcuate shape of the plate boundary, the Pacific and North American Plates converge at orientations ranging from perpendicular in the east to almost parallel in the west (Avé Lallemant and Oldow, 2000). Also unusual is that the crust of the overriding plate is separated into five structural blocks. Because much of the arc is experiencing westward-directed oblique subduction, these blocks have undergone clockwise rotation (Geist et al., 1988; Harbert, 1987; Krutikov et al., 2008). Due to the remote location of the Aleutian Arc, relatively few studies have characterized the along-arc variation in the rotation of the arc's structural blocks. The presence of a large number of faults in the older rocks of Unalaska Island suggests the accommodation of tectonic motion.

For this study, paleomagnetic core samples were collected from flows of the Lava Ramp sequence, probably Pleistocene in age, erupted from Makushin Volcano and exposed at the south margin of Driftwood Valley (See Figs. 1, 2, Nicolaysen and Hazlett, this volume). A second series of samples was obtained from the Tertiary Unalaska Formation exposed in Dutch Harbor. Finally, samples were drilled from the Captains Bay pluton to investigate whether measuring its polarity could better constrain the intrusion age. These samples were analyzed using alternating field and thermal demagnetization to determine whether or not rotation has occurred in the last 2 Ma on Unalaska Island. When used in conjunction with $^{40}Ar/^{39}Ar$ dating, the polarity of the magnetic signatures can constrain eruption ages of the sampled lava flows. Additionally, bulk rock geochemical analyses and compositional analyses of oxide and sulfide minerals of the Tertiary samples investigated whether these rocks were significantly altered post-emplacement.

GEOLOGIC SETTINGS

Lava Ramp Falls, Driftwood Bay (53°57'N, 167°9'W)

Lava Ramp Falls, so named here, is the prominent waterfall off the north margin of the Lava Ramp sequence at the south end of Driftwood Valley (See Fig. 3, Nicolaysen and Hazlett, this volume). The Lava Ramp, as described by Bean (1999) and McConnell et al. (1997), consists of two late Pleistocene andesitic lava flows that erupted from the northeast flank of Mt. Makushin. These lava flows are estimated by Bean (1999) to be <13 ka and <54 ka based on argon total fusion ages. During our field study, we observed a sequence of five distinct lavas in this area, though the two eruptive events identified by Bean and McConnell may have emplaced more than one lava flow.

The Lava Ramp Falls area is divided into lower and upper falls. Sampling began at the base of an exposure where the lower falls meets the valley floor. Based on calculations from altimeter readings, the flow is approximately 37.15 m thick.

At the upper falls, four flows were sampled stratigraphically (thicknesses 1.2-13.7 m). The west side of the ravine in which the flows are exposed is largely covered by colluvium, providing for limited drillable exposure. Cores were drilled approximately one to two meters from the base of the flow. The next youngest flow is blocky and was drilled approximately one to two meters from the flow base. The flow above this contains a small pyroduct from which the majority of the cores for this flow were drilled. The base of the top flow in the Lava Ramp Falls series, another blocky flow, was obscured; we estimate that drilling took place ~2 meters above the base.

Dutch Harbor (53°53'N, 167°27'W)

The rocks of Dutch Harbor are highly altered, intruded, and faulted, classic examples of the Tertiary Unalaska Formation. Samples for this study were obtained from an exposure behind a small strip mall near Amelia's restaurant. At least twelve small dikes intrude the country rock at this outcrop alone, some of which are highly magnetic and interfered with compass readings. There are also multiple features within the unit that appear to be faults. The expectation was that rocks of this age, with clear evidence of faults in the vicinity, would be most likely to show rotation since their formation. At this outcrop, cores were collected from the country rock and two of the dikes. Hand samples were collected from three areas interpreted to be country rock and from nine dikes.

The country rock is a highly fractured andesitic lava flow. The alteration of this unit increases in areas immediately surrounding intrusions. It was not possible to get a sun compass reading for this site, so bearings were taken to prominent landmarks nearby. Both of the dikes that were sampled are fine-grained, highly altered intrusions.

Granodiorite Quarry, Dutch Harbor (53°50'N, 167°30'W)

The third sampled area is an active granodiorite quarry located in Dutch Harbor. The age of this unit is constrained to younger than 9 Ma based on U-Pb dating of zircons (see Idleman, this volume). This unit is composed of a coarse-grained granodiorite with identifiable plagioclase and green amphibole, intruded by numerous aplitic dikelets.

FIELD METHODS

Oriented core samples were collected using a gas-powered rock core drill. The drill bits were made of stainless steel with tips of diamonds mounted in phosphor bronze. Once each sample was drilled, the orientation of the core with respect to horizontal and north was established using a Pomeroy device and sun compass. If cloud cover prevented a sun sighting, bearings to prominent landmarks served to orient the sample. At each site, between six and nine cores were drilled. Due to the small amount of drillable exposure available at many sites, most samples were drilled approximately one to five meters apart from each other within the same outcrop.

LABORATORY METHODS

Alternating-Field Demagnetization

In igneous rocks, the original paleomagnetic signature, or the characteristic remanent magnetization (ChRM), is locked into mineral grains as the rock cools. Over time, the ChRM may be overprinted by secondary magnetizations called natural remanent magnetizations (NRMs) as a result of the rock being heated or exposed to variations in Earth's magnetic field. Overprinted magnetic signatures must be erased from the sample until only the original signature from the time of petrogenesis remains (Butler, 1998). Alternating-field (AF) demagnetization is one commonly used method of isolating the ChRM in core samples.

For each site, five core segments were analyzed using AF demagnetization in the Paleomagnetics Lab at Pomona College. The NRM of each core before treatment was measured using a Minispin Magnetometer. The cores were then exposed to increasingly strong alternating fields in the AF demagnetizer, and the remaining magnetization was measured in the magnetometer between each level of treatment until the ChRM was measured.

Thermal Demagnetization

Thermal demagnetization is another commonly used method of isolating ChRM. Two core segments from each of the sampled sites were analyzed using this method. The NRM before treatment was measured in the Minispin Magnetometer, and the samples were exposed to progressively higher temperatures in an oven. This process was continued until all overprints were eliminated and only the ChRM was left.

X-Ray Fluorescence

X-ray fluorescence (XRF) analyses of six samples from Dutch Harbor and five samples from Driftwood Bay were carried out in the GeoAnalytical Lab at Washington State University. The samples were crushed and picked through to select the most pristine chips. These chips were ground in a tungsten carbide swing mill. The powder was mixed with dilithium tetraborate and melted into beads appropriate for XRF analysis. Using this method, the concentrations of 27 major and trace elements can be determined by comparing the x-ray intensity for each element with that of nine standard samples (Johnson et al., 1999).

SEM

To obtain compositions of the oxide and sulfide minerals within six samples from the Dutch Harbor site, polished thin sections were analyzed using the FEI Quanta 250 Scanning Electron Microscope (SEM) at Whitman College. For each thin section, between five and seven oxide minerals were analyzed, providing information about the phases carrying the magnetic signature of each sample.

RESULTS

Geochemical Analyses

Based on major element compositions, the Driftwood Bay lavas plot as basaltic andesites and andesites on a total alkali vs. silica diagram and correlate with findings of Nye et al. (1986). The Dutch Harbor samples are slightly less silicic, plotting as basalts and basaltic andesites.

Through SEM imaging, the magnetic phases within the six Dutch Harbor samples were identified. Sample dh09_3, one of the drilled magnetic dikes, contains pyrite (FeS) as the dominant magnetic mineral. Pyrite grains are present both in the groundmass and as inclusions in phenocrysts. No other magnetic phases were identified in this sample. The country rock unit, sample dh09_4, contains titanomagnetite and titanohematite. Small grains of these phases are very common in the groundmass, and some are present as inclusions. Some grains show evidence of exsolution (Fig. 1a). Sample dh09_5, the second magnetic dike that was drilled, contains abundant matrix grains of titanomagnetite and titanohematite. Certain areas within the section contain large grains of these minerals, some of which display shrinkage cracking and exsolution, characteristics of maghemite. This sample also contains a small amount of pyrite.

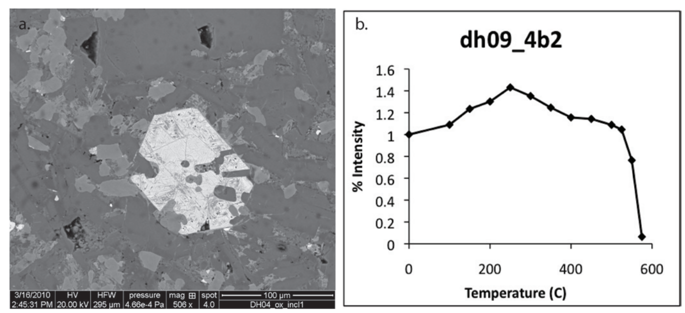

Figure 1. a. Back-scattered electron image of titanomagnetite grain showing exsolution of ilmenite. b. Plot of magnetic intensity versus temperature for sample dh09_4b2 displaying demagnetization of two different phases. Transition between phases occurs at ~300-400°C.

Paleomagnetic Analyses

For the five Driftwood Bay flows, all measured cores are included in mean calculations (Table 1). All sites have alpha-95 values less than 7°, and most values are less than 6°, indicating a high level of precision. All flows have normal polarity, which, combined with the maximum age constraints of <13 ka and <54 ka (Bean, 1999), suggests that these lavas erupted during the C1 polarity chron (Gradstein et al., 2004). Plots of magnetic intensity versus temperature for the thermal samples of sites db09_1, db09_2, and db09_3 display evidence of multiple phases responsible for the NRM in these rocks. Plots for samples db09_4 and db09_5 do not show any obvious phase change, but suggest a range of blocking temperatures for grains in the samples.

Table 1. Paleomagnetic results for Unalaska Island, Alaska.

Site I.D.	Rock Type	Site Location Lat./Long.	N/N_C	NRM (A/m)	Stability MDF	MDT	k	α95	D	I
Driftwood Bay										
db09_1	Lava flow	53.9501°/-166.8405°	7/7	8.823	12.89	256.35	132.8	5.68°	003.5°	74.6°
db09_2	Lava flow	53.9474°/-166.8385°	7/7	16.453	32.17	439.59	105.6	6.38°	314.6°	76.5°
db09_3	Lava flow	53.9474°/-166.8385°	7/7	12.398	32.53	499.44	132.6	5.69°	327.6°	84.7°
db09_4	Lava flow	53.9474°/-166.8385°	7/7	6.095	12.27	420.63	133.7	5.66°	337.9°	84.9°
db09_5	Lava flow	53.9474°/-166.8385°	7/7	5.496	19.51	388.04	225.2	4.36°	322.4°	88.3°
Dutch Harbor										
dh09_3	Dike	53.8879°/-166.5428°	7/7	0.298	27.41	510.44	111.3	6.21°	067.0°	-85.2°
dh09_4	Lava flow	53.8879°/-166.5428°	7/7	0.194	22.64	560.41	424.2	3.17°	034.5°	-85.1°
dh09_5	Dike	53.8879°/-166.5428°	4/7	0.645	2.46	n.d.	248.5	6.75°	106.9°	-79.8°
dq09_1	Quarry	53.8474°/-166.4847°	5/6	0.829	5.04	571.14	62.4	10.93°	025.9°	72.8°

N/N_C = number of cores used in final site mean calculation vs. number of cores measured; MDF = median destructive field or average AF level (mT) where 50% of NRM intensity is lost; MDT = median destructive temperature or average temperature (°C) where 50% of NRM intensity is lost; k = Fisher precision parameter (Fisher, 1953); α95 = radius of circle of confidence at 95% level; D = declination of ChRM; I = inclination of ChRM; n.d. = not determined.

The site mean vectors for each of the five flows are shown in Figure 2.

For the Dutch Harbor country rock and one dike, all measured cores were used for site mean calculations. From a third sample series from one of the highly magnetic dikes, three samples were rejected because they did not reveal any meaningful ChRM. Alpha-95 values for all three units are less than 7º. All three show reversed polarity, but this could represent any one of many different periods of reversal, as the only constraint on their age is >2 Ma. Plots of magnetic intensity versus temperature for the thermal samples of sites dh09_3 and dh09_4 show evidence of phase changes throughout demagnetization at temperatures that are consistent with the Curie temperatures of the minerals observed during SEM analysis (Fig. 1b). There is no meaningful pattern for sample dh09_5.

For the granodiorite quarry, one core was rejected because it was unsuitable for accurate measurement. This site has a high alpha-95 value, as can be expected for plutonic rocks, and it displays normal polarity.

One indication of the reliability of paleomagnetic data is the measurement of magnetic susceptibility of the samples. Samples with high susceptibility contain minerals that are highly magnetizable. Changes in susceptibility throughout thermal demagnetization are indicative of changes in composition. Generally, if a sample retains a large percentage of its initial susceptibility, there has been little change in composition. If the sample loses much of its initial susceptibility, certain minerals may have been metamorphosed due to heating during thermal demagnetization.

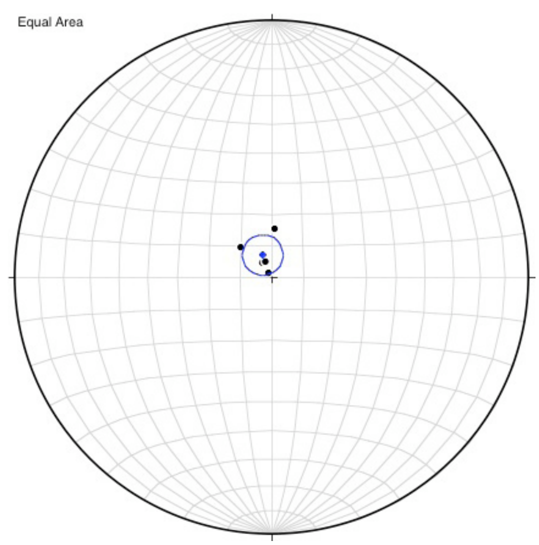

Figure 2. Equal area projection of mean vector directions for the five Driftwood Bay lava flows. Black dots represent individual flow means. Blue dot represents mean vector direction for the lavas. Blue circle represents the alpha-95 confidence limit.

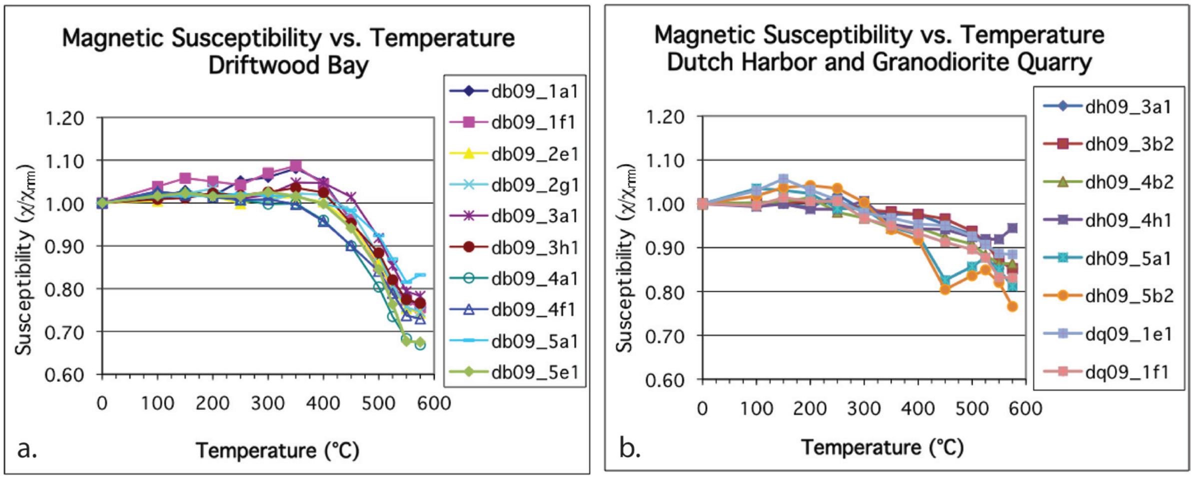

Figure 3. Graphs of susceptibility versus temperature for Driftwood Bay (a) and Dutch Harbor (b) samples.

The susceptibility versus temperature curves for the Dutch Harbor and Driftwood Bay samples are displayed in Figure 3. For Driftwood Bay, all samples retained between 70-80% of initial susceptibility with the exception of two outliers. The Dutch Harbor samples retained a slightly higher percentage (between 80-90%), also with the exception of two outliers. The outliers, both from dh09_5, produced the least meaningful paleomagnetic data of all the samples. It is likely that this lava contains Fe-bearing grains that are easily altered.

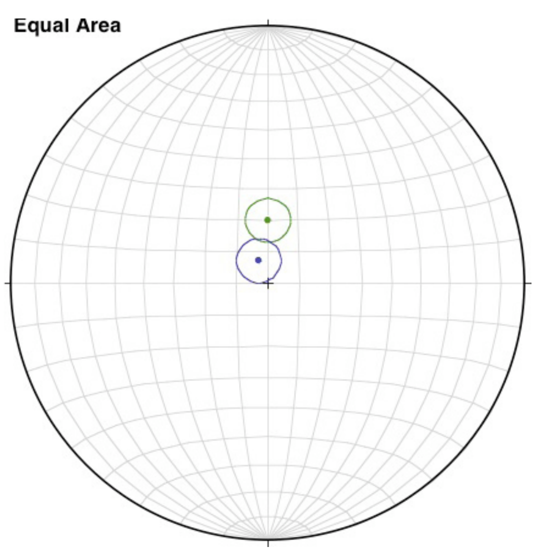

Figure 4. Equal area projection with blue dot representing mean vector for Lava Ramp sequence. Blue circle represents alpha-95 confidence limit for Driftwood Bay data. Green dot represents expected direction of the geocentric axial dipole (GAD) at Driftwood Bay. Green circle represents dispersion of the GAD.

DISCUSSION

The Lava Ramp flows seem to be a suitable sequence for determining whether rotation has occurred since their crystallization. For a sequence of flows to provide an accurate mean vector direction, it must span a large enough period of time (~10^5-10^6 ka) to average out secular variation (Butler, 1998). Based on the available dates of <13 ka and <54 ka for the Lava Ramp, secular variation should be accounted for in site mean calculations. To determine whether rotation has occurred, the site mean was plotted on a stereonet along with the expected geocentric axial dipole (GAD) for Unalaska Island (Fig. 4). Because these vectors plot similarly and the alpha-95 confidence limit for the site mean overlaps with the dispersion of the GAD, no significant rotation is seen in these rocks. Although Harbert (1987) and Krutikov et al. (2008) found rotation in the western Aleutians, no evidence for rotation in modern rocks is found for the eastern Aleutians (Stone and Layer, 2006; Krutikov et al., 2008). This study supports that finding. However, it is difficult to know how effectively secular variation has been averaged out because of the lack of exact dates of the sampled flows.

For the highly faulted Unalaska Formation, it was not possible to determine whether rotation has occurred since its emplacement since only three lavas were sampled. Although we attempted argon dating of the outcrop (see Idleman, this volume), the analysis was unsuccessful, thus the ages of these rocks are still poorly constrained.

CONCLUSION

This study determined that the compositions of the Lava Ramp flows range from basaltic andesite to andesite, and that the rocks of the Unalaska Formation exposed in Dutch Harbor are slightly more mafic, ranging from basalt to basaltic andesite. The Dutch Harbor samples contain a variety of Fe-bearing magnetic phases, including titanomagnetite, titanohematite, and pyrite, the combination of which determines the nature of the magnetic signature of that rock.

No conclusions about rotation can be drawn from the paleomagnetic analysis of three lavas of the Tertiary Unalaska Formation. However, analyses of samples from five Lava Ramp flows at the southeast margin of Driftwood Valley reveal that no significant rotation has occurred on Unalaska Island since their eruption (~54 ka).

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