# PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2015
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# KECK GEOLOGY CONSORTIUM
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# Keck Geology Consortium: Projects 2014-2015
# Short Contributions— Volcanic Hazards and Human Interaction, AK Project



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# SILICIC LAVAS OF MT. TANA AND THE ISLANDS OF THE FOUR MOUNTAINS, AK

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## INTRODUCTION

The Islands of the Four Mountains (IFM) are a cluster of small stratocones (5-10 km diameters, elevations 1300-1700 m) in the central Aleutian volcanic arc, comprised of Tana, Cleveland, Carlisle, Kagamil, and Herbert volcanoes. The Unangan (Aleut) people inhabited the IFM periodically since circa 2990 $^{14}$C yBP (see Loopesko, 2015 this volume). Obsidian flakes and tools as well as tools made of sparsely plagioclase-phyric, non-glassy lavas have been recovered from IFM archaeological deposits (see Bartlett, 2015 this volume). This study focused on sampling the most silicic lavas of four volcanoes to determine what lithic resources people most utilized. Additionally, geochemical analysis of these silicic lavas provides an opportunity for new insight into the volcanic and magmatic relationships among the IFM volcanoes, as well as with the rest of the Aleutian arc.

The majority of volcanoes in the United States lie within the Aleutian volcanic arc, and more than 40 have been historically active since 1760 (Schaefer & Nye, 2008). Despite the frequent activity of Mt. Cleveland, there is little published geological data on the IFM, and until 2014 all volcanic monitoring was conducted remotely. Thus, it is critically important to have monitoring systems in place for North Pacific volcanoes and have a detailed understanding of the geologic nature of these volcanoes to determine volcanic history and potential future behavior. The presence of highly explosive eruptions in the past in the IFM, evidenced by an ignimbrite deposit identified in this study, imply that similar events could happen again.

The IFM are an intriguing group of islands in the central Aleutians that stand out geochemically and culturally in the region. Approximately 112 rock samples were collected from the IFM (Tana, Cleveland, Carlisle, and Herbert) in 2014, including over 30 targeted specifically for their silicic nature. Whole rock XRF analyses give major and trace element data, and a detailed SEM petrographic study provide distinguishing textural data for the volcanic deposits. The ignimbrite found on northern Tana stands out as the most chemically and texturally unique deposit and reveals much about the area's explosive history.

## FIELD OBSERVATIONS

The primary focus of this study is Tana, the largest and furthest east of the IFM volcanoes. Tana has a series of overlapping eruptive centers and an active hydrothermal system. Evidence of older eruptive centers is present on Chuginadak's southern most point including Black Peak, the remnants of a large dissected cone. Tana has an extensive history of silicic volcanism overlain by Holocene mafic fissure eruption on its western side (Fig. 1.). A previously undocumented ignimbrite deposit on its northern flanks is reported here, which is of great interest to this project because it implies highly explosive volcanism occurred in the past (Fig. 2). Moreover the glassy nature of the welded portion is perhaps suitable for tool manufacture; testing this hypothesis requires petrographic and geochemical analysis.

Fine-grained silicic clasts and lavas that showed conchoidal fracture were also targeted for their potential as tool material. Two block and ash flows

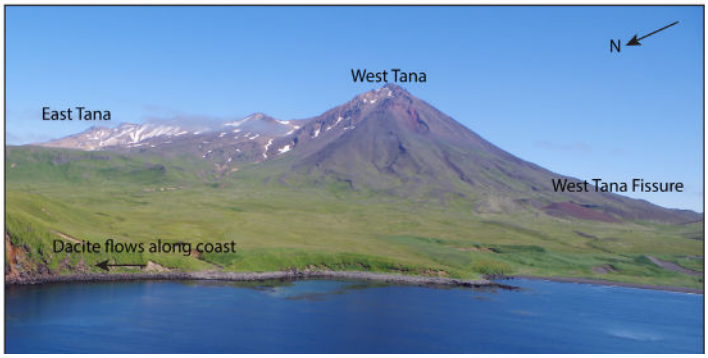


*Figure 1. Schematic of Tana's main morphological features. Older silicic deposits are exposed on the coast, and deposits to the east are noticeably siliceous. Mafic fissure deposits, including several small cinder cones, overly older, more silicic lava flows on Tana's western-most side.*

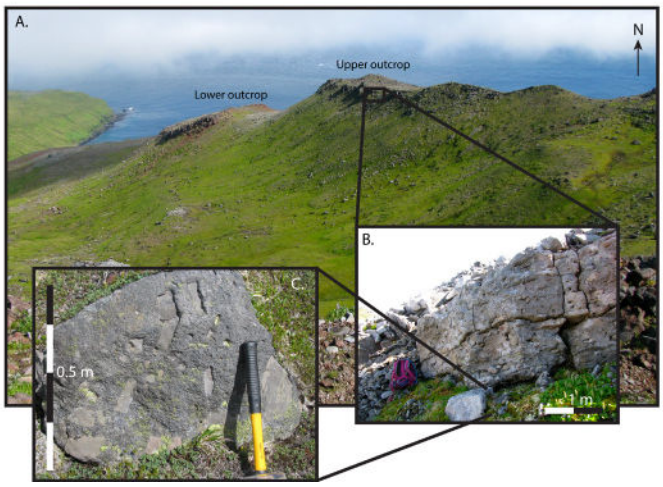


*Figure 2. (A) This photo shows the ignimbrite outcrops on the east side of a small valley on Tana's north flank. Skiff Cove can be seen in the distance. (B) The deposit is ~2 m thick at the upper outcrop, and the surface is heavily weathered. (C) Lithic clasts within the ignimbrite matrix are easily visible and angular.*

with glassy lithic blocks from the northern flank of Cleveland, one from the southern flank of Tana, and dome fragments from the flanks of Herbert volcano may be candidates for archeologically-significant source materials and were thus sampled thoroughly. A number of glassy lava flows are also exposed on the coast of Tana very near one of the largest archeological sites in the IFM.

## METHODOLOGY

I collected 29 samples and aided in the collection of some 83 additional samples from Tana, Cleveland, Carlisle, and Herbert volcanoes in exposures ranging from lava flows, silicic clasts in block and ash flows, a welded crystal lithic tuff, to a pumiceous tephra deposit. Tana, the largest of the IFM volcanoes, due to its proximity to archeological sites and its more silicic outcrops provided the largest sample set. These samples represent lava flows from the volcano's northwest, southwest, and southern flanks as well as a newly documented ignimbrite deposit from near the northern summit. The ignimbrite contains large, welded fiammé, clasts of a separate origin, and obsidian fragments

Samples of selected rocks were cut for standard petrographic thin section analysis by polarizing microscope, cathodoluminescence imaging, and with a Hitachi SU-70 field emission Scanning Electron Microscope equipped with backscattered and secondary electron detectors as well as an energy-dispersive spectrometer for qualitative chemical analysis. Seventeen samples were powdered for X-Ray Fluorescence (XRF) major element analysis at Pomona College using a tungsten-carbide mill. This was supplemented by XRF and ICP-MS analyses of forty-two 2014 samples and more than 60 analyses of samples obtained in 2002-2004 all performed at the WSU Geoanalytical lab. Major and selected trace element chemistry of bulk rock was obtained for samples prepared as a single, low-dilution fused bead that was analyzed by x-ray fluorescence at Pomona College and Washington State University. Methods and error analysis were similar to those used in Lackey et al. (2012).

## RESULTS

### PETROGRAPHY

The glassy matrix of the Tana ignimbrite has 20% plagioclase phenocrysts, and there are about 60% plagioclase phenocrysts in the lithic clasts. The matrix material exhibits vitrophyric texture with glomeroclots of plagioclase, olivine, and opx, as well as embayed plagioclase phenocrysts (Fig. 3-A.) The matrix also contains unusually euhedral olivine and opx crystals, as well as spherulite growth in the glassy groundmass (Fig. 3-B). Resistant lithic clasts protruded from the tuff and were typically elongate parallel to bedding consistent with flattening or flow orientation. The lithic clasts are highly crystalline and contain ~60% plagioclase phenocrysts in stark contrast to the

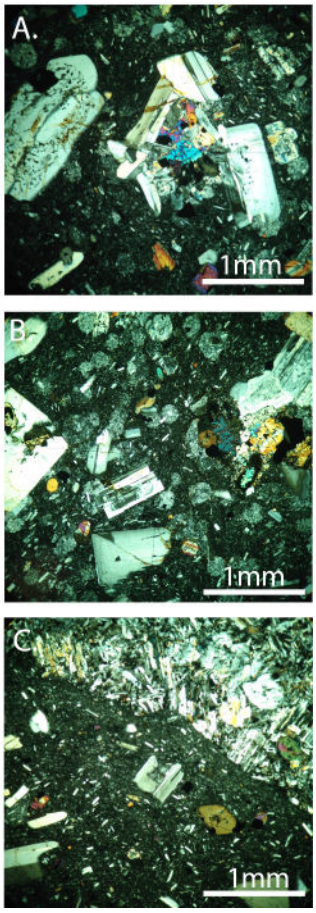


*Figure 3. (A) Photomicrograph of a glomeroclot from the Tana ignimbrite matrix, as well as a heavily sieved plagioclase phenocryst to the left. (B) Spherulite growth in the ignimbrite's glassy groundmass. (C) The contact between the ignimbrite matrix (with an embayed plagioclase in the lower left corner) and one of the highly crystalline clasts.*

ignimbrite matrix (Fig. 3-C) and contain ~15-20% pyroxene phenocrysts.

The glassy lava flows from Tana's northern coast near site CG02 contain an average of 25% plagioclase phenocrysts. In nearly all samples plagioclase phenocrysts show sieve textures, reaction rims, and oscillatory zoning and some had many crystal embayments. Sample 14TAAF-2 contains a highly crystalline xenolith or enclave that is very similar texturally to the ignimbrite lithic clasts, except for a lower pyroxene concentration.

The glassy lithics from the block and ash flows on the northern side of Cleveland contain roughly 35% plagioclase phenocrysts (0.5-3mm) and very glassy groundmasses with little devitrification. The plagioclase phenocrysts show extensive disequilibrium textures including, sieve texture, oscillatory zoning, and abundant melt inclusions.

## GEOCHEMISTRY

For the most silicic lavas and ignimbrite (>63 wt.% $SiO_2$) on Tana (including samples analyzed at both Pomona College and WSU), ranges of oxide concentrations normalized to a volatile free weight percentage are: 62.57-67.60 $SiO_2$, 0.65-0.88 $TiO_2$, 14.93-16.75 $Al_2O_3$, 4.15-5.54 FeO*, 0.09-0.12 MnO, 1.22-2.88 MgO, 3.46-5.78 CaO, and 1.85-2.65 $K_2O$ (Fig. 4). Silicic Tana samples have an average $SiO_2$ content of ~65 wt.% compared to an average of ~52 wt.% for the more mafic Tana fissure deposits on the western flank. Other differences between the older silicic deposits and the west Tana fissure eruption include MgO (6.5 wt.% fissure), CaO (5.9 wt.% fissure), and $K_2O$ (1.8 wt.% fissure). It is also of note that the silicic deposits have an average Rb concentration of 55.9 ppm, while the fissure deposits only have an average of ~9.3 ppm. The Tana ignimbrite matrix (bulk) rock plots in the dacite field of the total alkalis-silica (TAS) diagram of La Maitre (1989) at 67.6 wt.% $SiO_2$, whereas the lithic clasts it contains are basaltic andesite (56.3 wt.% $SiO_2$).

Figure 4 shows the compositional trends for all IFM volcanoes and obsidian samples from Okmok and Akutan on a TAS diagram. Okmok and Akutan are documented locations of Aleut obsidian use and their chemical data are used to compare to IFM silicic samples.

## DISCUSSION

The IFM islands are a cluster of calc-alkaline volcanoes in between several tholeiitic volcanoes to the east and west. Previous workers found that most Aleutian volcanoes are tholeiitic, including volcanic centers directly surrounding the IFM to the east and west (Kay et al., 1982; Zimmer et al., 2010). Tholeiitic volcanic centers tend to be large basaltic volcanoes between or at segments boundaries, whereas calc-alkaline volcanoes tend to be smaller, primarily andesitic, and at the centers of segments (Kay et al., 1982; Zimmer et al., 2010). The relatively small IFM volcanoes are located at the center of an arc segment following Kay et al. (1982). Their compositions may

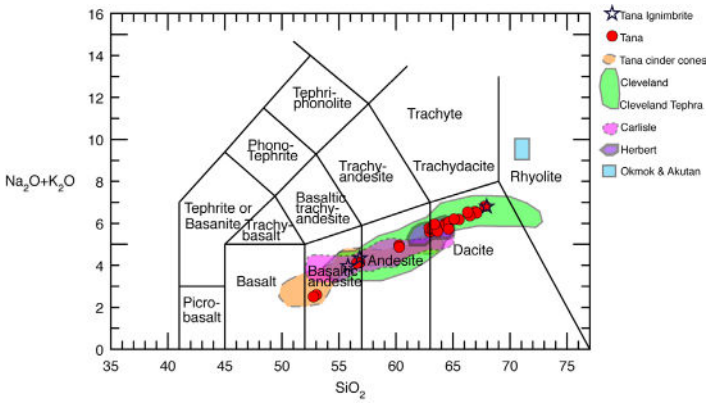


*Figure 4. Most IFM eruptions yield basaltic andesite and andesite. Tana has the largest proportion of dacite thus far. Note that the Cleveland field extends into the rhyolite range because of a single 2001 pumice; most of Cleveland's lavas are basaltic andesite and andesite.*

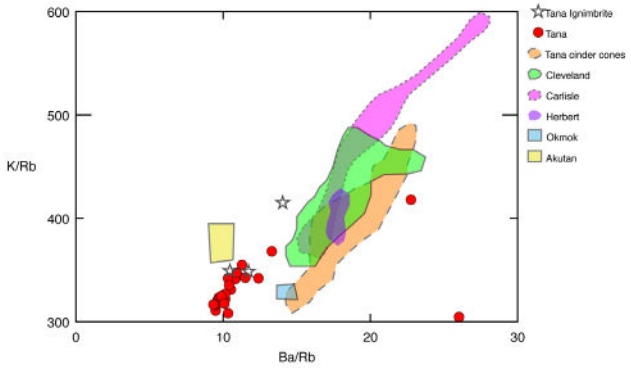


*Figure 5. Plot showing distinct subparallel trends that suggest different magma sources and/or degrees of partial melting.*

be due to greater crustal thickness at the center of the segment plus an increased magmatic water input.

The Tana ignimbrite was found in exposures on both sides of the valley that opens to Skiff Cove on the northern flank of the volcano (Fig. 2). In outcrop, the ignimbrite is 2-3 m thick, which is a minimum due to a high level of erosion in the area. Large blocks (>2m diameter) of similar ignimbrite material were found on the beach ~8 km south at Concord Point (the southern most point of Chuginadak Island) and ~18 km to the northwest on the southeast side of Carlisle. The wide distribution of ignimbrite blocks suggests a very large, caldera forming eruption eruption from either Tana or a nearby caldera system (P. Izbekov, pers. comm.).

CFE occurrence depends highly on tectonics, but the main control is the flux of basaltic magma from the mantle to produce and support large silicic systems (de Silva, 2008). CFE's can be part of regional ignimbrite flare-ups where spatially and temporally related centers erupt when triggered by a major change in mantle magma production (de Silva, 2008). With magma production rates of 182 $km^3$/km/m.y., the Aleutian arc is one of the most rapidly evolving arc systems (Jicha, Scholl, Singer, Yogodzinski, & Kay, 2006). The Aleutian arc has undergone several pulses of high magma production in the Eocene, Miocene, and Pliocene (Jicha et al., 2006). The most recent increase in magma production in the Pliocene (~6-0 Ma) and likely resulting CFE's could account for the silicious ignimbrite found in the IFM.

In a high silica source, mafic grains should be in disequilibrium, so it is rare for pyroxene crystals to be euhedral in an ignimbrite or welded tuff. Because the Tana ignimbrite contains unusually euhedral phenocrysts, it is interpreted to have undergone a magma-mixing episode immediately before eruption. This very vigorous and quick mixing episode could have been the final triggering mechanism for the explosive ignimbrite-forming eruption (e.g., Bergantz & Breidenthal, 2001). The lithic clasts within the welded matrix of the igimbrite are highly crystalline and likely too crystalline to have erupted as a flow suggesting a hypabyssal source that was fragmented by the explosive CFE eruption.

$K_2O$ and Rb concentrations in silicic Tana lavas and ignimbrite are notably higher than other IFM values (Fig. 5.). Hydrothermal alteration is unlikely to have caused the enriched Rb. Instead, Tana shows evidence for significant input of crustal sediment in the sub-arc mantle wedge. It is estimated that roughly 20% of elements in subducted sediments are recycled back into the volcanic arc, and this extent is influenced by sediment flux and convergence rate (Plank & Langmuir, 1993). Aleutian convergence rates vary from 5 cm/a in the eastern parts of the arc to 6.6-6.8 cm/a in the west near Seguam (Plank & Langmuir, 1993; Jicha et al., 2006). If sediment is high in an element, it is reflected in the arc volcanic compositions. The trace element compositions from Tana dacites are very close to reported sediment bulk compositions. For example, bulk sediment compositions for $K_2O$ and Rb were recorded at 2.22 wt.% and 59.7 ppm respectively (Plank & Langmuir,

1993); Tana dacites and ignimbrite have roughly 2 wt.% $K_2O$ and 45-69 ppm Rb, which are closer to sediment compositions than any of the other IFM volcanoes. In sum, the Tana lavas are thought to have melt sources with a higher sediment flux than previously recognized in the Aleutian arc.

A major goal of this study was to test whether Tana glassy dacites were possible sources for archeologically-significant stone tools on the islands. However, the majority of recovered tools and debitage are of rhyolitic obsidian, although others range from basalt to dacite (Bartlett 2015, this volume). The Tana dacitic ignimbrite matrix has some small glassy fragments, but these are not conclusive enough to be an obsidian source. The ignimbrite's matrix also has the highest silica content in the entire area with the exception of rare pumice from the 2001 Cleveland eruption (Nicolaysen, pers. comm.), so it would have been a great source of tool material if material from outcrops is not hydrated and devitrified. As yet, there have been no obsidian flows identified on the IFM. The recovered aphyric, non-glassy tools have yet unidentified sources. Obsidian data from Okmok, Akutan, and Margaret Bay do not plot chemically with any of the IFM data, implying that Tana's lavas are distinct from these other locations.

## CONCLUSIONS

The Islands of the Four Mountains are a group of small calc-alkaline volcanic cones in the central Aleutian arc. Their magma generation included high magmatic water content and varying levels of crustal sediment input likely based on time of generation and eruption. All volcanoes in the area appear to have produced silicic eruptions at one or more points in their histories. Relative to the other IFM volcanoes, Tana is the most compositionally diverse with a pronounced silicic phase in stratigraphically older units. The Tana ignimbrite is of similar composition as the Tana dacitic lava flows, but it includes unique, highly crystalline basaltic andesite clasts from a hypabyssal source. The welded ignimbrite is the first documented evidence of large explosive eruptions in the IFM, and may have been triggered by a mixing event just preceding eruption. Stratigraphically, this deposit is Quaternary in age and calls for further investigation.

This study of Tana's silicic deposits has failed to find an obsidian source on any of the Islands of the Four Mountains, though it is possible that the welded matrix of the ignimbrite, if crystal poor could have provided suitable material for tools. Further analyses and comparisons of IFM silicic lavas and prehistoric tools are in progress.

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