The Aleutian arc through and through: How subduction dynamics influence the generation, storage, and eruption of volatile-bearing magmas

Daniel Rasmussen (LDEO, Columbia University), Terry Plank (LDEO, Columbia University), Diana Roman (Carnegie Institution)

Does the volcano know about the slab? Our work in the central-eastern Aleutian arc seeks to address this question. Spanning from Seguam volcano (west) to Shishaldin volcano (east), our corridor is marked by significant variations in magmatic water contents, seismicity, deformation, and style and frequency of volcanism. By contrast, most subduction parameters, such as slab age and velocity, remain constant. One significant exception is the depth of the slab below the frontal arc volcanoes, which transitions from a near global minimum in the west (~65 km BSL) to a more typical depth in the east (~100 km BSL). This makes our corridor an ideal locality to isolate the role of slab depth in driving magmatic processes. After a one-year-long seismic deployment, forty five-gallon buckets of new rock samples, and one PhD dissertation, we are arriving at some answers.

The broad strokes of arc magma genesis are well established: hydrated sediment and oceanic lithosphere subduct and release fluids and/or solids that drive melting of the overlying mantle wedge, generating hydrous arc magmas that ascend to regions of melt coalescence either within or beneath the crust. However, understanding transport and storage of magmas in the crust represents a fundamental challenge to the study of evolution and eruption of arc magmas. Recent development of several geochemical and geophysical tools enables us to closely track the path of magma through the crust, particularly in the upper crust. We are employing these tools to illuminate the development and eruption of upper crustal reservoirs and link these processes to arc magma genesis.

Figure 1. The central-eastern Aleutian arc. (a) Map of our field area with historically active volcanic centers labeled. Dashed lines are slab contours from Syracuse and Abers (2006). The Amlia Fracture Zone (AFZ) is shown in the inset map. (b) Results of our new slab depth analyses for volcanoes studied here (colored symbols) and other volcanic centers (gray symbols). (c) Histogram of slab depths beneath arc frontal arc volcanoes worldwide from Syracuse and Abers (2006).
This work bridges the gap between the origin of volatile-bearing magmas and crustal magmatic processes, two big picture problems normally approached separately. We have gone to the central-eastern Aleutian arc to address these problems, capitalizing on the GeoPRISMS platform for Alaskan research and working in close collaboration with the Alaska Volcano Observatory and Deep Carbon Observatory. Our project combines melt-inclusion analysis, diffusion chronometry, gas geochemistry, and earthquake location and source-mechanism analysis to address several key questions:

1. How do magmas transit the crust prior to eruption?
2. Where do magmas stall and why?
3. How do subduction parameters influence primary magma compositions?

Slab depth may be an important subduction parameter controlling magmatic processes. Variation in slab depth below frontal arc volcanoes worldwide (60 km to more than 150 km; Syracuse and Abers, 2006) leads to profound variations in the sub-arc thermal structure of the slab and mantle wedge, controlling H₂O flux from the slab and melt production. For example, increased slab depth leads to progressive slab H₂O loss (van Keken et al., 2011) and hotter fluids that transport more silicate (Hermann et al., 2006), if melt transport is predominantly vertical. Thus, slab depth likely modulates the composition of arc magmas, which in turn may control their path through the crust. An ideal location to isolate the role of slab depth in arc magmatism is the central-eastern Aleutians (Seguam to Shishaldin, 172.5-164 °W; Fig. 1). Our new work shows that slab depth varies from a near global minimum of ~65 km (Seguam) to a more typical value of ~100 km (Shishaldin), consistent with earlier work (Syracuse and Abers, 2006). Other subduction parameters (e.g., slab age, velocity) do not vary significantly (<10%). Magmas in this corridor have long been known to exhibit a wide range of chemical composition, seismicity, and eruptive behavior (Larsen, 2016). How much of this variability might originate in the slab?

While the Aleutians provide an ideal laboratory for the study of tectonic and magmatic processes, a dearth of relevant rock samples and seismic data exist due to the remote locations. This motivated our field campaigns in the summers of 2015 and 2016.

Our objectives were fourfold:

- Deploy twelve broadband seismometers in the vicinity of Cleveland volcano for one year,
- Collect tephra along the entire corridor,
- Measure volcanic gas emissions,
- Avoid the bears.

Cleveland is a focal point for our work because it is both highly active and highly understudied. Our work was facilitated by the R/V *Maritime Maid*, which moved us between islands and provided logistical support, and a helicopter from *Maritime Helicopter*, which carried us to our field sites (Fig. 2). Despite challenging weather and field conditions, our fieldwork was an enormous success. We retrieved over 170 rock samples, six lake cores, gas data from the actively degassing volcanoes, and a year of seismic data that spanned multiple eruptive episodes at Cleveland volcano.

We have taken a top-down approach to our research, first focusing on how magmas transit the crust in the months, days, and hours before volcanic eruption.
We conducted a focused study of the 1999 eruption of Shishaldin volcano (Rasmussen et al., 2018c), which is compelling for multiple reasons. This sub-Plinian eruption had an unusually long phase of seismic activity preceding the eruption, and, despite the 43 million m$^3$ of tephra ejected, InSAR data recorded no discernable eruption-related deformation. We established a close temporal link between increased seismicity, stress field changes inferred from shear-wave splitting analysis, and magma mixing recorded by crystal clocks, confirming that precursory seismicity tracked the priming of the magmatic system for eruption by delivery of new magma (Fig. 3). Our study was the first to connect timescale information recorded in chemical zonation patterns in crystals with depth information recorded in melt inclusions, which we used along with geophysical data to interrogate a previously enigmatic magmatic plumbing system. We found that a shallow magmatic system located largely within the edifice (<3 km below the summit) persists between eruptions. Prior to the 1999 eruption, the shallow magmatic system was recharged with deep (>20 km) magma. InSAR observations at Shishaldin are insensitive to deformation emanating from the shallow and deep parts of the system, in part explaining the lack of an observed deformation signal. These results improve our understanding of eruption triggers and magmatic plumbing systems. But this work raises the question, is the magmatic system at Shishaldin unusually shallow?

Broadening our scope, we evaluated magma storage depths throughout our corridor (Rasmussen et al., 2018b). Geophysical constraints indicate these depths vary significantly (~2-8 km below the edifice; Fig. 4). The cause of such variability is poorly understood. Some have argued for the importance of intrinsic (e.g., buoyancy, viscosity) controls (Annen et al., 2006), while others have emphasized the importance of extrinsic (e.g., crustal structure) controls (Chaussard and Amelung, 2014). We investigated the influence of magmatic water content, a key intrinsic variable, on magma storage depth. Water is thought to be important because decompression-induced degassing during magma ascent results in an increase in melt viscosity and magma crystallinity, both promoting stalling. We estimated magmatic water content by measuring large suites of melt inclusions and taking the maximum observed water contents, which minimizes the influence of diffusive leakage of water. Water contents are variable (~2-5 wt.%) and correlate positively with geophysically determined magma storage depths, falling along the water-saturation curve (Fig. 4). The maximum water contents of melt inclusions often correlate with non-volatile trace elements, indicating diffusive leakage is not a major factor. Thus, our data support a model in which intrinsically drier magmas (like those that feed Shishaldin) degas and crystallize shallower than wet magmas, resulting in shallower storage prior to eruption. So, what controls primary water content?

Now in the final leg of our pursuit to understand the slab-volcano connection, we are focusing on the extent to which slab depth relates to the composition of arc magmas (Rasmussen et al., 2018a). We have collected major, trace, and volatile element data in melt inclusions and bulk rock samples from the eight target volcanic centers in our corridor (Fig. 1). These data exhibit systematic trends with slab depth (Fig. 5).
For example, Shishaldin has the greatest slab depth, and its magmas have the lowest $\text{H}_2\text{O}/\text{Ce}$ and highest $\text{Dy}/\text{Yb}$. This relationship holds overall, where $\text{H}_2\text{O}/\text{Ce}$ (1000-4500) and $\text{H}_2\text{O}/\text{K}_2\text{O}$ (2-9), both proxies for slab surface temperature (Plank et al., 2009), negatively correlate with slab depth. This implies slab temperatures are just above the $\text{H}_2\text{O}$-saturated sediment solidus at 65 km depth and ~250 °C above the solidus at 100 km depth. Greater temperatures of the slab would predict melting deeper into the slab, which might explain the observed increase in $\text{Dy}/\text{Yb}$ with slab depth. Interestingly, the volcanoes are generally larger and closer together where the slab depth is greater, possibly suggesting melt flux is greater in these locations. These results indicate that slab depth has a strong influence on the generation of arc magmas. Armed with this understanding, our final efforts on this project will focus on the missing link between the mantle melting process that is driven by slab inputs and the water contents of magmas that control magmatic plumbing systems.

Our work is a prime example of the strength of the GeoPRISMS Program in facilitating multi-disciplinary research to understand dynamic processes occurring at plate boundaries. Additionally, this work has been propelled forward by close partnerships with the Deep Carbon Observatory and Alaskan Volcano Observatory, which has led to several new active collaborations. Finally, our work has benefited from additional funding provided by the Don Richter Memorial Scholarship awarded by the Alaska Geological Society and the Jack Kleinman Grant for Volcano Research awarded by the Community Foundation for Southwest Washington and USGS.

**Figure 5.** Variation in volatile and trace element compositions of magmas with slab depth (Rasmussen et al., 2018a). (a) $\text{H}_2\text{O}/\text{Ce}$ and $\text{H}_2\text{O}/\text{K}_2\text{O}$ (agrees with $\text{H}_2\text{O}/\text{Ce}$, but not shown) are proxies for slab temperature. Temperature relative to the wet sediment solidus ($\Delta T$) is calculated using the thermometer of Plank et al. (2009). (b) Increased $\text{Dy}/\text{Yb}$ may indicate an increased role of garnet.

**References**


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