From the Slab to the Surface: Origin, Storage, Ascent and Eruption of Volatile-Bearing Magmas

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Proposed Sites: Unimak-to-Cleveland corridor; Cook Inlet (Augustine-to-Spurr) corridor (Fig. 1)

Related SCD Themes: This white paper directly supports the primary theme from the SCD Implementation Plan:
C. How are melts delivered from the mantle to the arc crust and out the volcano? What is the relationship between magmas that erupt and those that freeze in the crust?

Key Existing Data/Infrastructure*:
- PBO Volcanoes (AK, AU, OK, UN)
- AVO Intensive Mapping efforts (AU, AK, FI, MK, OK, RD, SH, SP)
- AVO/PBO Seismic Arrays (AK, AU, IL, MK, OK, RD, SH, SP, UN)
- Zimmer et al. (2010) baseline study of volatile contents (AK, AU, MK, OK, SH)
- Completed studies of precursory and non-eruptive volcanic earthquake swarms (AK, AU, IL, RD, SH, SP)

*Akutan (AK), Augustine (AU), Fisher (FI), Iliamna (IL), Makushin (MK), Okmok (OK), Redoubt (RD), Shishaldin (SH), Spurr (SP), Unimak Island (UN)

1. From the Slab to the Surface:

Volatiles (H_2O and CO_2) fuel volcanic eruptions, but what processes deliver different quantities of fuel to each volcano? How do volatiles leak out of magmas during ascent? And how do magma compositions and degassing processes affect the ascent, storage and eruption of magmas? At a convergent margin like Alaska, these questions are likely related all the way down to the devolatilization reactions in the subducting slab. One of the discoveries made by the MARGINS program is that volcanic plumbing systems may be imaged seismically down into the mantle. For example, a low Vp/Vs column beneath Nicaragua connects the volcanic system in the crust to the dehydrating system in the subducting slab (Syracuse et al., 2008). EarthScope researchers have discovered that volcanoes respire geodetically and speak seismically, revealing the depths of magma storage and degassing and the mechanisms of magma ascent. Connecting shallow and deep magmatic systems is a new challenge to GeoPrisms, but one that holds promise for linking - for the first time - subduction processes to eruptions and shallow intrusions.

Volatile Cycling - The deep-Earth volatile cycle contains 75-90% of Earth's water and carbon, yet its characteristics are poorly understood when compared with the surface cycle. The most significant interface between the surface and deep-Earth volatile cycles is the global subduction zone system; >99% of volatile input into the Earth's interior, >50% of volatile degassing, >90% of great earthquakes, and half of the Earth's volcanic activity occurs within 200km of a subduction trench. Volatile cycling between the surficial and deep-Earth cycles is initiated by transport of water-rich sediments and altered oceanic crust to the Earth's interior in subduction zones, where earthquakes testify to the processes of slab dehydration and deformation. Volcanoes deliver important volatile-bearing compounds from the deep Earth and vent gases (including greenhouse gases) into the atmosphere on timescales that are important to Earth's long-term climate variability. Yet the balance of delivery and return between the Earth's surface and interior is so poorly known that we don't even know whether the net flux of water or carbon is into - or out of - the Earth's interior, which is a key constraint on its evolution.

From the slab to the Moho - Combined geodynamic-petrological models now make predictions as to the flux of volatiles released from the subducting plate (van Keken et al., 2011) and seismic images can now illuminate the melting region in the mantle wedge, but these source regions have yet to be linked to volatile fluxes at the surface. Aleutian magmas record a link between water and other slab tracers (Fig. 2), but do higher erupted water contents reflect a wetter slab, more efficient recycling, or different mantle melting conditions?

From the Moho to midcrustal storage reservoirs - Magmas form storage reservoirs by stalling in the deep- to mid-crust, but it is not known whether the control is intrinsic (magma buoyancy, viscosity and volatile content) or extrinsic (regional stress regimes). The depth and duration of magma storage may set the mode of crustal evolution and the vigor of eruption. Geodetic, seismological and petrologic observations can be used in tandem to test models of magma ascent, stalling and freezing. Deep long period (LP) earthquakes (Power et al., 2004) occur at >10 km depth, and are thought to be linked with deep crustal magma storage and transport systems. For example, in Alaska, deep LPs are recorded both in association with eruptive activity, and in the absence of eruptions, at many volcanoes including Spurr, Redoubt, Iliamna, Akutan, and Makushin. A careful synthesis of geophysical and petrological data can potentially reveal melt and fluid transport pathways in the deep crust.

From storage to eruption - Imaging of reservoir-to-surface magma plumbing systems is possible through analysis of geodetic, seismic, and petrologic data. Melt inclusion studies not only provide information on arc volatile budgets, but can also be used to estimate storage conditions and conditions of dynamic crystallization during ascent. Pressure increases in midcrustal magma storage and transport systems are commonly signaled by an onset or increase in microseismic activity beneath the volcano, but only a fraction of these episodes of unrest proceed to eruption – is the fate of a batch of magma ascending through the shallow crust somehow linked to tectonic setting, magma volume and/or ascent rate, magma composition, or volatile contents (Fig. 3)?

2. Opportunities in Alaska:

Focusing of the GeoPRISMS effort on two specific Aleutian arc "discovery corridors", the Cook Inlet corridor and the Shishaldin-to-Cleveland corridor (Fig. 1), will provide an unprecedented opportunity to study relationships between tectonic setting, earthquakes, magmatic volatile transport, magma composition/rheology, and volcanism.

The Cook Inlet corridor extends for 200km from Mt. Spurr to Augustine Volcano at the easternmost terminus of the Aleutian arc, and is located on young continental crust. The Cook Inlet corridor is just south of the locus of the 2nd largest earthquake in recorded history (M9.2, Prince William Sound 1964), and just north of the largest volcanic eruption of the past century (1912 Katmai). The Cook Inlet corridor itself has experienced only a single >M7 earthquake over the past century (1909 M7.4 Kenai), indicating the presence of an actively slipping subduction megathrust. Cook Inlet corridor magmas are generally volatile- and crystal-rich andesites and dacite, and include the most water-rich volcanic system in the entire Aleutian arc (Augustine volcano). Geophysical and petrological evidence indicates short-term storage or hybridization occurring at about 4-10 km depth (Spurr, Redoubt, and Augustine: Gardner et al. 1998; Lahr et al., 1994; Roman et al., 2006; Larsen et al., 2010), fed by deeper sources (e.g., 20-40 km; Power et al., 2004). At Augustine volcano, syntheses of petrological, geochemical, and geophysical data indicate a conspicuous lack of long-term shallow magma storage, with magma stalling in a complex series of dikes 4-6 km beneath the summit (Roman et al., 2006), and remobilized by new inputs of basalt from depth (Larsen et al., 2010). Cook Inlet magmas may be especially prone to arrested transport through degassing-related crystallization, as seen in 1992 and 2004 at Mt. Spurr (Gardner et al., 1998; Coombs et al. 2006) and in 1996 at Iliamna Volcano (Roman et al., 2004), suggesting that the formation of plutons below arc volcanoes, and thus continental crust formation, is related to degassing-induced crystallization (Fig. 3).

The Unimak-to-Cleveland corridor extends for 500km from Cleveland volcano in the west to Shishaldin volcano in the east. This corridor straddles the continent-ocean boundary in the arc by equal amounts, and encompasses volcanoes with a range of pre-eruptive H_2O contents that span half the range observed in the Aleutian arc, including the lowest-H_2O volcano (Shishaldin) and is thus highly complementary to the extent of magma hydration observed in the Cook Inlet corridor. In addition, this corridor has experienced almost a dozen >M7 earthquakes over the past century, and was the site of a recent (2010) large earthquake swarm located just to the southeast of Cleveland. Magmas in the Unimak-to-Cleveland corridor are typically mafic (basaltic andesite) and remarkably phenocryst-poor. Okmok maintains a relatively long-lived shallow storage region between 3-5 km depth, based on geophysical and petrological evidence (e.g., Masterlark et al., 2010; Izbekovet al., 2005). The reservoir is almost constantly re-filled, as shown by geodetic observations over the past ~15 years, punctuated by two eruptions in 1997 and 2008. Although evidence for deeper supply exists, all data indicate that the shallow crustal reservoir is the main control on Okmok's frequent eruptive activity. Although less-well-understood, the occurrence of a sustained high rate of shallow LP seismicity beneath Shishaldin (Petersen et al., 2006) suggests a similar set of controls on Shishaldin's eruptive activity.

Together, the Cook Inlet and Unimak-to-Cleveland corridors capture nearly the entire spectrum of tectonic, seismic, petrologic, and volcanic activity displayed in the Aleutian arc, as well as the full range of magma storage depths and water contents. This diversity is contained within a combined arc length of 700km, less than 1/4th of the length of the arc. Although this represents a significant geographical area, it is an arc length that is similar to that of the Central American arc that was a focus site of the previous MARGINS program. The causes of the significant differences in the character of magma systems within the two corridors is an open question. A fundamental question that could be addressed within the GeoPRISMS themes would be the extent to which the differences in magmas between the Unimak-to-Cleveland and Cook Inlet corridors originate from a fundamental difference in their parental compositions, due to differences in volatile flux from the slab. Community-scale projects focused on these two corridors would be poised to answer questions about volatile budgets, formation of continental crust, how magmas and fluids are transported through the crust, and the relationship between magmas that freeze and those that erupt.

Figure 1

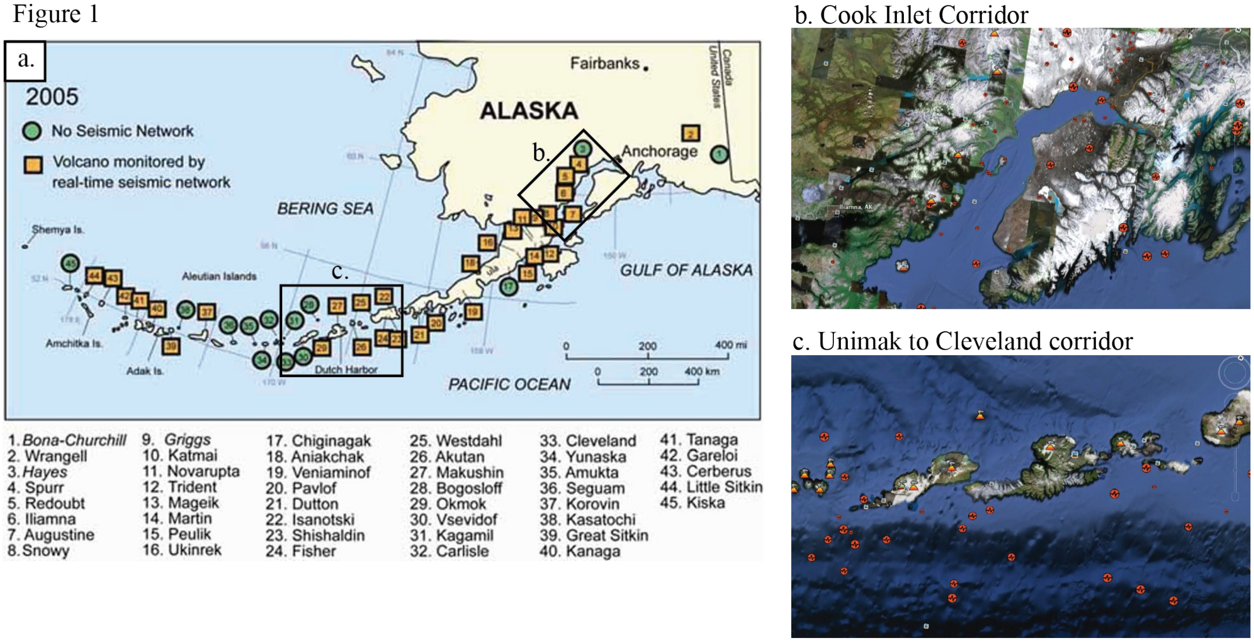
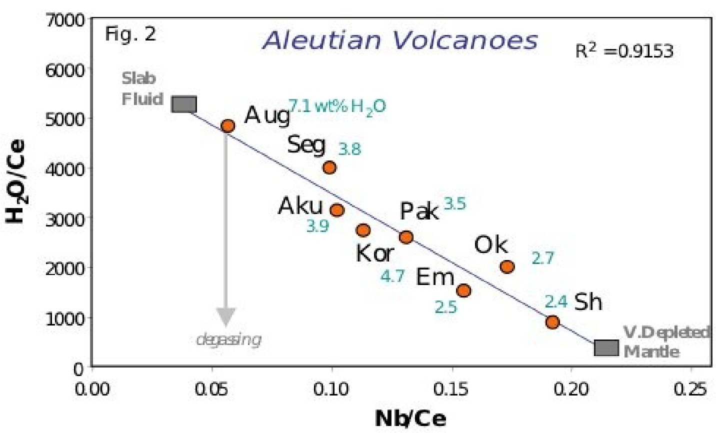


Figure 1. a) Location of seismically monitored volcanoes along the Aleutian arc (after Dixon et al., 2006). b) The Cook Inlet and c) Unimak-to-Cleveland corridors, showing the locations of major recent earthquakes.



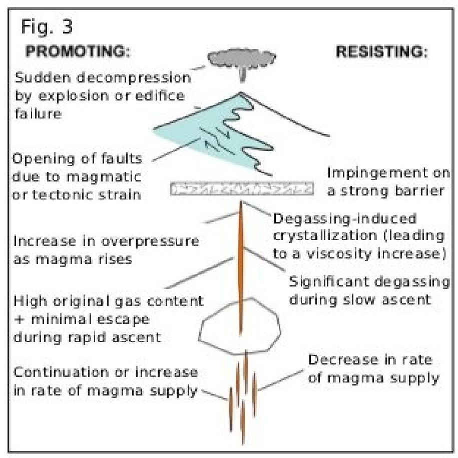


Figure 2. H_2O/Ce - Nb/Ce correlations in Aleutian volcanoes is consistent with a link between maximum pre-erupted H_2O (values in blue) and the amount of slab fluid added to the mantle. Zimmer et al. (2010; 2009).
Figure 3. (after Moran et al. 2011) Cartoon of forces promoting and resisting eruption of ascending magma.

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