Proposed studies of plutons in the oceanic Aleutian arc: Building blocks for continental crust via arc magmatism

Peter Kelemen, Steve Goldstein, Brian Jicha, Suzanne Mahlburg Kay,
Mike Perfit, Matt Rioux, Dave Scholl, Brad Singer, Tracy Vallier and Gene Yogodzinski

The Aleutian arc is unique among active intra-oceanic arcs in its widespread exposure of Paleogene and Neogene, mid-crustal plutonic rocks, as well as the lavas and sediments that these plutons intruded. In most arcs, plutons are inferred to be abundant, but are hidden beneath a veneer of lava and volcanoclastic debris. Aleutian plutonic rocks are predominantly felsic – quartz diorites and granodiorites – whereas Aleutian lavas are mostly mafic basalts (Kelemen et al. AGU Monograph 2003a). Aleutian relationships mirror global differences between arc plutons and lavas (Kelemen et al. Treatise on Geochem 2003b). Although there is plenty of variability, erupted arc lavas worldwide are dominantly basaltic. In contrast, in ancient, intra-oceanic arc crustal sections, plutonic rocks with $0.5 < Mg\# < 0.7$ have an average of 55 wt% SiO_2 and felsic plutonic rocks comprise more than half of the outcrop area (e.g., Talkeetna-Alaska Peninsula, Rioux et al. GSAB 2007, Tectonics 2010; Kohistan, Jagoutz et al. CMP 2009, 2010).

Felsic plutonic rocks formed in arcs are buoyant with respect to mantle peridotite over the entire range of relevant pressures and temperatures. They tend to remain at the Earth's surface, to form the fundamental building blocks of continental crust (CC). In the Aleutians, most felsic plutonic rocks have compositions that overlap estimates for the bulk composition of CC (Figure 1), *unlike* felsic arc plutonic rocks from Talkeetna, Kohistan, and Tanzawa that are depleted in light rare earth elements (LREE) and large ion lithophile elements (LILE) compared to CC. Understanding the genesis of Aleutian felsic plutonic rocks is a key to understanding continental genesis and evolution via arc magmatism, which is a central science goal for the MARGINS and GeoPRISMS Initiatives.

Aleutian plutonic rock compositions are significantly different from spatially associated lavas (Figure 2). This is fundamentally important because most studies of geochemical cycling in subduction systems assume that primitive basaltic lavas are representative of the compositional flux through the arc Moho, and/or the bulk composition of arc crust. These assumptions are rarely tested. The trace element data in Figure 4 suggest – *but do not prove!* – that many Aleutian plutonic rocks are derived from parental magmas that are geochemically distinct from typical basaltic lavas in the arc, perhaps because relatively hydrous magmas degas and stall in the mid-crust. If so, basaltic lavas might not be representative of arc bulk composition, or of net magmatic flux through the Moho into arcs. Alternatively, perhaps the plutonic rocks formed from similar parental magmas but via different chemical differentiation paths (e.g., Kay et al. CMP 1983). Or, they could contain "cumulate" accessory minerals, such as monazite, allanite or apatite, that are rich in incompatible trace elements. In any case, because the plutonic rocks are more similar to CC than the spatially associated volcanic rocks, it is important to make a systematic comparison of the composition of coeval Aleutian plutonic and volcanic rocks.

Continental crust has been generated via geochemical processes similar to arc magmatism, perhaps followed by later reworking of arc crust. However, arc lavas worldwide are dominantly "mafic", or basaltic, while continental crust is "felsic", with an andesitic or dacitic bulk composition. A variety of processes have been proposed to produce felsic crust from a mafic protolith, including (1) formation of a felsic mid-crust via magmatic differentiation of basalt, followed by (1a) "delamination" of dense, mafic or ultramafic lower crust, or (1b) subduction and then "relamination" of buoyant, felsic mid-crustal rocks during subduction erosion and arc-arc collisions. Alternatively, (2) mid-crustal plutons, or entire arc sections, may be derived from mantle-derived andesitic magmas, rather than from basaltic magmas.

Notably, recent seismic data on the Izu-Bonin-Mariana (IBM) arc, together with reconstructed arc seismic sections for the Jurassic Talkeetna arc and the Jurassic-Cretaceous Kohistan arc, all suggest that these intra-oceanic arcs have a relatively felsic bulk composition, at least above the seismic Moho (Behn & Kelemen JGR 2006; Jagoutz & Schmidt, submitted; Jagoutz & Kelemen in prep.). Perhaps (as in hypothesis 1), all three arcs underwent substantial modification by delamination. And, perhaps mafic to ultramafic cumulates are still present below the Moho (Aleutians: Fliedner & Klemperer JGR 1999; IBM: Tatsumi et al. JGR 2008). Alternatively, (as in 2) voluminous, early arc magmatism may have included a large proportion of primitive andesite. Seismic velocities for Aleutian lower crust appear to be higher than for IBM (compare Shillington et al. G-cubed 2004, Kodaira et al. JGR 2007), but interpretation of the Aleutian data is complicated by the unusual nature of the two arc crossings, and the oblique fore-arc to arc geometry of the single strike line. In any case, our focus here is on the plutonic middle crust.

Systematic study of coeval felsic and mafic rocks in the oceanic Aleutian arc will provide essential information needed to unravel these different hypotheses. For example, hypothesis (1) predicts that there is no systematic difference in radiogenic isotope ratios between felsic plutons and coeval mafic lavas, since both are derived from the same mantle source. Alternatively, systematic isotopic differences between felsic plutons and mafic lavas would support hypothesis (2). This is crucial, since (2) suggests that primitive basalts are not representative of the net magmatic flux through the Moho to form arc crust.

Furthermore, understanding the genesis of felsic plutons spatially associated with mafic lavas can provide fundamental insight into the processes of arc magmatism, regardless of whether felsic plutons are differentiated from typical arc basalts or not. Perhaps there has been a geochemical evolution in Aleutian magmatism, and the compositional distinction between plutons and lavas arises from the age difference between dominantly Miocene plutons, and the mainly Holocene lavas analyzed to date. On the other hand, perhaps plutons and *coeval* lavas are compositionally distinct. In this case, maybe high temperature, low-H_2O mafic melts with low viscosity erupt readily, whereas lower temperature, higher-H_2O felsic magmas undergo degassing in the mid-crust, and become too viscous to ascend further (Kay et al. CMP 1983; Kelemen et al. AGU Monograph 2003, Treatise on Geochem 2003). To understand general features of arc magmatism, it is essential to evaluate quantify any systematic sampling bias that could arise from such physical processes. For example, studies of H_2O in melt inclusions in erupted phenocrysts might not yield an unbiased estimate of H_2O contents in Aleutian primary magmas.

Current understanding of these topics is seriously limited by the paucity of data. Other than USGS U/Pb data for 4 samples, there are no Pb or Hf isotope ratios or ICP-MS trace element analyses for any Aleutian plutons. There are 11 Sr isotope ratios and 2 Nd isotope ratios for Aleutian plutons east of Adak (Perfit et al. CMP 1980; McCulloch & Perfit EPSL 1981). Published K/Ar ages from the 50's and 60's have proven to be unreliable in some cases, and a poor guide to the igneous crystallization age in others, while paleontological age constraints are approximate.

We propose an extensive study of Paleogene and Neogene plutonic rocks and coeval volcanic rocks, together with volcanoclastic rocks in the Aleutians. We need to compare samples from the same island that have similar ages, so an important secondary outcome of our study will be extensive data on the geochemical evolution of the arc over time. Volcanic and plutonic samples will undergo zircon and $^{40}Ar/^{39}Ar$ geochronology, XRF and ICP-MS geochemistry, and radiogenic isotope analyses, and we will undertake geochemical and detrital zircon studies on volcanoclastic rocks.

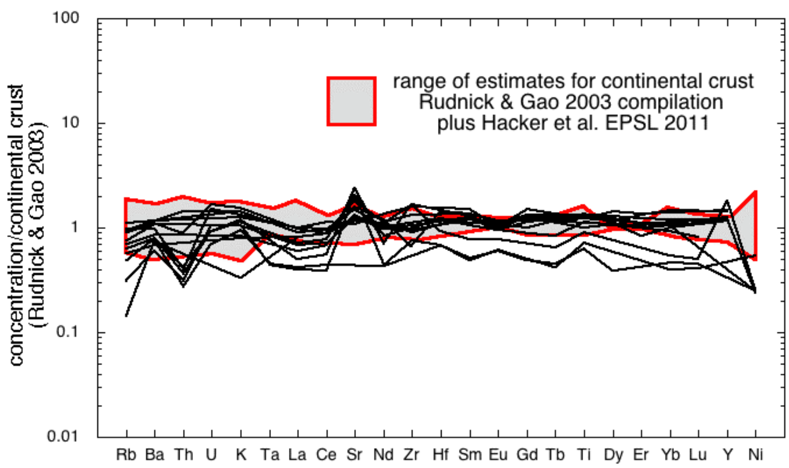
The groundwork for our proposed study was laid primarily by the US Geological Survey (USGS Bulletin 1028: Byers et al. 1959; Coats 1956a, 1956b, 1956c, 1961; Drewes et al. 1961; Fraser & Snyder 1959; Hein et al. 1984; Morgensen et al. 1985; Powers et al. 1960) evaluating the geology and mineral resources of the Aleutians. More detailed studies of the most accessible plutons, near commercial and military airports on Unalaska, Adak, Amchitka and Attu Islands, followed in the 70's and 80's, undertaken mainly by the Cornell group (Citron PhD 1980; S. Kay and R. Kay CMP & Geol 1985a,b; S. Kay et al. JGR 1982, CMP 1983, GSA SP 1990, GSA DNAG 1994; Perfit et al. CMP 1980; Yogodzinski et al. JGR 1993). These studies added trace element concentrations determined via Instrumental Neutron Activation Analysis (INAA), and some Sr and Nd isotope data for samples from Adak.

Preliminary work can be done on existing samples from [a] more detailed studies (Captains Bay pluton, Unalaska Island; Hidden Bay and Finger Bay plutons, Adak I.; Kagalaska pluton, Kalalaska I.), [b] reconnaissance mapping (large plutons other than Captains Bay on Unalaska I., southern parts of Atka I., Umnak I., Amchitka I., Attu I., Amlia I., Komandorksy Is.), and [c] dredging and submersible studies south of Adak and Kiska I. These will provide ages – including detrital zircons in volcanoclastic rocks – to extend $^{40}Ar/^{39}Ar$ work, and geochemical data for initial constraints on the extent of isotopic variability within and between plutonic and volcanic suites.

Following these initial studies, we propose to conduct field work on several islands containing a variety of plutons of varying ages, together with their older volcanic host rocks and younger, overlying volcanics. Because Adak is relatively well-studied, the best targets seem to be the southern part of Atka, where excellent reconnaissance mapping suggests great potential, and the relatively accessible plutonic rocks on Unalaska and Umnak. Away from Unalaska, outcrops are mainly on sea cliffs along the shore (e.g., Figure 3). Depending on the level of funding, this field work can be conducted via Zodiak, or – preferably – with helicopter support from a research vessel such as the Maritime Maid (http://www.maritimehelicopters.com/).

To expand our spatial and temporal coverage, we will propose separate dredging and/or submersible studies of steep topography in the fore-arc. (The oldest known sample from the Aleutian arc is a plutonic rock from Murray Canyon, south of Kiska I). And, we will seek continuing collaborations with Russian colleagues to continue studies of Paleocene to Eocene volcanoclastic arc rocks (Aleutian? pre-Aleutian?) in the Komandorsky Islands, with the understanding that we would be happy to assist in sample analyses.

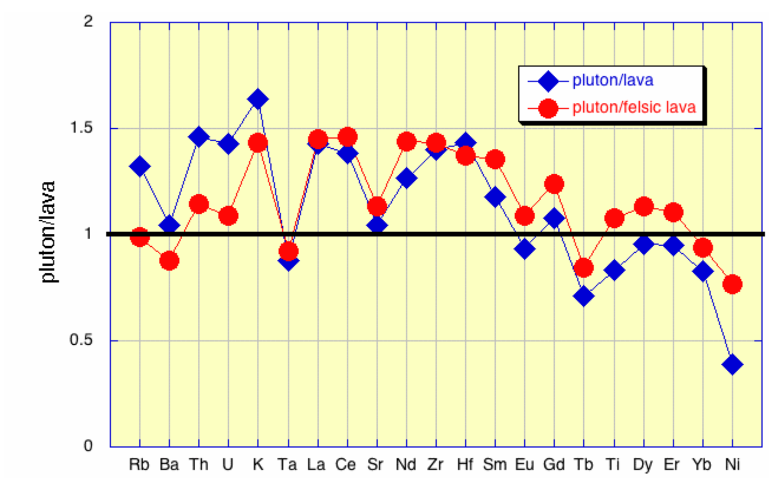
Our study will provide crucial information on mid-crustal rock compositions, together with the extent of fracturing and metamorphism, which can be used to interpret existing and proposed, new seismic data on the Aleutian arc. Similarly, petrological studies will provide constraints on the nature of deeper plutonic rocks in the middle and lower crust, that can be compared to inferences from seismic investigations to refine our understanding of arc lower crust, and the genesis and evolution of continental crust via arc magmatism.



Aleutian plutons
56 < wt% SiO2 < 65
0.4 < molar Mg# < 0.6

Figure 1: All Aleutian plutons with major elements similar to continental crust that have INAA trace element data, normalized to continental crustal estimate of Rudnick & Gao Treatise on Geochem 2003.

Figure 2: Average Aleutian felsic plutons as in Fig. 1, compared to average lavas (Kelemen et al. AGU Monograph 2003; Singer et al. JGR 2006), and average felsic lavas (56 < wt% SiO_2 < 65, 0.4 < Mg# < 0.6).



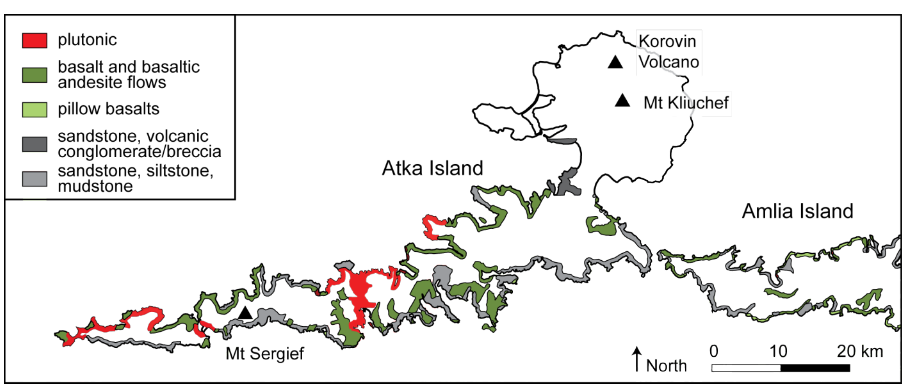


Figure 3: Geologic map of Atka Island, with its sister island Amlia extending to the east, redrawn from Hein et al. (USGS Bull 1609, 1984). Myers et al. (CMP 2002) published a detailed map of the volcanic northern peninsula.