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Current Perspectives on Energy and Mass Fluxes in Volcanic Arcs

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MEETINGS

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PAGE 531

Volcanoes of the Pacific Ring of Fire and other convergent margins worldwide are familiar manifestations of nature's energy, account for about 25% of global volcanic outputs, dominate volcanic gas emissions to the atmosphere, and pose significant physical threats to a large human population. Yet the processes behind this prolific activity remain poorly understood.

An international "State of the Arc" (SOTA) conference was held in August on the slopes of Mt. Hood, Oregon, to address current views on the energy and mass fluxes in volcanic arcs. This meeting brought together some 90 leading experts and students of subduction zones and their related magmatism.

SOTA was devoted largely to discussions of a series of thematic topics, reviewed below. A concluding workshop addressed broad questions posed during the meeting, with the goal of identifying future research avenues. These activities were complemented by field trips to Mt. St. Helens, Mt. Hood, and the central Oregon Cascades and Crater Lake.

Thermal structures of subduction zones (SZs). Compared to melting of "dry" mantle materials, effects of H_2O and CO_2 on melting in SZs are less constrained. There is a need to re-investigate vapor-saturated solidi of common mantle materials and formation conditions for volatile-rich magmas (including calcalkaline basalts and high-Mg# [=molar Mg/(Mg+Fe)] andesites). Numerical simulations provide one approach to understanding thermal conditions in SZs, but are sensitive to a modeling approach and require "calibration" against independent observations.

Questions remain concerning dehydration behavior of slabs, conditions under which slab materials melt, and the relative contributions of flux melting versus decompression melting of convecting sub-arc mantle. Magmatic temperatures estimated from arc lavas (or intrusive equivalents) and from laboratory experiments suggest that the sub-arc mantle may be warmer than predicted by many numerical models to date. Scaled fluid dynamic experiments imply that two-dimensional numerical models may underestimate actual thermal conditions. Thus, thermal structures predicted by indirect means need to be reconciled with those based on petrologic constraints. Variance of SZ thermal conditions must be considered when comparing the outputs of magmatism and fluid fluxes from different arcs or arc segments.

Sources, processes, and rates of mass fluxes originating below the Moho. A diversity of mafic magmas is recognized in arcs, ranging from calcalkaline to OIB- and MORB-like variants. A long-standing question concerns the relative roles of subducted sediments, oceanic crust, and variably hydrated slab mantle versus heterogeneous wedge mantle in producing the observed spectrum. Important questions remain concerning (1) how to discern effects of compositional heterogeneity in the mantle and slab from effects of melting processes; (2) transport properties and element partitioning among hydrous fluids, silicate melts, and mantle/slab minerals; and (3) the existence of compelling evidence for slab melting. Large ^{226}Ra and ^{230}Th excesses in young mafic arc lavas often correlate with anomalies in other robust "slab tracers" (e.g., ^{10}Be) and provide strong evidence for short (e.g., $\leq 10^4$ years) time scales for magma formation and transport from near slab depths. Implications of these data concerning mechanisms of elemental mobility, melting processes, and magma transport remain to be fully explored.

Chronologies and rates, mass contributions, and impacts of crustal level processes that influence arc magmatism. A clear message is that many, and perhaps most, arc lavas (including apparently primitive basalts) may experience some form of open system modification that may obscure details of sub-crustal magma petrogenesis. However, the extent to which this is evident depends, element by element, on the leverage exerted by the "crustal filter" through which magmas ascend. U-Th-Ra isotopic studies, petrography, crystal size distributions, and element diffusion profiles provide important constraints on time scales of magma differentiation, storage, and transport. Many studies document the entrainment of older crystal populations, magma mingling, and other open-system processes that attest to complexities in the formation of many evolved arc lavas. An outstanding question concerns the extent to which such magmas inherit their isotopic disequilibria from mantle sources, as opposed to higher-level processes. Unraveling subtle compositional effects due to magma-crust interaction is a widespread problem, as evidenced by complex isotopic and elemental variations in phenocrysts and petrographic, mineralogical, and geochemical variations in volcanic suites.

Energetics and dynamics of magma feeder systems. Mantle-derived basaltic magmas likely provide the fundamental energy driving arc volcanism. However, experimental studies suggest that many arc magmas, similar in composition to average crust (i.e., granodiorite/andesite), form by means of water-undersaturated melting of mafic to intermediate amphibolitic protoliths. Such melting may occur in response to underplating or intrusion of hot basaltic liquids. Numerical models incorporating thermal diffusion and time scales place restrictive bounds on the details of this process. Crustal contributions to erupted magmas and volatiles often are difficult to distinguish from sub-crustal inputs, but must be resolved and quantified to understand fully the nature of mantle reservoirs, as well as the physical behavior of arc volcanoes.

Moreover, the evolution of specific arc magma suites can differ from one volcano to another, even on small spatial or time scales. Energy-constrained models, simultaneously combining thermodynamics and kinetics, are helpful in understanding cooling, fractionation, and open system interaction between magmas and wall rocks or other assimilant material, and potentially provide realistic and self-consistent tests to evaluate geochemical details of magma evolution.

Origins, budgets, and influences of magmatic volatiles. The physical effects of volatiles (mainly H_2O) in driving magma ascent, vesiculation, and explosive eruptions need to be quantified. In particular, success in predicting eruptive styles hinges on a better understanding of volatile inventories and magmatic degassing. Volatile species (He, H_2O, CO_2, SO_2, N_2, Cl, etc.) provide additional constraints on sources and mass fluxes in SZs and play important roles in the behavior of arc volcanoes. Both sediment/slab and mantle sources appear to contribute to the fluxes of N and C species, based on elevated $CO_2/^3He$ and $N_2/^3He$ ratios. However, degassing from subducting slabs and from ascending arc magmas combine to obscure volatile budgets.

Issues needing further work include (1) forearc degassing fluxes (tied to metamorphic reaction paths in subducting slabs), (2) reconciliation of large ("cryptic") fluxes estimated for C and S with independent (and often lower) estimates based on petrologic constraints, and (3) effects of devolatilization on isotopic compositions of gas species (used in certain flux calculations).

These issues have important implications for gas behavior in magmatic systems, magma volumes, and recycling of volatiles from shallow magmato-hydrothermal systems. Improved remote sensing measurements are needed to better quantify local emissions. Also, existing monitoring should be expanded to other areas (particularly submarine volcanic plumes) and mass flux estimates (i.e., arc growth rates) should be improved to develop more representative element flux estimates. Sampling (fumaroles, hot springs, ground/airborne gas monitoring, and melt inclusion studies) and analytical methods are varied, sometimes with different results that need to be reconciled. Estimated subduction inputs and magmatic outputs for H_2O, CO_2, and Cl are qualitatively similar, suggesting efficient recycling of these volatiles back to the surface; however, forearc fluxes and plutonic sinks currently are ignored for lack of adequate data.

Future Directions/Research Objectives Identified

During the conference, the following questions emerged as critical to understanding arc magmatic processes:

- How can we better quantify thermal structures of SZs?
- What are the mass and energy fluxes in arcs, and how do they influence arc structure and evolution?
- How can we differentiate steady state processes from transient events in SZs, and how are these related to tectonic forcing functions?
- What is the composition of the mantle wedge, how does it melt, and what does it produce?
- What are the effects of the 'crustal filter' in modifying mantle magmatic inputs and/or in producing the observed compositional spectrum of arc magmas?
- How does the slab impart its signal (chemical/physical) to arc systems?
- How can we reconcile the disparate time scales implied by U-Th series radioisotopes?
- How can we better constrain the systematics and effects of degassing in the crust?
- What drives crystallization and degassing in magmas?

In Conclusion

Complex variations within and between volcanic arcs are products of the inherent variability in composition and history of the slab, wedge, and crustal reservoirs involved. Depending on experience and perspective, one may see different parts of the anecdotal elephant.

Conferences like SOTA increase communication and integrate expertise among many disparate specialists that may lead to a "unifying theory" to bring all these parts into common focus and eventually serve as a useful predictive tool.

Details of the conference, a participant list, and submitted abstracts are available at http://www.ruf.rice.edu/~leeman/SOTA2003/info.html. In the next year, a compilation of thematic papers submitted by conference participants will be published as a special volume of the *Journal of Volcanology and Geothermal Research*.

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