Summary of the State of the Arc Conference 2007

The meeting was held from Jan. 28 to Feb. 2 at Hotel Termas Puyehue in the Chilean lake district with a view of Volcán Puyehue from the terrace. A field trip to local volcanoes was led by Hugo Moreno and Jorge Muñoz on the third day. Abstracts from 77 of the participants were distributed among four main themes, each of which was accorded a day. The daily themes were in turn divided among a set of 16 key questions assembled by the program committee and distributed to participants in advance of the meeting. Shortly before the meeting, response teams were organized to respond to the questions. The following summaries are drawn from the response team reports.

Day 1: Origin of diversity among primary magmas in arcs

Theme questions were assembled by Jim Gill, Tim Grove, Yoshiyuki Tatsumi and Richard Arculus. The response team was led by Tim Grove, and included Richard Arculus, Osamu Ishizuka, Marlina Elburg, Andres Folguera, William Leeman, Victor Ramos, Susan Wacaster, Alberto Zanetti, Charlie Langmuir, Katherine Kelley, Peter Ulmer, Massimo Tiepolo, Colin MacPherson, Adam Goss, Marina Manea, Martin Streck, and Daniel Selles.

M-Q1: What spectrum of arc magma compositions in continental and oceanic arcs is potentially in equilibrium with mantle peridotite ± pyroxenite?

M-Q2: Which melting models for the mantle wedge are consistent with observations and what may cause a particular melting event in each case?

M-Q3: Are there 'global' versus 'local' trends in mantle-derived arc parent magma compositions as there are for MORB?

M-Q4: What is the spatial distribution of temperature and melt in the mantle wedge?

M-Q5: What are the mechanisms and the specific conditions that lead to arc magmas with adakitic signatures?

These questions were reshaped by the response team to reflect points raised in the course of the conference.

1) How can we distinguish among different forms/processes of element transport from slab to mantle?

Processes considered most important were mantle melting processes, slab melting processes, fluid transport from slab, fluid exchange in mantle, and slab melt - mantle exchange. Discussion revolved around the further question of what the mantle source is beneath arcs. Is there more diversity in the subarc mantle than in the MORB source before influences of the subducting slab are added? A need to link the communities considering ocean island, MOR and arc mantle variability is apparent.

2A) How do we explain lavas with arc and "non-subduction zone" signatures in such close juxtaposition?

2B) How are melting processes in back arcs and arcs related? Why do they sometimes appear to be totally separate but in other circumstances genetically linked?
Discussion revolved around separating characteristics that are carried uniformly in arcs versus those that may result from particular, location-specific, tectonic influences.

3) Temperature / Pressure in the mantle wedge:

- What are the controls on mantle wedge temperatures?
- What observables can be used to map T distribution?
- How does type of margin influence mantle temperature?
- What is the influence of Continental Crust vs. Oceanic Crust vs. Dynamic state?
- How do we separate melting variables T vs. P vs. H_2O

In discussion, the point was raised that back arc variations can be enlisted to address sub-arc variations. The degree of oxidation of the sub-arc mantle and where it is acquired were raised as further questions.

4) Regarding magmas with adakitic signatures, the response team summarized confusion over the term. Rocks may acquire adakitic attributes in various ways besides slab melting. e.g., melting of subducted eroded forearc crust, melting of deep arc lower crust, melting of delaminated lower crust, primary crystallization of garnet at depth. Adakitic signatures reflect high-pressure, wet, basaltic solid or magma precursors. The consensus was that the term adakite cannot be eradicated, although a substantial minority favored elimination of the term. The subcommittee proposed that "adakite" be relegated to adjective status, and thereby emphasize the descriptive compositional attributes rather than interpretive attributes.

Day 2: Fluids and volatiles: Slab to surface

Theme questions were assembled Paul Wallace, Maureen Feineman, Bill Leeman, and Terry Plank. The response team was led by Terry Plank, and included Brad Hacker, Paul Wallace, Vlad Constatin Manea, Maureen Feineman, Maria Marin-Ceron, Mark Reagan, Ivan Petrov Savov, Martin Rosner, Nathalie Vigouroux, and Christy Till.

V-Q6: How much H_2O and other volatiles are stored in serpentine in the oceanic upper mantle, and what are the roles of such volatiles in magma genesis and evolution? A major uncertainty in understanding volatiles in subduction zones is our poor knowledge of how much water and other volatiles (*e.g.,* Cl & B) are locked up in serpentinites, which are heterogeneously distributed within the subducted oceanic lithosphere. What are the proportions of serpentinized oceanic upper mantle that are related to transform zones versus disruption of subducted plates as they enter subduction zones? Over what depth ranges are volatiles and fluid-mobile elements released from subducted serpentinite, and what is the ultimate contribution of these fluids to magma genesis? Which elemental and isotopic signatures in arc magmas can be used to track volatile-recycling from serpentinite?

V-Q7: **What are the most important dehydration and decarbonation reactions in subducted oceanic crust and sediment, and how do temperature differences**

between old versus young subducted lithosphere affect volatile release as a function of depth?

V-Q8: How are volatiles transported and stored within the mantle wedge (forearc and subarc), and how does this influence primary magma generation? Water plays an important role in mantle melting in subduction zones, but there is limited consensus concerning both the phases(s) in which volatiles are transported from slab to wedge and the mechanism(s) of transport. Are volatiles and their solutes stored in the asthenospheric wedge in hydrous minerals before melting? How much water and other volatiles are stored in the cooler parts of the wedge beneath forearcs, and what is the long-term fate of these volatiles? To what degree are fluid-mobile elements fractionated during transport and/or by multi-stage storage?

V-Q9: What are the roles of dissolved and exsolved volatiles in determining the depth at which primitive arc magmas stall, crystallize, and partially degas, thereby affecting paths of chemical differentiation and the potential for explosive eruptive activity?

The response team answered with the following points for VQ 6 and 7:

1) There is a distinction between the "slab-derived component", which is a trace element signature (high Ba/Th, Ce/Pb, etc.) and water. Certain "fluid mobile" elements (B, As, Sb) correlate more strongly with water than others (Ba, U, Pb).
2) At lower pressures, the slab-derived fluid is dominantly water. Solute content increases with increasing pressure (and temperature). Fluids generated deep in the subduction zone (~6GPa) are >60% solute. (Solute and fluid may be decoupled as fluid rises to shallower depths in the mantle wedge?) High-solute fluids partition more trace elements.
3) Hotter slabs sometimes release a *lot* of fluid into the mantle wedge beneath volcanic arcs. This may be due to the fact that low-T, high-P phases such as lawsonite retain water well beyond the volcanic front in cold arcs.
4) Carbon dioxide in melt inclusions can be quite high (~2000 ppm), and CO_2 in undegassed magmas is certainly higher (~3000 ppm). The CO_2/Nb ratio in arc lavas may prove useful in identifying decarbonation reactions in the slab if it is > MORB. (Johnson) CO_2/He in gases. Fluxes of CO_2 out of volcanoes is less than input- Decarbonation at depth? Impure carbonate stability? Relation ship between carbonate and CO_2? Is CO_2 melted out of the mantle?
5) Accessory phases such as allanite, zoisite, rutile, apatite, and mica can dominate the budgets of specific trace elements.
6) Some fluids are stored in the wedge for some period, during which time they may react with the surrounding mantle, while others migrate quickly through the mantle with limited reaction. Isotope ratios ($\delta^{18}O$, $^{87}Sr/^{86}Sr$) and U-series disequilibria may enable us to distinguish between stored and fresh fluid sources. In some cases, the mode of fluid transport (reactive or non-reactive) may depend on physical characteristics of the subduction zone. It is also possible to have fluid migration by both reactive and non-reactive transport simultaneously.

7) The extent of melting is closely related to the amount of water present in the mantle.

With respect to VQ-8:

There is limited consensus concerning both the phases(s) in which volatiles are transported from slab to wedge and the mechanism(s) of transport. Are volatiles and their solutes stored in the asthenospheric wedge in hydrous minerals before melting? How much water and other volatiles are stored in the cooler parts of the wedge beneath forearcs, and what is the long-term fate of these volatiles? To what degree are fluid-mobile elements fractionated during transport and/or by multi-stage storage?

Fluid availability to first approximation depends on initial assemblage of subducted materials and, importantly the prograde metamorphic history during subduction. Variation in thermal structure of the downgoing slab controls its dehydration history, hence the retention of volatile components and fluid-mobile elements (FMEs). Both discrete and continuous reactions will tend to smooth the fluid release patterns as a function of depth. Because of the thermal gradient within slabs (cooling inward from the upper surface) dehydration reactions will be further smeared out over depth.

The fluid mobility of elements will depend on both their solubility in mixed volatile fluids and on their compatibility in residual metamorphic minerals. As a consequence mobilization patterns may vary between different elements despite their having similar *fluid* solubility.

Strong correlation between ^{10}Be and FMEs (B, As, Sb…) suggests that these are to great extent slab-derived and that the transport medium is likely to be in aqueous fluids. This view is enhanced by the fact that the aforementioned FMEs are selectively enriched in arc magmas (to varying degree). Alternatively, if slab-derived components are transported in near-supercritical fluids or melts the FMEs would behave in similar fashion to other elements having similar compatibility relative to residual source materials; thus, they would not be selectively enriched.

Enrichments in arc lavas of elements (e.g., Th, Nd) having relatively low fluid mobility are presumed to be transported in silicate melts. Conditions for producing such melts in the slab carry minimal thermal requirements, and potentially may provide useful constraints for evaluating SZ thermal models.

Combined with constraints from short-lived isotopic systems (e.g., U-series) differential enrichments of FMEs vs. other incompatible elements may help constrain the thermal history of subducting slabs.

Interpretation of the geochemistry of arc magmas also requires evaluation of the extent to which the slab-derived signal is modified by subsequent processes attending formation and ascent of the magmas.

The questions are recast

- What are the repositories for fluid components and FMEs and how are these distributed in subducting slabs and within the mantle wedge?
- Can we better establish that FMEs are indeed proxies for water? Available data for water contents in MIs seem contrary to B enrichment closer to the trench.
- What are the physical processes whereby fluids migrate?

- What constraints do we have for timing and spatial location(s) of slab-derived contributions?
- What are the relative contributions of volatile components within the lithospheric vs. asthenospheric parts of the mantle wedge?

Some key information required

- Careful evaluation of source(s) of the geochemical signals we hope to interpret SZ processes (e.g., wedge heterogeneity, modifications during ascent, etc.)
- Geologic framework and constraints on timing of fluid inputs
- Multiple approaches with sensitivity to specific processes
- Constraints on the mass fluxes involved

With respect to VQ-9, we have learned:
1) There is mounting evidence for significant amounts of crystallization during ascent and eruption of magmas, driven by the exsolution of H_2O from melt to vapor at 0-5 kb – recorded in:

melt inclusion H_2O-CO_2 vapor saturation pressures (ascent),
decreases in An (H_2O exsolution) and Mg# (crystallization),
increases in incompatible elements in melt (10's wt% crystallization).
crystals are young

Such a process may occur with little change in temperature, or even heating.

2) Melts through the entire crust may be vapor-saturated, initially with a CO_2-dominated vapor. If so, crystallization will begin during H_2O-undersaturated conditions.

3) While ascent drives crystallization, it may not lead to significant differentiation of (particularly felsic) magma, due to lack of separation of crystals and liquid.

4) Magmas with high water contents (as recorded in melt inclusions) tend to differentiate along Fe-depletion (calc-alkaline) trends.

5) ^{210}Pb-^{226}Ra equilibrium in some volcanic centers indicates that magmas cannot have degassed continuously for more than a year or two before they erupt. This implies that the final rise to the surface must begin from a staging reservoir that is not persistently losing gas. This is in contrast with other tectonic settings, which often have ^{210}Pb deficits perhaps due to long-term degassing of CO_2.

Key questions include

- At what depths do magmas stall in their ascent and crystallize, and do these depths have anything to do with the volatile content of the magma?

- How do we reconcile large and open-system CO_2 and sulfur gas fluxes with the lack of ^{210}Pb-^{226}Ra disequilibrium observed at some volcanic centers?

Day 4: Unravelling the connection between plutonic and volcanic rocks at arcs

Theme questions were assembled by Jon Blundy, Anita Grunder, Allen Glazner, Peter Kelemen. The response team for **P-Q10** and **P-Q12** was led by Charlie Bacon, and included Jon Blundy, Drew Coleman, Fidel Costa, Josef Dufek, Felipe Espinoza, Holli Frey, Estanislao Godoy, Brian Jicha, Rebecca Lange, Peter Lipman, Victoria Martin, Jürgen Michel, Aleksandar Miskovic, Victoria Smith, Madeline Humphreys

P-Q10: What insights may be gained from geochronological-petrological studies of rarely exposed plutonic-volcanic complexes? Are there consistent petrologic and geochemical differences between the erupted versus residual plutonic magmas? Can we derive insights into processes from geochronological investigations of such paired systems?

- Exposed intrusive–extrusive complexes are uncommon
- Plutonic xenoliths in volcanic rocks offer a view of the intrusive component, yet without spatial context
- Certain voluminous ignimbrites vented following rejuvenation of near-solidus plutons by underplating of mafic magma
- Residence time (often 10^4–>10^5 yr): Did crystal chronometers (e.g., zircon) exist in long-lived melt or were they recycled by thawing of mush or plutonic rock?

What are the timescales of magmatic processes and the lifetimes of volcanic centers and intrusive complexes?

- Timescales scale with system size
- Plutons can be assembled over as much as 10^7 yr, accompanied by thermal cycling (rejuvenation episodes)
- Major arc volcanoes have lifetimes of 10^5–10^6 yr
- Large volcanic fields may have lifetimes of 10^7 yr
- Diffusive relaxation of compositional zoning in crystals can constrain timescales of magmatic processes
- Durations of major events can be determined with precise geochronology
- The record in sedimentary rocks can be mined for chronology of volcanic and plutonic activity at the orogen scale

Are there fundamental differences in rates, volumes, and mechanisms of magma genesis, transport, differentiation, accumulation, and storage between volcanoes and plutons?

- It is often stated that the intrusive component as much as ten times the volume of erupted magma, yet little direct evidence
- Petrologic models of compositional diversity in plutons and volcanoes provide constraints on eruption/intrusion ratio
- New computational models need to include effects of volatile (especially H_2O) input

in primary magmas and of escape and transfer of a hydrous fluid during crystallization

- Better physical models of how melts escape from residues

Seismic, potential-field, and geodetic studies may give volumes and rates, and magma storage depths, for active systems

P-Q12: Are there differences between the timescales implicated in continental margin plutonic and volcanic systems? What are the time-scales of magmatic processes and the lifetimes of such magmatic systems? How can we reconcile the potentially long (up to 10 m.y.?) timescales of some plutonic complexes with the generally shorter (~1 m.y.) period of construction of most large arc volcanic centers? Are there fundamental differences between plutonic and volcanic systems in terms of the rates, volumes, and mechanisms of magma genesis, transport, differentiation, accumulation, and storage?

Are there consistent petrologic and geochemical differences between erupted magmas and frozen intrusions?

- Compositions of plutonic rocks may or may not be identical to volcanics from the same system
- Differentiated melt escaped from many crystallizing plutons during their lifetimes
- Need methods for correlating volcanic rocks or distal ash with plutons (e.g., trace element abundances and isotope tracers in durable crystals)
- Need to determine pluton geometry, and melt distribution within it, during active volcanic episodes

P-Q11: What are the large-scale magmatic mass balances in the arc crust? Do intrusive versus extrusive proportions and compositions vary with arc maturity, composition of the crust, and structure of the crust? How do volume estimates integrated at the crustal scale compare with volumes observed at the scale of a single plutonic or volcanic complex? How does protracted magmatism at convergent margins affect the volumetric growth, thermal and density structure, and/or compositional evolution of the crust at such margins?

Response team for **P-Q11** was led by Wendy Bohrson, and included Olivier Bachmann, Andy Barth, George Bergantz, Allen Glazner, Francisco Gutierrez, Mirian Mamani, Marcel Jose Marquez, Steven Ownby, David Pyle

Goal is to establish large-scale material balance in arc crust

- Material balance involves issue of scale.
- Scales of interest include (1) temporal (instantaneous vs. time-integrated mass balance), and (2) spatial (hand sample to crustal scale mass balance)
- Challenges include (1) multiple sources including hydrosphere, mantle wedge, subducted slab (±sediment), overriding lithospheric plate; (2) multiple processes, including a variety of chemical processes, each of which will impact elemental mass balance differently, and tectonic, including recycling, delamination, relamination
- Initial approach could include zero-order models using key elements from the likely sources (e.g., ^{10}Be, H_2O, ^3He, etc.). Such simple approaches potentially provide essential information that can inform more refined approaches

- Higher order approaches ultimately required and should address constraints from geochemistry, petrology, thermal and rheological properties, and structural data
- Ultimate goal must be to integrate information from these to constrain material balance

P-Q13: How well do geophysical methods image the scale and depth of magma accumulation in the crust and the rates of magma transport? Precisely what is being imaged when large travel-time delays are observed within the crust (magma body, crystal mush, migmatization)? What does the relative paucity of seismically imaged crustal 'magma bodies' indicate about the character, volume, and residence times of diverse magmas within the crust? How do geophysical images of the crust compare with petrologic images of where and how magmas accumulate and differentiate?

Day 5: By what means can mantle and crustal contributions to continental arc magmas be resolved?

Theme questions were assembled by Michael Dungan, Leo López-Escobar, Rosemary Hickey-Vargas, and Rhiannon George. Response team was led by Jim Gill, and included Yue Cai, Leo Lopez-Escobar, Rosemary Hickey-Vargas, Susanne Kay, Peter Keleman, Luis Lara, Anita Grunder, Robert Rapp, Gerhard Woerner, Jorge Muñoz

Issues of **Mass and Energy Balance** were considered a separate response team headed by Wendy Bohrson with participants Steven Ownby, Allen Glazner, David Pyle, Mirian Mamani, Francisco Gutierrez, Olivier Bachmann, Andrew Barth, George Bergantz, Marcelo Jose Marquez.

C-Q14: Open mantle source versus open-system evolution. (a) Can the subarc mantle wedge become substantially modified as a consequence of subduction-erosion of the lower forearc crust? **(b)** Has the subarc mantle been substantially modified by delamination and foundering of the dense, mafic lower arc crust in some long-lived continental arcs? If so, how can we quantitatively distinguish such 'mantle-derived' contributions of crustal components from the effects of intra-crustal open-system evolution?

C-Q15: Do evolved arc magmas typically record polybaric, multi-component, and multi-process differentiation histories? Is it currently feasible to undertake investigations of contaminated continental arc magmas wherein the depth(s), mechanism(s), component(s), and rate(s) of crustal assimilation are uniquely constrained? If so, which combinations of data and interpretive frameworks are necessary to arrive at meaningful conclusions? If not, which gaps in our knowledge and/or methodology need to be addressed first?

C-Q16: What are the key variables associated with intra-crustal overprints in arcs? Variations in crustal thickness have been cited as playing a major role in determining the degree to which magmas are contaminated by continental crust. To what additional extents are crustal composition, arc longevity, magma flux rates from the mantle, the consequent thermal and density structure of the crust, and tectonic controls important and distinctive?

To what degree are magmas in oceanic arcs the products of open-system evolution?

The "Gill" response team focused on question **CQ-14** and answered question (a) "Yes in favorable circumstances", and answered question (b) "Yes in special circumstances".

The group first discussed several reasons why the topic is important. Subduction erosion or delamination of the lower arc crust can have local geological significance, as a possible explanation for a specific magmatic episode. If the processes occur frequently, then they will increase the mass fraction of continental crust that is derived from eclogite, which will in turn affect the temporal evolution of continental crust. In additon, foundered forearcs or arc lower crust may contribute to the EM1 mantle component.

The group then addressed some general caveats about the topic. First, unless "*substantially modified*" means tens of wt% in the magma source, then usually it will be impossible to distinguish the geochemical effects of subduction erosion or delamination from the effects of ancient "enriched mantle" (EM1,2), ambient subcontinental mantle (e.g., in Mexico), or recently recycled sediment. Second, both erosion of the forearc and delamination of the lower crust are expected to be more episodic than the competing processes of the previous sentence, so geological context becomes important evidence. Finally, the group recognized that subduction of arc-derived volcanic ash is yet another way to get arc crust deep into the mantle , but we considered this processes insubstantial and did not discuss it.

Next the group considered whether and how one can distinguish contamination that occurs in the crust versus in the mantle, given all the things that can happen to magma as it passes through the "crustal filter". There was agreement that contamination happened in the crust if the crustal signature increases with measures of differentiation. Conversely, the contamination happened in the mantle if three conditions are met: the crustal signature occurs in primitive rocks (i.e., with high Mg#, Ni, and Cr); there is evidence of equilibration with eclogite; and the rocks can be shown not to have been mixed with a felsic melt. Evidence of contamination includes changes in isotope ratios of whole rocks, changes in isotopes within low-P phases like plagioclase, or changes in element concentrations or ratios that lie outside the range consistent with closed system fractional crystallization. Quantitative models are necessary to demonstrate that the changes cannot be produced simply by mixing magmas and crystals that can be produced by closed system processes.

Finally the group addressed how one might distinguish between forearc erosion versus delamination of the basal crust beneath the volcanic arc or reararc.
If the crust of the forearc and adjacent volcanic arc are compositionally different (e.g., Costa Rica, parts of Chile, NE Japan), and if the forearc composition shows up in the arc, then the signal is caused by forearc erosion. If the forearc rocks have experienced low-T alteration and that signature accompanies the forearc component, then the signature is caused by forearc erosion. Significantly heavy oxygen or lithium could be such evidence. (More fluid mobile elements like B will be swamped by slab fluid or serpentine). If primitive rocks with crustal traits are restricted in space and time to episodes for which there is independent evidence of forearc erosion (e.g., migration of the volcanic arc toward the foreland; sinking of the forearc; absence of forearc accretion), then the signal is caused by

forearc erosion. Central Chile in the Miocene may be an example. The least ambiguous examples of forearc erosion to date occur on active continental margins with relatively thick crust (>40 km). By itself, a garnet signature in primitive rocks is not sufficient evidence for forearc erosion but, when combined with other evidence listed above, it is confirmatory. The group thought of no equivalent chemical or geological diagnostic tests for the involvement of recently delaminated lower crust. Its role might be most likely after a major episode of rapid and large crustal thickening, but it may be lost from the mantle wedge before it can be recycled.

With respect to **Mass and Energy Balance (Questions C-Q15 and C-Q16)**, the "Bohrson" response team simplified the questions and made the following points:

- Mass balance has to be accounted for at various time and spatial scales
- All other questions need to be resolved to do mass balance in detail
- Projects need to be designed to specifically target mass and energy balance.

The group did a generalized mass balance using ^{10}Be and K as compositional indicators.

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