MARGINS Theoretical & Experimental Institute: Volatiles In The Subduction Factory
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Introduction

Subduction zones play a primary role in mediating the cycling of volatiles on Earth. The volatile constituents that are carried into subduction zones in minerals and pore fluids are dominated volumetrically by H_2O. Water exerts a fundamental control on a wide range of geophysical and geochemical processes in subduction zones. This includes the seismic coupling and the generation of earthquakes, aqueous fluid release and element transfer from the subducting slab, generation of serpentine and chlorite in the forearc and mantle wedge, stabilization of hydrous minerals in the slab and mantle wedge, mantle-wedge convection, melting of sub-arc mantle, and explosive volcanism. The pattern and amount of water-rich fluid released from subducting oceanic lithosphere has a first-order influence on the locations, volumes and eruptive style of arc volcanoes and the generation of juvenile continental crust. Though other volatile components are less voluminous than water, they nevertheless contribute to key geologic processes as well. For example, along with H_2O, carbon dioxide, reduced low-weight hydrocarbons, and sulfur- and halogen-bearing compounds contribute to the greenhouse gases when they are emitted from subduction zone volcanoes, and thus have a significant influence on climate at local to global scales. Carbon combines with water to exert a direct influence on the depths at which the mantle melts to yield arc magmas, on primary melt compositions, the nature of arc magma crystallization, and the rheology, conductivity and seismic velocity of the sub-arc mantle. Chlorine, fluorine and sulfur strongly modify the solubility and transport of other elements in the dynamic hydrologic settings of the slab and mantle wedge.

In the autumn of 2009, approximately 90 researchers gathered at Timberline Lodge on Mt. Hood, Oregon at a MARGINS Theoretical and Experimental Institute (TEI) focused on the behavior, mass-balance, and influence of volatiles in subduction zones. This meeting brought together geochemists and geophysicists to examine and discuss the current state of our knowledge on the budget of H_2O, CO_2, N, F, S, Cl, and noble gases in the two SubFac focus sites (Izu-Bonin-Mariana and Central America), to examine the role of these volatiles in major geochemical and geophysical observations, and to deepen our understanding of the influence of volatile elements on geologic processes fundamental to our understanding of subduction zones. The attendees at this meeting spent the final day in breakout groups discussing outstanding issues in subduction zone science that remain as unsolved problems. From these breakout groups, a coherent set of directions for future research emerged; these scientific directions are multidisciplinary and global in their significance, and they should form an important part of the future trajectory of any successor program to the current MARGINS initiative.

Future Directions in Subduction Zone Research

In the original Subduction Factory science plan incorporated as a part of MARGINS in 2000, fifteen major scientific questions were posed to guide the selection of focus sites and the directions of research within the scope of the program. Two-thirds of those questions dealt directly with the abundance and role of H_2O, CO_2 and other volatiles in subduction zone processes. This testifies strongly to the importance of volatiles in controlling what happens at subduction zones. Simply put, volatiles make subduction zones what they are, and this is no less true today than it was ten years ago.

The abundance of volatiles on Earth is likely the single major reason why Earth is the only planet in the solar system with subduction zones. The active plate tectonic cycle that now characterizes the surface expression of mantle convection depends critically on the strong impact that water has on the strength of mantle and crustal rocks. One need look no further than Venus or Mars to imagine how different Earth's tectonics would be on a dry one-plate planet without subduction zones. Beneath the plates, water influences mantle convection to a degree that belies its abundance. As little as 150 ppm H_2O (by weight) is sufficient to lower the viscosity of the mantle by three orders of magnitude below that of dry mantle. Volatiles also have a direct influence on the behavior of megathrust faults and the earthquakes they generate, as well as the overall thermal structure of the mantle wedge. In the upper 150 km of the mantle, the melting point drops by 200-300°C upon addition of as little as 0.1% of H_2O. This allows normal mantle beneath subduction zones to melt at depths where it would otherwise never melt in the absence of water. Volatiles are thus directly responsible for the existence and location of subduction zone volcanoes and the generation of new continental crust. When magma reaches the Earth's surface, the risk of explosive and violent eruptions depends almost entirely on its volatile content. In addition the volatile components released can have direct impact on short- and long-term climate evolution. Because of its strong influence on mantle convection, and the location and style of surface volcanism, and the impact of volcanoes on climate and public safety, the origin, distribution and influence of volatiles in subduction zones are among the most important issues in all of Earth science.

In order to understand the dynamics and structure of subduction zones and their influence on the chemical and physical evolution of the planet it is critical to understand the role of volatiles. This was strongly reflected in the key scientific questions that emerged from the breakout groups at the Volatiles TEI meeting. These questions are multidisciplinary in nature, and by necessity require a coordinated approach to field geology, volatile geochemistry, high-pressure experimentation, geophysical field experiments and data analysis, and convection and melt transport modeling that has been a strong hallmark of the existing MARGINS initiative.

Volatile cycling – Ocean Drilling Program (ODP) drill holes have given a first-order idea of the composition of sediments entering subduction zones around the world, but ODP hole locations have not yet been concentrated in any one area to a degree necessary to delineate along-strike variations in the composition of the plate entering any single subduction system. Sampling of fluids that emerge from convergent margin megathrusts and the forearc is similarly limited. These two near-surface observations place first-order constraints on the overall budget of volatiles entering subduction zones and advection of these volatiles into the sub-arc mantle. They are also subject to the greatest uncertainties among all the terms in budget calculations.

Various hydrous minerals are the carrier phases for volatiles into subduction zones and magmas are responsible for the return of these volatiles to the Earth's surface. It is therefore critical to be able to accurately predict the phase assemblages of subducting plates across the global array of subduction zones. Seismic imaging can test these predictions. For example, evidence is emerging for significant serpentinization of the slab mantle pre- and post-trench, and multi-scale layering at the top of the slab likely reflects volatile-influenced crustal mineralogies, and, in some cases fluid-filled fractures. The stability limits of slab minerals are first-order determinants on where fluids emerge from the downgoing plate. They also likely determine the mode of slip at the interface between the downgoing and overriding plates (e.g. earthquakes versus episodic tremor and slip) and the location of intermediate-depth seismicity.

Important questions remain on the role of volatiles once they are released at sub-arc depths from the descending slab. How do melts and volatiles transit, interact with, and modify the surrounding mantle and crust from the slab to eruption? Geophysical imaging is making progress in placing bounds on the form and amount of volatiles in the slab, melting region, and beneath the arc. Dense arrays of seismometers in the IBM and Central American subduction systems have resolved the velocity and attenuation structure of the slab and wedge with sufficient resolution that the competing effects of temperature, volatiles, and partial melt are beginning to be distinguished. Nonetheless, still higher resolution is required, particularly to illuminate the form of melt pathways from the wedge to the arc. Correlation with conductivity structure, although in a nascent stage, has the potential to yield important complementary constraints. However, interpretations of geophysical images are at present limited by uncertainties in the effects of volatiles and melt on geophysical observables, and further experimental studies are essential.

Magma volatile contents are now amenable to direct measurement in submarine glasses and melt inclusions, but large uncertainties remain in the magma generation and crustal growth rates at magmatic arcs. Remote atmospheric sensing of volatile gas output at arc volcanoes is limited to major eruptions, while direct sampling of volcanic gases is limited to occasional sampling at obvious fumaroles, often separated by many years and thus not amenable to time-series studies of gas output evolution. What is the partitioning of volcano degassing between major eruptions and passive quiescent venting?

Geodynamical modeling that accounts for volatile and melt transport and their rheological feedbacks is key to integrating geochemical and geophysical data and testing models of volatile cycling through subduction systems. However, basic questions remain regarding the geometry of mantle flow in subduction zones, and how the subducting plate couples to the surrounding mantle. The depth at which slab/mantle coupling terminates exercises a key control on the thermal structure of the subducting slab and hence on the locus of slab dehydration and of flux-melting in the overlying wedge. What controls the termination depth of slab/wedge coupling?

Volcano vigor– Magmatic arcs are the locations of the most spectacular, explosive and destructive volcanic eruptions that have occurred during recorded history. What are the geochemical and geophysical features that contribute to the wide variety of volcanic eruptive vigor? Magmatic water has an obvious influence on volcano explosivity, but most degassing of water from magma occurs in the upper few kilometers of the volcanic edifice. Do other less-abundant but also less-soluble volatiles also play a role in the accumulation of gas beneath explosive volcanoes? What is the feedback between stress changes (static and dynamic), local earthquakes, volcano degassing, and ultimately eruption? What aspects of volcano structure and composition can be used to help forecast volcano vigor in populated areas?

Climate - Along with H_2O, carbon dioxide, reduced low-weight hydrocarbons, and sulfur- and halogen-bearing compounds contribute to the global budget of greenhouse gases when they are emitted from subduction zone volcanoes, and thus have a significant influence on climate at local to global scales. Subduction zone volcanoes are the primary path for degassing of these volatiles directly into the atmosphere. Compared with anthropogenic input to the atmosphere, conventional wisdom holds that the flux of various volatiles from volcanoes is small, yet measurement of these fluxes is erratic and sparsely distributed. The lack of adequate sampling therefore causes an important failure to accurately capture the emanation of magmatic gas during volcano quiescence between major eruptions which likely dominates the total degassing flux. What is the real contribution of volcanic gas to climate change? How does the flux of magmatic gas from subduction zones vary with magma production and tectonic changes at convergent margins?

Growth Rate – The growth rate of magmatic arcs at subduction zones provides first-order estimates for magma-based flux calculations for volatile transport from the mantle to the exosphere and is the primary means by which we can calculate modern growth rates for continental crust. At spreading centers, magma generation rate is readily calculated from the kinematics of plate spreading. However, at convergent margins the plate geometry is less simple, addition of arc magma may be difficult to differentiate from pre-existing crust, and the stronger influence of volatiles on magma generation make it a significantly more complex phenomenon than at spreading centers. What insights into fluid formation, fluid flow, magma generation and mantle convection in subduction zones are required in order to advance our understanding of crustal growth in arcs? How does arc magma generation depend on tectonic forcing functions such as slab structure, age, convergence rate and nature of the overriding plate? How fast do arcs grow, and how precisely do arcs turn into continents? What is the partitioning of intrusive versus extrusive magmatic products at individual arcs, and how can this be determined? What are the mass and chemical balances of arc formation and evolution, and how do they relate to formation of continental crust?

Structure and Evolution of Arcs –Few compelling dynamic models exist for the initiation of a convergent margin and no sites have been clearly identified where nascent formation of a subduction zone is imminent or ongoing. How does subduction begin? What is the tectonic and structural transition to mature subduction zones? The large diversity of subduction zones raises further questions. What causes the heterogeneity in subduction zone structure? What factors result in the formation of back arc basins, and what are the interactions between the main arc and back arc? Why does strain partitioning between the plate interface and the upper plate vary so widely between subduction zones, and what are the implications for arc rheology? What is the long-term evolution of tectonics and magma mass flux over time during the lifetime of an individual arc? How do arcs and subduction processes vary in space and time, and what are the processes and dynamics that control those variations?

Deep Mantle Recycling - What is the physical and chemical state of the slab after subduction zone processing? What quantity of volatiles passes below the subduction zone factory? How does the rheology of the residual slab contribute to the generation of very deep earthquakes? How does the residual slab relate to mantle heterogeneity, and what role do subduction zones play in global-scale geochemical and volatile cycles, from the core to the atmosphere?

Deep Time - How does subduction influence the long-term geochemical evolution of the planet – mantle and atmosphere? What is the role of subduction zones in determining the deep-mantle budget of volatiles?

Hydrous minerals – Serpentine and chlorite are two important hydrous minerals that have great capacity for storing water. Their predicted stability fields suggest that they could be present in many key parts of the subduction system (the wedge corner, below the slab Moho, above the dewatering slab, at the base of the upper-plate Moho) and that therefore they may exert important controls on the dynamics of subduction zones. The ability to detect the presence of these minerals thus becomes important. What are the physical, rheological, seismic, and conductive properties of serpentine and chlorite? What is the abundance of these minerals at the predicted locations of their stability? Do other hydrous minerals, such as Phase A, the 10 Angstrom phase, or humite minerals, also play important roles in the storage and release of H_2O in or above subducting slabs? What is the role of hydrous minerals in plate locking at convergent margin megathrusts, and in decoupling between the slab and the mantle wedge? What is the role of these minerals in delivering volatiles to the zone of arc magma generation, and what is the chemical signature of their involvement? How does their importance at convergent margins vary with thermal state, along-strike, and at local and regional scales?

Convergent Margin Forcing Functions – We now have estimates of the concentration of H_2O in the magmas of most of the volcanoes in the two SubFac focus sites (IBM and Central America). In both areas there appears to be a clear signal of flux melting, with water contributing to increasing the degree of mantle melting in proportion to its abundance in the mantle. Yet water also shows a dichotomy in its behavior at these two subduction zones, with clear along-strike correlations in geochemical and geophysical variables in Central America but not at IBM. Equally perplexing, depth to slab below the arc, depth to apparent slab decoupling, and water output are relatively constant among arcs, while many properties of the subducting slab vary widely. What physical processes control this lack of correlation?

Infrastructure Required to Address Future Subduction Zone Research

Parallel multidisciplinary efforts in sea- and land-based field programs, experimental petrology and geochemistry, numerical modeling efforts, and geochemical-isotopic-volatile analytical programs have been a hallmark of the MARGINS program as a whole and of SubFac in particular.

• IODP drill cores are essential to obtain the composition of the incoming slab and provide the primary means by which sediment compositions and alteration state of the upper MORB crust are determined.

• Field programs to sample volcanic gases and melt inclusions have been a critical component in determining the volcanic output of volatiles at subduction zone volcanoes, as well as providing a means to examine how magmas differentiate in the crust and contribute to a vertical stratification in crustal composition.

• Deployments of seismometers and MT instruments, including ship-based support for ocean-bottom deployments, have been crucial to determining the seismic velocity and attenuation and conductivity structure of the mantle wedge and subducting slab, as well as imaging the thickness of arc crust along-strike and the state of fracturing and potential hydration of the incoming plate at the outer rise.

• Labs where high pressure and temperature experiments are conducted provide the fundamental data on magma composition, melt production, melting temperatures, volatile and trace element partitioning, and seismic velocity, and conductivity properties that permit us to turn geochemical and geophysical observations into realistic interpretations of deep-Earth structure, temperature and composition.

• Shore-based facilities for geochemical analysis and computational networks for modeling of earthquakes, convection, fluid and melt transport and seismic wave propagation are essential for an integrated approach to MARGINS science progress.

The Importance of a Coordinated Multidisciplinary Approach

A commonality of purpose among these multidisciplinary activities in SubFac has achieved a synergy of scientific results that would not have been possible in the absence of focus sites. The collocation of research efforts sponsored by the governments of Germany (in Central America) and Japan (in IBM) has greatly enhanced the scientific productivity and efficiently leveraged US funding. From a logistical point of view, coordination of field campaigns in geophysics and sampling (for gases and melt inclusions for geochemistry) has been achieved with an economy of both effort and cost at both focus sites. Scientifically, in both IBM and Central America, we now have constraints on sedimentary input, observations and measurements of forearc fluid flux, magma geochemistry and volatile content both along strike and across the arc, images of seismic velocity and attenuation variations, and dynamic models that are constrained by geophysical observables. From these coordinated efforts, it is now possible to make much more accurate interpretations of the geophysics and geochemistry than ever before possible at any subduction zone. Focus sites have made this happen in a way that would not have occurred by serendipity, without a concentration on specific active margins.

To contrast, through core EAR and OCE funding, there exist separate pieces of this scientific puzzle in places like the Aleutians, Tonga and South America – but the lack of a coordinated effort like SubFac has isolated the results of these individual studies, and as a result they lack the kind of multidisciplinary impact that has been achieved, and is continuing to emerge, from the focus of ideas and resources at a few specific sites. A combination of multidisciplinary efforts, concentrated at a few focus sites, has maximized the scientific impact of MARGINS funding.