SF	Collaborative Research: Determining the Volatile and Slab Flux from the Izu-Bonin-Marianas Active Margin Using Geothermal Fluids, Phenocrysts and Melt Inclusions	
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The persistence of plate tectonics on the Earth is the direct result of the presence of significant quantities of water in the Earth's mantle. Considering the influence that water has on mantle properties such as melting point, melt composition, rheology, conductivity and seismic velocity, it is important to understand the distribution of water and associated volatiles in the Earth. Nowhere is the role of volatiles more important than in convergent margins, where seawater-derived components and sediments are introduced into the mantle sources of arc magmas. H_2O is the most dominant volatile component (by mass) in arc magmas and is the transport medium for all other volatiles during magmatic degassing. Yet most conclusions regarding the transport of volatiles from the subducting slab into the mantle wedge and ultimately to the atmosphere are based on measurements of fluid mobile elements in erupted rocks, rather than the volatiles themselves.

We have begun an integrated study of volatiles in the Izu-Bonin-Marianas margin that includes the analyses of specific volatiles (H_2O, CO_2, Cl, F, S) and fluid soluble elements (Li, B, K, Rb, Ba and others) as well as their stable isotope (dD, $d^{11}B$, $d^{13}C$, $d^{18}O$, $d^{34}S$) systematics utilizing SIMS measurements of melt inclusions of recently erupted tephra. This extensive data set is being complemented by CO_2 and He abundance and isotopic measurements ($d^{13}C$ and $^3He/^4He$) in erupted phenocrysts and discharging volcanic and hydrothermal fluids. Additionally, we are measuring the complete gas composition and specifically the N-isotopes of the hydrothermal fluids in order to determine the present-day total volatile flux from the entire arc through normalization to ground-based SO_2 remote sensing measurements.

The combined data set will allow us to quantify:

1. the slab flux in terms of volatile composition (melt inclusion data)
2. the source of the slab flux in terms of oceanic basement, subducted carbonates or organic sediments (CO_2-He and N_2-He systematics)
3. the present day volatile flux to the atmosphere from the slab and mantle wedge (SO_2 flux and volcanic gas compositions)

Our work is the first systematic study of melt inclusions and volatile emissions in the Marianas-Izu-Bonin Arc System. It is also the first study that attempts to characterize arc volatiles using petrologic (melt inclusions), geochemical (He, C, N isotopes, gas chemistry) and volcanological (SO_2 flux) methods in a truly integrated approach.

To date we have made significant progress in terms of quantification and characterization of the slab flux as well as evaluating the state of mass balance (input via the trench versus out put via the arc) in the IBM subduction zone system. The following is a summary of our results and their significance to understanding volatile systematics in subduction zone systems.

Melt inclusions studies:

Prior studies of Mariana arc lavas and melt inclusions have shown that the magmas feeding the arc show varying contributions from sediment and altered oceanic crust components. Based on trace element, ^{238}U enrichments (Elliott et al., 1997), and B systematics (Ishikawa and Tera, 1999), lavas from Guguan volcano are thought to represent a geochemical endmember in which the subduction component is delivered to the site of melt generation by a hydrous fluid, presumably from the altered oceanic crust. At the other end of the spectrum is Agrigan volcano, the source of which is thought to be dominated by subducted sediments, with minimal contribution from the so-called fluid component. Assessing the role of water and other volatiles in the generation and transport of the fluid component in generating these lavas is one of the main goals of our ongoing study.

We have measured H_2O, CO_2, S, F and Cl abundances of olivine-hosted melt inclusions in recently-erupted tephras from nine Mariana arc volcanoes. We find that the highest water contents are not found in the fluid endmember volcano, but rather in melt inclusions from Agrigan, the sediment endmember. In addition, melt inclusions from Maug volcano define a previously-unrecognized low-H_2O endmember in the Marianas. The Maug melt inclusions contain high CO_2 indicating that degassing did not control the H_2O abundances. Thus, the Maug inclusions are similar to the dry arc melt inclusions from Galunggung studied by Sisson & Bronto (1998), and indicate that dry decompression melting occurs in the Marianas (Figure 1). The inter-volcano differences in H_2O cannot be ascribed to the degree of partial melting (based on Ti and Na contents at 6 wt % MgO) or to fractionation effects and thus must reflect true differences in the amount of H_2O being delivered to the sources of Mariana Arc volcanoes. This has important implications for the mechanisms of melt generation beneath the IBM arc, the reliability of trace element proxies for magma water content, and for our understanding of the relationship between water, halogens, noble gases, trace elements transported from the slab, and melt generation.

Assuming that the most volatile-rich samples best represent the volatile content of the undegassed sub-arc melt, we estimate absolute output fluxes along the arc for SO_2 (4.1 Mmol/yr/km of arc), CO_2 (2.0 Mmol/yr/km of arc) and H_2O (409 Mmol/yr/km of arc), using a magma production rate of 47 km^3/Ma/km arc (Dimalanta et al., 2002). In the case of CO_2 and H_2O, these output flux estimates represent 10.4 % and 335 %, respectively, of the sedimentary inputs (Plank and Langmuir, 1998). The excess water can be reconciled if we consider inputs from the altered oceanic crust, which, given the age of the subducting crust, are likely to dominate the input. In order to balance the water budget, we require an input from the altered oceanic crust of ~ 4×10^{11} mol H_2O/yr.

In addition, this study has produced the first measurements of hydrogen isotopes on melt inclusions from arc volcanoes. We find that the hydrogen isotopic composition of arc-related water ranges from ~ -30 to +15 ‰ (Figure 2), significantly higher than typical MORB values (-70 ± 10 ‰). High dD values in arc-related melts suggests that isotopic fractionation during dehydration from the slab is a key process controlling the isotopic composition of subduction-related water. The sense of dD fractionation is consistent with experimentally determined fractionation factors for hydrous minerals (Suzuoki and Epstein, 1976).

Volcanic and hydrothermal gas studies

Prior to our work, there have been no gas studies in the Marina section of the arc and only sporadic sampling of emissions in the Izu Bonin Islands. We have made an effort to systematically collect samples from all accessible localities and sampled four islands in the Marianas (Alamagan, Pagan, Agrigan, Uracas) and five of the Izu Islands (Shikinejima, Niijima, Oshima, Aogashima & Hachijojima). In total we collected on the order of 40 gas samples from bubbling springs, fumaroles and geothermal wells. The analyses of the Mariana samples have been completed (gas chemistry, He-C-N isotopes) and analyses of the Izu-Bonin samples are currently ongoing.
Helium and carbon isotope ratios reported in prior studies from the Izu-Bonin islands (Iwo Jima) reach values up to 5.6 R_A and + 1.5‰, respectively, suggesting a large contribution of slab derived carbon to the discharging fluids. The heavy carbon isotopic signature indicates that hydrothermally altered crust is the ultimate source of CO_2 in Iwo Jima gases (Sumino et al., 2004). Our data from the Mariana islands shows higher helium isotope ratios (7.4 to 7.9 R_A) that are within the MORB value of 8±1 R_A. Carbon isotope values (- 0.6‰) are similar to the value of carbonates (0.0‰) also suggesting a significant contribution of CO_2 from subducting hydrated oceanic basement.

Nitrogen isotopes and N_2/He ratios have been successfully used elsewhere to determine the source of volatiles in terms of mantle wedge and subducted hemipelagic sediments (i.e. Fischer et al., 2002). Although sample analyses are still in progress and we have not completed the Izu section of the arc yet, we see significant variations in N_2/He ratios and $d^{15}N$ values of the samples where we have robust data. The Mariana section of the arc, Agrigan in particular, shows less input from subducted hemipelagic sediments (0 to ~60%) than the Izu section of the arc (up to 80%) (Figure 3). An interesting and unexpected result of our combined melt inclusion and gas emission study is that Agrigan, which is considered the 'low fluid endmember' displays C-He-N systematics that suggest contributions from carbonates with minimal contribution from hemipleagic sediments (0%). Interestingly, Agrigan also has the highest water contents in melt inclusions, not expected for the 'low fluid endmember'. We are currently completing the gas analyses and preparing for presentation of our results at the AGU special session on MARGINS related studies in the IBM system.

Volatile emissions studies

The first historical eruption of Anatahan in May 2003, which injected ash and gases into the stratosphere, gave us the opportunity to observe the reawakening of an inactive volcano. Fischer and Hilton measured SO_2 flux and collected fresh samples 11 days after the onset of the eruption. Samples were distributed to the MARGINS geochemical/petrological community as well as the USGS for analyses. Results have been published in special issue of the Journal of Volcanology and Geothermal Research (2005, Hilton co-editor).

We measured, for the first time, the SO_2 flux from any Marina Islands volcano. Our results show that SO_2 and other volatiles had accumulated below a sealed carapace and in the hydrothermal system of Anatahan prior to eruption. As overpressure of the gas exceeded the strength of the overlying rock the explosive eruption occurred and initially released the accumulated volatiles along with large quantities of hydrothermally derived water vapor. It was this water vapor that produced the initial hydromagmatic deposits of Anatahan. As the eruption continued, deeper levels of the system were tapped and emitted volatiles directly from the magma body itself. The overall SO_2 emission during the eruption was about 200,000 tons and most of that (about 150,000 tons) had accumulated in the volcanic edifice prior to eruption (de Moor et al., 2005). We are now working on constraining the ultimate source of the magmatic SO_2. Preliminary results hint at a large and constantly degassing basaltic magma body at depth, consistent with the silica-poorer tephras ejected during the 2005 eruptions and Anatahan's continuing gas emissions. Our work has implications for the atmospheric impact of eruptions that are initially 'wet' and therefore inject large quantities of H_2SO_4 aerosols into the stratosphere, where they can potentially cause global surface cooling.

Ongoing work

1. Completion of analyses – mainly for the Izu Bonin section
2. Constrains on volatile source variations along strike of the arc
3. Correlation of volatile data with other geochemical tracers of slab flux
4. Mass balance considerations – input at trench vs. output through arc
5. Global implications and comparison to other subduction zones
6. Implications for geochemical evolution of the mantle and melt generation processes at subduction zones

Field Expeditions

Completion of 2 major field expeditions to (a) the Mariana Islands, and (b) Japan. Both expeditions had significant outreach components in that they were covered as 'web expeditions' (http://sio.ucsd.edu/marianas and http://sio.ucsd.edu/japan).

Two Rapid Response missions to the eruptions of Anatahan Volcano in May 2003 and March 2005. All samples were distributed for laboratory analyses to the MARGINS community.

Analytical Work

Collection of SO_2 flux data in from Anatahan Volcano 2003, 2004 and 2005. These are the only flux data from this volcano to date.

Edited Volumes and Special Sessions

Publication of special issue of Journal Volcanology & Geothermal Research dedicated to the 2003 eruption of Anatahan – co-edited by Hilton.

Special session at Fall AGU meeting (2003) dedicated to the May, 2003 Anatahan eruption (co-organized Fischer & Hilton + others)

Publications

a) Refereed journal articles

Hilton, D.R., Pallister, J.S. and Pua, R. (2005) Introduction to the special issue on the 2003 Eruption of Anatahan Volcano, Commonwealth of the Northern Mariana Islands (CNMI). J. Volcanol. Geotherm. Res. 146 pp 1-7.

de Moor, J. M., Fischer, T.P., Hilton, D.R., Hauri, E. Jaffe, L. A. and Camacho, J.T. (2005) Degassing at Anatahan volcano during the May 2003 eruption: Implications from petrology, ash leachates, and SO_2 emissions. J. Volcanol. Geotherm. Res. 146 pp 117-138.

Wade, J.A., Plank, T., Stern, R.J., Tollstrop, D., Gill, J., O'Leary, J., Eiler, J., Moore, R.B., Woodhead, J.D., Trusdell, F., Fischer, T.P and Hilton, D.R. (2005) The May 2003 eruption of Anatahan volcano, Mariana Islands: geochemical evolution of a silicic island arc volcano. J. Volcanol. Geotherm. Res. 146 pp 139-170

b) Other Publications

Hilton, D.R., Pallister, J.S., Fischer, T.P., Wiens, D.A., Trusdell, F.A., Chong, R.C. and Camacho, J.T. (2004) The 2003 eruption of Anatahan. MARGINS Newsletter 12, pp 1-4.

Fischer, T.P., Hilton, D.R. and White, R. A. (2005) MARGINS event response: Anatahan volcano. MARGINS Newsletter 14, pp 12-13.

c) Abstracts

Fischer, T.P., Hilton, D.R., Shaw, A.M., Hauri, E.H., Kazahaya, K., Mitchell, E., Shimizu, A., de Moor, J.M. Sharp, Z.D. (2005) Tracing slab inputs along the Izu-Bonin-Marianas subduction zone: results from volatile emissions. AGU Fall Meeting abstract

Shaw, A.M., Hauri, E., Kelley, K., Fischer, T., Hilton, D., Stern, R., Hawkins, J. and Plank, T. (2005) Hydrogen isotope variations in Mariana arc melt inclusions. Goldschmidt05 Conf. Abs. p A631.

Shaw, A., Hauri, E., Hilton, D., Fischer, T., Stern, R., Wade, J. and Plank, T. (2004) Insights into arc fluid budgets from Mariana melt inclusions. Goldschmidt 2004, Abstracts volume p 70.

Fischer, T.P., Hilton, D.R., Tsanev, V.I., McGonigle, A., Jaffe, L.A., Alison M.Shaw, A.M., de Moor, J.M. and Hauri, E. (2004) SO_2 flux measurements using the mini-DOAS: results from Masaya, Aso and Anatahan volcanoes, IAVCEI General Assembly Pucon, Chile.

Shaw, A.M., Hauri, E.H., Hilton, D.R., Fischer, T.P., Stern, R., Wade, J. and Plank, J. (2004) Insights into arc fluid budgets from Mariana melt inclusions, IAVCEI General Assembly, Pucon, Chile.

Hilton, D.R., Fischer, T.P., Wiens, D.A. and Camacho, J.T. (2003) Anatahan eruption of May, 2003: Integrated response of the MARGINS community. EOS Trans. Am. Geophys. Union 84 p F1394.

Fischer, T.P., Hilton, D.R., DeMoor, J., Jaffe, L., Spilde, M.N., Counce, D. and Camacho, J.T. (2003) The first historical eruption of Anatahan volcano, Marianas Islands. EOS Trans. Am. Geophys. Union 84 p F1561.

Wade, J.A., Plank, T., Stern, R., Hilton, D., Fischer, T.P., Moore, R., Trusdell, F. and Sako, M. (2003) Geochemical composition of volcanic rocks from the May, 2003 eruption of Anatahan volcano, Mariana Islands. EOS Trans. Am. Geophys. Union 84 p F1562.

Oleary, J.A., Eiler, J.M., Fischer, T., Hilton, D. and Laffee, L. (2003) Oxygen isotope geochemistry of the May 10th Anatahan eruption. EOS Trans. Am. Geophys. Union 84 p F1562.

Presentations in seminars

The Eruptions of Anatahan Volcano and ongoing volatile studies in the Mariana Arc. Ocean Research Institute, University of Tokyo, Japan (Fischer, June 2004).

The eruption of Anatahan volcano, the Marianas. Scripps Inst. Oceanography (Hilton, June, 2003).

Volatile mass balance and recycling at subduction zones , University of Michigan, Ann Arbor (Hilton, Jan, 2004).

MARGINS-related research: contrasting Central America with the Marianas. CRPG-CNRS, Nancy, France (Hilton, July, 2004).

Students and post doctoral researchers involved in the project

Fischer: Maarten de Moor (M.S. completed 2005); Euan Mitchell (M.S. ongoing)

Hauri: Dr. Alison Shaw (post doctoral fellow, DTM)