Anatomy of an Arc Section: A MASH Zone Revealed

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The Sierra Valle Fertil to La Huerta section of the Famatina arc in west central Argentina exposes the plutonic roots and associated host rocks in a 100 km long nearly continous section with paleo-depths of >25 km to 8 km or less. This tilted section exposes identifiable end-member components of a juvenile continental arc: large bodies of granodiorite and tonalites in the mid-to-upper crust, a mafic and ultramafic dominated lower crust, which is interlayered with a lithologically homogenous sequence of metapelites and other supracrustal compositions. The circulatory system of the arc is continuous and decipherable: all units described above are physically linked via hyper-solidus and migmatitic domains, veins and dikes that connect source rocks to plutons. The preservation is exceptional as arc magmatism was largely arrested by a soft collision during the prograde peak, before long-lasting magmatism had obliterated the architecture of a complete compositional cycle that occurred over a span of 4-5 Ma. Hence much as volcanic systems are a snapshot of a magmatic system, the Sierra Valle Fertil provides a snapshot of a juvenile, but crustal-scale plutonic system, without significant over-print of high temperature structures and very long-lived repeated magmatic processing.

Of special interest is the engine room of the arc: mafic to ultra-mafic cumulates (pyx, olv, amp, plag) to tonalites. These occur as a composite, heterogeneous, variably cumulate complex up to 15 km thick. The compositional variability is consistent with a fractionation model but one that requires a changing cumulate assemblage (gabbros) reflecting discrete episodes of extraction of daughter magmas (tonalites). Field identification of distinct mafic plutons is difficult as hyper-solidus conditions prevailed throughout the construction of the complex, blending new intrusions of mafic magma with existing cumulate mush. Based on Sr, Nd and O isotopic evidence, assimilation must have occurred, but low-K2O throughout the complex indicates that extraction of contaminated melts from the gabbroic mush was efficient. However crustal melting, whether of sedimentary host rocks, or mafic precursors, plays a minor role in the production of compositional diversity. Taken together this suggests that the Sierra Valle Fertil mafic complex was an archetypical MASH zone whose processes and products were largely conditioned by the tempo of mantle input.

Crustal magmatism as recorded in Ignimbrite Flare-ups

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Fueled by a transient elevated thermal flux from the mantle, an ignimbrite flare-up is a regional scale (>100 km^2) and long-lived (several to tens of millions of years) volcanic episode linked to profound crustal modification (Elston, 1984; de Silva, 1989; Best and Christiansen, 1991; Bryan et al., 2002; Lipman, 2007). Thus, such flare-ups account for a significant portion of what can be collectively termed crustal magmatism, mantle-powered but significantly crust-modified. The geologic imprint of these flare-ups are multi-cyclic caldera complexes that erupt hundreds to thousands of cubic kilometers of dacitic to rhyolitic ignimbrites in each eruption, along with abundant effusive volcanism. It is also being increasingly recognized that cordilleran batholiths are also constructed during these events (Ducea et al., 2001). Given the strong spatial, geochemical, petrological, and geophysical kinship between silicic volcanic and plutonic rocks it is reasonable to believe that volcanism must be accompanied by significant (and more voluminous) plutonic activity at depth. Co-genetic volcanic and plutonic rocks, with connections to deeper levels of the crust are to be expected. An integrated model for ignimbrite flare ups reveals that the high-level magmatism is the end result of feedbacks between lower crustal magma generation, advection of heat as magmas rise from depth, and the rheology of the crustal column. Such eruptions are rare and episodic suggesting that activity is modulated by crustal processes.

This is explored through the temporal record of the Altiplano-Puna Volcanic Complex of the Central Andes (de Silva et al., 2006), where the record of the flare-up reveals three types of signals. The broadest and dominant signal is that of the flare-up itself, a transient pulse magmatism of the order of 10^7 years that punctuates a background or baseline level of activity. This represents the waxing and waning of the heat engine, mantle power input. The second signal is system-wide episodicity that operates on a time scale roughly an order of magnitude faster. This is manifested by intense pulses of eruption that last from 10^5 to 10^6 years separated by periods of $2x10^6$ years. This is most likely the imprint of crustal processes, the crustal filter. The third signal is recorded in individual volcanic systems. Close correspondence between the timing of activity at separate long-lived caldera complexes, connotes a system-wide synchroneity in the development and eruption of these otherwise independent systems. This may reflect a tectonic imprint on the magmatic and volcanic record.

Role of density contrast on magmatic architecture in the Earth's crust

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Magma reservoirs probably grow incrementally by repeated sill-like intrusions. We investigate the conditions for repeated intrusions at the same crustal level by a feeder dike before a permanent molten reservoir can form. Sill inception requires that magma within a dike develop an overpressure that is large enough to overcome the strength of surrounding rocks. An efficient mechanism to achieve this involves ascent through layers with decreasing density, such that magma become negatively buoyant above some interface. Dike penetration through a succession of crustal layers with different densities was studied with a new numerical code. To significantly affect dike ascent, the density change in country rock must occur over a thickness of the order of the characteristic length-scale for the inflated nose region that develops below the dike tip. This characteristic length depends on the elastic properties of the host rocks, on magma buoyancy and on the flux of magma, and is typically around 1 km for basaltic magmas, which is of the same order of magnitude as the typical thickness of sedimentary strata and volcanic deposits.

A dike continues to rise even if magma becomes negatively buoyant above some interface due to the continuous input of new magma. In this case, it develops a swollen nose region that straddles the interface as the internal magma pressure builds up. Penetration characteristics and the magnitude of the magma overpressure are determined by a local buoyancy balance in the nose region, independently of the total buoyancy of the magma column between source and tip. For sill inception to occur, the thickness of the low density layers must exceed a threshold value which depends only on the rock strength and on the average negative buoyancy of magma independently of the magma flow rate. For basaltic melt, we estimate that this threshold thickness cannot be less than about 700 m and is 2 km on average. The overpressure that develops at the density inversion level is set by the vertical extent of the inflated dike nose region above that level, and hence is related to the volume of magma in that region. Thus, sill inception also requires that the total volume of magma available in an individual intrusion event exceeds a threshold value.

Physical controls on the frequency and magnitude of volcanic eruptions

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The frequency at which volcanic eruptions occur is inversely proportional to the volume of magma released in a single event. The volumes of erupted magma range from a fraction of a cubic kilometer up to thousands of cubic kilometers during rare super−eruptions. The rate at which magma is supplied from depth, the mechanical properties of the Earth′s crust and the regional tectonic regime are known to play a role in controlling volcanic eruptions, but their relative contribution has not been quantified. We combined results from thermo−mechanical modeling and Monte Carlo simulations to quantify the relative contribution of magma fluxes and the physical properties of the crust on likelihood and volume of volcanic eruptions. The calculations were performed considering the pulsative injection of magma and varying randomly and within geologically reasonable values, size, shape and frequency of magma injections together with the long−term average rate of magma input, and the visco−elastic properties of the crust.

The average rate of magma supplied to the upper crust over hundreds of thousands of years appears to control the volume of magma that can potentially be released during a single eruption, whereas the time interval between short−lived pulses of magmatism, affects the total duration of magma injection preceding an eruption.

Our calculations reconcile the relationship between erupted volume and upper crustal magma residence times, and replicate the correlation between erupted volumes and caldera dimensions. Our modeling shows that pressurization associated with magma injections is responsible for relatively small and frequent eruptions, whereas magma buoyancy is key to triggering super−eruptions. These calculations also permit to define the largest physically possible eruption that could occur on Earth, which is important to improve the statistical significance of the relationship between frequency and magnitude of volcanic eruptions.

The dynamics of magma recharge in persistently active basaltic andesite systems

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The triggering of eruptions by magma recharge is relatively well understood in systems where the resident magma and the recharge can be clearly differentiated. However, in persistently active basaltic andesite systems such as in the Southern Volcanic Zone of the Andes, in which both recharge and resident magmas are similar, the subtleties of the mixing and thermodynamics of the recharge have not been fully addressed. In order to formulate adequate thermodynamical models for these systems, a model for steady state recharge needs to be considered. This simple constraint implies inherent irreversibility of the recharge mechanism and permanent non-equilibrium conditions of the system. Under such conditions, the application of standard equilibrium approaches can simply not be justified. Keeping that in mind, in this work we have simulated the recharge and evolution of a steady state basaltic andesite system using alphaMELTS in small increments of evolution and recharge (quasistatic iterations), taking advantage of the fully automatic scripting capabilities of the code. Initial conditions of the calculations were based on geological constrains from both Villarrica and Llaima volcanoes, Chile. The results strongly suggest that recharge in this type of system can be modeled as a non-linear process that largely self-organizes under steady state conditions. This in turn implies that the narrow compositional range of the volcanic products in these systems (i.e. the basaltic andesite) is the direct consequence of the self-organization, while sudden changes in the behavior of the systems may be consequence of the non-linearity of dissipative structures. The calculations and model are in good agreement with the measurements of the crystal size distributions of the main mineral phases found in Villarrica and Llaima products and generated under a variety of eruptive situations. An obvious implication of these results is the inherent difficulties in using geochemistry for forecasting elevations in eruptive activity since small changes in the dynamics of the steady state system can have non-linear effects. Further work needs to be done to quantify the extent of changes that might produce a major eruptive events in these systems.

Rhythm of magma transport in deformable porous media

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Volcanic activity, which is the surface manifestation of magma transport, appears to be intermittent. Moreover, the distribution of volcanic activity often shows a characteristic spacing along intra-continental rifts, mid-oceanic ridges, subduction related volcanic arcs, or rift zones in volcanic complexes (e.g. Iceland, Hawaii). However the physical mechanisms at play to create these spatio–temporal patterns are still debated. Magma transport in the Earth involves flow of a slurry (crystals, liquid and bubbles) into an elastic solid matrix which can undergo compaction. A quantitative understanding of such a complex system is lacking. Here, we attempt to bridge this gap and to explain the origin of intermittency in magma transport system, using fluid dynamic modeling of buoyant plumes in a deformable–gel beads layer.

A thin transparent tank ($2\times20\times18$ cm^3) is filled with a mixture of hydrogel beads and a viscous fluid, as an analog to an elastic compacting lithosphere or crust containing some partial melting; a viscous fluid ($\sim$10 Pa.s) is supplied from a nozzle (inner diameter: 7.5 mm) or from a slit (gap: 5 mm) at a constant volume flux. The hydrogel beads (polyacrylamide, diameter: $\sim$5 mm, shear modulus: 1.2×10^4 Pa) are deformable and the volume fraction of the interstitial fluids is about 15%. For the point source experiments, we identify at least three types of fluid flow: homogeneous permeable flow, pulsating flow, and localized continuous flow. The flow behavior depends on the injection flow rate, the rheological properties of the mixture, and the volume fraction of the interstitial fluid. For the line source experiments, the flow pattern always shows a time-dependent behavior. As the viscous fluid is supplied from the source at a constant volume flux, the fluid percolates into the gel beads layer until a gravitational instability (Rayleigh–Taylor instability) occurs. Then, the flow is localized through channels with a characteristic spacing. The plume flow is relatively continuous around the source region; however, the flow along the channels can become unstable and create pulses. Their characteristic frequency is obtained by image analysis.

Our experimental model suggests that the spatio-temporal distribution of volcanic activity is inherent to magma transport in a weak elastic and compacting lithosphere or in a partially molten zone (like for exemple a magma chamber).

Revisiting Magmatic Rocks of Sri Lanka: Evidence for an Ancient Accretionary Complex?

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Sri Lanka is predominantly composed of Precambrian rocks of which majority are metamorphosed under high temperature conditions. Mainly, the rocks are distributed in four litho tectonic units namely, Highland Complex, Wanni Complex, Vijayan Complex and Kadugannawa Complex. These rocks include a vast volume of magmatic intrusions and some of them are now metamorphosed with their host metamorphites. According to the limited data, magmatic rocks of Sri Lanka cover a broad spectrum of composition from under-saturated alkaline types over metabasaltic to highly differentiated granites. The Kadugannawa Complex and the Vijayan Complex of Sri Lanka define chemical trends typical of calc-alkaline rock series whereas samples from the Highland-Wanni Complexes show a broad scatter suggesting bimodal distributions. The rocks with alkaline affinity show surprisingly high concentrations of Na_2O > 6 wt%, K_2O > 6 wt%, Ba up to 12000 ppm and Sr upto 4000 ppm. Based on the preliminary data available alkaline rocks in the Highland-Wanni Complexes can be distinguished into two groups. Group I alkaline rocks are extremely enriched in LREE with a marked decrease in HREE. Group II rocks are less strongly fractionated and display negative Eu anomalies. Some of these patterns appear to be affected by charnockite formation by a CO_2 rich magma flow from the mantle. There is a systematic elemental correlation displayed with continuous SiO_2 trends in variation diagrams inferring a cogenetic calc-alkaline rock suit and suggest subduction-type magmatism occurred along an old continental margin. Detailed investigations using advanced analytical facilities including geochronology are necessary to unravel their petrogenetic relationships with respect to space and time.

Petrogenesis and geodynamic significance of silicic volcanism in the western Trans-Mexican Volcanic Belt: the role of gabbroic cumulates.

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Large volumes of silicic volcanism are frequently explained by the two end-members of crustal melting and fractional crystallization from basalt. Both models present critical issues particularly in arc setting where extensive crustal melting is not always tectonically favoured and extensive basalt fractionation requires unrealistically large volume of cumulates.

In the western Trans-Mexican Volcanic Belt voluminous silicic volcanism has been associated to the rifting of the Jalisco block from mainland Mexico since the Pliocene. Based on new and published geochronologic, geochemical, and isotope data we revise this interpretation and propose a new petrogenetic model. Silicic volcanism began in Late Miocene after a major pulse of basaltic lavas dated 11 to 9 Ma. The first group of rhyolitic domes was emplaced north of Guadalajara with a volume of around 370 km3 and ages of 7.5 to 5 Ma. This was followed between 4.9 and 2.9 Ma by rhyolites (around 500 km3) emplaced between Guadalajara and Compostela. The youngest episode consist of around 430 km3 of rhyolites of Pleistocene age emplaced between Tequila and Guadalajara, with La Primavera caldera (around 35 km3) as the sole explosive volcanic episode.

Rhyolites and basalts have distinct compositional trends and the large silica gap suggests that rhyolites are not fractionating from basalts. At the same time the low Ba and Sr contents of rhyolites suggest extensive fractional crystallization. Rhyolite Sr isotope values are only slightly more radiogenic than the 11-8 basalts, whereas Nd isotope ratios are indistinguishable.

The similarity in Nd isotope compositions between basalt and rhyolites strongly argues for a mantle-origin of the rhyolites. Nevertheless, a problem posed by any basalt-origin model lies in the large (2:1) volume of intermediate cumulates that should be associated to the final silicic magmas. We propose an alternative model in which the production of the 7.5-3 Ma silicic magmatism is the result of partial melting of crustal gabbroic complexes underplated at the base of the crust during the Late Miocene pulse of volcanism. Subsequent basalt intrusion in the lower crust heated and melted these gabbroic complexes forming silicic magmas, which subsequently underwent AFC differentiation processes. Geochemical and isotope data of rhyolites can be successfully modelled by low degree of melting of the Late Miocene gabbroic complexes leaving a residue dominated by plagioclase and clinopyroxene. These melts are subsequently modified via AFC processes en-route to the surface. Late Miocene slab detachment and subsequent slab rollback produced pulses of mafic magma that decrease in volume with time, forming gabbroic cumulates. Melting of this newly formed gabbroic crust originate the first episode of silicic magma during a period of low tectonic activity. Extensional faulting since the Pliocene favours the eruption of both silicic magma and lesser amount of mafic lavas.

Fractional crystallization experiments from olivine-tholeiite to rhyolite at mid-crustal conditions and consequences for liquid extraction and magma transport

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Piston cylinder experiments starting from primary, hydrous olivine tholeiite at 0.7 GPa simulating near perfect fractional crystallization at mid-crustal levels were conducted to constrain phase assemblages, modes of cumulate phases, liquid compositions and trace element partitioning between liquid and solid phases along the liquid line of descent. Derivative liquids range from hydrous arc tholeiite (3 wt. % H_2O) at 1170C to andesite (980C) to rhyodacite (880C) to high-silica rhyolite (690C). The evolution of the melt fraction as a function of decreasing temperature is highly non-linear. Two ranges of extensive crystallization over a short temperature interval have been recorded: (1) between 1070 and 1000C the crystallization of cpx, opx, plag and amph + magnetite leads to a decrease of residual liquid from 80 to 40% driving the liquid composition from basalt to andesite; (2) below 700C where the final 20% liquid (relative to initial tholeiite) solidifies at the granite (eutectic) minimum within a few degrees. The crystallization behavior between 950 and 700C, i.e. from dacite to rhyolite, is of particular interest. Over this 250C interval only 44% of amphibole + plagioclase + magnetite (+ apatite below 900C) precipitate; the liquid compositions are strongly controlled by saturating phases, e.g. Ti, P, Ca and Mg contents decrease systematically providing excellent geothermometers to derive temperatures of derivative silica-rich liquids.

Complementary rheologic experiments were conducted to address the behavior of crystal-liquid-bubble systems under simple shear at high temperature-pressure conditions (Pistone et al., this conference) employing hydrous rhyolitic liquid, quartz crystals and a limited number of CO_2-rich bubbles. These experiments constrain the conditions that control weather magmas are likely to stall within the crust with potential extraction of interstitial liquids that can further rise or if they move as crystal-rich magmas through the crust ultimately forming shallow level plutons or generating large-explosive eruptions.

Combining the two complementary studies implies that mantle-derived, hydrous arc magmas will most likely encounter two stages where a sudden increase in crystallinity and, thus, bulk viscosity results in stalling of magma ascent thereby enabling effective extraction of interstitial liquids from crystal mushes (most likely by shear deformation of the mush and the consequent formation of melt enriched shear planes that allow escape of melt): (1) at ca. 1000C where the liquid is andesite saturated with cpx, opx, amph, plag and magnetite, and (2) close to the granite minimum at 700C where the liquid is a high-silica rhyolite saturated in plag, alkali-feldspar, quartz, biotite, apatite and Fe-Ti-oxide. In both cases, crystal-poor liquids can be extracted from the crystal mushes that further ascend and either form shallow level plutons or discharge as volcanics at the surface.

Petrology and Geochemistry of Gede-Salak Volcano Northwest Java: Evolution of magmatic process

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Gede-Salak volcano is located in the Banten Province, Northwest Java. This volcano is consisted of several volcanoes which are Gede, Salak, Batur, Wadas, Peda, Batu and Kedepel. Field mapping suggests that the formation of Gede-Salak volcano can be divided into two stages. The pre-caldera stage is consisted of Batu's lava, Gede's lava and Salak's lava. The post-caldera stage was formed by Batur's pyroclastic flows, Kedepel,Wadas and Peda lava dome. Most of the lavas are characterized by porphyritic texture and based on the composition of phenocrysts, they can be divided into 5 types, which are: Batu's lava is andesite hyperstene-augite; Gede's lava is basaltic andesite; Salak's lava is andesite; Kedepel and Wadas's lava domes are andesite hornblende and Peda's lava dome is andesite augite. Oscillatory zoning and opaque rim in hornblende are observed, which are related to the process of magmatism. Based on Harker and A-F-M diagrams the volcanic rocks of Gede-Salak volcano have Calc-alkaline affinity. The K_2O vs SiO_2 diagram suggests that pre-caldera and post-caldera Gede-Salak volcanic rocks belong to the medium-K calc alkaline and high-K calc alkaline. Results of analysis spider diagram, normalized to chondrite, primitive mantle and MORB, lava rock in Gede-Salak volcano have a relatively similar pattern, reveal a pattern indicating magma arc intermediates in the continent arc. The existence of several elements such as anomaly Pb and Ce, indicating magmatic process is affected by subduction components. Petrogenetic processes viewed in petrography and geochemical character are (a) the occurrence of magma mixing or assimilation, (b) loss of pressure in the initial phase of Gede-Salak volcano eruption, (c) anomaly of Pb and Ce, indicating the influenced of sediment or water in magmatic process and (d) comparison of the ratio element B indicates that the subduction component affects the magmatic process in Gede-Salak volcano.

Geochemistry of alkaline silicate-carbonatite rock associations within the intrusive complexes of Brava Island, Cape Verde

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Intrusive carbonatites often occur in intimate association with various silicate rocks such as phonolite, nephelinite, syenite and melilitite. Compared to the alkali-rich composition of the world's only existing carbonatite volcano Oldoinyo Lengai (Tanzania), the absence of alkalis in most calcitic carbonatites around the world may be a direct consequence of fluid-release (rich in alkalis) to the surrounding wall-rocks during crystallization (i.e., fenitization). This study focuses on physico-chemical interaction between carbonatite and silicate magmas, as well as on late stage fenitization processes in alkaline silicate-carbonatite complexes within the intrusive unit of Brava Island (Cape Verde).

Alkaline silicate rocks from Brava range in composition from phonolites, tephriphonolites, phonotephrites, basanites to nephelinites and melilitites. Compared to previous studies our new whole rock data (80 bulk rock samples) show that the previously inferred compositional gap between calico/magnesiocarbonatites and nephelinite/melilitite rocks is, in fact, chemically linked via a set of highly SiO_2-undersaturated (<30 wt%) alkaline rocks. Trace element chemistry of magnesio- and calciocarbonatite dikes crosscutting the alkaline silicate complexes suggests a direct petrogenetic link to their associated silicate rocks. Trace element plots show that calciocarbonatites are characterized by a positive correlation of REE (e.g., La vs. Sm) and are unequivocally more enriched in REE than magnesiocarbonatites which are defined by positive curvilinear trends. Interestingly, the associated alkaline silicate intrusives closely follow either the calico- or the magnesiocarbonatite REE trends, possibly indicating a common petrogenetic origin.

Some of the intermediate alkaline rocks display mingling textures consisting of carbonatite globules within a silicate matrix, whereas the exact transition between the two rock types is rather diffuse. Coulometric analyses show a bimodal variation in CO_2 within the carbonatite and alkaline silicate rock suites. Fenitized silicate rocks and mingled silicate/carbonatite rock associations define, together with the CO_2-rich carbonatite endmembers, a negative linear trend when the total alkalinity is plotted against CO_2 (ranging from 5-43 wt%). In contrast, nephelinites, melilitites and phonolites which are hardly affected by an overprint of fenitizing fluids display CO_2 concentrations less than 5 wt%. Within the carbonatites an internal variation in CO_2 concentration is observed, whereas a significant drop of CO_2 (from 40 to 20 wt%) is recorded in mingled rock samples displaying the effect of the increasing carbonatite fraction within silicate magmas. Thus, mixing proportions between these rheologically and chemically contrasting magmas may affect significantly the eruption dynamics within silicate-carbonatite volcanic provinces such as the Island of Brava.

Experimental constraints on the storage conditions and evolution of alkaline lavas at Erebus volcano, Antarctica: A case for CO_2-dominated volcanism

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We present new phase equilibria experiments on natural basanite and phonotephrite lavas, which elucidate the magma evolution and storage conditions beneath Erebus volcano, Antarctica with respect to H_2O and CO_2 contents, pressure, temperature, and crystallisation process occurring in the crust. Despite its remote location, Erebus volcano on Ross Island, Antarctica is very well monitored. It has an active phonolite lava lake, two complete compositional lineages of silica-undersaturated alkalic lavas, and a remarkably stable volcanic behaviour. Thanks to these features, Erebus is a wonderful natural laboratory to understand volcanic degassing trends, lava lake dynamics and shallow magmatic processes, and eruptive behaviour. The deep magma plumbing system, however, is not well known due to a lack of relevant experimental data for Erebus's silica-undersaturated basanite, phonotephrite, tephriphonolite, and phonolite lavas. The resulting glasses from experiments reported here span the compositional range from basanite to phonolite and track the compositional evolution of Erebus magmas at various stages in the crust. In addition, our results reveal how very minor changes in the initial conditions of the same parent basanite melt can evolve into the two separate lava lineages observed on Ross Island. Experiments were performed in internally heated pressure vessels (IHPVs) between 1000-1150 ℃ and 200-400 MPa at NNO+1, with XH_2O of the H_2O-CO_2 fluid varying between 0-1. Fe-Ti spinel is on the liquidus for both compositions, the growth of which is likely facilitated by the oxidizing experimental conditions. In the basanite, spinel is followed by olivine and clinopyroxene. In the phonotephrite, the first silicate phase is kaersutite (even for H_2O-poor conditions). Only in the most CO_2-rich experiments (XH_2O approaching 0) could the natural phase assemblages be reproduced. Our results, when combined with those from recent volatile solubility, melt inclusion, and in-situ gas measurement studies, make a strong case for volcanic processes at Erebus volcano and the surrounding volcanic centres being strongly influenced by the storage and exsolution of mantle-sourced carbon.

Evaluating the role of crustal assimilation on the oxidation state of arc magmas

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Oxygen fugacity governs magmatic evolution, phase assemblage, and gas speciation. Arc rocks tend to be several orders of magnitude more oxidized than those at mid-ocean ridges, however the processes that lead to oxidation have not been identified. Arc rocks may be more oxidized as a result of processes in the arc crust or variations in the oxygen fugacity (fO2) of the mantle source. Fractional crystallization and degassing processes appear unable to explain the disparity between the oxidation states of arc and mid-ocean ridge rocks. Here, we explore two additional mechanisms that may influence the oxidation state recorded by arc rocks: 1) assimilation of continental crust and 2) post- or syn-eruptive alteration. We use several proxies to estimate the fO2 recorded by natural samples from the Central Volcanic Zone of South America. Samples, including lavas, pumice and scoria were selected from a geographically constrained region (16°- 26°S) to ensure that they are the product of a similar mantle source. Samples span a range of crustal contribution, as indicated by their radiogenic isotope compositions ($^{87}Sr/^{86}Sr$ = 0.705-0.712), and cover the full range of magma compositions erupted during the Neogene history of the arc (52 - 74 wt.% SiO_2). Oxygen fugacity was estimated using three techniques: 1) whole rock Fe3+/$\sum$Fe ratios, 2) Fe3+/$\sum$Fe ratios in quartz- and olivine-hosted melt inclusions using micro X-ray absorption near-edge structure (XANES) spectroscopy, and 3) magnetite-ilmenite oxybarometry. Fe3+/$\sum$Fe ratios range from 20-80% in these samples. This full range is observed for all stages of magmatic differentiation (basaltic andesites to rhyolites) and crustal assimilation (30-100%), and all eruptive products (lavas, pumice and scoria). Between volcanic centers we see large ranges in $^{87}Sr/^{86}Sr$ and no associated systematic variation in Fe3+/$\sum$Fe as measured by wet chemistry. Samples from the same volcanic center but different eruptive events can span a large range in Fe3+/$\sum$Fe ratios (20-65%) measured by wet chemistry yet show little to no variation in degree of crustal assimilation. In some cases, Fe3+/$\sum$Fe ratios preserved in melt inclusions are inconsistent with whole rock ratios, suggesting that whole rock Fe3+/$\sum$Fe ratios may be modified by eruptive or weathering processes. The three techniques employed in this study (micro-colorimetry, XANES, and magnetite-ilmenite oxybarometry) indicate that crustal assimilation does not systematically oxidize continental arc magmas. In addition, there appears to be no systematic variation in the range of Fe3+/$\sum$Fe ratios as a function of fractionation, consistent with prior work.

Understanding the evolution of large-scale continental magmatic systems: a case study of the Purico-Chascon volcanic complex in northern Chile

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The Purico-Chascon volcanic complex in northern Chile is a long-lived silicic magmatic system that records 800 ky of continental arc magmatism. Volcanism at the Purico-Chascon volcanic complex initiated 1.0 ma with the eruption of the 60-80 km^3 Purico ignimbrite. Following the ignimbrite eruption, activity became significantly less explosive resulting in a series of intermediate lava domes and flows (10 km^3 total), the youngest of which (Cerro Chascon) erupted 200 ka. In this study, we combine textural, major element, trace element, and isotopic data from individual crystals within the Purico ignimbrite and Cerro Chascon lavas to determine how the Purico-Chascon magmatic system evolved.

Plagioclase crystals from the Purico ignimbrite have high, restricted $^{87}Sr/^{86}Sr$ isotope ratios (0.7085-0.7089) similar to whole-rock isotope ratios from the same unit. In contrast, Cerro Chascon contains two isotopically distinct types of plagioclase. The first type of plagioclase is texturally and isotopically indistinguishable from crystals within the Purico ignimbrite. The second type has significantly lower $^{87}Sr/^{86}Sr$ ratios (0.7060-0.7072). Phase equilibria obtained from crystalline and glass phases (plagioclase, amphibole, olivine, pyroxene, glass) indicate that the crystals within the Purico ignimbrite grew in a single, shallow (100-200 MPa; 4-8 km), relatively low temperature (800-875 degrees C) magma reservoir. In contrast, crystals from Cerro Chascon appear to be derived from two distinct magmas. Some crystals appear to have grown in conditions identical to crystals from the Purico ignimbrite. However, other crystals, particularly those in basaltic-andesite magmatic inclusions, appear to be derived from a much deeper (350-550 MPa; 12-20 km deep), higher temperature (950-1050 degrees C) magma source. Lastly, Fo_{81-85} olivine within the lavas yield olivine-melt temperatures of 1200 degrees C consistent with an even deeper source, possibly within the lower crust.

The lack of compositional and isotopic heterogeneity, high $^{87}Sr/^{86}Sr$ isotope ratios, and phase equilibria indicate that the upper crust was a site of significant magma generation and storage during the early evolution of the Purico-Chascon magmatic system. In contrast, the magmatism that led to the eruption of Cerro Chascon appears to have been concentrated in the mid-crust, and only had minor interactions the upper crustal Purico magma reservoir shortly prior to eruption. In the regional context, the Purico-Chascon system appears to be the last major eruptive center associated with a regional magmatic flare-up. Thus, the changes observed in the Purico-Chascon magmatic system might reflect changes in the thermal structure of the crust in response to decreased mantle heat input associated with the waning of the flare-up.

Climate and elevation influence the geochemistry of large-volume silicic magmas: new δ^{18}O data from the Central Andes: with comparison to N America and Kamchatka

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New delta^{18}O data from magmatic quartz, plagioclase and zircon crystals in Neogene large-volume, rhyodacitic ignimbrites from the Central Andean Ignimbrite Province reveal uniformly high-delta^{18}O values (delta^{18}O(Qtz) from +8.1 to +9.6 ‰; delta^{18}O(Plag) from +7.4 to +8.3 ‰; delta^{18}O(Zrc) from +6.7 to +7.8 ‰). These data, combined with crustal radiogenic isotopic signatures of Sr, Nd and Pb, implicate progressive contamination of basaltic magmas with up to 50 volume per cent upper crust in these large volume silicic systems. The narrow range of O-isotope values also demonstrate that surprising homogeneity was achieved through space (100's km) and time (10 Ma) in these large-volume magmas, via convection and residence in their parental upper crustal bodies.

In contrast, large-volume ignimbrites erupted during the Cenozoic North American ignimbrite flare-up of the North American Cordillera, whilst achieving equally high Sr and Nd isotope values, and by extension, amount of crustal assimilation, exhibit a much wider range in delta^{18}O(Qtz) (+2.6 to +10.1), delta^{18}O(Fspar) (-1.3 to 8.4) and delta^{18}O(Zrc) (-1.3 to +6 ‰) values. Large volume Kamchatkan ignimbrites, discussed here for comparison, are also universally lower in delta^{18}O. Based on oxygen and radiogenic isotope character and geochemical parameters, we demonstrate that despite vastly different tectonic associations, the fundamental control of basaltic magma assimilating many tens of percent of crust at each of these provinces remains robust, and broadly requires equal proportions of upper crust in the final magmas. The low-delta^{18}O values of many large volume silicic magmas in North America and Kamchatka reflect the influence of meteoric-hydrothermal events in lowering these delta^{18}O values. The lack of a low-delta^{18}O signature in the Central Andes and a few instances in North America, like the Great Basin of Nevada, may thus reflect a lack of meteoric hydrothermal events in these regions leading us to speculate that this portends a link between the O-isotope values of large volume silicic magmas and regional climate. In the Central Andes, and the Great Basin of Nevada, a heavy-delta^{18}O signature is interpreted as a reflection of how high elevation, aridity and evaporation rates limit the retention of large amounts of surface meteoric water and hydrothermal alteration of the shallow crust.

If as we propose, regional elevation and climate influences the geochemical signatures of the large volume magmas, O-isotope data can potentially be used to track the effects of a meteoric-hydrothermal derived delta^{18}O signature from upper crustal rocks that are subsequently assimilated to produce these magma types, and may provide a useful proxy for paleoclimate and paleoelevation.

Combined geophysical constraints on magmatism in the continental crust of volcanic arcs: Focus on the PLUTONS project in the central Andes

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To study the generation, transportation, and emplacement of magma in situ at depths of 10's of km in the continental crust requires geophysis: seismology, gravity, surface deformation, and electro-magnetic methods. While each method provides non-unique constraints on the crustal composition and depth and amount of partial melt, a clearer picture emerges when the techniques are used together at the same location. The ongoing PLUTONS project is just such a joint geophysical and geochemical study focused on the relationship between two current areas of surface uplift in the central Andes of Bolivia, Chile, and Argentina to magma intrusion within the middle to upper crust in the central Andes. This region is home to the world's largest zone of partial melt (the Altiplano-Puna Ultra Low Velocity Zone, or APULVZ), and the most recent ignimbrite flare-up in the world (over the last 10 million years – the Altiplano-Puna Volcanic Complex, or APVC). The primary PLUTONS target is Uturuncu volcano in southwestern Bolivia that is within the APULVZ and APVC and has been undergoing steady uplift over the past 20 years with persistent shallow earthquakes despite not having an eruption in almost 300,000 years. In addition to the 70 km diameter uplift pattern, several studies have shown a 150 km diameter moat of subsidence surrounding the uplift at Uturuncu suggesting large scale movement of materials in the crust. Seismic tomography, gravity and magnetotellurics indicate a complex structure in the upper 20 km consistent with previous evidence for partial melt. In addition to the widespread and throughgoing melt layer, seismic velocities and attenuation indicate prominent shallow features above the melt body extending upward toward the surface. The second PLUTONS target is the Lastarria-Cordon del Azufre (also known as Lazufre) on the Chile-Argentina border that has been uplifting since about 1998 and is also seismically active. While not located within the APULVZ or APVC it also shows evidence for current activity through a significant fraction of the crustal column as sources of ground deformation are located at about 10-15 km and 1 km below local relief. We will discuss the limits of what we can learn about the generation, transportation, and emplacement of magma from geophysics and how these geophysical inferences compare to those from geochemistry.

Active diapiric ascent of silicic magma beneath the Bolivian Altiplano

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Transport of large volumes of silicic magma drives the evolution of the Earth's continental crust and the dynamics of the largest magnitude volcanic eruptions on the planet. In partially molten source regions within the continental crust, melt segregates, accumulates and initiates its ascent to shallower crustal levels where it emplaces as plutons. However, the structural connection between a distributed configuration of melt-filled pores in the source and these plutons is still a highly debated open problem. The two end-members embodying this connection are dykes and diapiric structures. In recent years dyking has been favoured over diapirism, with the latter being essentially disregarded as a viable mechanism for magma ascent. Herein we show, for the first time, geophysical evidence constrained by petrological and geological observations, and consistent with mechanical considerations, of the on-going diapiric ascent of granitic magma through the hot, continental, mid-upper crust of the Central Andes.

The thickened continental crust of the Central Andes hosts the Altiplano-Puna Magma Body (APMB), the largest known active continental mid-crustal zone of partial melt. Directly above it, the Altiplano-Puna Volcanic Complex (APVC) is the largest Neogene ignimbrite province with a total erupted volume of >12000 km3, generated mostly in episodic, supervolcanic eruptions during a flare-up event. Current signs of unrest are evidenced by a long wavelength, monotonic ground uplift and a peripheral subsidence centred on Uturuncu volcano, which was initially detected by InSAR. We have expanded the time of observation by re-measuring existing geodetic levelling lines, and show that the rate of deformation has been fairly constant for at least 45 years. The depth of the source of deformation coincides with the top of the APMB, which makes the APMB-APVC system an ideal setting to study the ascent and emplacement of silicic magma in an active environment. Our primary data set is a new high-resolution Bouguer Anomaly over the APMB. Inversion of these data using petrological and geological constraints provides evidence for the presence of vertically elongated, partially molten granitic bodies massively rooted at the top of the APMB. The geometry of the anomalies precludes the presence of dykes, in favour of massive structures. We argue that our observations, together with the ground deformation pattern, the shallow brittle-ductile transition zone, high heat-flux and perturbed geotherm suggest that high power input and locally favourable tectonics in the APMB-APVC provide an adequate setting for the current diapiric ascent of silicic magmas in the mid-upper crust. We explore this hypothesis using a thermo-mechanical model of a gravitationally unstable dacitic sill overlain by felsic crust, with the perturbed geotherm of the APMB-APVC system. Our results show diapirs that rise 10 km from the source, and account for the gravity and ground deformation observations.

Mixing following assimilation-fractional crystallization at Cerro Uturuncu, Andean Central Volcanic Zone, SW Bolivia as revealed from in situ laser ablation isotopic analysis of plagioclase

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Cerro Uturuncu is an andesitic to dacitic composite volcano located in the APVC of the Andean Central Volcanic Zone, SW Bolivia. We present new major and trace element data combined with whole rock $\delta^{18}O$ (7.2-10.4‰), Sr ($^{87}Sr/^{86}Sr$= 0.71009-0.71653), Nd ($^{143}Nd/^{144}Nd$= 0.512135-0.512247) and Pb ($^{208}Pb/^{204}Pb$= 18.82-18.9, $^{207}Pb/^{204}Pb$= 15.56-15.66, $^{206}Pb/^{204}Pb$= 38.9-39.0) isotope data and Sr isotopic ratio profiles of plagioclase phenocrysts from Uturuncu lavas and domes.

We have identified four plagioclase phenocrysts populations resulting from assimilation of granitic and noritic crust (suggested by granitic and noritic xenoliths), mixing with a chemically and isotopically similar magma (suggested by whole rock data) then repeating these processes in the chamber. These populations are: (1) normally zoned, (2) reverse zoned, (3) oscillatory zoned, and (4) unzoned. Reverse and oscillatory zoned phenocrysts commonly display complex zoning patterns in An content ($An_{40\text{-}95}$) and $^{87}Sr/^{86}Sr$ ratios (0.7092-0.7276), the latter of which are in disequilibrium with whole rock ratios. Consistent core to rim decreases of $^{87}Sr/^{86}Sr$ ratios and coincident increases in Sr concentration in plagioclase with maximum $^{87}Sr/^{86}Sr$ ratios of 0.7139-0.7276 (significantly higher on average than those measured in in the whole rock) are found in the cores, and minimum ratios of 0.7105-0.7138 are found in near the outer rims. These data demonstrate that Uturuncu magmas, regardless of the nature of the mantle or crustal sources, were modified by open system processes operating at crustal depths. One-dimensional diffusion modeling suggests that observed isotopic crystal heterogeneities cannot have existed for more than a few thousand years (700-8000 years) at inferred magmatic temperatures (850-1050℃). The chemical and isotopic variability observed in Uturuncu phenocrysts within a single lava flow or dome suggest that although shallow crustal assimilation and magma mixing appear to have had limited effect on whole rock chemistry, a complex late-stage petrogenetic history is recorded within the magmatic cargo of crystals and magmatic inclusions.

The isotopic, textural and compositional characters of these phenocrysts suggest that these crystals were inherited from isotopically more evolved crust then periodically recharged by a higher- temperature, more mafic magma. Though no Sr isotopic ratios exist for plagioclase from basement rocks or local ignimbrites, An compositions of plagioclase core in Uturuncu lavas, domes and magmatic inclusions can be related to a combination of dissagregation of the magmatic inclusions and during mixing and crystallization in the hybrid melts.

Experimental constraints on the Altiplano-Puna Magma Body: a dacite factory in the Central Andean Volcanic Zone

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The Altiplano-Puna Magma Body (APMB) is a regional sill-like zone of partial melt, some 17 km deep in the crust, which is thought to be the source of much of the magmas erupted in the Andean Central Volcanic Zone historically. The extent of the APMB ultra-low velocity zone has been imaged seismically and with magnetotellurics but petrological knowledge of this magma body is lacking. We present phase equilibria experimental data using an andesitic starting composition from a magmatic inclusion sampled in lavas from Uturuncu, a dacitic composite volcano in SW Bolivia. The natural andesites are porphyritic with plagioclase and orthopyroxene typically the most abundant phenocrysts. Experiments have been performed between 500 and 1100 MPa, 920 to 980℃ at volatile-saturated and -undersaturated conditions with oxygen fugacity buffered around Ni-NiO.

Volatile-saturated experiments crystallise amphibole, clinopyroxene, orthopyroxene and spinel but plagioclase, the most abundant phase in Uturuncu andesitic inclusions, is absent. In volatile-undersaturated runs plagioclase is common along with amphibole, clinopyroxene, orthopyroxene and spinel. Phase assemblages are not expected to exactly match those in natural andesitic inclusions which have crystallized at lower pressures prior to eruption. At pressures and temperatures representative of APMB conditions (e.g., 950℃, 800 MPa) residual melt in andesite experiments is dacitic with major element compositions similar to those of whole-rock lava and dome rocks erupted at Uturuncu.

We propose a conceptual model where basalts are intruded into the base of the APMB. Subsequent fractional crystallization of these basalts combined with crustal assimilation produces volatile-undersaturated, plagioclase-rich andesitic magmas with 6 to 16 vol% plagioclase phenocrysts. Residual melt of these andesites is dacitic and buoyantly rises from the APMB periodically.

Complimentary phase equilibria experiments on Uturuncu dacite compositions indicate pre-eruptive storage conditions between 50 and 150 MPa at temperatures around 870℃. H_2O and CO_2 concentrations measured in plagioclase-hosted melt inclusions from Uturuncu dacites are 3.2±0.7 wt% and <100 ppm respectively. If these concentrations reflect pre-eruptive volatile compositions then dacite magmas would be volatile-saturated at such shallow storage levels consistent with the equilibrium phenocryst assemblage. We envisage that ascending dacite magmas become volatile-saturated and crystallize extensively at this level. The resulting increase in magma viscosity causes the magmas to stall. Eruptions are likely triggered by intrusion and mingling of hotter, less evolved andesitic magmas sourced from the APMB as evidenced by inclusions in dacite lavas.

Volatiles in large crystal-rich dacitic magma chambers: insights from the Cebolla Creek Ignimbrite, San Juan Volcanic Field, Colorado

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The San Juan Volcanic Field in SW Colorado consists of ~30 voluminous intermediate to silicic mid-Tertiary ignimbrites related to the "ignimbrite flare-up" event that erupted widespread volcanic deposits across much of the western United States. Individual eruptions involved thousands of cubic kilometers of crystal-rich dacitic magma that represented remobilized granodiorite plutons. Current models (Bachmann & Bergantz 2003, Burgisser & Bergantz 2011) require rapid influx of hot fluids into the magma chamber, where fluids percolate upward through the 'crystal mush' to trigger the eruption of homogeneous batches of crystal-rich magma. The goal of this study is to measure the compositions and volatile contents of melt inclusions trapped in quartz from these large ignimbrites to better understand magmatic conditions present before and after remobilization. For this initial study, we analyzed melt inclusions from quartz crystals in the Cebolla Creek Tuff for H_2O and CO_2 concentrations using FTIR. The Cebolla Creek Tuff (26.9 Ma) is one of three compositionally diverse ignimbrites that make up the San Luis Complex. These three ignimbrites were erupted within ~40,000 years of each other, suggesting a shorter recurrence rate for large explosive eruptions than has been previously documented (Lipman & McIntosh 2008). Preliminary results for quartz-hosted melt inclusions from the Cebolla Creek Tuff show values of 2.3-4.0 wt.% H_2O and CO_2 up to 300 ppm, where lower values of H_2O might be the result of post-entrapment H_2O loss. This yields minimum pressures of entrapment of ~1.4 kb, consistent with models for large shallow silicic magma storage regions. We will compare major and trace element analyses of the melt inclusions with those of reentrant and hourglass inclusions that are not fully sealed in the quartz host to gain insight into the remobilization process.

Simultaneous generation of multiple silicic magmas and their zoned magma chamber related to a caldera-forming eruption: Case studies of Shikotsu and Mashu volcanoes, Japan

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It has been widely believed that a large scale, caldera-forming eruption was derived from a zoned magma chamber, which was composed of single, voluminous silicic magma associated with a small amount of mafic magma. In almost all the cases, the mafic magma injected into the silicic magma before the eruption to erupt as mixed or mingled magma with the silicic one. This is consistent with both of the temporal change of eruptive magma during the eruption and evidence of magma mingling and/or mixing. However, there also exist several eruptions in which distinct types of slicic to intermediate magmas erupted with mafic magmas. In this study, we show three examples from Hokkaido, Japan, in which ditinct silicic magmas coexisted in addition to mafic magma. During caldera-forming eruption of Shikotsu volcano, voluminous rhyolitic magma erupted accompanied with distinct two or three dacitic magmas. In addition to these silicic magmas, mafic magma also erupted. The most voluminous rhyolitic magma mixed with not the mafic magma and but one of the dacitic magmas. Other dacitic magmas were injected with the mafic magma before the eruption. In the case of Mashu volcano, silicic magma during caldera-forming eruptions was mixing products of rhyolitic and dacitic magmas. These silicic magma was not related with the mafic magma of the volcano. The silicic magma during caldera-forming eruptions of these volcanoes was composed of several distinct types. These coexisted silicic magmas in both volcanoes can be distinguished by Sr isotope ratios, suggesting that one of these silicic magma is not the product of fractional crystallization of the other magma. The similar example is also shown by Matsumoto et al. (in this session). It has been widely believed that mafic magma plays as a heat source to produce silicic magma. If the silicic magmas were produced by crustal melting, partial melting of heterogeneous crustal materials might occur to produce several distinct silicic melts. It should be noted that the simultaneous generation of several types of felsic magma would be common especially in the case of large scale silicic magmatism such as caldera-forming eruptions. In such a case, mafic magma as a heat source would be enough large to melt crustal materials extensively.

Petrogenetic processes generating magma beneath the Nyos maar volcano (Cameroon Volcanic Line, West Africa): field relation and geochemical characterization of volcanic rocks

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The Nyos volcano is one of the four strato-volcanoes that make up the Oku Volcanic Group (OKVG) along the Cameroon volcanic Line (CVL). At an altitude greater than 1,000 m, the volcano hosts a 210 m - deep maar lake rich in CO2 gas. Sudden release of CO2 in 1986 from the maar lake resulted in the death of over 1,700 people and more than 3,000 cattle. A process of artificially removing the accumulated gas from the lake is currently underway. Previous studies of this catastrophic event have only focused on the nature and mechanisms of migration and accumulation of CO2 in the lake, and have concluded that the CO2 in Lake Nyos comes from the mantle. This finding raises the fundamental question as to why the Lake Nyos mantle is highly rich in CO2. This research is aimed at addressing this question by using trace elements and radiogenic (Sr-Nd-Pb-Os) isotope systematics in lavas to probe the mantle beneath Lake Nyos and other volcanoes of the OKVG for mantle petrogenetic processes producing the magmas. In the preliminary analysis of 8 volcanic rocks from the Nyos area, 7 samples present K2O/Na2O ratios ranging from 0.15 - 0.56 (SiO2 = 35.5 - 465.6 weight percent; Mg number = 47.7 - 66.3; Sr = 768 - 1011.7 ppm; Pb = 1.47 - 3.36 ppm), while 1 sample was distinct with K2O/Na2O ratio of 1.30 (SiO2 = 48.6 weight percentage; Mg number = 59.7; Sr = 299.3 ppm, Pb = 21.64 ppm). As for radiogenic isotopes, only four Rb-Sr, two Sm-Nd and one U-Pb isotopic data are currently available in literature for the OKVG samples with MgO >4 weight percent (22 - 23 Ma). In these samples 87Sr/86Sr ranges from 0.70333 - 0.70380, 143Nd/144Nd from 0.51260 - 0.51283 and 206,207,208Pb/204Pb are 18.77, 15.56 and 38.70, respectively. No Os isotope has yet been measured for this continental volcano. During November and December 2012, we conducted first comprehensive sampling of mafic volcanic rocks from the Nyos volcano and its surroundings. The basement rock of the Nyos area is dissected by tertiary volcanic rocks that overlie them as lava flows and pyroclastic surge. A total of 25 samples were collected. These samples are mafic presenting either aphyric or porphyritic texture with dominant phenocrysts of olivine, pyroxenes and plagioclase. The size of most phenocrysts ranges from 0.5 to 2 mm diameter. Some of these samples are vesicular with some hosting large crustal and peridotite xenoliths.

Clues to find out past lithospheric activities from lower crustal contaminated dikes of Deccan Volcanic Province, Ranale, India

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Xenoliths in volcanic rocks can provide important information on basement source activity.Investigation compares the geochemistry and petrographical data of basic and crustal xenolith dikes from Deccan Trap, India.I have studied a total of four basalt dikes from Ranale area,Dist.Nandurbar,India.Out of four dikes one dike is carrying abundant of lower crustal xenoliths with different lithological varieties like gneisses,quartzite,granite,mylonite,felsic granulite and carbonate rocks.All xenoliths are fragmented and infiltrated by basaltic melt.Whole rock geochemistry of xenoliths contamination supports a concomitant decrease in concentration of Sr with Zr.Incidentally the Sr values are 0.7044 to 0.7337 and Nd values are 0.5115 to 0.5128.When plotted for crustal xenolith shows 87Sr / 86Sr value extremely high value exceeding field for Bushe formation.Higher concentration in Sr shows Ranale dike further support the interaction of magma.Composition of SiO_2 for all dykes varies from 48 to 72 wt%.Majority of dyke samples are observed to fall in basaltic field with a sample (RAN1) falling in basalt andesitic field when plotted in Total Alkali vs. Silica (TAS) diagram.Ultramafic (UM) sample when plotted on TAS diagram is observed to plot in dacite field.

The 120 ka Largest Caldera-forming eruption of Kutcharo volcano (Kp IV), eastern Hokkaido, Japan (Part 1): Implications for successive pyroclastic flows from multiple vent system

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Kutcharo volcano, eastern Hokkaido, has repeated caldera-forming eruptions since 400 ka to form the largest Quaternary caldera (20 x 26 km) in Japan. The most voluminous (175 km3) eruption "Kp IV" occurred 120 ka. The eruption deposits can be divided into 4 units, in ascending order. Unit 1 consists of silt-sized, cohesive ash with widely dispersal. Unit 2 is composed of a thin, poor-sorted pumice fall deposit, characterized by narrow distribution and small volume (<0.2 km3). Unit 3 is the most voluminous and widely distributed pyroclastic flow deposits. Although Unit 4 is also composed of pyroclastic flow deposits, it is distributed in a limited area in north of the caldera. The boundary between Unit 3 and -4 is sharp and sometimes cuts lapilli pipe structures of Unit 3. These suggest that the final phase (Unit 4) was much smaller than climactic phase (Unit 3) and that there existed possible time gap between both units. Juvenile materials of Kp IV mainly consist of pumice (74-78 wt% in SiO2) associated with minor amount of mafic clasts (52-73 wt% in SiO2). The mafic clasts are only found from Unit 3 of the northern area and Unit 4. According to SiO2-P2O5 diagram, the mafic clasts can be classified into three types which vary in chemistry with stratigraphic levels: Low-P in the lower part of Unit 3, High-P in the upper part of Unit 3 and Medium-P types in Unit 4. These three types of the clasts make three distinct mixing trends in the diagram. Distinct lithofacies of Unit 3 between north and south and temporal change of contained mafic clasts, from Low-P to High-P, in the northern flows suggest that northern and southern flows of Unit 3 could be considered to be heterotopic, contemporaneous products derived from multiple vent systems. This would be consistent with types of lithic-rich layers in Unit 3. The northern flows of Unit 3 include ground layers which are rich in oxidized andesite. However, lithic concentration zones of the southern flows of Unit 3 are rich in porphyritic andesite. In the final eruption phase, northern vents system had been active to erupt medium-P mafic clasts with pumice. These types of magma and their sequence suggest that the three mafic magmas independently and intermittently injected into main silicic magma. Considering distribution of deposits containing mafic clasts, it seems that feeder vents for mafic clasts possibly located at northern area of the caldera to erupt with voluminous pumice magma, whereas other vents at the southern area only fed pumice magma. The volume ratio of pumice abruptly decreases in Unit 4, indicating that the silicic magma would be nearly exhausted.

Compared with typical caldera-forming eruptions, Kp IV eruption is characterized by the lack of a typical plinian column. Thus, it can be concluded that eruptive activity had suddenly reached its climax without making a stable column. This is possibly caused by the developments of multiple vent system in the early phase of the eruption.

The 120 ka Largest Caldera-forming eruption of Kutcharo volcano (Kp IV), east Hokkaido, Japan (Part 2): Generation and Preeruptive processes of Large Silicic magma system with Multiple Silicic magmas

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We present the detailed eruption sequence and general petrological features of eruptive materials of the Kp IV activity (Part 1: Hasegawa et al., in this meeting). In this study, we show petrological and geochemical data to discuss the formation and eruption processes of magma plumbing system of a large, silicic eruption. Kp IV eruption started with the ash and pumice fall (Unit 1 and -2), followed by a voluminous pyroclastic flow (Unit 3) and a small scale of mafic clasts-rich flow (Unit 4). The Kp IV juvenile materials are composed mainly of porphyritic pumice contained in all the units. In addition, a small amount of heterogeneous, nearly aphyric mafic clasts also appear in the northern flows of Unit 3 as well as Unit 4. On the basis of the mineral, whole-rock and matrix glass chemistries, we identified two silicic and three mafic end-member magmas: rhyolitic, dacitic, and three andesitic ones. Compositional variations of these andesitic magmas can be explained by fractional crystallization of a single primary magma. However, the rhyolite-MELTS program, mass balance calculation and Rayleigh fractionation models do not allow us to explain the generation of two silicic magmas by the fractional crystallization of these andesitic magmas. This suggests that these silicic magmas could be produced by partial melting of crustal materials, in which the andesitic magma could play as a heat source. On the other hand, the higher 87Sr/86Sr of dacitic pumice also suggests that the dacitic magma is not a parent of the rhyolitic one. Therefore, both rhyolitic and dacitic magmas would be produced independently at the same time. This would be possible that the partial melting of various crustal materials, which are heterogeneous in chemical compositions including Sr isotopes, to produce distinct silicic magmas. It has been believed that a large silicic magma system consists of a single silicic magma, which is evolved by the injection of mafic magma. However, we revealed that the silicic magma system in KP IV eruption was composed of two distinct magmas, dacitic and rhyolitic ones.

Whole-rock chemistry of the pumice suggests that dacitic magma had injected into rhyolitic one. Zoning profiles of orthopyroxene phenocrysts indicate that the dacitic magma had repeatedly injected into the rhyolitic one since several years before eruption, resulting in the formation of a zoned magma chamber. In contrast, on the basis of the durations of elemental diffusion in Fe-Ti oxides, three andesitic magmas sequentially injected into this zoned magma chamber less than a day before eruption. This injection could be considered as a trigger of caldera-forming eruption. Considering the temporal variations of whole-rock and matrix glass chemistries, upper part of the zoned magma was erupted in early phase (Unit 1 and -2), and lower dacitic magma was also withdrawn in climactic phase (Unit 3), resulting in the beginning of the Kp IV caldera-forming eruption.

Field, petrological, and geochemical evidence for injection of mafic magma into felsic reservoirs at the Mono domes and Mono Lake islands, California

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Long Valley caldera is best known as the site of the 760 ka Bishop Tuff supervolcanic eruption. Since 760 ka, magmatism in the area has occurred both within the caldera complex and around its periphery, primarily to the north. The most recent of these eruptions, starting 40 ka, emplaced the Mono and Inyo domes and the Mono Lake islands. While most post-caldera volcanism has been either basaltic or rhyolitic in composition, the Mono Lake lavas, as well as enclaves present in several of the Mono domes, represent the only recent intermediate composition (basaltic andesite, dacite) eruptive products. An improved understanding of the igneous processes responsible for the emplacement of this extensive magmatic suite is necessary to better gauge the likely locations and compositions of future eruptions in the Long Valley area. Field observations and petrological evidence support the hypothesis that the centimeter-scale mafic enclaves prevalent in several of the Mono and Inyo domes formed as hot injections into the more felsic magmas of the domes. Enclaves are stretched, commonly with chilled margins coupled with melting rims in the felsic host rock. Thin sections cut along the border between enclave and host reveal the presence of millimeter-scale felsic inclusions within the enclaves, and vice versa, implying some magma mingling occurred. Similarly, the petrology of the Mono Lake lavas may support injection of a fluid, mafic magma into a more voluminous, felsic magma body. While the Mono Lake lavas lack the enclaves of the domes further to the south, feldspar and pyroxene phenocrysts are revealed in thin section to have sieve textures and distinctive regrowth rims that could reflect injection of hot magma causing resorption of crystals. Chemically, the Mono domes are quite evolved, with low Sr and Ba concentrations (1-25 ppm and 10-40 ppm, respectively) and high Rb and Th concentrations (130-180 ppm and 18-22 ppm, respectively). Highly variable trace element concentrations suggest the presence of accessory mineral phases such as zircon (Zr), apatite (P_2O_5, Y), feldspar (K_2O, Ba, Eu), titanomagnetite (V), and a LREE phase. Given these evolved trace element concentrations, the Mono domes may have been extracted from a crystal mush or formed by partial melting. By contrast, the Mono Lake lavas are noticeably less evolved than the Mono domes despite their comparative youth, suggesting derivation from a different magma source. Mono Lake is dominated by dacites and low-silica rhyolites, which are characterized by high Sr concentrations, from 300-540 ppm; extremely high Ba concentrations, ranging from 1000 ppm to as high as 1600 ppm; and quite low Rb and Th concentrations (100-130 ppm Rb and 5-10 ppm Th). It is possible that there is source variation within the Mono Lake lavas themselves, as high field strength elements such as Y and Nb suggest that the islands are chemically segregated geographically.

Generation mechanism of the Nanzaki basanite in northern part of Izu Volcanic arc, Japan: petrological and geochemical constraints

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Petrological and geochemical studies were performed on the Nanzaki basanite (0.43 Ma) in the northern part of Izu-Bonin volcanic arc, Japan. The Nanzaki basanite is located 50 km off from the volcanic front, and covers Miocene volcaniclastic formations. Previous works have tried to study for this unique rocks (e.g., Goto and Arai, 1986; Aoki et al., 1987). The basanites are mostly composed of nepheline-bearing basanite lava and scoria. Phenocryst assemblage is olivine and clinopyroxene, and orthopyroxene is absent. Spinel, nepheline, and apatite are present in groundmass. Olivine Fo contents vary in 82-91 with a mean of 88, and clinopyroxenes are characterized by high TiO_2 and low Cr_2O_3. Whole-rock major element contents are: SiO_2 = 41.5-44.1, MgO = 10.2-13.1 , CaO = 11.9-13.3, K_2O = 0.4-1.9. The low values of FeO*/MgO (0.81-1.09), and high Ni and Cr contents for the Nanzaki basanite represent primary (undifferentiated) magmas generated in the upper mantle. Tightly distributed REE patterns, displaying light rare earth element (LREE) enriched and heavy rare earth element (HREE) depleted, are consistent with the above primary chemical features. Incompatible trace element patterns for the basanites show some peculiar features distinct from those of basanites in the oceanic tectonic setting, like Hawaii. High Sr and Ba, and REE and low K, Rb, Zr, Hf, and Ti contents suggest that the basanite magmas were generated from an enriched mantle previously affected by metasomatism with incompatible element enriched components. A possible candidate for the components is carbonatite magma (or melt) which could have much influenced the trace element characteristics of the mantle (e.g., Ionov et al., 1993; Hoernle et al., 2002).. Beside these, slight enrichment in Pb and Cs and some other elements in the diagrams may also be indicative of fluids probably from subducting oceanic slab. The Sr-Nd isotope characteristics for the basanites (both low Sr and Nd isotope values rather than those of basaltic rocks in the volcanic front), however, is consistent with across arc isotopic variations of the Izu-Bonin volcanic arc.

These results conduct to the model that the basanite magmas were generated from some enriched parts of mantle (probably wehrlite-like rock or similar source, partly including carbonates) with contributions of melts/fluids from subducting oceanic slab in arc setting.

The only one clinopyroxinite nodule with vesicular texture is found within the basanite lava, and this much rare existence of the nodule probably means that the original magma for the basanite was generated from relatively shallower mantle (lower part of lithosphere or upper part of asthenosphere). Also vesicular texture of the nodule is indicative of existence of some volatile components (CO_2, H_2O) in the host basanite magma. These observations and results support the above model.

Key words: Nanzaki basanite, Izu-Bonin volcanic arc, carbonatite metasomatized mantle

Geology and petrology of Taisetsu volcano group, Hokkaido, Japan ; The outline of eruptive history and temporal variation of magma during 1 My

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Taisetsu-Tokachi volcanic field, extending in the direction of NE-SW over 80km, locates at the southern end of Kuril arc, in which arc type volcanism has continued at least since late Miocene. In order to reveal the temporal change of magma generation processes and related tectonics at the arc-arc junction, we focus on the northen part of the field, Taisetsu volcano group. In the group, after large silicic pyroclastic eruptions during 2-1 Ma, andesitic stratovolcanoes and lava domes have been build up until now. Although previous studies (eg., NEDO, 1990; Saito, 1996) revealed the outline of structure and eruptive history of the group, detail chronological and petrological studies have not been carried out. In this paper, we report preliminary results of volcano geology and K-Ar age dating of the volcano group.Based on the temporal shift of eruption centers, mode of activity and petrological features of the rocks, the activity can be divided into five stages. Stage 1; Andesite lava flows were effused from several fissure vents to flat-shaped volcanic edifices which extends N-S direction. Stage 2: Relatively large stratovolcanoes were formed at the northwestern part of the group. After the formation, eruption centers had moved to the central part. Stage 3: Many eruptive centers were active to form lava domes and cones. Stage 4: The most explosive and voluminous pyroclastic eruption had occurred ca. 30 ka to form a small caldera 2km in diameter. Effused pyroclastic flows filled the deep valleys and were exposed as welded tuffs. Stage 5: After the formation of the caldera, the activity has continued at the southwestern part of the caldera to form sevarl stratovolcanoes, including Asahidake edifice (2291 m).The latest magmatic eruption occurred 5000 years ago. Phreatic explosions has repeated since then to form many craters. All of the rocks usually contain plagioclase, clinopyroxene, orthopyroxene and Ti-magnetite phenocrysts. In some of the rocks also include minor amounts of hornblende, olivine, and quartz phenocrysts. These volcanic rocks often contain mafic inclusions.The SiO_2 contents range from 56.4 to 68.5 wt.% for host rocks and from 52.2 to 56.2 for the inclusions. Almost all the rocks are defined as medium – K in SiO_2 – K_2O and CA type in SiO_2–FeO/MgO – SiO_2 diagram. Although some of major and trace elements of these rocks could be distinguished among stages and/or eruption centers, there exists no distinct features among these rocks especially in incompatible elements. Thus, it seems that similar primary magmas have been formed and differentiated by similar crustal processes during the last 1 My.

Sm-Nd mineral isochrons and trace element compositions of parent melts for Atsumi gabbroic xenoliths included in the late Miocene volcanic rocks, Atsumi area, western margin of NE Japan

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Age determination by mineral isochron method and trace element analysis were carried out for gabbroic xenoliths, included in the late Miocene volcanic rocks from the Atsumi area in order to know cumulate and parent melt pairs formed in the continental margin crust. The xenoliths are divided into clinopyroxene gabbro (GB), clinopyroxene-hornblende gabbro (PHGB), and hornblende gabbro (HGB). Eight Sm-Nd mineral isochron ages were well defined. The obtained ages are 28-32 Ma and 58-61 Ma for GB, 54-55 Ma and 66 Ma for PHGB, and 64Ma for HGB. Initial $^{143}Nd/^{144}Nd$ (NdIs) of all the xenoliths are similar in the ranges between 0.51286 and 0.51293. Initial $^{87}Sr/^{86}Sr$ ratios (SrIs), calculated using the Sm-Nd isochron ages and bulk rocks data, are 0.70323-0.70329. These NdIs and SrIs are common to the values shown by basaltic rocks formed after the opening of the Japan Sea basin. Calculated trace element compositions of parent magmas for GB and PHGB samples, assuming the distribution coefficients between clinopyroxene and basaltic melt, are alkali basalt and continental arc basalt individually. It is suggested that upwelling of asthenosphric mantle had already started in Oligocene age that is the initial stage of continental rifting to form the Japan sea basin.

Fuji 1707 Hoei Gabbro as a subvolcanic magma chamber by comparison with layered intrusions

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1) Introduction: Geochemical and mineralogical evidence indicates that the Hoei Gabbro (gabbroic ejecta of the 1707 Hoei eruption of the Fuji Volcano) and the Fuji basalts were derived from common parent magmas [1]. The Hoei Gabbro is divided into three groups, where O group is adcumulates and P and F groups are orthocumulates [1]. Based on the proposed model of a subvolcanic magma chamber of Fuji volcano [1], we discuss the evolution of the magma chamber in comparison with reported layered intrusions.

2) Bulk rock compositions of the Hoei Gabbro: The estimated mean percentages of melts were 4 for the O group, 7 for the F group, and 21 for the P group. The bulk compositions of the O and F group largely vary with the mineral assemblage (plagioclase, olivine, pyroxene and oxides) [1]. In contrast, the P group shows limited bulk compositional variations and plots between the averages of the O group and the Fuji basalts.

3) Plagioclase compositions of the Hoei Gabbro: The K2O variation of plagioclases from the Hoei Gabbro confirms the common parent magmas with the Fuji basalts. Plagioclases of the Hoei Gabbro, except for the plagioclase-rich subgroup of the O group (O2), tend to deplete in Fe and Mg relative to those of the Fuji basalts. Plagioclases could reequilibrate to the coexisting mafic minerals by diffusion during post-cumulate processes, and would deplete in Fe and Mg [2, 3]. Some plagioclases of the O2 subgroup, however, preserve the original FeO content because of small amounts of coexisting mafic minerals.

4) Comparison with layered intrusions: In the North Arm Mountain complex, the rhythmic layers intercurrent between the homogeneous gabbro [4]. The bulk rock compositions of the rhythmic layers are depleted in incompatible elements showing an efficient loss of melts as shown in the O group of the Hoei Gabbro. The homogeneous gabbro is affected by melts and varies in composition with similar pattern to the P group. The interstitial liquid was lost in an open system from adcumulates by compaction in the Stillwater complex [5].

5) An evolution model for the subvolcanic magma chamber: In a basaltic magma chamber, blobs of crystal mash settled down and rhythmic layers occurred by sorting of minerals. Subsequent compaction and crystallization squeezed out the interstitial melt effectively and left the O and F group cumulates. The main P group cumulates crystallized in-situ in the upper part of the chamber with an inefficient melt loss. After certain degrees of fractional crystallization, magma lost from the chamber by eruptions. Remained melts completely crystallized as a melt-rich subgroup of the P group in the center of the chamber. Later, the fresh magma of the 1707 eruption brought fragments of the preexisted solidified cumulates.

6) References: [1] Yasui et al. (1998) Kazan 43, 43. [2] Togashi et al. 2013LPSC, 2280. [3] Phinney (1992) GCA 56, 1885. [4] Komor et al.(1990) JP. 31, 1. [5] Meurer et al. (2006) CMP. 151, 187.

Linking magma chamber evolution to eruptive history using a simplified numerical model

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The eruptive history of a volcano is controlled by the non-linear interplay between mass recharge, crystallization and volatile exsolution modulated by the heat loss and outgassing out of the chamber to the surrounding crust which ultimately affect the stress field in and around the magma chamber. The complexity and coupling between these processes is a formidable challenge to our understanding of the response of volcanic systems to different forcing acting over different time scales. Here we propose a simplified model to capture, to a first order, how the coupling between the stress field and the thermodynamical state of the chamber (temperature, volume fraction of exsolved volatiles, crystals and melt) evolve during the injection of fresh magma into the chamber. In a first time, we impose that the influx of new magma scales linearly on the pressure difference between the magma chamber and a fixed imposed pressure at depth. In a second time, we use the results of Karlstrom et al. (2009) and assume a constant influx at depth but that the pressure in the chamber increases the lensing of feeder dikes towards the chamber (i.e. higher recharge flux as the pressure in the chamber increases, opposite of the first scenario). In our model we solve for the coupled non-linear mass balances for three phases (melt, crystals and exsolved volatiles) as well as a heat conservation equation for the multiphase system. In these governing equations we account for volatile exsolution, crystallization/melting, the visco-elastic relaxation of stresses around the chamber and passive degassing through a permeable crust. We allow for dikes to initiate from the chamber when it reaches a critical overpressure, if the overpressure remains large enough during the dike propagation to reach the surface, then an eruption of volume controlled by the excess pressure in the chamber occurs. The ability of the magma to erupt is also controlled by its crystallinity, with a threshold crystallinity set at 0.5 above which the magma is considered uneruptible (Marsh, 1981).

Using this simple model, we study the effect of the two scenarios for the magma recharge on the periodicity (or chaotic behavior) of eruptions and the volume of magma erupted (and its crystallinity and bubble content). The modularity and the simplicity of the model allow for rapid calculations and offer the flexibility to add different and sometimes competing processes and test their influence on the outputs.

Development and relationship of monogenetic and polygenetic volcanic fields in time and space: from field observations to numerical modeling

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In general, distributed volcanic fields are characterized by infrequent eruptions at monogenetic volcanoes, low average output rate, and a low spatial intensity of the eruptive vents. In contrast, central-vent-dominated systems, such as stratovolcanoes, and lava shields are characterized by frequent eruptions, high average flux rates, and high spatial intensity of eruptive vents. However, it has been observed that a stratovolcano is often associated to parasitic monogenetic vents on its flanks, related to the central silicic systems, and surrounded by an apron of monogenetic edifices that are part of the volcanic field but independent from the principal central system. It appears from spatial distribution and time-volume relationships that surface area of monogenetic fields reflects the lateral extent of the magma source region and the lack of magma focusing mechanisms. In contrast, magma is focused through a unique conduit system for polygenetic volcanoes, provided by a thermally and mechanically favorable pathway toward the surface that is maintained by frequent magma ascent and favorable stress conditions. We plan to relate surface observations of eruptive vents location and spatio-temporal evolution of the field area through time to processes that control magma focusing during ascent and storage in the crust. We choose to study fields that range from dispersed to central-vent dominated, through transitional fields (central felsic system with peripheral field of monogenetic vents independent from the rhyolitic system). We investigate different well-studied volcanic fields in the Western US and Western Europe in order to assess influence of the geodynamic setting and tectonic stress on the spatial distribution of magmatism, and extend our method to extra-terrestrial planets. We plan numerical simulations of lava flow inundation to look at field and edifice growth with time; and modeling of magma ascent in the crust to investigate magma focusing. In summary, incremental spatial intensity maps should reveal how fast a central conduit is created during the development of a volcanic field, and how this could influence the outbreak of dispersed monogenetic volcanoes that are not geochemically linked to the central system.

Amount, composition and timescale of magmas generated by melting in lower crust

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Magmatisms are various in continental margins and continental hot spots. Magmas with various petrologic features erupt at a certain volcano and are also different from other neighbor volcanoes. For the variety of the continental magmatism, magma genesis by crustal melting can be a key process. In this study, we try to understand variation of composition, amount, and generation timescale of magmas produced by melting of a lower crust due to hot magma injections using a one-dimensional physical model.

The model of crustal melting by Koyaguchi and Kaneko (2000) is followed. When a crust is melted by a hot magma injected into a crust, large heat flux from the convecting injected magma rapidly melts the overlying crust up to the degree of partial melting large enough to convect (100 yr timescale). After that, the injected magma and convecting region of partially-molten crust decrease in temperature and melt fraction, and hence cease to convect for melt fraction to decrease down to the critical melt fraction where the mixture of solid and liquid cannot convect. At this stage, heat transfer becomes only conductive and slow (>10,000 yr). When a new injection of a hot magma occurs, the above processes repeat. A characteristic of our model is that voluminous crustal melt close to the critical melt fraction tends to be produced.

We carried out calculations considering that gabbroic amphibolite with 2 wt. % water is melted by repeated injection of hot basaltic magmas with initial temperature of 1250 deg. C at 1 GPa. It is assumed that the critical melt fraction above which the materials are convective is 0.5. In the calculations, we change the initial temperature of the crust (500-700 deg. C) and injection rate (4-32 m/ky), thickness in a single injection (10-800 m), and water content (2-12 wt. %) of the injected hot magmas as parameters. It is assumed that the hot magmas repeatedly inject at the same level and that no segregation between melt and crystals occurs in our model.

The calculation results indicate that the generation of magma by crustal melting occurs on 10,000-year timescale and that various amounts of magma with various degrees of partial melting are generated by crustal melting for the four changed parameters. The injection rate of the hot magmas basically governs total melt amount produced by melting; larger injection rate produces larger amount of melt. On the other hand, the initial temperature of crust and the injection thickness of the hot magma affect the degree of partial melting of the crust. Thin intrusions in warm crust produces relatively much melt with small degree of partial melting (i.e. silicic melt) whereas thick intrusions in cold crust produces much melt close to the critical melt fraction (relatively large melt fraction) (i.e. mafic melt). These parameters can be some of factors governing the variety of the continental magmatism.

Modelling magma transport: a study of dyke injection under regional extensional stress

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The propagation of magma-filled cracks is the primary method of magma transport through the Earth's lithosphere. Dykes are widespread and are evidently important in feeding the supply of magma to volcanoes, thus the good understanding of the physics of crack propagation is critical for understanding the methods of magma supply. Dyke injection is also crucial at rift margins to accommodate strain and assist rifting. Scaled analogue experimental models can provide key insights into the mechanics and dynamics of magma transport in different tectonic settings.

In this study, the results from 41 laboratory analogue experiments, comprising the repeated injection of a fluid into an analogue crust (gelatine) under a remote extension, are presented. The experiments were designed to investigate the relationship between successive lateral dyke injections, by examining dyke injection size, amount of extension, injection spacing and injection orientation. A rotation angle defined as the angle between the orientations of each injection and the subsequent injection was also recorded. A cooling fluid (Vegetaline) was chosen as the magma analogue, so that it would solidify after injection to stop successive injections coalescing and preserve their structural relationship. To prevent solidification during the injection, allowing smooth propagation without melting the gelatine, the temperatures and flow rates were optimised at 60℃ and 0.25-0.32 rpm.

The experiments categorise the relationship between the dyke rotation angle and the distance from a previous intrusion under given extensional stress conditions. The results show that the size of the first injection is important. The rotation angle between two injections depends on the ratio of the fluid overpressure and the remote tensile stress. For small first injections, where the overpressure due to the fluid is small, the rotation angle between the injection and the subsequent one is also small. For large first injections, the rotation angle between the injection and a subsequent injection is larger and is dependent on the first injection overpressure, and is inversely proportional to the square of the normalised spacing. For larger normalised injection spacing, the rotation angle will be smaller. The experiments show that the stress field is perturbed the most, and locally becomes more compressive, near the centre of an injection. However, dyke injections at rift margins do not seem to occupy orientations other than rift-parallel, suggesting that the extensional stress is always larger than the amount relieved by dyke injections, or that the dyke intrusion timescale is longer than the time taken for extensional stresses to build up in the crust. The paucity of experimental studies investigating the effects of repeated injection in an extensional environment renders these experimental results a unique exploration of the phenomenon of multiple dyke injections at active rift margins.

Phenocryst fragmentation in crystalline silicic magma during explosive and effusive eruptions

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Fragmented phenocrysts in volcanic rocks have been linked with rapid decompression and/or shear-induced breakage during magma ascent (e.g. Best and Christiansen, 1997; Allen and McPhie, 2003). Because broken phenocrysts in lavas are generally less abundant than those in pyroclasts (e.g. Best and Christiansen, 1997), rapid decompression and melt inclusion foaming (Bindeman, 2005) are thought to be the dominant process. However, experimental studies (e.g. Cordonnier et al., 2009) demonstrate that shear stress yielding on crystals during shear flow may also induce crystal fragmentation. This process is probably controlled by magma crystallinity because shear stress concentrates on the contact between crystals. To investigate the relative roles of these different mechanisms of phenocryst fragmentation we conducted microstructural studies from crystal-rich pumices and lavas (crystallinity of 35-55 vol %) from seven voluminous eruptions in Central Andes (Chile, Bolivia, and Argentina). All samples were high-K dacites to rhyolites with pumices coming from voluminous ignimbrites and the lavas from individual such as the Chao dacite in Chile and post-caldera lavas.

Three dimensional (3D) images were obtained using X-ray CT (ScanXmate-D180RSS270, Comscantecno Co, Ltd). In pumices, the felsic minerals (plagioclase and quartz) are highly fragmented to varying degrees. The broken crystals show a jigsaw pattern, with no or only minimal movement after breakage. This indicates that crystals and hence, magma, experienced limited flow after the fragmentation of phenocrysts. This is in contrast to the lava samples, where this type of crystal fragmentation is not found. Instead some mafic minerals show sliding along prominent cleavage planes. Crystal size distributions (CSDs) constructed from the 3D and 2D CT images display steeper slopes on log-log plots of the CSD´s for pumices than in lavas. No clear variation is seen with respect to changing the crystallinity. The steep slopes of CSDs in the pumices correspond to the phenocryst fragmentation, i.e. the formation of small fragments from large phenocrysts. These results indicate that the rapid decompression upon magma ascent and fragmentation during the pyroclastic eruptions was the main cause for phenocryst fragmentation and that during the effusive eruptions magmas ascended without significant phenocryst fragmentation despite their crystal-rich and silicic composition. Evidence from both explosive and effusive samples suggests that shear-induced breakage of crystal during magma ascent is not important in these natural samples. Our observations on these natural samples may indicate that unknown mechanisms, e.g., gas bubbles formed in magma, suppress the shear-induced breakage of crystal in crystal-rich magma and control its rheology in natural system.

A possible link between ice lenses and gabbroic bands in peridotite complex

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Gabbroic bands in peridotite complex such as Horoman is one of the peculiar features, which provide indispensable information about state and process of partially melting in the upper mantle. They are found in well-developed layered structure of peridotites to exist sandwiched by harzburgite layers. Based on the geochemical relation between surrounding rocks several petrological models have been proposed (e.g., Obata and Nagahara 1987, Ozawa and Takazawa 1995), which mostly argue infiltration/segregation of melt in the partial molten state. Focused on the layering structure Toramaru et al. (2001) propose a fluid dynamical model for the formation of repeated banding structure. One of the complicated situations that have not yet clarified clearly is how this once-partially molten structure has been preserved during the emplacement to the crust. During the course to the surface retrograde processes including temperature decrease may have easily destroyed such a soft structure. In this presentation we would like to draw attention to morphological similarity between ice lenses in the periglacial situations and the gabbroic bands and propose a formation model.

Ice lenses are segregated ice layers horizontally lying in the subsurface of cm to hundreds meters depth. The typical thickness is several millimeter or centimeter. They are found to exist as multiple layers and their spacing and thickness are variable according to the environmental conditions. Starting from homogeneous mixture of water and solid grains the system transforms to be a heterogeneous structure upon gradual freezing. The segregated ice phase is considered to grow by the migration and solidification of water in partially frozen state during the advancement of freezing front (e.g., Rempel et al. 2004). This layered ice structure is similar to gabbroic bands in peridotite complex. We have performed systematic cooling experiments in water-particle system to observe the spacing and thickness of layered structure. Based on our experimental results that demonstrate the relationships between the behavior of layered structures and particle size, cooling rate and force balance, we consider possible formational analogy between ice lenses and gabbroic bands. Here we report the results of our cooling experiment and the implication for the layered structure in Horoman peridotite complex.

Factors controlling entablature formation in columnar joints: Suggestions from the analogue experiments and texture observation of water interacted structure in columnar joints in Iceland

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Columnar joints of lava and ignimbrite often feature two styles of jointing: colonnade and entablature. Columns in colonnade are relatively wide, straight and directionally organized, whereas the entablature features relatively narrow, curved and disorganized in terms of orientation. The formation of colonnade is generally well understood; it develops perpendicular to the isotherm because of volume contraction due to temperature decrease during cooling, while the formation of entablature still poorly understood; how the complex structure is related to the isotherm and what causes such an abrupt structural change between colonnade and entablature. In order to investigate what factors are important in formation of entablature and threefold structure of upper colonnade, entablature and lower colonnade, we have undertaken desiccation experiments using starch-water mixtures, which are similar to that used in earlier study examining the mechanics of colonnade formation. In order to simulate cooling of lava, the mixture is desiccated by using heat lamp. The drying rate (= cooling rate in case of lava or ignimbrite) is controlled by the distance between the surface of mixture and heat lamp. We conducted two experiments under different experimental setups; one is conducted under constant drying rate throughout and another is conducted where the drying rate is increased halfway. Experimental setup 1 is designed that it allowed the water to be evaporated from both upper and lower surfaces of the mixture by attaching a membrane to the basal surface. With a constant lamp distance of 10cm, the colonnade structure developed from both upper and lower surface without entablature between them. Experimental setup 2; Using the same starting condition of Experimental setup 1 (lamp distance of 10cm), when the colonnade structure developed halfway, the drying rate is increased abruptly by shortening the lamp distance to 1.5cm. As a result, the upper colonnade changed discontinuously forming curved and irregular jointing pattern. Analysis using Micro-focus X-ray CT images show the following: 1) Column size and number density of fractures suddenly decrease after changing the drying rate, 2) the new columns form at the triple or quadruple junctions of pre-existing cracks by which ordinary columns are constructed before changing the drying rate. In addition, the X-ray CT images show that crack tips develop perpendicular to an iso-surface of water concentration. Our results suggest that waved and smaller-scaled columns characteristic of entablature related to sudden change of contraction or cooling rate and inhomogeneous thermal structure of lava and ignimbrite.

Our experimental results will be compared to ongoing investigations of jointing patterns in the Thjorsa and Thjorsardalur lava flow in Iceland, which exhibit the threefold structure of upper colonnade, entablature and lower colonnade.