

³Dept. of Geology Geophysics, Univ. of Wisconsin, Madison, WI 53706, United States

Peridotites and eclogites are considered as the original hosts for diamonds in the mantle. However, it is now generally agreed that these mantle eclogites from kimberlites had their origin in the subduction of oceanic crust beneath the major cratons of the world. One of the first indications for such crustal protoliths was from studies of oxygen and carbon isotopes (e.g., Peter Deines and colleagues, Ian McGregor, as well as our group). Indeed, subsequent studies of such rocks have revealed several additional crustal signatures. A possible scenario involves the subduction of an ophiolite sequence, whereby the basaltic and lower mafic components were metamorphosed, devolatilized/partially melted, and otherwise transformed into eclogites. Being within the diamond-stability field, they later experience metasomatic diamond formation. Surprisingly, the closely associated diamondiferous peridotites are considered to be of original mantle origin. We pose the query: What became of the ultramafic portion at the bottom of the crustal sequence? Could this be the origin of at least some of the mantle peridotites?

The restricted $\delta^{13}\text{C}$ values for P-type (peridotitic) diamonds is commonly used as evidence for the mantle origin of peridotites. However, a compilation of $\delta^{13}\text{C}$ data, published by Peter Deines and our group, for P-type diamonds, mainly from numerous south African pipes, also shows a significant number of values that are well below the mantle field (to 20‰).

Fresh, clean garnets were carefully selected from over a hundred peridotites collected from several Yakutian kimberlites. These were subjected to oxygen-isotope analyses by laser-fluorination at the University of Wisconsin. The majority of the $\delta^{18}\text{O}$ values plot within the accepted mantle value of $5.5 \pm 0.4\text{‰}$ (Mattey et al., 1994). However, a significant number (~20%) lies outside this window, both above and below. These values are interpreted to represent the effects of both high- and low-temperature hydrothermal alterations that occurred in the crust.

Armed with these crustal signatures, we propose that some of the mantle peridotites that are hosts for diamonds have their ultimate origin in the crust, prior to subduction to depth, possibly along with eclogite crustal protoliths as well.

V51B-1270 0830h POSTER

Sr and Nd Isotope Decoupling in the Mantle Xenoliths Evidence for Carbonatitic Fluid/Melt Percolation Metasomatism

V. G. Malkovets^{1,2} (vomal@uiggm.nsc.ru)

L. A. Taylor¹

K. D. Litasov³

¹Planetary Geosciences Institute, Dept. of Geological Sciences, Knoxville, TN 37996, United States

²Institute of Mineralogy and Petrography, Siberian Branch, Russian Academy of Sciences, Novosibirsk 630090, Russian Federation

³Center for Northeastern Asian Studies, Tohoku University, Aoba, Aoba-ku, Sendai 9808578, Japan

Garnet and spinel peridotite and pyroxenite xenoliths from three upper Cretaceous basanitic explosion pipes in the Minusa region, southern Siberia have been studied to characterize off-cratonic upper mantle near the southwestern boundary of the Siberian craton. A lithospheric mantle section was constructed based on EMP and LA-ICP-MS analyses of minerals in representative xenoliths (Malkovets et al., 2000). Here we report results of a Sr-Nd isotope and trace-element study of metasomatized spinel-peridotite xenoliths from Kongarov and Krasnozersk basanitic explosion pipes (Malkovets et al., 2001). Some of those xenoliths plot off the Sr-Nd mantle array and show strong fractionation of elements with similar compatibility. We argue that those features can be explained by chromatographic effects of carbonatitic melt/fluid percolation in the peridotite mantle.

The contents of compatible to moderately incompatible elements in minerals of peridotites indicate that most of those rocks are residues after partial melting and melt extraction. The initially depleted xenoliths bear a record of later metasomatic events that produced enrichments in the incompatible-trace-element concentrations of pyroxenes. Trace-element compositions of clinopyroxene define two principal enrichment patterns. Type-I Cpx is characterized by very-high La/Ce and La/Nd ratios and lower concentrations of the middle REE and Sr, relative to Type-II Cpx. On primitive mantle-normalized, trace-element-distribution diagrams, Type-I Cpx have nearly flat HREE-MREE patterns, with moderate depletions from Eu to Nd, and a steep La-Ce inflection. Type-II Cpx has lower HREE concentrations, with a continuous increase in normalized REE concentrations from Ho to Ce. Both types of Cpx have negative Ti, Zr, Hf, and strong negative Nb anomalies, in addition to small to moderate positive Sr anomalies.

Sr-Nd isotopic compositions of mineral separates from the xenoliths indicate an unusual type of enrichment, with Sr decoupled from Nd. This results in Type-I Cpx having high $^{87}\text{Sr}/^{86}\text{Sr}$ but low $^{143}\text{Nd}/^{144}\text{Nd}$ values, thereby resulting in displacement of the data points to the right of the mantle array on Sr-Nd isotopic plots. Formation of the two groups of Cpx may be explained by the chromatographic effect during the percolation of carbonatitic melts/fluids through the peridotitic substratum. The chromatographic models imply the selective removal of elements with high Cpx/melt distribution coefficients, e.g., HREEs from a percolating melt. Those elements would interact with the Cpx from peridotite resulting in the progressive enrichment of the melt in incoherent elements at the percolation front. Since the cpx/melt K_D for Sr is lower than that for Nd, the front of Sr enrichment moves faster than the front of Nd enrichment. Thus, a zone can be formed in which the host peridotite has more radiogenic Sr. This would explain the position of the data points to the right of the mantle trend in the Sm-Nd isotopic plot. Type-I Cpx forms at the melt-percolation front. However, Type-II Cpx forms at later stages of the same metasomatic event and reflects larger degrees of the equilibrium with the percolating carbonatitic fluids/melts.

V51C MCC: 106 Friday 0830h

Evolution of the Igneous Rocks 2002 Edition I: The Rock Record, Models of Differentiation, and Assimilation (joint with OS, P)

Presiding: D Geist, University of Idaho; P B Kelemen, Woods Hole Oceanographic Institution

V51C-01 0830h

Rocks Whose Composition is Determined by Crystal Sorting: the Volcanic Perspective

Dennis Geist¹ (208-885-6491; dgeist@uidaho.edu)

Mike Garcia² (garcia@soest.hawaii.edu)

¹Geology, Univ. of Idaho - 3022, Moscow, ID 83844, United States

²Univ. of Hawaii, Geology and Geophysics, Honolulu, HI 96822, United States

Modern analytical and theoretical tools that were unavailable in Bowen's time provide independent tests of the crystal fractionation hypothesis. This evidence indicates that most of the compositional variations among Galapagos and Hawaiian lavas are related to crystal sorting. In the Galapagos, Volcan Alcedo has erupted a sequence of tholeiitic basalt through rhyolite. Mass-balance, thermodynamic, and isotopic fractionation calculations are consistent with the generation of the rhyolites by about 85% crystallization of basalt. The geochemistry precludes significant assimilation or crustal anatexis. Phenocrysts in the basalts are mostly unrelated to their host liquid, indicating multistage hybridization. The prevalence of plagioclase-phyric lavas at high elevation and accumulative picrites in submarine lavas suggest segregation by density. During the basaltic phase, a steady-state chamber underlies the calderas, where plagioclase floats and mafic minerals sink. Rhyolite is created as the magma supply is reduced and the chamber and cumulate pile cool. Crystal sorting within Hawaiian volcanoes follows a different path because of the higher rate and near continuity of magma supply. These conditions limit the extent of fractionation and lead to the observation that virtually all Hawaiian lavas of the shield-building stage are basalts. Compositional diversity among the basalts is mainly related to the removal or accumulation of olivine. Olivine and rock compositions correlate well in weakly porphyritic lavas, indicating efficient crystal-liquid separation. In contrast, olivines in the porphyritic lavas span compositions from 78 to 91% Fo. Many of these crystals are deformed indicating they are xenocrysts. At Kilauea volcano, the summit magma body is thought to act as a filter to allow lower density, sparsely porphyritic lavas (2.6-2.7 g/cc) to be erupted in the caldera and to promote the injection of denser, olivine-rich magmas (2.75-2.9 g/cc) into the volcanic rift zones. The effects of crystal fractionation and accumulation are superimposed on a continually varying resident magma composition, which undergoes cyclic variation. The impact of assimilation on compositional diversity is minor, because it involves rocks of similar composition as the magma.

V51C-02 0845h

Rocks Whose Compositions are NOT Determined by Crystal Sorting: Lessons From the Skaergaard Intrusion

Alexander R. McBirney (541-344-2539; mcbirney@darkwing.uoregon.edu)

Dept. of Geological Sciences, University of Oregon, Eugene, OR 97403, United States

Wager and Deer's Skaergaard Memoir, published shortly after the appearance of Bowen's "Evolution of Igneous Rocks" was widely viewed as the ideal confirmation of the dominant role of crystal fractionation in magmatic differentiation. The mineralogical sequence followed a course predicted by phase equilibria, and the spectacular layering seemed to offer clear evidence of crystal settling. Although the liquid line of descent proposed by Wager was closer to the "Fenner trend" of iron enrichment than to the one Bowen favored, there was no evidence that the rocks represented liquid compositions; they must have been formed by crystal sorting. This interpretation was supported by the elegant "cumulate" concept proposed a few years later by Wager and Brown. An elaborate system based on petrographic textures seen in the Skaergaard rocks soon became a pervasive paradigm for interpreting coarse-grained igneous rocks. Because of its remote location, nearly half a century passed before the Skaergaard Intrusion was seen by geologists who were not members of Wager's team. When an independent group examined the body they reported two simple observations that conflicted with earlier interpretations. First, it was noted that the plagioclase in graded "sedimentary" layers was less dense than the liquid through which it was said to have settled, and, second, some of the rocks were found to have been severely altered, both in texture and in bulk composition. The most conspicuous evidence was found in swarms of angular anorthositic blocks that had fallen from the roof. The present composition of these blocks is much more felsic than that of the unit from which they fell. Rinds of ferromagnesian minerals appear to be the mafic component that was somehow expelled from the residual plagioclase. When examined under the microscope, the contact between the block and its host, which seems so sharp in outcrops, is seen to be indistinct and gradational. The changes seen in these blocks must have occurred after they, for otherwise they could not have sunk. Further studies have shown that most, if not all of the rocks owe their present compositions, not to gravitational sorting, but to late-stage "post-cumulate" processes. This is not to say that they were not products of crystal fractionation. The compositional evolution of the magma clearly required crystal fractionation, but these processes did not end at the liquidus or even the solidus. As temperatures slowly declined, the rocks continued to re-equilibrate just as metamorphic rocks do under similar conditions.

V51C-03 0900h

Nature and Timing of Magma Interaction Processes in Arc Volcanic Systems: Data from Rocks and from Phase Equilibria Experiments

Malcolm J Rutherford (401-863-1927; macr@brown.edu)

Geology department, Brown university, 324 Book St., Providence, RI 02912, United States

The ongoing andesite eruption on Montserrat is producing andesite with clear and abundant evidence for a mingled basalt component in the magma. In addition to enclaves of basaltic composition, the andesite has much textural and compositional evidence for heating by the basalt, including outer Ti-rich rims on Ti-magnetite phenocrysts and Cpx reaction rims on quartz. There are pargasitic hornblende microphenocrysts in the andesite that are identical to those in basalt enclaves, and this pargasite can not be crystallized from the andesite bulk composition under any set of conditions in the hornblende stability field. The large (1-1.5 cm) hornblende phenocrysts in the andesite are composed of up to seven growth cycles that are optically discernible in sections parallel to c. Each growth zone begins with a sharp increase in Si and Mg (and a drop in Al and Fe) and then the original composition is gradually regained. A few of the zones show evidence of small amounts of resorption prior to the new cycle growth. According to experiments the compositional cycles are produced by a temperature change from 830 to 860 at 130 MPa water pressure, but hornblende growth is aided by the mingling in of pargasite-bearing basalt. The slow breakdown of the unstable pargasite is critical to making the thick cycles of hornblende growth because the amount of hornblende that can be resorbed into the andesitic melt in going from 830 to 860 C is very small. Similar cyclic compositional zones are present in the hornblende crystals of the Fish canyon Tuff, although the zone are much thinner and variable in thickness in this large volume eruption. The compositions of hornblende phenocrysts in the F.C. Tuff indicate that injection of mafic magma and hornblende crystallization went on

at a higher pressure of approximately 220 MPa. Less pronounced zoning is also present in hornblende of the 1980 Mount St. Helens eruption products. The variable preservation of this zoning, when totally characterized and modeled, should reveal the length of time involved in hornblende phenocryst growth in these continuously re-injected silicic magma systems.

V51C-04 0915h

Melting of the Continental Crust: Products and Processes

Michael Brown¹ (301 405 4080; mbrown@geol.umd.edu)

Tim Johnson¹ (timj@geol.umd.edu)

¹University of Maryland, Laboratory for Crustal Petrology, Department of Geology, College Park, MD 20742-4211, United States

Earth's continental crust is unique compared to the 'basaltic' crusts of other inner planets; this is a consequence of free water on Earth and recycling of Earth's primary basaltic crust. Although there is no agreement about the average chemical composition of bulk continental crust or about secular change in composition, there is agreement that upper crust is more felsic than lower crust. Further, it is widely accepted that intracrustal differentiation by melting is responsible for the difference in composition, even though controversy remains about whether part of the inventory of lower crust has been lost by delamination. Magmatic additions from the mantle, recycling through erosion, sedimentation and burial via subduction and/or orogenesis, and regeneration through multiple orogenic events have developed a diversity of crustal rocks that neither melt nor behave uniformly.

Water is an important constituent of crustal rocks, but the lower crust may be essentially 'dry', so that melting is controlled by successive dehydration of muscovite, biotite and hornblende in bulk compositions that vary from 'granodioritic' or 'pelitic' to 'dioritic' or 'basaltic'. Thus, the products of melting of continental crust are varied, both in terms of melt compositions, and in terms of the residue. Further, since H₂O is partitioned in a hydrous silicate melt, cooling of melt bearing crust in a closed system potentially will lead to retrogression by back reaction between melt and residue, unless segregation has separated them sufficiently to avoid reaction during cooling. This raises the issue of equilibration domains and local equilibrium. The common occurrence of pristine to weakly retrogressed residual granulites suggests melt loss from the lower crust, consistent with the presence of leucogranites in the upper crust.

We illustrate the 'reaction principle' (Bowen, N.L., 1922, The Reaction Principle in Petrogenesis, *Journal of Geology*, 30, 177-198) with reference to microstructures in natural systems, and by the use of pseudosections [including T-X and P-X pseudo-binaries (or projections) of fixed bulk compositions] modeled in the MnNCKFMASH system under suprasolidus conditions using an internally consistent thermodynamic database and the software THERMOCALC. Such diagrams are potentially powerful interpretative tools, and it is instructive to consider the consequences of a range of possible paths through them. For example, univariant reactions are rarely intersected ('seen') by single rocks (fixed bulk compositions) during burial and exhumation, even in relatively simple sub-systems (e.g., KF-MASH). Modeling melt loss from metapelitic compositions in the MnNCKFMASH system shows that both bulk composition and proportion of melt lost give rise to a wide variation in retrograde behavior consistent with observation of lower crustal rocks. This point is important in understanding evolution of the melts produced, since retrograde (back) reactions occur at peritectics in the system. Thus, modeling of fractionation processes must take into account the possibility of such reactions and the consequent change in phase assemblages.

In the absence of a robust thermodynamic model for sapphirine, and for Ti in model granite melt compositions, we are not yet able to model metapelitic compositions under ultra-high temperature metamorphic conditions. Further, in the absence of a robust thermodynamic model for the amphiboles, we are not yet able to model crustal melting of metabasaltic compositions. Experimental data are available that partly remedy this deficiency and provide some information about melt compositions and solid residues, but only for a limited range of fixed bulk compositions or for compositionally restricted sub-systems.

V51C-05 0930h

SiO₂ and Time are not Interchangeable on the Abscissa of Magmatic Evolution

John Eichelberger (1-907-474-5530; eich@gl.alaska.edu)

Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive PO Box 757320, Fairbanks, AK 99775-7320, United States

A lifetime ago, Bowen pointed us away from the imagined processes of liquid immiscibility, fluid transfer, Soret diffusion, and superheat and toward the simple constraints that thermal and chemical contact between silicate melt and silicate crystals impose on a system. He emphasized volcanic glasses as our best guide to what actually exists at depth as magmatic melts, though in mistaking bubble-free obsidians as vapor unsaturated and therefore dry granitic magma he missed some of the importance of water. Bowen focused his experimentalists eye on the micro-scale of magma bodies and not on the distracting outward form. Although this path has stood the test of time, it is the application of a vision of evolution to the macro system where much difficulty remains. Examinations of zoned plutons, zoned tuff sheets, and volcanic sequences fail to show fractional crystallization caught in the act. Instead, the more we look in detail the more we see a chaos of magma batches that can be related directly to each other only by appealing to arcane processes that Bowen argued against. Indeed, chaos reaches down to the micro-scale, where crystals of wholly different thermal and chemical histories are juxtaposed in melts they only recently encountered, a situation Bowen could not have fully appreciated given the analytical tools of the day. Despite what one might expect from Bowen's treatise, a Harker variation diagram for an igneous system is not a simple liquid line of descent, in which time can replace SiO₂ on the abscissa. And in many systems the line is discontinuous: the Daly Gap is a real feature of the frequency distribution of bulk compositions. It does not go away because one can find intermediate composition melts. This says something about the physics of how mobile magmatic masses separate from their forebears.

There is thus little reason to believe that silicic differentiates are produced by a grand, uninterrupted march from primary basalt to petrogeny residua system. Yet the enthusiasm to postulate giant magma chambers to accomplish everything Bowen imagined in a single long-lived container has left petrologists at odds with geophysicists who see only modest zones of partial melt. Some of these conflicts can be resolved by postulating the following: 1. Fractional crystallization per se, the progressive settling or plating out of crystals from a melt-rich magma, is only efficient in mafic systems where melt viscosity is low; the farther differentiation proceeds, the more it is impeded. 2. At higher SiO₂ contents, crystal/liquid separation may occur dominantly by filter pressing extracting silicic melt from mostly crystals, instead of crystals from mostly melt. This source mush may be either earlier emplaced plutons of the same episode, old heated crust, or both. 3. The steady-state for silicic systems is quiescent mush zones; melt-rich systems are ephemeral. 4. The steady state is perturbed by the release and ascent of new melt-rich batches from depth. These new releases may be more silicic (silicic replenishment) or more mafic (mafic replenishment) than the old magma stored at shallow depth. Such events may trigger eruption, in which old + new magma is expelled either as a mixture or as separate but contiguous batches. The latter include zoned tuff sheets sometimes mistaken for snapshots of differentiation.

Such a view satisfies a number of observations in subduction zone magma systems where geophysical anomalies are subtle, silicic magmas are isotopically distinct - especially for short half life isotopes - but not hugely different from mafic associates, and the composition of the volcanic output jumps back and forth with time.

V51C-06 0945h

Bowens Unsolved Problem: The Mechanics of Differentiation

Bruce D Marsh (410-516-4652; bmarsh@jhu.edu)

Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218, United States

The compositional diversity of the igneous rocks is well explained by Bowen's Reaction Series. Residual melts generally become increasingly silica-rich with increasing crystal content and diminishing temperature. F. A. Fouque came upon this effect in the 1870s when he separated and analyzed the groundmass of an intermediate lava on Santorini. In lieu of any knowledge of silicate phase equilibria, the bimodality reflected by apparent preponderance of basalts and granites was, until Bowen, inferred to reflect a system of phase equilibria dominated by two eutectic-like pole compositions in a binary system. Building from Days plagioclase work, Bowen soon found that when the ternary [with solid solutions] comes in at the door, the binary goes out at the window. His geological common sense, especially his understanding of compelling field relations, and his analytical use of physical chemistry allowed him to see every igneous suite as a simple result of fractional crystallization. He became a master at constructing a path through a ternary to yield the liquid line of descent of any cooling magma chamber. At a purely chemical level, with the spatial context of each analyzed rock not a part of the problem, this style of interpretation became a fundamental truth. This is still true to this day. But because the senior petrologists in Bowen's early years were field based, he still had to prove two things: First, that crystals could really settle in magma, and second, that the latest, most

siliceous melt could be reasonably extracted. He solved the first problem with his famous picrite experiment. Doubt continued, even to the extent that Wager felt the need to preface his work on layered intrusions with Bowen's picture of his thin sections through the picrite charge. That crystals settle in magma is, indeed, a fundamental truth. But the second problem, of collecting siliceous melt by fractional crystallization, haunted Bowen throughout his career. For example (1915): We now return to the commonly observed association of diabase and its silicic differentiates during the period when the magma has largely crystallized, the straining-off or squeezing out of the residual fluid magma [Harker, 1909] is the most important process. Later he specifically described the squeezing as possibly happening as a result of tectonic deformation, but then later still withdrew this idea when he realized the difference in time scales of deformation and crystallization. As voluminous volcanic (Kilauea) and magmatic systems (Skaergaard) were found to exhibit little silicic differentiates, he suggested (1947) that perhaps cooling has been at such a rate that fractionation is unable to effect the separation of liquid at intermediate stages or that the magma did not retain its volatiles and was too dry to stabilize phases like biotite and hornblende which are strong silica fractionators. The fact is the problem of how crystal fractionation takes place is still with us. Magmatic bodies initially free of crystals solidify to uniformity inward from the margins via ever-thickening crusts or solidification fronts (SFs). There are no or very tiny crystals in the interior, precluding conventional fractionation. And the residual melt only starts getting siliceous beyond a crystallinity depth of about 50percent where the matrix has significant strength. The processes to study are spatial ones that operate within SFs and vertically extensive and integrated mush column magmatic systems. It is time to move on from repetitive chemical studies of orchestral crystal fractionation.

V51C-07 1020h INVITED

Assimilation is Essential

P B Kelemen (peterk@whoi.edu)

WHOI, MS 8, Woods Hole, MA 02543, United States

Norman Bowen's 1922 paper, The behavior of inclusions in igneous magmas, and its abridged version in The Evolution of the Igneous Rocks, are the classic papers on reaction between silicate melt and minerals. Bowen showed that dissolution of minerals in magma above its liquidus temperature is limited to a few percent of the melt mass, because the heat of fusion of silicates is much larger than the heat capacity of silicate melt. Thus, he proposed that for extensive reaction between melt and rock, there must be a link between dissolution of one phase and crystallization of another. Bowen's reasoning should be the starting point for all studies of igneous open systems.

Nonetheless, Bowen reached some controversial conclusions. He wrote, It is doubtful whether the presence of foreign matter is ever essential to the production of any particular type of differentiate. This was during debate over the calc-alkaline trend, with high Mg/(Mg+Fe), or Mg#, over a range of silica contents. Bowen reasoned that the calc-alkaline trend started with basalt, a primary melt, and ended with granite, the end-product of fractional crystallization, so the entire trend must be due to fractional crystallization. However, Clarence Fenner thought that fractional crystallization of basalt produced decreasing Mg# at nearly constant silica, a tholeiitic trend. For Fenner, the debate was about granite, but about intermediate, calc-alkaline andesites, (i.e., high Mg# andesite, 54 wt% < SiO₂ < 63 wt%, Mg# > 0.45).

This debate is still not resolved, but there are cases in which reaction of basaltic melt with granitic rock was essential in producing high Mg# andesites. Similarly, some high Mg# andesites arise via magma mixing, a kind of incorporation of foreign matter. Some high Mg# andesites are partial melts of peridotite, and some arise via melt-rock reaction in the mantle. The andesite problem has extra importance because continental crust has a high Mg# andesite composition.

Bowen quantified the energy required to heat wall rock to magmatic temperature, and showed how it limited the extent of reaction. This reflected an implicit emphasis on crustal processes. Also, Bowen was probably unaware of reactions between melt and mantle peridotite, resulting from (1) changing peridotite/melt equilibria with pressure, (2) gradual cooling of rising melt in the mantle lithosphere, and (3) partial melting of subducted basalt and/or sediment. Because reactions between melt and mantle do not require heating cold rock, they can be very extensive. Some common reactions produce more liquid at mantle conditions, even in systems closed to heat transfer.

Melt-rock reactions in the mantle can have a dramatic effect on resulting liquid. Trace element exchange during porous flow can enrich liquid in incompatible elements to the theoretical limit of an infinitesimally small degree melt via zone refining (Harris GCA 1959). Decreasing melt mass during trace element exchange produces additional enrichment. Increasing volatile content can even produce separation of immiscible carbonate and silicate melts. Because zone refining maintains equilibrium between liquid and peridotite, it can produce a variety of different primary melts from the same parental liquid.

Melt-mantle reactions also form solid products, such as discordant mantle dunites. Dunites with replacive contact relationships form via reaction between ascending melt and peridotite because the olivine primary phase volume expands with decreasing pressure. Open-system processes are essential to formation of these rocks. In turn, dunites transport olivine-saturated basalt through orthopyroxene-bearing, shallow mantle peridotite, and thus play a key role in determining the composition of oceanic crust.

V51C-08 1035h

Assimilation Yesterday, Today and Tomorrow

John A. Wolff¹ (509-335-2825; jawolff@mail.wsu.edu)

Frank C. Ramos¹ (509-335-7857; frames@wsu.edu)

¹Department of Geology, Washington State University, Pullman, WA 99164

N.L. Bowen pointed out that the effect of assimilating fusible rock into a cooling magma is to increase the volume of residual liquids, not change the cotectic relations that govern the compositions of those liquids. Accurate estimation of volumes of initial and residual liquids in evolving magmatic systems remains impossible, and petrologists interested in assimilation have tended to focus instead on identifying passive chemical tracers of crustal input into volcanic systems, especially during the last ~35 years in which high-quality trace element and isotope data have been available. Much of the motivation for these studies has arisen from the desire to use basaltic magmas as probes of mantle geochemistry, which relies on stripping from the basalt any chemical changes resulting from interaction between mantle-derived magma and crust. Despite the impressive array of high quality whole rock chemical data (typically concentrations of ~40 elements, and isotopic ratios from any or all of the systems Rb/Sr, Sm/Nd, U/Th/Pb, Lu/Hf, Re/Os, O and U/Th) applied to individual cases, two different investigators can interpret the same data set to arrive at highly disparate conclusions about the amount of crustal assimilation involved in the petrogenesis of, say, lavas from a continental volcanic field. In part, this situation arises from a decoupling between the sophistication of the chemical data and the naiveté with which we view processes of magma transport and storage.

Two current developments promise to greatly improve our understanding of assimilation over the 25 years until the centenary celebrations of the publication of "The Evolution of the Igneous Rocks". First, models such as energy-constrained assimilation-fractional crystallization [1] that link a physical (in this case, thermodynamic) description of a magmatic system with the evolution of trace element abundances and isotopic ratios are revealing the wide range of results that arise from interaction of basaltic magmas with fusible crust. Second, the arrival of microsampling methods for trace elements and isotope ratios has sparked a renewed interest in petrography, particularly in linking isotopic heterogeneity within and among phenocrysts to rock textures and magmatic histories. These investigations show that isotopic change in mafic, intermediate, silicic and alkaline magmas at crustal pressures seems to be the rule rather than the exception, indicating a near-ubiquitous role for crustal assimilation. The following examples from diverse geologic settings serve as illustrations: 1. Basalts with greater than 6% MgO from Pisgah Crater show extensive ⁸⁷Sr/⁸⁶Sr variations on all scales (i.e. within and between plagioclase, clinopyroxene, amphibole, olivine, and groundmass); 2. Plagioclase feldspars from Columbia River Basalt flows are zoned in ⁸⁷Sr/⁸⁶Sr from less radiogenic cores to more radiogenic rims, while groundmass is more radiogenic still; 3. Sr, Pb and O isotope variations among feldspars and glasses from the high-silica rhyolite Bandelier Tuff indicate that assimilation accompanied magma chamber zonation, with a contamination spike associated with the eruption itself; 4. Feldspar-glass Pb isotopic disequilibrium from Tenerife phonolites demonstrate similar magma-crust interactions in ocean islands. In all these cases, the preservation of isotopic disequilibrium also places constraints on the timescales over which measurable isotopic change occurs in magmas. Also, it is clear from the last two cases that even low-temperature silicic magmas that lie at the water-saturated minima in Petrogenys Residua system are capable of assimilating crust.

[1] Spera FJ & Bohron WA (2001) J. Petrol. 42, 999-1018.

V51C-09 1050h

A Diamond Anniversary Perspective on "The Effects of Assimilation": Energy, Mass and Chemical Constraints on Open-System Magmatic Processes

Wendy A Bohron¹ (509.963.2835; bohron@geology.cwu.edu)

Frank J Spera² (805.893.4880; spera@magma.geol.ucsb.edu)

¹Dept. Geol. Sci., Central Washington University, Ellensburg, WA 98926, United States

²Inst. Crustal Studies, UCSB, Santa Barbara, CA 93106, United States

In "The Evolution of Igneous Rocks," (1928) Norman Bowen described the ongoing debate regarding the role that "foreign material" plays in generating compositional diversity in terrestrial magmas. A critical aspect of Bowen's discussion of "The Effects of Assimilation" (Ch. 10) centered on the availability of enough energy to generate assimilated melt, and the effects that assimilation has on magma composition. Seventy-five years later, this debate is just as lively and reflects fundamental questions in igneous petrology/geochemistry: What are the energy, mass and chemical consequences of open-system magmatic processes, and how do these processes complicate our ability to characterize the mantle? Energy-Constrained Recharge, Assimilation, Fractional Crystallization (EC-RAFC) is a tool that tracks the thermochemical evolution of a magma body (melt+solids) undergoing recharge, assimilation, and fractional crystallization. The EC-RAFC algorithm is based on solution of a system of coupled non-linear differential equations that express conservation of energy (enthalpy), mass and species (trace elements, isotope ratios). The constraint of energy conservation provides information about the efficacy of assimilation in a range of thermal environments. For example, EC-RAFC results suggest that mafic magma intruded into mafic lower crust can assimilate up to 40% of the original mass of the magma body, yielding ratios of mass of material assimilated/mass of material crystallized of up to 0.8. For typical lower crustal Sr concentrations ([Sr]) and isotope values (230 ppm, 0.7100), the Sr isotope signature of a mafic magma (400 ppm, 0.7035) can increase by up to 1500 ppm. Production of mafic magmas with more radiogenic Sr isotope values and relatively enriched [Sr] is favored by lower crust that has a lower liquidus temperature and/or is thermally mature. The ability to track the mass and chemical consequences of wallrock partial melting further illustrates the importance of the energy-constrained approach. For the magmatic system described above, changing the characteristics of the crust profoundly affects the trace element and isotopic signatures of the derivative magmas: doubling the Sr budget or increasing ⁸⁷Sr/⁸⁶Sr to 0.7150 yields magmas with Sr isotope signatures of up to 0.706 and [Sr] of up to 500 ppm. Mafic magma intruded into typical upper crust (350 ppm, 0.7220) yields magmas that have ⁸⁷Sr/⁸⁶Sr of 0.710 and 300 ppm Sr. An equally important outcome of EC-RAFC is that geochemical trends, such as [Sr] vs. ⁸⁷Sr/⁸⁶Sr, are not necessarily monotonic. Thus, negating the importance of crustal processes on the basis of the absence of correlated trends may be misleading. In the decades since publication of Bowen's work, geochemical, petrologic, and petrographic data collected on genetically-related suites of igneous rocks and crystals point to the critical conclusion that each magmatic system has a distinct thermochemical history that reflects the complex interplay between mantle and crustal processes. Each system must be systematically evaluated in order to assess the consequences of shallow-vs. deep-level processes. Advances in analytical techniques, phase equilibria, and thermodynamically-based tools such as EC-RAFC provide the framework for quantitative assessment of crustal-level open-system processes. Armed with mass, thermal and chemical constraints, crustal contributions can be calibrated, and, as a consequence, the character of sub-crustal reservoirs will come into better focus.

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V51C-10 1105h

Rates, Mechanisms, and Implications of Crustal Assimilation in Continental Arcs

Michael Dungan¹ (+41 22 702 6630; Michael.Dungan@terre.unige.ch)

Jon Davidson² (+44 (0) 191 374 2528; J.P.Davidson@durham.ac.uk)

¹Section des Sciences de la Terre, University of Geneva, Geneva 1204, Switzerland

²Dept. Geol. Sciences, University of Durham, Durham DH1 3LE, United Kingdom

Contrary to the limiting constraints postulated by Bowen for the coupled thermal and mass balance implicated in assimilation, many studies [1-6] suggest that multi-stage and multi-component assimilation, abetted by magma mixing, may be volumetrically important and have profound consequences for the chemistry of basaltic and evolved magmas in long-lived continental magmatic systems. The probability of a primitive or evolved basalt arriving at the Earth's surface having undergone perfectly closed-system evolution during passage through 25-60 km of continental crust is vanishingly low. A case-by-case demonstration that the intra-crustal chemical overprint is trivial, or that it can be quantified and subtracted, is an essential step in any evaluation of mantle source-region chemistry and processes based on inversion of continental basalt compositions.

In magmatic systems characterized by mafic magma recharge the thermal energy and physical dynamism needed for assimilation are not constrained to come uniquely from one magma batch [7, 8]. Equally important is that assimilation is rarely equivalent to bulk melting of ingested blocks followed by reservoir-wide homogenization. The mechanics of crustal assimilation are governed by grain boundary melting, disaggregation, and dispersal of refractory solids (including xenocryst settling) wherein liberated low-density, incompatible element-enriched partial melts have the capacity to render primitive arc magma batches variably modified, as well as heterogeneous on short length-scales. Evidence that basalts thermally erode surface channels and conduit walls, and new observations constraining the maximum time that some extensively melted xenoliths have resided in their host magmas, indicate that the time required to impose an open-system overprint on a hot basaltic magma (days to yrs) is far shorter than typical repose periods at most arc volcanoes (50-500 yrs).

Assimilative recycling of broadly gabbroic arc cumulates has had large chemical consequences for whole-rock compositions of arc basalts at the Tatara-San Pedro complex (TSPC), Chilean Andes. This occurrence, although thermally challenged according to the traditional paradigm, demonstrates that significant modifications of trace element abundances and ratios need not shift the host magma composition outside the basaltic range. In fact, the retention of micro-xenolithic clots rich in olivine and augite has produced positive correlations between incompatible and compatible elements in some magmas, and ⁸⁷Sr/⁸⁶Sr decreases from 0.7041 to 0.7039 with increasing Rb (8-27 ppm). Hornblende and plagioclase in mafic arc plutonic xenoliths promote rapid digestion by lowering solidus temperatures and such melts amplify the chemical overprint in contaminated magmas, but partially melted gabbroic and troctolitic xenoliths lacking hydrous minerals are widespread at the TSFC, and many mafic magmas contain micro-xenolithic plutonic crystal clots derived from such lithologies that volumetrically rival the true phenocryst assemblage. Among the implications of these observations is that long-lived arc volcanoes may extensively recycle their own plutonic roots. [1] Huppert HH & Sparks RSJ (1985) E.P.S.Lett., 74, 371-386. [2] Dungan et al. (1986) J. Geophys. Res., 91, 5999-6028. [3] Philpotts AR & Asher PM (1993) J. Petrol., 34, 1029-1058. [4] Heliker C (1995) J. Volc. Geoth. Res., 6, 115-135. [5] Reiners et al. (1995) Geology, 23, 563-566. [6] Spera FJ & Bohron WA (2001) J. Petrol., 42, 999-1018. [7] Grove et al. (1988) Contrib. Min. Petrol., 99, 320-343. [8] Dungan et al. (2001) J. Petrol., 42, 555-626.

V51C-11 1120h

Basaltic Inputs to a Dacitic Magma: Results From Phase I Drilling at Unzen Volcano, Japan

Thomas A Vogel¹ (vogel@msu.edu)

Lina C Patino¹ (patinoL@msu.edu)

Brandon L Brown² (ftblb@uaf.edu)

John C Eichelberger² (eich@gi.alaska.edu)

Jonathan Dehn² (jdehn@gi.alaska.edu)

¹Michigan State University, Department of Geological Sciences, East Lansing, MI 48824-1115, United States

²University of Alaska Fairbanks, Geophysical Institute, Fairbanks, AK 99775-7320, United States

Samples from Phase I drilling at Unzen volcano, Japan, record hundreds of injections of basaltic magma that interacted with dacitic host magma, and are interpreted as reflecting the repetitive replenishment, and commingling and partial mixing of basaltic magma into a silicic crystal-rich crustal reservoir. Quenched, ellipsoidal basaltic enclaves are abundant and evenly distributed throughout the drill core (up to 1500m depth), and vary in size from 0.5 cm to >10 cm. The ranges of major-element compositions (in wt. %) of the host are SiO₂ 61.8 to 64.7; Al₂O₃ 15.6 to 17.0; Fe₂O_{3(t)} 4.8 to 6.0; MgO 2.1 to 3.0. The ranges of the inclusions are SiO₂ 51.3 to 58.9; Al₂O₃ 16.8 to 18.0; Fe₂O_{3(t)} 6.5 to 10.2; MgO 3.0 to 4.6. REEs of the host and inclusions are different; the host has consistently lower HREE concentrations and generally higher LREE concentrations. Rb, Pb and U are twice the concentration in the host compared to the inclusions, whereas Y is depleted in the host compared to the inclusions. Ba concentrations in the host are much higher than the inclusion (the most silicic host has 534 ppm, the most mafic inclusion has 272 ppm), whereas Sr in the most silicic host is lower than in the most mafic inclusion (364 and 516 respectively). The Ba/Sr ratio of the silicic host is much higher than the mafic inclusion (1.47 and 0.53 respectively).

Many phenocrysts in the dacite host have sieved margins consisting of abundant glass inclusions with a clear inclusion-free rim. A common rimmed plagioclase phenocryst in the host consists of a of 50-60% An in the main part of the crystal and 76-87% An on the rim.

The trace elements compositions for the core of these phenocrysts are Ba 182-229 ppm, Sr 726-920 ppm, and Ba/Sr ratios 0.22-0.25. The composition of the rim are distinctly different - Ba 36-55 ppm, Sr 943-1057 ppm, and Ba/Sr ratios 0.04-0.05. Sr/Ca ratios for core are higher ($\text{Sr}/\text{Ca} \times 10^{-3}$ 12.9-15.0 core) than those of the rim ($\text{Sr}/\text{Ca} \times 10^{-3}$ 7.7 to 8.9).

Microphenocrysts in the inclusions typically contain 80-83% An in the center to 55-58% An on the rim. The rim of these phenocrysts is too thin for laser ICP-MS probing, but the cores of these microphenocrysts contain Ba 75-125 ppm, Sr 876-1096 ppm, Ba/Sr ratios 0.07-0.11 and $\text{Sr}/\text{Ca} \times 10^{-3}$ ratios and 7.9-10.3 respectively.

Phenocrysts from the dacitic hosts are usually rimmed with plagioclase of higher anorthite content, lower Ba and higher Sr than the cores. Rims have lower Ba/Sr ratios. Microphenocrysts from the basaltic inclusions are rimmed with lower anorthite content. Ba and anorthite content of the cores of these microphenocrysts overlap those of the rims of the host phenocrysts. However, the Ba concentrations of the microphenocrysts are not as low as those in the rims of the phenocrysts from the dacite.

Our interpretation of these data is that sieved and rimmed host phenocrysts reflect a close encounter with basaltic magma during the injection of basaltic magma into a dacitic, crystal-rich crustal reservoir. Ba concentrations and Ba/Sr ratios of the dacitic host magma are higher than those of the mafic inclusions, whereas Sr concentrations of the inclusions are higher than those of the host. The plagioclase rims in the dacitic host plagioclase reflect the composition of the basaltic magma that was injected. The trace-element concentration (Ba) of the cores of microphenocrysts from the basaltic inclusions are somewhat modified, perhaps because it was easier to mix liquid from the dacitic host into the lower viscosity basaltic inclusions.

V51C-12 1135h

Integrating isotopic fingerprinting with petrology: how do igneous rocks evolve?

Jon P. Davidson (+44 (0)191 374 2520; j.p.davidson@durham.ac.uk)

University of Durham, Dept of Geological Sciences
University of Durham, Durham DH13LE, United Kingdom

In the title of his seminal work, N.L. Bowen recognized the fundamental importance of magmatic evolution in producing the spectrum of igneous rocks. Indeed it is difficult to imagine a hot highly reactive fluid passing through c. 100 km of a chemically distinct medium (lithosphere) without evolving through cooling, crystallization and interaction with the wall rocks. The fact that magmas evolve - almost invariably through open system processes - has been largely marginalized in the past 30 years by the desire to use them as probes of mantle source regions. This perspective has been driven principally by advances offered by isotope geochemistry, through which components and sources can be effectively fingerprinted. Two fundamental observations urge caution in ignoring differentiation effects; 1) the scarcity of truly primary magmas according to geochemical criteria (recognized long ago by petrologists), and 2) the common occurrence of petrographic criteria attesting to open system evolution.

Recent advances in multicollector mass spectrometry permit integration of the powerful diagnostic tools of isotope geochemistry with petrographic observations through accurate and precise analysis of small samples. Laser ablation and microdrilling enable sampling within and between mineral phases. The results of our microsampling investigations give widespread support for open system evolution of magmas, and provide insights into the mechanisms and timescales over which this occurs. For example; 1) core-rim decreases in $^{87}\text{Sr}/^{86}\text{Sr}$ in zoned plagioclase crystals from 1982 lavas of El Chichon volcano, Mexico, argue that the zoning and isotopic changes are in response to magma recharge mixing with an originally contaminated resident magma; 2) Single grain and intra-grain isotopic analyses of mineral phases from Ngauruhoe andesites (New Zealand) are highly variable, arguing that bulk rock data reflect mechanical aggregations of components which have evolved in discrete domains of the magma storage and delivery system; 3) $^{87}\text{Sr}/^{86}\text{Sr}$ variations within feldspars from a single ignimbrite exceed the entire rhyolite bulk rock range of $^{87}\text{Sr}/^{86}\text{Sr}$ recorded from the Taupo volcanic zone, New Zealand; arguing that the isotopic heterogeneity encountered during differentiation is greater than that erupted; and 4) Gabbros from the Rum intrusion (NW Scotland) exhibit inter and intra-grain isotopic heterogeneity arguing that accumulation involved mixing of crystal populations which evolved in different domains of an open system magma chamber.

These studies suggest that isotopic modification of magmas in the crust (according to P-T estimates of plagioclase stability) is the rule rather than the exception. Although it is conceivable that isotopic signatures are all inherited from mantle-derived melts which interacted before, during and after crystal growth, it is more likely that the isotopic diversity reflects contamination and mixing which obscures the signature of the

mantle contributions. Furthermore, it is perhaps unrealistic to think of the evolution of a particular igneous rock. Rather each rock appears to be an aggregate of components with separate evolutionary histories. Because isotopic composition is leveraged by the mass balance of these components (Sr is typically concentrated in plagioclase, Nd in glass and accessories, Hf in zircon, Pb in feldspar and glass), the isotopic systematics of bulk rocks can become decoupled from each other. Thus the isotope characteristics of the rock components give a more faithful record of evolution processes than the bulk rock itself.

V51C-13 1150h

Magma Migration Through the Continental Crust 3-D Seismic and Thermo-mechanical Constraints on Sites of Crustal Contamination

Marjorie Wilson¹ (44-113-343-5236; M.Wilson@earth.leeds.ac.uk)

Walter Wheeler² (47-5599-6078; Walter.Wheeler@hydro.com)

¹Leeds University, School of Earth Sciences, Leeds LS2 9JT, United Kingdom

²Norsk Hydro ASA, Research Centre PO Box 7190, Bergen N-5020, Norway

Current understanding of the processes and pathways by which magma travels from its mantle source, through the crust to the Earth's surface is limited by the lack of continuously exposed sections through fossil magmatic systems. We report results from a 50 x 30 km 3-D seismic reflection survey of part of the Voring rifted continental margin of Norway which provide the first detailed images of an entire crustal magmatic plumbing system, from a Moho-level magma chamber, through complexes of sills and dykes in the mid to upper crust, to lavas and vent fields extruded at the early Tertiary paleosurface.

The Voring margin of Norway formed during a period of Late Cretaceous to early Tertiary (Eocene) continental break-up when Greenland rifted away from Eurasia, resulting in the opening the NE Atlantic Ocean. Rifting was accompanied by widespread magmatic activity, inferred to be related to the impingement of the Iceland mantle plume on the base of the continental lithosphere. Regionally, magma migration occurred in at least two pulses: 62-59 Ma (main initial phase) and 57-54 Ma (continental break-up phase).

Wide-angle seismic experiments indicate the presence of a lacolith-like high-velocity body (HVB) in the lower crust beneath most of the outer Voring Basin with P-wave velocities (V_p 7.1-7.4 km/s) characteristic of basaltic igneous rocks, overlying typical mantle rocks with V_p of over 8 km/s. The HVB locally reaches 8 km thickness and at break-up (54 Ma) measured 300 km x 500 km corresponding to a volume of 450,000 cubic km of basaltic magma. It is interpreted as a magmatic underplate formed over a period of several million years as rising basaltic magmas ponded at the Moho at their level of neutral buoyancy.

A laterally extensive sill complex (1000 m thick) occurs at the interface between thinned crystalline basement and the overlying Mesozoic sedimentary sequence. This is interpreted as one of the main intra-crustal magma storage reservoirs and is the most likely site for magmatic differentiation and wall-rock assimilation. Magma migrating up through the sedimentary section from this mid-crustal magma storage system appears to flow from sill to sill via a complex system of narrow, dyke-like feeders. Locally boat-shaped nests of sills occur within the Mesozoic sediments. Individual sills are about 15 km long, 10 km wide and may reach 100 m thick. The boat shape is controlled by the half-graben tilt-block geometry: on one side magma follows dipping strata, on the other the oppositely dipping fault.

The thermal structure of the crust becomes altered by the intrusion of successive batches of basaltic magma, which induces rheological weakening of the lower crust and enhances the potential for crustal assimilation.

Bowen had a strong interest in the process of crustal contamination of magmas, as illustrated by Chapters X and XVII of the Evolution of the Igneous Rocks. He would have undoubtedly been fascinated by our ability to image fossil crustal magma storage systems and to use geophysical data to constrain petrogenetic processes.

V52A MCC: Hall C Friday 1330h MORB and More Posters

Presiding: K M Haase, Universität
Kiel

V52A-1271 1330h POSTER

Accepted U-Series Constraints on MORB Melting are Invalid

John K Osmond (850-644-5860; osmond@gly.fsu.edu)
Dept of Geological Sciences, Florida State University,
Tallahassee, FL 32306-4100, United States

Prevailing models of basalt formation under ridges impose severe restrictions as to depth and flow rate because of mistaken interpretations of U-series disequilibria observed in MORB. The observed radioactivity excesses of radium and protactinium daughters relative to parent uranium cannot be explained on the basis of the assumed incompatible behavior of uranium and thorium during mantle melting. Rather, application of fundamental mass balance principles shows that when basalt migrates to the surface, most of the U and Th remains behind, probably sequestered in residual accessory minerals. Daughter diffusion and alpha recoil across the accessory grain boundaries would result in daughter deficiencies in the accessory minerals and daughter excesses in surrounding major mantle minerals. The two complementary disequilibrium phases exist as a steady-state condition in the outer mantle prior to the onset of melting. Preferential melting of the silicates can thus produce basalt with extreme daughter/parent activity ratios regardless of depth or partial melt fraction.

V52A-1272 1330h POSTER

Cycling of Volatiles at Mid-ocean Ridges: Magma-Seawater Interactions at Three Regions of the Northern EPR (8-10°N, 12-14°N & 15-18°N)

Petrus J le Roux¹ (leroux@dtm.ciw.edu)

Steven B Shirey¹

Erik H Hauri¹

Mike R Perfit²

¹DTM, Carnegie Inst. Washington, Washington, DC 20015

²Dept of Geological Sciences, U. Florida, Gainesville, FL 32611

The extent of magma contamination by seawater-derived components or magma assimilation of altered crust beneath mid-ocean ridges is generally ill-defined but thought pervasive, especially at fast-spreading ridges. Three regions of the northern East Pacific Rise (EPR) (8-10°N, 12-14°N & 15-18°N) were selected for intensive study aimed at identifying, quantifying and relating such magma-seawater interactions to fine-scale tectonic and morphological ridge features. These EPR sections have extensive, existing glass collections, with well-constrained general geochemistry and petrology. Significant differences in spreading rate, axial depth and axial morphology differentiate these EPR sections. Geophysical surveys also indicate sub-axial magma chambers (AMC) at various crustal depths in each region.

Volatile, halogen and light-element data of basaltic samples from these northern EPR regions exhibit variable over-enrichments (i.e. above that due to crystallization). Mostly off-axis 8-10°N samples have over-enriched H₂O, F, Cl, Be & B; on- and off-axis 12-14°N samples are similarly, but less, over-enriched; but 15-18°N samples have little significant over-enrichments (over-enrichments decrease northward). High Cl/K ratios are not correlated with incompatible element ratios, e.g. K/Ti, precluding enriched or variable mantle source compositions as the origin of over-enrichments. Cl and H₂O data in 8-10°N & 12-14°N samples indicate variable magma contamination with <0.75wt% seawater-derived brines (15-50wt% NaCl equivalent). In the 15-18°N region (spreading rate 8.4cm/yr) vapor super-saturated magmas indicate rapid ascent from as deep as the shallowest regional AMC (~1400m), with no significant contamination. In the 12-14°N region (spreading rate 10.4cm/yr) magma degassing and contamination occurred at depths <1200m, above the AMC (~1500m). In the 15-18°N region (spreading rate 12.0cm/yr) magma degassing and contamination occurred above 900m crustal depth, above the deepest regional AMC (~1800m). Preliminary $^{11}\text{B}/^{10}\text{B}$ data (2σ precision as low as ~1‰) for selected samples will be used to further investigate magma contamination in these EPR regions.