

V32C-0990 1330h POSTER

Are UHP Rocks in Norway Allochthonous? A Major Revision of the Tectonostratigraphy.

David J Young¹ (young@geol.ucsb.edu)Bradley R Hacker¹ (hacker@geol.ucsb.edu)Torgeir B Andersen² (t.b.andersen@geologi.uio.no)¹Department of Geological Sciences, University of California, Santa Barbara, CA 93106, United States²Department of Geology, University of Oslo, PO Box 1047 Blindern, Oslo NO-0316, Norway

Ultrahigh pressure (UHP) rocks in the Norwegian Caledonides formed during the Caledonian collision between the Baltica and Laurentia continental plates in the Late Silurian/Early Devonian. Most geological maps show the UHP rocks as part of the Western Gneiss Complex, which lies beneath a stack of allochthonous nappes. Because the Western Gneiss Complex is correlated with autochthonous Baltica basement farther east, previous tectonic models have thus assumed that the UHP province is the leading, western edge of the subducted Baltica basement. In our view, one weakness of this interpretation is that the magnitude of both coaxial and non-coaxial deformation during the Devonian late-orogenic extension is insufficient to have exhumed the UHP rocks from mantle depths.

To resolve this issue, we conducted detailed structural and lithological mapping over the last two summers. Our mapping has carried the well-defined sequence of Western Gneiss Complex and overlying allochthonous sheets in the non-UHP Sandane area northward into the UHP Stadlandet area. We find that at least the Stadlandet area of the UHP terrane lies structurally above the Nordfjord-Sogn Detachment and the Western Gneiss Complex, and may be correlated with rocktypes of the Middle Allochthon farther south. This revision of the tectonostratigraphy has several important implications regarding the formation and exhumation of UHP rocks: 1) The trailing edges of nappes belonging to the Middle Allochthon were subducted to mantle depths, overturning a long-held belief that they remained at crustal levels. 2) The problem with the magnitude of the extensional event is alleviated, as the UHP rocks now must lie in a) the footwall of an (unidentified) large-scale normal fault, and b) the hanging wall of a large-scale thrust fault, perhaps the precursor of the Nordfjord-Sogn Detachment. 3) Exhumation of the UHP rocks from the mantle may have been coeval with thrust emplacement of the Middle Allochthon over Baltica.

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Foreland to Hinterland Regional Variation in Pressure-Temperature-Deformation Histories of the Norwegian UHP-HP Terrane

Emily O. Walsh¹ (1-805-893-7999;

emily@geol.ucsb.edu)

Bradley R. Hacker¹¹University of California, Dept. of Geological Sciences, Santa Barbara, CA 93106, United States

The Scandinavian Caledonides of Norway consist of stacked thrust sheets emplaced to the SE onto the Precambrian Baltic Shield during the Silurian/Devonian(?) collision between Baltica and Laurentia. The Western Gneiss Complex (WGC), the parautochthonous equivalent of the Baltic Shield, is a terrane of amphibolite- to epidoteamphibolite-facies orthogneisses, structurally overlain by allochthonous rocks of predominantly oceanic affinity. The allochthons can be traced from their low-grade type sections in the foreland, westward into the UHP core of the orogen. Eclogites crop out in both the WGC orthogneisses and in the overlying allochthonous rocks. Eclogites and granulites show an eastward decreasing PT gradient. This study focuses on the regional variation in PT deformation histories of rocks along a 160-km long transect from the foreland into the core of the orogen. Such a wide-scale study will assist in answering the larger questions of the Scandinavian UHP exhumation, such as: What mechanism drove the UHP exhumation? By what method were the UHP rocks ultimately exhumed?

Our structural studies reveal the order of deformational events along the EW transect: 1) emplacement of thrust sheets onto the Baltic Shield; 2) folding of allochthonous material into the basement in overturned, W-vergent synforms; 3) folding of EW trending isoclines; 4) amphibolite-facies metamorphism; 5) late-stage brittle/ductile faulting, and 6) broad open folding.

Our thermobarometry on pelitic rocks shows surprising results: 1) structurally higher allochthonous rocks record higher pressures (1.2 GPa) than basement rocks (0.6 GPa); 2) allochthons record isothermal decompression, while basement rocks indicate iso-

baric cooling, and 3) the pelitic P gradient increases to the SE, opposite to the regional eclogite P gradient. This significant difference in the P gradients of the pelitic rocks and the eclogites implies crustal imbrication, and hence negates the simplest model of UHP exhumation, the coherent-slab rollback model. UThPb dating of monazites will divulge the relative timing of the HP metamorphism of the allochthons and the HT metamorphism of the basement rocks, providing additional means for constraining other existing exhumation models.

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Pressure-Temperature-Time-Strain Path of Eclogites and Gneiss from the Ultrahigh Pressure Province of Western Norway:

Loïc Labrousse¹ (0033144275256;

labrous@lgs.jussieu.fr)

Laurent Jolivet¹ (0033144275907;

jolivet@lgs.jussieu.fr)

Urs Schärer² (scharer@ipgp.jussieu.fr)Torgeir B Andersen³ (t.b.andersen@geologi.uio.no)¹Laboratoire de Tectonique UPMC UMR CNRS 7072, T26 El case 129 4, Place Jussieu, Paris 75252, France²Gosciences Azur UMR CNRS 6526, Université de Nice Sophia-Antipolis Parc Valrose, Nice 06108, France³Department of Geology, University of Oslo Postboks 1047 Blindern, Oslo 0316, Norway

The UHP province of Western Norway is the part of the Baltic shield subducted to more than 100 km depth during the Caledonian orogeny. Field study in the Nordfjord area, north to the Hornelen Devonian basin reveals the heterogeneous behavior of the continental crust during its exhumation. Crustal-scale boudinage occurs during ductile constrictional stretching in amphibolitic conditions, preserving UHP and protolith in the core of boudins. The rims of the Nordfjord area boudins are characterized by a pervasive migmatization during exhumation, that lowers the average viscosity of the subducted crust. Top-to-the-west shearing associated to the Nordfjord-Sogn detachment overprints this constrictional fabric. Dating of a UHP eclogite in Stadlandet area by U-Pb method on rutile and omphacite fractions gives an age of 389.4±3.4 Ma for the crystallization of the UHP paragenesis. The same method used on titanite and Kfeldspars fractions from the surrounding migmatitic gneisses gives an age of 369.2±3.9 Ma for the end of the migmatitic event. Those calibrations added to P-T estimations allow to deduce exhumation rate of 2.5 and 3.7 mm±yr or the two successive stages of exhumation from UHP to amphibolitic depths and from amphibolitic depths to the surface respectively. The present age for UHP eclogite leads to some new considerations about the Caledonian history: (1) the ages of eclogites in the WGR scattered from 420 to 389 Ma can only be explained by a continuous exhumation of continental crust during subduction (2) most of extensional structures dated between 407 and 389 Ma are necessarily syn-orogenic (3) the deposition of the Devonian basins occurred while eclogites were still exhuming between 390 and 370 Ma.

A new scenario is proposed for the latest stages of the Caledonian orogeny, where exhumation of crustal lenses in a subduction channel lubricated by migmatization occurs at depths while transtension controls the deposition of conglomerates at the surface. Overall extension, probably correlated to plate divergence, is then responsible for the last stages of exhumation associated to the detachment system.

V32D MC: Hall D Wednesday 1330h

Magmatic Evolution of Volcanic Systems

Presiding: J B Lowenstern, U.S.

Geological Survey

V32D-0993 1330h POSTER

Evolution of rhyolitic magma from Ata caldera: progressive melting model for chemical variation

Hisayoshi Yokose¹ (+81-963423414;

yokose@aster.sci.kumamoto-u.ac.jp)

Yasuhiko Nakamura² (+81-962821638;

yasuhiko@aso.sci.kumamoto-u.ac.jp)

¹Dept. Earth Sci. Kumamoto Univ., 2-39-1 Kurokami, Kumamoto 860-8555, Japan²Kongo co., environmental Sci. division, 3-8-1 Kami-Kumamoto, Kumamoto 860-8555, Japan

In order to understand a magmatic evolution of caldera forming rhyolitic eruption, essential fragments from Ata caldera, which is one of the four gigantic Quaternary caldera in Kyushu Japan, have been analyzed on bulk rock and glass chemistry. Rhyolitic magmas formed Ata caldera have two different rock types: pyroxene dacite and hornblende rhyolite. Phenocrystic minerals of hornblende rhyolite consists hornblende, plagioclase, and quartz. On the other hand, pyroxene dacite is plagioclase as a main phenocrystic mineral, accompanied by small amounts of fine grain pyroxenes.

Concentration of LIL elements, such as K₂O, Ba, Na₂O, Rb, in both types are the same level, but concentration of HFS elements, such as Nb, Y, Zr and Zn, decrease with increasing SiO₂. Geochemical contrast between them are also obvious in the diagram of REE abundance pattern. REE patterns of hornblende rhyolites have lower than basaltic rocks and are depleted in MREE. REE patterns of pyroxene dacite are equal or even lower than that of basalt and higher than hornblende dacite. The REE patterns imply that hornblende, which has high distribution coefficients in MREE should be residual mineral for hornblende dacite and is not liquidus facies in pyroxene dacites.

Rhyolitic magmas are produced by the dehydration melting reaction which can be drawn as following equation: Pl(1) + Bi + Qz + K-feld + Hbl to melt(1) + Pl(2) + Qz + Hbl + Opx. In this reaction, accessory minerals may not be involved due to their small solubility such low temperature. When the source region become hotter, then the reaction advance further. Above equation will change to following one: Pl(2) + Qz + Hbl + Opx + Mt to melt(2) + Pl(3) + Cpx + Opx + Mt Incompatible elements may increase in the melt due to breaking down of hornblende and dissolving accessory minerals in more higher condition, both minerals have high distribution coefficients for HFSE. Geochemical characteristics of essential fragments from Ata caldera arranged in the volcano stratigraphic sequences can be explained reasonably by dehydration melting process in the source region than fractionation and contamination in the magma chamber.

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The Shevlin Park Tuff, Central Oregon Cascade Range: Magmatic Processes Recorded in an Arc-Related Ash-Flow Tuff

Richard M Conrey¹ (509-332-6610;

conrey@mail.wsu.edu)

Julie Donnelly-Nolan²Edward M Taylor³Duane Champion²Thomas Bullen²¹Dept. of Geology, Washington State Univ., Pullman, WA 99164²USGS, 345 Middlefield Rd., Menlo Park, CA 94025³Dept. of Geoscience, Wilkinson Hall 102 Oregon State University, Corvallis, OR 97331

The circa 260 ka Shevlin Park Tuff is found throughout an area of some 400 square km west of the city of Bend, OR. The tuff is composed of several flow units, the lowest of which was mapped separately in the past as the Century Drive Tuff. We have found the Century Drive to be chemically and paleomagnetically similar to the Shevlin Park. The spatial distribution and pumice imbrication of the Shevlin Park suggest a source at an elevation near 2000 m on the Bend Highland 5-6 km east of Broken Top volcano. Deposition of the Shevlin Park may have been preceded by a Plinian airfall eruption, now mainly preserved in the Columbia Canal irrigation ditch, which is likely equivalent in the distal tephra record to the Summer Lake NN layer. Despite our extensive database of bulk pumice and glass geochemistry, we cannot corroborate an earlier correlation of the Shevlin Park with the Summer Lake JJ tephra.

The Shevlin Park Tuff is compositionally bimodal, with black pumice ranging from 55-62% silica, and commonly paler silicic pumice from 64-68%. Lower flow units appear to contain proportionally more silicic pumice and slightly more fractionated (lower MgO) mafic pumice. Mafic pumice is much more heterogeneous for a given silica percentage than silicic pumice, especially in P, Fe/Mg, and Sr. Both types of pumice are crystal-poor, and thus the bulk pumice and glass compositions are similar. Phenocrysts present in pumice include plagioclase (dominantly reversely zoned An₃₀₋₄₀, but ranging up to skeletal An₈₂), two pyroxenes (typically reversely zoned), olivine (Fo₇₁₋₇₆), magnetite, and ilmenite. The phenocryst assemblage and mineral chemistry of the Columbia Canal pumice are similar, with the exception of slightly more Fe-rich opx.

Mixing of mafic and silicic magma appears to be the dominant process in the generation of the wide compositional range within the Shevlin Park. A simple mixing model can account for most of the major and trace

element, and Sr isotopic variations. The wider range in Fe/Mg and Sr in the mafic pumices can be modeled with approximately 20% crystal fractionation, but variations in P, and in P/Zr ratio, cannot be explained by a fractionation model. The P variations suggest a three component mixing model of silicic magma and two mafic magmas, with the most fractionated mafic magma having the highest P and P/Zr. The latter magma may have resorbed apatite during its evolution to account for its higher P/Zr ratio.

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Textural and Compositional Zoning of Plagioclase Phenocrysts of the Current Eruption at Arenal Volcano, Costa Rica

Meghan Lunney¹ (503-274-4067; Meghanlunney@hotmail.com)

Martin J Streck¹

Micheal A Dungan²

Francois Bussy³

¹Portland State Univ., P.O. Box 751, Portland, OR 97207, United States

²Dept. of Mineralogy, Univ. of Geneva, Geneva, Switzerland

³Dept. of Mineralogy, Univ. of Lausanne, Lausanne, Switzerland

Since 1968, Arenal Volcano, Costa Rica has undergone 33 yrs of continuous eruption maintaining a basaltic andesite composition ranging from 54-55 wt.% SiO₂. Lavas are mostly phenocryst-rich (40%) dominated by plagioclase with lesser amounts of orthopyroxene, clinopyroxene, and titanomagnetite.

Plagioclase from 20 samples ranging in age from 1968-1996 was studied petrographically using Nomarski Differential Interference Contrast (NDIC) microscopy. Core-rim microprobe traverses collected compositional data every 3-4 μm for most of the 125 analyzed phenocrysts ranging from 90-3500 μm in size. Plagioclase of each lava sample display almost the same large variation in compositions (An₉₄-An₅₅) and textural styles.

The majority of phenocrysts are cored with mottled (patchy) or flat texture. Mottled cores are irregularly shaped ranging in An from 94-70, whereas flat cores are mainly euhedral with narrower An ranges (94-84 to 95-94). Zoning styles of overgrowth on plag cores include oscillatory zoning (straight, convolute or hieroglyphic), pitted zones (boxy cellular or spongy cellular) or remain unzoned appearing as a texturally homogeneous growth zone. Compositions of most overgrowths (excluding rim) are within An 85-65 and zoning can be normal to reverse. A minor amount of phenocrysts are oscillatory zoned from center to rim and are compositionally alike overgrowths of cored phenocrysts. Regardless of the crystal's interior, most phenocrysts have rims defined by one last growth zone (5-20 μm). This growth zone is texturally flat but compositionally strongly zoned displaying a drop in An content from 70-57, similar to compositions of microlites in the groundmass.

We favor continuous, sporadic, and rapid growth environments to produce homogenous zones, oscillatory zoning and boxy textures, respectively, whereas resorption conditions may create spongy textures. The large range of compositional and textural plag growth stratigraphies in single lava samples can only be the product of magma mixing which has juxtaposed various crystals as late as shortly before the last overgrowth crystallized during final ascent at the time of eruption.

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Micrometer scale ferric/ferrous zoning quantified by Synchrotron microXANES spectroscopy, of pyroxene phenocrysts in phonolitic eruptives from Plio-Pleistocene volcano, Satiman, Tanzanian

Jeremy S Delaney¹ (jsd@rci.rutgers.edu)

Godwin Mollen¹ (gmollen@eden.rutgers.edu)

Gail M Ashley¹ (gmashley@rci.rutgers.edu)

M Darby Dyar² (mddyar@amherst.edu)

S R Sutton³ (sutton@cars3.uchicago.edu)

¹Geological Sci., Rutgers Univ., Piscataway, NJ 08854, United States

²Mt Holyoke Coll., 50 College St, South Hadley, MA 01075, United States

³Geophys.Sci., Univ. Chicago, Chicago, IL 60637, United States

Phonolitic eruptives (1-3 Myr) from the volcano Satiman were collected during systematic studies of

sources of tuffs at Olduvai Gorge, Tanzania. Cpx phenocrysts from two lavas show dramatic oscillatory zoning. BSE imaging reveals at least 30 bands 1-150 μm wide showing compositional oscillations in the mantles of these grains. In one instance the core (15% area of grain) is En₁₈-20Fs₂₅Wo₄₂ with Ac_m8Jd₃ while the mantle (75% area) is En₈-10Fs₃₅Wo₄₂ with Jd₃-5Ac_m-7. An obvious break in zoning pattern occurs between core and mantle. A 10-30 μm discontinuous rim (10% area) surrounds the crystal. Titanite is present but no oxides occur as inclusions or in the matrix. Electron probe results suggest that the core has constant Fs₂₅ but increasing acmite (Ac_m8-14) toward the interface with the mantle where a 10% rise in Fs and a 8% drop in Ac_m component occurs. In situ Synchrotron microXANES (SmX) determination of ferric/ferrous on 15-20 μm areas in the core, mantle and rim indicate values of Fe³⁺/TotalFe = 30-35% in the core increasing to 45% at the core-mantle interface and a drop to 25-30% in the mantle. The rim is 60% ferric. Matrix cpx is 40-45%. As the cpx is very sodic, calculations of Ac_m and Fs give more usable ferric/ferrous values than typical e-probe data. Orientation effects contribute no scatter to SmX results as analyses are made at constant orientation.

Fe oxidation state changes within crystals are inconsistent with simple oxidation as the magma evolved. The growth of ferric-rich cpx inhibited formation of oxides so conventional oxybarometry is not usable. Other than the rim, the highest ferric is in the outer core of the cpx and suggest that the magma become oxidized during early growth. A major change in crystallization conditions is represented by the onset of very fine scale oscillations in the mantles that perhaps reflect many small-scale changes in a closed magma chamber (convective cycling?). Redox conditions were constant throughout this phase but oxidizing conditions became important again at the end of cpx growth, perhaps during the eruptive phase. The subdued oxidation state changes in the mantle despite the prominent compositional changes perhaps reflect constant oxygen content during magma evolution in a closed chamber, although decreasing fO₂ between the core and mantle growth stages of cpx is probable. Fine fO₂ variations in a Satiman magma chamber can be extracted from the ferric/ferrous measurements.

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Origin of Textural and Chemical Variations in a Small Mafic Intrusion by Multiple Injections of Magma and the Redistribution of Evolved Liquids

Craig M. White (1-208-426-3633; cwhite@boisestate.edu)

Boise State University, Geosciences Department, Boise, ID 83725, United States

The Graveyard Point intrusion is a small tholeiitic mafic complex consisting of one or more irregularly shaped but generally sheet-like intrusions and numerous smaller dikes exposed in an area of 7 km by 3 km adjacent to the Oregon-Idaho border. The complex is late Miocene in age and was emplaced during the early development of the western Snake River Plain. The dikes and thinner parts of the sill-like bodies are composed of relatively uniform olivine diabase; however, where the intrusion is greater than 100 m thick it is strikingly inhomogeneous and contains laterally extensive, generally subhorizontal zones of gabbroic cumulates, ophitic textured gabbro, pegmatoidal ferrogabbro and granophyre. Detailed mapping has shown that these zones are not uniformly parallel but instead tend to pinch out or have low-angle cross-cutting relations, indicating that liquids or mushes moved relative to one another as discrete packages. This conclusion is supported by bulk-rock analyses, which show small but distinct breaks or steps within the otherwise smooth, typically tholeiitic trends. In addition, microprobe analyses of the cores of plagioclase and clinopyroxene crystals in samples from measured sections show step-wise offsets rather than smooth variations when plotted versus stratigraphic height. By combining detailed mapping of rock textures with bulk-rock and mineral analyses, it is possible to attribute the lithologic variations in this intrusion to a combination of processes that include at least three injections of progressively more evolved magma followed by the formation and redistribution of water-rich granophyric liquids.

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Systematic Variation of Sr, Nd and Pb Isotopes with Time Observed in lavas of Mauritius Island

Susumu Nohda¹ (snohda@sci.kumamoto-u.ac.jp)

Ichiro Kaneoka² (kaneoka@eri.u-tokyo.ac.jp)

Takeshi Hanyu² (hanyu@eri.u-tokyo.ac.jp)

Kozo Uto³ (uto@gsgj.go.jp)

¹Department of Environmental Sciences, Kumamoto University, Kurokami 2-39-1, Kumamoto 860-8555, Japan

²Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Yayoi 1-1-1, Tokyo 113-0032, Japan

³Geological Survey of Japan, Higashi 1-1-3, Tsukuba 305-8567, Japan

The active volcanism of the Reunion mantle plume began with the emission of huge volumes of flood basalts of the Deccan Traps at the end of Cretaceous. Subsequent products from this hotspot can be traced on the seafloor of the Indian Ocean. We report Sr, Nd and Pb isotopic compositions for the rocks of Mauritius Island which is the second youngest Island by the Reunion hotspot activity. The lavas of the older series (8 - 5.5 Ma) seems to be directly related to the hotspot, and showed the limited range of Sr isotopic composition from 0.70411 to 0.70422, which is consistent with those of Reunion Island (2Ma - present). Via Intermediate series volcanism (3.5 to 2.0 Ma), the Younger stage lavas (0.7 to 0.2 Ma) show slightly depleted isotopic signatures. Systematic variations of these isotopes with time can be attributed to the change in the structure or composition of the mantle from the less depleted to the more depleted, more MORB-like signature. The present variations are correlated with those of Hawaii and French Polynesia, but the trace elements distributions are not identical with them.

V32D-0999 1330h POSTER

Isotopic Constraints (U, Th, Pb, Sr, Ar) on the Timing of Magma Generation, Storage and Eruption of a Late-Pleistocene Subvolcanic Granite, Alid Volcanic Center, Eritrea

J. B. Lowenstern¹ (650-329-5238;

jlownstrn@usgs.gov); B. L.A. Charlier²; J. L.

Wooden¹; M. A. Lanphere¹; M. A. Clyne¹; T.

D. Bullen¹

¹U.S. Geological Survey, 345 Middlefield Road, MS 910, Menlo Park, CA 94025, United States

²University of Durham, Dept. Geological Sciences South Rd., Durham DH1 3LE, United Kingdom

Isotopic analyses demonstrate that a shallow granophyric intrusion from the Alid volcanic center (AVC) was generated, intruded and crystallized over a 20,000-year period in the latest Pleistocene. The granophyre is not exposed, but was ejected as unmelted blocks within a ~1 km³ pyroclastic flow deposit around 15 ka and is a subvolcanic equivalent of the erupted rhyolitic pumice (Lowenstern et al., 1997; J Petrol 12, p. 1707-1721). The rock contains <~ 1-mm-sized phenocrysts of Nansandine, quartz, ferroaugite, Fe-rich biotite (replacing pyroxene), and magnetite. Accessory phases include zircon, apatite, pyrrhotite, fluorite and rare chevkinite. The groundmass is a micrographic intergrowth of Nansandine and quartz.

We interpret the silicic magma to have intruded subsequent to eruption of a basaltic lava flow at 36 ± 9 ka (Ar-Ar age); the lava was strongly tilted by structural doming associated with the intrusion. The granophyre was completely crystallized by the time of the final pyroclastic flow eruption that brought the intrusive blocks to the surface. From the pumice in this deposit, the weighted mean Ar-Ar age of two splits of Nansandine (density > 2.59) is 15.2 ± 5.8 ka (all errors are 2 σ). Two other splits with lower density (thus higher in Na) yielded ages older than 24 ka, and may retain some excess Ar. Thus, the time between intrusion and complete crystallization for the granophyre was <~20,000 years.

The ⁸⁷Sr/⁸⁶Sr ratio (0.7047) of the granophyre is similar to those of basalts erupted from the AVC and far less radiogenic than most basement granites and schists that form escarpments bordering the Danakil Depression and are found as unmelted lithic xenoliths in lavas and tuffs of the AVC. Pb isotopes also rule out significant assimilation of Precambrian basement during genesis of the young granophyre. Similarly zircon grains, analyzed with the Stanford-USGS SHRIMP-RG, show little evidence for inheritance, with only a single 760 Ma zircon (U-Pb age) that was also petrographically different from the 130 other zircons in the mount. The other zircons yielded SHRIMP ²³⁸U/²³⁰Th disequilibrium ages of < 65 ka, with no discernible difference between ages of cores and rims. The weighted mean ²³⁸U/²³⁰Th age of 23 analyzed zircons is 24.7 ± 3.3 ka.

The whole-rock U-Th isotopic values of the granophyre, by TIMS, show extreme enrichment of ²³⁰Th (²³⁰Th/²³²Th = 1.064; [²³⁸U/²³²Th] = 0.602; Th/U = 5.04). On an activity ratio diagram, the whole-rock value is essentially colinear with clinopyroxene, Nansandine, apatite and magnetite separates, forming an apparent isochron of 21.5 ± 2.4 ka, similar to the zircon data (both SHRIMP and multiple-grain TIMS). The ferroaugite separate is more Th-enriched than the whole-rock, probably due to rare chevkinite inclusions.

Isotopic and trace-element data indicate melt generation by partial melting of Quaternary mafic rocks, accompanied by minor (< 5%) assimilation of older basement. All mineral phases in the granophyre appear to

have precipitated from the melt between about 36 and 15 ka, after intrusion into the shallow crust.

URL: <http://wrgis.wr.usgs.gov/docs/geologic/jlwnstrn/alid/Alidpage.html>

V32D-1000 1330h POSTER

The Complex Geochemistry of Magma Bodies Undergoing Open-System Processes: Energy-Constrained Recharge, Assimilation and Fractional Crystallization (EC-RAFC)

Wendy A. Bohron¹ (509-963-2835; bohron@geology.cwu.edu)

Frank J. Spera² (805-893-4880; spera@magma.geol.ucsb.edu)

¹Dept of Geological Sciences, Central Washington University, Ellensburg, WA 98926, United States

²Dept of Geological Sciences, UCSB, Santa Barbara, CA 93106, United States

A new version of the energy-constrained simulator tracks the thermal and geochemical evolution of a magma body undergoing the processes of magma recharge, assimilation, and fractional crystallization (EC-RAFC). The conceptual framework is presented in a companion abstract (Spera and Bohron, this issue). The EC-RAFC model tracks trace element and isotopic trends of a magma body (melt + solids) undergoing fractional crystallization and continuous or episodic magma recharge; assimilation may or may not occur. EC-RAFC yields complex, distinctly non-monotonic element-element and element-isotope trends that are a consequence of the nonlinear, coupled nature of the processes that influence the system. Among the plethora of petrologic problems that can be investigated with this simulator are the geochemical distinctions that arise when a magma body undergoes continuous vs. episodic recharge, the connection between erupted magmas and associated cumulate bodies, the geochemical fingerprints of mafic enclaves that form as a consequence of mafic recharge into a more silicic magma body, and the conditions under which magmatic systems reach chemical "steady-state." All of these have important, well-documented analogues in nature and thus, the ability to predict associated geochemical signatures affords the opportunity to begin to discriminate among the many physicochemical and tectonomagmatic models involving complex magmatic systems. Investigation of the effects of continuous vs. episodic recharge for an initially mafic magma undergoing assimilation and recharge in the lower crust indicates that the resulting geochemical trends for melt and solids are highly sensitive to the style of recharge. Geochemical differences in systems experiencing episodic vs. continuous recharge can be well outside analytical uncertainty, suggesting that EC-RAFC represents a tool that can directly link volcanological and geochemical models of magmatic systems. EC-RAFC also predicts complex geochemical trends among cumulates that form as crystallization products of a magma body and enclaves (chilled recharge magma) that form as recharge magma is injected into a magma body. This window into the composition of solids associated with open-system magma bodies allows assessment of the relationships between, for example, layered mafic intrusions and flood basalts, and mafic enclaves and their intermediate-composition volcanic or plutonic hosts. A commonly postulated scenario regarding magmatic systems that appear to erupt relatively homogeneous composition magma over time involves magma recharge as the agent to maintain this geochemical "steady-state." The EC-RAFC simulator allows specific scenarios to be investigated that can be used to assess the conditions that lead to geochemical homogeneity. Preliminary results indicate that very specific combinations of bulk Ds and element concentrations are required to achieve compositional "steady state" during an RAFC or RFC event. In summary, EC-RAFC provides a method to quantitatively investigate complex magmatic systems in a thermodynamic context; it predicts complex, non-monotonic geochemical trends for which there are analogues in nature and that previously have been difficult to model; and finally, EC-RAFC establishes an essential link between the chemical and physical dimensions of a magmatic system.

V32D-1001 1330h POSTER

Magma Chamber Processes Within Kilauea Volcano, Hawaii Based on Petrology of Recent Summit Lavas

Michael O. Garcia¹ (808-988-2653; garcia@soest.hawaii.edu)

A. J. Pietruszka² (202-478-8476; pietrus@dtm.ciw.edu)

J. M. Rhodes³ (413-545-2841; jmrhodes@geo.umass.edu)

¹Geology-Geophysics Dept, Univ. of Hawaii, Honolulu, HI 96822

²D.T.M., Carnegie Inst. of Washington, DC 20015

³Geosciences Dept., Univ. of Massachusetts, Amherst, MA 01003

Time series analyses of petrologic and geochemical parameters are effective in delineating magmatic processes of active volcanoes. The frequent eruptions of Kilauea Volcano make it an excellent candidate for such an analysis. No systematic study has been previously undertaken of the historic lavas from this classic volcano. We assembled a comprehensive suite of lavas and tephra ranging from 15th century phreatomagmatic explosions to the 1982 effusive eruptions to document magmatic processes within Kilauea's summit magma reservoir. Detailed petrographic, and glass, mineral and whole-rock geochemical data for these rocks indicate that crystal fractionation is the dominant process over short time scales (months to years). This signature is superimposed on a large (e.g., 45% change in K) and progressive, longer term change (decades) in lava chemistry that preceded and followed Kilauea's 1924 summit collapse. These systematic trends indicate rapid changes in the parental magma composition delivered to Kilauea and that the summit reservoir is a single, well-mixed body. Assimilation is also an important magma chamber process but mainly effects only oxygen isotope ratios because Kilauea lavas are assimilated. Most lavas from historical intracaldera eruptions are weakly olivine-phyric in contrast to extracaldera and prehistorical summit eruptions. These differences point to the formation of a crown of crystal-poor magma in the summit reservoir during the last few thousand years due to the continuous settling of entrained olivine.

V32D-1002 1330h POSTER

Two-Stage AFC-FC Model for the Evolution of Large-Volume Rhyolitic Ignimbrites (LRIs).

Lisa Hammersley¹ (510 643 4466; leela@uclink4.berkeley.edu)

Donald J DePaolo¹ (510 642 5063; depaolo@socrates.berkeley.edu)

¹University of California, Berkeley, Center for Isotope Geochemistry 307 McCone Hall, Berkeley, CA 94720-4767, United States

Questions concerning the generation of large-volume rhyolitic ignimbrites (LRIs) involve the relative roles of fractional crystallization (FC), crustal assimilation (A) and magma source. Major and trace element data, combined with petrologic observations can be used to assess the role of melting and the order and extent of fractional crystallization. Isotopic data can be used to evaluate the role of magma source versus crustal assimilation. Many LRIs (e.g. Mount Taylor, NM; Long Valley, CA; Chalupas, Ecuador) show evidence for multiple stages of evolution within the crust with the amount of assimilation varying as magma evolves from basalt to rhyolite.

We evaluate the processes involved using new data from the Clear Lake, CA, and Chalupas, Ecuador, volcanic suites. A key observation is that isotopic variability occurs only in lavas with < 57% SiO₂, with very little difference in the Nd or Sr isotopes apparent in lavas with greater than 57% SiO₂. Hence, compositions ranging from andesite through rhyolite can all be traced to the same magma source and parental magma composition. We have modeled the evolution of these magmatic systems with a two-stage finite difference model that accounts for major and trace elements as well as isotopes. The fractionating mineral assemblage is determined by petrographic observations and varies as the magma evolves. Distribution coefficients depend on the fractionating assemblage and the SiO₂ content of the magma. During Stage I, primitive basaltic magma originating from below the lithosphere evolves to andesite through AFC in the lower crust. Stage I occurs either in small magma chambers or in dikes; assimilation is allowed by the high wall rock temperatures. Once the magma reaches approximately 57% SiO₂ it continues its ascent through the crust and is either erupted as andesite or goes to Stage II evolution in a shallow magma chamber. During stage II, wall rock temperatures are too low to allow for crustal assimilation and crystallization is fast hence andesite evolves to rhyolite through FC. What physical process (eg. sidewall crystallization) is responsible for the FC stage is not constrained. What limits Stage I to magma with less than 56-59% SiO₂ is also unclear (density, viscosity?), but assimilation is required by the large shifts in Nd isotopes observed in some systems (with the caveat that some of this shift may occur in the mantle lithosphere).

V32D-1003 1330h POSTER

On the Volume and Depth of the Magma Chamber of El Chichon Volcano, Chiapas, Mexico

JUAN-MANUEL ESPINDOLA¹ (52-5-622-4124; jmec@servidor.unam.mx)

ZENON JIMENEZ¹ (52-5-622-4138; zenon@ollin.igeofcu.unam.mx)

JOSE LUIS MACIAS¹ (52-5-622-4124; macias@tonatiuh.igeofcu.unam.mx)

JUAN CARLOS MORA¹ (52-5-622-4119; jcmora@tonatiuh.igeofcu.unam.mx)

¹INSTITUTO DE GEOFISICA UNAM, AV. UNIVERSIDAD 3000 COL. COPILCO, MEXICO, DF 04510, Mexico

Jimenez et al (1999) suggested that a zone of seismic quiescence found in the seismicity preceding the 1982 eruption of El Chichon Volcano (Chiapas, Mexico) was the location of the volcano's magma chamber. The zone is located at depths between 8 and 14km below the summit and its length is also of about 6km. However, due to the poor coverage of the registering network these results were doubtful. In this work we present other evidences that strengthen such assumption. Following Wiemer and Benoit (1996) we obtained b-values as a function of depth for all events occurring one month after the eruption. B-values oscillate between 0.8 and 1.0 except at depths of about 13km where they were higher.

We also used the model of mass erupted of Bower and Woods (1997) for a magma chamber of spherical shape located 8km below the surface and a radius of 3 Km. Using the parameters estimated in the literature for that eruption (such as water and crystal content) we obtained a total mass erupted of the order of 2.0E+12 Kg, in accordance with the estimated mass of the deposits.

Luhr et al, (1990) estimated the depth of equilibration of the magmatic liquid at a pressure of 2kbar or a lithostatic depth of about 8km. Analysis of aluminum content in hornblende (hornblende geobarometer) from samples of the plinian fall deposit of an eruption occurring some 550 years ago indicates a formation pressure of about 4 Kbar (or around 16km in depth) a depth roughly double than that found for the 1982 eruption. These facts suggest that after the eruption of 550 years ago the magma chamber equilibrated at a position a few kilometers upward from its former location, or the existence of a deeper chamber.

Bower SM, AW Woods, J Geophys Res 102, NO. B5, 10273-10290, 1997

Jimenez Z, VH Espindola, JM Espindola, Bull Volcanol 61: 411-422, 1999

Luhr JF, J. Petrol. 31,5,1072-1114, 1990

Wiemer S, JP Benoit, Geophys Res Let 23, 1557-1560,1996

V32D-1004 1330h POSTER

Open-System Magmatic Processes: Energy-Constrained Recharge, Assimilation and Fractional Crystallization (EC-RAFC)

Frank J. Spera¹ (805-893-4880; spera@magma.geol.ucsb.edu)

Wendy A. Bohron² (509-963-2835; bohron@geology.cwu.edu)

¹Department of Geological Sciences, UCSB, Santa Barbara, CA 93106, United States

²Department of Geological Sciences, Central Washington University, Ellensburg, WA 98926, United States

Geochemical data for igneous rocks provide conclusive evidence for the occurrence of open-system processes within magma bodies, the most critical of which are magma recharge (including enclave formation), assimilation of anatectic melt, and formation of cumulates by fractional crystallization. We have previously derived a model that tracks the composition of a magma body undergoing AFC; explicit in this model is accounting of country rock heating and the compositional effects of partial melting. The EC-AFC algorithm is based on solution of a system of differential equations that express conservation of energy (enthalpy), mass and species (trace elements and isotope ratios) (Spera and Bohron 2001, Bohron and Spera 2001). Here EC-AFC is extended to incorporate the effects of enthalpy, matter and species transport during magma recharge; this model, EC-RAFC, tracks the trace element and isotopic composition of melt, enclaves and cumulates as thermal equilibration is approached. EC-RAFC is formulated as a set of 3+t+i+s coupled nonlinear ordinary differential equations, where the number of trace elements, radiogenic and stable isotope ratios simultaneously modeled are t, i, and s, respectively. Solution of the EC-RAFC equations provides values for the average temperature of wallrock, mass of melt within the magma body, mass of cumulates and enclaves, mass of wall rock, mass of anatectic melt assimilated, concentration of t trace elements and i+s isotopic ratios in standing melt, cumulates, enclaves and anatectic melt as a function of the local temperature of standing magma. Input parameters include equilibration temperature, initial temperature and composition of magma, recharge magma, and wallrock, distribution coefficients, heat of fusion of wallrock and heats of crystallization of pristine and

recharge magma, and isobaric specific heat capacities of all constituents. The magma recharge mass function is specified a priori and defines how recharge magma is added to standing magma (e.g., episodically, continuously). The present EC-RAFC simulator incorporates a weak coupling to major element mass balance and phase relations by means of a set of melt productivity functions based on laboratory experiments or Gibbs Energy minimization simulations (e.g., MELTS, Ghiorso 1997). Melt productivity functions prescribe the relationship between melt mass fraction and temperature. The EC-RAFC model, although a simplification of complex natural systems, is the first to examine systems characterized by magma recharge in a manner that self-consistently conserves energy, mass, and species. EC-RAFC not only provides an essential link between the physical and chemical controls governing complex open-system magma chambers, but also predicts complex geochemical behaviors that have analogues in natural magmatic systems; a number of these are examined in a companion abstract (Bohrson and Spera, this issue).

V32D-1005 1330h POSTER

Thermodynamic Consideration of Post-Entrapment Crystallization in Igneous Phenocrysts

Victor C Kress¹ (206-616-8512; kress@u.washington.edu)

Mark S Ghiorso¹ (206-685-2482; ghiorso@u.washington.edu)

¹Earth and Space Sciences, University of Washington, Seattle, WA 98195

The proliferation and refinement of micro-beam analytical techniques has revolutionized the use of melt inclusion chemistry as a window into pre-eruptive conditions in igneous environments. Several well recognized processes can obscure or destroy information originally contained in the inclusion. Among these processes is post-entrapment crystallization (PEC). One successful approach to the problem of looking through the effects of PEC has been to incrementally add estimated equilibrium host phase to the inclusion until the melt is in equilibrium with the bulk host composition.

PEC is not an isobaric process. This is due both to the higher thermal expansivity of melts relative to solids and to the fact that silicates have negative volumes of crystallization. To the extent to which the thermal expansion of solid can be neglected, PEC can be considered an isochoric process. PEC is not purely isochoric, however, as the thermal expansivity of the host phase is not zero. The effect of crystallization on pressure is about three times that of host thermal expansion, though this depends on the composition considered.

Phase relations based on isothermal-isobaric equilibrium are of limited applicability in estimating equilibrium during PEC, and thus in backing out pre-entrapment conditions. Simple heating experiments on melt inclusions in-situ can be used to restore pre-entrapment conditions, however, it is not possible to measure pressure or composition during the experiment lessening the usefulness of this approach. The only viable way to explore PEC in detail is through thermodynamic calculation.

Using thermodynamic models from the MELTS package we explore relative contributions and effects of each aspect of PEC. Cooling of an alkali olivine basalt inclusion 100° below the liquidus at 2 kbar results in crystallization of 8 wt% olivine and a pressure drop of 1.2 kbar. Cooling the same inclusion isobarically over the same temperature interval results in crystallization of 8 wt% olivine and 10 wt% cpx. The pressure drop accompanying cooling suppresses cpx crystallization in the semi-isochoric case. Relative oxygen fugacity changes accompanying PEC is variable, ranging from near zero in the alkali olivine basalt case to nearly a log unit in an olivine tholeiite.

The approach described above can be reversed to calculate pre-entrapment conditions from input melt composition and bulk host-phase composition. This method is used to refine conditions of mixed magmas from recent Popocatepetl eruptions.

V32D-1006 1330h POSTER

Sourcing Phenocrysts in Zoned Eruption Sequences Using Trace Elements: the Diego Hernandez Formation, Tenerife, Canary Islands

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

Else-Ragnhild Neumann²
(e.r.neumann@geologi.uio.no)

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

²Department of Geology, University of Oslo, P.O. Box 1047 Blindern, N-0316 Oslo, Norway

The Diego Hernandez Formation (DHF) consists of several plinian fallout and ignimbrite sequences. With

few exceptions, the dominant volume of each eruptive package consists of compositionally variable phonolite with smaller amounts of basaltic and intermediate components. In addition to mixing with the mafic components, compositional variations among the phonolitic component are due to crystal-liquid separation corresponding to up to 60% crystallization of a phonolitic starting liquid. Spene crystallization plays a dominant role in controlling abundances of REE and HFSE among Tenerife phonolites. Spene preferentially sequesters MREE, leading to strongly parabolic REE patterns among residual liquids. We have used this feature of the zoned Tenerife phonolites to match the REE content of individual pyroxene crystals, analyzed by laser ablation ICP-MS, to observed liquids using the elastic strain mineral-melt partitioning model of Blundy and Wood [1]. The strongly parabolic REE patterns of the liquids allow matching solely using the calculated Youngs modulus of the host M2 cation site in pyroxene, without any independent constraint on the strain-free partition coefficient D_0 . For sodian salite pyroxenes in the phonolites, we find that most did not grow from the host liquid represented by the pumice clasts in which the crystals were erupted. Instead, most grew from liquids significantly more evolved, with lower MREE/LREE and MREE/HREE than the observed host. Elevated Zr contents in the salites support this conclusion, although the Zr abundances cannot be modelled with the same degree of confidence as the REE. The required liquids correspond to both the most-evolved phonolite compositions observed within the DHF, and to cognate syenite fragments found in the ignimbrites. Sodian salite also occurs as cores to titanite grains that grew from the basaltic component. These observations are consistent with a model in which invading basaltic magma melts syenite, and/or stagnant syenitic crystal mush with highly evolved interstitial liquid, to produce phonolite-dominated mixed magma.

[1] Blundy and Wood (1994) Nature 372, 452-454.

V32D-1007 1330h POSTER

The Control of Britholite, Chevkinite, and Allanite on Trace Element Behavior in High-Silica Rhyolites: Banelier Tuff, New Mexico

Roger Lee Winters¹ (509-335-5987; rwinters@wsu.edu)

Scott B. Cornelius¹ (cornelius@wsu.edu)

John A. Wolff¹ (jawloff@mail.wsu.edu)

Steve Self² (stephen.self@open.ac.uk)

¹Department of Geology, Washington State University, Pullman, WA 99163, United States

²Department of Earth Sciences, The Open University, Milton Keynes MK7 6AA, United Kingdom

The Otowi (lower) Member of the Banelier Tuff erupted from the Valles Caldera, NM, at 1.61 Ma. The Otowi consists of 350 km³ DRE of high-silica rhyolitic pumice deposited as plinian fallout units and ignimbrites. After deposition of an initial plinian fallout unit (unit a), eruption of fallout and pyroclastic flows was simultaneous, and the entire compositional range seen in the ignimbrite is duplicated in the fallout. Quartz and sanidine phenocryst contents in pumice range from less than 5 percent up to 20 percent. Minor and trace phases include magnetite, hedenbergite, fayalite, zircon, allanite, chevkinite and britholite. Fayalite is confined to unit a. The REE-Ti silicate mineral chevkinite, and britholite, a REE-rich silicophosphate of the apatite group, occur as inclusions in fayalite, hedenbergite and magnetite. Relative to whole pumice, allanite and chevkinite have high LREE/MREE, while britholite is enriched in MREE. Otowi britholites represent an extreme example of REE substitution into apatite via the mechanism REE+Si = Ca+P, with a temperature dependence consistent with the experimental results of Watson and Green (1981).

Whole-pumice trace element behavior is consistent with separation of the observed phenocryst and trace phase assemblage from rhyolitic liquid. Cs, Rb, Th, U, Nb, Ta and heavy REE behave incompatibly throughout the system. REE show decreasing compatibility with increasing atomic number (a well known effect in high-silica rhyolites), ascribed to the very high mineral/melt distribution coefficients for LREE in chevkinite and allanite. Plots of Otowi MREE vs. incompatible elements show an inflection among the most fractionated compositions. This inflection coincides with the point at which britholite joins the fractionating assemblage; hence britholite represents a new addition to the list of trace phases that control REE abundances in strongly differentiated magmas.

V32D-1008 1330h POSTER

Dissolved Volatiles in Melt Inclusions, Banelier Tuff, New Mexico

Pamela Hartman¹ (509 335 1288; phartman@mail.wsu.edu)

John A. Wolff¹ (jawloff@mail.wsu.edu)

R. Lee Winters¹ (rwinters@wsu.edu)

Stephen Self² (stephen.self@open.ac.uk)

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

²Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, United Kingdom

The Otowi (lower) Member of the Banelier Tuff consists of approximately 350 km³ DRE of high-silica rhyolite magma that erupted from the Valles caldera at 1.61 Ma. The eruption began with an initial weak plinian phase that deposited a single, narrowly dispersed fallout. Thereafter, fallout and pyroclastic flow-producing activity are inferred to have been simultaneous, based on similarity of compositional range within both fall and flow. We have made FTIR determinations of dissolved water and carbon dioxide concentrations in glass inclusions hosted within bipyramidal quartz phenocrysts from the fallout. Quartz crystals with de-ventilated inclusions, hourglass inclusions, or inclusions located along a crack within the crystal were eliminated from the sample set. Dissolved water contents are highly variable, in agreement with the earlier ion probe results of Dunbar and Hervig [1]. Water and carbon dioxide contents are consistent with vapor saturation at pressures between 500 and 1500 bars. The upper value agrees with estimates for the minimum depth to the sub-Valles magma chamber [2], while the lower value suggests entrapment of inclusions at depths of less than 2 km. This is consistent with a model for the Otowi magma based on Sr isotope ratios of trapped glasses [3], which invokes late growth of quartz phenocrysts contemporaneously with minor assimilation of stoped granitic blocks, as the magma began its journey to the surface prior to eruption. We envisage that gas-saturated magma formed an intrusion above the main chamber, occupying space made by stoping. Crystallization of quartz over a range of pressures, resulting in entrapment of inclusions having a range of volatile contents, may itself have been forced by degassing. These events may have been accompanied by the development of a vapor cap over the magma, creating favorable conditions for caldera collapse.

[1] N.W. Dunbar and R.L. Hervig, 1992, JGR 97, 15,151-15,170; [2] D.L. Nielson and J.B. Hulen, 1984, JGR 89, 8695-8711; [3] Wolff et al., 2000, GSA abs. w. Progs. 32/7, A147.

V32D-1009 1330h POSTER

Petrological and Geochemical Evolution, during the last 40,000 years of the Tacaná Volcano Chiapas, Mexico

Juan Carlos Mora¹ (52-56224119; jcmora@tonatiuh.igeofcu.unam.mx); Jose Luis Macias¹; Armando Garcia-palomos²; Juan Manuel Espindola¹; Piero Manetti³; Orlando Vaselli³

¹Instituto de Geofisica, UNAM, Circuito Universitario, UNAM, Mexico D.F. 04510, Mexico

²Instituto de Geologia, Circuito Universitario, Unam, Mexico D.F. 04510, Mexico

³Dipartimento di Scienze della Terra, Universita di Firenze, Giorgio La Pira 5, Florence, Italy

The Tacaná Volcanic Complex (TVC) is located in SW Chiapas, Mexico. Its highest peak constitutes a marker of the international border with Guatemala. Fieldwork aided by photo interpretation has allowed us to recognize three different volcanic centers at the TVC: Chichuj (EVCh; 3,800 masl.), Tacan, which gives name to the complex (EVT; 4,060 masl.), and San Antonio (EVSA; 3,700 masl.). The volcanic deposits from these three centers consist mainly of block-and-ash flows, lavas, and summit domes. In this work we analyzed selected samples of lava flows, lava domes, and juvenile clasts from the most recent pyroclastic flows. The lava flows and the domes have andesitic-dacitic composition, and the juvenile clasts are andesitic. Basaltic andesite enclaves found in the 2000 yr BP Mixcun pyroclastic flow are the most basic of all analyzed products in the CVT (andesitic basalt). All the products are porphyritic with phenocrysts of plagioclase, orthopyroxene and clinopyroxene, and amphibole.

Using two pyroxenes and ilmenite-titanomagnetite geothermometers, we estimated the temperature of crystallization, which varies between 910° and 950°C. The geochemical data (majors elements, trace elements and isotopes) shows that crystal fractionation was the principal process of evolution, with a small assimilation of granitic crustal rocks.

V32D-1010 1330h POSTER

Origin of chemical variation of the magmas formed Aso caldera

Masahiro YASUHARA¹ (+81-963430638; yasuhara@es.sci.kumamoto-u.ac.jp)

Hisayoshi YOKOSE¹ (+81-963423414; yokose@aster.sci.kumamoto-u.ac.jp)

¹Dept. Earth Sci. Kumamoto University, 2-39-1 Kurokami, Kumamoto 8608555, Japan

Aso caldera has been considered to form by four large scale pyroclastic flow eruptions, Aso 1-4, small scale Plinian eruption, Aso 2/1-4/3, and lavas. The volcanic rocks consist basalt, trachyte, dacite and rhyolite. These volcanic rocks are characterized by high alkaline contents compared with volcanic rocks occur on the volcanic front elsewhere.

There are many evidences that geochemical characteristics of Aso caldera can not be able to explain cooling process in single magma chamber (Yasuhara and Yokose, 1998, 1999): (1) LILE-HFSE have a positive correlations, (2) incompatible elements (K, Y, Zr, Nb and REE) / SiO₂ ratios decrease through eruption cycles, (3) incompatible trace element abundances pattern on spider diagram does not similar to island arc signature, (4) chemical variations cannot indicate as a single trend, (5) volcanic glass in essential fragments does not change through eruption cycles and have a similar composition systematically, (6) there are geochemical differences between pumice from pyroclastic flow deposits and fall deposits. These chemical variations in the magmas of Aso caldera can not be explained by AFC or magma mixing models.

In order to understand the contribution of fluids on magma genesis, we have analyzed on chlorine and sulfur contents in the pumices. Chlorine contents indicates positive correlation with SiO₂ and LILE, and negative correlation with Sr. This positive correlations imply that increasing of volatile elements in a melt correspond to increasing with degree of melting. The negative correlation may be linked with stability of plagioclase. The ratios of HFSE / Cl have wide variation and become small to the order of lava, scoria, pyroclastic fall deposit and pyroclastic flow deposits. As eruption cycle becomes new, the ratio decrease gradually. It suggests that volatile components represented by Cl may control the degree of melting and abundance of incompatible elements.

Based on the above observations, geochemical variation in volcanic rocks from Aso caldera is not created in the magma chamber, but in the source region by progressive dehydration melting. It is conceivable that there were few volatile components in the partial melting at the early stage of eruption cycles, and the volatile component increased in the partial melting at the late stage of eruption cycles. Concentrations of the volatile elements play an important role in the reaction.

V32D-1011 1330h POSTER

Miocene to Holocene Magmatism in the Eastern Trans-Mexican Volcanic Belt (Palma Sola, Mexico): Mantle Sources, Slab Contributions and Crustal Contamination

Arturo Gómez-Tuena¹ (tuena@servidor.unam.mx)

Alexandra LaGatta² (lagatta@ldeo.columbia.edu)

Charles H Langmuir² (langmuir@ldeo.columbia.edu)

Fernando Ortega-Gutiérrez¹ (fortega@servidor.unam.mx)

Steven L Goldstein² (steveg@ldeo.columbia.edu)

¹Instituto de Geología, UNAM, Cd. Universitaria, Mexico, DF 04510, Mexico

²Lamont Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10964, United States

The Miocene to Holocene stratigraphic record of the Easternmost part of the Transmexican Volcanic Belt can be divided into 3 main groups in terms of its stratigraphic, geologic and geochemical characteristics: Middle-Late Miocene plutons, Late Miocene-Pliocene plateau basalts and Pleistocene-Holocene cinder cones. The plutonic rocks and cinder cones are calc-alkaline and have trace element patterns compatible with a subduction environment (Ba/Nb=16-101 and Pb/Ce=0.07-0.25). In contrast, the plateau basalts are alkaline and have either moderate or negligible subduction contributions (Ba/Nb=6-31 and Pb/Ce=0.04-0.1). Sr, Nd and Pb isotopic compositions of the plutons and plateau basalts do not correlate with indices of differentiation indicating a negligible role of crustal contamination in their petrogenesis. In contrast, isotopic enrichment in the cinder cones correlates with SiO₂ and MgO contents, implying contamination with the local continental crust. The alkaline rocks have higher Nb concentrations (22-58 ppm) and lower Zr/Nb ratios (9.7-5.5) than pacific MORB, suggesting that the oceanic mantle wedge is significantly enriched. The

plateau basalts have very radiogenic ²⁰⁶Pb/²⁰⁴Pb ratios (up to 18.963), and form an array in ²⁰⁶Pb/²⁰⁴Pb - ²⁰⁷Pb/²⁰⁴Pb space that trends towards the composition of the bulk subducted sediment. These radiogenic Pb isotopes are inversely correlated with Ba/Nb, Th/Nb and Pb/Nb ratios, reflective of the subduction component. Isotopic and trace element-ratio systematics in the plateau basalts require the addition of a subduction component with high Th/Nd and low ¹⁴³Nd/¹⁴⁴Nd, a component consistent with a sediment melt. This component also has lower Pb/Nd and Sr/Nd ratios than the bulk subducted sediment, suggesting that a significant proportion of the fluid mobile elements may have been lost to a fluid phase prior to melting. The geochemical data of the plateau basalts can be modeled by adding less than 4% of a dehydrated sediment melt into the enriched mantle wedge. The Pb isotopes of the plutonic rocks follow a different trend than the plateau basalts, they are bracketed by the subducted sediments and the Pacific MORB. The distinct Pb isotopic composition of the plutonic rocks thus require the participation of an unradiogenic component in addition to the sediments. High La/Yb (46) and Sr/Y (53) ratios in the least radiogenic and evolved plutonic sample (SiO₂=56.8%) might indicate the participation of melts coming from the subducted MORB.

V32D-1012 1330h POSTER

Hybrid Enclaves in Arc Plutons: A Possible Link Between Plutonic Processes and Eruption

Darren G. Chertkoff¹ (907-474-6171; ftdgc@uaf.edu)

Robert A. Wiebe² (717-291-3820; R.Wiebe@Acad.FandM.edu)

Jessica F. Larsen¹ (907-474-7992; faust@gi.alaska.edu)

John C. Eichelberger¹ (907-474-5530; eich@gi.alaska.edu)

Paul W. Layer¹ (907-474-5514; player@gi.alaska.edu)

¹Geophysical Institute & Department of Geology and Geophysics, University of Alaska Fairbanks, Fairbanks, AK 99775, United States

²Department of Earth Sciences, Franklin and Marshall College, Lancaster, PA 17604, United States

It has been well documented that magma mixing plays an important role in the petrogenesis of both arc volcanic and plutonic systems. Plutons and analogous volcanic rocks often contain the same straightforward evidence for magma mixing, in the form of magmatic enclaves, preservation of disequilibrium phase assemblages, and dramatic compositional zoning of phenocrysts. Yet, despite the abundant and similar evidence of magma mixing in both volcanic and plutonic systems, relatively little work has been done to understand the linkage between these two igneous regimes. In order to elucidate the relationship between arc volcanism and plutonism, the authors have conducted a study of the associated Captains Bay pluton and Unalaska formation volcanics from Unalaska Island, Alaska. Previous K-Ar dating of the presumably pencontemporaneous Shaler pluton suggests that intrusion of the plutons on Unalaska occurred at approximately 11.1 Ma (Marlow et al., 1973). Ar³⁹-Ar⁴⁰ dating of the Unalaska formation by the authors indicates the volcanics to be of similar age (9.8 ± 0.6 Ma). Additional Ar³⁹-Ar⁴⁰ dating of mineral separates from the Captains Bay pluton itself will hopefully further constrain the age of pluton emplacement. Comparison of whole rock compositions between the two suites shows they span a similar range (~52-67 wt.% SiO₂) and particular plutonic units correspond chemically to specific volcanic products. Further, mineral phases (in particular, plagioclase) from these chemically similar units display comparable textures and compositional zoning patterns. Most strikingly, magmatic enclaves found within the pluton show a chemical affinity for andesite lavas from the volcanic suite. Both plutonic enclaves and andesite lavas appear to be hybrid in origin, as evidenced by the presence of both calcic (zoned from ~An₈₀ cores to ~An₅₀ rims) and sodic (zoned from ~An₄₀ cores to ~An₆₀ rims) plagioclase. In igneous texture, however, the lavas and enclaves differ substantially. Generation of enclave compositions and textures may be attributed to the same or similar recharge events as the lavas if the time scales of direct chemical mixing of melts and crystallization in response to heat transfer are sufficiently different. Mixing of melts and extrusion of hybrid lava may be a prompt response to recharge, whereas the enclaves may represent leftovers that thermally equilibrated with the reservoir as a whole. Eruption of andesitic hybrids while the dominantly silicic reservoir remains behind is consistent with the generally more silicic character of the plutonic versus the erupted suites.

V32D-1013 1330h POSTER

Multiple Sources In Ultrapotassic Arc Magmas Inferred From Combined Microthermometry And In-Situ Chemical Analysis Of Melt Inclusions In Olivine And Clinopyroxene Phenocrysts From Batu Tara Volcano, Indonesia

Jason S Herrin¹ (00-31-30-253-5067; jherrin@geo.uu.nl)

Igor K Nikogosian² (00-31-20-444-7373; niki@geo.vu.nl)

Manfred J van Bergen¹ (00-31-30-253-5036; vbergen@geo.uu.nl)

Paul RD Mason¹ (31-30-253-5120; mason@geo.uu.nl)

¹Universiteit Utrecht, Faculty of Earth Sciences Budapestlaan 4, Utrecht 3584 CD, Netherlands

²Vrije Universiteit Amsterdam, Faculty of Earth Sciences De Boelelaan 1085, Amsterdam 1081 HV, Netherlands

Batu Tara is an active, leucite-normative, ultrapotassic volcano located approximately 75 km behind the main magmatic front of the eastern Sunda arc, Indonesia. Clinopyroxene, olivine, plagioclase, leucite, Ti-magnetite, minor apatite and occasional biotite occur as phenocrysts. The exact mechanism for genesis of ultrapotassic arc rocks remains elusive, particularly in island arc settings. Concise determination of primary magma chemistry is often impeded by complex histories of crystallization and magma mixing. Melt inclusions in olivine and pyroxene phenocrysts from Batu Tara have been investigated by high-temperature microthermometry, EPMA, and LA-ICP-MS to constrain parent magma composition and shed light on the genesis of ultrapotassic magmas in island arc settings. Variation in homogenization temperature, major and trace element composition, and volatile content correlate with petrographic observation of three distinct populations of olivine phenocrysts which can be distinguished by the presence or absence of apatite mineral inclusions and CO₂ fluid inclusions. Clinopyroxenes commonly exhibit pronounced chemical zonation with individual zones preserving melt inclusions of unique composition, indicating that these phenocrysts were involved in complex mixing processes and repeatedly subject to end-member magma compositions. Melt inclusions preserve a record of: (1) Early spinel, olivine and clinopyroxene crystallization, followed by later crystallization of abundant apatite; (2) Exsolution of volatile species (S, CO₂, Cl, H₂O) during magma degassing; (3) Mixing of multiple magmas, originating from chemically and likely genetically distinct sources, and; (4) A significant but variable component of fluid addition to the magma source inferred from systematics of incompatible trace elements.

V32D-1014 1330h POSTER

The Role of Boundary Layers During Entrapment of Melt Inclusions: Evidence From Melt Inclusions in Plagioclase, Allanite and Zircon From the Toba Tuffs, Sumatra, Indonesia

Jay B Thomas¹ (540-231-8829; jathoma2@vt.edu)

Robert J Bodnar¹ (540-231-7455; bubbles@vt.edu)

Nobu Shimizu² (508-289-2963; nshimizu@whoi.edu)

Craig Chesner³ (217-581-6323; cfcec@eiu.edu)

¹Virginia Tech, 4044 Derring Hall Dept. of Geological Sciences, Blacksburg, VA 24061, United States

²Woods Hole Oceanographic Institution, Dept. of Geology and Geophysics, Woods Hole, MA 02543, United States

³Eastern Illinois University, Department of Geology and Geography, Charleston, IL 61920, United States

A chemically differentiated boundary layer develops adjacent to minerals during growth from a melt, but its role in affecting the melt inclusion trace element chemistry is poorly known. To better understand the role of boundary layers during melt inclusion formation, the trace element chemistry (Sr and rare earth elements (REE)) of melt inclusions in plagioclase, allanite and zircon from the Toba Tuffs, Sumatra, Indonesia were examined. According to existing models, highly compatible light REE should be depleted in melts adjacent to allanite, compatible heavy REE should be depleted in melts adjacent to growing zircon crystals and the compatible element Sr should be depleted in melts adjacent to plagioclase. Melts adjacent to plagioclase should be enriched in all REE relative to the bulk melt, and melts adjacent to zircon crystals should be enriched in light REE. To test this hypothesis, trace element abundances in melt inclusions were determined by ion microprobe. The results show that La abundances of melt inclusions hosted in allanite (25.7-41.5

ppm) are not lower than La abundances of melt inclusions hosted by plagioclase (24.6-40.6 ppm), zircon (20.2-45.6 ppm), or matrix glasses (27.4-41.9 ppm) suggesting that the light REE were not depleted from the melt at the allanite-melt interface during crystallization. Likewise, Sr concentrations in the melt inclusions hosted by plagioclase (38.7-75.1 ppm) are not significantly lower than Sr in melt inclusions hosted in zircon (26.4-69.7 ppm), allanite (18.8-20 ppm) or in matrix glasses (49.9-97 ppm) as would be expected if plagioclase crystallization had caused depletion of the compatible element Sr at the crystal-melt interface. Yb is enriched in the melt inclusions hosted by zircon (1.62-71.4 ppm), relative to the Yb abundances of melt inclusions hosted by plagioclase (1.3-2.4 ppm), allanite (1-3 ppm) and in matrix glasses (1.2-25.3 ppm). Similarly, elements that are incompatible in the host phases (e.g. La in zircon) are not enriched in the melt inclusions. Based on analyses of melt inclusions contained in minerals with significantly different trace element partitioning behavior, boundary layer processes do not appear to have affected the compositions of melt inclusions studied here. We note that all of the inclusions analyzed here are within the size range of 15-90 microns. This does not preclude, however, that boundary layer processes could significantly affect compositions of inclusions smaller than the lower limit of the spot size for ion microprobes (approximately 10 microns).

V32D-1015 1330h POSTER

Magnetite Composition as a Tool for Judging Phreatomagmatic Eruptions: Case Studies on Usu and Miyakejima Volcano, Japan.

Akihiko Tomiya¹ (81-298-61-3727; a.tomiya@aist.go.jp)

Isoji Miyagi¹ (81-298-61-3788; miyagi.iso14000@aist.go.jp)

¹ Geological Survey of Japan, AIST, Tsukuba Central 7, 1-1-1 Higashi, Tsukuba 305-8567, Japan

In 2000 A.D., two major phreatomagmatic eruptions occurred in Japan, one was at Usu Volcano and the other was at Miyakejima Volcano. For both eruptions, identification of essential materials was controversial, however, detailed observation of microtextures of eruptives and analyses of magnetite compositions enabled us to determine the essential materials (Tomiya et al., 2000; Miyagi et al., 2000). Here, we introduce the two cases.

[case 1: The 2000 eruption of Usu volcano] The first and largest explosion occurred at 31 March, where ash and small amount of pumice were ejected. The pumice (Us-2000pm; Tomiya et al., 2000) was once thought to be recycled Us-1977 pumice (ejected at the 1977 eruption) because of similar appearance, bulk composition, glass composition and plagioclase composition. However, we concluded that Us-2000pm is essential, because the magnetite composition of Us-2000pm was unique among any known Usu pumices, including Us-1977. The same technique also revealed that Us-2000g (fresh glass with many micro-bubbles and microlites, account for about a half of the ash) was the essential material of the phreatomagmatic eruption.

[case 2: The 2000 eruption of Miyakejima volcano] There were several major phreatomagmatic explosions at the summit since 14 July. The largest one occurred at 18 August, where large amount of ash and cauliflower-shaped bomb were ejected. The cauliflower-shaped bomb is undoubtedly essential material because it was hot at its landing. On the other hand, presence or absence of essential materials in the ashes was controversial. Again, our analysis on magnetite in the ash particles specified the essential material (Myk2000g-2; Miyagi et al., 2000), which is "fresh glass with many microbubbles and microlites" and accounts for a large part (10 ~ 40 %) of the ash.

Textual and compositional features of Myk2000g-2 were mostly the same among the vigorous eruptions (14-15 July; 10, 13, 18 August), except that magnetite showed drastic change between 10 August and 13 August. They were initially euhedral and homogeneous (in 14-15 July and 10 August), but they became dissolved in texture and less abundant since 13 August. The dissolution of magnetite is considered to represent the change of magmatic conditions (e.g., temperature, fO_2 , melt composition), and to be a precursor for the climactic explosion at 18 August and the start of unprecedented amount (tens of thousand tons per day) of SO_2 degassing at Miyakejima volcano.

V32D-1016 1330h POSTER

Petrology of Fe-Ti Oxides in Subaerial and Submarine Basalts and Their Effect on Magnetic Rock Properties

Heike Delius¹ (hd21@le.ac.uk)

Timothy S Brewer¹

Peter K Harvey¹

¹ Department of Geology, University of Leicester, Leicester LE1 7RH, United Kingdom

Six sites were drilled during ODP Leg 183 on the Kerguelen Plateau, two of which were logged in the basaltic basement. The transected subaerial (Site 1137) and submarine (Site 1140) lava flows show characteristic structural features, which are reflected by changes in physical rock properties.

To validate the causes of the variation shown in the total magnetic field log, which is derived from the general purpose inclinometer tool, core measurements such as intensity of remanent magnetization and susceptibility were examined as well as the petrology of Fe-Ti oxide in thin sections. High core recovery enables detailed core-log integration and direct comparison of the logging data with core data.

We find that in the subaerial lava flows the relatively fresh flow interiors show low remanent magnetization, susceptibility and a slight negative anomaly in the earth's magnetic field because ilmenite/ilmenohematite is identified to be the dominant ore mineral. The composition of Fe-Ti oxide changes significantly in the altered flow top and base. There we detect the highest remanent magnetization, susceptibility and a strong negative anomaly in the earth's magnetic field. This correlates with an increased Fe-Ti mineral content, namely titanomagnetite/-magnetite, magnetite/magnetite and hematite. The Fe-Ti oxide petrology is variably modified by low temperature alteration in submarine lava flows. The quantity and the size of titanomagnetite/-magnetite, the main carrier of magnetic remanence, are reduced in altered parts of the flow and in this case the remanent magnetization and susceptibility are lower than in the fresh parts.

V32D-1017 1330h POSTER

Mantle and Crustal Components in pre-Caldera Lavas of the Jemez Mountains Volcanic Field, New Mexico

Michael C Rowe¹ ((541) 754-2322; rowem@geo.orst.edu)

John A Wolff² (jawolff@mail.wsu.edu)

Rachel Teasdale³ (rachel@iron.mines.uidaho.edu)

Jamie N Gardner⁴ (jgardner@lanl.gov)

¹ Department of Geology, Oregon State University, Corvallis, OR 97331, United States

² Department of Geology, Washington State University, Pullman, WA 99164, United States

³ Department of Geology and Geological Engineering, University of Idaho, Moscow, ID, United States

⁴ Earth and Environmental Sciences, LANL, Los Alamos, NM 87545

The Jemez Mountains Volcanic Field (JMVF) sits on the western shoulder of the Rio Grande rift. Volcanism in the JMVF spanned at least 14 m.y. prior to the establishment of a large rhyolitic magma system that erupted to form the Bandelier Tuff and Valles caldera after 2 Ma [1]. The Keres Group (13 Ma - 6 Ma) and Tschicoma Formation (7 Ma - 2 Ma) dominate the pre-caldera geology. The Keres Group ranges in composition from basalt to high-silica rhyolite, but is volumetrically dominated by basaltic andesite and andesite, while the Tschicoma Formation consists mostly of dacite. Basaltic volcanism has continued episodically around the periphery of the volcanic field from at least 16 Ma [1]. We identify two primary mantle-derived magma types in the JMVF and surrounding region: (i) basanite to nephelinite, strongly enriched in incompatible trace elements and probably derived by partial melting of metasomatized lithosphere; (ii) tholeiite similar to E-MORB, probably derived from the asthenosphere. Both types have, except for a very few flows, interacted with crustal rocks to varying degrees to yield the intermediate and silicic lavas. Crustal contamination effectively masks the true character of type (i) magma [2]. Both types are significant components in the Keres Group and in peripheral lava fields, while mafic enclaves in Tschicoma Formation dacites are contaminated equivalents of type (i) primary magma. The silicic component in all formations originated in the regional Proterozoic continental crust, although the crustal lithologies involved may have changed with time. Modeling of trace element abundances and Sr, Nd and Pb isotope ratios suggests that the crustal component in the Keres Group was derived from partial melting of amphibolite, whereas that in the Tschicoma Formation represents melted granitoid gneiss. Crustal melting by rising mafic magma was facilitated by a regionally high geotherm, the result of lithospheric attenuation during rifting. [1] J.N. Gardner et al., 1986, JGR. [2] J.A. Wolff et al., 2000, Geology

V32D-1018 1330h POSTER

New Constraints on Crystal Residence in the Glass Mountain Rhyolites, Long Valley, California

Justin I. Simon¹ ((310) 206-9292; jisimon@ucla.edu)

Mary R. Reid¹ (reid@ess.ucla.edu)

¹ Department of Earth and Space Sciences, UCLA, Los Angeles, CA 90095, United States

Rhyolite lavas of Glass Mountain (GM) represent silicic precaldern magmatism associated with the Long Valley magma system that began at ~ 2.2 Ma and culminated in eruption of the caldera-related Bishop Tuff at 0.76 Ma. Differentiation and crystallization of the GM rhyolites has been inferred to have preceded eruption by as much as 360 ky on the basis of whole rock-glass-mineral Sr isochrons (e.g. Halliday et al., 1989; Davies et al., 1994; Davies and Halliday, 1998). One possible consequence of this is the existence of a long-lived magma chamber. This protracted residence is, however, difficult to reconcile with storage of the relatively small volume GM rhyolites in shallow level magma chambers. Here we report zircon crystallization ages for selected GM lavas obtained by in situ ^{238}U - ^{206}Pb ion microprobe analyses. Because the ages are relatively free of uncertainties in the inherited Pb isotope signature and because the role of xenocrysts can be identified, we can independently assess the crystallization history and magmatic residence times of GM lavas.

Zircons were obtained from two older GM lavas that apparently erupted ~ 300 ky apart: OC (1.99 Ma; sanidine Ar/Ar age) and OD (1.69; sanidine Ar/Ar age). Sr isochron ages suggest that magma(s) responsible for both lavas may have differentiated and crystallized at ~ 2.05 Ma. Zircon crystallization ages range from approximately those of eruption to ~ 2.20 and ~ 2.01 Ma for OC and OD, respectively. For the OC lava, the youngest zircon crystallization ages (~ 1.8 Ma) are somewhat younger than expected but agree well with the 1.89 ± 0.02 Ma (2 σ) composite Sr feldspar rim-glass age, indicating that eruption of this lava may have been later than presently constrained by 40Ar/39Ar dating. Ages obtained for rims of individual zircon grains are younger than those for their cores. Mean zircon crystallization ages (OC: 2.00 ± 0.03 Ma, 2 σ , N=33, MSWD=3.2; OD: 1.87 ± 0.03 Ma, 2 σ , N=25, MSWD=2.3) are younger than whole rock-glass-mineral and whole rock-glass Sr isochron ages.

Zircons were also obtained from a younger GM lava: YG erupted ~ 0.9 Ma. A mean zircon crystallization age of 954 ± 50 ka (2 σ , N=14/16, MSWD=0.98) for YG is within error of the reported whole rock-glass-mineral Sr isochron age. Except for the two relatively old outliers omitted from the mean age calculation, zircon crystallization ages obtained from YG overlap the time-span implied by the existing Sr isochron ages. The duration of zircon crystallization in YG may be less than tens of ky.

The apparent onset of zircon crystallization in both older GM lavas agrees well with their respective whole rock-glass-mineral Sr isochron ages. This agreement lends support to previous evidence for differentiation and/or crystallization well before eruption. Even after omission of possible outliers, the scatter in the ages of both older GM lavas is greater than can be explained solely by analytical uncertainties. This, together with the rimward younging of ages, shows that the age distributions are not merely mixtures of different aged zircon populations but are a result of at least two episodes of crystal growth. At present, neither the zircon crystallization ages nor the Sr isochrons provide unequivocal evidence of regular magmatic crystallization from a persistent volume of melt. Current investigations are aimed at establishing whether ages intermediate between the two extremes represent sampling of young and old age domains or whether they are evidence of more continuous crystallization.

V32D-1019 1330h POSTER

Timescales of Magmatic Evolution by Coupling Core-to-rim ^{238}U - ^{230}Th Ages and Chemical Compositions of Mineral Zoning in Allanite From the Youngest Toba Tuff

Jorge A Vazquez¹ (310-206-1938; jvazquez@ess.ucla.edu)

Mary R Reid¹

¹ UCLA, Dept of Earth and Space Sciences, Los Angeles, CA 90095-1567, United States

A direct approach to determining the kinematics of magmatic evolution and the crystallization histories of individual phenocrysts is to couple the chemical compositions and ages of mineral zoning within single crystals. However, temporal constraints have been difficult to place on mineral zoning records, particularly due to poor analytical resolution relative to the short timescales (10's-100's of ky) associated with crystal

growth as well as the poor spatial resolution of traditional isotopic dating techniques. Allanite, a Th and LREE-rich epidote mineral, offers the unique opportunity to couple intra-crystal age distributions obtained via in situ ion microprobe analysis with the range of chemical variations in this compositionally rich mineral and therefore to resolve the timescales of magmatic evolution recorded by mineral zoning. We present the time-composition characteristics of chemical zoning in volcanic allanite (Th and LREE-rich epidote mineral) from compositionally diverse (69-75 wt.% SiO₂) pumice associated with the voluminous (~3000 km³) Youngest Toba Tuff, Indonesia, erupted at 75 ka. High ThO₂ concentrations (1-2 wt.%) in the Toba allanite allow in situ determination of ages from the magnitude of ²³⁸U-²³⁰Th disequilibrium in grains less than ~500 ka in age; most ages in the Toba allanite are <150 ka with most rim ages identical to that of eruption. Optically recognizable/identifiable zoning in the Toba allanite is on the scale of 10's of microns and is defined by changes in both major and minor elements. Electron probe analyses reveal core-to-rim zoning trends of decreasing LREE, MgO, and La/Nd, and increasing MREE, FeO, and ThO₂, which can be simply ascribed to progressive growth from an evolving melt. However, less-abundant grains display opposite zoning trends and/or contain resorbed and evolved cores, suggesting complex crystal and magma histories. Intracrystal core-to-rim age distributions suggest that the allanite zoning records crystal growth and magmatic evolution involving crystal-melt fractionation over 10's of ky. Furthermore, the coupled time-composition relations between different allanite are disparate such that there is no distinctive concentration of major or minor elements in the crystals at any absolute age. This in turn suggests a complex growth/magmatic history for individual allanite and/or their host melts in this voluminous rhyolite. One consequence of this is that correlations of growth histories between associated allanite grains should be approached with caution.

V32D-1020 1330h POSTER

Calderas of the Central Sector of the Mexican Volcanic Belt

Gerardo J Aguirre-Diaz (525 623 4105; ger@unicit.unam.mx)

Universidad Nacional Autonoma de Mexico, UNICIT-Juriquilla, Queretaro, Qro 76230, Mexico

The central sector of the Mexican Volcanic Belt (MVB) (-99 to 103, Long W) has the largest number of calderas so far identified in this province. The calderas (with their age range in Ma, and distance to the Middle America Trench in km, in parenthesis) are: Amazcala (7-6, 480), Apaseo (7-6, 440), Huichapan (5-4, 420), Agustinos (5-4, 400), Amealco (5-4, 400), Macua (4-3, 410), Muerta (? , 380), Catedral (6-5, 370), Azufres (4.5-0.03, 370 Pradal & Robin, 1994), and Zitácuaro (12-0.5, 320 Capra et al., 1997). Most calderas completed their activity in about 1 Ma, but Azufres and Zitácuaro had longer lives, mostly as post-caldera lava domes and associated pyroclastic flows. Amazcala is rhyolitic, peraluminous-peralkaline, and 10x14 km in diameter. Apaseo is a 11x14 km center that started as andesitic-dacitic and ended rhyolitic and mildly peraluminous; Huichapan started with dacitic ignimbrites and ended with a major rhyolitic ignimbrite; Agustinos is a > 6 km open semi-circle structure that erupted first an andesitic ignimbrite and then a rhyolitic one; Amealco is 10 km in size and erupted a succession of three ignimbrites with mingled glasses with compositions from trachyandesite to rhyolite; Macua is a summit crater structure, 3x5 km, that erupted an unwelded rhyolitic ignimbrite; Muerta is a sector collapse caldera, 4x5 km, associated to lithic-rich ignimbrite eruptions; next to Mexico-City is Catedral, a 9x6 km in diameter caldera with silicic ignimbrites and rim and central lava domes, some of which erupted block-and-ash flows; Azufres has been a matter of debate, but according to Padral and Robin (1994), is a long-lived structure, about 20 km in diameter, with the major caldera eruption at 4.5-3.4 Ma, and repeated dome and pyroclastic flow activity until 26 Ka ago; Zitácuaro (Capra et al., 1997) is another long-lived center, with eruptive cycles at 12 Ma (the caldera-forming event), 5 Ma and 0.5 Ma (mostly domes and associated pyroclastic flows). Most calderas cluster at 4-6 Ma and at 370-420 km from the actual trench. This peak in caldera eruptions coincides with major plate reorganizations offshore SW Mexico, such as the opening of the Gulf of California, an eastward jump of the East Pacific Rise (EPR), and a change from fast to slower spreading rates at the EPR and the Rivera-Pacific rise, which may be related to an increase in explosive volcanism in the central MVB.

V32E MC: Hall D Wednesday 1330h

Plutonic Systems: Felsic to Basic

Presiding: A Schmitt, UCLA

V32E-1021 1330h POSTER

Rb-Sr Isotopic Systematics of Felsic Igneous Rocks, Wichita Mountains, Oklahoma

Kyoung-Won Min¹ (82-33-250-6255; kwmin@kangwon.ac.kr)

M. Charles Gilbert² (405-325-3253; mcgilbert@ou.edu)

¹Kyoung-Won Min, Dept. of System Engineering, Kangwon National University, Chunchon 200-701, Korea, Republic of

²M. Charles Gilbert, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019-1009, United States

Recently determined Rb-Sr isotopic characteristics of twelve of the recognized felsic units of the Cambrian Southern Oklahoma Aulacogen, which crop out in the Wichita Mountains of the southwestern Oklahoma, give some clues to the petrogenesis of these felsic units. 1) Plots of ⁸⁷Rb/⁸⁶Sr vs. ⁸⁷Sr/⁸⁶Sr form subsets yielding dates of 516 Ma and 522 Ma, discrepancies of about 10 to 20 Ma from the U-Pb zircon age for the Mount Scott Granite of 534 Ma, probably attributable to a systematic loss of radiogenic ⁸⁷Sr for these units. 2) The Mount Scott Granite and related units (n=7) including Medicine Park Granite and Saddle Mountain Granite give a probable pseudoisochron of 516±4Ma and an initial ⁸⁷Sr/⁸⁶Sr of 0.7045±4, indicating derivation from a primitive mantle source with little crustal contamination. 3) A well-regressed line of 522±2 Ma with an initial ⁸⁷Sr/⁸⁶Sr of 0.7059±7 is shown by the Long Mountain Granite (n=3), one of the finer-grained western granites, and the Fort Sill Section of the Carlton Rhyolite (n=2) in the eastern Wichitas, which indicates that both were possibly derived contemporaneously from a mixed crustal-mantle source. 4) The Lugert Granite of the western Wichitas has variable and relatively high ⁸⁷Sr/⁸⁶Sr initials at 516 Ma probably indicating heterogeneous crustal sources. Interpretation of these data can be made with the following scenario: The earliest known felsic unit is the Carlton Rhyolite, Fort Sill Section. This must have been generated mostly from crustal melting around large mafic plutons in the mid- to lower crust. Crustal melting around the mafic plutons continued to generate liquids rising to the emplacement position, e.g., Long Mountain Granite. Following this, the host magma for the Mount Scott set of units originated dominantly by fractional crystallization from the mafic plutons. Subsequently, additional mafic magma must have moved into the lower- to mid-crust, at some other stratigraphic level, melting a more heterogeneous mixture of rock types to yield the Lugert Granite. Thus, in this rather narrow rift zone, felsic magmas of varying origin, but similar chemistry, have risen to the same emplacement level.

V32E-1022 1330h POSTER

Trace Elements in Igneous Quartz: a new Petrogenetic Tool for the Study of Granite Pegmatite Genesis

Rune B. Larsen^{1,2} (rune.larsen@ngu.no); Belinda Flem¹; Iain Henderson¹; Peter M. Ihlen^{1,2}; Yann Lahaye³; Terje Malvik²; Tore Prestvik²

¹Geological Survey of Norway, N-7491 Trondheim, Norway

²Norwegian School of Science and Technology, N-7491 Trondheim, Norway

³Johann Wolfgang Goethe-Universitat, Institut Fur Mineralogie D-60054 Frankfurt, Germany

The trace-element chemistry of quartz is rarely, if ever, considered when evaluating the origin and evolution of silica over-saturated igneous rocks. Analytical obstacles have efficiently prevented in-depth studies of the trace-element chemistry of quartz because the most interesting elements are present at the sub-ppm level and because mineral separation of quartz for traditional solution analysis is a time-consuming process. Also, igneous quartz may contain both fluid and solid inclusions that are difficult to identify during hand-picking and may influence the analytical results significantly. However, in the present study we utilised in situ Laser Ablation of quartz specimens with direct introduction of the ablated material in to a double focusing sector field, ICP-MS instrument, and we developed a method that is fine-tuned for the analysis of trace elements in quartz (Flem et al., Chemical Geology, in

press). Among the elements covered by the method we have focused on substitutional trace-elements replacing Si⁴⁺ (e.g. Ti, Ge, Al, Fe and P) or elements that represent charge compensators that are accommodated in lattice vacancies or in structural channels (e.g. Li, B, K, Ca, Be).

Elements analysed at low, medium and high resolutions include Li, B, Be, Al, Mn, Ge, Rb, Sr, Ba, Pb, Th, Mg, P, Ti, Ca, Cr, Fe and K. 29Si or 30Si, were used as internal standards.

In the present study we evaluate the chemical evolution of quartz by comparing with the chemistry of co-existing alkali-feldspar, for which the compositional changes during igneous evolution is well known from the literature.

The study includes 75 strongly zoned gadolinite-type REE-Nb-Ta rich chamber pegmatites from two major Neoproterozoic pegmatite fields in SE-Norway. Analysis of alkali-feldspar for major and accessory elements including the REE shows that the pegmatites were formed from progressively more evolved liquids through extreme fractionation of primitive granitic melts.

The total concentration of trace elements in quartz is 100 to 250 ppm with Al, P, Li, Ti, Ge and Fe, in that order, being most abundant. Distributions of trace elements in quartz are well correlated with major and trace elements in alkali-feldspar that are used to monitor the chemical evolution of the granite pegmatite liquids. For example, Al, Ti and Ge are positively correlated with Ca and Sr in alkali-feldspar. Accordingly, the trace element distribution in quartz develops a progressively more evolved signature as igneous differentiation of the parental melts proceeds. Although the pegmatite fields apparently are closely related both in terms of space, time and chemistry, the distribution patterns of trace elements in quartz are markedly different thus suggesting that granite pegmatites in the two fields were derived from distinctively different sources. This conclusion is confirmed by the REE-chemistry of alkali-feldspar and by the REE-mineral assemblages characterising the pegmatite fields.

V32E-1023 1330h POSTER

Limitations on Mid-crustal Assimilation in the Sierra Nevada Batholith (SNB), California

Lingsen Zeng¹ ((626)395-6271; lzens@gps.caltech.edu)

Jason B. Saleeby¹ ((626) 395-6141; Jason@gps.caltech.edu)

Mihai N. Ducea² (ducea@geo.arizona.edu)

¹Division of Geological and Planetary Sciences, California Institute of Technology, MC 100-23, Caltech, Pasadena, CA 91125

²University of Arizona, Department of Geological Sciences, University of Arizona, Tucson, AZ 85721

The extent to which pre-existing continental crustal components have been introduced into granitic magmas of the SNB as melted sediments within source and/or ascent domains has been the focus of much attention. In order to test the potential importance of this process at relatively deep ascent levels (3-5 kb) we have performed a detailed study of one of the best developed migmatite complexes observed throughout the metasedimentary framework of the SNB, and in the immediately adjacent 100Ma Goat Ranch granodioritic intrusion (GRg), which drove partial melting in a 50 ~500 m wide zone in adjacent psammite-pelitic rocks. Isotopic analyses of Nd and Sr, and major and trace elemental abundance were measured on non-migmatitic distal wallrocks (sillimanite grade), leucosomes from the migmatites; and on traverses into the GRg away from contacts with the migmatites. We also analyzed a suite of mafic enclaves in the GRg which yielded bulk compositions of andesite and which have mineralogically equilibrated with the host GRg. Sr(i=100Ma) of GRg range from 0.7061 to 0.7071, and $v_{Nd}(i)$ from -1.1 to -6.5, while mafic enclaves yield a similar range. Leucosomes have Sr(i) from 0.7125 to 0.7247, and $v_{Nd}(i)$ from -6.0 to -11.3 while nonmigmatitic metapelites yield a similar range. Contamination of GRg, as seen by large shifts in Sr(i) and $v_{Nd}(i)$ is restricted to immediate proximity to migmatitic wallrocks. Isotopic heterogeneity of the GRg is not related to assimilation at or near the level of exposure, a similar conclusion reached for 100 Ma (ca. 8kb) SNB rocks located further south in an oblique crustal section (Pickett and Saleeby, 1994). Isotopic variation patterns in 10-20 kb SNB lower crustal residue assemblages carried as xenoliths in Neogene volcanic rocks lie along the same trend as the GRg data (Ducea and Saleeby, 1998), and suggest that the GRg heterogeneity is inherited from such a source. Leucosomes in the migmatite complex appear to have crystallized nearly in place after segregation. This as well as the limitation in contamination of the GRg appears to have been energy limited. Mafic enclaves in the GRg strongly resemble remnants of disrupted cummingled mafic dikes observed elsewhere in the southern SNB. Elemental chemistry shows that they are not residues from melted metapelite. There was possible isotopic exchanges (particularly Sr) between the enclaves and GRg.