

an average delay time of 1.60 sec; (3) Western Iceland: weaker anisotropy (average delay time 0.57 sec) with less well-constrained fast polarization directions. These observations suggest that the plume-ridge interaction does not dominate the anisotropic pattern; instead the splitting results are mainly attributed to shear of the North American and Eurasian plate motion relative to a background mantle flow with a direction of S10°E and a magnitude of approximately 20 mm/yr in the hotspot reference frame. The absence of anisotropy in western Iceland may suggest a strong vertical heterogeneity beneath western Iceland, and the splitting observations may be more reflective of the fast polarization directions of the lithosphere or crust. This heterogeneity may be caused by the complex lithosphere-asthenosphere boundaries that disturb the asthenosphere flow beneath Western Iceland.

V12B-0596 1330h POSTER

Constraining the Temporal and Spatial Evolution of Mantle Plumes Using the Stratigraphic Record

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Gravitational and tomographic studies provide a snap-shot of mantle plumes at the present day. However, these techniques are unable to constrain how mantle plumes have evolved, temporally and spatially, to their present day structures. A mantle plume will generate vertical motions in the overlying plate. These vertical motions will be recorded in the stratigraphic record of the region, enabling the size and planform of the mantle plume to be mapped out over time. During Cenozoic times, anomalous uplift and subsidence occurred throughout the North Atlantic region. These vertical motions most likely result from temporal and spatial variations of Iceland Plume activity. Quantifying uplift generated by the convective support of the Iceland Plume enables the extent of the Iceland Plume head to be mapped out. Here, we describe the record of activity of the southern half of the Iceland Plume head, which affected a region encompassing the British Isles, southern Greenland and eastern Canada. This record is based on stratigraphy along the extensional margins which fringe the North Atlantic Ocean. A detailed study has been carried out on the Moray Firth Basin, part of the North Sea rift system, using back-stripped well-log data. The effect of tectonic subsidence has been removed from the basement subsidence profiles of 50 wells, enabling anomalous residual uplift and subsidence to be isolated. A transient Paleocene uplift-subsidence event, with a duration of approximately 15 Ma, is recorded throughout the Moray Firth Basin. The magnitude of peak uplift is 150–500 m. This transient uplift event has previously been identified in basins surrounding the British Isles, including the Faroe-Shetland Basin, the Porcupine Basin and the North Viking Graben. The initiating Iceland Plume provided dynamic support to the overlying plate and generated uplift. As the effect of the Iceland Plume in the British Isles region waned, subsidence occurred. These results from subsidence analysis agree with estimates of dynamic support from the palaeotopographic reconstruction of the coastline of the British Isles at the Paleocene/Eocene boundary. The stratigraphic record of the North Atlantic region yields information about the temporal and spatial evolution of the Iceland Plume during Cenozoic time. Such records of mantle plume evolution will provide important new constraints for models of mantle convection.

V12C MCC: Level 1 Monday 1330h

Melting of the Mantle and Formation of Basalt Magmas: Experiments, Field Studies, and Models I Posters (joint with OS)

Presiding: G Gudfinnsson, Carnegie Institution of Washington; S Keshav, Florida International University

V12C-0597 1330h POSTER

Ocean Island Lavas: Garnet Clinopyroxenite or CO₂-bearing Mantle Lherzolite?

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We combine new results of an experimental melting study of a Hawaiian garnet clinopyroxenite (SL) at 2.0–2.5 GPa pressure with data from lherzolite (4-CO₂) in the CMAS and natural systems to evaluate the origin of alkalic basalts (AB) that erupt at oceanic islands. The experimental data on SL are also used to map the behavior of partial melts as a function of pressure (P), temperature (T), and degree of melting (F). The solidus of SL, a tholeiitic picrite with 1wt% Na₂O, is bracketed at 1295±15 and 1335±15 degree Celsius at 2.0 and 2.5 GPa, respectively. These brackets are slightly lower than those of anhydrous mantle lherzolite at identical pressures. Chemically, the high and low-F melts are ol-hy normative and moderately to strongly re-normative, which can be ascribed to the effect of Na and Fe in expanding the "eclogite surface" in natural systems. There is very little overlap between primitive AB and partial melts of SL. These differences are most pronounced for MgO, Al₂O₃, CaO, CaO/Al₂O₃, and CaO/MgO. SL melts partially resemble AB only in terms of SiO₂ and Na₂O+K₂O. Partial melts of anhydrous mantle lherzolite also partially overlap AB, but even the lowest degree melts analyzed are far removed from most of the AB. However, partial melts generated at 3–6 GPa from carbonated mantle lherzolite in CMAS-CO₂ and natural systems can generate the AB clan of lavas from oceanic islands. Experimental melting studies in simple CMAS-CO₂ and natural lherzolitic systems demonstrate that isobaric increases in F lead to a moderate decrease in CaO+MgO in partial melts. With increasing F, CaO/MgO and CaO/Al₂O₃ drop sharply in the partial melts. Based on CaO/Al₂O₃, CaO, CaO+MgO, Al₂O₃, and Mg# systematics, it is proposed that the Hawaiian, Samoan, and Polynesian lavas have tapped the shallowest (3.0–3.5 GPa) part of the melting column within the garnet stability field in the presence of a low-to-moderate amount of CO₂ in their respective mantle sources. In addition, on the basis of CaO and CaO/MgO systematics, Hawaiian, Samoan, and Polynesian lavas appear to be produced by relatively high F. Within Hawaii, lavas from Oahu may have equilibrated at a slightly higher pressure than those from Koloa. On the other hand, based on higher CaO, CaO/Al₂O₃, and CaO+MgO, coupled with lower CaO/MgO, and Al₂O₃, it is inferred that lavas from the Gran Canaria have equilibrated at a slightly higher pressure (3.5–4.5 GPa) in the presence of slightly higher CO₂. Chemical systematics also suggest that lavas from Gran Canaria may have been products of relatively lower F. It is proposed here that major element systematics of AB and also nephelinites/melilitites cannot be modeled by garnet clinopyroxenite (with anhydrous mantle lherzolite) at the pressures of investigation. CO₂ is required in the mantle source regions of AB on ocean islands.

V12C-0598 1330h POSTER

Melting experiments of a peridotite from Penghu area, Taiwan, at pressures up to 2 GPa.

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A peridotite occurred as a xenolith in alkali basalt of Penghu, Islands, in Taiwan Strait, Taiwan, was studied with a quenching furnace and a piston-cylinder apparatus. The compositions of melting products showed the trends as the decreasing of Al₂O₃, CaO, Na₂O, and K₂O and the increasing of MgO as the melting temperature increased at specific pressure. At the specific temperature, the SiO₂ of melting products decreased as the pressure increased. The basalts of Penghu can be classified as alkali basalt, olivine tholeiite, and quartz tholeiite based on the classification of basalt tetrahedron. The quartz tholeiite of Penghu could be modeled as 10% to 24% partial melt product from the peridotite at 0.5 GPa. The olivine tholeiite of Penghu was proposed to be the partial melting, up to 23%, products from the peridotite at 1.0 and 1.5 GPa. Comparing the compositions of melting products with the basalts of Penghu, we proposed that the primitive basaltic magmas of Penghu had been fractional crystallized to produce the basalts of Penghu.

V12C-0599 1330h POSTER

Long-term Rates of Mafic Magma Emplacement and Implications for Heat Advection

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Rates of magmatism (magma emplacement rate) including both volcanic products and intrusive bodies were obtained for terrestrial petroecologic systems where reliable volumes can be estimated and geochronological data exist. Approximately 50 estimates of magma emplacement rates have been extracted from the literature published between 1982 and 2003 for persistent basaltic systems with durations from 1 ka to 5 Ma. Although the volcanic output is highly episodic, the data indicate that the mass output rate at individual hotspot volcanoes is on the order of 10⁻³ km³/yr when averaged over several thousand years. This differs from the estimated output rates of large igneous provinces, such as continental flood basalts and oceanic plateaus, which have maximal output rates on the order of 1 km³/yr per province. For globally averaged mid-ocean ridges, the total volcanic emplacement rate is only 10⁻⁶ km³/yr/100 km of ridge. Ratios of intrusive to extrusive emplacement are subject to much uncertainty, but generally lie in the range 6:1 to 10:1 for most crustal mafic magma systems. Recent seismic, geodetic, and gravity work suggests that there may be large regions of underplating and storage in subcrustal magma chambers in areas of basaltic volcanism previously not widely considered in intrusive volume estimates that may increase most of these ratios to 10:1. Rates of magmatism may be translated into excess heat flows for specific magmatic provinces to obtain estimates of advected heat transport via magmatism at regional scales over magmatic province timescales. For mafic eruption rate V and an intrusive/extrusive ratio of R , the volumetric rate of magma flow into the crust is RV . The excess heat power (J/yr) associated with magma transport from mantle to crust is $RV\rho\delta T$ [$C_p + \delta h/(T_{liquidus} - T_{solidus})$] where δT is the temperature difference between the magma and host crust, δh is the enthalpy of crystallization (250–400 kJ/kg dependent on magma composition), ρ is magma density, C_p is the isobaric heat capacity of the magma, and the liquidus to solidus temperature interval is pressure and composition dependant but typically equals 300 K. The excess heat power into the crust due to mafic magmatism is roughly 2e+19 J/yr for a volumetric eruption rate of 1 km³/a. As an example, consider the Skye sub-province (area 1600 km²) of the British Tertiary Igneous Province (BTIP). For the estimated volume eruption rate of 2e-3 km³/a and $R=5$ the average excess heat flow is 3 e+7 J/m²a or 1 W/m². The excess heat flux is a factor of ten greater than the average terrestrial global heat flux 0.09 W/m². The 'excess' heat flux is associated with a crustal thickening rate of 3 km/Ma in the time interval 60–53 Ma. We conclude that the volume flux of magma in the active years of this part of the BTIP focused heat flow about an order of magnitude above background at the regional scale for 5 Myr. The regional energy/mass balance estimate is consistent with geochemical modeling of Skye intrusive and volcanic rocks that point to significant magma recharge during the magmatic evolution at Skye.

V12C-0600 1330h POSTER

Mantle Melting in the Plagioclase-Spinel Transition Zone; Reconciling Experiments and Thermodynamic Models

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The slope of the solidus of plagioclase and spinel bearing lherzolite is important as it controls mantle melting behaviour during isentropic decompression. The invariant point in $CaO - MgO - Al_2O_3 - SiO_2$ (CMAS), where the reaction of plagioclase lherzolite to spinel lherzolite intersects the solidus, expands to form a divariant surface in $CaO - MgO - Al_2O_3 - SiO_2 - Na_2O - FeO$ (CMASNF). Experimental results in two five component systems, CMASN and CMASF, suggest that the temperature of the surface increases slightly with pressure, so that the plagioclase-spinel transition interval could be the site of enhanced melting consistent with seismic observations (Presnall et al., 2000 and references therein). In contrast, calculations using the MELTS (Ghiorso & Sack, 1995) and pMELTS (Ghiorso, 1998) algorithms predict a strong or weak temperature drop respectively as pressure is increased, giving a pronounced cusp in the solidus where melts would freeze (Asimow et al., 1995). We are currently using an integrated experimental and theoretical approach to explore the equilibrium between plagioclase, spinel, olivine, orthopyroxene, clinopyroxene and liquid to see if these results may be reconciled. Piston-cylinder experiments are being carried out in CMASNF and sub-systems. Using the parameterisation of Walter & Presnall (1994) we have chosen a suitable bulk composition in CMASN that should intersect the univariant melting reaction over a range of pressures (11-15 kbar) whilst maximizing the modal proportion of each phase above and below the reaction. To account for interlaboratory differences in pressure-calibration we are re-determining the CMAS invariant point. We are also developing calibration software suitable for a new thermodynamic model of peridotite melting. The CMASNF system is outside the calibrated composition ranges of MELTS and pMELTS, which were constructed exclusively from natural system data. By using experiments from CMAS, CMASN and CMASF in our calibration procedure, together with suitable estimates of experimental uncertainty and the best available silicate liquid equations of state, we can test whether a thermodynamically consistent polybaric model can be generated that successfully reproduces the positive Clapeyron slope of the plagioclase-spinel lherzolite melting reaction observed by Presnall and co-workers.

V12C-0601 1330h POSTER

Along-Axis Geochemical Variations in Basaltic Glasses From the Incipient Rift Adjacent to the East Pacific Rise at 2°40'N

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The east-west-trending Incipient Rift (IR) is located adjacent to the East Pacific Rise (EPR) at 2°40'N in the equatorial Pacific. This slow-spreading (~0-30 mm/yr), magmatic rift forms the boundary between the Cocos plate and Galapagos microplate (Lonsdale, 1988) and connects to the East Pacific Rise (EPR) through a magnetically active linking ridge. This study examines glass compositions from 41 dredges and one wax core collected along a 60-km section of the IR, including two dredges from an on-axis volcano, as well as four dredges and three wax cores from the adjacent EPR. This represents the most thorough sampling of the IR to date, with previous sampling limited to 11 wax cores collected during the 1999 Hess Deep expedition and a single dredge from an earlier cruise. To first order, IR samples are similar in major and trace element compositions to basalts erupted at the adjacent EPR. IR glasses, in general, become more evolved with increasing distance from the EPR (Mg# 67-41). The samples are generally depleted ((La/Sm)_N: 0.38-0.86), with the most depleted samples occurring within ~7 km of the EPR. Samples >7 km from the EPR are less depleted than the near-EPR samples and have a relatively constant range of (La/Sm)_N (0.61-0.73). Trace element ratios indicative of source heterogeneity (e.g. Zr/Hf) and garnet signature in the melting

residue ((Sm/Yb)_N) are also lower in the near-EPR samples than those >7 km from the EPR. Fe₈₀ values, an indicator of pressure of melting, range from 9.2-10.4 and increase away from the EPR for ~10 km. At distances >10 km, Fe₈₀ values are variable (10.4-11.6) exhibiting no clear spatial trend. Samples from the volcano ~13 km from the EPR are the least depleted ((La/Sm)_N: 0.85-0.86); have the strongest garnet signature; and are most primitive among the IR samples. The data from the IR will be examined in the context of geophysical and geochemical modeling results on the nature of melting and melt focusing beneath the adjacent EPR, as well as compared to other propagating rifts, triple junctions, and ultra-slow spreading centers.

V12C-0602 1330h POSTER

Tectonic and Geologic Characterization of the Incipient Rift, east of the East Pacific Rise at 2°40'N

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The "Incipient Rift" (IR), first identified by P. Lonsdale and co-workers, is located immediately east of and orthogonal to the East Pacific Rise (EPR) at 2°40'N. The IR is a slowly diverging (approx. 15 mm/yr full-rate) spreading center separating the Cocos and Galapagos plates. Interest in the IR stems, first, from the fact that because it is adjacent and orthogonal to the robust EPR, it may tap less pooled magmas produced within the wide melting regime feeding the EPR; and second, because it is a sparsely explored limb of the complex plate boundary surrounding the Galapagos microplate. In August, 2002, we mapped and sampled a broad area centered on the IR, including its intersection with the EPR and apparent termination approx. 75 km to the east. Data sets collected include complete Seabeam 2000 bathymetric and side-scan (amplitude) coverage, sea-surface magnetics, 14 camera tows (WHOI Towed Camera), rock sampling (53 dredges, 5 wax cores) and hydrothermal surveying (MAPR and CTD). Based on these data, the IR can be divided into three distinct tectonic and magmatic provinces from west to east: a) "The Linking Ridge," following Lonsdale's demarcation, from EPR to 101°59'N, a zone of robust magmatism; b) "The Magmatic Gore," from 101°59'W to 101°53'W, transitional between the Linking Ridge and the Faulted Gore to the east; and c) "The Faulted Gore" from 101°53' to the undisturbed N-S EPR-parallel abyssal hills at 101°26'W. The Faulted Gore is a highly tectonized zone of rifting, with EPR parallel abyssal hills extensively stretched with faults oriented in E-W. Recent magmatism in the Faulted Gore was found to be confined to a narrow zone that runs through the southern portion of the Rift, just north of the faults that define its southern boundary. In general, sediment cover and tectonism (faulting) increase, and the quality of fresh glass decreases, with distance from the EPR. However, photographic evidence of recent magmatism (e.g., fissures erupting lava over sedimented terrain) in areas far east of the EPR axis, as well as a high in magnetization, support the idea that sporadic, recent magmatic activity occurs along the length of the IR (geochemistry: Hanna et al., 2003). No evidence of hydrothermal activity was found along the IR, although a hydrothermal plume was detected in the water depth over the adjacent EPR, and photos on the Linking Ridge show old hydrothermal deposits. A brief SeaBeam survey of the area northeast of the Incipient Rift during our transit revealed the probable existence of a second, perhaps larger propagating rift (Smith et al., 2003), which further emphasizes the complicated nature of the microplate boundaries in this region.

V12C-0603 1330h POSTER

Trace Element Partitioning Between low-Ca Pyroxene and Ultracalcic Liquids.

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Low-Ca pyroxene or pigeonite (~0.25-0.35 Ca per formula unit, pfu) is an important residual phase during high temperature melting of refractory mantle (e.g., ankaramite formation). High-Ca cpx (>0.6-0.7 Ca pfu) may be residual to relatively low temperature melting of fertile mantle (MOR and OI), but the opx-cpx solvus narrows considerably at higher temperatures (>1330-1350°C), leading to coexisting opx and low-Ca cpx. Little is known about the trace element partitioning of such low-Ca cpx at upper mantle conditions. Our new partitioning experiments investigate the role of low-Ca cpx during melting of depleted peridotite. Normally anhydrous experiments with graphite-lined Pt-capsules were conducted at 1.4 GPa and 1360-1370°C. The synthetic starting material is close in composition to an ultracalcic liquid saturated in opx+pigeonite+olivine+spinel. The experiments yielded assemblages of glass, low-Ca cpx, ol, and minor Cr-spinel; opx is absent. The low-Ca clinopyroxenes have 0.20 and 0.32 Ca pfu at 1370 and 1360°C, respectively, and tetrahedral Al₂ of 0.046 and 0.067 pfu. The liquids have ~50 wt% SiO₂, ~12.5 wt% CaO and CaO/Al₂O₃ of 1.44-1.54. Pyroxenes and glasses were analyzed for trace elements (La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, Lu, Sc, Y, Sr, Zr, Hf, V, Cr, Mn, Co, Zn) by LA-ICP-MS using a 193 nm ArF excimer laser coupled to an Elan 6100 mass spectrometer. Ablation occurred in He, and ablation spot sizes were 15-30 μm for minerals and 50 μm for glasses. Trace element concentrations in pyroxenes were low for most 3+ and 4+ cations. This resulted in small mineral/melt partition coefficients (D-values), approximately an order of magnitude lower than those for high-Ca cpx associated with peridotite melting, thus making the low-Ca cpx partitioning behavior rather similar to the behavior of peridotitic opx. Cpx with 0.32 Ca pfu has slightly elevated D-values for 3+ cations when compared to the 0.20 Ca pfu cpx: $D_{Sc} = 0.45$, $D_Y = 0.11$, $D_{Zr} = 0.054$ and $D_{Yb} = 0.141$, compared to values of 0.32, 0.065, 0.016 and 0.075, respectively. Regardless of Ca content, V, Mn, Co and Zn are mildly incompatible (Ds ~0.5-0.9). Therefore, only Sc, V, Cr, Mn, Co, Ni and Zn are retained during partial mantle melting with a pigeonite+opx+ol residue. Most other elements partition strongly into the melt, and barring exotic residual minerals, the composition of ultracalcic liquids reflects the incompatible trace element budget of the depleted peridotite source.

V12C-0604 1330h POSTER

The Effect of Carbonate Composition and Concentration on the Solidus of Carbonated Eclogite: An Experimental Study at 3 GPa

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Subduction of carbonated oceanic crust transfers a substantial amount of carbon into the mantle. Some or all of this carbon is released to surrounding mantle by partial melting of carbonated eclogite, which thus has a key influence on the distribution of carbon in the mantle. Previous experiments have determined melting relations for a particular bulk composition (e.g., 60% eclogite + 40% calcite). However, solidus temperature depends on near solidus melt composition, which may vary in the mantle. Importantly, it may also depend on the composition and quantity of carbonate added to experimental charges. To investigate this effect, we performed partial melting experiments with different starting materials at a single pressure of 3 GPa. Salt Lake crater eclogite (SLE) from Oahu, Hawaii was used as the base silicate composition. This starting material, which is a close approximation of subducted ocean crust after extraction of small degree partial melts/siliceous hydrous fluids, was modified by varying the composition and amount of added carbonates. Near solidus carbonate melt compositions are Na-Fe dolomitic for all starting compositions, whereas the stable carbonate mineral at the solidus varies as a function of added carbonate compositions: SLE+calcite runs produced calcite_{ss} (Ca/(Ca+Mg) = 0.83) whereas Fedolomite_{ss} (Ca/(Ca+Mg) = 0.5) is stable when CO₂ was added as a mixture of Fe-Mg-Ca carbonates. Garnet, cpx, and ilmenite were present at the solidus for all the compositions investigated. The solidus of carbonated eclogite decreases from ca. 1200 °C to ca. 1050 °C as the molar Ca/(Ca+Mg) and Na₂O of the bulk starting material was changed from 0.52 to 0.42 and 1.4 to 1.75 wt.% respectively (molar Ca/Na decreased from ~13 to ~9). Also, the solidus of SLE+5 wt.% calcite is near 1125 °C, but with 10 wt.% calcite it is ~1200 °C.

Larger amounts of added calcite produce near-solidus melts with higher Ca/(Ca+Mg) and Ca/Na, and consequently a higher solidus. Thus, experiments with large amounts of added CO₂ may not be easily applied to natural carbonated eclogite, which has a small proportion of CO₂, unless the experimentally-added carbonate produces liquids similar to those expected near the solidus of natural bulk compositions.

V12C-0605 1330h POSTER

Grain-Scale Processes during Isobaric and Isothermal Melting of Lherzolite

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During partial melting of spinel lherzolite at moderate pressures olivine and melt are produced at the expense of pyroxenes and spinel via the reaction $\text{cpx} + \text{opx} + \text{sp} \rightarrow \text{ol} + \text{melt}$. In detail, however, the grain-scale processes through which this melting reaction takes place are still not well understood. For example, the zonation in residual pyroxenes of most lherzolite melting experiments is attributed to simple solid-state diffusion during re-equilibration. However, recent theoretical studies have shown that more complicated processes such as dissolution and re-precipitation are likely to take place during isothermal and isobaric melting of solid solution forming minerals. To better understand the grain-scale processes of lherzolite melting in the laboratory, we conducted a series of partial melting experiments at 1340°C and 1.5 GPa for 48 to 80 hours using reaction couples formed by juxtaposing pre-synthesized harzburgite against pre-synthesized melt-bearing clinopyroxenite. Starting minerals were from a fertile spinel lherzolite xenolith. A typical quenched experimental charge consists of three zones separated by nearly planar interfaces: 1) ol + opx (harzburgite) + melt, 2) a reaction zone made of ol + cpx + melt, 3) cpx + melt. The reaction zone is opx-free and its thickness increases with time (up to 250 μm after 80 hours) at the expense of the harzburgite. Modal abundance of cpx decreases in the reaction zone whereas the mode of olivine and the melt increases with time. Olivine grain size is also significantly larger in the reaction zone than in the harzburgite. Detailed microprobe traverses across the charge and X-ray intensity maps of selected elements of the reaction zone, show that individual olivine grains are not zoned, whereas individual cpx grains are zoned and vary in composition within the reaction zone. Clinopyroxenes are rich in MgO, FeO, and SiO₂ near the harzburgite, and rich in CaO, and jadeite component near the clinopyroxenite. When plotted in an oxide or 6-oxygen based cation correlation diagram, such as Al³⁺ vs. Ca²⁺, the variations in composition exhibited by our pyroxenes are virtually identical to the pyroxene core-to-rim variations reported in recent lherzolite partial melting studies that were conducted under similar run conditions. Pyroxenes and olivine Mg# are 91.8 and nearly constant through out the charge except in the reaction zone where cpx Mg# decreases down to 90.5. The systematic variations in mineralogy and mineral chemistry of our experiments are consistent with a process where three fundamental mechanism of dissolution and re-precipitation are operating at the same time: 1) complete dissolution of orthopyroxene due to the reaction with the melt-bearing clinopyroxenite, 2) diffusive mixing of the dissolved opx and cpx component in the melt, 3) precipitation in the reaction zone of cpx with low jadeite component and olivine around pre-existing olivine grains. Thus, the cpx of varying composition in the reaction zone cannot be produced by diffusion in the solid alone because cation diffusion rates in cpx are too slow. The dominant transport mechanism here is diffusion in the melt. It is possible that the same process is producing the pyroxene zonation observed in other lherzolite melting studies. One of the objectives of this study will be to determine whether local equilibrium is achieved during partial melting of lherzolite and its implications for trace element fractionation.

V12C-0606 1330h POSTER

Experimental Determination of the Liquid Line of Descent of Anhydrous Mantle Derived Tholeiitic Liquids by Fractional and Equilibrium Crystallisation at 1.0 GPa

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To constrain phase equilibria as well as solid and liquid compositions along the liquid line of descent of primary basaltic magmas in reservoirs that are located at the base of the continental crust, two series of anhydrous experiments have been performed in end-loaded piston cylinder apparatus at 1.0 GPa pressure and temperatures in the range 1060 to 1330°C. As starting material an experimentally produced mantle-derived tholeiitic basalt that is in equilibrium with a lherzolite residue at 1.5 GPa and 1300°C (Hirose & Kushiro, 1993; EPSL 114, 477-489) was used. The first series are equilibrium crystallisation experiments on a single bulk composition. For the second series a step-wise approach was used to achieve near-perfect fractional crystallisation: Melting experiments were performed with temperature steps of 30°C and starting compositions corresponding to the liquid composition of the previous, higher temperature glass composition. Liquids of fractional crystallisation experiments evolve through constant silica increase from basalts to dacites, whereas liquids from equilibrium crystallisation experiments remain basaltic and display only a moderate SiO₂ increase accompanied by more pronounced alumina enrichment. Responsible for these contrasting trends are suppression of the peritectic olivine + liquid = opx reaction and earlier plagioclase saturation in the fractionation experiments compared to the equilibrium experiments. At high pressure both processes form large volumes of ultramafic cumulates related to the suppression of plagioclase crystallisation relative to pyroxenes. This is in contrast to fractionation of tholeiitic liquids at low pressures, where silica is enriched in the latest stage of differentiation and early fractionation of plagioclase lead to the production of troctolites followed by (olivine-)gabbros. Compositional variation of pyroxenes and plagioclase are influenced by the fractionation process. In fractional crystallisation experiments, the Al content systematically decreases at lower temperature while in equilibrium crystallisation it does not. Thermodynamic calculations using the MELTS program indicates that the Al activity in the liquid exerts a fundamental control on Al partitioning between liquid and pyroxenes. Likewise different An contents in plagioclase at similar CaO/Na₂O ratios in the liquid are controlled by Na and K activity in the residual liquid. This suggests that liquid composition potentially is an important factor in controlling crystal-liquid partitioning.

V12C-0607 1330h POSTER

Hydrous and anhydrous garnet-bearing mantle xenoliths from Hawaii: Isotopic Heterogeneity?

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This study focuses on the petrography, major element mineral chemistry, and bulk-rock trace element and Sr-Nd isotopes compositions of a suite of garnet-bearing xenoliths from Oahu, Hawaii, in an attempt to answer the following questions: (1) Are these xenoliths restites, cumulates, or frozen melts? (2) Are they related to Koolau-like (shield stage) magmas or post-erosional Honolulu Volcanics (HV)-type magmas? Large clinopyroxene (cpx) is the dominant phase; however, large garnet (gt), orthopyroxene (opx), olivine (ol), and spinel (sp) are also present. Some xenoliths also have trace (less than 1 percent) amounts of phlogopite of different shapes and sizes. Cpx has exsolved opx, sp, and gt. Mineral chemically, cpx is a low-Cr, high-Al, Na, Ti, and Fe/Mg variety. Garnet is a low-Cr and high Fe/Mg type. The Mg#s of cpx and gt range from 74-85 and 61-74, respectively. The Mg# of opx ranges from 80-84. Spinel are of the pleonaste type. Chemical traits of cpx, gt, and sp indicate that these xenoliths cannot be treated as either restites or frozen melts. Post-exsolution and "igneous" stage temperatures based on cpx-gt thermometry range from 950-1350°C and 1290-1470°C. Cpx and gt are in Mg# equilibrium with each other. Opx has not equilibrated with cpx or gt in terms of Mg/Fe. The anhydrous xenoliths are distinct from the Pacific-MORB and Koolau, but are virtually identical to the HV lavas, confirming previous suggestions that the garnet pyroxenites are genetically related to parental magmas. However, some hydrous xenoliths have more radiogenic Sr isotope (for a given Nd) than both HV and the anhydrous xenoliths, and fall outside the compositions of the Hawaiian lavas in the Sr-Nd isotope space. From Sr-Nd data on these xenoliths, the following becomes clear: (1) All the anhydrous and some hydrous xenoliths pyroxenite are virtually identical to the HV; (2) Higher Sr isotope compositions of the hydrous variety indicates that water-bearing phases may be partially responsible for

the isotopic heterogeneity among this suite of xenoliths. It is proposed here that later melts that are perhaps hydrous infiltrate these lower lithospheric xenoliths, resulting in the precipitation of phlogopite (of different Sr isotopic composition) in relatively anhydrous, high-pressure crystal extracts.

V12C-0608 1330h POSTER

Trace element partitioning between clinopyroxene and silicic alkaline, aluminous melts

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Clinopyroxene is considered the most important phase for controlling the partitioning of trace elements during mantle melting. Glasses rich in silica, alumina and alkalis are often found in mantle xenoliths and could coexist with lherzolitic and harzburgitic assemblages, possibly being produced by the diffusive infiltration of alkali process. We have investigated CPX-melt partitioning for two different silica-rich bulk compositions in order to understand how melt polymerization influences element partitioning. Starting materials were synthesized from high purity oxides and corresponding to observed glasses from experiments by Draper and Green (EPSL 170, 255, 1999) and silicic glass found within a harzburgite xenolith studied by Vannucci et al. (EPSL 158, 39, 1998). Experiments were run in a piston cylinder apparatus in unsealed graphite capsules. The Draper composition produces a melt with 62 wt% SiO₂ and 11.8 wt% total alkalis coexisting with olivine (Fo90), orthopyroxene and clinopyroxene at 1.1 GPa and 1145°C. The Vannucci composition produces a melt with 67 wt% SiO₂ and 8.1% total alkalis coexisting with diopsidic clinopyroxene at 1 GPa and 1155°C. Selected run products were analyzed for major element composition by EPMA (University of Chicago) and trace element composition by laser ablation ICP-MS (University of Maryland). The most important result is that the heavy rare earth elements (HREE) are compatible in clinopyroxene as previously observed (Blundy et al., EPSL 160, 493, 1998). Four experiments all produce smoothly changing REE patterns with La being slightly incompatible, Sm being slightly compatible and the pattern peaking at Er with Dyb always less than DEr. High field strength elements and U and Th have partition coefficients in the low 10⁻² range. These results may imply that element partitioning in the shallow depleted melting column could produce REE patterns similar to those expected for melting in the garnet stability field.

V12C-0609 1330h POSTER

An alternative model for within plate basalts generation suggested by their major elements, trace elements and Pb-Sr-Nd isotope compositions

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Based on geochemistry, the recent favor model for within-plate basalts (WPB) is plumes with eclogite originally formed by inversion of basaltic oceanic crust into eclogite in subduction zones (e.g. Hauri, 1996). Melting experiments of basalt/peridotite hybrids (Kogiso and Takahashi, 1998), however, have demonstrated that the hybrid source model could not explain major element features of WPB, such as FeO* enrichment and Al₂O₃ depletion compared with MORB. Melting experiments of peridotites and basalt/peridotite hybrids indicate that the sources of WPB are peridotites abnormally enriched in FeO*. Such Fe-rich sources could not be formed by extraction of basalt melt from typical peridotite or mixing of basalt and typical peridotite. A potential candidate for the abnormally Fe-rich source is Archean peridotitic komatiite (APK) which is enriched in FeO* compared with typical peridotite. Attractive features of the recycled APK melting model are as follows: 1) It explains why within-plate basalts are FeO*-rich and Al₂O₃-poor relative to MORB because of large proportion of cpx in APK. 2) Moderate partial melting of APK forms LREE-enriched partial melts because of selective fusion of cpx. 3) It explains near bulk earth Nd isotope compositions because of relatively flat REE patterns of APK. 4) Archean age of APK is consistent with Pb isotope of WPB suggesting their sources have Archean age. 5) Compositional spectrum of Archean komatiite suites ranging from peridotitic komatiite to basalts explains that of WPB from silica-undersaturated basalt to silica-oversaturated andesite.

V12C-0610 1330h POSTER

Melt Evolution Beneath Mid-Ocean Ridges and Mantle Plumes From a Coupled Thermodynamic and Geodynamic Model

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We have developed a model that combines a Gibbs free energy minimization routine incorporating the thermodynamic database for melts, pMELTS (Ghiorso et al., G3, 2002) and a geodynamic multiflow 2D numerical model that solves transport equations for mass, heat, momentum and chemical elements. The effects of latent heat, viscous dissipation and adiabatic heating are also included in the model. For brevity only few common features for melting in mid-ocean ridges and plumes are discussed here. Local equilibrium approximation is the main assumption of the model (Knapp, GCA, 1989). From experimental data on diffusion in mantle minerals, the approximation seems reasonable if porous flow is assumed as the mechanism of melt transport within the molten region. Channeling flow, induced by dissolution reactions (melting) (Spiegelman et al., JGR, 2001), is observed through large portions of the mantle. The location of the channels is extremely variable in time and size. Channels are defined here as mantle regions where melt fraction is approximately 2-3 times higher than the surrounding mantle and where melt transport is still controlled by porous flow. Melt far from the plume/ridge axis accumulates at the base of the lithosphere (Sparks and Parmentier, EPSL, 1991) and the residence time in this area determines periodic fluctuations in the melt extraction to the surface. In the plume model, reactivation of the melting process is observed at about 350 km from the plume axis. Petrology and geochemistry of residual solids and melt are the result of a polybaric process with continuous melt mixing. Preliminary comparison with data from lavas, melt inclusions, abyssal peridotites and mantle nodules shows that the model, within the limits of the available thermodynamic database, produces petrological and major elements geochemical variability similar to that observed in natural samples.

V12C-0611 1330h POSTER

Mantle Heterogeneity Beneath the Southwest Indian Ridge (9° - 25° E)

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Recent isotopic measurements of 20 glasses from 9° to 25° E on the Southwest Indian Ridge reveal striking correlations with trace element data. The isotopic variation in Sr, Nd, Hf, and Pb of these lavas confirms that along-axis heterogeneity exists in the MORB source beneath this part of the SWIR. Major and trace element systematics and isotopic compositions indicate that the along-axis variation in basalt chemistry, specifically the contrast between orthogonal supersegment and oblique supersegment lavas, can likely be explained by 1) variable extents of melting of a heterogeneous depleted peridotite lithology, or 2) variable extents of melting of a two component MORB source; a heterogeneous depleted peridotite lithology and a pyroxenite/eclogite lithology of varying proportion. This chemical variation is coupled with distinct tectonic and morphologic differences between the orthogonal supersegment and the oblique supersegment. One of the most noticeable differences between the two segments is the spreading geometry. The orthogonal supersegment spreads nearly perpendicular to the spreading axis, while the oblique supersegment spreads at up to 35° from the axis. This abrupt change in ridge obliquity results in an effective spreading rate or mantle upwelling rate on the oblique supersegment as low as 4.5 mm/yr (half-rate), which may dramatically influence the thermal structure of the melting zone. Systematic enrichment of the mantle source from east to west along the orthogonal supersegment (16° to 25° E) is contrasted with a more variable, but more highly enriched isotopic and trace element composition on the oblique supersegment (9° to 16° E) (Figure 1A; see link below). Present day influence from the Bouvet Hotspot is unlikely, as the oblique supersegment lies nearly 800 km to the east, and the most enriched lavas are found on the eastern end of the oblique supersegment. Interestingly, the two areas of high magmatic flux on the oblique supersegment, Joseph Mayes Seamount, an axial volcano, and Narrowgate, a long-lived cross-axis volcanic high, have very different isotopic signatures, further suggesting a difference in the source composition or possibly a difference in the amount of time-integrated depletion of each residual mantle column. Figure 1B (see

link below) illustrates a well-defined linear correlation between 143/144 Nd and La/Sm (normalized to chondrite) for both oblique supersegment (filled) and orthogonal supersegment (open) lavas. This strong coupling of trace element and isotopic ratios supports our interpretation of a heterogeneous mantle source, but also presents the possibility that the observed glass compositions are the result of variable melting parameters (depth, extent, temperature). Isotope ratios are also generally correlated with major element indices, such as K/Ti and Mg#, providing additional constraints on the petrogenetic evolution of these basalts and lithologic character of the depleted upper mantle. Forward modeling of peridotite versus pyroxenite/eclogite melting should provide useful constraints on the source composition, while inverse trace and major element modeling will add additional limits on the amount of melting on each segment.

URL: <http://www.whoi.edu/science/GG/jstandish/Fall03agu.jpg>

V12C-0612 1330h POSTER

Channelling of Melt Above Plumes and Beneath MORs

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We investigate melt transportation in partially molten rocks under different stress fields above the head of a mantle plume or beneath a spreading mid-oceanic ridge under hydrous and anhydrous conditions. We model such aggregates with the 2D-FD code FD-CON [1] by means of a porous deformable matrix with melt under the influence of a given stress field to clarify the following key questions: Could channeling occur in a matrix containing a random melt distribution under a given stress field? Which orientation does it take? Is it possible to achieve a focusing of melt towards a MOR (dykes)? Does applying simple or pure shear to the matrix result in a difference in the formation and orientation of channels? How does the channel instability evolve during finite simple shear? In a deforming partially molten aggregate, weakening of the solid matrix due to the presence of melt creates an instability in which melt is localized by the following mechanism: regions of initially high melt fraction are areas of low viscosity and pressure, so that melt is drawn into these regions from higher pressure surroundings. This further enhances the melt weakening, producing a self-excited localization mechanism [2]. The channeling developing in models with a random melt distribution of $3.5 \pm 0.5\%$ shows that melt is accumulated preferably in inclined channels. For both, simple as well as pure shear, the growth rate is highest for an orientation parallel to the direction of the maximum compressive stress and proportional to applied stress and the reverse of the Melt Retention Number. This also confirms the theoretical growth rate found by Stevenson [2]. In our isothermal models we found that the influence of water reduces the growth rate, in contrast to non-isothermal models of Hall [3]. Under simple shear melt channels evolve from an irregular melt distribution at angles of 45 degrees to the direction of shear. Upon further straining they rotate out of the orientation of maximum growth rate and partly disrupt. At later stages the mean channel orientation deviates from the compressive stress orientation. We further seek to clarify which physical quantities may affect the orientation of channels and their wavelengths. Possible factors are the compaction length and the nature of the stress field. The latter assumption will be tested combining pure and simple shear. References [1] H. Schmeling. Partial melting and melt segregation in a Convecting mantle. Physics and chemistry of partially molten rocks; N. Bagdassarov and D. Laporte and A. B. Thompson, Kluwer Academic Publishers, 141-178, 2000 [2] D.J. Stevenson. Spontaneous small-scale melt segregation in partial melts undergoing deformation. Geophys. Res. Lett., 16(9):1067-1070, 1989 [3] C.E. Hall and E.M. Parmentier. Spontaneous melt localization in a deforming solid with viscosity variations due to water weakening. Geophys. Res. Lett., 27:9-12, 2000

V12D MCC: Level 1 Monday 1330h

Igneous Differentiation Posters

Presiding: F J Spera, University of California, Santa Barbara

V12D-0613 1330h POSTER

Open-System Magma Chamber Evolution: an Energy-Constrained Geochemical Model Incorporating the Effects of Concurrent Eruption, Recharge, Imperfect Assimilation and Fractional Crystallization (EC-E'RA_χFC)

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Geochemical data for many plutonic and volcanic cognetic suites provide overwhelming evidence for open system behavior. Significant petrogenetic processes influencing the geochemical evolution of magma bodies include magma Recharge, heating and partial melting (Assimilation) of country rock, formation and separation of cumulates by Fractional Crystallization and the formation of enclaves by rapid chilling of newly-intruded recharge magma. We have extended the EC-RAFC trace element and isotopic geochemical model (Spera and Bohrsen, 2002; Bohrsen and Spera, 2002) to include the effects of magma Eruption and variable amounts of assimilation, A_{χ} . The EC-E'RA_χFC model tracks the geochemical path (trace element and isotopic composition) of magma body melt (host melt), eruptive magma, cumulates and enclaves for magma undergoing simultaneous eruption, recharge, assimilation and fractional crystallization as a function of magma temperature. EC-E'RA_χFC is formulated as a set of $4 + t + i + s$ coupled nonlinear ordinary differential equations, where the number of trace elements, radiogenic and stable isotope ratios simultaneously modeled are t , i and s , respectively. There are no limitations on the values of t , i or s . Solution of the EC-E'RA_χFC equations provides values for the average temperature of wall rock (T_a), mass of host melt within the magma body (M_m), masses of cumulates (M_{ct}), enclaves (M_{en}) and wall rock involved in the thermal interaction (M_{ao}), the mass of anatectic melt generated (M_{a*}) and assimilated (χM_{a*}), the concentration of t trace elements and $i+s$ isotopic ratios in host melt (C_m), eruptive magma, cumulates (C_{ct}), enclaves (C_{en}) and anatectic melt (C_a) as a function of magma temperature (T_m). Input parameters include the (user-defined) equilibration temperature (T_{eq}), the efficiency of mixing of anatectic melt factor (χ), the initial temperature and composition of pristine host melt (T_{mo} , C_{mo} , c_{mo}), recharge melt (T_{ro} , C_{ro}) and wall rock (T_{ao} , C_{ao}), distribution coefficients (D_m , D_r , D_a) and their temperature dependencies (ΔH_m , ΔH_r , ΔH_a), heat of transition for wall rock (ΔH_a), pristine (ΔH_m) and recharge (ΔH_r) and the isobaric specific heat capacity of assimilant ($C_{p,a}$), pristine ($C_{p,m}$) and recharge melt ($C_{p,r}$). The magma recharge mass and eruptive magma mass functions $Mr(T_m)$ and $Me(T_m)$, respectively, are specified a priori and allow one to predict the effects of recharge and magma eruption on the geochemical evolution of the system. Melt productivity functions, which prescribe the relationship between melt mass fraction and temperature, are defined for end-member bulk compositions characterizing the local geologic site. EC-E'RA_χFC makes testable quantitative predictions for relative masses and compositions for volcanic and plutonic products of magma system evolution which can be compared to information gathered from field studies to critically test petrogenetic hypotheses. The 'systems' approach to understanding magma chamber evolution promises to enhance the ability to describe the efficacy of petrologic processes in various petrotectonic settings. Illustrative examples of complex EC-E'RA_χFC simulations are presented to highlight the salient features of the model.

URL: <http://magma.geol.ucsb.edu/>

V12D-0614 1330h POSTER

Closed System Behavior of Trace Elements During Basalt Crystallization in the Makaopuhi Lava Lake, Hawaii.

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