Based on a compilation of whole-rock Pb isotopic compositions of Precambrian juvenile intrusions we conclude that; 1) Rocks in ca. 2.8-2.6 Ga, ca. 2.0-1.8 Ga, and ca. 1.3-1.0 Ga age-provinces in eastern Laurentia have coherent Pb isotopic signatures that vary systematically as if they were derived from the same homogeneous mantle reservoir that evolved with a constant μ-value. 2) Signatures of ca. 1.3-1.0 Ga age provinces from Amazonia, Antarctica, Australia, Baltica, Kalahari, Oaxaca, and Laurentia overlap each other and define two global Pb isotopic signatures suggesting the presence of at least two large, isotopically-distinct mantle reservoirs during the Mesoproterozoic. Pb isotopic compositions of modern oceanic crust indicate the existence of two Mesozoic/Cenozoic, isotopically-distinct mantle reservoirs, referred to as "normal" mantle in the northern hemisphere and DUPAL mantle in the southern hemisphere. Compositions of Precambrian juvenile intrusions indicate that similar, long-lived reservoirs may have existed earlier in Earth's history.

V42D-0389 1330h POSTER

Ion Microprobe U-Pb Dating and REE Analysis of Apatite from Kerogen-rich Silica Dike from North Pole Area, Pilbara Craton, Western Australia

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In order to provide a time constraint on the 13C-depleted kerogen in silica dikes that intruded 3.5 Ga greenstone from Pilbara Craton in Western Australia, we have carried out an ion microprobe U-Pb dating and rare earth element (REE) analysis of apatite from the dike. Two types of apatite were identified in the dikes based on their occurrences. One is stick-shape apatites (Type 1) in secondary silica micro-veins that cut the silica dike. The other is granular apatites (Type 2) that occurs in matrix of the dike. Occurrence in the secondary micro-veins (Type 1), non-igenous chondrite normalized REE patterns (Type 1 and 2), chemical zoning (some of Type 1 and 2), and presence of mineral inclusion that is composed of Fe and S (some of Type 2) suggest that both Type 1 and 2 apatites were crystallized in the silica dike. Ion microprobe U-Pb dating of Type 1 apatite did not give a meaningful age, while Type 2 apatite yields a Tera-Wasserburg concordia intercept age of 3214 +/- 140 Ma (95 per cent confidence level, MSWD = 0.6) in a three-dimensional 238U/206Pb-207Pb/206Pb-204Pb/206Pb diagram, and a 204Pb/206Pb-207Pb/206Pb isochron age of 3191 +/- 150 Ma (95 per cent confidence level, MSWD = 0.5). It is difficult to judge whether the U-Pb and Pb-Pb age of Type 2 apatite is crystallization age or metamorphic age, since the estimated range of closure temperature of U-Pb system in the apatite and that of metamorphic temperature is partly overlapped. In either case, it can be safely concluded that the minimum age of the dike and kerogen is 3.0 Ga. These ages might allow the interpretation that the kerogen was produced by biological carbon fixation and/or abiological reaction (such as Fischer-Tropsch Type reaction) at least before 3.0 Ga.

V42D-0390 1330h POSTER

Flux and size fractionation of IDP-borne ^{3}He from Antarctic ice core samples

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Previous measurements of helium isotopes in particles from polar ice yielded extraterrestrial ^{3}He fluxes similar to results from marine sediments (Brook et al., 2000, GRL, 27, 3145-3148). The agreement is surprising since the area-time product (sample mass divided by mass accumulation rate) for these samples is relatively small. We now report new helium measurements from larger samples of the Vostok Ice Core (Antarctica) and results of a series of size fraction experiments designed to determine the dominant particle size transporting ^{3}He in Interplanetary Dust Particles (IDP's) to earth. The mean ^{3}He flux from 8 longitudinally cut replicate ice samples (821-1201 g each) from the 112-115 m interval (3.8-4 ka) at Vostok is 1.1$\pm$0.3 x 10^{-12} cm^3 STP cm^{-2} ka^{-1}. These samples have a mean area-time product of 0.05 m^{2}a, which is 5 times that of the previous ice measurements. The inferred ^{3}He fluxes are similar to values previously reported from late Quaternary ice samples and marine sediments, further demonstrating the potential of ice cores as archives of ^{3}He accretion. We also separated dust from one 1.5 kg sample of Vostok ice into 5 size fractions, >63, 20-63, 10-20, 5-10, and 0.45-5 microns, using sieves and filters. Models predict that most ^{3}He in IDP's is carried in relatively large particles, in the 5-35 micron range. However, the new data shows that over 76% of the ^{3}He is found in the 5-10 micron size interval, and only 18% of the ^{3}He in size classes larger than this. Implications for reconstructing the IDP ^{3}He flux will be discussed.

V42E MCC: 3008 Thursday 1340h

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

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

V42E-01 1345h

Eclogitic Minerals in Diamond: MORB Reincarnated

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Following participation in creation of oceanic lithosphere, MORB and related rocks can be altered, contaminated and eventually subducted. Evidence for these processes survives in Alpine eclogites, subcratonic eclogite xenoliths and especially in some diamonds. One of the key pieces of evidence exists as anomalous oxygen isotope values of silicates in these high-pressure assemblages. Sea floor alteration changes the d18-O VSMOW values of MORB from +5.7 +/- 0.2 per mil in fresh samples, to values as high as +27 per mil in examples that have undergone low-T ocean floor weathering. High d18-O values are also found in ophiolite basalts (to +20 per mil) and Alpine eclogites (to +16 per mil), but d18-O values of mantle eclogite xenoliths are only somewhat anomalous (to +9.3 per mil). Using SIMS, we have studied the stable isotope composition of diamonds and their eclogitic mineral inclusions from Guaniamo, Venezuela, in situ in polished section. The d18-O values of six coesite inclusions in four diamonds are in the range +10.2 to +16.9 per mil, and eight garnets in five diamonds are in the range +8.8 to +12.9 per mil, with a ninth example at +5.5 per mil. As oxygen isotope fractionations are known to be small under mantle conditions, these data provide compelling evidence for an altered ocean floor basalt protolith for this eclogitic diamond suite. Carbon isotope values (d13-C PDB) of host diamonds are very low (approximately in the range -12 to -22 per mil), values considered by many workers to indicate a significant component of biogenic carbon in the diamonds. Two stones have higher values of d13-C (-7 to -8 per mil), more typical of mantle carbon, but also consistent with a crustal source. Although isotopically light carbon can be created by mantle fractionation processes, the correlation we have shown here between anomalous oxygen and carbon isotope signatures within single diamonds strongly supports a crustal biogenic source for the carbon in these diamonds.

V42E-02 1400h

The Composition of the Depleted Mantle

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We present an estimate for the composition of the depleted mantle (DM), the source for mid-ocean ridge basalts (MORBs). Several avenues are used to derive the estimated composition of the DM. Since trace element ratios can be better determined than absolute concentrations, absolute concentrations are only estimated for a few elements and the majority of the trace element concentrations are based on trace element ratios. The most reliable estimates of trace element ratios are estimates of parent-daughter ratios which are based on the isotopic composition of mid-ocean ridge basalts. These estimates form the "backbone of our trace element estimates. A second way of estimating trace element ratios is through the average composition of primitive normal-type mid ocean ridge basalts. A third group of estimates is derived from the elemental and isotopic composition of peridotites. The major element composition is obtained by subtraction of a low degree melt from a bulk silicate Earth composition. A last group of trace element ratios is derived from continental crust (CC). CC is thought to be approximately complementary to the DM and ratios that are chondritic in the continental crust are expected to also be chondritic in the DM. Volatile element and noble gas concentrations are estimated using constraints from the composition of MORBs and ocean island basalts (OIBs). We have varied the age of the DM and the isotopic composition of the DM to bring La/Nb and Ce/Pb within the range observed in primitive mid-ocean ridge basalts. Only a narrow range of ages, 1.6-2.2Ga, yields appropriate trace element ratios. Mass balance with continental crust indicates that the CC and this estimate of the DM are not complementary reservoirs.

V42E-03 1415h INVITED

Mineralogical and Seismic Heterogeneity of the Mantle; the Fate of Young Slabs

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Can we explain all terrestrial magmatism with a single unifying theory? If the mantle is convectively stirred to the point of homogeneity at all scales, then certainly not. Plate tectonics introduces heterogeneity into the mantle having dimensions of slabs. As a slab sinks it may become deformed or stretched if shear stress gradients are high. The Rayleigh numbers used in simulations of mantle convection lead to chaotic convection and rapid mixing. Plumes are invoked to reintroduce heterogeneity into the upper mantle. These calculations ignore effects of plates, continents, pressure, phase changes, and layered convection. Plate tectonics, lithosphere, continental roots, pressure effects, high Prandtl number, stratification and free-slip boundary conditions organize and impede mantle flow. The mantle, convecting sluggishly and passively, is not well mixed. Convective stirring takes time and heterogeneities are constantly being introduced into the shallow mantle. Processes at ridges, however, homogenize the products of heterogeneous mantle melting. New data confirms that under lower mantle (LM) conditions, material rich in Ca, Al and Na (i.e. eclogite) is less dense than pyrolite or any plausible LM mineralogy. The idea that slabs, particularly young ones, will be stuck in the UM is strengthened. Piclogite, particularly if carbonated, melts deeper and at lower temperature than normal mantle; it can develop low seismic velocities as it equilibrates (Presnall, 2003). About 15% of ocean floor surface area is composed of young (<20 My) lithosphere approaching trenches and in back-arc basins; roughly 0.2 km^3/year of such material is currently entering trenches. This is about the magma budget of 'midplate' magmatism. A similar area (plateaus, aseismic ridges) has thick crust. Young and thick-crust material does not subduct to great depths. It warms up and thermally equilibrates on short times scales, becoming neutrally buoyant, and can be sampled again by partial melting on characteristic time scales of 1-2 Gy at leaky transform faults, incipient plate boundaries, extensional regions of the lithosphere and migrating ridges. Thicker slabs of older oceanic crust are more likely to sink deeper into the mantle, after contributing their sediments and fluids to the shallow mantle. The upper mantle is therefore a highly heterogeneous assemblage of enriched and depleted lithologies representing a wide range in chemical composition, scales, ages, melting point, fertility, and isotopic compositions. The homogeneous nature of MORB usually attributed to long-term stirring and mixing of the mantle source is more likely due to homogenization near the extraction site by the sampling process (partial melting and magma mixing). Ubiquitous crustal and slab-scale heterogeneities comprised of recycled oceanic crust or lithosphere in the shallow mantle explains the statistical properties of oceanic basalts and may also be responsible for melting anomalies themselves. Shallow chemical heterogeneities cause

topographic and crustal thickness anomalies without substantial thermal anomalies. Scattering of high frequency seismic waves is one way to test this hypothesis. The anisotropy and anelasticity of the asthenosphere is consistent with such a structure .The presence of CO_2 in the upper mantle, long advocated by Dean Presnall, explains the missing-CO_2 problem (and the helium paradoxes) and, together with trapped young slabs, may be responsible for the low seismic velocities, Q, and melting anomalies, at 'normal' mantle temperatures. Shallow recycling of crust- and slab-sized objects obviates the need for concentrated hot jets localized under 'hotspot' volcanoes and deep mantle reservoirs.

V42E-04 1430h

The Implications of Different Geotherms for the Generation of Carbonatites, Kimberlites and Melilitites

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Dalton and Presnall (1998) and Gudfinnsson and Presnall (2003) determined the melting relations of model garnet lherzolite in the system CaO-MgO-Al_2O_3-SiO_2-CO_2 (CMAS-CO_2) at 3-8 GPa, 1245-1800°C. These phase relations comprise a divariant surface in P-T space. The high-temperature side of the surface is bounded by the solidus curve for garnet lherzolite in the CO_2-free system. At several hundred degrees lower temperature, the surface is bounded by the solidus curve for CO_2-bearing compositions as a carbonate phase joins the phase assemblage. The garnet lherzolite phase assemblage coexists with CO_2-bearing melts along the divariant surface, and continuous gradations occur between carbonatitic, kimberlitic, and melilititic melts. The carbonatite melts are generated at the lowest temperatures, while kimberlites are generated at higher temperatures as the CO_2 content of the melts decreases and the SiO_2 content increases. At a pressure below 4 GPa, the kimberlites grade into melilitites, which contain less MgO and more Al_2O_3 than the kimberlites. Parameterization of the compositions of all the phases as a function of pressure and temperature and the use of published algebraic methods allows modeling of the melting of any selected CO_2-bearing garnet lherzolite composition within the CMAS-CO_2 system, including incipient melting near the carbonate-bearing solidus. We have modeled the melting of a relatively CO_2-rich garnet lherzolite composition containing 0.15 wt% CO_2. Because of the low melting degrees involved, the melting paths closely approach solid adiabats. A relatively cool adiabat with a potential temperature (T_P) of 1310°C and a slope of 15°C/GPa intersects the carbonate-bearing solidus at a pressure of about 7 GPa, and the melting path follows the solidus for a narrow pressure range until all the carbonate is exhausted after about 0.3-0.4% melting. Melting continues in the divariant field, and at a pressure of 3 GPa only about 0.5% melting has occurred, generating carbonatitic melts only. An adiabat with a T_P of 1510°C intersects the carbonate-bearing solidus at a pressure considerably higher than the range of our data, but at 7 GPa the melt composition is about to change from carbonatitic to kimberlitic as the extent of melting has reached about 0.6-0.7%. At lower pressures, the melt changes from kimberlite to melilitite composition. Thus, elevated geotherms are needed to generate kimberlite and melilitite magmas. This requirement is lessened, however, if considerable amounts of water are present. For example, Price *et al.* (2000) came to the conclusion that the Jericho Pipe kimberlite magmas contained about 6% H_2O, which will lower the equilibrium temperature 200-300°C. The other most important mantle component not present in the CMAS-CO_2 system, FeO, is likely to have only small effect on kimberlite generation, but its effect on the stability of carbonates, and hence the generation of carbonatites, could be important. As carbonatite melts could become interconnected at less than 0.1% melting (Minarik and Watson, 1995), they may be highly mobile in the upper mantle, and as they commonly carry large amounts of incompatible elements, they could have an important effect on the trace element signatures of basalt lavas (Presnall *et al.*, 2002).

V42E-05 1445h

Experimental constraints on the role of pyroxenite partial melting in formation of basaltic magmas

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Mafic lithologies (pyroxenites) are a minor but ubiquitous component in the Earth's mantle, and may play an important role in formation of basaltic magmas. The volumetrically dominant composition of pyroxenite in the mantle may originate from ancient subducted oceanic crust and be similar to MORB, but a wide range of pyroxenite composition may exist in basalt source regions, as indicated by the diversity of pyroxenites sampled from xenoliths and alpine-type peridotite massifs. A variety of magmas can be produced from such diverse pyroxenite compositions, and it is important to reveal systematic relationships between bulk compositions of pyroxenite and their partial melts for understanding the influence of pyroxenite on the chemistry and dynamics of basalt generation. We review experimental phase equilibria associated with partial melting of pyroxenites to examine the relationship between bulk composition and melting relations. An important aspect of pyroxenite phase equilibria is the existence of the garnet-pyroxene thermal divide, defined by enstatite - Ca-Tschermak pyroxene - diopside plane in CMAS projections. This divide appears at pressures above ~2 GPa at which garnet and pyroxenes are the principal residual phases in pyroxenite compositions. Pyroxenites on the silica-deficient (olivine-rich) side of the garnet-pyroxene divide produce low-silica liquids that also plot on the silica-deficient side of the divide, and silica-excess (quartz-rich) pyroxenites generate silica-rich melts that plot on the silica-excess side of the divide. Many of the silica-poor partial melts from silica-deficient pyroxenites have nepheline-normative compositions, and the silica-rich partial melts from silica-excess pyroxenites principally have hypersthene- or quartz-normative compositions. Silica-deficient pyroxenites are generally richer in olivine component, and thus their partial melts generally have higher MgO contents than those from silica-excess pyroxenites. Changes in phase volumes of residual minerals are another key factor controlling partial melt compositions. The phase volume of garnet expands relative to clinopyroxene with increasing pressure, producing liquids enriched in CaO and depleted in Al_2O_3 at higher pressures. As many silica-deficient pyroxenites lack olivine during partial melting, they produce high Ca/Al liquids with moderate MgO contents, which have strong similarities to nepheline-normative OIB lavas from many hotspots. Silica-excess pyroxenites also produce high Ca/Al melts with low MgO contents at high pressures, which have similarities to the silica-rich endmember of Hawaiian tholeiites.

V42E-06 1500h

Stability of Carbonated Eclogite in the Upper Mantle: Experimental Solidus from 2 to 9 GPa

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Carbonates are pervasive alteration products of the oceanic crust and likely survive subduction-related dehydration and/or melting. Thus, significant quantities of carbonated refractory eclogite are probably delivered to the deeper mantle. The melting behavior of such recycled carbonate influences the fate of recycled carbon, determines the possible sources and depths of carbonated metasomatic melts in the mantle, and delimits the conditions under which carbonated eclogite may act as a source of carbonatite and other types of magmatic CO_2. We present partial melting experiments of carbonated eclogite that constrain the solidus and near solidus phase relations from 2 to 9 GPa. To simulate the near-isochemical nature of ocean floor carbonation, the starting material was prepared by adding 5 wt.% CO_2 in the form of a mixture of Fe-Mg-Ca-Na-K carbonates to a bimineralic eclogite from Salt Lake crater, Oahu, Hawaii. The starting composition is a reasonable approximation of carbonated oceanic crust from which siliceous hydrous fluid has been extracted by subduction. We find that melt-present versus melt-absent conditions can be distinguished based on textural criteria. Garnet and cpx appear in all the experiments. Between 2 and 3 GPa, the subsolidus assemblage also includes calcite-dolomite$_{ss}$ + ilmenite, whereas above the solidus (950-975 °C at 2 GPa and 1050-1075 °C at 3 GPa) calcio-dolomitic liquid appears. From 3 to 4.5 GPa, dolomite$_{ss}$ becomes stable at the solidus and the near solidus melt becomes increasingly dolomitic. Appearance of dolomite above 3 GPa is accompanied by a negative Clapeyron slope of the solidus, with the cusp located between 995 and 1025 °C at *ca.* 4 GPa. Above 4-4.5 GPa, the solidus again rises with increasing pressure to *ca.* 1245 °C at 9 GPa and magnesite becomes the subsolidus carbonate. Dolomitic melt coexists with magnesite + garnet + cpx + rutile between 5 and 9 GPa. If extrapolated to higher pressures, the carbonated eclogite solidus intersects the oceanic geotherm deeper than 400 km. Thus, eclogite cannot host carbonates in the asthenosphere. Carbonated eclogite bodies entering the convecting upper mantle would release carbonate melt in the mantle transition zone. Upon release, this small volume, highly reactive melt could be an effective agent of deep mantle metasomatism. Comparison of our eclogite-CO_2 solidus with that of peridotite-CO_2 shows a shallower solidus-geotherm intersection for the latter. This implies that carbonated peridotite is a more likely proximal source of magmatic carbon in oceanic provinces. However, carbonated eclogite is a potential source of continental carbonatites, as its solidus crosses the continental shield geotherm at *ca.* 4 GPa.

V42E-07 1515h

Chemical Order in Silicate Melts: Implications for Microscopic Origins of Mantle Melting Behavior

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Configurational thermodynamic properties of silicate melts (e.g. activity coefficient of silica) at high pressure govern composition of melts in equilibrium with mantle mineral assemblages. These properties are controlled by the distribution of framework units (e.g. $^{[4]}$Si, $^{[5,6]}$Si, $^{[4]}$Al), and the disorder among network-modifying cations (e.g. Ca^{2+}, Mg^{2+}, Na^{+}) in the melts (Lee, Fei, Cody, & Mysen, Geophys. Res. Lett., 2003, 30, 1845; Lee and Stebbins, Geochim. Cosmochim. Acta., 2003, 67, 1699). Spectroscopic data obtained in the diamond anvil cell (DAC) together with quantum chemical simulations, allow us to measure details of distributions of framework units and network modifying cations with varying pressure, temperature and compositions. Here we report structural details of model basaltic melts (sodium silicate and aluminosilicates with varying degree of polymerization) mainly using solid state NMR, vibrational spectroscopy and synchrotron X-ray with DAC. These results highlight the tendency for chemical ordering resulted from cation mixing in silicate melts and glasses at ambient as well as high pressure (6-10 GPa). The chemical ordering among framework units leads to the formation of $^{[5,6]}$Si-O-$^{[4]}$Si in silicates and $^{[5,6]}$Al-O-$^{[4]}$Si in aluminosilicates, contributing to the total negative deviation of silica activity from ideal solution in silicate melts at high pressure. Network-modifying cations also prefer to form dissimilar pairs (e.g. Ca-Na and Mg-Ba). These results indicate that there will be a further reduction in the activity coefficient of silica in multi-component melts. We also present modeling results of configurational enthalpy and entropy of multi-component silicate melts derived from the spectroscopic analysis and calculated the effect of degree of chemical order in melt properties. Increasing chemical ordering among framework units leads to a decrease in configurational entropy and enthalpy of melts, and also contributes to the decrease of silica activity coefficient in melts. Structural ordering in the melts, together with extensive mixing among framework units, strongly affect the composition of the partial melts. The alkali or silica content in equilibrium with mantle peridotite can increase as a results of these structural effects, thus manifesting the strong links between melt structures, properties and magmatic processes.

V42F MCC: 3006 Thursday 1340h

Modeling Metamorphism II *(joint with T)*

Presiding: **M. Brown,** University of Maryland**; B. Dutrow,** Louisiana State University

V

V42F-01 1345h INVITED

Heat production distributions and the geochemical self-organization of the crust

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The distribution of the heat producing elements within the lithosphere provides an important control on continental thermal regimes and the mechanical strength