V32F-07 1510h

The Origin of Continental Crust by Intracrustal Differentiation of Basalt in Magmatic Arcs: Trace and Major Element Evidence From Lower Crustal Eclogites Beneath the Sierra Nevada Batholith

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Continental crust (CC) is defined as that part of the crust that is unsubductable. Based on geologic observations, CC originates from island arcs or from intraplate magmatism (e.g., oceanic plateaus). However, the CC is andesitic in composition whereas island arcs and intraplate magmas are basaltic and represent direct mantle melts. The CC is therefore not mafic enough to be a direct mantle melt. Another fundamental imbalance is the low Nb/Ta (∼12) of CC with respect to primitive mantle (PM) (∼14). Nb and Ta do not fractionate during anhydrous mantle melting, such as beneath mid-ocean ridges. This suggests that during formation of CC, Nb is fractionated from Ta. Key to understanding the origin of CC is finding the "missing" high Nb/Ta and mafic reservoir(s). The two dominant hypotheses solving these chemical imbalances are direct melting of subducted eclogitized oceanic crust to form silicic melts, and intracrustal differentiation of basaltic crust into complementary felsic and mafic components, followed by physical removal of the mafic component. One attraction of the intracrustal differentiation model is that it is viable throughout geologic time, whereas the slab melt model is largely restricted to the Archean. The intracrustal differentiation model, however, is nearly impossible to test if the putative mafic complement to the CC has already been lost as is required by the model. "Eclogite" xenoliths (garnet-clinopyroxenites) erupted in Miocene diatremes in the Sierra Nevada arc, California represent one of extremely few localities where this "missing" mafic complement has been sampled. Here, we show that these "eclogite" xenoliths indeed have the necessary major element and HFSE (Nb, Ta, Zr, Hf) compositions to balance the andesitic composition of CC with respect to a basaltic parent. Ten "eclogites" were analyzed by XRF for major elements and by ICP-MS for trace elements. Preliminary results show that most of these xenoliths have Nb/Ta and Zr/Hf exceeding chondrite and recent PM estimates. On a Nb/Ta vs. Zr/Hf diagram, they lie off the terrestrial array towards anomalously high Nb/Ta. These Nb/Ta ratios are similar to those of Archean oceanic eclogites (AOEs), but differ distinctly in that the AOEs have largely subchondritic Zr/Hf. Mg and Ca concentrations are significantly higher than typical basalt whereas Al and Si concentrations are lower. The Sierran "eclogites" are therefore more mafic than typical basalts in contrast to the currently accepted average composition of the less mafic lower crust. On a MgO versus SiO2 diagram, a simple two-stage model for the origin of CC arises. Crystallization of average Sierran "eclogite" from primitive basalt can drive the composition of the residual melt towards the average composition of bulk CC, which subsequently undergoes further intracrustal differentiation to generate the petrologic differences we see in CC. The lack of Eu anomalies in the Sierran "eclogites" argues against an origin by subsolidus transformation from plagioclase cumulates to garnet-bearing lithologies. Instead, the Sierran "eclogites" represent high pressure cumulates where garnet and clinopyroxene are on the liquidus. We further propose that this "eclogitic" cumulate delaminates or founders back into the convecting mantle, imposing a deficit in mafic component in the CC. Alternatively, the "eclogite" may simply be seismically invisible. Because this simple model can explain most of the geochemical "paradoxes" of the CC and could have operated throughout Earth's history, we suggest that most of the continental crust originates from differentiation of basaltic magmas in arcs.

V32F-08 1525h

Generation of Sulfur-rich, Sulfur-undersaturated Basaltic Melts in Oxidized Arc Sources.

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Although sulfur is a minor element in the Earth, it has a disproportionate impact because it commonly occurs as sulfide. Sulfides largely control the behavior of chalcophile (e.g., Cu, Ni) and highly siderophile elements (Ru, Rh, Pd, Re, Os, Ir, Pt, and Au) that are of interest because either they are economically important or because they provide valuable information about geochemical processes. Island arc basalts are more oxidized than basalts from other tectonic settings and therefore, in these settings, sulfur maybe present not as sulfide but as sulfate. In addition to the impact on the behavior of chalcophile and siderophile elements, sulfur speciation as sulfate may have a role on the occurrence of sulfur-rich explosive volcanism, which has been linked to significant short-term variations in global climate. However, little is known about the range in oxygen fugacity for the transition from solubility as sulfide to solubility as sulfate. We used experimental data on the solubility of sulfur in basaltic melts saturated with either sulfide or sulfate at different oxygen fugacities to model this transition. Our model shows that the ten-fold increase in the solubility of sulfur (from 0.14 wt.% to 1.5 wt.%) observed experimentally occurs at oxygen fugacities between ∼FMQ+1 and ∼FMQ+2, conditions under which many arc magmas are thought to be generated. The increase in the solubility of sulfur with increasing oxygen fugacity implies that in oxidized arc sources very low degrees of partial melting are sufficient to generate basaltic melts that are simultaneously sulfur-rich and sulfur-undersaturated. In the absence of sulfides, oxides and metallic alloys may influence the behavior of some (but not all) the highly siderophile elements whereas the chalcophile and some siderophile elements become incompatible. As a consequence, melting of oxidized sources in which sulfides are not stable would favor incorporation of metals such as Cu, Ni, Au and Pd in the melts and increase the ability of those melts to generate Au-rich and Pd-rich ore deposits. In addition, partitioning of sulfur into a hydrous phase upon decompression and mixing of a sulfur-rich basaltic melt with water-rich felsic magmas provides a feasible mechanism to explain the sulfur-rich degassing observed in some volcanoes. We emphasize the importance of accounting for the oxidation state of sulfur when modeling magmatic processes in which sulfur is a key component, specially in arc magmas where sulfur is likely to be present both as sulfide and sulfate.

V32G MCC: 3008 Wednesday 1600h

Frontiers in High-Pressure Research: Earth's Deep Interior II *(joint with GP, MR, DI)*

Presiding: **B Kiefer,** New Mexico State University**; R J Hemley,** Carnegie Institution of Washington

V32G-01 1600h INVITED

Experimental and Theoretical Mineral Physics Challenges Posed by Core Formation and Evolution Models

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The current state of Earth's core is a legacy of its formation and evolution. It is likely that many of our notions of this are simplistic and arise from an ignorance of what took place, but this does not reduce the merit of considering the relevant experiments and calculations that are motivated by current ideas. The perspective I will adopt is that Earth's core is an ensemble of different sources: A source that may have formed in precursor bodies and thus reflects relatively low temperature, low pressure equilibration at a very early stage; a source that experienced high T and maybe P created immediately after a giant impact, a source that arises from equilibration at the base of a magma ocean (the most popular current idea) and perhaps a source that arises from core-mantle boundary interactions. I will accordingly focus on three kinds of challenges: (1) What is the behavior of metallic iron-liquid silicate mixing and equilibration under extreme temperature? This may be needed to understand some aspects of what happens during the prompt Rayleigh-Taylor instabilities that follow giant impacts. On general thermodynamic grounds, we expect immiscibility to decrease at high temperature. I will discuss likely estimates of critical temperature and how solubility should scale as temperature decreases.(2) What is the nature and consequences of dissolution from the core as the outer core cools? On quite general thermodynamic grounds, we can expect that the least soluble mantle constituent (probably MgO but not really known) is also the one most likely to become saturated in the outer core as the core cools. Silica or the combination with MgO (Mg perovskite) may also become saturated. I will discuss how this would show up in earth properties (e.g., seismology, geodesy) and how this would be important for the energy source for the dynamo. (3) How is the siderophile pattern of residual mantle affected by the likely equilibration between mostly solidified mantle and core-forming melt? This is relevant to the bottom of a magma ocean and the last equilibration of core forming liquid with mantle. The "bottom" of the magma ocean is rheologically defined and is therefore mostly solid, not liquid. In each of these cases I will describe what kind of experiments or calculations are needed to make progress.

V32G-02 1615h

Expanded Stability of the hcp Structure in Iron-Rich Alloys

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The Earth's core is composed of an Fe-rich alloy, with a solid inner core probably in the hcp structure. However, in pure Fe the hcp structure exists only at pressures too high, or temperatures too low, for many important geochemical measurements to be applied to the phase most relevant to the core, using standard multi-anvil apparatus. In the present work it is demonstrated that the stability of the hcp phase can be enhanced by alloying Fe with Ru or Os, permitting experimental investigation of Fe-rich hcp metal at lower pressures and/or higher temperatures than is possible in the pure Fe system. Pure metal starting materials were mixed with alumina to limit annealing and loaded in the 250 ton multi-anvil press at beamline 13-BMD at the Advanced Photon Source. The metal compositions were homogenized in situ at high P and T, and the phase diagram of the alloy composition was determined by synchrotron x-ray diffraction. Pressures were calibrated using the Au equation of state. At each P,T condition the sample was allowed to diffusively equilibrate; this was essential to obtaining reliable results. In the pressure range 5-15 GPa, it was found that 17 at% Ru, 26 at% Ru, and 29 at% Os in the alloy elevated the temperature limit of the hcp phase region by 250 K, 700 K, and 650 K, respectively, relative to pure Fe. At still higher T the hcp phase persists in fcc+hcp coexistence regions. An alloy containing only 10 at% Os had a fcc+hcp phase region extending 600 K above the hcp/fcc boundary of pure Fe, but the pure hcp phase region was not significantly expanded at this composition. The slopes of the phase boundaries are similar to that of the hcp/fcc boundary in Fe. The enhanced stability of the hcp structure demonstrated here is sufficient to permit investigation of chemical and physical properties of Fe-rich hcp alloys when the properties of pure hcp-Fe are inaccessible to experiment.

V32G-03 1630h

Frontiers of High-Pressure Research: Next Generation Large Volume Gem Anvil Devices

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By any measure, the diamond anvil cell has revolutionized static high-pressure research, and in particular experimental study of Earth and planetary deep interiors. Despite the prowess of the technique, however, its range of applicability is in many ways quite limited and its potential not yet fully realized. We have embarked on a program to develop the next generation high-pressure devices that will allow new classes of in situ high *P-T* measurements critical to understanding the structure, dynamics, and evolution of planetary bodies. A crucial component of this effort is the enlargement of sample volume without sacrificing the unmatched pressure range and versatility of diamond anvil cells. In conventional studies, pressures to several hundred GPa are generated on sample volumes down to the picoliter range. The small sample size is determined by the availability of perfect diamonds as anvils, which are currently of order of 0.2-0.4 up to a few carats. The small sample size has precluded, or greatly limited the accuracy of, certain classes of high pressure experiments. The production of high-quality single-crystal

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diamond by microwave plasma chemical vapor deposition (CVD) at very high growth rate of 50-150 μm/h has opened new opportunities for the creation of large perfect single crystal diamond as anvils.[1] This morphology, photoluminescence, Raman spectra, and mechanical properties of the CVD diamond have been examined in detail. Of particular interest is our finding of very high strength and improved optical properties of CVD diamond annealed at high pressures and temperatures.[2] In addition, hybrid conventional synthetic/CVD single crystals have been successfully used to generate pressures in the multimegabar range (>200 GPa).[3] A parallel initiative involves the continued development of moissanite anvils, which can already be produced as large, perfect crystals and can reach pressures above 60 GPa. Recent advances include the design and fabrication of supported moissanite anvils for enhanced sample volumes.[4] These developments will make possible new classes of high *P-T* experiments, including neutron diffraction, inelastic neutron scattering, various inelastic x-ray scattering measurements, magnetic resonance and susceptibility, ultrasonics, and rheological studies in the megabar range. [1] C.S. Yan et al., *Proc. Nat. Acad. Sci.* **99**, 12523 (2002) [2] C.S. Yan et al., to be published. [3] W. Mao et al., to be published. [4] J. Xu et al., to be published.

V32G-04 1645h

Study of Sound Velocities of Iron With Nuclear Resonant Inelastic X-ray Scattering Under High Pressure and Temperature

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Iron is the most important component in the Earth's core. Understanding its physical properties under high pressures and high temperatures is crucial for interpreting and constraining geophysical and geochemical models. We have built a double-sided YLF laser heating system to study iron with nuclear resonant inelastic x-ray scattering technique under simultaneously high pressures and high temperatures. Inelastic x-ray scattering spectra of hcp-Fe have been collected up to approximately 58 GPa and 1500 K in a laser-heated diamond anvil cell. Temperature-dependent inelastic x-ray spectra provide independent temperature measurement of the laser-heated iron, in which the measured temperatures were in fairly good agreement with temperatures measured from thermal radiation spectra fitted to Planck radiation function. This independent temperature measurement of the laser-heated sample confirms the validity of temperatures determined from Planck radiation law in the laser-heated diamond anvil cell experiments. Sound velocities of hcp-Fe are obtained from the measured phonon density of states up to approximately 58 GPa and 1500 K. The compressional and shear wave velocity of hcp-Fe decrease with increasing temperature under high pressures. Our results for the compressional and shear wave velocity of hcp-Fe show that the compressional and shear wave velocity are not linearly related to the density at high temperatures and pressures. This study also provides a new technique of measuring the melting curve of iron under extreme pressures.

V32G-05 1700h

Elastic And Vibrational Properties Of Cobalt To 120 GPa

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The elastic and vibrational properties of hcp Co were studied by impulsive stimulated light scattering (ISLS) and by Raman spectroscopy to 120 GPa at room temperature in a diamond anvil cell. At pressures above 60 GPa the shear elastic modulus and the Raman frequency of the E2g transverse optical mode exhibit a departure from a linear dependence on density. We interpret this behavior as evidence for the high-pressure hcp-fcc transition reported previously (C. S. Yoo et al., PRL 84, 4132 2000) that is related to the collapse of the magnetic moment under pressure.

V32G-06 1715h

Laser-driven shock compression on precompressed water: Exploring icy giant interiors

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Although the giant gas planets are comprised of mostly hydrogen and helium, the icy giants Neptune and Uranus are believed to be composed of ∼50% water (by mass), as well as significant amounts of methane and ammonia (Hubbard, 1984). Most of the water is in an ultra-condensed, high-temperature state forming an "icy" interior layer with pressures ranging between 10 and 500 GPa and temperatures between 2000 and 5000 K (Hubbard, 1997). It is theorized that it is in this hot, dense layer that the planet's magnetic field is produced. To explore the physical properties of water at the extreme conditions of this icy interior layer, we performed laser-driven shock experiments on precompressed samples accessing thermodynamic conditions unreachable by either static or single-shock compression techniques alone. Recent experiments using Rutherford Appleton Laboratory's Vulcan Laser achieved final pressures up to ∼200 GPa and temperatures up to 5,000 K in water samples precompressed in a diamond cell to ∼1 GPa, thereby validating this new technique.

V32G-07 1730h

Electrical Conductivity of SiO_2 above 1 Mbar

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Optical reflectivities of a few percent are detected when SiO_2 is shock-compressed above the melt transition, rising steadily with increasing pressure. Measurements of the optical reflectivity of laser-driven shock waves in α-quartz and fused silica were performed over a range of pressures above 1 Mbar. By comparing the reflectivities measured on the fused silica and α-quartz Hugoniots, which probe different regions of the SiO_2 phase diagram, we can infer the temperature dependence of the electrical conductivity for fluid SiO_2. The results have implications for understanding planetary phenomena ranging from mantle-core interactions to meteorite impact processes.

V32G-08 1745h

Accurate Determination of Fluid Thermodynamics at High Pressure and Temperature

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Prerequisite for geochemical modeling of deep earth systems are accurate thermodynamic properties of all constituents at elevated pressures and temperatures. Unfortunately, fundamental data above a few tenths of GPa are sparse and do not uniformly satisfy all thermodynamic cross relationships. We present an experimental strategy for the determination of an internally consistent and complete equation of state for fluids at high pressure. Sound velocities measured on a grid of pressure-temperature points can be recursively integrated to delineate density, heat capacity, thermal expansivity, energy, and all associated uncertainties. Using impulsive stimulated scattering to measure velocities of fluids in an externally heated diamond anvil cell, we have extended equations of state for several fluids into previously unexplored regimes of pressure and temperature. Properties of water have now been fully explored to 6 GPa and 673 K. The equation of state for water as recommended by the International Association for the Properties of Water and Steam (IAPWS) diverges less from experiment than other commonly used equations of state. However, even this formula predicts velocities that deviate from the highest-pressure measurements by almost 20 times the estimated experimental uncertainty. Uncertainty in densities range from 0.1% at 1 GPa (the IAPWS estimate) to 0.3% at 6 GPa (a regime formerly of prediction without associated uncertainty estimates). Heat capacities and thermal expansion have uncertainty of no more than a few percent. Hugoniot data are correctly predicted by a modest extrapolation of the new equation of state. Reinterpreted densities from inclusion studies to 3 GPa and 1873 K are also consistent with the new equation of state.

V32H MCC: 3006 Wednesday 1600h

Arc and Continental Magmatism II

Presiding: **J F Luhr,** Department of Mineral Sciences Smithsonian Institution**; A H Wulff,** Western Kentucky University

V32H-01 1600h

Recycling Lower Continental Crust: Evidence From High Mg Andesites in the North China Craton

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Magmatic additions to the crust are dominated by basalts, while the continental crust has an andesitic bulk composition. One way to explain this compositional dichotomy is to recycle mafic-ultramafic lower crust into the deep Earth through density foundering. However, such lower crustal recycling is a difficult hypothesis to test. Geological, geochemical and geophysical lines of evidence suggest that the deep lithosphere of the Archaean North China craton was removed at some point after the Ordovician, but the mechanism and timing of this lithosphere removal event is uncertain. Early Cretaceous high-magnesium adakite, andesite and dacite from western Liaoning, North China craton, have chemical and petrographic features consistent with their origin as partial melts of eclogite that subsequently interacted with mantle peridotite: they