

edge adjacent to the region where the lithologic boundary between the dikes and overlying extrusive section had been mapped by submersible dives. 2 of these profiles extended across the East Pacific Rise so that the shallow seismic structure could be continuously mapped from zero-age crust to the tectonic window where the shallow stratigraphy is exposed. The program also acquired 7 scarp-perpendicular MCS profiles, one of which extended across the Hess Deep rift onto the plateau adjacent to the south wall of the rift. Initial processing indicates that the layer 2A reflector is imaged on all profiles; additional processing will allow us to map the layer 2A/2B boundary across a 15 km x 25 km region. For all profiles travel times of refractions were picked on every 10th shot gather (every 375 m) and were also used to map the layer 2A/2B boundary along each profile. Patterns in layer 2A thickness are very consistent between adjacent profiles which are located 0.5-2.0 km apart. In at least part of the study region there is a good correlation between depth to the layer 2A/2B boundary and the observed lithologic boundary between dikes and the overlying extrusives; additional analysis will be required to determine if this correlation exists over the entire survey area.

#### T11B-05 0900h

##### Axial High Topography and Thermal Structure Along the Plume-Influenced Western Galapagos Spreading Center

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Recent studies propose that the axial high topography observed at intermediate- and fast-spreading mid-ocean ridges (MORs) reflects the thermal structure and stress state of the MOR lithosphere. Hotspot related variations in thermal structure along the western Galapagos Spreading Center (GSC) thus offer an opportunity to test some of the proposed causes for axial high topography. Along the intermediate rate spreading western GSC we observe axial high topography from ~92.5°W to 91°W similar to that seen along portions of the fast-spreading East Pacific Rise. In this region we see large variations in the amplitude of the axial high with the height decreasing dramatically with distance away from the Galapagos hotspot. The decrease in amplitude of the axial high corresponds remarkably well to an increase in the depth of the seismically imaged axial magma lens. Eberle and Forsyth (1998) suggest that dike injections above the magma lens relieve tension in the shallow crust and generate large vertical variations in horizontal stress. The resulting bending moment thus uplifts the ridge axis. Contrary to our observations at the GSC, their model predicts increasing uplift with increasing depth of the magma lens. Alternatively, Shah and Buck (2001) propose that the crust is hot and partially molten directly beneath the ridge axis and that material rapidly cools and accretes to the plate as it moves off axis. As it cools, the crust becomes more dense and tends to sink relative to the level at which it accreted to the plate resulting in a topographic high at the axis. If the axial magma lens is deeper, then the change in temperature with distance from the axis is reduced and the near-axis lithosphere is strengthened, resulting in a smaller axial high. Thus it appears that Shah and Buck's (2001) model is more consistent with our observations of the western GSC than Eberle and Forsyth's (1998) hypothesis. We can constrain the width of the region of rapid cooling off axis using seismic refraction studies, which show a zone of low seismic wave velocity beneath the ridge axis. Using constraints from multichannel seismic imaging of the axial magma lens, seismic refraction data, gravity and bathymetry measurements we will investigate aspects of the thermal structure of the western GSC between 93°W and 91.5°W including width of the hydrothermal cooling region, crustal strength, and percent melt present in the lower crust to further our understanding of the causes of axial high topography at mid-ocean ridges.

#### T11B-06 0915h

##### Plume-Ridge Interaction North of Iceland: Constraints from Crustal Thickness.

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Hotspot-ridge interactions affect the melt production at nearby mid-ocean ridges causing spatial and temporal variations in crustal thickness. We present results from a seismic refraction experiment to measure crustal thickness along and across the Kolbeinsey ridge north of Iceland. We surveyed a 230-km-long along-axis line, situated about 10 km east of the Kolbeinsey Ridge, and two cross-axis lines which are 710 and 140 km long, located 70 and 180 km north of the Icelandic coast, respectively. The ocean bottom seismometer spacing was 15 km along the ridge, 10 km across the ridge, and 30 km east of the Iceland margin. The seismic source was a 4800 cu. in. airgun array with 200 m shot spacing. For each refraction line, we invert *Pg* and *PmP* arrivals using the tomography method of *Korenaga et al.* (JGR, 1999). We find that crustal thickness decreases to the north along the Kolbeinsey Ridge; the crust is about 13 km (10 km) thick 200 km (400 km) from the center of the Iceland hotspot. The melt flux at the Kolbeinsey Ridge appears smaller than at similar distances along the Reykjanes Ridge south of Iceland; where crustal thickness is 16.5 km (12.5 km), at 200 km (400 km) from the hotspot center. This observation is consistent with the north-south asymmetry in geochemistry and ridge axis elevation; between 200 and 400 km from the hotspot center the axis of the Reykjanes Ridge is 500 m shallower than the axis of the Kolbeinsey Ridge. Thus the Iceland hotspot enhances melting more substantially at the Reykjanes Ridge than at the Kolbeinsey Ridge; this asymmetry has not yet been explained by geodynamic models. Quantifying crustal thickness will help determine whether the asymmetry in ridge axis depth can be explained isostatically or if dynamic support is required. Our across-axis profiles suggest undulations in crustal thickness similar to those associated with the V-shaped ridges of the Reykjanes Ridge. Thus temporal variability in the influence of the hotspot on spreading-center melt production is observed both north and south of Iceland.

#### T11B-07 0930h

##### Heat Flow and Hydrothermal Circulation of the Lucky Strike Segment, Mid Atlantic Ridge

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In June 2003, expedition Luckyflux aboard the R/V Poseidon conducted a heat flow survey of a zone centered on the Lucky Strike segment of the Mid Atlantic ridge south of the Azores between ~35°N and 39°N. Using a 5 m-long lance with 7 outrigger thermal probes, about 150 successful thermal gradient measurements were obtained, 140 of these with in-situ thermal conductivity. Measurements were made at ~1 mile intervals along several profiles, where adequately sedimented sites were identified using 6-channel and 3.5 kHz seismic data from the previous Sudazores'98 cruise. We conducted heat flow measurements in two areas: a near axis region within the V-shaped ridge of overthickened crust that emanated from the Azores hotspot between ~14 and 4 Ma, and an off-axis region East of the V-shaped ridge. The off-axis region is characterized by an homogeneous sediment cover, 300-400 m thick, and crustal ages varying between ~6 and >10 Ma. Long

wavelength (tens of km) low heat flow anomalies can be identified but the mean of 160 mWm<sup>-2</sup> is comparable to the conductive heat flow expected for a crust of that age. Along two 80-km profiles perpendicular to the ridge, we observed coherent but different patterns. On the first profile, low heat flow values of 20-50 mWm<sup>-2</sup> are observed at the base of the V-shaped ridge. These values are 100 mWm<sup>-2</sup> below the profile average, showing that hydrothermal circulations can also affect oceanic crust beneath a thick and relatively impermeable sediment cover. On the other profile, heat flow generally decreases from west to east. On both profiles, higher than average values of heat flow are also present, associated on one of them with a nearly outcropping basement elevation. These contrasting overall heat flow patterns in similar geological context indicate that the likely pattern of hydrothermal circulations is mainly 3D, and not driven only by the presence of basement outcrops. In the near-axis region, where the tectonic structure is more complicated and the sediment cover heterogeneous, heat flow data show no clear spatial variation and their mean value, 60 to 90 mWm<sup>-2</sup>, is systematically lower than theoretical conductive values for young seafloor. These heat flow differences will be used to estimate the importance of advection in the heat budget. This characterization of the regional thermal state around a slow-spreading segment will provide the basis for future long-term studies on the structure, thermal evolution and the hydrothermal systems within the MOMAR (MONitoring the Mid Atlantic Ridge) project.

URL: <http://www.ipgp.jussieu.fr/rech/lgm/luckyflux>

#### T11B-08 0945h

##### Ocean-floor Asymmetry and Its Relationship with Transform Faults

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Based on elevation data along 20 profiles across major divergent plate boundaries, a recent study (Doglioni et al., 2003 Tectonics) found that the eastern sides of the major oceanic and some continental rifts are on average 100-300 m higher than the conjugate western sides. The same study proposed that the asymmetry is caused by a global-scale westward shift of the lithosphere relative to the depleted and lighter asthenosphere. To verify the intriguing observation, we extract elevation data at about 473,000 locations along 2130 profiles of 1100 km in length on each side of the Mid-Atlantic Ridge (MAR), from a database of ocean-floor topography, and obtained the elevation difference between the east and west sides of the MAR. Interestingly, we find that the difference at most of the lithospheric blocks confined by the 22 longest transform faults (TFs) is closely related to the direction and amount of displacement along the faults. Positive difference (e.g., higher on the eastern than the western sides of MAR) is observed on blocks that drifted westward, and negative difference is observed on blocks that drifted eastward, suggesting that westward drift of lithosphere relative to the asthenosphere is not a global feature. On average, the east-west difference has a mean value of 155±7 m along the MAR in the latitude range between 50S and 50N latitudes. In addition, we found that the difference in east-west elevation is positively correlated with the amount of displacement along the TFs. The best-fitting curve suggest that a displacement of 100 km along the TFs leads to an east-west elevation difference of about 200 - 300 m. We propose a model involving movement of the lithosphere along the TFs relative to the location of maximum buoyancy in the asthenosphere to explain the observation.

#### T11C MCC: Level 1 Monday 0830h

##### New Views of the Structure and Composition of the Deep Earth I Posters (joint with GP, S, V, MR, DI)

Presiding: D L Farber, Lawrence

Livermore National Laboratory; J Badro, University Paris VI - Institut de Physique du Globe

#### T11C-0397 0830h POSTER

##### Kinetics of grain-growth in wadsleyite: implications for point defect chemistry

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We investigate the kinetics of grain-growth in wadsleyite for two reasons. First, grain-growth kinetics controls the grain-size of wadsleyite in the mantle transition zone which in turn controls the rheology in that region. Second, the detailed knowledge of grain-growth kinetics will provide us with important constraints on the defect-related properties of this mineral which may control other properties such as diffusion, electrical conductivity and creep. We carried out the grain-growth experiments by using KIWI 1000-ton Kawai-type multi-anvil apparatus installed at Yale University. Starting material was synthesized from powdered San Carlos olivine. The grain-growth experiments were conducted at 15 GPa and 1100-1500°C for 1-24 hours. We used Mo, Ni and Re foil capsules, in order to control the oxygen fugacity by metal-oxide buffer. For "wet" experiments (water-saturated), a mixture of talc and brucite was packed into a capsule together with a wadsleyite sample separated by metal foils. We used a Au-Pd outer capsule which is known to be a good barrier for hydrogen diffusion. Water content in each sample was determined after an experiment by FTIR analysis of a doubly polished thin section. Grain-size was measured on a polished section using an intercept method. One of the difficulties in these experiments is to reduce the amount of water in wadsleyite. Even in nominally "dry" experiments in which no water is added, a significant amount of water (upto  $\sim 25,000$  H/10<sup>6</sup> Si) was detected, which comes presumably from some components in the sample assembly such as the cement. This water-uptake by wadsleyite can be minimized by surrounding it with a Au-Pd capsule. In this truly "dry" sample assembly, the water content of wadsleyite (after an experiment) is reduced to less than  $\sim 100$  H/10<sup>6</sup> Si, a water content similar to typical "dry" experiments on olivine. Compared at similar water content, the kinetics of grain-growth in wadsleyite is significantly slower than that in olivine. The oxygen fugacity is shown to have a strong effect on grain-growth kinetics. At "wet" conditions, the grain-growth becomes significantly faster with increasing oxygen fugacity. In contrast, at "dry" conditions, preliminary results suggest that the effect of oxygen fugacity is opposite to the "wet" conditions. This suggests that the dominant defect that controls the rate of grain-growth may be different between "dry" and "wet" conditions. In contrast to the strong dependence of grain-growth kinetics on oxygen fugacity, the total amount of water dissolved in wadsleyite depends very weakly on oxygen fugacity. This implies that the defect that controls the rate of grain-growth in wadsleyite is different from the dominant defect. Our study demonstrates that chemical environment including water and oxygen fugacity has important influence on grain-growth kinetics in wadsleyite. Therefore careful control and/or characterization of chemical environment is essential in experimental studies on this type of defect-related properties, and the evaluation of effects of these parameters in Earth is needed when these results are applied to Earth.

**T11C-0398 0830h POSTER****Seismic structure near the inner core boundary around the South Pole**Toshiki Ohtaki<sup>1</sup> (t-ohtaki@aist.go.jp)Satoshi Kaneshima<sup>2</sup> (kane@geo.titech.ac.jp)Kenji Kanjo<sup>3</sup> (kkanjo@met.kishou.go.jp)Hiroshi Inoue<sup>4</sup> (inoue@bosai.go.jp)Ibnu Purwana<sup>5</sup> (ibnu@bmg.go.id)<sup>1</sup>Geological Survey of Japan, AIST, AIST Tsukuba Central 7, Tsukuba 305-8567, Japan<sup>2</sup>Dept. Earth and Planetary Science, Tokyo Institute of Technology, Ookayama, Tokyo 152-0033, Japan<sup>3</sup>Matsuro Seismological Observatory, JMA, Matsuro, Nagano 381-1232, Japan<sup>4</sup>National Research Institute for Earth Science and Disaster Prevention, Tennoudai, Tsukuba 305-0006, Japan<sup>5</sup>Bureau of Meteorology and Geophysics, Jl Angkasa 1 No.2 Kemayoran, Jakarta 10720, Indonesia

We deployed the broadband seismic network in central and western Indonesia called JISNET. Seismic waves from earthquakes of the southern South America to Indonesia pass through in the inner core beneath Antarctica. Using the waveforms observed at JISNET and other broadband stations around Indonesia, we analyze the seismic structure near the inner-core boundary (ICB) around the South Pole. We chose the data whose turning point of PKP<sub>df</sub> or one of its intersections at the ICB is located at south of 70°S, and of good S/N ratio. We selected 89 vertical component seismograms for the 15 earthquakes from 1998 to 2002 whose core

phases that meet the above-mentioned criteria are observed in more than 4 JISNET stations. The epicentral distances of the data we selected are from 130 to 164 degrees. We computed the synthetics using the Direct Solution Method (Takeuchi et al., 1996) with the earth reference model PREM. The observed and synthesized waveforms are bandpass-filtered at frequencies between 0.01-0.5 Hz. Our preliminary waveform analysis shows that the observed waveforms require a 150-km thick constant velocity zone above the ICB and the low velocity below the ICB. There remains trade-off between the low velocity zone in the outer core and low Q in the inner core. We evaluate the effect of the low Q model which has Q<sub>p</sub>=200 in the uppermost 100 or 200 km of the inner core on the synthesized waveforms, and found that it does not significantly affect the result. This low velocity zone above the ICB is consistent with the results of previous travel-time studies (e.g., Souriau and Poupinet, 1991). We will also show whether the waveforms from earthquakes of north South America to JISNET, which pass through beneath the equatorial area, will require the same seismic structure near the ICB as that beneath the South

**T11C-0399 0830h POSTER****Equation of State of Iron-Silicon Alloys to Megabar Pressure: Implication for the Earth's Core**Naohisa Hirao<sup>1</sup> (+81-22-217-6668;  
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Iron is a dominant component in the Earth's core. Seismic data indicates that the core is less dense than pure iron at pressures and temperatures of the core [Mao et al., 1990]. The density deficit of the Earth's core is explained by the dissolution of one or more light elements, such as H, C, O, S, and/or Si, on the basis of geochemistry [Hilgert et al., 2000]. Silicon has long been a favorite light element. A number of experimental and theoretical studies have been made in order to estimate silicon solubility in iron under the core conditions, but these results are not consistent with each other and give varying values of 0~20 wt.% of the silicon content in the core. Previous studies on Fe-Si system up to 270 GPa have been conducted by the shock compression method [Balchan and Cowan, 1966] and there are no compressibility measurements for the Fe-Si system by the static compression method under the core conditions. In order to understanding the stable phase and equation of state relevant to the Earth's core, we have investigated the stable phase and pressure-volume equation of state of iron-silicon alloys, Fe-8.7 wt.% Si and Fe-17.8 wt.% Si, using diamond-anvil cell (DAC) technique up to 196 GPa and 124 GPa, respectively.

In situ high-pressure X-ray powder diffraction experiments were performed at the BL13A and BL18C beamlines in the Photon Factory, National Laboratory for High Energy Physics (KEK). A body-centered cubic (bcc) Fe-8.7 wt.% Si transformed to a hexagonal close-packed (hcp) structure at around 16~36 GPa, which is in good agreement with previous work [Lin et al., 2002; 2003]. The high-pressure phase of hcp Fe-8.7 wt.% Si was found to be stable up to 196 GPa and no phase transition of bcc Fe-17.8 wt.% Si was observed up to 124 GPa. The pressure-volume data was fitted to a third-order Birch-Murnaghan equation of state with zero-pressure parameters: the zero-pressure volume  $V_0 = 22.2(8) \text{ \AA}^3$ , the isothermal bulk modulus  $K_0 = 198(9) \text{ GPa}$ , and the pressure derivative of bulk modulus  $K'_0 = 4.7(3)$  for hcp Fe-8.7 wt.% Si and  $V_0 = 179.41(45) \text{ \AA}^3$ ,  $K_0 = 207(15) \text{ GPa}$  and  $K'_0 = 5.1(6)$  for Fe-17.8 wt.% Si. The bulk moduli of iron-silicon alloys obtained in the present study are higher than those of the other iron compounds, such as FeS, FeO, and Fe<sub>3</sub>C. The density and bulk sound velocity of hcp Fe-8.7 wt.% Si suggest that the iron inner core containing a few weight % Si would satisfy the density and bulk sound velocity of the seismological data (PREM). Lin et al. (2002) and Dubrovinsky et al. (2003) show that a Si-poor hcp-structured phase appears at high pressure and high temperature. If the inner core contains silicon, it may be composed of a hcp-structured phase with a few weight % silicon and/or a Si-rich phase (bcc-and/or B2-structured).

**T11C-0400 0830h POSTER****P-V-T equation of state of  $\epsilon$ -FeSi**Kenji Mibe<sup>1</sup> (k.mibe@gl.ciw.edu)Yingwei Fei<sup>1</sup> (y.fe@gl.ciw.edu)Mark Frank<sup>2</sup> (T60MRF1@wpo.cso.niu.edu)Heather Watson<sup>1</sup> (h.watson@gl.ciw.edu)<sup>1</sup>Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road, NW, Washington, DC 20015, United States<sup>2</sup>Department of Geology and Environmental Geosciences, Northern Illinois University, Davis Hall 312, Normal Rd., DeKalb, IL 60115, United States

The Earth's core is believed to consist of iron-nickel alloy together with some light alloying elements. Silicon has been suggested as a candidate for a possible light element in the core. In order to quantitatively understand the incorporation of silicon in the core, it is important to determine the solubility of Si in metallic iron at high pressure and its effect on the equation of state. We report new P-V-T data on  $\epsilon$ -FeSi. The in situ X-ray diffraction experiments were conducted using a Kawai-type double stage multi-anvil (SPEED-1500) installed at SPring-8, Japan. White synchrotron X-ray radiation was used as the incident X-ray beam and the energy-dispersive diffraction data was collected with a Ge solid state detector. The starting material is fine-grained powder of the synthetic  $\epsilon$ -FeSi. MgO powder or MgO + Au powder mixture were used as the pressure calibrants. The experimental conditions were up to 22 GPa and 1873 K. Unit-cell parameters of iron silicide were determined by a least-squares fitting of the diffraction data. These data were used to establish a thermal equation of state for iron silicide.

**T11C-0401 0830h POSTER****Stability of Perovskite under Lower Mantle Pressure and Temperature Conditions**Li Zhang<sup>1</sup> (miazi1980@hotmail.com)Zizheng Gong<sup>1,2</sup> (202-478-9827; z.gong@gl.ciw.edu)Yingwei Fei<sup>2</sup> (202-478-8936; fei@gl.ciw.edu)Fuqian Jing<sup>3</sup> (86-0816-2484720; jingfq@caep.ac.cn)<sup>1</sup>Institute of Physics, Southwest Jiaotong University, No.111, North section, second circle Rd., Chengdu 610031, China<sup>2</sup>Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch, NW., Washington, DC 20015, United States<sup>3</sup>Laboratory for Shock Wave and Detonation Physics Research, Institute of Fluid Physics, P.O.Box 919, Mianyang 621900, China

Shock recovery experiments of (Mg<sub>0.92</sub>, Fe<sub>0.08</sub>)SiO<sub>3</sub> enstatite were conducted at pressures between 60 and 120GPa with the corresponding temperatures of 1600-3000K. X-ray diffraction (XRD) and infrared absorption spectra (IR) analysis on recovered samples indicates that the main phase of the recovered samples is not perovskite, but similar to enstatite. There is no evidence for presence of oxides SiO<sub>2</sub> and (Mg<sub>0.92</sub>, Fe<sub>0.08</sub>)O in the recovered samples. The XRD data show that some diffraction peaks of the recovered samples cannot be matched with the diffraction pattern of the original sample. These peaks are more obvious with increasing pressure. The shock recovery experiments were performed in the stability field of perovskite. The shocked sample is expected to be of the perovskite structure, supported by the observed Hugoniot equation of state of perovskite. The non-perovskite phase in the recovered sample is likely resulted from a retrogressive transformation of the shocked samples during the unloading process. It is evident that the high-pressure phase did not undergo a chemical decomposition reaction of (Mg<sub>0.92</sub>, Fe<sub>0.08</sub>)SiO<sub>3</sub> to oxides SiO<sub>2</sub> and (Mg<sub>0.92</sub>, Fe<sub>0.08</sub>)O during the shock compression because no SiO<sub>2</sub> and (Mg<sub>0.92</sub>, Fe<sub>0.08</sub>)O oxides were found in the recovered samples. The observed extra diffraction in the recovered sample may be caused by crystal distortion. Further characterization of the recovered sample by TEM may shine some light on the nature of the retrogressive transformation of the shocked samples.

**T11C-0402 0830h POSTER****Reaction Between Liquid Iron and Mg-perovskite**Takaaki Kawazoe<sup>1</sup> (kawazoe@ganko.tohoku.ac.jp)Eiji Ohtani<sup>1</sup> (ohtani@mail.tains.tohoku.ac.jp)<sup>1</sup>Institute of Mineralogy, Petrology and Economic Geology, Faculty of Science, Tohoku University, Aobaku, Sendai 980-8578, Japan

Reaction between liquid iron and Mg-perovskite was investigated at 27 GPa and up to about 3700 K to study nature of core forming process and light elements in the Earth's core. The Earth's core is supposed to contain small amount of light elements. These light elements were dissolved into liquid iron during core forming process. Deep magma ocean is supposed to have

extended to the depth of the uppermost lower mantle in the core forming stage (Ohtani et al., 1997; Li and Agee, 2001). Because Mg-perovskite is the most dominant mineral in the lower mantle, reaction between the liquid iron and the Mg-perovskite occurred at base of the deep magma ocean and may have provided Si and O as the light elements into the liquid iron. And another importance of this reaction is that it may occur at core-mantle boundary to form the D" layer. Knittle and Jeanloz (1991) and Hillgren and Boehler (1999) have studied this reaction with laser-heating diamond anvil cell. But their studies had large temperature gradient in the sample room resulting in a possibility of disequilibrium. In this study, high pressure and temperature experiments were conducted with the Kawai-type multi-anvil apparatus and the sample was reached to equilibrium with uniform heating by Re cylindrical heater. Pure iron rod was packed into MgSiO<sub>3</sub> powder capsule, which transformed to Mg-perovskite in the experimental conditions. The sample was compressed to desired load and then heated to desired temperature and kept constant and finally quenched. Run products were analyzed with the electron microprobe. Magnesio-wüstite was formed at boundary between liquid iron and Mg-perovskite in both runs at about 3700 and 3100 K. Quenched liquid iron contained oxide blobs in both runs and stishovite grew in the quenched liquid in the run made at about 3700 K. The liquid iron reacted with Mg-perovskite to form the magnesio-wüstite and Si and O dissolved into the liquid iron at temperatures above 3100 K. The Si and O contents in the liquid iron were increased with increasing temperature up to 2.3 wt% O and 1.7 wt% Si in the run made at about 3700 K. Our experimental result implies that liquid iron can contain about 2 wt% Si and O at base of the deep magma ocean. The dissolution reaction of Si and O may occur also at the core-mantle boundary.

T11C-0403 0830h POSTER

Effects of Aluminum on the Compressibility of Silicate Perovskite

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Among the elements present in all mantle compositional models, aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) is estimated to amount 4 to 5 mole %. While aluminum is incorporated in specific minerals such as garnet and majorite in the upper mantle, it is believed to be incorporated into (Mg,Fe)SiO<sub>3</sub>-perovskite under the pressure and temperature conditions of the lower mantle. However, the effect of Al on the elastic parameters of perovskite has received less attention. It was considered to be insignificant, until Zhang and Weidner [1] presented for an Al-bearing silicate perovskite a bulk modulus 10% smaller than that of the end-member MgSiO<sub>3</sub>-perovskite. Since then, numerous experimental studies have been devoted to understanding and confirming that issue. We present here two sets of volume measurements up to 40 GPa, for two Mg-perovskite with respectively 5 and 7.7 mol % aluminum. Samples were either synthesized in a multi-anvil apparatus or in a diamond anvil cell by laser heating a 20 micron thin glass plate of the relevant composition. Samples were studied in a diamond anvil cell with neon as a hydrostatic pressure transmitting medium and were annealed with a YAG laser within their pressure stability filed. Angle dispersive diffraction patterns were collected upon compression to the peak pressure, at the ID9 dedicated high-pressure beamline of the ESRF. From the two data sets fitted to a Birch-Murnaghan equation of state, we deduce that the dependence of the bulk modulus of silicate perovskite is not simply linearly dependent on the aluminum content. Whereas 5 mol % aluminum has very little effect on the compressibility of silicate perovskite, 7.7 mol % aluminum strongly decreases the bulk modulus. These results might be related to the substitution mechanism of Al into perovskite, suggesting that the coupled substitution mechanism might be efficient at low Al content, but is then replaced an oxygen vacancy mechanism at higher Al content. This indicates that the investigations of the chemical and petrological compositions of the lower mantle and heterogeneities should definitely take into account the effect of Al on the thermoelastic properties of perovskite. Moreover, taking into account the elastic effects of Al in

perovskite is thus necessary for assessing the Si/Mg ratio of the lower mantle, and thus the large scale stratification of the Earth. [1] Zhang, J., and D.J. Weidner, *Science*, 284, 782, 1999.

T11C-0404 0830h POSTER

Thermodynamic Properties Across Seismic Discontinuities Show Strong Variations due to Compositional Effects

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Thermodynamic properties of solid solution phases change with pressure, temperature and composition. In regions involving several of such phases, the change of pressure and temperature leads to a change in their composition. For the MgO - FeO - SiO<sub>2</sub> system, we demonstrate that the values of specific properties may change up to a 100% due to compositional effects in the regions associated with the 410 km and 660 km seismic discontinuities. However such changes are negligible in the lower mantle. The Figures show two examples of large compositional effects on heat capacity and bulk modulus in the transition zone for a pyrolytic overall composition (Mg<sub>90.9</sub>Fe<sub>0.1</sub>)<sub>2</sub>SiO<sub>4</sub> without pyroxene

T11C-0405 0830h POSTER

A Thermodynamic Model for Dissolution of Volatiles in Nominally Volatile-Free Minerals

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Most nominally volatile-free minerals are known to dissolve certain amounts of volatiles such as hydrogen or carbon. Understanding how the solubility of volatiles depends on thermodynamic conditions is critical to our understanding of the dynamics and evolution of this planet. A simple thermodynamic analysis shows that the solubility of a volatile depends on pressure and temperature as

$$C_x(P, T) = Af_{Xn}^r O_m(P, T) \exp[-(\Delta E + P\Delta V)/RT]$$

where  $f_{Xn}^r O_m$  is the fugacity of a fluid phase (such as H<sub>2</sub>O or CO<sub>2</sub>) containing the volatile species X, r is a constant that depends on the mechanism of dissolution, and  $\Delta E$  and  $\Delta V$  are the change in internal energy and volume associated with the reaction. Therefore the important quantities controlling the P-T dependence of solubility are the fugacity of relevant fluid phase (water or carbon dioxide), the power, r,  $\Delta E$  and  $\Delta V$ . The fugacities of water and carbon dioxide are calculated from their respective equations of state, and the parameters r and  $\Delta V$  are determined from the experimental data on the dependence of solubility of volatiles on pressure. Experimental results on the solubility of hydrogen in olivine and wadsleyite, as well as solubility of carbon in olivine support a model in which the dominant volatile-bearing defect is a fully charge-compensated defect at Mg- and Si-site ( $(2H)_{Mg}^{\times}$  and  $C_{Si}^{\times}$ ) respectively. The present analysis shows that the volume term ( $\Delta V$ ) corresponds approximately to the volume of MgO (~11 cm<sup>3</sup>/mol) and SiO<sub>2</sub> (~22 cm<sup>3</sup>/mol) in these minerals for hydrogen and carbon dissolution respectively. Due to a relatively small volume change, hydrogen solubility in minerals increases significantly with pressure, whereas the large volume change associated with carbon dissolution limits its solubility at high pressures. We note that although the dominant volatile-bearing defects are fully charge-compensated defects, defects that control the transport properties are in most cases charged defects. Thermodynamic analysis of experimental data on these properties must distinguish the contribution of dominant defects from that of minor defects.

T11C-0406 0830h POSTER

Calculating Upper Mantle Heat Flow Values Using Xenolith P-T Data and Temperature-Dependent Thermal Conductivity Estimates

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Lithosphere properties and dynamics are controlled primarily by composition (including fluid content) and temperature. Temperatures may be extrapolated to depth in stable lithosphere from near-surface heat-flow data, but these extrapolated values become increasingly uncertain with depth because of lack of knowledge of depth variations in thermal conductivity and radiogenic heat production. Most heat production, and thus its variability, is concentrated in the continental crust. However, variations in thermal conductivity of rocks that are likely candidates to form a bulk of the middle and lower crust are relatively minor and are relatively temperature insensitive. For oceanic crust the structure and composition are relatively well known and their thermal parameters may be reasonably estimated. At mantle depths, where the extrapolations become more uncertain, heat production is generally very low (although it may be significant over a depth range of 100 km or more), but experimental data suggest that ultramafic compositions dominated by olivine are strongly temperature dependant. Uncertainty in extrapolation of heat flow to depth, and problems in converting this heat flow to temperature because of uncertainties in thermal conductivity, make desirable another method of determining mantle-lithosphere temperatures and heat flow. Mantle xenoliths, pieces of the mantle lithosphere entrained in magmas and brought to the surface by volcanism, generally retain mineral equilibria representative of their pressure (depth) and temperature of origin. Some of these equilibria may be used to estimate these pressures and temperatures allowing the depths and temperatures, the geotherm, from which the xenoliths were extracted to be estimated. Using experimental data, a temperature-dependent relation for the conductivity of olivine has been determined. A new transformation has been developed between the xenolith temperatures and the temperature-dependent thermal conductivity that allows heat flow to be calculated from the slope of the transformed temperature vs. depth data, thus allowing the xenolith data to be used both to provide mantle-lithosphere temperatures and mantle-lithosphere heat flow with temperature-dependent conductivities.

T11C-0407 0830h POSTER

Impact of Temperature and Pressure Dependent Thermal Conductivity and Viscosity and Core-Mantle Coupling on Planetary Thermal Evolution

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Secular cooling of terrestrial planets is largely controlled by the heat transport through thermal convection of the silicate mantle enclosing the metallic core. Similar to the well known temperature dependence of mantle viscosity  $\eta(T)$  (Tozer, 1972), thermal conductivity  $k$ , dominated by a lattice dynamical component  $k_{lat}$  as in Hofmeisters (1999) model, also decreases with temperature. In previous work we have shown, for isoviscous models, without mantle core coupling, that secular cooling is substantially delayed, by one to two billion year, for models based on variable  $k(T, P)$ , compared to constant  $k$  models. Here we present results of numerical mantle convection models for both variable  $k(T, P)$  and  $\eta(T, P)$  and we also consider thermal coupling between the mantle and the core, represented by an isothermal heat reservoir. The results show that the delay in secular cooling of the models with variable conductivity of the Hofmeister type, compared to the constant  $k$  model, is a robust feature also in mantle convections models with variable viscosity. These

results show that thermal conductivity, like viscosity, plays a major role in controlling planetary thermal evolution. The thermal evolution of the core is driven by conductive heat transport through the core mantle boundary (CMB) and is therefore also sensitive to the particular model of thermal conductivity. In this respect the radiative conductivity component  $k_{rad}$ , related to phonon transport is particularly important as it increases with temperature and plays a stabilizing role in the bottom thermal boundary layer. Our results show that the temperature contrast  $\delta T$  across the thermal boundary layer at the bottom of the mantle continues to increase from a zero initial value to values between 400 K and 800 K, for variable  $k$  and constant  $k$  respectively and within the variable  $k$  models  $\delta$  increases with the relative contribution of the radiative conductivity  $k_{rad}$ . The smaller temperature contrast across the bottom thermal boundary layer for the variable  $k$  models is reflected in a reduced tendency for plume formation at the CMB in the variable  $k$  models. The heat flux from the core shows an increasing tendency with time and strong fluctuations originating from thermal interaction of the core with cold downwellings and hot upwellings in the mantle convective flow at the CMB. We varied the initial CMB temperature between 3273 and 4273 K and found that high  $T_{CMB}$  results in higher cooling rates, stronger time dependence and an increased contribution of the radiative conductivity  $k_{rad}$ . In general we found the cooling rate of the mantle to be strongly time dependent, fluctuating around values of 100 – 150 K/Gyr. These mean values are fairly constant or even slightly increasing with time, illustrating the buffering effect of the core heat flux, increasing with time.

#### T11C-0408 0830h POSTER

### The Viscosity of Peridotite Liquid up to 6.9 GPa Measured by in-situ Falling Sphere Viscometry

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The viscosity of silicate melts plays an important role in controlling magmatic processes in the Earth. In particular, the viscosity of molten peridotite at mantle pressures is a crucial parameter for modeling the dynamics and crystallization of a deep magma ocean and early differentiation processes within the Earth. The viscosity of peridotite liquid has been measured between 2.5 and 6.9 GPa and temperatures between 2043 K and 2323 K. by in-situ falling sphere viscometry involving a x-ray- radiographic method with a high resolution CCD camera. Experiments were conducted in a multianvil apparatus at SPring-8 synchrotron facility in Japan. In order to avoid the sphere dropping while heating through the broad sub-liquidus region (around 400 K) we have developed a new capsule design which delays the drop of the sphere until stable temperature conditions above the liquidus are reached. This is achieved by initially locating the rhenium sphere outside the hotspot of the furnace at the end of a stepped molybdenum capsule. In addition, the sphere is embedded in a mixture of forsterite (Fo) and Enstatite (En) with the same Si/Mg ratio as the peridotite composition but with a higher melting temperature. Restricting the volume of the Fo-En mixture to 6% of the total sample minimizes its effect in contaminating the peridotite liquid. Experiments were performed between 2.5 and 6.9 GPa. Measured viscosities range from 0.13 Pa·s at 2093 K and 2.5 GPa to 0.02 Pa·s at 2223 K and 3.4 GPa. An Arrhenius equation was fitted to the data, giving an activation energy of  $256 \pm 44$  kJ/mol. The viscosity increases with pressure, giving a positive activation volume of  $6.0 \pm 2$  cm<sup>3</sup>/mol in the investigated pressure range. Using these parameters to extrapolate our experimental data indicates that the viscosity of a magma ocean will increase by three orders of magnitude at constant temperature when the pressure increases to 30 GPa (depth of about 800 km). A decrease in viscosity of about 1.2 log units is expected if the temperature increases from 2573 to 3273 K. Our results are compared with recent viscosity data for diopside liquid which has been considered as a simple analog for a peridotitic composition.

#### T11C-0409 0830h POSTER

### The Liquid and Solid Values of the Grüneisen Ratio for hcp Iron at Core Conditions

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Verhoogen first emphasized that the value of the Grüneisen ratio,  $\gamma$ , may be different for solid iron than for liquid iron at core conditions. In calculations involving the adiabatic temperature of the outer core, iron must be considered as in the liquid state. In calculations involving the Hugoniot, however, the measured data up to melting will be taken from the solid state ( $\gamma_c$  corresponds to the crystalline state, and  $\gamma_l$  to the liquid state). The difference between  $\gamma_l$  and  $\gamma_c$  for iron at  $P = 0$  is quite large ( $\gamma_l = 2.44$  and  $\gamma_c = 1.66$ ). Experimental data show that  $\gamma_l$  changes considerably with pressure, becoming 1.52 at 135 GPa, according to Alfè et al. (2002). At higher pressures,  $\gamma_l$  changes much more slowly with pressure, becoming 1.51 at 330 GPa, according to Alfè et al. (2002).  $\gamma_c$  has a component from lattice vibrations that decreases with pressure and a component from free electrons (activated at very high temperatures) that increases strongly with temperature. Along the adiabat of the outer core, the decrease in the vibrational component is almost exactly compensated for by the increase in  $\gamma_c$  due to increased temperature. Anderson and Isaak (2003) have shown that  $\gamma_c$  varies from 1.62 at 135 GPa to 1.52 at 330 GPa along the core adiabat. Thus, we see that  $\gamma_l$  is only slightly larger than  $\gamma_c$  along the adiabat of Earth's outer core. Further, the difference between  $\gamma_l$  and  $\gamma_c$  decreases as the pressure increases. This is consistent with a decrease in both the volume of melting,  $\Delta V_m$ , and the heat of crystallization,  $\Delta H_m$ , with pressure along the core adiabat. Both become quite small at 330 GPa. In the planets Mercury, Mars, and the Moon, the pressure never gets as large as the pressure in the Earth's core, being only about 29 GPa for Mercury. So for these planets, assuming that the core is mostly iron, the value of  $\gamma_l$  will be very much larger than the value of  $\gamma_c$ . Care must be taken to ensure that the  $\gamma$  used in calculations of core physical properties for these planets is for the liquid state (using values measured for  $\gamma_c$  will lead to large errors).

#### T11C-0410 0830h POSTER

### Inelastic x-ray scattering in extreme conditions: a tool for investigating deep planetary interiors.

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To address the structure and composition of planetary interiors, and to confront mineralogical models with geophysical (i.e. seismological) observations, it is essential to measure the effects of pressure on the elastic properties of geo-materials. To date, many techniques have been employed for that purpose, such as ultrasonic techniques, inelastic neutron scattering, high-pressure Brillouin scattering, nuclear resonant inelastic scattering, radial x-ray diffraction, inelastic x-ray scattering (IXS), or more recently, impulse stimulated light scattering. Among all these techniques, only IXS in conjunction with the diamond anvil cell provides a direct measurement of acoustic (collective) excitations across the Brillouin zone to pressures in excess of 100 GPa [Fiquet et al., 2001] and with accuracies better than a few percent on any material (transparent, opaque, powder, single-crystal, etc...). Such measurements allow a simple and direct derivation of sound

velocities and elastic moduli that are model independent. We will present an overview of several IXS experiments on Fe and FeO at high pressure and on FeS at high pressure and temperature. These experiments were performed on poly-crystalline samples at the IXS-dedicated beamline ID28 of the European Synchrotron Radiation Facility. We will conclude by presenting results of IXS experiments performed on oriented single crystals that provide direct determinations of the phonon dispersion curves of molybdenum along its high symmetry crystallographic direction up to 37 GPa. G. Fiquet, J. Badro, F. Guyot, H. Requardt, and M. Krisch, Science **291**, 468 (2001).

#### T11C-0411 0830h POSTER

### First Direct Shock Wave Loading Experiments on Wadsleyite

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We are conducting the first direct shock wave loading experiments on Mg<sub>2</sub>SiO<sub>4</sub> wadsleyite, one of the high-pressure polymorphs of olivine and a dominant phase in the Earth's mantle transition zone. Equation of State (EoS) measurements are performed simultaneously on two polycrystalline samples: 1) a disk of pure forsterite, hot-pressed to full crystal density (3.2-3.22 g/cc) at 3 GPa and 1573 K in the piston-cylinder; and 2) wadsleyite (3.37-3.4 g/cc), synthesized from forsterite at 16 GPa and 1373 K in a multi-anvil press using a special assembly designed to yield samples with large enough diameter for the EoS experiments. Our first experiment was conducted at a projectile velocity of 1.96 km/s on the Caltech 40-mm powder gun, using a tungsten flyer-driver combination. We used the inclined-mirror technique in order to constrain the behavior of both the elastic and deformational (plastic) shock waves in each sample. A two-wave structure was observed in the streak record of the forsterite, consistent with previous results. In the wadsleyite, however, the plastic shock wave superceded the elastic wave. The final shock states in the samples were: 1) forsterite,  $U_p = 1.52$  km/s;  $U_s = 7.97$  km/s;  $P = 38.8$  GPa;  $\rho = 3.97$  g/cc; 2) wadsleyite,  $U_p = 1.51$  km/s;  $U_s = 7.82$  km/s;  $P = 39.8$  GPa;  $\rho = 4.18$  g/cc. The result for forsterite is in accord with the previously established Hugoniot and with the EoS at 300 K extrapolated from static compression experiments. The Hugoniot point for wadsleyite, however, gives a significantly higher density than that predicted (4.08 g/cc) for the same pressure along the 300 K isotherm (using  $K = 172$  GPa,  $K' = 4.2$ ). This suggests that, during shock compression, wadsleyite may partially convert to a higher-pressure phase or phase assemblage at conditions under which forsterite remains metastably in the low-pressure phase state. Obviously, more experiments are needed to confirm this trend. Future experiments are planned for both lower shock pressures on the 40-mm gun and higher shock pressures using the two-stage light-gas gun. By comparing the Hugoniot of the two samples, which are shocked to different internal energy states at equal volume, we expect to gain constraints on the Grüneisen parameters of the polymorphs as well as their breakdown products at higher pressures (periclase and MgSiO<sub>3</sub>-perovskite).

#### T11C-0412 0830h POSTER

### Phase Transformation of Al<sub>2</sub>O<sub>3</sub> Under High Pressure and High Temperature and its Effect on Ruby Pressure Scale

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Corundum ( $\alpha$ -Al<sub>2</sub>O<sub>3</sub>) is an important material in geophysics, high-pressure physics, and ceramic science. The pressure-induced shift of the Cr<sup>3+</sup> fluorescence wavelength of ruby (Cr<sup>3+</sup> doped  $\alpha$ -Al<sub>2</sub>O<sub>3</sub>) is widely used as a pressure calibrant in diamond anvil

cell experiments. Theoretical calculations predict that the corundum transforms to the  $\text{Rh}_2\text{O}_3(\text{II})$  structure (space group: Pbcn) and then to the Pbnm-perovskite structure under high pressures (Marton and Cohen, 1994; Thomson et al., 1996). The phase transformation from the corundum structure to the  $\text{Rh}_2\text{O}_3(\text{II})$  structure was reported to occur at about 100 GPa in the high-pressure X-ray diffraction experiments after high-temperature laser heating at about 1000 K (Fumamori and Jeanloz, 1997), but other high-pressure X-ray diffraction experiments to 175 GPa at 300 K did not observe such a phase transformation (Jephcoat et al., 1988). Recent shock-wave experiments on corundum show that two transitions occurred at 79 GPa and 250 GPa (Hama and Suito, 2002), consistent with the theoretical calculations (Thomson et al., 1996). To understand the crystal structure of the high-pressure phase and the effect of the phase transformation on the ruby pressure scale, we have studied  $\text{Al}_2\text{O}_3$  with in situ X-ray diffraction in a laser-heated diamond anvil cell up to 130 GPa and 2300 K. A phase transformation in  $\text{Al}_2\text{O}_3$  was observed to occur above 100 GPa and at high temperatures. The powder diffraction lines of the high-pressure phase are consistent with that of the  $\text{Rh}_2\text{O}_3(\text{II})$  structure model. The refined crystal structure of the high-pressure phase will be discussed in this paper. Moreover, the ruby fluorescence spectra of the quenched  $\text{Al}_2\text{O}_3$  samples under ambient conditions show significant red shifts; i.e. the  $\text{R}_1$  peak of the quenched sample occurs at 696 nm while the  $\text{R}_1$  peak for the sample before pressurizing occurs at 692 nm. The fossilized pressure indicates that chromium atoms have been re-distributed in the  $\text{Al}_2\text{O}_3$  structure during laser heating. The evidence also suggests that a phase transformation in ruby at high pressures after high-temperature laser heating may affect the ruby calibration scale.

#### T11C-0413 0830h POSTER

##### Equation of State of $(\text{Mg}_{0.92}, \text{Fe}_{0.08})\text{SiO}_3$ Perovskite from Shock Wave Study and its Geophysical Implications

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We performed shock wave experiments on  $(\text{Mg}_{0.92}, \text{Fe}_{0.08})\text{SiO}_3$  enstatite with initial density of  $3.06\text{g}/\text{cm}^3$ . 13 shock compression data points for  $(\text{Mg}_{0.92}, \text{Fe}_{0.08})\text{SiO}_3$  perovskite were collected between 46 and 140 GPa, using impedance-match method and electrical probe technique. The relationship between shock wave velocity  $D$  and particle velocity  $u$  can be described linearly by  $D = 4.13 + 1.39u$  (km/s). There is no evidence of phase transition in the experimental shock pressure range. Our experimental Hugoniot is about 7% denser than the model Hugoniot of  $(\text{Mg}_{0.92}, \text{Fe}_{0.08})\text{O}$  (Mw.) plus  $\text{SiO}_2(\text{St.})$  calculated by additive principle. This excludes the possibility of chemical decomposition of perovskite to oxides during the shock compression up to 140 GPa. The Grüneisen parameter  $g$  obtained by fitting our experimental data can be expressed by  $\gamma = \gamma_0(\rho_0/\rho)^q$ , where  $\gamma_0 = 1.40$  and  $q = 2.19$ . Using the third-order Birch-Murnaghan finite strain equation of state (EOS), our shock experimental data yield a zero-pressure bulk modulus  $K_{0s} = 260.09$  GPa and its pressure derivative  $K'_{0s} = 4.17$ , with  $\rho_0 = 4.19\text{g}/\text{cm}^3$ . A comparison of the calculated density profiles from our thermal equation of state of perovskite with that derived from PREM prefers a perovskite-dominant lower mantle model.

#### T11C-0414 0830h POSTER

##### The Effect of Water on the Compressibility of Wadsleyite

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It has been known for nearly a decade that nominally anhydrous olivine polymorphs are capable of incorporating significant amounts of water in their structures. Marked decrease in densities with increasing water content and rapid hydrogen diffusion in these materials may explain the apparent sharpness in the seismic discontinuity at 410-km depth, which corresponds to the olivine-wadsleyite transition. Characterization of the effect of water content on the properties of these materials is key in understanding the nature of these seismic discontinuities, and holds clues to the possible cycling of water between the mantle and hydrosphere. Three samples of  $\text{Fo}_{100}$  wadsleyite with various water contents were analyzed at room temperature in the diamond anvil cell by single-crystal X-ray diffraction. Unit cell parameters were measured at eight or more pressures for each sample. Preliminary values of bulk moduli are 172 (4) for dry wadsleyite, 152 (6) for wadsleyite with 1 wt%  $\text{H}_2\text{O}$ , and 136 (3) for wadsleyite with 1.5 wt%  $\text{H}_2\text{O}$ . Preliminary values of  $dK/dP$  are 3.9 (11), 6.5 (20), and 12.2 (11), respectively. Values obtained from this study show a marked decrease in  $K_0$  with increasing water content. This decrease is larger than the effect of temperature over the stability field of wadsleyite. However,  $dK/dP$  also shows a dramatic increase with increasing water content, suggesting that at Transition Zone pressure-temperature conditions hydrous wadsleyite may have a value of bulk modulus comparable to or greater than that of anhydrous wadsleyite, while maintaining a lower density.

#### T11C-0415 0830h POSTER

##### Behavior and Elastic Properties of Mantle Perovskites

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Behavior and elastic properties of Earth minerals as a function of pressure and temperature are in great need in interpreting seismic discontinuities and tomographic images. Advanced ultrasonic techniques in conjunction with state-of-the-art synchrotron facilities allow us to conduct simultaneous measurements of sound velocities, crystal structure and unit cell parameters, and rheological properties of candidate materials to  $P$  greater than 25 GPa and/or  $T$  around 1600K in the laboratory. Recently, we have applied these techniques to the study of many mantle phases, including olivine, wadsleyite, calcium silicate perovskite(s), and magnesium silicate perovskite. For the unquenched calcium silicate perovskite, a hot-pressed wollastonite sample was used as starting material. Fully transformation from amorphized wollastonite to cubic perovskite phase was obtained at about 14 GPa 1200K as confirmed by X-ray diffraction data. Travel times, X-ray images of sample and X-ray diffraction spectra were collected along multiple heating/cooling cycles at various pressures during decompression. We observed an anomalous behavior of  $P$  and  $S$  wave velocities at high pressure and high temperature, which might be caused by the phase transformation as, proposed in some recent studies. Unfortunately, the X-ray diffraction data collected using the energy dispersive method has very limited resolution to confirm such a phase transition. Following similar procedures as described above, measurements of  $P$  and  $S$  wave velocity on magnesium silicate perovskite phase have been extended to  $P$  greater than 25 GPa at ambient temperature. Combining these new measurements with our previous data to 9 GPa 873K, the pressure and temperature derivatives of the elastic moduli are determined. These new results allow us to investigate the visibility of calcium silicate perovskite in the lower mantle as well as velocity profiles in the lower mantle.

#### T11C-0416 0830h POSTER

##### Stabilities of Dense Hydrous Magnesium Silicates in the Earth's Upper Mantle: From Water-Undersaturated Experiments

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Water ( $\text{H}_2\text{O}$ ) has significant effects on the mantle dynamics such as melting temperature, rheological property, electrical conductivity, and possible origin of subduction zone seismicity. A group of dense hydrous magnesium silicates (DHMSs) are stable in the mantle system and, therefore, are possible candidates as water storages in the Earth's mantle. Most previous experimental studies showed the phase relations of the DHMSs in water-oversaturated condition, although excess fluid is not expected in deep upper-mantle condition. The post-antigorite (serpentine) assemblage is hydrous phase A, enstatite, and water at relatively cold region in the deep mantle, i.e. subduction zone. This assemblage should become water-absent assemblage of hydrous phase A and enstatite, due to the free water penetration to the surface. Our Schreinemakers analysis on the previous water-excess experiments predicted that water-absent solid-solid reaction is a key for the determination of the stability field of the DHMS in actual subduction process. In the present study, we investigated stability relations after phase A and enstatite assemblage in a water-undersaturated condition by the high-pressure experiments in a multi-anvil apparatus from 10 to 15 GPa and from 600 to 1100°C, in order to clarify the stabilities of the DHMSs in the deep upper-mantle conditions. The starting material is a mixture of reagent powders (MgO: 48.3%,  $\text{SiO}_2$ : 41.5%, and  $\text{Mg}(\text{OH})_2$ : 10.2%, in mole), which is the composition of phase A and enstatite with water content of 3.67 wt.% (phase A : enstatite = 7 : 71, in mole). The results show that phase A + enstatite transformed to forsterite + water at 10 GPa, 1000°C and at 11.5 GPa, 1100°C and to hydrous phase E + forsterite at 12.5 GPa, 800°C. The high-pressure limit of phase A and enstatite is represented by the solid-solid reaction: phase A + enstatite = phase E + forsterite. As the low-pressure limit of this assemblage by the dehydration reaction: forsterite + water = phase A + enstatite is located at around 5 GPa (Komabayashi et al., 2003 submitted), the assemblage of phase A and enstatite is stable over 7 GPa, correspondingly from 150-km to 380-km depth. During subduction, whole water in phase A is transported to phase E by the solid-solid reaction described above. Since the phase A and enstatite assemblage occurs over 200 km-depth, the physical properties of this mixture may have importance on both the dynamics and the seismological observation of the deep subduction zone. We will further discuss phase relations of the DHMSs in water-undersaturated condition down to the bottom of the upper mantle.

#### T11C-0417 0830h POSTER

##### The Fe-Si and Fe-S Binary Systems at 15 GPa: Important Relations for the Light Element Constituent of the Earth's Core.

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The identity of the light element, or combination of light elements, within the Earth's core remains elusive. Two commonly proposed alloying elements which may explain the density of the core are silicon and sulphur. Multi-anvil experiments at 15 GPa have been conducted to examine the iron-rich portions of the Fe-Si and Fe-S phase diagrams. The Fe-Si system has proven difficult to study experimentally due to silicon reactivity with oxygen as well as commonly used sample capsule materials. We have tested different capsule materials and have found the use of fused silica capsules, transforming to stishovite at experimental conditions, to be the most effective of those tried. The oxygen within these charges will be buffered against the highly reducing redox reaction  $\text{Si} + \text{O}_2 = \text{SiO}_2$ . Initial results have verified the presence of two coexisting subsolidus iron-silicon phases between 6 and 8 wt% silicon to 1300°C as discussed by Lin et al. (Science, 2002). Experiments above the solidus have also been conducted and are continuing, however, they have yet to yield reliable data on the liquidus loop in the iron-rich portion of the Fe-Si system. The Fe-S system has been more readily studied using MgO capsules. Measurements of iron wustite content in the MgO capsule contacting the experimental charge specify oxygen fugacities below 1W-2. Results indicate the presence of a eutectic at about 900°C and 21.5wt% sulphur at 15 GPa. At eutectic temperatures, over 1wt% sulphur is found dissolved in the solid iron-rich phase. Experiments below the eutectic temperature confirm the existence of the high-pressure  $\text{Fe}_3\text{S}_2$  phase described by Fei et al. (Science, 1997). Experiments at higher pressures and into the Fe-S-Si ternary system are underway.

## T11C-0418 0830h POSTER

High-Pressure Raman Spectroscopic Studies of FeS<sub>2</sub> PyriteAnnette K Kleppe<sup>1</sup> (+44 1865 272067; annettek@earth.ox.ac.uk)Andrew P Jephcoat<sup>2</sup> (andrew@earth.ox.ac.uk)<sup>1</sup>University of Oxford, Department of Earth Sciences Parks Road, Oxford OX1 3PR, United Kingdom<sup>2</sup>Diamond Light Source Ltd. and University of Oxford, Department of Earth Sciences Parks Road, Oxford OX1 3PR, United Kingdom

The transition metal dichalcogenide FeS<sub>2</sub>, pyrite, is the most abundant of the sulphide minerals and common in a variety of geological environments. Strong geophysical interest in its physical and chemical properties under high-pressures and high-temperatures has arisen in the context of the F-S system's role in core formation, evolution and composition. It is known from X-ray diffraction studies that the equation of state of pyrite depends strongly on the degree of non-hydrostatic stress in the sample. In order to determine any possible influence of such intrinsic strength effects on the dynamical properties of FeS<sub>2</sub> we have investigated natural iron pyrite with Micro-Raman spectroscopy in the diamond-anvil cell to 55 GPa. Comparative measurements were performed under hydrostatic conditions with helium as a pressure-transmitting medium and without a pressure-medium. In fact, there have been few (if any) light scattering studies of opaque, highly reflective minerals at high-pressures. Despite the high opacity we observe (in analogy with previous work on high-pressure metallic phases) strong Raman modes at all pressures. Four out of five Raman modes are resolved with helium as a pressure-transmitting medium. The fifth mode, T<sub>g</sub>(2), is <math>2\text{cm}^{-1}</math> apart from the strong A<sub>g</sub> mode that dominates the spectrum. We observe an increase in the separation of the E<sub>g</sub> and T<sub>g</sub>(1) mode under compression. In contrast the A<sub>g</sub> (in-phase S<sub>2</sub> stretch) and T<sub>g</sub>(2) (out-of-phase S<sub>2</sub> stretch) mode do not separate with pressure. All observed frequencies increase continuously under compression giving no evidence for a structural phase transition in accord with diffraction and shock wave studies. The main effect of non-hydrostatic conditions on the Raman modes is a strong pressure-induced broadening; the pressure-dependence of the frequencies is not affected within the error of the measurements. The Raman data are consistent with recent bond-length vs pressure calculations supporting a strengthening of the S-S and Fe-S bond under pressure.

## T11C-0419 0830h POSTER

Monochromatic Powder Diffraction Coupled With <sup>19</sup>F and <sup>23</sup>Na NMR: A Study of K<sub>(x)</sub>Na<sub>(1-x)</sub>MgF<sub>3</sub> PerovskiteCharles David Martin<sup>1</sup> (631-632-8197; ph.d.c@hotmail.com)Santanu Chaudhuri<sup>2</sup> (631-835-9332; sachaud@ic.sunysb.edu)Clare P Grey<sup>2</sup> (631-632-9548; clare.grey@sunysb.edu)John B Parise<sup>1</sup> (631-632-8196; jparise@notes.cc.sunysb.edu)<sup>1</sup>Geosciences Department, State University of New York at Stony Brook, Stony Brook, NY 11794-2100, United States<sup>2</sup>Chemistry Department, State University of New York at Stony Brook, Stony Brook, NY 11794-3400, United States

Structural phase transitions from orthorhombic (O, Pbnm) to tetragonal (T, P4/mnm) to cubic (C, Pm3m) and an increase in unit cell volume are confirmed as potassium is substituted for Na in Neighborite (NaMgF<sub>3</sub>). Substitution of the 19% larger potassium ion for sodium in the A-site of the perovskite structure decreases tilting of MgF<sub>6</sub> octahedra. Transition from O to the T and C phases, as determined by powder XRD, occurs at ~37 and 47 mole % substitution, respectively. Superlattice reflections, expected if ordering were to occur in the A-sites, are not observed. The superlattice reflections, uniquely defining the symmetry of the O- and T-phases, broaden between each perovskite endmember, possibly indicating a conflicting coherence length between small domains of variously tilted octahedra. <sup>19</sup>F MAS NMR reveals multiple environments for fluorine that depend on the number and type of cations in the 1<sup>st</sup> A-cation coordination shell, F(Na)<sub>y</sub>(K)<sub>5-y</sub>. At intermediate substitution levels (30 - 60%), all five of these possible fluorine coordination environments are found, but the concentration of the environments with y = 2 are much lower than expected based on random substitution of K for Na on the A cation site. This data suggests that upon substitution of 15% K into NaMgF<sub>3</sub>, potassium appears to segregate into domains resembling KMgF<sub>3</sub> but smaller than the coherence length of X-rays. The <sup>23</sup>Na NMR is very sensitive to the O/T to C transition.

For x > 0.5, a sharp resonance is observed due to sodium atoms in a cubic environment, while broader resonances are observed for x < 0.5.

## T11C-0420 0830h POSTER

Thermodynamic Parameters of Uvarovite (Ca<sub>3</sub>Cr<sub>2</sub>Si<sub>3</sub>O<sub>12</sub>) from Single Crystal Raman SpectroscopyAnastasia Chopelas<sup>1</sup> (206-543-9586; chopelas@phys.washington.edu)Fallon B. Savage<sup>2</sup> (fsavage@u.washington.edu)<sup>1</sup>Department of Physics, University of Washington, Box 35-1560, Seattle, WA 98195-1560, United States<sup>2</sup>Department of Chemistry, University of Washington, Box 35-1700, Seattle, WA 98195-1700

Garnets are ubiquitous in the crust and mantle and are key minerals in geothermometry and geobarometry as well as in the transition zone of the mantle. Uvarovites are found in nature as nearly end-member compositions in some terranes, and are significant components in diamond inclusions. They have not been studied as extensively as pyrope garnets. Raman spectroscopic studies of uvarovite provide several advantages for understanding the behavior of garnets. Thermodynamic properties, such as heat capacity and entropy, can be calculated using vibrational modeling. Using vibrational spectroscopy with cation substitution provides insight into how the properties vary with composition. The nonlinear behavior of garnet solid solutions is well-known, details of this behavior can be probed with spectroscopy (see F. Savage, A. Chopelas abstract this volume). Uvarovite is a calcic garnet with chromium at its octahedral site. It is close in volume to grossular (Al at the octahedral site), while the mass of the trivalent cation is similar to andradite (ferric iron at the octahedral site). All three have lattice parameters around 12 Å, much larger than for pyrope garnets (lattice parameters around 11.5 Å). The samples in this study were synthetic end member uvarovite, a binary nearly halfway between andradite and uvarovite (Uv<sub>59</sub>An<sub>41</sub>), and 2 other uvarovites, one with a small pyrope content and the other with a small grossular content. Single crystal polarized spectra on the end-member revealed 23 of the 25 Raman modes expected by symmetry. The high energy modes of uvarovite closely matched those of grossular while the low energy modes more closely matched those for andradite. This is not a surprising result since the high energy modes dominated by silicate stretching and bending modes, depend nearly entirely on the lattice parameter, while the low energy modes, mainly cation translations, have a heavier dependence of the mass of the cations. Other silicate minerals exhibit this same behavior suggesting a simple treatment of the silicate modes upon substitution. Andradite's unusual intensity distribution with a very strong high energy Eg mode is repeated in end member uvarovite but not in any of the mixed uvarovites. The Uv<sub>59</sub>An<sub>41</sub> has only a very small volume change and the lattice parameter is much closer to uvarovite's than would be expected by composition. This is reflected in the behavior of the modes, which will be further discussed. Thermodynamic calculations will also be presented.

## T11C-0421 0830h POSTER

## Single Crystal Raman Spectroscopy and Thermodynamics of Garnet Solid Solutions II: Pyrope - Almandine Binary

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Garnets are ubiquitous in the crust and mantle and are key minerals in geothermometry and geobarometry. Macroscopic properties, such as enthalpy and volume, exhibit non-linear behavior in solid solutions making it difficult to model their behavior. Insights into the cause of the non-linearity of such properties may be found by investigating the effects of compositional variation using a microscopic technique such as vibrational spectroscopy. A further advantage of using vibrational spectroscopy is the ability to probe the effect of small changes in the frequencies on the thermodynamic properties using vibrational modeling. Investigating the pyrope-almandine (substitution of ferric iron for magnesium) binary allows the examination of the effect of doubling the mass on the dodecahedral cation without significantly changing the cell parameter (11.45 to 11.52 Å, compare to approx. 12 for Ca

bearing garnets). The garnet samples here have low moisture content, eliminating a possible source of non-linear behavior. Although previous infrared data\* show linear behavior across this series, our data show this not to be the case. Raman modes vary from linearity but all modes do not vary in the same way. Generally the trend is to have lower frequencies in the solid solution than expected for linear behavior, as in the andradite-grossular binary. However, a few modes at low frequencies have higher frequencies than the linear trend. Since the lowest frequency modes are most strongly affected by the divalent cation, this would suggest that the electronic and magnetic effects of iron play a role in this unexpected variation. Substitution of ferric iron into minerals raises the heat capacity above the values that can be accounted for by vibrational modeling. The effect of adjusting vibrational models for this non-linear frequency shift will be further discussed. Preliminary thermodynamic models will also be presented. \*Hofmeister et al., Am. Min. 1996, 81: 418-428.

## T11D MCC: Level 1 Monday 0830h

## Seismotectonics of the Eastern San Francisco Bay Area I Posters (joint with G, S)

Presiding: D E Moore, U.S. Geological Survey; D A Ponce, U.S. Geological Survey

## T11D-0422 0830h POSTER

## Tectonic implications of the thermal regime, San Francisco Bay Area, California

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An integral element to understanding tectonics, continental deformation, evolution and geodynamics is knowledge of the subsurface thermal regime. Five boreholes, recently drilled for strain meter emplacement along the San Andreas Fault System (SAFS) in the San Francisco Bay Area, California provided an opportunity to collect new heat flow values within this dynamic area. These new values fill gaps in existing heat flow coverage in the central and northern Bay Area, and help constrain the role of temperature in determining the spatial and temporal pattern of deformation within this plate boundary zone. The five boreholes vary in depth from 140 to 220 meters and penetrate Cretaceous and Jurassic age sedimentary, metamorphic and igneous rocks of the Franciscan and Salinian blocks. Temperature profiles were recorded in each borehole, and more than 200 thermal conductivities were measured on drill cuttings and core samples. Reliable heat flow values were acquired at four of the five sites and range from approximately 78 to 92 mW m<sup>-2</sup>. The average heat flow from these four sites together with 12 previously published values from the San Francisco Bay Area west of the Calaveras fault is 87 mW m<sup>-2</sup> with a standard deviation of 8 mW m<sup>-2</sup>. Overall, the new data within the SAFS are consistent with elevated heat flow that characterizes the California Coast Ranges and confirm the continuation of this thermal regime along both the northern segment of the Hayward fault and the section of the San Andreas fault offshore San Francisco. Locally, variations in heat flow along the SAFS may reconcile along strike discrepancies between observed surface slip after the 1906 San Francisco earthquake and geodetic models for coseismic slip, through the influence of thermal conditions on the maximum depth of seismic moment release.

## T11D-0423 0830h POSTER

## The Hayward Fault in the East San Francisco Bay Region, California: A Regional Geophysical and Geological Perspective

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