

Hydrogen transport into the bottom of the lower mantle by phase H- phase delta solid solution $\text{MgSiO}_2(\text{OH})_2$ - AlOOH

OHTANI, Eiji^{1*} ; AMAIKE, Yohei¹ ; OHIRA, Itaru¹ ; KAMADA, Seiji¹ ; SAKAMAKI, Tatsuya¹ ; HIRAO, Naohisa²

¹Tohoku University, ²SPring-8

Water circulation in a global scale is a key for understanding dynamics and evolution of the Earth. Subducting slabs transport water into the Earth's deep interior. There are many studies on the stability of hydrous phases under the deep mantle conditions, and several hydrous minerals such as phase D and superhydrous phase B have been reported to be stable to the top of the lower mantle. It has been reported that hydrous phase δ - AlOOH is stable up to the bottom of the lower mantle (Ohtani et al., 2005; Sano et al., 2008). Tsuchiya (2013) theoretically predicted that Phase H, $\text{MgSiO}_2(\text{OH})_2$, which is the iso-structure with δ - AlOOH , is stable from 45 GPa to 55 GPa. This phase was experimentally confirmed at around 50 GPa (Nishi et al., 2014). Here, we present our recent results on synthesis experiments of hydrous phase H and a solid solution of phase H and phase δ up to the base of the lower mantle along the normal mantle geotherm. The high pressure and high temperature in situ X-ray diffraction experiments were performed by using a double-sided laser heated diamond anvil cell at BL10XU, SPing-8. We observed that the stability field of this new candidate of water reservoir, hydrous phase H, under the lower mantle conditions up to 75 GPa and 2000 K in the $\text{MgO-SiO}_2\text{-H}_2\text{O}$ system, although the previous studies claimed that phase H is broken down at pressures above 55 GPa. Thus, hydrous phase H is a host phase of water in the lower mantle at least up to the depth of 2000 km along both slab and normal mantle geotherms. Our experiments also revealed that the solid solution of phase H and phase δ , $\text{AlOOH-MgSiO}_2(\text{OH})_2$, containing 15 mol % of $\text{MgSiO}_2(\text{OH})_2$ can coexist with Mg-perovskite and/or Mg-post perovskite up to 135 GPa and 2000 K. If this hydrous phase contacts with the metallic outer core, hydrogen could be dissolved into the core by forming iron hydride, FeH (Terasaki et al., 2012).

Keywords: hydrogen, hydrous phase H, hydrous phase delta, $\text{MgSiO}_2(\text{OH})_2$, AlOOH , lower mantle

Influence of H₂ fluid on the stability of MgSiO₃ enstatite in the upper mantle condition

SHINOZAKI, Ayako^{1*} ; KAGI, Hiroyuki¹ ; HIRAI, Hisako² ; OHFUJI, Hiroaki² ; OKADA, Taku³ ; NAKANO, Satoshi⁴ ; YAGI, Takehiko²

¹GCRC, The university of Tokyo, ²GRC, Ehime university, ³ISSP, The university of Tokyo, ⁴NIMS

C-O-H fluids affect the phase relation and melting of silicate minerals in the mantle of the Earth. The mantle is expected to become progressively reduced with increasing depth, so that H₂ fluid is considered to exist in the deep mantle with H₂O fluids. In this study, influence of H₂ fluid on stability and phase relation of enstatite, which was the secondary most abundant mineral in the upper mantle, was examined using a laser heated diamond anvil cell.

In this presentation, we will report the results of MgSiO₃-H₂ system, which is non-iron-bearing system. After heating at 3.1-13.8 GPa and about 1500-2000 K, decomposition of enstatite and formation of forsterite (Mg₂SiO₄), periclase (MgO) and coesite/stishovite (SiO₂) were observed from XRD measurements. The presence of H₂ fluid were observed from Raman spectra even after the heating. Since the studied P-T range is in the stability field of orthoenstatite and high pressure clinoenstatite under dry condition, the decomposition reaction observed in the present study was presumably induced by H₂ fluid. Formation process of these silicate phases were evaluated by observation of quench texture of the recovered samples using SEM and TEM.

Keywords: enstatite, H₂ fluid, upper mantle, laser heated diamond anvil cell

Dehydration boundary and the EoS of chlorite under high pressure and temperature

SUENAMI, Hideki¹ ; INOUE, Toru^{1*} ; KAKIZAWA, Sho¹ ; KIKEGAWA, Takumi²

¹Geodynamics Research Center, Ehime University, ²High Energy Accelerator Research Organization

Water in hydrous minerals has been transported to deep Earth's interior by subducting slab, which dehydrate at certain pressure and temperature. The existence of deep Earth's water affects the physical properties of Earth's mantle minerals, such as melting point, viscosity, elastic velocity, and so on. Therefore it is important to study the effect of water for the subducting slab materials. Serpentine ((Mg,Fe)₆Si₄O₁₀(OH)₈) is major hydrous mineral in subducting slab, and chlorite ((Mg,Fe,Al)₆(Si,Al)₄O₁₀(OH)₈) should be also important hydrous mineral in the subducting slab because Al is included in slab materials. In this study, the dehydration reactions of chlorite were determined by time-resolved X-ray diffraction analysis under high pressure and temperature using MAX80, PF-AR, KEK. In addition, P-V-T experiments of chlorite have also been conducted under HPHT. We found that chlorite was quickly dehydrated to forsterite + pyrope + fluid within 1 hour at 3 - 7 GPa when across the phase equilibrium boundary. On the other hand, the kinetic boundary was observed above 7 GPa because of low temperature phase equilibrium boundary, and the dehydration product was Mg-sursassite + unknown + fluid, The result of P-V-T experiments will be also reported.

Keywords: chlorite, hydrous phase, subducting slab, dehydration, equation of state, synchrotron X-ray in-situ experiment

Composition and nature of melts, supercritical fluids and liquids formed by dehydration of subducted oceanic lithosphere

ULMER, Peter^{1*} ; SCHMIDT, Max W.¹ ; PETTKE, Thomas² ; LUGINBUEHL, Stefanie¹

¹Department of Earth Sciences, ETH Zurich, ²Inst. Geol. Sciences, University of Bern

At crustal pressures, phase relations in natural rock-H₂O systems involve low density aqueous fluids and/or high density hydrous melts. The wide miscibility gap between these two liquid phases leads to a dichotomy of mobile phases with quite distinct major element solubilities and trace element geochemical signatures. With increasing pressure, the fluid-melt miscibility gap closes until the crest of the miscibility gap intersects the fluid-saturated solidus, leaving a single supercritical liquid that has chemical and physical properties continuously evolving with temperature. The question is if the endpoint of the solidus is relevant for natural rock compositions. We have experimentally determined these endpoints in a variety of systems ranging from MOR basalt, to pelitic systems and to the simplified mantle systems MgO-SiO₂-H₂O (MSH) using different experimental techniques in the P-T range from 2.0 GPa/700 °C to 13.5 GPa/1300 °C. Supercriticality occurs over a wide range of P-T conditions ranging from 1 GPa/1100 °C for the SiO₂-H₂O system to 12-13 GPa in the SiO₂-poor part of the MSH system.

In the MORB system, major element compositions of the fluid/melt phase evolve from peralkaline, H₂O-rich, granite-like compositions to metaluminous, andesitic to basaltic compositions with increasing temperature. The endpoint of the fluid-saturated solidus occurs around 5 GPa and 1000 °C; thus, the dichotomy of fluid versus melt ceases to exist in the oceanic crust. Similar conditions were determined for pelitic to greywacke systems representing deep-sea sediments. In the mantle-like system MSH critical endpoints for fluid/melt solvi along the solidus are located between 12 and 13.5 GPa at 1100 °C. Melt compositions buffered by olivine and opx remain enstatite - olivine normative below the critical endpoint; in contrast, fluids below the endpoint become progressively enriched in MgO and are silica undersaturated (Mg/Si ratios >2) at pressures exceeding 6 GPa. Supercritical liquids coexisting with forsterite and enstatite or dense hydrous silicates are strongly silica undersaturated. The P-T evolution of fluids and liquids in the MSH system allows drawing conclusions regarding the effects of Mg-Si metasomatism in the overlying mantle wedge of a subduction system.

The consequences of the various nature of hydrous mobile phases emanating from hydrated subducted oceanic lithosphere were investigated in the MORB system by determining trace element partitioning between cpx, gar, amphibole, epidote, rutile, titanite, staurolite and phengite and liquid, the latter either being an aqueous fluid, a hydrous melt, or a supercritical liquid. Hydrous melts and supercritical liquids have almost identical trace element pattern. Thus, recycling rates of these elements are not indicative of melting, and in the fast and steep circum-pacific subduction zones, they most likely testify for production of a mobile phase from the subducting crust in the supercritical liquid regime (i.e. at pressure in excess of 4-5 GPa).

Modeling of trace element signatures of fluids, melts and supercritical liquids generated in or passing through eclogitic crustal lithologies during their ascent into the overlying mantle wedge indicate that (1) the mode of fluid advection - porous flow or - focused fluid flow - produces rather contrasting trace element signatures and (2) the presence or absence of accessory phases such as epidote, staurolite, rutile/titanite controls to a large extent the concentrations of high field strength, light REE elements and Th, U. Thus, inversion of geochemical compositions of igneous products in arc settings used to constrain the nature and composition of metasomatizing agents released from the subducted oceanic lithosphere is not straightforward and it is unlikely that an unequivocal solution is obtained.

Keywords: hydrous fluid, supercritical liquid, trace element partitioning, fluid metasomatism, high pressure experiments, subducted oceanic lithosphere

Trace element mass balance in hydrous adiabatic mantle melting: The HAMMS1 model

KIMURA, Jun-ichi^{1*}; KAWABATA, Hiroshi²

¹JAMSTEC, ²Kochi University

A numerical mass balance calculation model for the adiabatic melting of a hydrous metasomatized peridotite source was programmed in order to simulate trace element compositions of mid ocean ridge basalt, back arc basin basalt, ocean island basalt, and large igneous province basalt. The Excel spreadsheet-based calculator, Hydrous Adiabatic Mantle Melting Simulator ver.1 (HAMMS1) uses: (1) a thermodynamic adiabatic melting model of mantle peridotite; with (2) experimentally parameterized melting relationships in terms of pressure, temperature, water content, and degree of partial melting. The trace element composition of the model basalt is calculated from the accumulated incremental melts within adiabatic melting, with consideration of source mantle depletion. The mineralogic mode in the mantle in adiabat is calculated using experimental parameterization, and is incorporated into the program. Partition coefficients of the residual mantle minerals are from lattice strain model based parameterization tested by the latest compilations of experimental results. The parameters that control the trace element composition in the model are: (1) mantle potential temperature, (2) water content in the source mantle, (3) depth of termination of adiabatic melting, and (4) source mantle depletion. It is possible to obtain the above controlling parameters by using Monte Carlo fitting calculations and comparing the calculated basalt compositions with primary basalt compositions. Additionally, HAMMS1 compares those melting parameters with its major element model. HAMMS1 provides a unique estimate of the source conditions of basalt genesis using an incompatible trace element mass balance.

Keywords: peridotite, water, adiabatic melting, trace element, forward model

Very Large Intramolecular D-H Partitioning in Hydrated Silicate Melts Synthesized at Upper Mantle P and T

CODY, George^{1*} ; WANG, Ying¹ ; CODY, Samantha¹ ; FOUSTOUKOS, Dionysis¹ ; MYSEN, Bjorn¹ ; LE LOSQ, Charles¹

¹Geophysical Laboratory, Carnegie Institution of Washington

Hydrogen isotope fractionation during magmatic processes is key to understanding the deep Earth hydrological cycle and may place constraints on the origin of Earth's oceans. It is well established that the D/H content of water in hydrated nominally anhydrous mantle minerals is systematically lower (<-100 ‰) than the standard mean ocean water (SMOW, $D/H = 1.5576 \times 10^{-4}$, defined as 0 ‰). Experiments have revealed significant hydrogen isotope partitioning between melts and fluids or vapors at magmatic temperatures. The origin of such fractionation, given the high temperatures of magmatic processes, is not likely due to classical isotope effects as described by bond energies via statistical mechanics.

It is well known that water has a very high affinity for silicate melts, it both dissolves in the melt as molecular water and hydrolyzes Si-O-Si linkages forming Si-OH. Whereas the molecular forms of water in melts are limited to H₂O and OH, the variety of environments available for water to reside in the melt structure is surprising large. In order to study water in silicate melts one is restricted to molecular spectroscopy, e.g. Raman spectroscopy in the mid infrared regime, in windowed high pressure devices, e.g. the hydrothermal diamond anvil cell. Alternatively, one can study melts quenched to glass, where the structure of the glass corresponds to the structure of the melt at the glass transition temperature. The advantage of glasses is that one can use Solid State Nuclear Magnetic Resonance (NMR) Spectroscopy. The hydrogen isotopes conveniently provide two stable nuclei with spin, ¹H (H) and ²H (D), thus we can use D and H solid state NMR to analyze the nature of water in silicate melts quenched to glass. Given that glass transition temperatures for silicate melts are high (500-600 °C), one does not expect H and D to behave differently. D-NMR can, however, be useful in characterizing the molecular dynamics of water in various sites in the glass.

We studied hydrated (with D₂O and H₂O) sodium tetrasilicate glasses, quenched from melts at 1400°C and 1.5 GPa, using ¹H, ²H and ²⁹Si solid state NMR. Whereas D₂O and H₂O depolymerize the silicate melt to similar degrees, as would be expected, we surprisingly find that protium (H) and deuterium (D) intramolecular partitioning between different molecular sites within the glasses is very large and controlled by a strong preferential association of deuterons to sites with short O-D-O distances. This preference is independent of total water content and D/H ratio. Substantial intramolecular D-H partitioning is also observed in a glass with a model hydrous basalt composition. Such large isotope partitioning cannot result from classic fractionation effects because of the high synthesis temperatures. Potential kinetic isotope effects are excluded via a slow quench experiment. The partitioning is likely governed by density/molar volume isotope effects, where deuterium prefers sites with smaller molar volume. Large intramolecular site partitioning in melts could lead to significant D-H partitioning between water saturated melt and exsolved aqueous fluid (where $D/H_{W,Melt} \neq D/H_{W,Fluid}$) during crystallization of Earth's magma ocean, potentially controlling the D/H content of the Earth's oceans.

Keywords: Silicate Melt, D-H fractionation, NMR, Magma Ocean

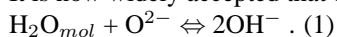
Chemical dependence of the speciation and structural position of water in silicate melts

LE LOSQ, Charles^{1*} ; CODY, George¹ ; MYSEN, Bjorn¹

¹Geophysical Laboratory, Carnegie Institution of Washington

Water is the main volatile component affecting the thermodynamic, structural and rheological properties of magmatic liquids in the Earth's interior resulting in major influence on past history and present magmatic activity of the Earth. Previous experiments and modelling have shown that water can be dissolved as H₂O molecules (H₂O_{mol}) and OH⁻ groups, with the OH⁻ groups bonded to the silicate network to form Si-OH or Al-OH bonds and perhaps alkali-OH and alkaline earth-OH complexes. However, important questions remain as to how bulk chemistry governs the link between the different OH groups and the silicate network, and the global H₂O_{mol}/OH ratio.

It is now widely accepted that dissolved water reacts with the O²⁻ oxygen composing the silicate network following:



As O²⁻ from the silicate network is involved in this reaction, its equilibrium constant must depend on the activities of bridging (BO), non-bridging (NBO), and free oxygen species potentially present in silicate melts, and hence on their global chemistry. Even if Al-OH and Si-OH bonding were the only variables (and, therefore, the Al/Si ratio of a melt), reaction (1) implies that the H₂O_{mol}/OH should depend on silicate melt composition. However, as the activity of NBO species is also affected by the ionic field strength of alkali and alkaline earth cations, we expect the equilibrium of reaction (1) to be affected by those cations.

To test and to quantify the occurrence and the impact of chemical effects on the speciation of water in quenched, hydrous silicate melt (glass), we analysed M₂Si₄O₉ glasses (M = Li, Na or K) containing different amounts of water (from 3.3 up to 17.6 mol%) with the help of ¹H and ²⁹Si MAS NMR, Raman and Infrared spectroscopy. Glasses were formed by temperature quenching (~100 °C/s) at 1.5 GPa. Raman and infrared spectroscopy show three different bands close to 2300, 2800 and 3600 cm⁻¹. These are assigned to O-H stretching from OH groups bonded to silicate components and from H₂O molecules. Correlation of those frequencies with the O ··· O distances in minerals suggest that those three bands arise from OH stretching in two main different environments: one with a mean O ··· O distance close to ~0.26 nm and another one with a ~0.29 nm O ··· O distance. In the ¹H MAS NMR spectra, we retrieved signals near 15 and 5 ppm arising from the ~0.26 and ~0.29 nm environments respectively. Increasing the alkali radius tends to increase the intensities of the 15 ppm ¹H MAS NMR peak and of the 2000-2900 cm⁻¹ Raman region, indicating an increase of the population of OH groups in the ~0.26 nm environment. In addition, the higher the alkali radius the higher the effect of water on the polymerization degree is, as testified by changes of the ²⁹Si NMR and Raman signals.

Those NMR and Raman observations suggest that the H₂O_{mol}/OH ratio in quenched hydrous silicate melts decreases in the order Li, Na, K. The greater the radius of alkali, the higher the proportion of OH⁻ the smaller the mean O ··· O distance in their environment, and hence the more extensive hydrogen bonding. We propose that this structural evolution arises from a combination of steric hindrance and electron distribution around alkali elements that affects both equilibrium reaction (1), which will decrease in the order K > Na > Li, and the local environment of the formed OH⁻ groups. This interplay between the nature of the alkali modifier, the speciation of water and the polymerization of the silicate network must result in non-negligible differences in viscosity of Li, Na and K silicate melts. Therefore, following this study, variation of the concentration of alkali and alkaline-earth elements in natural hydrous magmas, following their origin, will result in changes of their rheological properties, not only because of the different effects of alkali/alkaline earth elements on Si-O bonds, but also because of differences in the water speciation and OH⁻ environments.

Keywords: water, silicate glass, Raman spectroscopy, NMR spectroscopy

Large ion lithophile elements delivered by saline fluids to sub-arc mantle

KAWAMOTO, Tatsuhiko^{1*} ; MIBE, Kenji²

¹Inst Geotherm Sci, Grad School Sci, Kyoto Univ, ²Earth Research Institute, Univ of Tokyo

Geochemical signatures of arc basalts are explained by addition of aqueous fluids, melts, and/or supercritical fluids from subducting slab to sub-arc mantle. Partitioning of large ion lithophile elements between aqueous fluids and melts is crucial as these two liquid phases are present in the sub-arc pressure-temperature conditions. Using synchrotron x-ray beams, in-situ x-ray fluorescence (XRF) spectra are obtained from aqueous fluids and silicate melts at high-temperature and high-pressure conditions under varied concentrations of (Na, K)Cl (0-25 wt.%). There is a positive correlation between partition coefficients and pressure, as well as partition coefficients and salinity. In the systems with 13-25 wt.% (Na, K)Cl, partition coefficients of Rb, Cs, and Pb are greater than unity, indicating the capacity of such highly saline fluids to effectively transfer those elements. Enrichment of large ion lithophile elements in arc basalts relative to mid oceanic ridge basalts has been attributed to the mantle source fertilization by aqueous fluids from dehydrating oceanic plate. Such aqueous fluids are likely to contain Cl, although their amount remains to be quantified.

Keywords: subduction zone, magma, high temperature and high pressure, mantle wedge, synchrotron X-ray, chlorine

In-situ characterization of carbon-speciation in silicate-C-O-H fluid and melt with temperature, pressure, and redox con

MYSEN, Bjorn^{1*}

¹Geophysical Laboratory, CIW, USA

Speciation and partitioning of C-bearing volatiles species in and between silicate-saturated C-O-H fluids and (C-O-H)-saturated melts have been determined in-situ with the samples to pressures and temperatures of ~2GPa and 900°C, respectively. Structural characterization was conducted with vibrational spectroscopy of samples contained in externally-heated, hydrothermal diamond anvil cells. The redox conditions were controlled near that of the Fe+H₂O=FeO+H₂ (reducing, RED) and Ni+H₂O=NiO+H₂ (oxidizing, OX) equilibria, respectively. Melts are, therefore saturated in H₂O, H₂, and C-bearing species (redox dependent) and coexisting fluids saturated in silicate components. Solubility of volatile and silicate components depend on both temperature and pressure.

The melt/fluid partition coefficients of the C-bearing species vary with redox conditions and temperature with the $\Delta H_{RED}^{melt/fluid} = 44(7)$ kJ/mol and $\Delta H_{OX}^{melt/fluid} = -70(32)$ kJ/mol. Pressure is a dependent variable and increases with increasing temperature. It is assumed no pressure effect of the partition coefficients.

The solution equilibria under reducing and oxidizing conditions, respectively, were; (1) $2CH_3^- + H_2O + Q^{n+1} = 2CH_4 + Q^n$ and (2) $2CO_3^{2-} + H_2O + 2Q^{n+1} = HCO_3^- + 2Q^n$, where the superscript, n, in the Q-species denotes number of bridging oxygen in the silicate species (Q-species). In the absence of H₂O equilibrium (1) changes to $CH_3^- + Q^n = CH_4 + Q^{n+1}$. For oxidized carbon, there is an analogous expression expressing equilibrium between molecular CO₂ and structurally bound CO₃²⁻-groups. Under both oxidizing and reducing conditions, the abundance ratios, CH₄/CH₃⁻ and HCO₃⁻/CO₃²⁻ increase with temperature. The enthalpy change associated with the species transformation does, however, differ for fluids and melts and also for oxidized and reduced carbon ($\Delta H_{(1)}^{fluid} = -16(5)$ kJ/mol, $\Delta H_{(1)}^{melt} = -49(5)$ kJ/mol, $\Delta H_{(2)}^{fluid} = 81(14)$ kJ/mol). For the exchange equilibrium of CH₄ and CH₃⁻ species, the temperature-dependent equilibrium constant yields $\Delta H = 34(3)$ kJ/mol.

Reactions (1) and (2) involve changes in silicate polymerization where increasing abundance ratios, CH₄/CH₃⁻ and CO₃²⁻/HCO₃⁻ lead to increased silicate melt polymerization. As a result of the relations between speciation of C-bearing species and melt and fluid structure, stable isotope (C and H) and element partition coefficients between melts and fluids, which depend on and silicate polymerization and silicate speciation, also vary with speciation of C-bearing species in silicate-C-O-H systems. Pressure, temperature, and redox control on the C-speciation also govern those (and other) properties.

Keywords: COH volatiles, fluid structure, melt structure, high pressure, high temperature, redox conditions

Effect of CO₂ content on melting phase relations in kimberlite group I at 6.5 GPa and 1200-1600°C

SHATSKIY, Anton¹ ; LITASOV, Konstantin^{1*} ; SHARYGIN, Igor¹ ; OHTANI, Eiji²

¹V.S. Sobolev Institute of Geology and Mineralogy SB RAS, Novosibirsk 630090, Russia, ²Department of Earth and Planetary Material Science, Graduate School of Science, Tohoku University

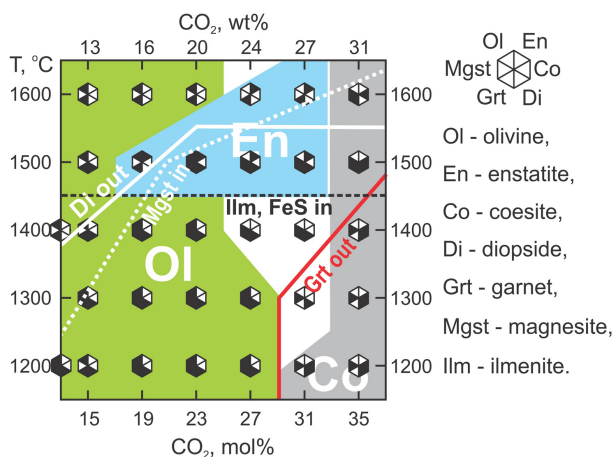
Our understanding of kimberlite petrogenesis is significantly hampered by uncertainty about the compositions of kimberlite magma. It is generally accepted that the last equilibration of kimberlite magma with surrounding mantle (garnet lherzolite) occurred beneath cratons at 6-7 GPa prior its rapid ascent (about 70 km/h) to the surface. This conclusion is based on the following facts. The deepest (170-220 km depths) and hottest (1200-1500°C) xenoliths entrapped by kimberlites are sheared garnet lherzolites originating from the lower part of lithospheric mantle. The preservation of deformation features in sheared lherzolites indicates that the rock was undergoing dynamic recrystallization just before it was picked up by the magma and that it reached the surface after less than a few days or even hours in magma rising by crack propagation (Green and Gueguen, 1983; Meyer, 1985; Sparks et al., 2006). Based on our recent study (Sharygin et al., 2013) of melting phase relations in an exceptionally fresh kimberlite group I from Udachnaya-East kimberlite (UEK) pipe at 3.0-6.5 GPa and 900-1500°C, the kimberlite melt had essentially Na-K-Ca carbonatite composition <15 wt.% SiO₂, Na₂O + K₂O = 5-18 wt%, Na/K = 2, Cl >1.5 wt%, and Ca/(Ca+Mg) >0.5. However, the mineral assemblages obtained in these experiments differ from known mantle parageneses. This may be due to unaccounted CO₂ budget missed at shallow depth as a result of decarbonation reactions at 1.5-2.5 GPa. Therefore, in present study we examined the effect of additional CO₂ on melting phase relations in synthetic UEK kimberlite system at 6.5 GPa and 1200-1600°C.

Based on obtained results mineral assemblage equilibrated with kimberlite partial melt gradually changes from peridotite to eclogite paragenesis with increasing its CO₂ content from 13 to 35 mol %. As can be seen at 6.5 GPa kimberlite partial melt (i.e. Na-K-Ca carbonatite melt) becomes equilibrium with garnet lherzolite (i.e. olivine + enstatite + diopside + garnet + FeS + ilmenite assembly) at 1500°C and 23 mol % (20 wt%) CO₂. This value is 10 mol% more than natural abundance of CO₂ in the Udachnaya-East kimberlite rock (group I kimberlite). In other words, the kimberlite magma lost almost half of the CO₂ budget during the eruption.

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Figure. Melting phase relations in Udachnaya-East kimberlite (kimberlite group I) versus temperature and CO₂ content at 6.5 GPa. 13 mol % CO₂ corresponds to the natural abundance of CO₂ in UEK rock.

Keywords: kimberlite, carbonatite, carbon dioxide, high-pressure experiment, Earth's mantle, melting



Carbon dioxide in granitic magma under lower crustal conditions

YOSHIMURA, Shumpei^{1*}; NAKAMURA, Michihiko²; YURIMOTO, Hisayoshi³

¹Department of Earth and Environmental Sciences, Yamagata University, ²Department of Earth Science, Tohoku University, ³Department of Natural History Sciences, Hokkaido University

<Introduction>

Carbon dioxide is a major volatile component in the crust and mantle. Its solubility and speciation in silicate melts are important in understanding of mechanisms of magmatism and volcanism. However, they are not well constrained under lower-crustal conditions, especially in granitic magma, which is common in the crustal magmatism. In this study, we carried out equilibrium experiments in the CO₂-H₂O-granitic melt system to investigate the solubility and speciation of CO₂.

<Experimental procedure>

High-PT experiments were performed using a piston cylinder apparatus and a cold-seal pressure vessel. Obsidian flakes of a granitic composition and oxalic acid dehydrate (fluid source) were put in a gold or platinum capsule and run at 1123 and 1473 K and 0.1-1.5 GPa. Oxygen fugacity was estimated to be close to NNO. After quench, volatiles dissolved in the glass were analysed with FTIR spectroscopy. The composition of the coexisting fluid was quantified either by manometric analysis or based on the low-pressure solubility law and volatile contents of the glass.

<Results>

FTIR spectra showed that both CO₂ molecules (CO_{2mol}) and carbonate anions (CO₃²⁻) were present in all of the glass samples. The concentrations of CO_{2mol}, CO₃²⁻ and total H₂O increased generally with increasing pressure; they were 9200 ppm, 2100 ppm and 6.1 wt%, respectively, at 1.5 GPa and 1473 K. Here, we used new molar absorption coefficients of 2350 cm⁻¹ (1192 ± 130 L cm⁻¹ mol⁻¹; CO_{2mol}) and 1410 cm⁻¹ (91 ± 28 L cm⁻¹ mol⁻¹; CO₃²⁻) determined in this study. The fraction of CO₃²⁻ to total CO₂ in the granitic melt increased with increasing total CO₂ content, from 0.09 (total CO₂ = 260 ppm) to 0.19 (11300 ppm). The molar fractions of CO₂ in the fluids (X_{CO₂}^{fluid}) were 0.25-0.48 for the cold-seal experiments and 0.73-0.79 for the piston cylinder experiments.

<Discussion>

We formulated the solubility law of CO_{2mol} based on a vapour-liquid equilibrium equation. On the basis of the reaction CO₂ (vapour) ⇌ CO_{2mol} (melt), we calculated the partial molar volume of CO_{2mol} in the granitic melt and the reaction enthalpy to be 24.9 ± 2.0 cm³/mol and -22.2 ± 6.3 kJ/mol, respectively. These values are similar to those in previous experiments carried out at <6.6 kbar (Fogel and Rutherford, 1989; Behrens et al., 2004), indicating that the low-pressure solubility law can be extrapolated to 1.5 GPa. As for the formation of CO₃²⁻, we assumed a reaction CO_{2mol} + O²⁻ (non-bridging oxygen) ⇌ CO₃²⁻. Possible factors shifting the equilibrium to the right-hand side include the total pressure (e.g., Fine and Stolper, 1985; Guillot and Sator, 2011) and water content (King and Holloway, 1992; Behrens et al., 2004). In this study, it was difficult to evaluate these parameters separately, since the water content increased simultaneously with total pressure. If we assume that the effect of water is small enough to be neglected, the change of the partial molar volume of CO₂ in the melt and the reaction enthalpy can be calculated to be -8.6 ± 6.0 cm³/mol and -0.4 ± 3.1 kJ/mol, respectively.

<Application>

Recently, unusually CO₂-rich rhyolitic melt inclusions (up to 1.7 wt% total CO₂) were reported by Blundy et al. (2010). The saturation pressure of this CO₂ content is estimated to be 1.4 GPa when CO₂ dissolved only as CO_{2mol} (X_{CO₂}^{fluid} = 1; T=1173 K). If we consider the formation of CO₃²⁻, the saturation pressure is estimated to 1.2 GPa.

Keywords: CO₂, H₂O, solubility, granitic melt