Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SIT04-P01 Room:Convention Hall Time:May 19 18:15-19:30

On the stability of thermal stratification of highly compressible fluids with depth-dependent physical properties

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We examined in an analytical manner the stability of thermal stratification of highly compressible fluids with depth-dependent physical properties, in order to obtain the fundamental insights into the convective motion in the mantles of "super-Earths". We consider a stability in a horizontal layer of a highly compressible fluid which is in a hydrostatic (motionless) state under a uniform gravitational field. As a model of pressure-dependence in material properties, for simplicity, we employed an exponential decrease in thermal expansivity and exponential increase in thermal conductivity with depth. By using the "parcel method" as in meteorological studies, we investigated the change in the stability of thermal stratification depending on the changes in the depth-dependence of thermal expansivity and conductivity and/or those in the compressibility of fluids, with a special emphasis on the changes in the depth ranges (or the vertical extent) of unstable thermal stratifications.

Our analysis demonstrated that, for given magnitudes of compressibility and depth-dependence in thermal conductivity, the decrease in thermal expansivity enhances the instability within the entire layer. This is because the smaller thermal expansion at depth reduces the adiabatic temperature gradient there despite a high temperature, which further results in a smaller loss of thermal buoyancy associated with the vertical motion of the parcel. We also found that, under the conditions relevant to super-Earths whose mass is 10 times larger than the Earth's mass, the stability of the thermal stratification is strongly affected depending on the combinations of various parameters of the fluid layer. For example, the fluid becomes unstable in the entire layer only for the cases with a significant decrease in thermal expansion with depth and/or a sufficiently low temperature at the top surface. In particular, when the above conditions are not met, the layer of compressible fluids can be split into sublayers as in the atmosphere, i.e., a "troposphere" with an unstable thermal stratification and a "stratosphere" with a stable stratification. Since the present results are in a stark contrast with those for the cases without the compressibility of fluids, our study strongly suggests the crucial importance of the effects of adiabatic (de)compression in the understanding of the dynamics and/or the evolution of the mantles of massive super-Earths.

We also found that, under some extreme conditions with very high temperatures at the top surface, the thermal stratification can be stable in the entire depth of the fluid layer. This result may imply the possibility of super-Earths orbiting their parent stars very closely whose mantle never convects.

Keywords: super-Earths, mantle convection, compressibility, thermal stratification

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Frequency-dependence of the tidal dissipation on the Moon: Effect of the low-viscosity zone at the lowermost mantle

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In the present study, in order to estimate the effect of the low-viscosity zone at the lowermost mantle exerted on the frequency-dependence of the tidal dissipation on the Moon quantitatively, model calculation of the viscoelastic tidal deformation was performed with respect to the monthly and annual periods. Here the seismologically-derived internal structure is given concerning the density and elasticity structure. Concerning the viscosity structure, on the other hand, although not only the existence of the low-viscosity layer but also those of the lithosphere and asthenosphere is taken into consideration, only the viscosity value of the low-viscosity layer is adjusted while those of the remaining two layers are regarded as uniform and constant. Moreover, the mechanical constitutive relation in this calculation follows the rheological law of Maxwell body. And finally, the interior structure, particularly the viscosity of this specific zone is determined by comparing the present numerical result with the preexisting observational result.

As a result of the present calculation, the additional influence of the low-viscosity layer successfully provides the viscosity structure which has no inconsistency with the geodetic observables on the tidal dissipation. More specifically, its viscosity satisfies the quality factor derived from the lunar laser ranging for both monthly and annual periods. This viscosity value is extremely low, which Maxwell relaxation time is close to the tidal periods. Also, the theoretical range of the complex tidal Love number corresponding to this viscosity structure restricted through the quality factor almost corresponds at the same time to the observational range based on the precision orbit determination of the historical lunar orbiters.

This result reveals that, as far as the low-viscosity layer is assumed to exist, even such simple linear rheology can easily interpret the frequency-dependence of the lunar tidal dissipation. One of the former attempts suggested that the observed frequency-dependence on the tidal dissipation is not necessarily interpretable even if following, instead of the Maxwell model, more complicated rheological model like the Burgers model. However, the low-viscosity layer as a simple and natural precondition leads to the different suggestion.

The conclusion obtained from the present result is that the low-viscosity layer certainly exists at the lowermost part of the lunar mantle, and also that this layer induces tidal energy dissipation very effectively. The most important knowledge clarified through this work is that the high seismic attenuation zone is equivalent also to the low-viscosity zone. That is, it is thought that the portion of exceedingly low viscosity exists adjacent to the core-mantle boundary on the Moon as well as on the Earth. The fact that the relaxation time of this ultralow-viscosity zone is close to the tidal periods means that the tidal heating is nearly the maximum within the range of the internal structure defined in the above calculation. Moreover, there is a possibility that partial melting occurs in the deeper part as has previously been pointed out. Perhaps substantial amount of melt is created, even suggesting the rheologically critical state.

Keywords: the Moon, tidal dissipation, mantle, viscosity

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Thermal diffusivity and thermal conductivity of pyroxenes under pressure and the thermal state of subducting slabs

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Pyroxene is an important constituent next to olivine in the upper part of the Earth's mantle. Therefore, its thermal properties are indispensable for investigation of the thermal state of the mantle. Moreover, alike olivine, pyroxene reveals anisotropy in thermal conduction. Magnesium-iron bearing pyroxene has the most significance, however, measurements of thermal diffusivity or thermal conductivity of single crystal pyroxene mineral, such as enstatite, are hard to perform under pressure because obtaining sufficient size of sample is a hurdle. So using polycrystalline sample is the next best thing. We measured thermal diffusivity and thermal conductivity of jadeite as a pyroxene analogue material. In addition, we conducted measurements on omphacite and diopside. Omphacite, mostly composed of a solid solution of jadeite and diopside, is the main component of eclogite, a major rock in deep subduction zone and lowermost crust of thickened continents.

Jadeite sample was a natural aggregate of which source was Itoigawa, central Japan. Omphacite and diopside samples were prepared from fused glass of reagent mixture to sintered polycrystals. The synthesis and sintering were carried out using the Kawai-type apparatus at ISEI. The sample cell was installed in a magnesia pressure medium of 25 mm edge-length. The cell assembly was compressed by anvils with a trancation length of 15mm. The synthetic conditions were 5 GPa, 1100 ^{o}C and 120 minutes for omphacite and 5 GPa, 1200 ^{o}C and 120 for diopside. The recovered samples were confirmed by X-ray diffraction and EPMA analysis, and were seen to have small porosity by SEM observations.

Thermal diffusivity and thermal conductivity were measured simultaneously using the one-dimensional pulse heating method (Osako et al., 2004). This method requires three identical sample disks. Measurements of jadeite were carried out using an 18 mm edge-length MgO octahedral pressure medium up to 10 GPa by anvils with 11 mm truncated edge. The diameter of the jadeite sample was 4.3 mm and the total thickness was 1.05 mm, whereas omphacite and diopside samples had a diameter of 3 mm and a thickness of 0.75 mm. The measurements of these minerals were performed at pressures up to 15 GPa using a 14 mm edge-length MgO octahedral pressure medium and anvils with 8 mm truncated edge.

It is remarkable that omphacite has considerable low thermal conductivity, that is 55-60 % of those of its end members, diopside and jadeite. This value is close to that of garnet. The low thermal conductivity of omphacite may come from disturbed ordering of cations in the structure. Dobson et al. (2010) showed that thermal diffusivity (and hence thermal conductivity) of eclogite was equal to that of olivine, whereas majorite has low thermal conductivity compared with those of surrounding materials (wadsleyite- or ringwoodite-rich assemblages). He suggested that this contrast in thermal conductivities yields deep earthquake activity in the deeper part of subducting slab. Whereas our measurements on thermal conductivity of omphacite (and garnet) could lead to low thermal conductivity or thermal diffusivity of eclogite compared with that of olivine. This would cause the same condition at the eclogite bearing layer in the subduction zone. Moreover, the considerable low thermal conductivity of serpentine (antigorite) would even have such potential in the shallower part (depths$<$150 km) of the subduction zone.

Keywords: thermal diffusivity, thermal conductivity, pyroxene, high-pressure, subduction zon

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H/D interdiffusion in Wadsleyite

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Wadsleyite which is thought to be the dominant mineral in the upper half of the mantle transition zone, can incorporate large amount of H in its structure. Knowledge of relationship between hydrogen diffusion and proton conduction in wadsleyite is essential to accurately estimate the amount of water present in the transition zone. But so far, there is only hydrogen diffusion data obtained from polycrystalline wadsleyite (Hae et al. 2006), whose result showed one log unit higher than the hydrogen diffusion coeffcient expected from conductivity measurement data because of unavoidable grain boundary diffusion and low spatial resolution of FITR.

Shatskiy et al (2006) succeeded to synthesize big hydrous wadsleyite single crystals (>1mm and 3000ppm H2O) by Kawai-type multi-anvil press. Thus, we can currently measure the hydrogen self-diffusion and exclude the grain boundary effect. Recently, hydrogen-deuterium interdiffusion method was demonstrated in olivine to obtain more accurate hydrogen self-diffusion rate (Du Frane et al. 2006). We improved Shatskiy's method to synthetize big single crystal with different hydrogen and deuterium content (maximum 7000ppm) at 16 GPa by multi-anvil to do H/D interdiffusion experiments.

After determination of crystallographic orientation, a pair of hydrous wadsleyite and deurterium wadsleyite crystals was put together into gold capsule and fed a fine gold powder (1 micrometer) to the fill with the space. The polished surface was tightly contact each other. For every orientation, we did three diffusion experiments at different temperatures 1000K, 1200K, 1400K respectively. The preliminary results for D/H diffusion profile were obtained from micro Raman analysis using OD/OH peak ratio. The diffusion coefficient calculated by the Fick's second law indicates that single crystal experiments showed slower diffusion rates than Hae's polycrystalline results and more consistent with the electrical conductivity result. In order to obtain more accurate lattice D/H interdiffusion coefficient in wadsleyite, the diffusion profiles will be measured by SIMS. The SIMS results also will be introduced in this presentation.

Keywords: wadsleyite, mantle transition zone, hydrogen, deurterium, interdiffusion, conductivity

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Effects of pressure and temperature on the silicon diffusivity of pyrope-rich garnet

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We determine the pressure and temperature dependencies of Si volume diffusion rates in single crystal of Pyp75Alm15Gr10 garnet at 6-25 GPa and 1673-2073 K by the ^{29}Si tracer diffusion method. High-pressure experiments are conducted by using the Kawai-type multi-anvil high-pressure apparatus. The diffusion profiles are obtained by using the secondary ion mass spectrometry in the depth-profiling mode. The Si diffusion coefficient in garnet (D_{gt}) is expressed by the Arrhenius equation: $D_{gt} = D_0 \exp(-(E + PV)/RT)$, with $\log_{10}D_0$ = -7.9 m^2s^{-1}, E = 330 $kJmol^{-1}$, and V = 4.6 cm^3mol^{-1}. Si diffusion seems to be the slowest in the major constituent elements and controls rates of plastic deformation under the upper mantle to the mantle transition zone conditions. The comparisons of Si diffusion rates between garnet and wadsleyite/ringwoodite suggest that garnet has almost similar or slightly higher strength (at most 4 times) compared with wadsleyite and ringwoodite at the temperature ranging from 1173 to 1573 K. Thus, the subducted oceanic crust may have plastically similar or slightly higher strength compared with the underlying peridotite layer at the mantle transition zone conditions. This result suggests that the separation of the subducted oceanic crust from the underlying peridotite layer may not occur.

Keywords: garnet, diffusion, rheology, subducted oceanic crust

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Lattice preferred orientation of stishovite in shear deformation

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Seismic observations reveal strong polarization anisotropy (VSV> VSH) at around 550 km depth in the lower part of mantle transition zone (Visser et al., 2008). The observed anisotropy can be caused by lattice preferred orientation (LPO) of constituting material when the material is elastically anisotropic. Majorite and ringwoodite, which are the dominant minerals in this region, are nearly isotropic (Chai et al., 1997; Weidner et al., 1984). On the other hand, stishovite, which may occur in significant amounts in this region derived from the delaminated subducting basaltic layer (Karato et al., 1997) and continental crust (Kawai et al., 2012), shows strong elastic anisotropy indicated by the acoustic velocities study (Yoneda et al., 2012) on single crystal of stishovite. Therefore, the LPO of stishovite has a high potential to interpret the seismic anisotropy in the lower part of the transition zone.

To investigate the LPO of stishovite, deformation experiments on stishovite were conducted in the simple shear geometry. We prepared starting material of polycrystalline stishovite with grain size of ˜30 micron at 12 GPa and 1723 K in a Kawai-type high-pressure apparatus. Then shear deformation experiments were carried out at 12 GPa and 1873 K by Kawai-type apparatus for triaxial deformation (KATD) with 200 micron thickness of sample. Shear strain was ˜0.8 estimated from the rotation of platinum strain maker after deformation. The microstructure and crystallographic orientation of the deformed samples were investigated by SEM with EBSD.

Recovered sample shows the recrystallization occurred during deformation, meaning that the dominant deformation mechanism is dislocation creep. Based on preliminary analysis of LPO, the dominant slip system of stishovite is considered to be [001](100). With the assumption of transverse isotropy of polycrystalline stishovite, our result is consistent with seismic observation (VSV>VSH).

Keywords: stishovite, shear deformation, LPO

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Plastic deformation of ice VII in sub-Neptune-size icy planets

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It is indispensable to construct flow laws of high-pressure ices to understand the convecting interiors of large icy moons and planets. Ice VII is stable over large pressure ranges and possibly major constituent of the icy mantle of the recently found Sub-Neptune-size icy planet (Beaulieu et al., Nature2006). Rheology of high-pressure ices has been studied by using a gas-medium deformation apparatus up to several hundreds MPa. To expand the pressure range in the interior of the large icy objects, we newly conducted a synchrotron radiation study on high-pressure ice rheology.

Plastic deformation experiments of ice VII were carried out by using a deformation-DIA (D-DIA) apparatus installed at NE7A of Photon Factory, Japan (Shiraishi et al., HPR2011). We used monochromatic X-ray (50 keV, collimated to 100-500 microns) and obtained two-dimensional X-ray diffraction (2D-XRD) patterns every 3-5 minutes using imaging plate (IP). The number of diffraction spots on IP that fulfill the Bragg condition is proportional to the grain density. We expect to observe changes of the grain size from the evolution of numbers of diffraction spots as a function of time (Kubo et al., JPCS2010). Differential stress of the sample in uniaxial compression can be measured from distortions of Debye ring on IP. X-ray radiography image is used to determine the sample strain during plastic deformation.

We first compressed water enclosed in teflon capsule using D-DIA at 300K, and synthesized relatively coarse-grained ice VII showing spotty diffraction patterns. Then, the polycrystalline ice VII was uniaxially deformed at 3-10 GPa, 300-650K, and constant strain rates of around 10-5-10-6/s. The total strain reached up to 30%. We observed that the flow stress increases from 40 MPa to about 300 MPa with the pressure from 4 GPa to 10 GPa, at the strain rate of 5x10-5/s and 300K. The flow stress of ice VII is almost comparable to that of ice VI previously reported in the gas apparatus (Durham et al., JGR1996) at around 4GPa, but the pressure dependence is smaller in ice VII. The number of diffraction spots increased with plastic strain, which may indicate dynamic recrystallization of ice VII in the dislocation creep regime. Based on the relationship between the number of spots and the grain sizes in standard samples, we estimated the grain size decreased from 30-40 micron to 10-20 micron during the plastic deformation. Although some further improvements are needed to conduct the quantitative grain-size measurement, we expect that these experimental methods based on synchrotron radiation are useful to explore both GSI and GSS creep of high-pressure ices.

The stress and the temperature dependence of the strain rate will be analysed to construct the flow law of ice VII. It has been known that the diffusion mechanism in water ice changes at high pressures from molecular to ionic migration (e.g., Katoh et al., Science2002). It has also been suggested that a plastic ice phase may appear when heating ice VII above several GPa (e.g., Takii et al., JCP2008). These changes may affect the ice VII rheology in sub-Neptune-size icy planets. Our present deformation experiments cover these conditions and quantitative analysis of the obtained creep data is indispensable to know the effects on the plastic deformation of ice VII.

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Development of fluid-particle coupled simulation method in the Stokes flow regime: toward 3-D geodynamic magma simulatio

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A fluid-particle two-phase flow has been widely studied in geodynamics, because particle-saturated fluid layer is important for understanding the dynamics of solidifying and melting process in the magma chamber or magma ocean. In order to deal with such particle-fluid systems as the geodynamical modeling in 3-D geometry, we develop a new coupled simulation code of Finite Difference method (FDM) for fluid flow and Discrete Element method (DEM) for solid particles. Although this type of numerical method has been well developed in the engineering field to investigate the fluidized bed especially for the high Reynolds number in short time scales, the method for the low Reynolds number over long time scales has not yet been fully addressed.

In the geodynamic modeling with highly viscous fluid, the fluid motion can be treated as the Stokes flow. We employ empirically derived a coupling term between fluid flow and particle motion providing good fit with experimental data of the creeping flow. When this coupling force is directly introduced to the normal DEM equation of particles, we have to numerically solve dumped oscillation with a small time step dt ˜1/eta for high fluid viscosity eta. Thus the normal DEM does not seem to be suitable solution method for our target problems. We therefore propose to drop off the inertial term from the governing equation of DEM based on the Stokes flow approximation and solve the force balance equation as same as that for the fluid. With this approach, we can employ the large dt˜eta for the problems with highly viscos fluid.

Since our original solution algorithms for both of FDM and DEM are designed for the massively vector parallel architectures with two characteristic numerical techniques, we can solve large size of problems in 3-D geometry. 1. The geometric multi grid method of our robust Stokes flow solver is implemented with agglomeration technique to enhance the parallel efficiency in coarse grid operations. 2. Our DEM utilizes the parallel algorithms for a summation of contact force and search of particle pairs using particle labels sorted by the cell number to improve computational efficiency of the code.

We introduce details of our coupled model treatment of the granular medium and demonstrate the validation test with an analogue experiment.

Keywords: magma flow, DEM, Stokes flow, particle-fluid coupled simulation

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Expanding-Contracting Earth

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Since the birth of the Earth by giant impact at 4.56 Ga, the Earth has been regarded to be cooled, hence shrunk over geologic time. However, if the Earth was double-layered in convection, the story must have been different with a peak of expanding during a uni-directional cooling. Using the thermal evolution model of Breuyer and Spohn (1995), we calculated expanding-contracting effect, using the First Principle Calculation. The result shows ca.60km in radius larger Earth right after the consolidation of magma-ocean on the surface shrunk 50km in radius within ca. 10 m.y., and gradually expanded 11km in radius due to radiogenic heating in the lower mantle in spite of cooling in upper mantle in the Archean. This was due to double-layered convection in the Archean with final collapse of overturn, presumably by the end of Archean. Since then, the Earth has been gradually cooled down to reduce its radius 12km up to now.

Geologic evidences support the late Archean mantle overturn ca. 2.6Ga, e.g., the global distribution of super-liquidus flood basalts on nearly all cratonic fragments >35 examples. If this is correct, the surface environment of the Earth must have suffered from extensive volcanism and emergence of local landmasses, because of thin ocean cover 3-5km thickness. Global unconformity appeared for each cratonic fragment with stromatolite back to 2.9Ga with a peak at 2.6Ga. The global magmatism brought extensive crustal melting to yield explosive felsic volcanism to transport volcanic ash into stratosphere during the catastrophic mantle overturn. This event seems to be recorded by sulfur mass-independent fractionation (SMIF) at 2.6Ga. During the mantle overturn, numbers of mantle plume penetrated into upper mantle and caused local doming ca. 2-3km upward to lead local landmasses above sea-level. This led the rapid increase of atmospheric oxygen enabling life from Prokyaryotes to Eukyarhyotes by 2.1Ga or much earlier.