SIT04-01   Room:201B   Time:May 19 14:15-14:30

Lattice thermal conductivity of MgO periclase at high pressure

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The heat flow at the core-mantle boundary affects the core evolution, the thermal convection of the mantle and core, and geo-magnetism from driving the geodynamo. The core-mantle boundary region is thermal boundary layer, therefore heat is transported dominantly by conduction from the core to the mantle. Previous studies have estimated thermal conductivity at the lowermost mantle in a wide range as 5-30 W/m/K (e.g. Lay et al. 2008). However, thermal conductivity of the lower mantle minerals is not well constrained yet due to a difficulty in measurement at high pressure condition. In this study, the lattice thermal conductivity of MgO periclase was obtained up to 100 GPa by measuring thermal diffusivity at room temperature in a diamond-anvil cell. We measured thermal diffusivity with the light pulse thermo-reflectance technique, which was recently developed (Yagi et al. 2011). This is an only method to measure the thermal diffusivity at high-pressure condition corresponding to the core-mantle boundary. Based on the pressure effect revealed in this study and the temperature dependence proposed previously (e.g. Hofmeister 1999), the lattice thermal conductivity of MgO periclase at the core-mantle boundary region was calculated. Combined with the values for MgSiO3 perovskite and post-perovskite recently determined (Ohta et al. 2012), the lattice thermal conductivity at the base of the mantle was estimated. Here we will discuss the core-mantle heat flow.

Keywords: thermal conductivity, periclase, core-mantle boundary heat flow, thermal diffusivity

SIT04-02   Room:201B   Time:May 19 14:30-14:45

Single crystal elasticity of Pbnm-CaIrO3, Cmcm-CaIrO3, and Antigorite determined by inelastic X-ray Scattering

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Single crystal elasticity of Pbnm-, Cmcm- CaIrO3 and Antigorite was measured at Spring8 BL35 by using inelastic X-ray scattering method. The former two phases are well known analog of perovskite (Pv) and post perovskite (pPv) MgSiO3, respectively. The last one is important hydrous mineral in subduction slab.

Keywords: Perovskite, Post-Perovskite, Antigorite, crystal elasticity, inelastic X ray scattering

Tomographic properties from mantle convection in a 3-D spherical shell with the self-consistently calculated mineralogy

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We use numerical thermo-chemical mantle convection simulations in a 3-D spherical shell with the self-consistently calculated mineral physics to investigate various statistical properties using global tomography models (root-mean-square, cross-correlations and spectral amplitude of seismic anomalies). Four compositional models are assumed here, which has been already used in a paper published recently [Nakagawa et al., 2012]. In order to be the similar resolution to current global tomographic images, we use spherical harmonic filter technique instead of tomographic filtering technique [e.g. Davies, et al., 2012]. The truncation of spherical harmonic filter is used as degree of 16, 24, 32 and 40 to compare with the original resolution (96x288x96x2, which is equivalent to 384x192x96 or degree of 192 of spherical harmonic expansion). The statistical properties of tomographic image could be explained by thermo-chemical cases (e.g. RMS amplitude and anti-correlation in the deep mantle). However, it would be difficult to explain the ratio of Vs and Vp or Vb for thermo-chemical origin of mantle heterogeneities, which is similar profiles to isochemical cases. On the other hand, the ratio of Vs and density could explain the mineral physics constraint [e.g. Karato and Karki, 2001] with thermo-chemical origin of mantle heterogeneity. In conclusion, in order to assess global tomographic image as a consequence of mantle convection, RMS amplitude, cross-correlation and the ratio of Vs and Vb ratio might have useful information to understand what happens in a convecting mantle inferred from tomographic images in the deep mantle.

Keywords: Mantle convection, Self-consistently calculated mineralogy, Seismic tomography, Spherical harmonic filtering, statistical analysis

Numerical investigations of effects of spatial variations in physical properties on the mantle convection patterns

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1. Introduction

There exist large differences in temperature and pressure within the mantle of terrestrial planets. In the Earth's mantle, for example, a pressure increases by about 135GPa with increasing depth, while a temperature does by about 3500K. These large differences in temperature and pressure are expected to yield substantial variations in the physical properties of mantle materials and, hence, significantly affect the dynamic behaviors in the mantle. Indeed, as had been inferred by several earlier studies, the spatial variations in mineral properties play an important role in the internal structures observed in the mantle of the Earth and terrestrial planets. We will study how the spatial variation of physical properties of mantle materials affects the flow patterns of thermal convection.

2. Model and Procedure of numerical experiments

We carried out numerical experiments of thermal convection in highly viscous and incompressible fluids, in order to study the influences of the spatial variations in physical properties of fluids (viscosity, thermal conductivity and thermal expansivity) on the convecting flow patterns in the mantle of terrestrial planets. We present the results of a series of numerical calculations using (1) a linear stability analysis on the onset of thermal convection in fluids confined in planar layers, and (2) a nonlinear (finite-amplitude) time-dependent thermal convection in a two-dimensional Cartesian box of aspect ratio (width/height) of 6, with systematically varying the magnitude of (i) decrease in viscosity with temperature, (ii) increase in thermal conductivity with pressure (or depth), and (iii) decrease in thermal expansivity with pressure. By comparing the results with those in the presence of their spatial variations, we will discuss the changes on the critical conditions, dominant vertical flow structures, and the convection regimes caused by their spatial variations.

3. Results

From the changes in flow patterns with increasing the amplitudes of temperature dependence of viscosity, we successfully identified the transition into the 'stagnant lid' (ST) regime, where the convection occurs only beneath a thick and stagnant lid of cold fluid at the top surface. We also found by both linear and nonlinear numerical calculations, that the transition takes place regardless of the spatial variations in thermal conductivity and/or expansivity. However, detailed analysis of the numerical results showed a quantitative difference in the critical condition for the onset of ST convection due to the presence of spatial variations in thermal conductivity and expansivity. Especially we focused on the horizontal wave number of perturbation which is largely decreased by the introduction of spatial variations in these properties. We further developed an analytical model of convection cells which consider the thickness of stagnant lid and convective vigor beneath it. The model successfully reproduced the mechanism of increasing horizontal length scale of ST regime convection cells for each condition of spatial variations in physical properties.

4. Discussion and concluding remarks

The results of present studies indicate that, under certain conditions, the convection of fluids with strongly temperature-dependent viscosity takes place which is characterized simultaneously by (i) large horizontal length scales of convective cells and (ii) thick stiff lid of highly viscous fluid above it. This is in a stark contrast with earlier numerical studies using constant thermal conductivity and expansivity where the convection beneath stagnant lids is always associated with cells with small horizontal length scales. Our findings therefore highlight the essential roles of the spatial variation of the thermal conductivity and thermal expansivity on the convection patterns in the mantle of terrestrial planets.

Keywords: mantle convection, viscosity, thermal conductivity, thermal expansivity, stagnant-lid convection

High-pressure transitions in FeCr2O4 and crystal structures of new post-spinel phases

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Introduction

$FeCr_2O_4$ chromite has the spinel (Sp) structure, and forms the solid solution with $MgAl_2O_4$ and $MgCr_2O_4$ which occurs in the Earth's mantle. The chromitite composed of mostly $FeCr_2O_4$-rich spinel includes high-pressure minerals such as diamond and coesite, which suggest possible indicators of material cycles in the deep mantle (Arai, 2010; Yamamoto et al., 2009). Chen et al. (2003) reported occurrence of the high-pressure polymorphs of $FeCr_2O_4$-rich composition in Suizhou meteorite and synthesized them with diamond anvil cell. They demostrated that the natural chromite spinel transforms to calcium ferrite (CF)-type at 12.5 GPa and to calcium titanate (CT)-type above 20 GPa. High-pressure transiton study of pure $FeCr_2O_4$ end-member demonstrated that cubic spinel of $FeCr_2O_4$ transforms to tetragonal at high-pressure and room temperature (Kyono et al., 2012). In this sudy, we report experimental results on the phase relations in $FeCr_2O_4$ at high pressure and high temperature and the crystal structure analyses of new post-spinel phases.

Experimantal methods

$FeCr_2O_4$ spinel was synthesized from a mixture of Fe_2O_3 and Cr_2O_3 with a 1:2 molar ratio by heating at 1200C for 24 h in a controlled oxygen fugacity using a mixture of H_2, CO_2 and Ar with volume ratios of 1:1:2. High-pressure experiments were made by quenching method at 12-28 GPa and 800-1600C with a Kawai-type 6-8 multianvil high-pressure apparatus at Gakushuin University. Phase identification of each recovered sample was made with powder and microfocus X-ray diffractometers, and compositional analysis was made with a SEM-EDS. The recovered $FeCr_2O_4$ sample was observed by a TEM at Geodynamics Research Center of Ehime University. Angle-dispersive synchrotron X-ray diffraction measurements of some recovered samples were made at ambient conditions using the beam line BL02-B2 at SPring-8 for Rietveld analysis with the RIETAN-FP software (Izumi and Momma, 2007).

Results and discussion

Sp-type $FeCr_2O_4$ first dissociates into a mixture of $Fe_2Cr_2O_5 + Cr_2O_3$ at about 15 GPa, and further transforms to a CF-like phase at lower temperature than 1300C and CT-type $FeCr_2O_4$ at higher temperature at around 20 GPa. Although the CF-like phase had the same space group as the CF-type structure from the result of TEM observation, the X-ray diffraction pattern was somewhat different from that of the CF-type structure. Rietveld refinement confirmed that the $FeCr_2O_4$ synthesized above about 20 GPa at higher temperature than 1300C has the CT-type structure and that $Fe_2Cr_2O_5$ phase is isostructural to the high-pressure $Mg_2Al_2O_5$ phase (Enomoto et al., 2009). The CT-type phase with pure $FeCr_2O_4$ composition and the $Mg_2Al_2O_5$-type $Fe_2Cr_2O_5$ were synthesized for the first time, and the structure analyses of the phases were carried out.

Keywords: post-spinel, high-pressure, Rietveld analysis, chromite, FeCr2O4, TEM observation

SIT04-06   Room:201B   Time:May 19 15:30-15:45

Effects of Thermodynamic Properties on the Geometrical Evolution of Subducting Slabs

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In this study, we perform a series of numerical experiments to investigate the effects of thermodynamic properties on the geometrical evolution of subducting slabs. We calculate density, thermal expansivity, and heat capacity of mantle mineral assemblages of a lherzolite composition over a range of pressure and temperature (PT) conditions applicable to the Earth's mantle, using the thermodynamic database of Stixrude and Lithgow-Bertelloni (2011) and the thermodynamic calculation code Perple_X (Connolly, 2009). Following Nakagawa et al. (2009), we assume that thermal diffusivity follows a theoretical power-law relationship with density and derive thermal conductivity from the calculated density, expansivity, and diffusivity. The calculations show that density, expansivity, and conductivity varies significantly with depth; for example, the ranges of their values for a typical mantle geotherm are 3300-5100 km/m^3, 1.5-3.5 10^{-5}/K, and 3-18 W/m K, respectively. The change in heat capacity is relatively small ($< 5\%$). We incorporate the effects of these thermodynamic properties into a 2-D finite element code with compressible convection formulations under the anelastic liquid approximation (Lee and King, 2009) and develop a thermodynamically consistent dynamic subduction model with kinematic boundary conditions. In the model, we use a composite mantle rheology that accounts for both diffusion and dislocation creep for the upper mantle with rheological parameterization for wet olivine (Hirth and Kohlstedt, 2003). For the lower mantle, following Billen and Hirth (2007) and Lee and King (2011), we adjust the rheological parameter values for wet olivine diffusion creep to test the effects of viscosity contrast between the upper and lower mantle on slab evolution. In models with PT-dependent density, lithostatic pressure in the lower mantle at a given depth is higher than a case with a constant density (by ~800 kg/m^3 at the core-mantle boundary). The higher pressure leads to stronger mantle due to the pressure dependence of the mantle viscosity, leading to a different viscosity structure from the case with a constant density. This change in the viscosity structure due to PT-dependent density alone can have a significant effect on the simulation of slab evolution; for example, for a given set of rheological parameters, a model with PT-dependent density predicts buckling of the slab in the lower mantle while a model with constant density shows no buckling. To focus on the effects of thermodynamic properties, we remove this rheological effect of density variation by adjusting the rheological parameters for the lower mantle to maintain a similar viscosity structure for each set of experiments. When no viscosity contrast is imposed between the upper and the lower mantle, the model predicts that the slab sinks vertically into the lower mantle without experiencing much resistance regardless of the effects of thermodynamic properties. When viscosity contrast of~10-100 is imposed, the model with constant thermodynamic properties predicts the buckling of the slab immediately below the transition zone. In contrast, the thermodynamically consistent model with the same viscosity structure predicts that the slab sinks sub-vertically into the lower mantle, and slab buckling tends to occur in the bottom half of the lower mantle. When large viscosity contrast (>100) is imposed, however, slab buckling occurs immediately below the transition zone even in a thermodynamically consistent model. These modeling results indicate that in numerical simulations, particularly those with viscosity contrast of $<$~100, noticeably different slab geometry can evolve, depending on the treatment of thermodynamic properties.

Keywords: Dynamic slab model, Thermodynamic properties, Mantle viscosity, Slab geometry, Slab buckling

SIT04-07　　　　　　　Room:201B　　　　　　　Time:May 19 16:15-16:30

Sound velocities of CaSiO3 perovskite

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Calcium silicate perovskite (CPv) is the most significant Ca-bearing mineral of the mantle transition zone and the third most abundant phase of the lower mantle within the pyrolite assumption (ONeill and Jeanloz, 1990; Ringwood, 1976). In addition, it is believed that subducted materials such as Mid-Ocean Ridge Basalts (MORB) may involve substantial amount of CPv. Thus the high-pressure and high-temperature structural and elastic behaviours of CPv have been extensively studied for their importance in understanding the internal structure of the Earth mantle. However, and besides reports by theoretical calculations, high-pressure experimental measurements of sound velocities of CPv are few (Li et al., 2004; Kudo et al., 2012).

Here, we examined the sound velocities of $CaSiO_3$ perovskite in situ at high-pressure and high-temperature up to 23 GPa and 1700 K using a combination of ultrasonic interferometry and synchrotron X-ray diffraction techniques within a DIA-type multi-anvil press apparatus at BL04B1 in SPring-8. The velocities of P- and S-wave appeared to behave quasi-linearly within the P and T range studied. Linear fitting for the tetragonal structure of CPv at 300 K yielded $V_P(0) = 10.171$ km/s and $V_S(0) = 5.285$ km/s. Generally our results agreed with Kudo et al. (2012), with V_S being slower than previous estimates by theoretical and experimental methods. In addition we present new high P and T data for the cubic structure of CPv, which displayed velocities about ~5% faster than the tetragonal structure at T > 500 K.

This new results suggested that V_P and V_S of CPv are high compared to surrounding mantle in the uppermost part of the mantle transition region (MTR). In the lowermost part of the MTR, CPv would have velocities comparable to PREM velocities, which make this phase barely detectable in this region. On the other hand, velocities of CPv would be significantly slower than lower mantle.

Keywords: CaSiO3 perovskite, high-pressure, high-temperature, ultrasonic interferometry, X-ray diffraction

SIT04-08   Room:201B   Time:May 19 16:30-16:45

Electrical conductivity of stishovite: effects of Al2O3 and water

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Stishovite is one of the major constituent minerals in subducted oceanic crust. At pressures above 25 GPa, the post-garnet assembly transformed from garnetite originated from eclogite contains up to 25 vol.% stishovite. On the other hand, if Archean continental crust mainly consisteing of tonalite-trondhjemite-granodiorite (TTG) was destructed and subucted into the deep mantle, its assembly contains more than 80 vol.% stishovite. In this case, stishovite should be considered as a main controling phase for the electrical conductivity structure of the mantle. Electrical conductivity of stishovite is expected to be very low because migration of Si and O vacancies is quite slow even high temperature. However, electrical conductivity of stishovite may drastically increase because of their fast mobility as a charge carrier when stishovite crystals contain small amounts of Al and H.

In the present study, effects of Al and H components on electrical conductivity of stishovite was investigated to consider as a cause of the high conductivity anomaly observed in the mantle transition zone. The starting materials were prepared from SiO_2 powder with various amounts of $Al(OH)_3$. Stishovite aggregates were synthesized at 12 GPa and 1673 K. Chemical composition of the run products was SiO_2 with various amounts of Al_2O_3 (0, 1, 5 wt.%) and water. The electrical conductivity measurements were performed at 12 GPa and various temperature conditions to detect effect of water. Relatively dry conditions were accomplished by annealing at 1900 K, proton conduction can be detected under relatively lower temperature conditions less than 1100 K. The conductivity of stishovite increases with increasing H_2O and Al_2O_3 contents. This trend implies that the charge carrier in stishovite is probably interstitial alkali ion in association with substitutional Al in Si site. At low temperatures, the Al-related defect occupied by proton in Si site could be a main charge carrier. Because activation enthalpy for proton conduction is lower than that for Al^{3+}-M^+ pair and its dissociation products, proton conduction could be dominant conduction mechanism below 1100 K.

Electrical conductivity of Al-bearing stishovite (more than 1 wt.% Al_2O_3) is more than one order of magnitude higher than those of wadsleyite and ringwoodite. The high conductivity values observed in the mantle transition zone can be explained by a presence of aluminous stishovite derived from subduction of Archean continental crust.

Keywords: stishovite, electrical conductivity, mantle transition zone

SIT04-09   Room:201B   Time:May 19 16:45-17:00

First principles prediction of a new dense hydrous magnesium silicate

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The global circulation of water in the earth is important to investigate the evolution history and dynamics of the earth, since the physical properties (e.g. atomic diffusivity, melting temperature, electrical conductivity and seismic velocities) of the constituent minerals are considerably changed by the presence of water. It has been reported that water is carried into the deep Earth's interior by hydrous minerals such as the dense hydrous magnesium silicates (DHMSs) in the descending cold plate. However, high pressure behavior of DHMSs, especially the stability of phase D which is the highest pressure phase of DHMSs has not been clarified so far. In this study, I explored the possibility of further phase transition and dissociation of phase D into the hydrous or anhydrous minerals. As a result, the new phase which has lower enthalpy than phase D has been found above about 40 GPa. Therefore, there is a possibility that this new phase in subducting slab takes over water and carries into the deeper part of earth's lower mantle. The detail of the structure and the high pressure-temperature phase boundary determined by quasi-harmonic approximation will be shown and the possible geophysical implications will also be discussed at the presentation.

Keywords: DHMS, first principles calculation, hydrous mineral, high pressure

Melting temperature measurements of water using a laser-heated diamond anvil cell technique with CO_2 laser

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The phase relations and physical properties of water at high pressures and temperatures are important to physical, geophysical, and planetary problems. For example, recent molecular dynamics calculations suggest that water is superionic at high densities relevant to planets such as Uranus and Neptune, and this predicted property plays a key role in dynamo models to explain the unusual non-dipolar magnetic field structure of these planets. The advances in combining techniques such as synchrotron x-ray diffraction or in situ optical Raman spectroscopy with diamond anvil cell (DAC) technologies allow us to measure the melting temperature of water to within a few percent for pressures up to 35 GPa. However, at pressures above 35 GPa, recently reported values of melting temperature exhibit significant differences with each other. This discrepancy should be caused by a chemical reaction occurred between the metal absorber contained in the DAC and the dissociated water. By using CO_2 laser for sample heating, the metal is not necessary because water has significant absorption in the wavelength range of CO_2 laser (10.6 micron). We report the melting temperature of water in a diamond anvil cell more than 35 GPa using CO_2 laser heating system.

We performed the experiments using a DAC with diamonds having flats of 300 micron diameter. Third distilled H_2O was loaded into a ˜100 micron diameter and ˜50 micron thick sample chamber in a DAC. A rhenium gasket was used to contain the sample. The samples were first compressed to a required pressure at room temperature and then heated by two CO_2 lasers with a both-sided heating technique reducing the axial temperature gradient in the sample. The incident angle of radiation of the CO_2 lasers (Synrad 100 W) is about 20 degree. The laser beams were focused by ZnSe lens onto the sample in a DAC. The heated area, which corresponds to about ˜30 micron, is imaged from both sides of sample on the slit of the entrance of the spectrometer and the two charge coupled device (CCD) detectors, respectively. The temperature was measured by the spectro-radiometric method. The uncertainty in temperature within the 30 micron area was less than approximately 7 % stemming from radial temperature gradients.

Melting was determined by plotting the laser power / sample temperature function and looking for the thermal anomaly associated with melting. We found a temperature plateau arising from the melting of water at each pressure. This temperature was determined as the melting point. Another heating experiment of water including a small amount of Ir powder (<10 micron) was performed for cross-check of the melting temperature determined from the relation between the power and the temperature. The temperature when the powder moves was in good agreement with that of the plateau at each pressure. This fact supports that the temperature of the plateau corresponds to the melting point.

The melting temperatures determined in this experiment are much lower than those of the planetary isentropes of Neptune and Uranus. Therefore, at least, solid water might not exist in the interiors of Uranus and Neptune at 100 GPa.

Keywords: water, laser-heated DAC technique, high pressure

SIT04-11 Room:201B Time:May 19 17:15-17:30

Seismic attenuation in the upper mantle beneath the Ontong Java plateau

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We investigate attenuation structure in the upper mantle beneath the Ontong Java plateau (OJP) to identify the origin of this largest LIPs (Large Igneous Provinces) in the globe. Previous studies have shown that S-wave velocities in the upper mantle beneath the OJP are slower than those in the surrounding regions (Richardson et al., 2000). On the other hand, only a few studies have been performed on the attenuation beneath the OJP. Gomer and Okal (2003) showed that ScS-waves traveling beneath the OJP exhibit weaker attenuation than those traveling in the surrounding regions, from which they suggested that the slow velocities in the upper mantle beneath the OJP are not of thermal origin. However, the attenuation of the ScS waves represents average attenuation in the entire mantle beneath the OJP, not in the upper mantle. We need to determine the attenuation in the upper mantle to compare with the slow velocity anomalies in the upper mantle beneath the OJP.

We analyzed teleseismic broadband waveforms of transverse component from deep earthquakes beneath the Solomon Islands subduction zone. Spectral ratios of the sS and S waves were computed to extract information of the attenuation in the upper mantle beneath the OJP. We made correction for crustal structure in and around the OJP, since the sS waveforms are sensitive to the crustal structure at the surface bounce points. Qs values were estimated to be 30-50 for the sS waves of which bounce points are located in the OJP and 40-100 for the sS waves traveling out of the OJP. The Qs values beneath the OJP are well lower than those estimated in other back-arc regions (70-90; Flanagan and Wiens, 1994). The Qs values outside the OJP are close to those in back-arc region. Differential travel time residuals of sS-S are also measured. The differential residuals are well correlated with attenuation pattern: sS waves bouncing at the OJP travel slower by 3 sec than those outside the OJP, which is consistent with the previous studies (e.g., Richardson et al., 2000). These results suggest that the slow velocity anomalies in the upper mantle beneath the OJP are caused mainly by thermal effects.

Keywords: Ontong Java plateau, Seismic attenuation

The thermal history of the Earth's mantle that evolves in two stages

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The thermal history of the mantle calculated from numerical models of a coupled magmatism-mantle convection system is compared with that of the Earth. Both magmatism and mantle convection with tectonic plates are self-consistently reproduced in a two-dimensional rectangular box. The mantle evolves in two stages in these models. On the earlier stage that continues for 1-2 Gyr, heat producing elements (HPEs) and heat flux from the core (HFC) strongly heat the deep mantle, and frequently let hot materials there ascend to the surface as bursts. The mantle-bursts cause vigorous magmatism, stir the mantle efficiently, and make plates move chaotically. As HPEs and HFC decay, however, mantle-bursts stop. On the later stage, subducted basaltic crusts accumulate on the core mantle boundary to form compositionally dense basaltic piles, and plate motion becomes more stable. The average temperature in the entire mantle Tw steadily decreases with time owing to heat extraction by magmatism and mantle convection. The cooling rate is 80-130 K/Gyr on average depending on the internal heating rate. The thermal history of the upper mantle is, however, quite different from this: The average temperature in the upper mantle Tu drops to about 1800 K within the first 100 Myr, and remains almost constant at 1700-1800 K for the subsequent 3 Gyr or even longer regardless of the internal and basal heating rate as well as the initial temperature; Tu gradually decreases to around 1600 K only after that. The thermostat effect of magmatism keeps Tu below 1800 K on the earlier stage no matter how strongly the mantle is heated or how high the initial temperature is. Tu does not decrease on the later stage till 3 Gyr because subducted slabs stagnate on the CMB and do not return back to cool the upper mantle till that time; the steady decrease in Tw during this period is due to the cooling of the lower mantle. The delayed cooling of the upper mantle makes the heat flux at the surface remain almost constant throughout the 4.5 Gyr history of the mantle. At 4.5 Gyr, the Urey ratio is as low as 0.4-0.5 depending on the internal heating rate, and the lower mantle is significantly colder than expected from adiabatic extrapolation from the upper mantle.

Keywords: mantle evolution, plate tectonics, magmatism, numerical simulation, thermal history

SIT04-13   Room:201B   Time:May 19 17:45-18:00

Origin of life: Mechanism of leaking Earth; Fate of cooling Earth

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Supply of nutrients is essential to bear life. To enable a nutrient supply, a landmass must appear above sea level, because continental crust (landmass) is nutrient-enriched. Through weathering, erosion, and transportation of nutrient-enriched rocks, particles are eventually fined to a sufficient size for life to ingest. The emergence of a landmass is caused by a drop in sea level. Here, the cause of sea level change through time is discussed.

Mechanism of change of ocean thickness through time

In the early 2 Ga, after the birth of the ocean, the surface ocean thickness increased through the degassing of a water-rich magma generated from a primordial mantle,. This is a theoretical speculation based on the geologic constraints. From the Archean to the Proterozoic Earth, mantle potential temperature was 200-150K higher than that of today. The subduction-zone geotherm, as documented by P-T conditions of regional metamorphic belts, prohibits water transportation into the mantle through the subduction of hydrated slabs.

Since the Archean, OIBs, such as komatiites and picrites, are enriched in H_2O and CO_2, as well as MORBs with minor water and CO_2, all of which tend to increase the ocean volume through time. On the other hand, the volume of the ocean never reaches sufficient size to bury all of the continents in the Precambrian. Presumably, the maximum thickness of the ocean would have been less than 1km.

Subduction of ocean water and hydrated oceanic slabs began at the onset of the Phanerozoic, as discussed below. About 700-600 Ma ago, the ocean thickness started to decrease, with the reduction of about 600 m until now through the fluctuations in the balance between output versus input of water into the mantle.

Phase diagrams of MORB + H_2O and peridotite + H_2O indicate that the ocean level would decrease though subduction of hydrated oceanic slabs if the top of the descending slab changes to temperatures lower than 600oC at Moho depth of 30km through time from hot Archean mantle to the present. The subduction zone geotherm along the surface of the descending slab turns to generate blueschist-facies rocks if it crosses the high-temperature corner of the blueschist facies in a P-T space defining the subduction zone geotherm and passing to the point at 10kb, 600oC. A plot of the P-T conditions of the regional metamorphic belts over the world since the Archean shows that the first appearance of blueschist was ca. 700Ma, and the subduction zone rapidly cooled at the onset of Phanerozoic. The temperature of Moho depth was higher than 600oC before 700Ma, but rapidly cooled below 600oC, thereafter, and down to 200oC at present. This suggests that the initiation of return-flow of seawater into the mantle began in the Latest Proterozoic, as estimated by the phase diagrams. The observed drop in sea-level clearly supports the idea, and the proposed sea-level-change curve shows that ca. 600m thick ocean has been removed from the surface into the mantle, at the 410-660km depth transition zone, which has a capability to store about 5 times of the total mass water of surface oceans.

The sea-level fluctuation of plus minus 300m in the Phanerozoic could be explained by the glacial/non-glacial periods, as well as the partial mantle overturn when high-temperature and fertile lower mantle materials catastrophically replaced the upper mantle, such as during the Cretaceous (120-85Ma), a major period of magmatic-driven activity. Another pulse was during the mid-Paleozoic, when huge batholith belts were formed similar to the Cretaceous pulse. If the rate of decreasing ocean volume continues over the next 1.0-1.5 b.y., the Earth will finally dry up, which will mark the end of life.

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

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

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

SIT04-P04 Room:Convention Hall Time:May 19 18:15-19:30

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

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^{2}s^{-1}, $E = 330$ kJmol^{-1}, and $V = 4.6$ cm^{3}mol^{-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

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

SIT04-P07   Room:Convention Hall   Time:May 19 18:15-19:30

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.

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

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.