Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SIT35-01 Room:106 Time:May 26 14:15-14:30

High-P,T elasticity of hcp iron

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Earth's inner core (329~364 GPa and 5000~6000 K) is known to be composed of hexagonal closed pack (hcp) structured solid Fe-Ni alloy and seismologically anisotropic. Thermoelasticity of hcp (ϵ) iron is therefore a key to interpreting seismological information of the inner core. Since experimental measurements are still technically impractical, theoretical approaches in particular ab initio density functional computation have substantial roles. There are two different ways to simulate high-P,T elastic constants (c_{ij}) of crystals. One is based on the lattice dynamics method + quasiharmonic approximation (Sha and Cohen, 2010a,b) and the other is based on the molecular dynamics method (Vocadlo et al., 2009; Martorell et al., 2013). The former and the latter basically fail to capture higher-order anharmonicity and low-temperature quantum effects, which would be substantial and marginal in subsolidus condition, respectively. Due to these problems, distinct differences can be seen in high-P,T c_{ij} and their temperature dependences calculated by these different approaches. In this study, we performed ab initio molecular dynamics simulations employing a supercell containing 96 Fe, which is 50% larger than in the previous study with 64 atoms (Vocadlo et al., 2009; Martorell et al., 2013), to check the previous results. Technical details for computing high-P,T c_{ij} are basically the same as in our previous studies (Ichikawa et al., 2014; Kawai and Tsuchiya, 2015). We will present temperature dependences of elastic wave velocities and their anisotropies at the Earth's inner core pressures over 300 GPa.

Kawai and Tsuchiya, Geophys. Res. Lett. (2015) under review; Ichikawa et al., J. Geophys. Res., 119, 240 (2014); Martorell et al., Science 342, 466 (2013); Sha and Cohen, Phys. Rev. B 81, 094105 (2010a); Sha and Cohen, Geophys. Res. Lett. 37, L10302 (2010b); Vocadlo et al., Earth Planet. Sci. Lett. 288, 534 (2009)

Keywords: Ab initio calculation method, Hcp iron, Elasticity, Earth's inner core

SIT35-02 Room:106 Time:May 26 14:30-14:45

Fcc FeHx at core pressure

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Hydrogen is one of the most important candidates of light element(s) of the components the core of the Earth which explain the density deficit of the core. During the core formation, hydrogen preferentially dissolved into the metallic core as FeHx (e.g. Fukai, 1984; Okuchi et al., 1997). However, the phase diagram of FeHx is limited to relatively low pressure (Sakamaki et al., 2009), and its crystal structure under core pressure and temperature has not been revealed. Energetic calculations indicate the transition of double-hexagonal close packed (dhcp) to hexagonal close packed (hcp), and hcp to face-centered cubic (fcc) structure at lower mantle pressure (Isaev et al., 2007), but it has not been verified by experiments. We examined the phase transition from dhcp- or hcp-FeHx to fcc-FeHx by high-pressure and temperature experiments using laser-heated diamond-anvil cell technique and synchrotron X-ray diffraction measurements at SPring-8. It was revealed that dhcp-FeHx disappeared and hcp-FeHx formed at ~60 GPa, and hcp-FeHx transformed into fcc-FeHx at ~70 GPa. The compression behavior of fcc-FeHx was also obtained at 26 to 137 GPa. The pressure-volume relations and the compressivity showed an almost discontinuous change at ~70 GPa, which may reflect the magnetic transition of fcc-FeHx, as indicated by theoretical calculations in Isaev et al., 2007. According to these results, the structure of FeHx at core conditions of the Earth may be fcc rather than dhcp.

Keywords: core, hydrogen, fcc structure, high pressure, X-ray diffraction

SIT35-03 Room:106 Time:May 26 14:45-15:00

Sound velocities of liquid Fe-Si alloys at Earth's core pressures by laser-shock compression

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Sound velocity at Earth's core conditions are one of the most important physical properties in Earth science because it can be directly compared with the seismological Earth model (PREM: Preliminary Reference Earth Model) [1]. The composition of solid inner core is estimated from the comparison of the model [1] and the extrapolation of sound velocities as a function of density of iron and iron alloys obtained by the static compression experiment [2, 3]. Birch's law, a linear sound velocity-density relation [4], is used to extrapolate sound velocities to densities in the core condition. On the other hand, the composition of liquid outer core is estimated from the partitioning and solubility data in the inner core boundary condition for the composition of solid core. There has been some works for the sound velocity of iron on the Earth's core condition by dynamic techniques using explosive [5], gas gun [5, 6], and laser [7]. However, the previous dynamic compression experiments are not enough to reveal the core of Earth, giant planets [8], and super-Earth which is at core pressures over 800 GPa [9]. In this study, we measure the sound velocity and density of liquid iron alloys by shock-compression method using high-power laser at pressures corresponding to super-Earth core pressures.

We conducted shock-compression experiments using a High Intensity Plasma Experimental Research (HIPER) system at the GEKKO-XII laser irradiation facility [10] at the Institute of Laser Engineering, Osaka University. The samples are Fe-Si alloys ($Fe_{95}Si_5$, $Fe_{90}Si_{10}$, $Fe_{80}Si_{20}$ and $Fe_{66}Si_{34}$ in weight percent). The sound velocities and densities of shock-compressed Fe-Si alloys using the high-power laser were measured by x-ray radiography [7, 11, 12] at pressures up to 960 GPa. The linear relation between the sound velocity and the density for FeSi alloy well follows Birch's law [4] up to 960 GPa along the Hugoniot. The extrapolated sound velocity of FeSi alloy was about 40% faster than that of PREM at inner core boundary pressure. The outer core is composed of Fe-Si alloy with 5-13 wt.% Si assuming Si is only light element at the core. This Si content is consistent with the results of previous work by sound velocity measurement [13] and shock-compression experiment [14].

We thank Naoya Yokoyama for his help with the laser-shock experiments and data analysis. Part of this work was performed under the joint research project of the Institute of Laser Engineering, Osaka University.

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Keywords: sound velocity, laser, shock wave, Fe-Si alloys, Earth's core, experiment

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SIT35-04 Room:106 Time:May 26 15:00-15:15

Sound velocity of liquid Fe-Ni-S alloy at high pressure: Sulfur in the core?

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The liquid Earth's outer core is composed mainly of iron (Fe)-nickel (Ni) alloy. Birch (1952) first found that the core is less dense than pure iron based on comparison between seismological observations and experimental measurements of the density of solid iron. This is the so called "core density deficit" problem. He suggested the existence of lighter component(s) in the core, and hydrogen (H), carbon (C), nitrogen (N), oxygen (O), silicon (Si), and sulfur (S) have been identified as likely candidates from cosmochemical and geochemical arguments (e.g., Poirier et al., 1994). The density difference between the outer core and the pure iron has been estimated to be 5-10%, depending on the assumed outer core geotherm (e.g., Anderson and Isaak, 2002). The nature of light elements has remained one of the biggest enigmas for the more than half-century since the Birch's work (1952). To justify the kind and quantity of the light elements in the core, sound velocity measurements of liquid iron alloying with possible lighter elements are fundamental because they link directly to seismological observations. We have launched the project on the sound velocity measurements for liquid iron alloys at high pressure in externally-heated and laser-heated diamond-anvil cells (DAC). The sound velocity of liquid $(Fe,Ni)_3S$ was ,measured via a high resolution inelastic X-ray scattering (IXS) measurements at BL35XU of the SPring-8 synchrotron facility, Japan (Baron et al, 2001). We sucessfully determined the sound velocity of liquid $(Fe,Ni)_3S$ up to the pressure of 50 GPa, which corresponds to the center of Mars. With our newly obtained results, we discuss the possibility of sulfur in the liquid cores of Earth and Mars.

Keywords: Sound velocity, liquid iron alloy, sulfur, outer core, Martian core

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SIT35-05 Room:106 Time:May 26 15:15-15:30

Earth's outer core composition constrained by ab initio thermoelasticites of liquid Fe alloys

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The density deficit of the Earth's outer core indicates substantial amounts of light elements (O, Si, S, C, and H) incorporated in the outer core (Birch, 1952; 1964). The chemistry and amount of the light elements have been strongly debated for over 60 years. Ab initio molecular dynamics (AIMD) simulations have been widely applied to investigate several properties of liquid Fe and Fe alloys (e.g., Alfe et al., 2002; 2007; Badro et al, 2014; Ichikawa et al, 2014). Badro et al. (2014) recently reported a likely compositional model being consistent with seismological data. However with applying empirical pressure corrections, the model suggests smaller amount of light elements to reproduce the ICB density jump. In our study, adopting the Ichikawa et al. (2014) technique we determined the equations of state (EoS) of the liquid Fe alloys by means of the AIMD method in the P, T condition widely covering the entire outer core condition without any pressure corrections. From the EoS, densities, adiabatic bulk moduli, and finally P-wave velocities were calculated and compared with the seismological data (PREM) (Dziewonski and Anderson, 1981). After examining alloy systems from binary to quaternary, we could find some optimized compositional models. However, these have almost comparable reproducibility to PREM, suggesting that other observables are required to make further constraints on the outer core composition. If considering the observed large ICB density jump additionally, Fe-Ni-Si-O and Fe-Ni-S-O compositions appear the most likely.

Keywords: Earth's outer core compositional models, Ab initio molecular dynamics simulations, Equation of state of liquid Fe alloys

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SIT35-06 Room:106 Time:May 26 15:30-15:45

Fine seismic velocity structure of the lowermost outer core determined using outer core sensitive phases

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The liquid outer core of the Earth is regarded as homogeneous and approximately in hydrostatic equilibrium [Stevenson, 1987]. However, a low-velocity layer appears at the base of the outer core (F-layer) [Souriau and Poupinet, 1991; Kennett et al., 1995]. This basal layer may exhibit hemispherical features, as reported by Yu et al. [2005], corresponding to the quasi-hemispherical pattern of the inner core [Tanaka and Hamaguchi, 1997; Wen and Niu, 2002]. The pattern of the inner core is suggested to reflect solidification and melting at the inner core boundary (ICB), which might cause an Fe-rich or Fe-poor layer in the F-layer [Gubbins et al., 2008; Alboussiere et al., 2010; Monnereau et al., 2010]. However, the seismic profile of the F-layer is poorly revealed because of the non-uniqueness of the profiles investigated using previous methods and the interdependence of the F-layer velocity and other seismic properties of the Earth. Thus, a better constrained F-layer velocity is required before discussing its composition.

In this study, we investigated the velocity profile of the F-layer using two new methods: frequency dispersion of the traveltimes of waves that graze or are diffracted at the ICB, and differential traveltimes between waves reflected from the boundary and those that turn above the boundary. The first approach is sensitive to velocity gradients in the layer, while the second is sensitive to velocity excesses or deficits relative to a reference model for the layer; neither approach is sensitive to inner core properties or its radius. We analyzed seismograms of South American earthquakes observed using the Hi-net array [Okada et al., 2004] and the J-array network [J-Array Group, 1993] in Japan. The area investigated in the study is beneath the eastern Pacific, which is placed on the quasi-western hemisphere of the inner core.

Our results show that Vp values in the F-layer are intermediate between those of AK135 and PREM, and that the vertical velocity gradient is larger than that of AK135. Nearly constant velocities in the F-layer are not suited to observations.

Keywords: P-wave velocity in the lowermost outer core, F-layer, Traveltime dispersion of PKPbc, differential traveltimes between PKiKP and PKPbc

SIT35-07 Room:106 Time:May 26 16:15-16:30

Role of Plate Tectonics for Habitable Planet

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Plate tectonics plays a role of global material circulation from the surface of the earth to the bottom of mantle since ca.4.0Ga. This is a due function both to bear habitable planet and to evolve as a habitable planet.

In spite of empirical recognition of importance of plate tectonics, nobody succeeded to synthesize the role of plate tectonics. However, the author completed this task by using following data; (1) geophysical constraints for the mechanism of plate tectonics, (2) petrological and geochemical characteristics of lithosphere, and (3) geologic history of the Earth, specifically the structural and petrological remarks of rock components and dynamics recorded in orogenic belts over the world.

As the result, basic condition for the operation of plate tectonics and following 6 roles of plate tectonics were summarized. The reason why plate tectonics is operated on the Earth is because mid-oceanic ridge is hydrated to enable plate to subduct which is helped by the lubricant water-rich fluids on the bottom of lithosphere. Roles of plate tectonics are (1) Global material circulation of CO2 and H2O, (2) Role of tectonic erosion, (3) Production of nutrients-source rocks at subduction zone, (4) Driving force of Earth's magnetic filed, (5) The buffer of Earth's system, and (6) The controller of thermal history of the Earth.

SIT35-08 Room:106 Time:May 26 16:30-16:45

East-west hemispherical structures in the Earth and their implications for global dynamics

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Hemispherical structures have been found in the inner core (Tanaka and Hamaguchi, 1997; Waszek et al., 2011; and the references therein), the outer core (Tanaka and Hamaguchi, 1993; Yu et al., 2005), and the mantle (Iwamori and Nakamura, 2012). While seismic velocities characterize the core hemispherical structures, the mantle east-west hemispheres have been proposed based on geochemistry, rather than south-north division as has been long argued for (Hart, 1984, known as “Dupal anomaly”). In order to better characterize and interpret the mantle geochemical hemispheres in both spatial and compositional domains, and to discuss whether the hemispherical structures in the core and mantle have any dynamical linkage or not, a total of 6854 young basalt data consisting of five isotopic ratios of Sr, Nd and Pb from almost all tectonic settings (mid-ocean ridge, ocean island, arc and continent) have been statistically analyzed (Iwamori and Nakamura, 2015).

As a result, it has been found that the continental basalts are mostly distributed only in the eastern hemisphere, while other basalts are distributed evenly. Using multivariate analysis (Independent Component Analysis, ICA), two independent compositional vectors have been extracted, which explain most of the sample variance (95%). Therefore, almost all young basalts from various tectonic settings plot on a single isotopic compositional plane, and can be explained solely by two elemental differentiation processes (e.g., melting and aqueous fluid-rock interaction, Iwamori and Albarede, 2008). One of the independent components (IC2) represents ‘anciently subducted aqueous fluid component’ stored for 300 to 900 million years in the mantle, and defines the fluid component-rich (=positive IC2) eastern hemisphere, while the western hemisphere shows the opposite polarity. We have also found a striking geometrical similarity between the IC2 and the inner core hemispheric structures (Iwamori and Nakamura, 2015): the eastern hemisphere shows positive IC2 in the mantle and high seismic velocities in the inner core. Combining these constraints, we propose ‘top-down hemispherical dynamics’: focused subduction within and around the supercontinent has created a fluid component-rich hemisphere with a lower temperature, compared to the oceanic mantle. The colder hemisphere seems to have been anchored to the asthenosphere during the continental dispersal, and may affect the temperature and growth rate of the inner core, resulting in the coupled hemispherical structures in the mantle and the core.

Keywords: mantle, core, supercontinent, hemispherical structure, isotope, independent component analysis

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SIT35-09 Room:106 Time:May 26 16:45-17:00

Slab dynamics and water transport in the lower mantle

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Cold and dense subducting slabs characterize Earth's mantle convection. The structure and evolution of the lower mantle must be significantly influenced from the lower mantle slab, as seismic tomographic images indicate that the slabs penetrate into the lower mantle. For example, the morphology of the large low shear velocity provinces (LLSVPs) at the base of the lower mantle (Romanowicz, 2003) and distribution of a fluid mobile component show the relationship with the subduction history (Iwamori and Nakamura, 2012). We perform a numerical study to investigate influences of the lower mantle properties on the mechanical interactions of the subducted slab with the lower mantle structure.

We use a 2-D Cartesian model of the mantle convection system in which plate-like motion is realized without any imposed forces. We incorporate hydrous mineral phase diagrams (Iwamori, 2004, 2007) and water transport into the model. A chemically dense layer and a post-perovskite (PPV) phase change are introduced to examine interaction between the subducted slab and the D" layer. We also consider effects of various depth dependence of viscosity and a thermal expansivity. Furthermore, yield strengths of the slab are varied.

In the cases with the slab yield strength of 200 MPa except when the lowermost mantle viscosity is as small as 10^{22} Pa s, the subducted slabs experience buckling. By introducing the thermal expansivity declining with the depth, the slab buckling occurs even when the slab yield strength is 300 MPa. The reason of this is that the depth dependence of the thermal expansivity decreases the slab negative buoyancy in the deeper mantle. On the other hand, the depth-dependent thermal expansivity promotes the subduction of the lithosphere, because of the larger value of the thermal expansion coefficient than that for the constant case in the shallow mantle. Accordingly, the plate motion at the surface is less affected by the slab behavior in the lower mantle. The wavelength and the slab descent rate depend on the viscosity profile.

The slab viscosity in the lowermost mantle also influences segregation of the slab materials in the CMB region. In the case with small lowermost mantle viscosity, the slab descends as fast as 20 cm/yr. The rapid slab collision with CMB generates a kink of the slab above the CMB. This reduces the viscosity of the slab by means of the yielding. This causes that a hydrated layer in the upper-side of the slab tends to be segregated from the slab. The hydrated materials are distributed to the overriding-plate side of the slab. When the slab sluggishly descends in the CMB region, the hydrated layer is not peeled. Even in this case, introduction of the viscosity reduction due to the PPV phase transition induces the hydrated slab layer segregation.

In summary, the yield strength and the thermal expansivity play a key role to control the slab-lower mantle interaction. We also emphasize that the viscosity of the PPV phase affects water transport in the lowermost mantle.

Keywords: free convection, subducting slab, slab buckling, lower mantle structure, water transport

SIT35-10 Room:106 Time:May 26 17:00-17:15

Mapping the North American continent with inter-station phase and amplitude data of surface waves

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The investigation of a three-dimensional upper mantle structure using seismic surface waves has been generally based on the measurements of phase delay. The lateral heterogeneity in the Earth, however, not only affects the phase of surface waves, but also modulates their amplitude through focusing/defocusing effects. Such amplitude anomalies caused by elastic focusing are dependent on the second derivative of phase velocity across the ray path, and thus they are sensitive to short-wavelength structure than the conventional phase data, which should be useful for improving the lateral resolution of phase velocity models. In this study, we collect a large-number of inter-station phase velocity and amplitude ratio data working with a non-linear waveform fitting technique using USArray seismograms. Phase velocity maps of North America are then constructed using both phase and amplitude data of both Rayleigh and Love waves to check the validity and utility of inter-station amplitude measurements for enhancing the quality of the phase velocity models.

The phase velocity maps derived only from phase data reflect large-scale tectonic features well; e.g., slow anomalies in the tectonically active western U.S. and fast anomalies in the eastern cratonic region. To the contrary, phase speed models derived from amplitude data tends to emphasize smaller-scale structures characterized by strong lateral velocity gradients; e.g., significant slow anomalies in Snake River Plain and Rio Grande Rift, where the local amplification due to elastic focusing has been observed at USArray stations. Our results indicate that inter-station amplitude-ratio data reflect the effects of the second derivatives of phase velocity distribution well, and are extremely useful for reconstructing shorter-wavelength elastic structures. Thus, the measurements of inter-station amplitude ratios across a dense seismic array can be used to enhance the horizontal resolution of phase velocity models of surface waves.

Keywords: surface wave, phase velocity, amplitude, tomography, North America

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SIT35-11 Room:106 Time:May 26 17:15-17:30

Detection of an asthoenospheric thermal event: approach from lithospheric mantle xenoliths

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Convective mantle heat flux through the continental lithosphere is not well constrained because of high heat generation in the overlying continental crust (Sclater et al., 1980; Pollack et al., 1993; Jaupart et al., 2007; Jaupart and Mareschal, 2007). Its proper estimation and its temporal variation through the earth's history is important to know the overall rate of heat loss from the convecting interior of the earth (Labrosse and Jaupart, 2007; Korenaga, 2008), although the earth is thought to be losing most of its internal heat through the oceanic lithosphere (~70%; Jaupart et al.,2007; Mareschal et al., 2012). The sub-continental lithosphere-asthenosphere boundary (LAB) is the interface through which entropy transported to the asthenosphere beneath the LAB via mantle convection from the depth of the earth is passed on to the entropy transfer in either steady or transient state through the sub-continental lithosphere (Jaupart and Mareschal, 2007; Michaut and Jaupart, 2007; transient important). There are three important mechanisms of entropy transfer through the LAB: heat conduction, soid-state flow, and magmatism (Jaupart and Mareschal, 2007). The upper most zone of the asthenosphere acts as the upper thermal boundary layer of the convecting mantle and that the heat was transferred via heat conduction in the continental lithosphere with or without LAB modification (thickening or delamination/thermal erosion of the lithosphere; Moore et al., 1999; Jurine et al., 2005). Another important aspect of the sub-continental LAB is that it roughly corresponds to a boundary where melting and segregation of melt take place either via decompressional melting in the asthenosphere or melting of the lithospheric mantle induced by the heat input or material influx. This implies that entropy can be transferred from the convecting interior to the lithosphere via magmatism involving heat release or absorption by melting, crystallization, and open-system reactions. It is important to know where magmas are generated and crystallized during its ascent to the earth's surface in the continental region in order to evaluate the role of magmatism in heat transfer through the sub-continental LAB. If a magma generated in the asthenosphere releases heat directly on the earth's surface ending as volcanic eruption and intrusion, then heat loss via magmatism is at maximum efficiency (Ogawa, 1988). Contrary to this, if the magma releases heat within the lithosphere or crust by freezing all the melt there, it heat up the host layer. In this case, the enhancement of heat loss via magmatism depends on the depth of magma freezing, though it is higher than exclusively conductive heat transfer.

In order to examine heat transfer near the sub-continental LAB, it is important to scrutinize the thermal state and its temporal and spatial variability of the mantle material near the LAB and concomitant magma formation and its subsequent magmatism. Fortunately, we have many samples from the continental lithosphere as mantle xenoliths, though xenoliths from the asthenosphere are limited. The continental lithospheric mantle has long history of its formation and modification, but we can extract not only thermal records when xenoliths were entrapped by erupted magmas (mantle geotherm) but also their temporal change before the entrapment by carefully looking at reaction processes took place responding to various thermal and chemical changes taking place in the vicinity of the LAB.

Keywords: asthenosphere, lithosphere, thermal event, mantle xenolith, mineral zoning

SIT35-12 Room:106 Time:May 26 17:30-17:45

An alternative formulation of the dynamics equation system of Maxwellian viscoelastic media

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The traditional dynamics equation system for Maxwellian viscoelastic media is re-examined to find an alternative form which has clearer and sounder physical basis. In the alternative formulation, in the equation of motion only elastic stress should be considered regardless of time scales, while the constitutive equation should be rewritten into such an alternative form that expresses transformation of elastic strain into permanent (plastic) strain with a time constant of the Maxwell relaxation time. Generally for long time scale phenomena, the equation system expresses gradual transformation of elastic strain into permanent strain by always keeping quasi-elastostatic balanced state. Particularly in incompressible case, the system becomes mathematically equivalent with the equation of viscous fluid motion, if the changing rate of elastic to permanent displacement is identified with fluid velocity. Practical method to time-integrate the equation system is investigated. Guided by the new formulation and underlying conception questionable points in traditional treatments of geophysical dynamics are discussed.

Keywords: plate-mantle coupled system dynamics, mantle convection, Maxwellian viscoelastic medium, viscoelastic medium dynamics, elastico-plastic medium dynamics