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強い圧縮性と深度依存物性をもつ流体中の温度成層の安定性: スーパー地球のマントル対流に関する考察
On the stability of thermal stratification of highly compressible fluids with depth-dependent physical properties

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近年の天文学的観測手法の進歩により、太陽系以外の惑星系の存在が数多く知られるようになってくると、そこには地球より大きな地球型惑星がいくつか含まれているらしいことも分かってきた。これらは最大で地球の 10 倍程度の質量を持っており、「スーパー地球」(super Earth) などと呼ばれている。「スーパー地球」の発見により、地球より大きな地球型惑星のマントルダイナミクスが新たな研究テーマの 1 つになってきた。しかしながら過去の研究のほとんど全てにおいて、「スーパー地球のマントル対流」が地球用モデルからの単なる「外挿」として取り扱われており、惑星の大きさの違いに起因するさまざまな効果が十分に反映されているとはいえない。そこで本研究では、スーパー地球のマントル内部に存在する大きな圧力 (〜TPa) 条件下で重要になると期待される、マントル物質の (i) 断熱的圧力変化、および (ii) 熱膨張率と熱伝導率の深さ変化、の 2 つに注目し、これらがスーパー地球のマントル内の鉛直方向の流れに与える基本的な影響を考察した。

モデルとして、静止状態にある圧縮性流体の層を考える。流体中の重力加速度と定圧比熱は一定とするが、熱膨張率と熱伝導率は深さとともに指数関数的に変化 (前者は減少、後者は増加) するものとした。流体層の上面と下面での温度は一定とし、流体層内部の温度分布は鉛直方向の定常 1 次元熱伝導状態によって与えられるものとする。本研究では、この流体中の温度成層構造の安定性を「パーセル法」により検討する。具体的には、ある深さにある流体塊 (パーセル) を鉛直方向に断熱的に (微小) 変位させたときに、流体塊がそのまま動き続ける (静力学的不安定) か、あるいは元の位置に戻ろうとする (静力学的安定) かのどちらかを調べる。特にここでは、流体の熱膨張率・熱伝導率の深度依存性、及び流体の圧縮性の効果の強さをさまざまに変化させたときに、流体層中で静力学的不安定となる深度の範囲がどう変化するかを調べた。

本研究の結果、圧縮性の効果を取り入れた場合には、熱膨張率の深度依存性が大きいほど流体層全体が不安定になりやすいことが分かった。これは深部の熱膨張率が小さいほど断熱温度勾配が小さく、鉛直方向の変位によって熱的な浮力を失いにくいことに起因している。また地球質量 10 倍の「スーパー地球」に相当する条件では、静力学的に不安定となる深さ範囲が、流体層の置かれた条件によって大きく変わることも分かった。例えば流体層全体が静力学的に不安定となるのは、熱膨張率の深さ依存性が十分強く、かつ表面温度が十分低い場合に限られる。特にこれらの条件を満足しない「スーパー地球」のマントルの内部は、静力学的に不安定な「対流圏 (troposphere)」と安定な「成層圏 (stratosphere)」の 2 つの層に分離している可能性が示唆される。なおこれらの結果は圧縮性の効果を無視した場合とは極めて対照的であり、「スーパー地球」のマントル対流の描像や進化の過程を理解する上で、圧縮性の効果が決定的に重要であることを意味している。

さらに極端な例として、表面温度が極めて高い条件で解析を行ったところ、流体層全体が静力学に安定になる場合が検出された。これより、主星に近い軌道を公転するスーパー地球の中には、マントルが全く対流しない惑星が存在する可能性すら考えられる。

キーワード: スーパー地球, マントル対流, 断熱圧縮, 温度成層
Keywords: super-Earths, mantle convection, compressibility, thermal stratification

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月の潮汐散逸の周波数依存性：最下部マントルの低粘性領域の効果
Frequency-dependence of the tidal dissipation on the Moon: Effect of the low-viscosity zone at the lowermost mantle

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一般に固体天体の潮汐エネルギー散逸は重要な地球物理学的現象の一つである．先ず潮汐散逸は内部構造，特に粘性構造に依存するから，その制約条件と成り得る．更に天体内部の潮汐発熱や粘性分布は熱的状態や軌道状態と関連するから，延いては熱進化や軌道進化に対しても制約を与えられる可能性がある．それは月も例外でない．

月の潮汐散逸の内部構造依存性に関するモデル計算は過去に幾つか行なわれているが，それらは何れも依然として，測地学的観測から得られた実際の潮汐散逸の周波数依存性を説明出来ているとは言い難い．特に長年の月レーザー測距から得られたクオリティファクターは弱い周波数依存性を示している．しかし従来のモデル計算では，観測された周波数依存性を完全に説明していないか，或いはそもそも周波数依存性を無視している．

上述の周波数依存性の問題を解決する事は月の科学の観点で有意義である．少なくとも周波数依存性と調和的な内部構造を見出すという事は，内部構造に対して新たな制約条件を課す事と同義である．それに加えて熱進化や軌道進化といった歴史を復元する為の示唆を与える事さえも出来るかもしれない．

ここで周波数依存性を説明する為に特に着目すべき事はマントルの低粘性層の影響である．既に月震の観測から，月のマントルの底には地震波の減衰の大きな領域が存在する，という事が知られている．この高減衰領域の存在は，マントルの最下部の粘性が上部と比べて低い事を暗示する．もしそうであれば，最下部領域が潮汐散逸に及ぼす影響を考慮すれば周波数依存性を説明可能かもしれないが，先行研究では検討されていなかった．

そこで本研究では，月の潮汐散逸の周波数依存性に及ぼす最下部マントルの低粘性領域の効果を定量的に見積もる為，一箇月周期と一年周期に関する粘弾性潮汐変形のモデル計算を実行した．ここで密度構造と弾性構造に関しては月震に基づく内部構造に従った．一方，粘性構造に関しては低粘性層と共にリソスフェアとアセノスフェアの存在も考慮するが，低粘性層の粘性のみ調整して残りの二層の粘性は均一かつ一定とした．又，この計算における力学的構成関係はマクスウェル物体のレオロジー則に従った．そして計算結果を既存の観測結果と比較する事によって内部構造，特にこの特殊な領域の粘性を決定した．

本計算の結果，低粘性層の影響を加味する事によって潮汐散逸に関する測地学的観測量と矛盾の無い粘性構造を得る事が出来た．より具体的には，一箇月と一年の各周期における月レーザー測距のクオリティファクターを共に満足する粘性率が得られた．その粘性値は極めて低く，そのマクスウェル緩和時間は潮汐周期に近かった．しかもクオリティファクターにより制限された粘性構造に対応する複素潮汐ラブ数の理論値は，過去の月周回衛星の精密軌道決定に基づく観測値とも概ね調和的であった．

この結果は，低粘性層の存在さえ仮定すれば，単純な線形のレオロジーを想定しても月の潮汐散逸の周波数依存性は容易に説明され得る，という事を明示した．或る先行例では，マクスウェルモデルのみならずバーガースモデルのような複雑なレオロジーモデルに従っても，観測された潮汐散逸の周波数依存性は説明不可能と指摘されていた．しかしそれと異なる示唆が低粘性層という単純かつ自然な前提条件によって導かれた．

本結果から得られる結論は，月マントル最下部には低粘性層が確かに存在し，かつそれによって非常に効率的な潮汐エネルギー散逸が励起されている，という事である．本研究が明らかにした最も重要な知見は，地震波の高減衰領域が低粘性領域にも相当する点である．即ち月の場合でも地球と同様に核マントル境界付近に極めて粘性の低い領域が存在すると考えられる．そしてこの超低粘性領域の緩和時間が潮汐周期に近いという事実は，上記の計算の中で定義された内部構造の範囲内において潮汐発熱がほぼ最大であるという事を意味する．又，従来指摘されていたように深部で部分溶融が起こっている可能性がある．若しかしたら多量のメルトを含んでおり，レオロジー的臨界状態にあるかもしれない．

本結論は月の熱進化や軌道進化に対しても更なる示唆を与え得る．中でも潮汐散逸が低粘性層に局在化している事は特筆に値する．換言すれば，低粘性層は核の冷却に対して毛布の如く振る舞うと予想される．従ってこの層は，放射性核種に富むチタン鉄鉱集積層と類似の影響を有する筈である．又，このような低粘性層内の潮汐発熱は，マントルの対流，及び部分溶融状態ならメルトの分離も含む熱輸送と平衡しているのかもしれない．かつ熱的平衡を保つ最適な粘性が自己調節的に選択されていると考えられる．このような熱史は月の軌道進化に支配される．潮汐進化によってポテンシャルの周期や振幅が遷移すれば，それに応じてマントルの粘性や温度も変化する．

キーワード: 月, 潮汐散逸, マントル, 粘性
Keywords: the Moon, tidal dissipation, mantle, viscosity

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高圧下の輝石の熱拡散率・熱伝導率と沈み込むスラブの熱的状態
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.

キーワード: 熱拡散率, 熱伝導率, 輝石, 高圧力, 沈み込み帯
Keywords: thermal diffusivity, thermal conductivity, pyroxene, high-pressure, subduction zon

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H/D interdiffusion in Wadsleyite
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.

キーワード: wadsleyite, mantle transition zone, hydrogen, deurterium, interdiffusion, conductivity
Keywords: wadsleyite, mantle transition zone, hydrogen, deurterium, interdiffusion, conductivity

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パイロープに富むガーネット中の Si 拡散の温度と圧力依存性
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

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Lattice preferred orientation of stishovite in shear deformation
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).

キーワード: stishovite, shear deformation, LPO
Keywords: stishovite, shear deformation, LPO

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大型氷天体内部における氷 VII 相の塑性流動
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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マグマ等の高粘性における流体ー粒子混相流シミュレーションコードの開発
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.

キーワード: マグマ対流, DEM, Stokes 流れ, 混相流シミュレーション
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.