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水が沈み込むスラブの挙動に与える効果
Effects of hydrous rocks on behaviors of subducting slabs

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はじめに　深部マントルに数十から数百 ppm 含まれるとされる水は，プレートテクトニクスの発生と活性化・沈み込み帯火山・内陸および深発地震・親水元素の大規模輸送などの地球固有のダイナミクスを引き起こすと考えられている．その重要性から，マントル内部の水輸送の数値シミュレーションが行われてきたが，それらのモデルではプレートの速度や形状が人為的に与えられてきた．本研究では，一切の外力を与えないマントル全域に亘る数値モデルにより，地球深部への水輸送，およびそれに伴って水がどのようにスラブの自発的な挙動を変化させるかを同時に調べる．

手　　法　２次元流体力学シミュレーション (Tagawa *et al*., 2007, *EPS*) に基づき，固相の運動を解く．含水した岩石の移流は粒子法により解き，脱水・再含水反応は，実験に基づく含水玄武岩および含水かんらん岩の相平衡図 (Iwamori, 2007, *Chem. Geol*.) により評価した．含水した岩石の構成方程式 (*e.g*. Karato and Wu, 1993, *Science*) と状態方程式を導入することで，水輸送と固相のダイナミクスとが相互に作用するようになっている．構成方程式中のr (= 0, 0.7, 1.0, 1.93; 含水化による粘性低下の大きさ) と状態方程式中のβ (= 0. 1.0, 2.0; 含水化による密度低下の大きさ) の２者のみを変化させ，その他の設定は統一して計算を行った．

結果と議論　計算結果で，スラブ上面の岩石の反応経路（p-T経路）はいずれも西南日本のものと同一のものとなり (Iwamori, 2007)，200 km 以深で含水かんらん岩の層がスラブ上に形成された (NAMs 中に 2000 ppmH_2O 程度)．背弧拡大には含水域が軟らかくなることが必要のようである．スラブ沈み込みにより上盤プレート内部に引張応力が生ずるのに伴い，含水した低粘性域に変形が集中するからである．計算結果同士を比較すると，rが大きくなるにつれ，海洋プレート速度が速くなる．これは，スラブ上面の含水層が粘性抵抗を減らす効果で説明できる．一方，βが大きくなるにつれ，海洋プレート速度は遅くなる．これは，含水岩石がスラブの負の浮力を部分的に相殺する効果で説明できる．沈み込み速度は，マントルウェッジ内のコーナー流れの速さを決める最も重要なパラメータである．コーナー流れが速い場合，スラブ表面にかかる吸い上げの力が大きくなり，沈み込み角度は浅くなる．速いコーナー流れはまた，マントル深部から表面への移流による熱輸送を活性化させ，急速で継続的な背弧の拡大に寄与する．このような解析的な議論によって，rとβを変化させた場合の計算結果の違いを説明できる．東アジアでは，スタグナントスラブと背弧とが広域に分布するが，その両者を実現するためには，大きなrと小さなβが必要である．両者の生成には強いコーナー流れが必要だが，βはそれを妨げる力を生むからである．このように，スラブの形状や背弧拡大の寿命などから，マントルウェッジ内に働く含水化に伴う浮力の大きさと粘性低下の大きさを制約できる可能性がある．

キーワード: 水輸送, 自由対流, 沈み込みのダイナミクス, プレート速度, 大マントルウェッジ
Keywords: water transportation, free convection, subduction dynamics, plate velocity, big mantle wedge

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Hi-net で計測される日本列島における splitting intensity の空間的変化について II
Regional scale variation of splitting intensity observed in Japanese islands by Hi-net II

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To systematically investigate the spatial variation of seismic anisotropy around the Japanese islands, we measured the splitting intensity (SI) of teleseismic SKS and SKKS phases by Hi-net (Ogawa et al., 2013, SSJ). SI is first introduced by Chevrot (2000) as a method of measuring seismic anisotropy; it is based on cross-correlation of polarized waveforms, and can be modeled like the delay time of seismic tomography considering the effect of finite frequency (e.g., Favier and Chevrot, 2003). In this study, we extend our previous work by measuring SI for a large number of dataset recorded by the dense seismic station network, Hi-net. We use data from tilt-meters of Hi-net from October in 2000 to September in 2013. We have selected the recordings of SKS phases for epicentral distances between 90 and 135 degrees and SKKS beyond 105 degrees, and Mw larger than 6.0, resulting in a total number of events to be 189 that is much larger than the previous case. For the actual analysis, we apply a band-pass filter between 0.05 and 0.125 Hz, and the measurement error of each SI will be carefully estimated using a new formulation, as there appears an error in the Chevrot (2000)'s original treatment. The preliminary analysis indicates regional scale variations of SI patterns that apparently depend on the back azimuth of seismic event, which may be influenced by the subducting slabs.

キーワード: 地震波異方性
Keywords: seismic anisotropy, splitting intensity

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660km 不連続面付近におけるパイロライト、MORB、ハルツバージャイトの相関係の比較：マルチセル法を用いた精密実験
Comparison of phase relations in pyrolite, MORB and harzburgite across 660-km discontinuity

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Pyrolite is the model rock which composes the average upper mantle. It is accepted that 660-km seismic discontinuity is formed by post-spinel transition of pyrolite. MORB (mid-ocean ridge basalt) and harzburgite in slabs subduct to 660-km seismic discontinuity due to their higher densities than pyrolitic average mantle. It has been considered that the density cross-over between pyrolite and slab materials occurs due to post-spinel transition in pyrolite at the 660-km discontinuity, and MORB and harzburgite are trapped around the depth (e.g. Ringwood and Irifune, 1988). Therefore, the phase transition pressures of these mantle rocks are the important parameters to elucidate the dynamics around 660-km seismic discontinuity. We investigated detailed phase relations of pyrolite, MORB and harzburgite with multi-sample cell technique.

The starting materials were prepared from the oxide mixtures of pyrolite, MORB and harzburgite composition after McDonugh and Sun (1995) (excluding MnO, K_2O and P_2O_5), Melson et al. (1976) (P_2O_5) and Michael and Bonatti (1975), respectively. High-pressure and high-temperature experiments by quench method were performed at about 20-28 GPa and 1600-2200C for 2-10 hours using a Kawai-type 6-8 multianvil high-pressure apparatus at Gakushuin University. These samples were packed with pressure calibrants ($MgSiO_3$ or pyrope) in a Re multi-sample capsule with four holes. Temperature was controlled with a LaCrO3 heater and measured with a W5%Re-W26%Re thermocouple inserted in a Cr_2O_3-doped MgO pressure medium. Phases of recovered samples were identified with microfocus-Xray diffractometer and SEM-EDS.

In pyrolite at 1600-2200C, the mineral assemblage of $MgSiO_3$-rich perovskite (Mpv) + magnesiowustite (Mw) + garnet (Gt) + $CaSiO_3$-perovskite (Cpv) is stable at pressure range of 22-24 GPa, and changes to that of Mpv + Mw + Cpv above 24 GPa. The mineral assemblage of ringwoodite (Rw) + Gt + Cpv at 1600C transforms to that of Rw + Mw + Gt + Cpv due to transition of Rw to Gt + Mw at 1800-2000C, and Rw disappears perfectly above 2200C. In MORB, the mineral assemblage of Gt + stishovite (St) + Cpv changes to that of Mpv + St + Al-rich phase + Cpv with continuous post-garnet transition. In harzburgite at 1600C, the mineral assemblage of akimotoite (Ak) + Rw + Gt changes to that of Mpv + Mw by post-spinel transition after the Ak to Mpv transition. Above 1800C, no Ak was observed.

At 1600C, post-spinel transition in pyrolite occurred by about 0.5 GPa and 2 GPa lower pressure than that of harzburgite and post-garnet transition in MORB, respectively. The Clapeyron slope of post-spinel transition in harzburgite is larger than that of pyrolite, and both boundaries intersect at 2000C. From the comparisons of density profiles at 1600C, MORB and harzburgite have lower densities than pyrolite by post-spinel transition in pyrolite.

キーワード: ポストスピネル転移, ポストガーネット転移, 660-km 地震波不連続面, パイロライト, MORB, ハルツバージャイト
Keywords: post-spinel transition, post-garnet transition, 660-km discontinuity, pyrolite, MORB, harzburgite

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ミッシングキセノン問題に対する鉄キセノン系の融解実験
Melting experiments in the system Fe-Xe and Earth's missing xenon

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The abundances of noble gases in the Earth's atmosphere should be consistent with those in CI chondrite. However, xenon in the atmosphere is depleted relative to chondritic abundance, while lighter rare gases, Ne,Ar, and Kr, are less depleted. This is the so-called "missing xenon" problem and its reservoir has been discussed for a long time. Since xenon is too heavy to escape toward outer space, the missing xenon (Xe) might be hidden in the deep Earth.

The potential reservoirs are the mantle and core because xenon has a good reactivity under high pressure. Although extensive studies on the reactions of Xe and various mantle materials have been performed, none of those found a Xe reservoir (e.g., Sanloup et al., 2005; 2011; Brock et al., 2011). On the other hand, the alloying of iron with xenon has been expected based on the fact that Xe becomes metallic above 130 GPa (e.g., Eremets et al., 2000). While first-principle calculations suggested that the solubility of xenon in hcp iron is 0.8 mol% at Earth's core conditions (Lee et al., 2006), experimental study showed that the solid Fe-Xe reaction did not occur at least up to 155 GPa and 3000 K (Nishio-Hamane et al., 2010). Here we performed melting experiments in the Fe-Xe system to 86 GPa and 6450 K.

High pressure and temperature (P-T) conditions were generated in a laser-heated diamond-anvil cell. We used pure iron foil as a starting material. Xe was loaded cryogenically. Angle-dispersive X-ray diffraction (XRD) measurements in-situ at high P-T were conducted at BL10XU, SPring-8. The textural and chemical characterizations of recovered samples were made by using a field-emission-type scannning electron-microprobe (FE-SEM) equipped with energy dispersive x-ray spectrometry (EDS). Both cross section and surface of a sample were carefully examined by combining a focused Ga ion beam (FIB) with FE-SEM.

Any evidence for the reaction was not observed at least up to 83 GPa and 3810 K based on both XRD measurements and chemical analyses. On the other hand, chemical analysis on the sample recovered from 86 GPa and 6450 K, the highest P-T condition achieved in this study, showed Fe alloyed with up to ˜1.6 wt.% Xe as tiny grains. This sample had a difference in the texture between heated and unheated regions. We calculated the concentration of Xe in the entire molten area by assuming the heated region and the small grains of Fe-Xe alloy as a cylinder and spheres, respectively. The xenon content was estimated to be 0.02 wt. % for the heated area which is high enough to account for the missing xenon problem (10^{-10} wt.% Xe in the core). The present results could be a clue to solve the "missing xenon" paradox. Since the temperature of the present Earth's core is most likely lower than 6000 K, xenon might be incorporated into the core during Earth's early history at higher temperature.

キーワード: ミッシングキセノン, 高温高圧, 融解実験, コア
Keywords: Missing Xe, melting experiments, High pressure and temperature, core

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全マントル P 波鉛直異方性トモグラフィー
Whole-mantle P-wave radial anisotropy tomography

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1. はじめに

地震波の異方性を研究する際には，ほとんどの場合において六方対称の異方性（即ち，transverse isotropy）が仮定される．その対称軸は，水平面内（即ち，方位異方性）又は鉛直方向（即ち，radial anisotropy）にとることが多い．

マントル内の地震波の異方性は，かんらん石などの造岩鉱物のもつ結晶方位異方性，及び応力のかかることによるそれらの選択配向（lattice preferred orientation, LPO）によるものと考えられる (e.g., Zhang & Karato, 1995; Tommasi et al., 2000; Kaminski & Ribe, 2001)．地震波の異方性と地球内部物質の状態との関係が分かれば，異方性を観測することで地球内部の構造とダイナミクスを解き明かすことができる (Silver, 1996)．地震波の方位異方性に関する研究は数多く行われている．一方, 異方性は鉛直方向のみに存在すると仮定した鉛直異方性に関する研究は, P 波走時データを用いて Wang & Zhao (2013) により東北地方と九州地方で行われた．

本研究では全マントルの鉛直異方性を考慮に入れたグローバルトモグラフィーを実施し, マントルダイナミクスの研究を試みた．

2. データ・手法

国際地震センター (ISC) の EHB カタログから山本・趙 (2010) によって選択された 6765 点の観測点で観測された 12,657 個の地震を解析に用いた．約 140 万個の P, pP, PP, PcP と Pdiff 波の走時データをインバージョンに使用した．

解析に用いた手法は, Wang & Zhao (2013) の鉛直異方性トモグラフィーの手法を Zhao et al. (2013) によるグローバルトモグラフィーの手法に組み込んだものである．三次元等方速度構造を表す格子点の間隔は２度 (約 220 km) であり, 三次元異方性構造を表す格子点の間隔は１０度 (約 1100 km) である．

3. 結果

鉛直異方性を考慮に入れたトモグラフィーを実施した結果, 等方成分のみを考慮したモデルに比べて最終的な root-mean-square (RMS) 走時残差は減少した．　上部マントルには環太平洋に低速度異常が, 安定大陸の下には著しい高速度異常が見られた．また, 南太平洋とアフリカの下には核―マントル境界 (CMB) から地表まで連続した低速度異常が見られるなど等方成分については先行研究で行われた等方トモグラフィーの結果と非常に調和的であった．異方性成分は, 太平洋スーパープルームなどでは鉛直方向の速度が水平方向より卓越している領域が見られ, マントル中の鉛直方向の運動を表していると考えられる．

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キーワード: トモグラフィー, マントル, 異方性トモグラフィー
Keywords: tomography, mantle, anisotropy tomography

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CO_2 レーザー両側加熱ダイヤモンドアンビルセルを用いたMgO-$MgSiO_3$ 系の溶融実験
Melting experiments on the MgO-$MgSiO_3$ system using double CO_2 lasers heated diamond anvil cell

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Seismological studies suggest the presence of ultralow-velocity zones (ULVZ) near the core mantle boundary (CMB). Partial melting of the lower mantle materials has been proposed to explain these zones, but experimental validation at the appropriate temperature and pressure regimes remains challenging. The melting curve of the lower mantle material is a key to constrain the existence of melt at the base of the mantle. A laser heated diamond anvil cell (LHDAC) provides an enabling tool for determination of melting temperatures of materials under high *P-T* conditions. Although YAG, YLF lasers (the wavelengths are about 1 μm) have been generally used for LHDAC experiments, the use of metal absorber is required to heat silicate materials. However, the thermal absorber may cause a chemical reaction and a temperature gradient in the sample. The accuracy of temperature determination is suffered from the chemical reaction and the temperature gradient. In contrast, the CO_2 laser with the wavelength of about 10 μm can directly heat silicate materials. For the minimization of temperature gradients, double-sided heating system for LHDAC was suggested by Shen *et al*. (1996). This technique using the YAG laser has been widely used to study the behavior of materials under high *P-T* conditions. However, the double CO_2 laser heating system has not been used due to the wavelength of this laser is different from that of visible light.

The requirements for the pressure medium in laser heating experiments are low thermal conductivity and chemical inertness. Ar, which is a noble gas, is one of the suitable pressure mediums. However, loading Ar into the DAC is difficult under room temperature and ambient pressure. Therefore, a simplified method to load Ar into the DAC is required. In this study, I established new experimental technique for the minimization of temperature gradients and chemical reactions and performed melting experiments of the lower mantle materials using LHDAC.

First, a double-sided heating system using CO_2 laser was developed by separating optical elements. This system consists of the heating system using two CO_2 lasers which have the high power (100 W), the observation systems and the temperature measurement system. By using lenses designed for the CO_2 laser wavelength, the laser system is separated from observation and temperature measurement system. Two dimensional images and radiation spectrums are observed by Charge Coupled Device (CCD) camera and spectrometer, respectively.

Second, a simplified method to load Ar into the DAC was developed by the cryogenic technique. In this technique, Ar is cooled using liquefied N_2 until it forms a liquid, and the liquefied Ar is loaded into the sample chamber of the DAC. Cu was used to enhance cooling efficiency.

Finally, I performed melting experiments of the lower mantle materials using the double CO_2 lasers heated diamond anvil cell and Ar as the pressure medium. I used forsterite (Mg_2SiO_4) and mixtures of MgO and $MgSiO_3$ as the starting material. After the complete pressure release, the sample was recovered from the DAC and examined by FE-SEM. From the surface texture of recovered samples, I discussed melting temperatures of the lower mantle materials under high *P-T* conditions.

The double CO_2 laser heating and loading Ar methods developed in this study could powerful tool for determination of melting temperatures of the lower mantle materials.

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2 段式加圧方式 DAC による超高圧発生への試み
Ultra high pressure generation using the double-stage diamond anvil cell

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SAKAI, Takeshi[1*] ; YAGI, Takehiko[1] ; OHFUJI, Hiroaki[1] ; IRIFUNE, Tetsuo[1] ; OHISHI, Yasuo[3] ; HIRAO, Naohisa[3] ; SUZUKI, Yuya[4] ; KURODA, Yasushi[4] ; ASAKAWA, Takayuki[4] ; KANEMURA, Takashi[4]

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高圧物性科学にとって 1 TPa 領域は今も未開拓地である。ダイヤモンドアンビルセル (以下 DAC) による静的圧縮実験としての最高圧力は 400 GPa 程度 (Akahama and Kawamura, 2010) であった。これに対し、Dubrovinsky et al. (2012) が DAC を用いた 2 段式加圧方式により 640 GPa を発生したと報告し、静的圧縮による 1 TPa の発生は目指しうる目標として見えてきた。しかしこの報告では、1 段目に通常のダイヤモンドアンビル、2 段目に炭素から直接変換した半球状のナノ多結晶ダイヤを対向させたものが使用されており、マイクロアンビルの形状制御が困難、アンビルの位置がずれやすい、試料設置が困難等により再現性ある実験を行うことが難しいといった問題点がある。

本研究では、集束イオンビーム（FIB）加工機によるマイクロアンビルの作成を行った。この利点は、アンビルの形状制御ができる、サブミクロン精度での組み立て可能、試料も同時に作成可能、素材によらず加工が可能といった点で、種々のパラメータを制御しながら再現性良く実験を繰り返すことができる。我々はこの手法により現在最高で 340 GPa までの発生に成功しており、その詳細について報告する。

キーワード: ナノ多結晶ダイヤ, マイクロアンビル
Keywords: nano-polycrystalline diamond (NPD), microanvil

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第一原理分子動力学法による Fe-O 液体の相分離に関する研究
Ab initio molecular dynamics study on a phase separation in liquid Fe-O

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The Earth's outer core is mainly composed of liquid Fe-Ni alloy. The density of the outer core is, however, ˜10% smaller than this alloy. The density deficit indicates that substantial amount of light elements are present in the outer core [Birch, 1964]. Recent seismological observations proposed that seismic wave velocity is ˜3% slower than PREM below a few hundred kilometers of the CMB [Helffrich and Kaneshima, 2010]. The low-velocity anomaly is considered to be cause by stratification. However, mechanisms of the stratification have not been clarified yet. One possible cause is phase separation into Fe-rich and light element-rich liquid. Oxygen is one of the most important light elements, because an iron-oxygen phase separation was observed experimentally at low-pressure condition [Tsuno et al., 2007]. This immiscible behavior is, however, still unclear at the outer core pressure.

In this study, we calculated liquid Fe-O alloy at the outer core condition by means of *ab initio* molecular dynamics simulations. First, we analyzed local structures of liquid Fe-O alloy to detect signs of phase separation. Second, we evaluated its excess enthalpy. Both indicate that the liquid was well-mixed. Finally, we computed P-wave velocity in liquid Fe-O alloy. P-wave velocity was found to increase with increasing the oxygen concentration. All these results suggest that the simple enrichment process is less suitable to explain the low-velocity anomaly.

Keywords: ab initio molecular dynamics simulation, phase separation, liquid Fe-O alloy

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放射光 X 線その場観察と川井式マルチアンビル装置を用いた 30 GPa までのクロム苦土鉱の相関係の解明
In situ X-ray observations of phase transitions in MgCr2O4 to 30 GPa using Kawai-type multianvil apparatus

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Phase relations in $MgCr_2O_4$ (magnesiochromite) have been studied up to 30 GPa and 1600 ℃, using a large volume Kawai-type multianvil apparatus and in situ X-ray diffraction measurements system installed at SPring-8/BL04B1. $MgCr_2O_4$ spinel dissociates into $Mg_2Cr_2O_5$ (orthorhombic type) + Cr_2O_3 (eskolate) at 9 GPa and 1200 ℃, and then reunion to higher pressure phase ($CaTi_2O_4$ type) at 22 GPa and 1200 ℃. Moreover, another high-pressure phase was observed above $CaTi_2O_4$ type structure phase, and this phase was unquenchable to ambient condition. In addition, pressure-induced phase transition in $MgCr_2O_4$ was confirmed without decomposition under cold compression process. In this cause, Magnesiochromite is directly transformed to high-pressure phase through the mixture of spinel and high-pressure phase. In this study, $CaFe_2O_4$ type and ε-phase, which reported in earlier studies in $MgAl_2O_4$ were not observed. The Birch-Murnaghan equation of state was used for least-squares fitting of the volume data (assuming $K_0{}'$ =4). Thus, determined zero-pressure bulk modulus (K_0) of the $CaTi_2O_4$ type $MgCr_2O_4$ was 195 GPa.

In this presentation, we will discuss further details of high-pressure phase relation and physical properties of high-pressure phases in $MgCr_2O_4$ series.

Keywords: Magnesiochromite, in situ X-ray diffraction measurement, Kawai-type multianvil apparatus, phase transition

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地球核条件下にレーザー衝撃圧縮された Fe-Ni 合金の音速
Sound velocities of laser-shocked Fe-Ni alloys under Earth core conditions

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When we consider the structure of Earth's interior, the sound velocity is one of the important physical properties of the interior materials because it can be directly compared with the seismological data (1) which can yield the physical properties of the Earth's interior. Cosmochemical data and the composition of iron meteorites suggest that Earth's core contains mainly Fe-Ni alloy with 5-25 wt.% Ni. Although Lin et al. (2) and Kantor et al. (3) measured compressional sound velocities of Fe-Ni alloys at room temperature by inelastic x-ray scattering (IXS) at diamond anvil cell (DAC), the sound velocity data of liquid Fe-Ni alloys is very few (4).

We performed laser-shock experiments of liquid Fe-Ni alloys at HIPER system of Gekko-XII laser in Institute of Laser Engineering, Osaka University (5). Sound velocities were measured by side-on radiography (6, 7). We obtained sound velocities of Fe-Ni alloys at pressures up to 770 GPa. The sound velocity of Fe-Ni alloy was about 10% lower than that of liquid Fe at inner core boundary (ICB) pressure.

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Keywords: sound velocity, laser, shock wave, iron alloy, Earth's core, experiment