様　式　C－19、F－19－1、Z－19　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Mapping Water in the Deep Mantle

研究課題名（英文）Mapping Water in the Deep Mantle

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交付決定額（研究期間全体）：（直接経費）　　2,200,000円

研究成果の概要（和文）：マントル遷移層は、地球の上部マントルと下部マントルを隔てる層である。マントル遷移帯の鉱物はマントルの中で最大の貯水量を持ち、この地域の水をマッピングすることは、地球の総水収支を理解する上で極めて重要である。ハウザー主任研究員は地震反射の測定と解釈を行い、土屋共同研究員は第一原理分子動力学法を用いて、地球深部マントルにおける高密度含水マグネシウムケイ酸塩の安定性を調べています。その結果、沈み込みに伴ってマントルに漏れ出した水素は、希少な含水鉱物相に蓄えられ、マントル全体は概ね乾燥した状態になることがわかりました。水は、最大容量まで飽和した層ではなく、小さな局所的なパッチとして観測されます。

研究成果の学術的意義や社会的意義
This project sets limits on Earth's deep water storage to understand how the Earth trapped water during formation and maintains the water cycle. We find interior water present in small regions while most water returns to the surface allowing life to emerge and sustain itself over billions of years.

研究成果の概要（英文）：The mantle transition zone is the layer separating the Earth's upper and lower mantle. The unique mantle transition zone minerals have the largest water storage capacity in the mantle such that mapping water in this region is critical to understanding the Earth's total water budget. PI Houser measures and interprets seismic reflections, and Co-I Tsuchiya develops ab initio molecular dynamics to examine the stability of dense hydrous magnesium silicates in Earth's deep mantle. We find hydrogen leaking into mantle during subduction would be stored in the rare hydrous mineral phases, leaving the overall mantle generally dry. We observe water as small local patches rather than a layer saturated to the maximum capacity. Additional work shows that nitrogen in today's mantle originated from early subducted sediments rather than a magma ocean. Our results support the ingassing through subduction rather than outgassing from a magma ocean of volatile elements from Earth's mantle.

研究分野：Global seismology

キーワード：Mantle transition zone　hydrous minerals　global seismology　Earth composition　plate tectonics　mineral physics

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様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Hydrogen is the most abundant element in the universe. Hydrogen mainly exists as water, the liquid phase of H_2O, on the Earth's surface. Although water content of very primitive carbonaceous chondrite (e.g. CI chondrites) is relatively large (up to about 20 wt%), the proportion of the mass of water which covers 70% of the current Earth's surface to the total mass is actually very small ~0.023%. However, water is known to be closely related to the various dynamic activities on the Earth such as igneous activity in the island arc volcanoes, and is also investigated in connection with deep seismicity. It is also argued that plate tectonics and mantle flow characteristics are closely related to the existence of water in the mantle minerals (e.g. Jung and Karato, Science, 293, 2001). Water significantly changes the phase stability and the physical properties such as melting temperature, electrical conductivity, viscosity and etc. of Earth's constituent materials. However, such effects of water have been quantitatively elucidated at the limited pressure range down to the upper mantle (about 0-14 GPa) and little is known about the existence of water below the mantle transition zone and the effect of water on the physical properties of lower mantle minerals.

２．研究の目的

Wadsleyite and ringwoodite, which are the main constituent minerals of the mantle transition zone, have modified spinel and spinel structure, respectively. They can contain up to about 3 wt% of water as a form of hydroxyl (OH), and are called nominally anhydrous minerals (NAMs), meaning they typically do not have water in their crystal structure, but can host it as a substitution. The total amount of water should be several times the present seawater when integrated over the entire transition zone since the NAMs are the main constituent minerals (Smyth, American Mineralogist, 72, 1987, Ohtani and Sakai, PEPI, 170, 2008). Therefore, these minerals in the transition zone are considered to be the most important reservoir of water in the deep Earth because they can retain water even under average temperature conditions of the mantle transition zone. Although the actual water content of the transition zone is unknown, hydrous ringwoodite containing 1.4wt%H_2O has been found in natural diamond inclusions recently (Pearson et al., Nature, 507, 2014), which shows strong evidence that the mantle transition zone is at least partially hydrated. Seismic waves are sensitive to changes in water content which provides the best tool to identify water in the mantle transition zone where hydrated rock has a thick transition zone and slow shear velocity.

３．研究の方法

The effect of temperature and hydration on seismic velocities are similar, i.e. water and higher temperature decrease seismic velocity. Therefore, we need to distinguish between these effects. In order to map water in the transition zone, knowledge about the effects of the temperature, hydration, and impurities such as Fe on the seismic parameters (S and P wave velocities, and the depth of the 410 and 660 km discontinuities) are needed. Previously, those parameters were assumed to linearly depend on the amount of water and temperature increase and also determined by the extrapolation of previous experimental studies toward higher pressure and temperature (e.g. Suetsugu et al., AGU Mono. 157, 2006).

We extended the phase diagram and the elasticity of wadsleyite and ringwoodite to high temperature by ab initio calculation. Tsuchiya has already reported the phase diagram of hydrous phases and also elasticity of wadsleyite at static 0 K condition. We implement the high temperature elasticity by calculating the vibrational frequencies and using quasi harmonic approximation (e.g. Wentzcovitch et al., PNAS, 103, 2006).

Houser selected the high-quality SS waveforms from recent studies to update her SS precursor catalog. The SS precursors are the underside reflections off the 410 and 660 km discontinuities that arrive before the main SS phase, and are the only data that can provide global mapping of 410 and 660 km discontinuity topography. Since we need depth and velocity to distinguish between the effects of water and temperature, Houser created a generalized transition zone velocity model emphasizing slow and fast regions common to most recent tomography models. The seismic signal of water in subducting slabs is difficult to resolve with previous methods due to the dominance of the cold temperatures on seismic velocity, so an iterative and collaborative approach is necessary to improve water detection in the deep interior. Our transition zone hydration map accounts for the quality of global seismic topography and velocity observations and the degree to which they are explained by hydration of wadsleyite and/or ringwoodite.

４．研究成果

The mantle transition zone is the layer separating the Earth's upper and lower mantle. The unique mantle transition zone minerals have the largest water storage capacity in the mantle such that mapping water in this region is critical to understanding the Earth's total water budget. PI Houser measures and interprets seismic reflections, and Co-I Tsuchiya develops ab initio molecular dynamics to examine the stability of dense hydrous magnesium silicates in Earth's deep mantle. We find hydrogen leaking into mantle during subduction would be stored in the rare hydrous mineral phases, leaving the overall mantle generally dry. We observe water as small local patches rather than a layer saturated to the maximum capacity. Additional work shows that nitrogen in today's mantle originated from early subducted sediments rather than a magma ocean. Our results support the ingassing through subduction rather than outgassing from a magma ocean of volatile elements from Earth's mantle.

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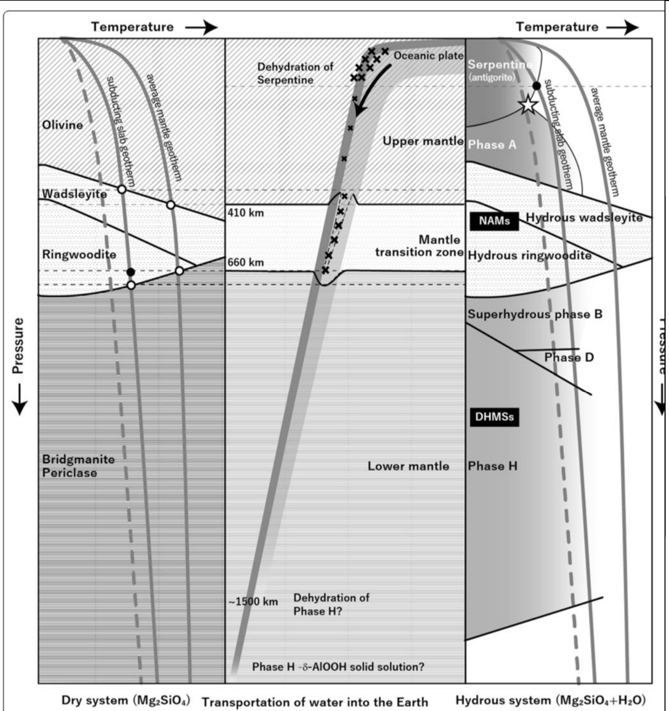

Fig. 1 Schematic illustration of the subducting slab (middle) and phase diagram of dry Mg_2SiO_4 (left) and "stability diagram" of wet systems (right). More detailed stability diagrams of hydrous phases are given in Ohtani et al. (2001b); Nishi et al. (2014); Ohtani (2020). The cross symbols indicate th seismicity observed in the subducting oceanic plate. The "choke point" is shown as the star symbol. Below the choke point temperature, hydrous mineral can transport water into the deeper part of the Earth's interior
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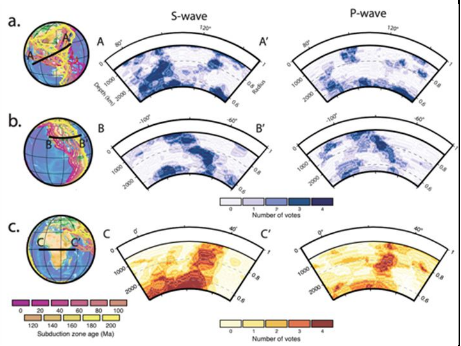

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<td>The funded research uses molecular dynamics to understand how water is distributed in mantle transition zone minerals.</td>
<td>The funded research shows the chemical signature of ancient ocean plates as they cross the mantle powering plate tectonics.</td>
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５．主な発表論文等

〔雑誌論文〕　計8件（うち査読付論文　8件／うち国際共著　8件／うちオープンアクセス　4件）

１．著者名 J. Su, C. Houser, J.W. Hernlund, F. Deschamps	４．巻 234
２．論文標題 Tomographic filtering of shear and compressional wave models reveals uncorrelated variations in the lowermost mantle	５．発行年 2023年
３．雑誌名 Geophysical Journal International	６．最初と最後の頁 2114-2127
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/gji/ggad190	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 J. Tsuchiya and E.C. Thompson	４．巻 9:63
２．論文標題 The role of hydrogen bonds in hydrous minerals stable at lower mantle pressure conditions	５．発行年 2022年
３．雑誌名 Progress in Earth and Planetary Science	６．最初と最後の頁 1
掲載論文のDOI（デジタルオブジェクト識別子） 10.1186/s40645-022-00521-3	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 E.C. Thompson, A.J. Tsuchiya, and J. Tsuchiya	４．巻 12
２．論文標題 Calculated Elasticity of Al-Bearing Phase D	５．発行年 2022年
３．雑誌名 Minerals	６．最初と最後の頁 922
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/ min12080922	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 G. Shephard, C.Houser, J.W.Hernlund, J.Valencia-Cardona, R. Tronnes, R.M.Wentzcovitch	４．巻 12
２．論文標題 Seismological expression of the iron spin crossover in ferropericlase in the Earth’s lower mantle	５．発行年 2021年
３．雑誌名 Nature Communications	６．最初と最後の頁 5905
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-021-26115-z	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 H. Kurokawa, M. Laneuville, Y. Li, N. Zhang, Y. Fujii, H. Sakuraba, C. Houser, H. J. Cleaves II	4．巻 1
2．論文標題 The origin of Earth’s mantle nitrogen: primordial or early biogeochemical cycling?	5．発行年 2022年
3．雑誌名 Geochemistry, Geophysics, Geosystems	6．最初と最後の頁 *
掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2021GC010295	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 C.Houser, J.W.Hernlund, J.Valencia-Cardona, R.M.Wentzcovitch	4．巻 308
2．論文標題 Discriminating lower mantle composition	5．発行年 2020年
3．雑誌名 Physics of the Earth and Planetary Interiors	6．最初と最後の頁 106552
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.pepi.2020.106552	査読の有無 有
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1．著者名 B. Foley, C. Houser, L. Noack, N. Tosi	4．巻 1
2．論文標題 The heat budget of rocky planets	5．発行年 2020年
3．雑誌名 Planetary Diversity	6．最初と最後の頁 4-1 4-53
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/2514-3433/abb4d9ch4	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 E.C. Thompson, A.J. Campbell, J. Tsuchiya	4．巻 1
2．論文標題 Elastic properties of the pyrite‐type FeOOH-AlOOH system from first principles calculations	5．発行年 2021年
3．雑誌名 Geochemistry, Geophysics, Geosystems	6．最初と最後の頁 e2021GC009703
掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2021GC009703	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計6件（うち招待講演　0件／うち国際学会　0件）

1．発表者名 J. Su, C. Houser, J. W. Hernlund, F. Deschamps
2．発表標題 Mantle Mixing and Heterogeneity Revealed by Tomographic Filtering of Geodynamic Models
3．学会等名 American Geophysical Union
4．発表年 2021年

1．発表者名 E.C. Thompson, Z. Liu, J. Tsuchiya, A. Campbell
2．発表標題 FeOOH Polymorphs in the Deep Earth: Combining Theoretical and Experimental Approaches
3．学会等名 American Geophysical Union
4．発表年 2021年

1．発表者名 G. Shephard, C. Houser, J.W. Hernlund, R.G. Tronnes, J. Valencia-Cardona, R. Wentzcovitch
2．発表標題 Detecting the iron spin crossover in ferropericlase
3．学会等名 American Geophysical Union
4．発表年 2021年

1．発表者名 J. Su, C. Houser, J. W. Hernlund, F. Deschamps
2．発表標題 Joint Seismological-Geodynamical Assessment of Lower Mantle Temperature and Composition Variations
3．学会等名 Goldschmidt
4．発表年 2021年

1．発表者名 C. Houser, J. Tsuchiya, C. Unterborn
2．発表標題 Water Storage Capacity of Rocky Exoplanet Interiors
3．学会等名 Japan Geophysical Union
4．発表年 2020年

1．発表者名 J. Su, C. Houser, J.W. Hernlund, F. Deschamps
2．発表標題 Uncorrelated Velocity Variations in the Lowermost Mantle: Towards a Chemical Perspective
3．学会等名 Studies of the Earth's Deep Interior
4．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
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7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計2件

国際研究集会	開催年
Seismology Frontiers	2021年～2021年
Feedbacks Between Mantle Composition, Structure, and Evolution	2020年～2020年

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関