核マントルの相互作用と共進化
～統合的地球深部科学の創成～

領域番号：2706

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科学研究費助成事業（科学研究費補助金）

（新学術領域研究（研究領域提案型））

研究成果報告書

令和 4 年 9 月

領域代表者　土屋　卓久

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はしがき

本報告書は、文部科学省科学研究費補助金「新学術領域研究（研究領域提案型）」の支援を受けて、平成 27 年度から令和元年度までの 5 年間にコロナ禍による 2 年の延長を加えた計 7 年の期間において実施された大型共同研究プロジェクト「核ーマントルの相互作用と共進化　～統合的地球深部科学の創成～」の研究教育活動及び成果をまとめたものである。

本領域の目的は、地球惑星科学においてそれぞれ独立に大きな進展を遂げてきた高圧地球科学、地球化学、グローバル地震学、理論シミュレーションに新たに素粒子地球科学を加え、これらが融合することにより、下部マントルや核の組成、形成・進化プロセスといった地球深部科学における大きな未解決問題を解き明かすことであった。当初はこれだけ広い分野の研究者を集めて、相乗効果を引き出す有機的な連携が本当に実現できるのかという懸念も無いわけではなかった。しかし毎年開かれた成果発表会をはじめ、国内外の学会での特別セッションや複数の計画研究で共催した合同研究集会、また国際スクールなど様々な情報交換の場を設置し目的意識の共有を徹底したことにより、従来には無かった異分野の協同による新たな視点での研究成果が数多く見られるようになった。下部マントルや核の問題に対しては、従来のグローバル地震学や高圧地球科学だけでは観測量や測定量が圧倒的に不足していたが、近年精度向上が著しい地球化学の微量元素・同位体超精密分析技術、長足の進歩をとげた第一原理鉱物シミュレーションによる元素分配や輸送特性の定量データ、また地球ニュートリノ観測により初めて取得できるようになった新たな観測データなど、様々な分野の最新の手法と知見を組み合わせることにより、大きな前進が可能だということを示すことができた。これにより、例えば、地球下部マントルの平均化学組成の特定をはじめとして、地球進化にかかわる動的現象へのアプローチを可能としたメガバール領域における変形実験や電気伝導度測定などの革新技術の開発、タングステン同位体や希ガスの超高精度分析や数値計算に基づく核ーマントルの化学的相互作用の有力な手掛かりの発見、新たな高圧安定含水鉱物の発見と核との反応に基づく揮発性元素循環モデルの構築、下部マントルと核の熱特性の精密化と地震波形解析技術の高度化に基づく核ーマントルの物理的相互作用と外核の不均質構造の理解の深化など、様々な成果を得るに至った。これらの成果を、Nature 誌(7 件)、Nature Geo.誌(4 件)、Nature Comm.誌(14 件)、Science 誌(2 件)、PNAS 誌(5 件)などの高インパクトジャーナルをはじめとする著名な国際学術誌において総計 600 件以上の原著論文として公表するとともに、領域全体の成果を取り纏め国内外の関連分野の発展や教育に資するべく和文及び英文書籍（現在印刷中）として出版した。

これら多岐にわたる活動が国内外で認められた結果、研究期間を通して計 36 件と多くの学会賞等（内国際賞 14 件、学生賞は除く）を受賞するに至った。その他、学会奨励賞や優秀発表賞等計 24 件に及ぶ若手の受賞や、47 名に達する若手の研究職への就職（内 19 名が無期雇用）に繋がるなど、若手育成の観点からも多大な貢献を行った。本領域において構築されたあらたな研究領域、培われた技術や得られた知見、また次世代を担う人材は、固体地球科学分野のみならず、地球環境学、宇宙生命学、物性物理学、材料科学など関連他分野にも大きな波及効果を与えるものであるといえる。

本報告書にまとめた研究成果は、研究分担者、領域により雇用された特任助教や研究員、大学院生などの領域メンバー及び国内外の多数の共同研究者による日々の研究努力により成し遂げられたものである。本領域に参画頂いたすべてのメンバー及び共同研究者に感謝したい。また、総括班会議や成果発表会等に出席いただき、領域の推進に関して適切なアドバイスをいただいた学術調査官の先生方及びアドバイザリーボードの先生方にも深く御礼を申し上げたい。

令和 4 年 9 月　　領域代表者　　土屋　卓久

研究組織

＜計画班＞

領域代表者　土屋　卓久　（愛媛大学・地球深部ダイナミクス研究センター・教授）

X00「核ーマントルの相互作用と共進化」の推進と支援（課題番号：15H05826）

研究代表者　土屋　卓久（愛媛大学・地球深部ダイナミクス研究センター・教授）

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研究分担者　鈴木　昭夫（東北大学　理学研究科・教授）

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研究分担者　田中　宏幸（東京大学　地震研究所・教授）

研究分担者　鍵　裕之（東京大学　理学系研究科・教授）

Y00「核ーマントルの相互作用と共進化」の国際活動支援（課題番号：15K21712）

研究代表者　土屋　卓久（愛媛大学・地球深部ダイナミクス研究センター・教授）

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研究分担者　田中　宏幸（東京大学　地震研究所・教授）

研究分担者　鍵　裕之（東京大学　理学系研究科・教授）

A01-1 ダイナミクス班　核ーマントル物質の動的挙動（課題番号：15H05827）

研究代表者　芳野　極（岡山大学　惑星物質研究所・教授）

研究分担者　安東　淳一（広島大学　理学研究科・教授）

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研究分担者　西原　遊（愛媛大学　地球深部ダイナミクス研究センター・准教授）

研究分担者　平賀　岳彦（東京大学　地震研究所・准教授）

A01-2　構造物性班　核ーマントル物質の構造と物性（課題番号：15H05828）

研究代表者　鈴木　昭夫（東北大学　理学研究科・教授）

研究分担者　鍵　裕之（東京大学　理学系研究科・教授）

研究分担者　井上　徹（広島大学　理学研究科・教授）

研究分担者　舟越　賢一（一般財団法人総合科学研究機構 中性子科学センター・主任研究員）

研究分担者　寺﨑　英紀（大阪大学 大学院理学研究科・准教授）
研究分担者　肥後　祐司（公益財団法人高輝度光科学研究センター利用研究促進部門・主幹研究員）
研究分担者　栗林　貴弘（東北大学　理学研究科・准教授）
研究分担者　山田　明寛（滋賀県立大学　ガラス工学研究センター・助教）
研究分担者　村上　元彦（東北大学　理学研究科・教授）（～H29年7月）

A01-3　技術開発班　核-マントル物質の精密高圧実験技術の開発（課題番号：15H05829）
研究代表者　入舩　徹男（愛媛大学　地球深部ダイナミクス研究センター・教授）
研究分担者　山崎　大輔（岡山大学　惑星物質研究所・准教授）
研究分担者　小松　一生（東京大学　理学系研究科・准教授）
研究分担者　西　真之（愛媛大学　地球深部ダイナミクス研究センター・助教）
研究分担者　境　毅（愛媛大学　地球深部ダイナミクス研究センター・准教授）
研究分担者　石松　直樹（広島大学　理学研究科・助教）

A02-1　同位体班　同位体から制約する核－マントルの共進化（課題番号：15H05830）
研究代表者　鈴木　勝彦（国立研究開発法人海洋研究開発機構　海底資源センター・センター長）
研究分担者　下田　玄（国立研究開発法人産業技術総合研究所地質情報研究部門・研究グループ長）
研究分担者　佐野　有司（東京大学　大気海洋研究所・教授）
研究分担者　佐野　亜沙美（大学共同利用機関法人高エネルギー加速器研究機構　物質構造科学研究所・特別准教授）
研究分担者　野村　龍一（京都大学 白眉センター・准教授）
研究分担者　石川　晃（東京工業大学 理学院地球惑星科学系・准教授）
連携研究者　横山　哲也（東京工業大学　理工学研究科・教授）（～H30年3月）

A02-2　元素分配班　元素分配から制約する核－マントルの相互作用（課題番号：15H05831）
研究代表者　M., Satish-Kumar（新潟大学　自然科学系・教授）
研究分担者　小木曽　哲（京都大学　人間・環境学研究科・教授）
研究分担者　三部　賢治（東京大学　地震研究所・助教）
研究分担者　鎌田　誠司（東北大学　学際科学フロンティア研究所・助教）
研究分担者　舘野　繁彦（東京工業大学 地球生命研究所・研究員）
研究分担者　秋澤　紀克（東京大学 大気海洋研究所・助教）

A03-1　地震・電磁気班　核―マントルの地震・電磁気観測（課題番号：15H05832）
研究代表者　田中　聡（国立研究開発法人海洋研究開発機構 火山・地球内部研究センター・分野長代理）
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研究分担者　清水　久芳（東京大学　地震研究所・教授）
研究分担者　金嶋　聰（九州大学　理学研究院・教授）
研究分担者　Helffrich, George（東京工業大学　地球生命研究所・教授）
研究分担者　Houser, Christine（東京工業大学　地球生命研究所・特任助教）

研究分担者　大滝　壽樹（国立研究開発法人産業技術総合研究所　地質情報研究部門・主任研究員）
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研究分担者　山本　裕二（高知大学　海洋コア総合研究センター・教授）
研究分担者　松島　政貴（東京工業大学　理学院地球惑星科学系・助教）
連携研究者　末次　大輔（国立研究開発法人海洋研究開発機構　地球深部ダイナミクス研究分野・分野長）（～H30年3月）

A03-2　ニュートリノ班　ニュートリノ観測から制約する核－マントルの化学組成（課題番号：15H05833）
研究代表者　田中　宏幸（東京大学　地震研究所・教授）
研究分担者　山野　誠（東京大学　地震研究所・教授）
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研究分担者　三井　唯夫（東北大学　ニュートリノ科学研究センター・准教授）
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連携研究者　池田　晴雄（東北大学　ニュートリノ科学研究センター・助教）(～H30 年 3 月）
連携研究者　井上　邦雄（東北大学　ニュートリノ科学研究センター・教授）(～H30年3月）
連携研究者　古賀　真之（東北大学　ニュートリノ科学研究センター・准教授）(～H30年3月）
連携研究者　清水　格（東北大学　ニュートリノ科学研究センター・准教授）(～H30年3月）
連携研究者　岩森　光（国立研究開発法人海洋研究開発機構　地球内部物質循環研究分野・分野長）(～H30年3月）
連携研究者　松本　拓己（国立研究開発法人防災科学技術研究所　地震・火山防災研究ユニット・次長）(～H30年3月）
連携研究者　田中　明子（国立研究開発法人産業技術総合研究所 活断層火山研究部門・グループ長）(～H30年3月）
連携研究者　濱元　栄起（埼玉県環境科学国際センター 土壌地下水地盤担当・専門研究員）（～H30年3月）

A04-1　理論計算班　核－マントル物質とダイナミクスの理論モデリング（課題番号：15H05834）
研究代表者　土屋　卓久（愛媛大学　地球深部ダイナミクス研究センター・教授）
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研究分担者　出倉　春彦（愛媛大学　地球深部ダイナミクス研究センター・助教）
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研究分担者　高橋　太（九州大学　理学研究院・准教授）
研究分担者　Hernlund, John（東京工業大学　地球生命研究所・教授）
研究分担者　竹広　真一（京都大学　数理解析研究所・准教授）
研究分担者　中川　貴司（国立研究開発法人海洋研究開発機構 数理科学・先端技術研究分野・主任研究

員）(～H30年3月）

＜特任助教・研究員等＞
A01-1　五味　斎（東京工業大学　地球生命研究所）
A01-2　飯塚　理子（東京大学　理学系研究科）
A01-2　柿澤　翔（東京大学　理学系研究科）
A02-1　天川　裕史（東京大学大気海洋研究所）
A02-2　Banerjee, Anupam（新潟大学　自然科学系）
A03-2　原口　悟（東京大学　地震研究所）
A01-2　岡田　卓（東京大学　理学系研究科）（～H28年10月）
A01-3　桑原　秀治（愛媛大学 地球深部ダイナミクス研究センター）（～H30年3月）
A02-1　賞雅　朝子（国立研究開発法人海洋研究開発機構　海底資源センター）（～H29年10月）
A02-2　田阪　美樹（新潟大学　自然科学系）（～H29年1月）
A02-2　青山　慎之介（新潟大学　自然科学系）（～H31年3月）
A03-1　三好　崇之（東京大学　地震研究所）（～H29年3月）
A03-1　入谷　良平（東京大学　地震研究所）（～H31年3月）
A03-1　Noisagool, Sutthipong（東京大学　地震研究所）（～H29年3月）
A03-1　Roy, Sunil K.（東京大学　地震研究所）（～H30年3月）
A04-1　Xiong, Zhihua（愛媛大学 地球深部ダイナミクス研究センター）（～H30年3月）
Y00　Ritterbex, Sebastian（愛媛大学 地球深部ダイナミクス研究センター）（～H31年3月）

＜公募研究＞
前期公募研究（平成 28 年度～平成 29 年度）
(課題番号：16H01119)
A01 ハイパワーレーザー衝撃圧縮を用いた溶融鉄合金の輸送特性解明
研究代表者　尾崎　典雅（大阪大学大学院理学研究科・准教授）
(課題番号：16H01122）
A01 下部マントル条件下におけるブリッジマナイトの結晶方位定向配列に関する実験的研究
研究代表者　大内　智博（愛媛大学地球深部ダイナミクス研究センター・講師）
(課題番号：16H01113）
A02 超高感度レーザー希ガス局所分析から制約する核ーマントル共進化
研究代表者　角野　浩史（東京大学総合文化研究科・准教授）
(課題番号：16H01115）
A02 従来手法を統合した下部マントルにおける融解現象の理解
研究代表者　新名　良介（東京工業大学地球生命研究所・特任助教）
(課題番号：16H01123）
A02 マントル３５億年の熱・化学進化解明
研究代表者　木村　純一（国立研究開発法人海洋研究開発機構　地球内部物質循環研究分野・分野長代理）
(課題番号：16H01116）

A03　地磁気データで明らかにする核ーマントル結合の時空間変動
研究代表者　松島　政貴（東京工業大学理工学研究科・助教）
(課題番号：16H01121）
A03　地球自由振動の解析による核-マントル境界領域と内核の構造に関する研究
研究代表者　須田　直樹（広島大学理学系・教授）
(課題番号：16H01124）
A03　CMBにおける局所超低速度異常領域のグローバルマッピング
研究代表者　大林　政行（国立研究開発法人海洋研究開発機構 地球深部ダイナミクス研究分野・主任研究員）
(課題番号：16H01117）
A04　核マントル境界直下の安定成層の形成および破壊に関する流体力学的研究
研究代表者　竹広　真一（京都大学数理解析研究所・准教授）
(課題番号：16H01112）
B01　地球内核の組成と異方性の解明
研究代表者　坂巻　竜也（東北大学理学研究科・助教）
(課題番号：16H01114）
B01　ニュートリノ振動を用いた地球深部の化学組成構造の測定
研究代表者　武多　昭道（東京大学地震研究所・助教）
(課題番号：16H01118）
B01　二次イオン質量分析法とイオン注入法の融合による元素定量分析法の開発
研究代表者　伊藤　正一（京都大学理学研究科・准教授）

後期公募研究（平成 30 年度～令和元年度）
(課題番号：18H04368)
A01　ハイパワーレーザーショックとＸＦＥＬを用いた溶融鉄合金の総合的理解
研究代表者　尾崎　典雅（大阪大学大学院理学研究科・准教授）
(課題番号：18H04369）
A01　下部マントルでの二相系のレオロジーの制約：多様な粘性率構造の解明に向けて
研究代表者　辻野　典秀（岡山大学惑星物質研究所・ 助手）
(課題番号：18H04370）
A01　回転式ダイヤモンドアンビル装置による沈み込んだスラブ内レオロジーの検証
研究代表者　東　真太郎（東京工業大学理学院・助教）
(課題番号：18H04372 ）
研究代表者　角野　浩史　東京大学総合文化研究科・准教授
A02　マントル３５億年の水・化学・熱進化解明　研究代表者　木村　純一（国立研究開発法人海洋研究開発機構　地球内部物質循環研究分野・シニアスタッフ）
A03　波形インバージョンによるＣＭＢ局所異常解明 (課題番号：18H04373）
研究代表者　大林　政行（国立研究開発法人海洋研究開発機構　地球深部ダイナミクス研究分野・主任研究員）
(課題番号：18H04371）

A04　軽元素の含有による液体鉄合金の輸送特性変化に関する第一原理的研究
研究代表者　大村　訓史（広島工業大学工学部・准教授）
(課題番号：18H04366）
B01　高速２次元測温法から探る核マントル物質の融解現象
研究代表者　新名　良介（明治大学理工学部・専任准教授）
(課題番号：18H04367）
B01　二次イオン質量分析法とイオン注入法を融合した軽元素定量分析及び同位体比分析
研究代表者　伊藤　正一（京都大学理学研究科・准教授）

交付決定額（配分額）

領域全体

	直接経費	間接経費	合計
平成 27 年度	257,700,000 円	77,310,000 円	335,010,000 円
平成 28 年度	245,100,000 円	73,530,000 円	318,630,000 円
平成 29 年度	243,100,000 円	72,930,000 円	316,030,000 円
平成 30 年度	222,400,000 円	66,720,000 円	289,120,000 円
令和元年度	195,100,000 円	58,530,000 円	253,630,000 円
総計	1,163,400,000 円	349,020,000 円	1,512,420,000 円

成果取りまとめ

	直接経費	間接経費	合計
令和 2 年度	3,000,000 円	900,000 円	3,900,000 円

研究発表

査読付き論文

(令和 2 年度以降)

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図書

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土屋卓久　核ーマントルの相互作用と共進化から探る地球深部科学の新たな展開, 太田健二・末広翔・奥田善之　地球中心核とマントルの熱伝導率, 石川晃　レイトベニアとマントル進化　ー親鉄元素地球化学からの制約ー, 竹内希・上木賢太・飯塚毅・榎本三四郎　地殻化学組成 3 次元分布の統計モデリングによる地球ニュートリノ観測の高度化, 鍵裕之・福山鴻・飯塚理子　マントルでの軽元素のふるまい, 山崎大輔　川井型マルチアンビル装置でのマントル D”層の圧力条件の発生, 鎌田誠司・M. Satish-Kumar　核に隠れている軽元素, 金嶋聰・George Helffrich　外核最上部の安定成層構造, 大滝壽樹・金嶋聰　外核最下部 F 層の速度, 中川貴司　核ーマントルの熱的結合による長時間スケールにわたる地球中心核の熱進化, 2018 年

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その他

異なる分野から 70 名を超える研究者が参画する本領域では、領域全体の研究目的をメンバー全員が共有するなど領域内の一体感の醸成が、研究目的を達成するために極めて重要であった。そこで領域内のネットワークやコミュニケーションの緊密化を目的として、毎年度末に領域全体での成果発表会を開催し、各領域メンバーが最新の研究成果を発表するとともに、領域の方針の周知徹底、全体計画に対する各計画研究の進行状況の確認及び計画研究間の調整を行った。また、学会での特別セッションや夏の学校・冬の学校、毎月一回メールニュース配信を通じて情報交換を緊密に行い、領域が目指す分野間連携による学際研究を強く奨励した。さらに成果発表会だけでなく、各計画研究が行う班会議や複数の計画研究や公募研究が合同して行う合同班会議も領域代表者出席のもと毎年度開催し、異なる分野の研究者間での問題意識の共有や連携研究の充実化を図った。この他、毎年度 3 回総括班会議を開催し、活動の進捗状況と事業計画を丹念に確認するとともに、総括班会議には各分野を代表する研究者により構成されるアドバイザリーボードや学術調査官にも出席いただき、個別及び領域全体の研究や運営方針についてアドバイスをいただいた。これらを通じて領域の連帯感が大きく向上した結果、高圧地球科学と地震学分野の従来の連携に加え、高圧地球科学分野と地球化学分野、高圧地球科学分野とニュートリノ分野、地震学分野と地球化学分野の連携が続々開始され、融合研究論文数も順調に増加し新たな研究領域の開拓が着実に進んだ。

本領域は、高圧地球科学や地震学、地球電磁気学を中心とした従来の地球深部科学の研究者に加え、地球化学や素粒子物理学、計算物理学といった複数分野の研究者が新たに連携する異分野融合型の組織である。複数分野を横断する研究プロジェクトから新しい統合的地球科学の創成を目指す本領域の方針を長期的に発展させるには、従来の地球深部科学分野の枠に縛られず、新たな分野を切り拓くことに積極的な若手研究者の育成が重要であると考え、このような観点のもと本領域においては様々な教育プログラムを準備し、国際的・学際的な研究推進との相乗効果により、幅広い視野を持つ次世代を担う人材育成の取り組みを行った。

具体的には海外著名研究者を招いた国際レクチャー及び国際セミナー、夏の学校、冬の学校の開催、各分野の拠点施設における先端技術インターンシップの実施、主要学会における領域セッションや年度末に行う領域成果発表会での発表機会の提供、若手の会の組織化などを行った。国際レクチャーは計 9

回、国際セミナーは計 27 回実施し、特に国際レクチャーでは領域全体に対し分野の異なる若手研究者の積極的な参加を広く呼び掛け、基礎から最先端の応用まで数日間をかけて集中講義形式で講義を開催して先端教育を行った。さらにこれらとは別に、素粒子物理学と地球化学、高圧地球科学が連携した夏の学校をヨーロッパのコミュニティーと共同してイタリア・ラクイラにおい国際スクール：カミオカンデ内でのレクチャー（2019.3.7～10）て開催し、領域代表者を含む講師 2 名と受講生を領域から派遣した。また、平成 28 年度及び平成 30 年度には、高圧地球科学、地震学、地球化学、地球力学の世界的権威を海外から招き、地球深部の不均質と始原物質をテーマとした第 1 回国際冬の学校を群馬県草津温泉において、地球内部のエネルギー循環や熱史をテーマとした第 2 回国際冬の学校を岐阜県飛騨市において、それぞれ主催した。国内外から受講者を募り選抜を行い、領域内のみならず領域外の若手研究者に対しても先端教育を提供した。異なる分野をそれぞれ代表する第一級の研究者の講義を一度に聴講できる貴重な機会となっただけでなく、国内外の様々な大学や研究機関から受講者が集まったため、分野や国籍を超えて若手研究者や大学院生が交流し国際的な人脈をつくる非常に重要な場にもなった。さらに受講者が自らの研究を発表するポスターセッションも開催し、互いに活発に議論を行った他、関連分野の講師陣による個別指導（メンターワークショップ）も実施した。世界的権威による直接指導は、若手研究者にとって単なる助言の枠を超えて今後の励みとなる貴重な経験となり、受講者から大きな好評を得た。その他、各計画研究が導入した先端機器と領域内の共同研究体制を活用して、若手研究者が異なる分野の研究手法を学ぶ先端技術インターンシップを期間中に計 5 回開催し、領域全体として技術面からの若手育成にも取り組んだ。また、総括班が主体となって行った高度先端教育の取り組みに加え、領域内の若手研究者や大学院生を中心とした組織「若手の会」を発足させ、独自に企画した研究集会を計 5 回実施するなど主体的に分野の枠を超えた活動を行った。この若手の会の活動は年々活発化し、そこで得た着想に基づき自主的に共同研究を実施して論文発表まで至った事例が得られるなど、当初の想定以上に大きな成果をあげた。このように本領域では従来の分野の枠を超えた新たな学術領域ならではの専門教育を推進した。多様な分野の交流は、領域内の若手研究者の視野を広げることに資する一方で、分野を超えて職を獲得する可能性も広がり、領域全体の底上げにも大きく寄与した。

また本領域では、最新の研究成果の社会への発信も重要な使命の一つと位置付け、アウトリーチ活動にも精力的に取り組んだ。具体的には、本報告集巻末にまとめてあるニュースレター（年 2 回）の発行、プレスリリース、一般普及講演会、中高生向けの授業などのアウトリーチ活動などを積極的に実施した。更に SNS を活用した、領域の活動内容等の発信などにも取り組み、その結果、Twitter を見て領域主催の研究集会に参加したという大学院生や学会ブースへのリピーターの親子が現れるなど、大きな効果があった。

<研究集会・シンポジウム（主催・共催）>

・キックオフシンポジウム, 2015 年 8 月 7 日～8 日, 愛媛大学（愛媛県松山市）
・The Earth’s Mantle and Core: Structure, Composition, Evolution, 2015 年 11 月 4 日～7 日, 道後プリンスホテル（愛媛県松山市）
・Neutrino Research and Thermal Evolution of the Earth Workshop, 2016 年 10 月 25 日～27 日, 東北大学（宮城県仙台市）
・平成 27 年度成果発表会,2016 年 3 月 28 日～29 日, 東京大学地震研究所（東京都文京区）
Origin and Evolution of Deep Primordial Reservoirs, 2017 年 1 月 9 日～12 日, 中澤ヴィレッジ（群馬県吾妻群草津町）

・The 2016 international conference on the Earth’s Deep Interior, 2016 年 11 月 4 日～6 日, ニュービーコンルーグアンインターナショナルホテル (中国武漢市)
・International Summer Institute “Using Particle Physics to Understand and Image the Earth”, 2016 年 7 月 11 日～21 日, グランサッソ国立研究所 (イタリアライクラ市)
・平成 28 年度成果発表会, 2017 年 3 月 26 日～28 日, JAMSTEC 横浜研究所（神奈川県横浜市）
・”Crust to Core” Workshop, 2017 年 7 月 30 日～8 月 1 日, ふるさと憩の家（愛媛県今治市）
・GRC 1st NPD Workshop, 2018 年 2 月 28・3 月 1 日, 愛媛大学（愛媛県松山市）
・International Symposium & FY2018 Annual General Meeting, 2018 年 3 月 26～29 日, 愛媛大学（愛媛県松山市）
・Workshop on properties of planetary interiors, 2019 年 1 月 30 日, 大阪大学（大阪府吹田市）
・NBP International Workshop, 2019 年 2 月 28 日～3 月 2 日 55, 愛媛大学（愛媛県松山市）
・International School “Thermal evolution, energy sources and associated heterogeneity”, 2019 年 3 月 7 日～10 日, ホテル季古里（岐阜県飛騨市）
・Misasa 2019 International Symposium & CMC Annual General Meeting “Origin, Evolution & Dynamics of the Earth & Planetary Interiors”, 2019 年 3 月 18 日～21 日, ブランナールみささ（鳥取県東伯郡三朝町）
・International Symposium “Geoneutrinos and Quantitative Geochemical Modeling, 2019 年 5 月 25 日, ホテルニューオータニ幕張（千葉県千葉市）
・International Workshop for Geophysical observation in Thailand –Present and Future–, 2019 年 8 月 1 日～2 日, マヒドン大学理学部（タイ王国バンコク）

<班会議>
・A04-1 理論計算班合同研究集会, 2016 年 8 月 18 日～20 日, しもなの郷（高知県吾川郡）
・A02 化学分析班合同研究集会, 2016 年 10 月 21 日～23 日, 京都教育文化センター・京都大学（京都府京都市）
・A04-1 理論計算班合同研究集, 会 2018 年 8 月 5 日～7 日, しもなの郷（高知県吾川郡）
・A01-2,A02,A03-1 合同班会議, 2018 年 10 月 18 日～20 日, 東北大学（宮城県仙台市）
・A04-1 理論計算班合同研究集会, 2019 年 8 月 25～27 日, しもなの郷（高知県吾川郡）
・A01-2,A02,A03-1 合同班会議, 2019 年 11 月 22～24 日, 新潟大学（新潟県新潟市）

<若手の会>
・第一回若手研究集会, 2017 年 8 月 25 日～27 日, 東北大学（宮城県仙台市）
・第二回若手研究集会, 2018 年 3 月 5 日～7 日, ホテルルーセントタカミヤ（山形県山形市）
・第三回若手研究集会, 2018 年 8 月 22～24 日, サンライズ城が浜 (新潟県佐渡島)
・第四回若手研究集会, 2019 年 8 月 21～23 日, アポイ山荘（北海道様似郡）
・第五回若手研究集会, 2020 年 1 月 11～13 日, ホテル花月園（神奈川県足柄下郡）

<一般公演・一般向けアウトリーチ活動（主催）>
・一般公開講演「地震と物理で探る地球の内部」, 2016 年 4 月 29 日, 愛媛大学（愛媛県松山市）
・日本地球惑星科学連合 連合大会 2016 年大会, ブース出展, 2016 年 5 月 22 日～26 日, 幕張メッセ（千葉県千葉市）

・JpGU-AGU Joint Meeting 2017, ブース出展, 2017 年 5 月 20 日～24 日，幕張メッセ（千葉県千葉市）
・一般公開講演「物理で明かす地球の深部，化学でひも解く地球の歴史，地震で探る日本の地下」愛媛大学（愛媛県松山市）2018 年 3 月 25 日
・日本地球惑星科学連合 連合大会 ，ブース出展, 2018 年 5 月 20 日～25 日，幕張メッセ（千葉県千葉市）
・高校生向けパブリックセッション, 2019 年 3 月 7 日，ホテル季古里（岐阜県飛騨市）
・日本地球惑星科学連合 連合大会 2019 年大会，ブース出展, 2019 年 5 月 26 日～30 日，幕張メッセ（千葉県千葉市）
・大学生向け講義「量子力学からの地球深部科学」, 2019 年 8 月 1 日，マヒドン大学（タイ王国バンコク）

<インターンシップ>
・A01-2 構造物性班・A02-2 元素分配班インターンシップ, 2016 年 3 月 29 日～30 日，東京大学（東京都文京区）
・A04-1 理論計算班インターンシップ, 2017 年 5 月 15 日～6 月 22 日，愛媛大学（愛媛県松山市）
・A02-2 元素分配班インターンシップ, 2017 年 6 月 19 日～24 日，新潟大学（新潟県新潟市）
・A04-1 理論計算班インターンシップ, 2018 年 6 月 25 日～7 月 26 日，愛媛大学（愛媛県松山市）
・A02-1 同位体班・A03-2 ニュートリノ班インターンシップ, 2019 年 6 月 15 日，7 月 5 日，8 月 23 日，10 月 18 日,JAMSTEC（神奈川県横浜市）

<国際レクチャー>
1. High pressure devices and typical applications. An introduction(Part I）, Water and ice: A case for neutrons and x-rays (Part II), 講師：Prof. Stefan Klotz (University Pierre et Marie Curie), 2016 年 6 月 2 日・9 日，東京大学（東京都文京区）
2. Seismological Constraints on the Earth's Physical Property, 講師：Prof. Miaki Ishii (Harvard University), 2016 年 6 月 16～17 日，愛媛大学（愛媛県松山市）
3. Towards integrated models of the Earth's core, 講師：Prof. Konstantin Litasov (Sobolev Institute of Geology andMineralogy, Nobosibirsk State University）, 2016 年 7 月 11 日，東京大学（東京都文京区）
4. Applied Mineralogy and Phase Diagrams of Earth's Material, 講師：Dr. Sujoy K Ghosh（Department of Geology & Geophysics,Indian Institute of Technology）, 2017 年 7 月 3～5 日，東北大学（宮城県仙台市）
5. 固体地球科学特論 II, 講師：Dr. Maxim D. Ballmer (ETH Zürich), 2018 年 1 月 17～19 日愛媛大学（愛媛県松山市）
6. Physics and Chemistry of the Earth's mantle 講師：Prof. Tomo Katsura (BGI, University of Bayreuth), 2018 年 2 月 22～23 日，愛媛大学（愛媛県松山市）Recent Advancements in Multi-anvil High-pressure Science, 講師：Prof. Yanbing Wang　(University of Chicago), 2018 年 3 月 25 日，愛媛大学（愛媛県松山市）
7. Phase Diagrams of Earth's Material, 講師：Dr. Sujoy K Ghosh（Department of Geology & Geophysics,Indian Institute of Technology）, 2018 年 7 月 2 日～4 日，東北大学（宮城県仙台市）
8. Rheology of Deep Earth Materials, 講師：Prof. Patrick Cordier (Universite Lille 1), 2018 年 11 月 5～6 日，愛媛大学（愛媛県松山市）

<国際セミナー>
1. Composition and origin of the Moon, 講師：Prof. Shun-ichiro Karato (Yale University), 2016年3月25日，愛

媛大学（愛媛県松山市）

2. Atmosphere-mantle Interactions Using Noble Gasesx, 講師：Dr. Colin Jackson (Geophysical Laboratory, CarnegieInstitute for Science), 2016 年 6 月 3 日，愛媛大学（愛媛県松山市）
3. Earthquakes Great and Small: how they become large and howthey evade detection, 講師：Prof. Miaki Ishii (Harvard University), 2016 年 6 月 17 日，愛媛大学（愛媛県松山市）
4. Material transport in the deep Earth's mantle, 講師：Prof. Konstantin Litasov （Sobolev Institute of Geology andMineralogy）, 2016 年 7 月 8 日，愛媛大学（愛媛県松山市）
5. Carbon-bearing magmas and material transport in the deepEarth's mantle, 講師：Prof. Konstantin Litasov (V.S. Sobolev Institute of Geologyand Mineralogy), 2016 年 11 月 17 日，愛媛大学（愛媛県松山市）
6. Experimental investigation into the fate of subducted carbonatesand origin of super-deep diamonds, 講師：Prof. Jie Li (University of Michigan), 2017 年 1 月 13 日，愛媛大学（愛媛県松山市）
7. Thermo-chemical-tectonic evolution of terrestrial planets: the keyinfluence of magmatism, 講師：Prof. Paul J. Tackley (ETH Zurich, Zurich, Switzerland), 2017 年 1 月 16 日，愛媛大学（愛媛県松山市）
8. Dynamics of the fault motion and the origin of contrasting tectonicstyle between Earth and Venus, 講師：Prof. Shun-ichiro Karato (Yale University), 2017 年 3 月 21 日，愛媛大学（愛媛県松山市）
9. Experimental reproduction of mantle earthquakes analogues byantigorite dehydration & comparison with naturalpseudotachylytes, 講師：Dr. Thomas Ferrand (ENS Paris), 2017 年 5 月 9 日，愛媛大学（愛媛県松山市）
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12. A laboratory-based framework for the interpretation ofseismological models, 講師：Dr. Ian Jackson (Australian National University), 2017 年 5 月 29 日，愛媛大学（愛媛県松山市）
13. Stably stratified layer formed by superionic NH3 in Uranus andNeptune, 講師：Dr. Tomoaki Kimura (Tohoku University), 2017 年 6 月 21 日，愛媛大学（愛媛県松山市）
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15. Optical measurements of the electronic and transport properties ofmolecular and metallic systems at deep planetary interiorconditions, 講師：Dr. Stewart McWilliams (The University of Edinburgh), 2017 年 6 月 21 日，愛媛大学（愛媛県松山市）
16. Geodynamic mechanisms for the preservation of large-scaleprimordial heterogeneity in the Earth's mantle, 講師：Dr. Maxim D. Ballmer (ETH Zürich), 2018 年 1 月 29 日，愛媛大学（愛媛県松山市）
17. Binary phase relations between ringwoodite and bridgmanite +ferropericlase: implication for sharpness of the 660-kmdiscontinuity, 講師：Prof. Tomo Katsura (BGI, University of Bayreuth), 2018 年 2 月 23 日，愛媛大学（愛媛県松山市）
18. Optimal control in MHD: towards kinematic and dynamic dynamos, 講師：Prof. Andrew Jackson (ETH), 2018 年 4 月 10 日，東京大学（東京都文京区）
19. Magma genesis in Hawaii plume: melting experiments onbasalt/peridotite layered sample up to 8 Gpa, 講師：Prof. Eichi Takahashi (Guangzhou Institute ofGeochemistry,CAS), 2018 年 5 月 16 日，愛媛大学（愛媛

県松山市）

20. Experimental Discovery of Superionic Water with dynamiccompression, 講師：Dr. Marius Millot (Lawrence Livermore National Laboratory), 2018 年 5 月 25 日，愛媛大学（愛媛県松山市）
21. Silicon abundance in the Earth’s core constrained by a multitechniqueapproach, 講師：Dr. Daniele Antonangeli (Sorbonne Université), 2018 年 5 月 28 日，愛媛大学（愛媛県松山市）
22. Mantle plumes rooted at the core-mantle boundary: evidence fromseismic waveform tomography, 講師：Prof. Barbara Romanowicz（UC Berkeley/IPGP/College deFrance）, 2019 年 3 月 11 日，東京大学（東京都文京区）
23. Some Petrological Effects on Subduction Dynamics, 講師：Prof. Craig R. Bina (Northwestern University), 2019 年 3 月 25 日，愛媛大学（愛媛県松山市）
24. The Fate of Deeply Subducted Volatiles in Earth’s Deep Mantle, 講師：Dr. Michael Walter (Carnegie Institution for Science), 2019 年 3 月 25 日，愛媛大学（愛媛県松山市）
25. On the large-scale geochemical anomalies in the deep mantleinferred from the hydrous mantle convection simulations, 講師：Prof. Takashi Nakagawa (The University of Hong Kong), 2019 年 3 月 27 日，愛媛大学（愛媛県松山市）
26. P-V-T equation-of-state of liquid Fe to the TPa regime from abinitiosimulations, and what we learn for super-Earth interiors, 講師：Dr. Gerd Steinle-Neumann (University of Bayreuth), 2019 年 5 月 24 日，愛媛大学（愛媛県松山市）
27. Experimental constraints +B79:D96on the crystallography andseismic velocity of calcium perovskite, 講師：Dr. Andrew Thomson (Department of Earth Sciences,University College London), 2019 年 11 月 20 日，愛媛大学（愛媛県松山市）

<ホームページ等>
日本語版ホームページ　http://core-mantle.jp/
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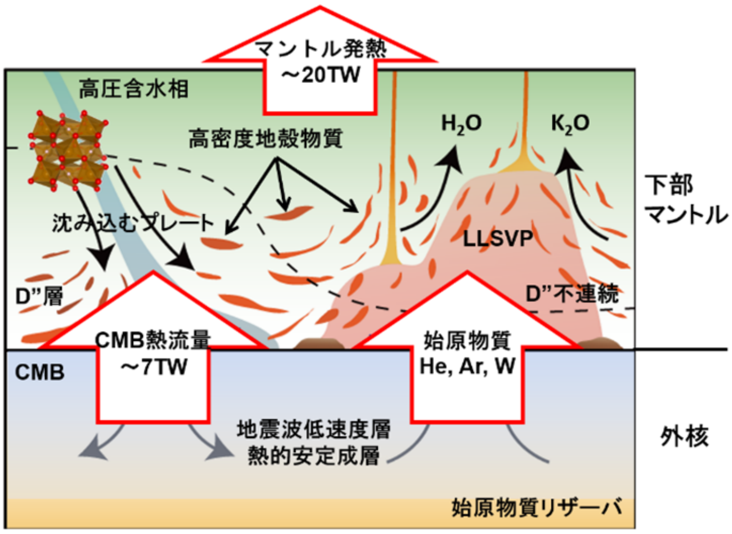
研究成果

鉱物物理学、地球化学、固体地球物理学、素粒子物理学の各分野に属する我が国のトップレベルの研究者が協働することにより、これまでには行われてこなかったレベルでの統合的な地球深部科学研究が実施された。特に本領域を特徴づける新たな試みとして、ニュートリノ科学分野や第一原理計算分野などの新たな分野との連携研究や、タイ全土を網羅した広域地震観測網の敷設をはじめとした大規模国際共同研究が極めて活発に展開された。これらの活動を通じて様々な研究成果が生産され、得られた知見を総括して領域全体として地球の核～マントル領域に関して新たな描像を構築した（右図）。本領域で得られた研究成果の要点について以下にまとめる。



①核ーマントルの物理的相互作用

・エネルギー輸送と外核の不均質構造　超高圧下で測定した六方最密型純鉄の電気抵抗 (Ohta et al. 2016 Nature)と、第一原理計算に基づく下部マントル鉱物（ブリッジマナイト、ポスト・ペロブスカイト、フェロペリクレース）の格子熱伝導率(Tsuchiya et al. 2020 Ann. Rev. Earth Planet Sci.)を、核ーマントル結合系シミュレーション (Takehiro and Sasaki 2018 Front. Earth Sci.)に当てはめると、外核最上部に軽元素濃度の低い熱的安定成層が形成されることが分かった。この低速度層は地震学的に観測される大きな速度勾配を持つ領域(Kaneshima 2015 PEPI)に対応するものと考えられ、核ーマントルの熱的相互作用について統一的なモデルが得られた。

②核ーマントルの化学的相互作用

・地球深部水　第一原理計算及び高温高圧実験により、マントル最下部まで安定な新たな高圧含水鉱物相を発見し(Nishi et al. 2017 Nature)、従来水を多く含むことはないと考えられていた下部マントルも、沈み込んだ水を大量に貯水できる可能性があることを示した。その後、新たな高圧含水相の安定性を考慮したマントル対流計算が行われ(Nakagawa et al. 2018 Prog. Earth Planet. Sci.)、初期地球には現在の地球表層の海水量の最大 10 倍以上を持つ海洋が存在し、プレートテクトニクスによってほとんどの海水が下部マントルに沈み込み、現在の海水量となったという知見が得られた。

・始原物質　代表的なホットスポット火山であるハワイ、ロイヒ火山、サモアの海洋島玄武岩に含まれるタングステンの同位体において、核ーマントル相互作用の痕跡を示す顕著な負異常値が得られた(Takamasa et al. 2020 Geochem. J.)。この結果は、ハワイプルームがマントル最下部において発生し上昇しているとする地震学からの知見と調和的である。また高圧下での拡散実験から、タングステンは核からマントルへ浸透するのに十分な粒界拡散係数を有していることが分かり(Yoshino et al. 2020 EPSL)、タングステン同位体の負異常値の起源が核からのタングステンにより説明できることを示した。一方、タングステンと同様にロイヒ玄武岩に多く含まれるヘリウムの鉄ーケイ酸塩間分配を第一原理計算により調べたところ、マントル最下部圧力において十分核に分配される程度の分配係数を有することが分かった(Xiong and Tsuchiya 2021 GRL)。これらの結果は、ヘリウム 3 などの始原的同位体は核に貯蔵されており、核マントル相互作用を通じてマントル、ひいては地表にもたらされていることを示唆する。

・**熱源元素量**　地球ニュートリノ観測データの精度向上(Watanabe et al., 準備中)と統計学的手法による日本の地殻の新たな岩石学モデルの構築(Takeuchi et al. 2019 PEPI)により、マントル以深における放射性同位体の崩壊熱総量のより定量的な見積もりに成功した。一方、第一原理計算により主要熱源元素であるカリウム 40 はウランやトリウムと同様、核に含まれないことが分かった(Xiong et al. 2018 JGR)。これにより従来大きな不確定性があったマントルの自己発熱量について約 20TW であると制約できた。

これら個別の研究成果は、Nature 誌(7 件)、Nature Geo.誌(4 件)、Nature Comm.誌(14 件)、Science 誌(2 件)、PNAS 誌(5 件)などの高インパクトジャーナルをはじめとする著名な国際学術誌において、総計 600 件以上の査読付き原著論文として公表された。また、個々の原著論文とは別に領域全体として成果の取りまとめを行い、月刊地球総特集において邦文解説集として出版した他、英文書籍を執筆・編集し現在米国地球物理学連合から印刷中となっている。これらの領域の活動は国内外において高く評価され、領域全体として計 36 件の学会賞等（学生発表賞等除く）の受賞につながった。また計 47 名の若手研究者が常勤研究職に就職するなど（内 19 名が無期雇用)、次世代を担う人材の育成にも大きく貢献した。

(1)成果の具体例

・**純鉄の電気抵抗率測定から外核の大きな熱伝導率を提案**：外核に相当する温度圧力条件で六方最密充填構造の純鉄の電気抵抗率の測定に世界に先駆けて成功し、外核の大きな伝導熱流量を推定した(Ohta et al. 2016 Nature)。

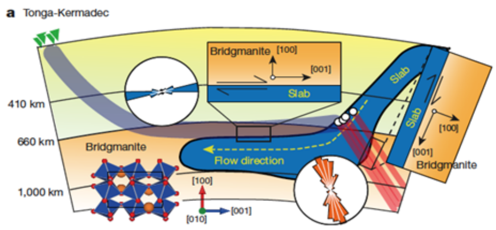


図 1 トンガーケルマディックスラブ近傍のマントル構造の模式図

・**下部マントルにおける沈み込んだスラブの流動様式の解明**：下部マントル条件下で下部マントルの主要鉱物であるブリッジマナイトの変形実験に成功し、沈み込んだスラブの流動パターンを推定した（図 1）(Tsujino et al. 2016 Nature)。

・**下部マントル領域での精密弾性波速度測定**：超高圧下での高品質多結晶焼結体技術(Irifune et al. 2016 Nature Comm.)と超音波測定技術を組み合わせ、従来困難であった $CaSiO_3$ ペロブスカイトの弾性波速度測定に成功し、下部マントル最上部における不均質に関する知見を得た（図 2）(Greaux et al. 2019 Nature)。

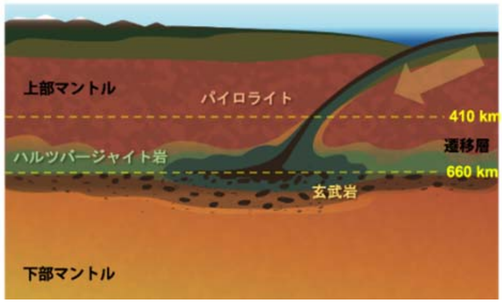


図2 弾性波速度に基づく下部マントル上部の不均質構造モデル

・**D-DIA 型変形装置における高圧発生**：D-DIA 型変形装置にて用いるアンビルの超硬部をジャケット材で補強するにより、圧力発生効率を維持しつつ耐荷重性能を向上させ、24GPa の圧力発生に成功した(Ohuchi et al. 2017 Nature Geo.)。

・**西太平洋直下マントル最下部の微細構造**：タイ・マヒドン大との国際共同研究によりタイ全土に大規模臨時地震観測網を敷設した。この観測網と周辺の既存観測網のデータを統合して西太平洋下マントル最下部の地震波速度構造を推定し、沈み込んだプレートと小規模な上昇流の混在を解明した（図 3）(Suzuki et al. 2020 PEPI)。

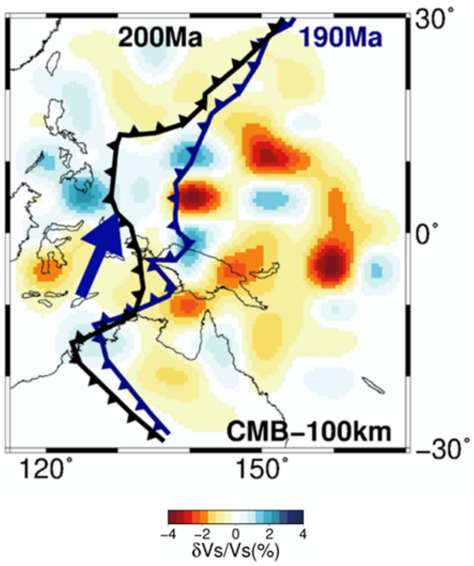


図 3 西太平洋直下マントル最下部の S 波速度不均質構造

・**客観的地球ニュートリノ流量の導出**：日本列島に存在する岩石種を網羅する岩石化学組成データベースを構築し、深部岩相や岩石組成などすべてを確率分布関数として表現すること

によって、客観的地球ニュートリノ流量を導出した(Takeuchi et al. 2019 PEPI)。

・内核の流動特性：内核条件（330 万気圧、~5000°C）における hcp 鉄の粘性率の第一原理計算に成功し、内核の並進運動や差動回転が安定ではないことを示した(Ritterbex and Tsuchiya 2020 Sci. Rep.)。

・含水鉱物の新しい高圧相の発見：下部マントル条件下で安定となる FeOOH の新しい高圧相（図 4）を報告した(Nishi et al. 2017 Nature)。またマントルにおける水素の挙動を制約し、現在の海洋の約 10 倍の水を含む可能性を示した(Nakagawa et al. 2018 Prog. Earth Planet. Sci.)。

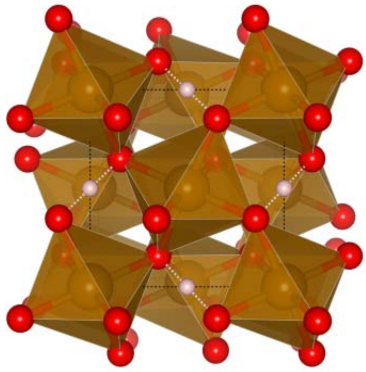


図 4 発見された新高圧含水相の結晶構造（赤：酸素、茶色：鉄、ピンク：水素）

・下部マントル平均化学組成の特定：第一原理計算により下部マントル主要鉱物の高温高圧熱弾性特性を計算し、パイロライト組成が下部マントルの地震波速度をよく再現できることを示した(Wang et al. 2015 Nature Geo.)。

(2)今後の展望

本研究により、地球の核圧力において物性を測定する高圧実験技術、輸送特性（熱伝導率、原子拡散）や元素分配の高精度予測を可能とした第一原理計算、地球ニュートリノデータからマントル中の熱源量を解析するモデリング手法、稠密アレイデータを用いた高分解能波形インバージョン手法などの最新の研究手法が確立されるとともに、多数の分野が協働する固体地球科学における先進的研究プラットフォームが構築された。このプラットフォームのもとで研究を継続することにより、マントル及び核の熱化学進化の理解を、時間軸の詳細を含めてさらに進展させることが可能である。これらの手法の多くはまた地球のみならず他の惑星にも適用可能であり、惑星科学への拡張は今後大きく発展する可能性を有する新たな方向性の一つであると考えられる。