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研究課題名（英文）Study of reef biota and sediment distribution in the South Ryukyus and application to paleoenvironmental interpretation of Quaternary fossil reef deposits

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交付決定額（研究期間全体）：（直接経費）　　3,400,000円

研究成果の概要（和文）：本研究では、(1)水深30m以深のメソフォティックゾーンにおけるサンゴ礁生態系の海洋生物および堆積物の性質と分布　(2)第四紀のサンゴ礁の発達と海水準変動の2つの主要研究テーマについて調査した。１つ目の研究テーマに取り組むため、琉球列島南部の石西礁湖周辺の3地点で新しい軽量自律型無人潜水機（AUV）を試験運転し、成功させた。また、6地点で遠隔操作型無人潜水機（ROV）による海底画像の取得を行った。第２の研究テーマにおいては、（1）沖縄本島南部の港川層の中期更新世後期の石灰岩　（2）北琉球小宝島の完新世隆起サンゴ礁段丘（3）オーストラリア東部の第四紀後期の沈水した化石礁について調査を実施した。

研究成果の学術的意義や社会的意義
This research led to a better understanding of the distribution and composition of reef organisms at mesophotic depths in the South Ryukyus, to the development of a new AUV, and shed light on Quaternary reef growth and sea-level history in the Ryukyu Islands and the Great Barrier Reef of Australia.

研究成果の概要（英文）：In this study, two main research themes were investigated: (1) the nature and distribution of marine organisms and sediments in coral reef ecosystems in deep (>30 m) mesophotic settings, and (2) Quaternary reef growth and sea-level history. To address the first research theme, a new lightweight autonomous underwater vehicle (AUV) was successfully tested at three sites around the Sekisei Lagoon, southern Ryukyu Islands. Additional seafloor images were acquired at six sites by remotely operated vehicles (ROVs). The surveys were conducted at depths of 30-70 m and revealed significant differences in benthos and bottom topography among the surveyed sites. To address the second theme, research was conducted on (1) late Middle Pleistocene limestones of the Minatogawa Formation in southern Okinawa-jima, (2) Holocene raised coral reef terraces of Kodakara-jima in the North Ryukyus, and (3) a late Quaternary submerged fossil reef in eastern Australia.

研究分野：Geology

キーワード：Coral reef　Ryukyu Islands　AUV　ROV　Mesophotic　Quaternary　Sea level change　Environmental change

1. Background

Fossil coral reefs and reef organisms are highly valuable archives of past climate and sea-level changes; they provide a unique window into Quaternary sea-level and climate history, and the responses of coral reef ecosystems to environmental perturbations. In particular, reef corals and crustose coralline algae are powerful sea-level and paleo-environmental indicators because (1) their distribution is controlled by environmental factors, such as light –depth–, wave exposure, and sea surface temperature, and (2) their fossilized remains can be radiometrically dated. However, although shallow coral communities have been well studied there is still relatively limited information on reef organisms inhabiting deep –mesophotic– reef habitats below 30 m. It is therefore important to explore coral reef ecosystems at mesophotic depths where data are lacking.

2. Objectives

The objective of this research is twofold: (1) test a new prototype of autonomous underwater vehicle (AUV) and acquire information on the composition and distribution of reef organisms and sediments at mesophotic depths in the South Ryukyus, and (2) apply the new and existing knowledge on the composition and distribution of reef organisms and sediments to reconstruct Quaternary sea-level and reef growth history.

3. Material and Methods

The survey of the mesophotic seafloor was conducted around the Sekisei Lagoon, located between Ishigaki-jima and Iriomote-Jima in the South Ryukyus. A new lightweight AUV (HATTORI-2; Fig. 1a) designed and built by Prof. Toshihiro Maki's lab (The University of Tokyo) was tested during ten dives at three sites (Fig. 1b): one site 60–70 m deep along the southern margin of the Sekisei Lagoon (Katagua site –Kg–), and two sites 30–40 m deep along the southern margin of the Sekisei Lagoon (Taketomi site 1 –Tk1– and 2 –Tk2–). HATTORI-2 is capable of acquiring video images of the seafloor while maintaining a constant depth along a predetermined path, and can also be equipped with depth, temperature, salinity, and light sensors. Additional video data were acquired by two small remotely operated vehicles (BlueRov 2, Blue Robotics Inc., and FullDepth DiveUnit 300, FullDepth Co., Ltd.) to explore the previous sites and three other sites (Fig. 1b): two along the southern margin of the Sekisei Lagoon (Kuroshima –Kr– and Sekisei South –Sk–), and one site south of Ishigaki-jima (Ishigaki South –Is–). Furthermore, a total of ten sediment grab samples were collected at the surveyed sites to investigate the nature of bottom sediments, one sample for each site, except site Kr (two grab samples) and site Tk1 (three grab samples).

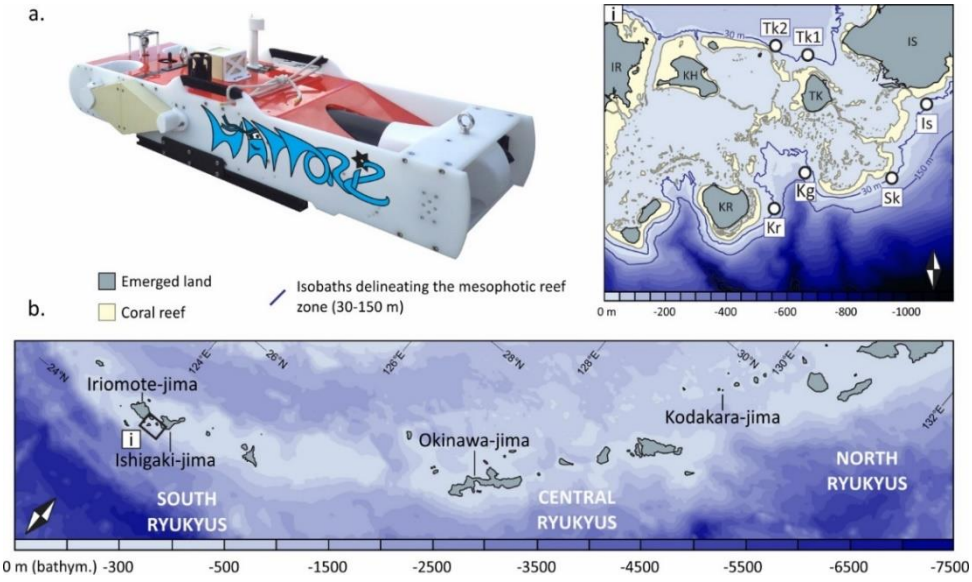

Figure 1: Image of AUV HATTORI-2 (a) and location of AUV-ROV survey sites in the Ryukyu Islands (b). IR. Iriomote, IS. Ishigaki-jima, KH. Kohama-jima, KR. Kuroshima, TK. Taketomi-jima. Source: Humblet et al. (2021).

Cores and outcrops of fossil reef limestones were investigated to reconstruct Quaternary sea-level and reef growth history. Specifically, the material studied consisted of (1)

outcrops of the late Middle Pleistocene Minatogawa Formation at Horikawa quarry in southern Okinawa-jima (Fig. 2a), (2) 78 m of cores from five boreholes drilled in Holocene raised coral reef terraces at Kodakara-jima (Fig. 2b), and (3) 21.5 m of cores of reef and off-reef limestones dated at 10–39 ka from two boreholes (40 A and 41A) drilled at 131 m water depth along the shelf edge of the Great Barrier Reef of Australia by Integrated Ocean Drilling Program (IODP) Expedition 325 (Webster et al., 2011; Fig. 2c). Analysis of the sedimentologic and biotic content of these limestones, compiled with radiometric age data (for the cores only), were used to reconstruct relative sea-level and reef growth history.

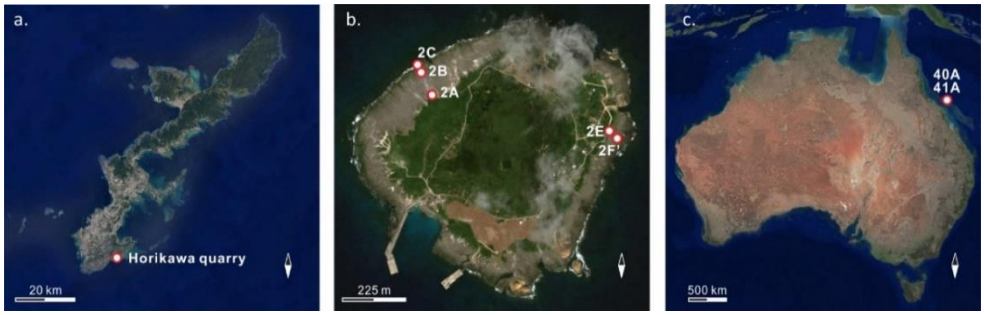

Figure 2: Location of outcrops and cores of Quaternary reef limestones used in this study: outcrops of the late Middle Pleistocene Minatogawa Formation at Horikawa quarry in southern Okinawa-jima (a), the five boreholes drilled at Kodakara-jima (b), and the two boreholes (40A and 41A) drilled along the shelf edge of the Great Barrier Reef (c).

4. Results

4.1. AUV-ROV survey (Sekisei Lagoon)

The AUV HATTORI-2 was successfully tested and mapped the seafloor at three sites (Tk1, Tk2, and Kg; Noguchi et al., 2022). The AUV-ROV survey of mesophotic seafloor around the Sekisei Lagoon revealed significant differences in benthos and bottom topography among the surveyed sites (Humblet et al., 2021; Fig. 3). At Tk1 and Tk2 and water depths of 30–50 m, the benthic community is dominated by scleractinian corals and encrusting coralline algae. The surveyed area comprises spurs and grooves, and isolated pinnacles. Coral cover is higher on topographic highs, where it can reach >80%, compared with adjacent areas where corals are very sparse. At site Is and water depths of 30–40 m, remarkable landforms composed of ridges, pinnacles, and troughs, extend offshore to at least 1 km from the reef edge. Abundant corals and coralline algae occupy the flanks and tops of topographic highs with cover up to 100%. Coral gravel fills the space between ridges and pinnacles. Site Kg, the deepest site surveyed at 60–70 m, is characterized by a diverse benthic community comprising corals, octocorallians, comatulids, and large benthic foraminifers. The abundance of octocorallians, including sea fans, increases with depth. The benthos occurs on a low ridge adjacent to a large expanse of bare sand. The two remaining sites, Sk and Kr, at water depths of 50 and 29–56 m, respectively, are characterized by the dominance of macroalgae (Fig. 3).

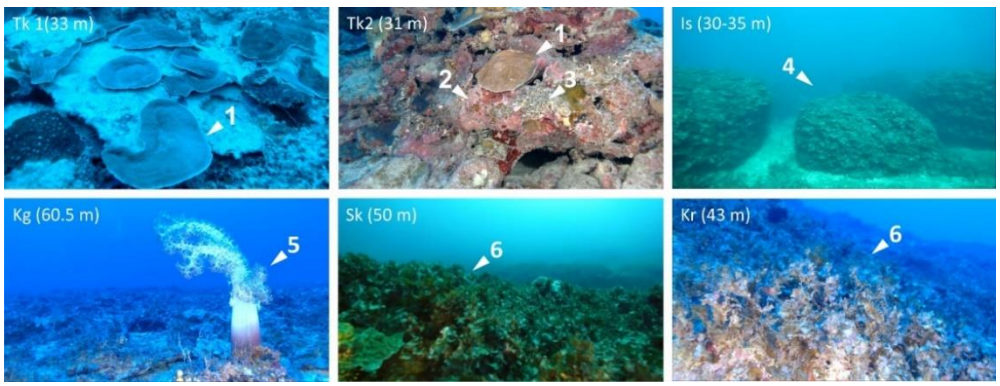

Figure 3: Representative images of the surveyed sites around the Sekisei Lagoon. 1. *Pachyseris speciosa*, 2. encrusting coralline alga, 3. *Discosoma* sp.?, 4. extensive network of ridges, pinnacles and troughs of site Is, 5. *Umbellulifera* sp., 6. macroalgal bed (*Ulva* sp.?). Source: Humblet et al. (2021).

4.2. Late Middle Pleistocene Minatogawa Formation (southern Okinawa-jima)

The stratigraphy, sedimentology, and fossil content of the late Middle Pleistocene limestones of the Minatogawa Formation exposed in Horikawa quarry in southern Okinawa-jima were studied to reconstruct its depositional history and relative sea-level change (Fig. 4). The

main results of this study can be summarized as follows (Tomatsu et al., 2021; Tomatsu, 2021): (1) seven fossil coral assemblages were identified, indicating a range of environmental settings, from high-energy shallow reef environment to low-energy deeper reef slope or turbid setting, (2) vertical trends in taxonomic composition reflects temporal changes in paleo-water depth during distinct stages of reef growth: from reef initiation during a marine transgression, followed by vertical reef accretion as sea-level continued to rise, and finally, reef demise by exposure during a relative sea-level fall, (3) spatial (lateral) variations in coral assemblages indicate contrasting wave exposure, (4) in addition to the two previously recognized episodes of sea-level fall associated with two paleosol horizons, the occurrence of an irregular erosional surface and of dissolution cavities at the boundary between the coral limestone and well-sorted detrital limestone suggests yet another interruption of vertical reef growth, either due to sea-level fall, or stabilization accompanied by wave- or current-driven erosion (Fig. 4a), and (5) the discovery of at least one syn-depositional fault suggests that tectonic activity influenced reef growth by causing abrupt relative sea-level change.

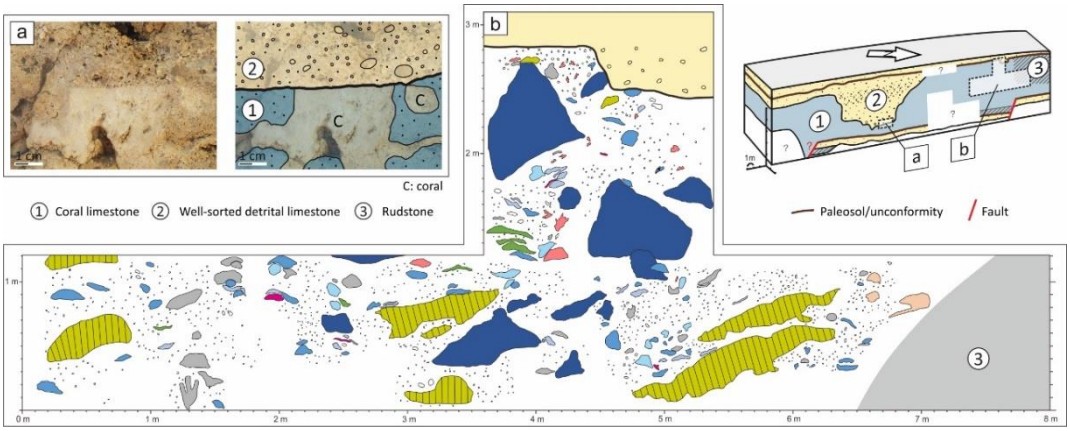

Figure 4: Selected outcrop of Pleistocene limestones (Minatogawa Formation) exposed in Horikawa quarry, with image of the erosional surface between the coral limestone and detrital limestone (a), and sketch of fossil coral colonies (different colors indicate different coral taxa) (b). Source: Tomatsu et al. (2021).

4.3. Holocene raised coral reef terraces (Kodakara-jima)

The Holocene reef growth history of the high-latitude coral reef at Kodakara-jima was reconstructed using cores from five boreholes drilled along two transects perpendicular to the shoreline (Ono et al., 2021; Ono, 2022; Figs. 2b and 5). Analysis of the core material revealed five coral assemblages (A-E). Coral reefs began to develop at 8.8–8.3 ka on the northwest coast and at 8.0 ka on the east coast. Pioneer assemblages D (diverse) and E (*Montipora*) directly overly the Miocene basement (volcanic tuff) and were influenced by terrigenous sediments. Coral assemblage B (massive *Porites*) became dominant at 6-7 ka on the northwest coast, and was replaced by assemblage A (Acropora) and C (Merulinidae) after 6 ka (i.e., timing of mid-Holocene sea-level stabilization).

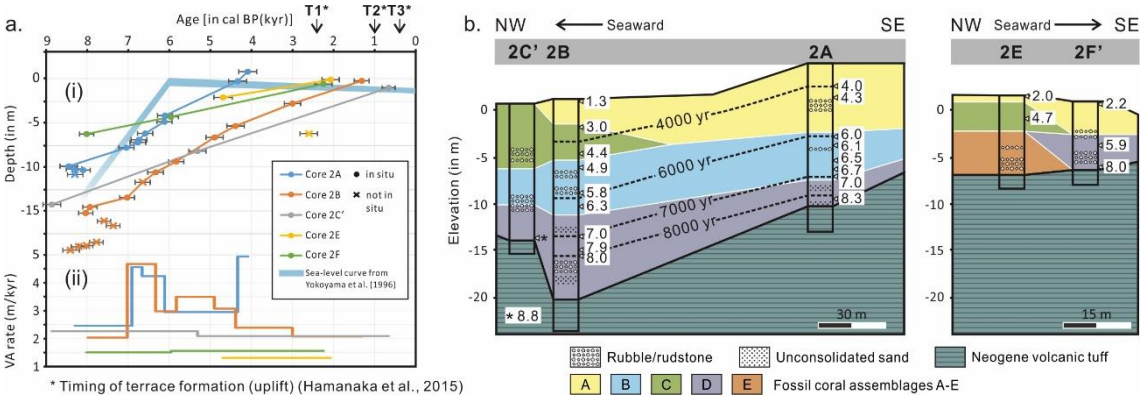

Figure 5: (a-i) Age-elevation (depth below MSL) plot derived from holes 2A-F' superimposed on the Holocene sea-level curve (in blue) from Yokoyama et al. (1996). (a-ii) Vertical reef accretion (VA) rates as a function of time derived from the new cores of Kodakara-jima. The timing of the three uplift events (T1-T3) is from Hamanaka et al. (2015). (b) Cross section and ^{14}C ages of fossil coral samples of the northwestern transect (holes 2A-2C') and of the eastern transect (holes 2E-2F'). Source: Ono et al. (2021).

4.4. Glacial-deglacial reef sequences of the Great Barrier Reef

Analysis of cores from boreholes 40A and 41A revealed two episodes of reef growth, one during Marine Isotope Stage (MIS) 2 and the other at the onset of the deglaciation, both characterized by abundant microbialite crusts and distinct coral assemblages (Humblet et al., 2022; Fig. 6). The MIS 2 and early deglacial reef sections are characterized by paleo-water depths ranging from 30 to 60 m and from 20 to 30 m, respectively. The first episode of reef growth initiated at 27 to 25 ka. Sometime between 24 and 19 ka, reef accretion was reduced or ceased. This episode coincides with the rapid 20 m sea-level fall of the peak Last Glacial Maximum and minima of sea surface temperatures (SST). Reef growth then resumed at 19.5-18.5 ka during a period of moderate sea-level rise and increasing SSTs at the onset of the deglaciation. Reef growth ended at ca. 17 ka. The timing of reef growth termination coincides with a major episode of reef demise previously identified in adjacent mid and outer terrace cores, linked to reduced water quality combined with rapid deglacial sea-level rise. Vertical accretion (VA) rates were calculated based on two methods: linear visual fitting and Bayesian modelling. The highest VA rates are associated with microbialite boundstone. Reef ecosystems dominated by microbialite and corals developed at intermediate and mesophotic depths, and grew vertically at maximum rates of 2 to 5 mm yr^{-1} depending on the method used, over a period of rapid environmental change during the transition from MIS 3 to MIS 1 (Humblet et al., 2022).

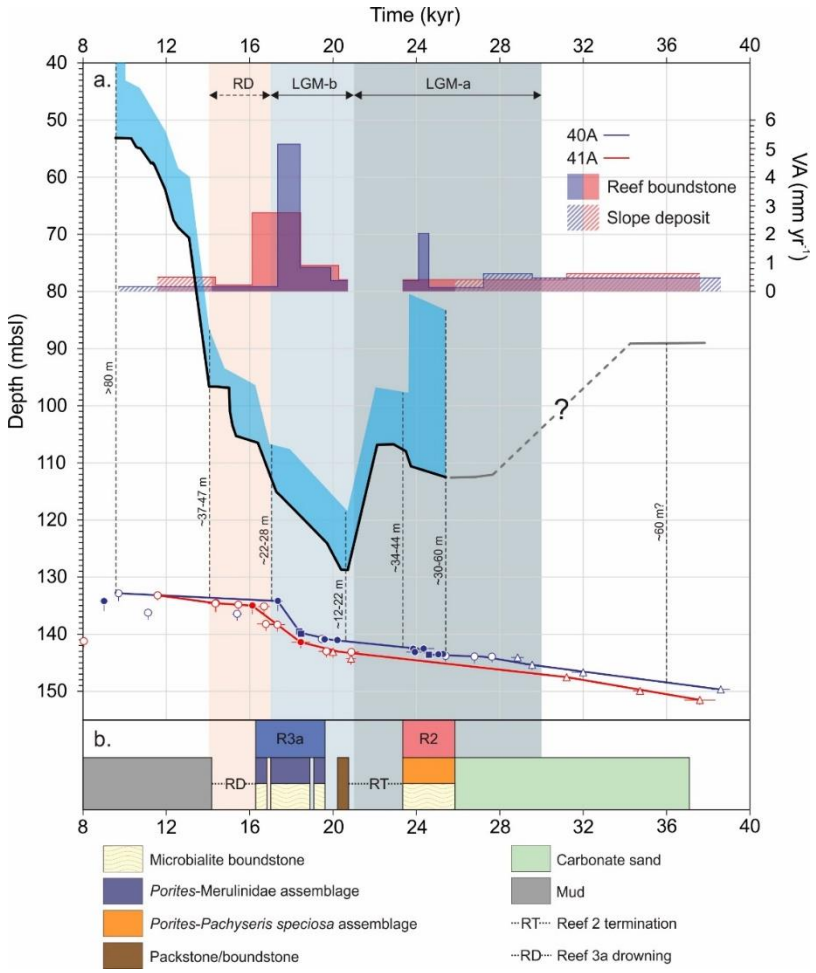

Figure 6: (a) Relative sea-level (RSL) curve for transect HYD-01C (black line) and segment of the RSL curve obtained for transect NOG-01B (grey line) (Yokoyama et al., 2018), vertical accretion (VA) rates, and dated in situ samples plotted as a function of age and depth (see Fig. 2 for the meaning of colors and symbols); vertical dashed lines illustrate variation in paleo-water depths over time. (b) Schematic representation of the depositional history and major facies over the period 8–40 ka in Hole 40A. Source: Humblet et al. (2022).

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５．主な発表論文等

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２．論文標題 Low-altitude and high-speed terrain tracking method for lightweight AUVs	５．発行年 2018年
３．雑誌名 Journal of Robotics and Mechatronics	６．最初と最後の頁 971-979
掲載論文のDOI（デジタルオブジェクト識別子） 10.20965/jrm.2018.p0971	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 －

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３．雑誌名 Marine Technology Society Journal	６．最初と最後の頁 74-89
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３．雑誌名 International Association of Sedimentologists Special Publication	６．最初と最後の頁 189-214
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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 －

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１．発表者名 Humblet, M., Maki, T., Furushima, Y., Noguchi, Y., Horimoto, H., Sakamaki, T., Ito, S., and Suzuki, S.
２．発表標題 ROV and AUV seafloor imaging at mesophotic depths in the South Ryukyus, Japan
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2．出版社 Springer Nature	5．総ページ数 1003
3．書名 Ryukyu Islands, Japan (in: Mesophotic Coral Ecosystems, Coral Reefs of the World 12)	

〔産業財産権〕

〔その他〕

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6．研究組織

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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0件

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