様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　６ 年　６ 月 ２５ 日現在

機関番号：１８００１
研究種目：基盤研究(C)（一般）
研究期間：2020～2023
課題番号：２０Ｋ０６２１０

研究課題名（和文）Mesophotic Coral Ecosystems in the West Pacific: threatened ecosystems or hope for the reefs?

研究課題名（英文）Mesophotic Coral Ecosystems in the West Pacific: threatened ecosystems or hope for the reefs?

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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：本研究では、浅場と深場（水深40m）のサンゴを比較し、深場サンゴの熱耐性について明らかにした。深場サンゴの絶対最大温度閾値は低いものの、週積算高水温（DHWs）を用いた差では、深場サンゴは高い熱ストレスにも耐えうることが明らかとなった。また、深場レフュジア仮説のモデルとなるトゲサンゴには遺伝的多様性がみられたが、深度との関連はみられなかった。沖縄とフィリピンのトゲサンゴ間では遺伝的多様性は類似したが、インドネシアではより局所的に高い多様性を示した。さらに、日本とインドネシアに共通の遺伝子型が複数みられたことから、本種の一部が、将来沖縄の温暖化した海で生き残る可能性があることを示唆した。

研究成果の学術的意義や社会的意義
This project showed the importance of the local adaptation of corals to their environment and finding the same species at different latitudes (or depths) does not means they can rapidly transfer from one location to the other.

研究成果の概要（英文）：This research revealed the differences in thermal thresholds of various mesophotic coral species by comparing them with shallow counterparts. Interestingly, while the absolute maximum temperature threshold was lower in mesophotic corals, these deeper coral could tolerate a higher level of thermal stress when measured in terms of difference from the temperatures they are used to (degree heating week). We also confirmed that Seriatopora, a model coral for the Deep reef refugia hypothesis, contained cryptic diversity, but this diversity is not related to the depth. The new development of this research was to expand to the coral triangle and we could show similarities in the Seriatopora genetic diversity between Okinawa and the Philippines, while Indonesia had a higher level of localised diversity within Seriatopora. Some genotypes present from Japan to Indonesia suggest that some of these corals may be able to survive the warming ocean in Okinawa.

研究分野：Biodiversity

キーワード：Scleractinia

１．研究開始当初の背景

Warming seawater temperatures threaten coral reefs worldwide through increasing rates of coral bleaching events. Recently, coral reefs found below 30 m and down to over 100 m in depth, referred to as Mesophotic Coral Ecosystems (MCEs) due to the low amount of light reaching below 30 m, have received increasing attention worldwide. Due to the depth acting as a buffer from extreme temperature changes occurring in shallow waters, MCEs have been suggested to serve as a refuge for shallow coral in the context of ocean warming (the Deep Reef Refugia Hypothesis, DRRH)[1]. We found robust evidence in Japan that several shallow coral species can survive massive bleaching events thanks to the colonies living in MCEs[2]. Unfortunately, the oceans will keep warming for decades, and we can expect that conditions for coral reefs will not improve in the following decades/centuries. In this context, it is essential to think beyond the potential of MCEs to serve as a source of larvae to recolonize shallow reefs and understand the resilience of MCEs in a warming ocean.

Mesophotic corals will need to adapt to increasing temperatures, both in peak temperatures and rising average temperatures. Species-specific tolerance to heat stress will be determinant in the resilience of MCEs to ocean warming, and future MCEs will be composed of both thermal stress-tolerant species and "migrant" corals expanding from regions currently experiencing warmer temperatures (warm-adapted species). However, the thermal tolerance of mesophotic corals is still unknown, and it is unclear if deep specimens of species found deep and shallow (depth generalists) have the same thermal tolerance as their shallow counterparts. Deep specimens may have adapted to the moderated conditions found in MCEs and developed higher sensitivity to thermal stress. In this context, the survival of a species in a location may rely on the contribution of deep corals expanding from lower latitudes (already adapted to higher temperatures).

２．研究の目的

This project aimed to further our understanding of how mesophotic corals in Okinawa will react to climate change, considering the biogeographic relationships between Okinawa and the Coral Triangle (where sea temperatures are already warmer).

Three sub-objectives allowed to address this aim:

(1) Understanding the diversity in the deeper parts of the reefs and how mesophotic organisms interact.
(2) Understanding mesophotic corals' thermal thresholds and comparing their adaptability with shallow coral species.
(3) Understand the phylogeography of selected coral species in the broad region (from Okinawa to the Coral Triangle).

３．研究の方法

To address each of the sub-objectives, I used a variety of approaches with students and collaborators.

The diversity and organism interactions were surveyed using photoquadrats and specimen morphological and molecular analyses. Thermal stress experiments were conducted ex-situ in aquarium systems with the measurements of various parameters such as survival, bleaching, and photophysiology. A variety of shallow, deep, and generalist species were used. Shallow coral juveniles were also transplanted to deeper parts of the reef to understand their adaptability.

The phylogeography study resulted from a collaborative effort with colleagues and students from Indonesia and the Philippines. This part of the project focused on *Seriatopora* and used mostly mitochondrial DNA to reveal its structure across the regions.

Figure 1: transplanting juvenile corals between depths to study how they can adapt.

４．研究成果

The survey of the biodiversity in the deepest parts of the reefs confirmed the expected trend of *Leptoseris* corals' occurrence increasing with depth and the strong presence of algae at depths that become challenging for photosymbiotic corals[3]. However, it also showed a very high diversity of communities in the same depth range and a relatively high coral cover, even at 60 m depth and below. *Seriatopora* was observed down to 70 m, confirming its status of depth generalist coral. However, in addition to the rich biodiversity, evidence of human impact was also observed, with a dense coral community between 50 and 70 m depth nearly destroyed within two years by the impact of anchors of construction ships in this area. Despite alerting the government (in charge of the construction work), no change was observed in the subsequent years. This part of the project also allowed us to observe the world's deepest specimen of a butterflyfish, expanding its known depth range by several tens of meters[4].

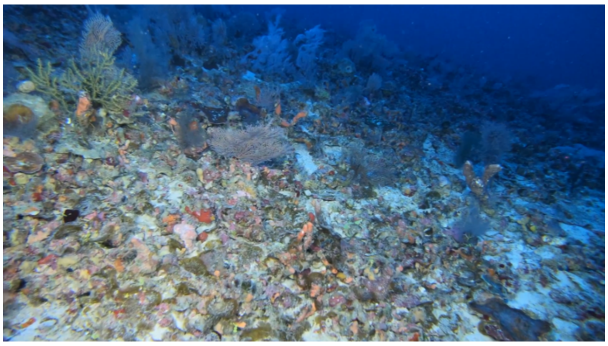

Figure 2: Deepest part of the reefs where the dominance shifts from hard corals to non-photosymbiotic gorgonians.

At shallower depths (40 m), we also quantified and characterized the presence of two species of coral-killing sponges[5]. While the prevalence of these sponges is relatively high at sites with dense coral cover, it is still being determined whether they represent a threat and how this competitive relationship will evolve in a changing environment. In this perspective, our established baseline will be crucial to understanding the long-term dynamics between corals and sponges at upper mesophotic depths.

In terms of thermal thresholds, among the 11 shallow and mesophotic coral species tested, overall, the mesophotic corals could not stand as high temperatures as the shallow corals[6]. However, when considering heat stress, the difference of heat from the average temperature the corals are living in, which is measured as Degree Heating Weeks (DHWs); at 4 DHWs, all but one species of mesophotic corals survived, while several shallow corals showed signs of bleaching. This suggests that mesophotic corals will be able to tolerate some levels of thermal stress; however, if the increase in temperature becomes extreme and too rapid, the mesophotic coral ecosystems will not act as a refuge from bleaching.

However, we also found that juveniles of shallow coral species can acclimate to deeper depths, even if variability was observed between species. This supports the idea that some shallow corals may shift their distribution to deeper parts of the reefs, which are more protected from extreme temperatures[7]. The reverse was tested with *Seriatopora*, where juveniles originating from the mesophotic refuge at 40 m could thrive at 20 m depth but not when transplanted directly from 40 to 3 m depth. However, throughout this project, we observed a natural return of some *Seriatopora* to depths as shallow as 4 m. This suggests that the recolonization of shallow reefs may happen via a steppingstone at 20 m, where corals from 40 m could adapt to brighter light and higher temperatures, releasing larvae that will then be able to colonise the shallowest depths[8].

Figure 3: Juvenile colony of *Seriatopora* naturally coming back to 4 m depth.

Mitochondrial DNA from *Seriatopora* specimens from Okinawa, the Philippines, and Indonesia confirmed the earlier findings from Japan that while *Seriatopora hystrix* may be composed of several cryptic species, none of these species are restricted to one depth zone[9]. While in the earlier study in Japan only, no clear geographic patterns were observed, when including specimens from the Philippines and Indonesia, clear similarities are observed between Okinawa and the Philippines. On the opposite, despite several genotypes shared all over the region, Indonesia showed a higher haplotype diversity and a more fragmented geographic distribution of the haplotypes (Sinniger et al. in prep.).

References: [1]Bongaerts et al. 2010. *Coral Reefs* 29, 309–327; [2]Sinniger et al. 2023. *Coral Reefs* 32, 153; [3]Sinniger et al. 2021. *Galaxea, Journal of Coral Reef Studies* 24, 41–49; [4]Sinniger et al. 2021. *Galaxea, Journal of Coral Reef Studies* 24, 39–40; [5]Albelda et al. 2024. *Bulletin of Marine Science*, in press; [6]Tavakoli-Kolour et al. 2023. *Frontiers in Marine Science*

10, 1210662; [7]Tavakoli-Kolour et al. 2023. *Marine Pollution Bulletin* 188, 114698 ; [8]Prasetia et al. 2022. *Scientific Reports* 12, 12836 ; [9]Sinniger et al. 2017. Frontiers in Marine Science 4, 155.

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 Albelda Ritzelle L、Sinniger Frederic、Ise Yuji、Harii Saki	４．巻 online first
２．論文標題 Presence of coral-killing sponges in Okinawan mesophotic coral ecosystems	５．発行年 2024年
３．雑誌名 Bulletin of Marine Science	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） 10.5343/bms.2023.0173	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 Tavakoli-Kolour Parviz、Sinniger Frederic、Morita Masaya、Nakamura Takashi、Harii Saki	４．巻 10
２．論文標題 Variability in thermal stress thresholds of corals across depths	５．発行年 2023年
３．雑誌名 Frontiers in Marine Science	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） 10.3389/fmars.2023.1210662	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 Tavakoli-Kolour Parviz、Sinniger Frederic、Morita Masaya、Hazraty-Kari Sanaz、Nakamura Takashi、Harii Saki	４．巻 197
２．論文標題 Plasticity of shallow reef corals across a depth gradient	５．発行年 2023年
３．雑誌名 Marine Pollution Bulletin	６．最初と最後の頁 115792～115792
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.marpolbul.2023.115792	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 Tavakoli-Kolour Parviz、Sinniger Frederic、Morita Masaya、Harii Saki	４．巻 188
２．論文標題 Acclimation potential of Acropora to mesophotic environment	５．発行年 2023年
３．雑誌名 Marine Pollution Bulletin	６．最初と最後の頁 114698～114698
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.marpolbul.2023.114698	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 Prasetia Rian、Sinniger Frederic、Nakamura Takashi、Harii Saki	4．巻 12
2．論文標題 Limited acclimation of early life stages of the coral Seriatopora hystrix from mesophotic depth to shallow reefs	5．発行年 2022年
3．雑誌名 Scientific Reports	6．最初と最後の頁 1～12
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-022-16024-6	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 Sinniger Frederic、Albelda Ritzelle L.、Prasetia Rian、Rouze Heloise、Sitorus Erlangga D.、Harii Saki	4．巻 24
2．論文標題 Overview of the mesophotic coral ecosystems around Sesoko Island, Okinawa, Japan	5．発行年 2022年
3．雑誌名 Galaxea, Journal of Coral Reef Studies	6．最初と最後の頁 69～76
掲載論文のDOI（デジタルオブジェクト識別子） 10.3755/galaxea.G2021_S11N	査読の有無 有
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2．論文標題 Deepest observation of the butterflyfish Coradion altivelis (Perciformes: Chaetodontidae) in Japan	5．発行年 2022年
3．雑誌名 Galaxea, Journal of Coral Reef Studies	6．最初と最後の頁 39～40
掲載論文のDOI（デジタルオブジェクト識別子） 10.3755/galaxea.G2021_S8PG	査読の有無 有
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1．著者名 Albelda Ritzelle L.、Cabaitan Patrick C.、Sinniger Frederic、Dumalagan Edwin E.、Quimpo Timothy Joseph R.、Olavides Ronald Dionnie D.、Munar Jeffrey C.、Villanoy Cesar L.、Siringan Fernando P.	4．巻 40
2．論文標題 Juvenile scleractinian assemblage and its association with adults and benthos at shallow and upper mesophotic depths in fringing and atoll reefs in the Philippines	5．発行年 2020年
3．雑誌名 Regional Studies in Marine Science	6．最初と最後の頁 101514～101514
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.rsma.2020.101514	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9件（うち招待講演　1件／うち国際学会　7件）

1．発表者名
F. Sinniger, M. Pichon, S. Harii

2．発表標題
Scleractinian biodiversity at the deepest edge of the reef in Japan

3．学会等名
Asia Pacific Coral Reef Symposium（国際学会）

4．発表年
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1．発表者名
S. Harii, F. Sinniger

2．発表標題
Corals in a warming Ocean

3．学会等名
Gathering of the Swiss Universities alumni in Tokyo（招待講演）

4．発表年
2024年

1．発表者名
F. Sinniger, M. Pichon, S. Harii

2．発表標題
Scleractinian biodiversity at the deepest edge of the reef in Japan

3．学会等名
Asia Pacific Coral Reef Symposium（国際学会）

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1．発表者名
Sinniger, F., Pichon, M., Albelda, R.L., Thornton, B., Harii, S.

2．発表標題
REFUGES FOR SHALLOW CORALS OR UNIQUE ENDANGERED ECOSYSTEMS? AN OVERVIEW OF THE STATUS OF MESOPHOTIC CORAL ECOSYSTEMS IN OKINAWA.

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INTECOL2022（国際学会）

4．発表年
2022年

1．発表者名 Sinniger, F., Pichon, Harii, S.
2．発表標題 Scleractinian communities at the deepest edge of the reef in Okinawa.
3．学会等名 Japan Coral Reef Society Annual meeting
4．発表年 2022年

1．発表者名 Sinniger, F., Pichon, Harii, S.
2．発表標題 Scleractinian communities in the deeper parts of the reef in Okinawa.
3．学会等名 Gordon Research Conference on Mesophotic Coral Reef Ecosystems（国際学会）
4．発表年 2023年

1．発表者名 F. Sinniger, M. Pichon, H. Rouze, B. Thornton, J. Walker, S. Harii
2．発表標題 MCES in Okinawa: unique ecosystems, lifeboats for coral reefs or both?
3．学会等名 14th International Coral Reefs Symposium Virtual（国際学会）
4．発表年 2021年

1．発表者名 F. Sinniger, S. Mills, D. Macpherson
2．発表標題 New deep sea zoantharian diversity in the South Pacific
3．学会等名 5th World Conference on Marine Biodiverstiy（国際学会）
4．発表年 2020年

１．発表者名 F. Sinniger, S. Mills, D. Macpherson
２．発表標題 New Zealand deep sea: a hotspot for deep zoantharian diversity?
３．学会等名 eDSBS, 16th Deep Sea Biology Symposium（国際学会）
４．発表年 2020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

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