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研究課題名（和文）Reconstruction of late Quaternary sea-level and reef growth history in the Ryukyu Islands

研究課題名（英文）Reconstruction of late Quaternary sea-level and reef growth history in the Ryukyu Islands

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研究成果の概要（和文）：沖縄本島に分布する港川層は、有孔虫粒岩とサンゴに富む石灰岩からなるユニークな中期更新世後期から後期更新世の炭酸塩堆積記録である。この地層は第四紀の海水準とサンゴ礁の成長史に関する重要な情報をもたらす。本研究では、湊川層群に掘削された12本のボーリング孔から188 mのコア切片を回収した。堆積相の横方向の変化を記録するために、海岸線に垂直な2本の横断線に沿って掘削した。1本目は6本、2本目は5本のボーリング孔を掘削した。2つのトランセクトの間に1つのボーリング孔が掘削された。湊川層の下にある古い更新世の基盤は、1孔を除くすべての孔で到達した。湊川層の厚さは0-24mである。

研究成果の学術的意義や社会的意義
The cores from the Minatogawa Formation provide a unique window into the late Middle to Late Pleistocene sea-level and reef growth history in the Northwest Pacific. This time window is particularly important to study rapid environmental changes and their impact on coral reef ecosystems.

研究成果の概要（英文）：The Minatogawa Formation in Okinawa-jima represents a unique late Middle to Late Pleistocene record of carbonate sedimentation consisting of well-sorted foraminiferal grainstones and coral-rich limestones. This formation yields important information on Quaternary sea-level and reef growth history. In this study, we have recovered 188 m of core sections from twelve boreholes drilled into the Minatogawa Formation in southern Okinawa-jima. In order to record lateral variations in sedimentary facies, we have drilled along two transects about 1 km apart and perpendicular to the shoreline. Six boreholes (Hole 1-6) were drilled along the first transect and five (Hole 1b-5b) along the second. One borehole (Hole C) was drilled between the two transects. The older Pleistocene basement (Naha Formation) underlying the Minatogawa Formation was reached in all but one hole. The thickness of the Minatogawa Formation ranges from 0 m in the most inland holes to 24 m closer to the shoreline.

研究分野：Geology

キーワード：Coral reef　Sea level change　Climate change　Quaternary　Minatogawa Formation　Ryukyu Islands　Okinawa

1. 研究開始当初の背景

Quaternary glacial-interglacial climate cycles over the past 800,000 years have been characterized by large global sea-level fluctuations with maximum amplitudes of 100-120 m. Understanding sea-level history and its relationship with polar ice sheet dynamics is key to validate models predicting the future trajectory of climate and sea level. Among archives of past sea-level change, fossil coral reefs are particularly useful because their distribution is restricted to the euphotic zone, and the species composition of reef corals and coralline algae, the two main reef-builders, are controlled by light and wave energy (Woodroffe & Webster, 2014). Well-preserved fossil corals can also be radiometrically dated. Therefore, the distribution of fossil coral reefs and their internal facies architecture and composition can provide important information on the timing and amplitude of past sea-level change (Yokoyama et al., 2018). In addition, the study of fossil reefs can also provide key insight into the response of reef communities to climate and sea-level change and the environmental boundaries of reef growth, i.e., the environmental conditions favorable for reef initiation and those leading to reef demise (Humblet et al., 2019; Webster et al., 2018). Despite significant progress in recent years, the Pleistocene record of sea-level change and its impact of coral reef ecosystems is still fragmentary and more research needs to be done to fill this knowledge gap.

In Japan, late Middle to Late Pleistocene fossil coral reef deposits are distributed in Okinawa-jima. The Minatogawa Formation, as they have been formally named, has a maximum thickness of about 20 m and rests unconformably on older Pleistocene limestones at elevations of up to 60 m (Fujita et al., 2018). The currently accepted age of the Minatogawa Formation is <450 ka (Watanabe et al., 2023). The present research project is focused on this formation and aims to clarify its depositional history and reconstruct relative sea-level changes based on the study of its fossil content and sedimentary facies.

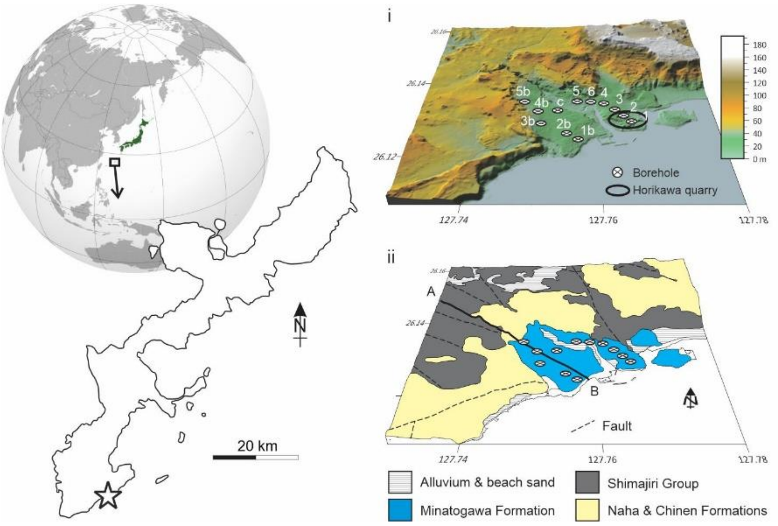

Figure 1: Location of Okinawa-jima (framed area on the world map above) and of the study area (black star) in southern Okinawa-jima. The location of the twelve boreholes are shown on a topographic (i) and geological (ii) map. The geological map shows the distribution of the Minatogawa Formation, Naha and Chinen Formations, and Shimajiri Group. For simplification's sake the Naha and Chinen Formations share the same color in this figure. (sources: world map from Wikipedia; digital elevation model from the Geospatial Information Authority of Japan; geological map and cross-section modified from Kaneko & Ujiie, 2006).

2. 研究の目的

The major objectives of this research are (1) reconstruct the depositional history of the Minatogawa Formation and its link with global sea-level change, (2) study the response of coral reefs and reef communities to environmental and sea-level changes, (3) constrain the timing of the major phase of uplift that has led to the present-day physiography of the Ryukyu Islands, and, based on a meta-analysis combining the new dataset with data from existing cores drilled at various latitudes, (4) investigate large-scale trends in reef composition over the course of the Quaternary along a latitudinal gradient.

3. 研究の方法

The study area is in southern Okinawa-jima where the Minatogawa Formation is distributed. In order to reconstruct the three-dimensional facies architecture of the Minatogawa Formation, a drilling campaign was conducted in 2021-2022. Drilling efforts focused on two transects perpendicular to the shoreline. Twelve boreholes with a total cored length of 188 m and core recovery of nearly 100% were drilled to record vertical and horizontal facies variations of the Minatogawa Formation. Six boreholes were drilled along the first transect (T1; Holes 1–6), five along the second transect (T2; Holes 1b–5b), and one additional borehole was drilled between the first and second transect (Hole C) (Fig. 1). Holes 1 and 2 were drilled in Horikawa quarry where the Minatogawa Formation has been studied by Fujita et al. (2018). The drilled lengths of individual boreholes range from 10 to 27 meters.

After shipping the cores to the Kochi Core Center for safe storage, X-ray Computed Tomography (XCT) imaging was performed on each core. XCT scanning is a useful imaging technique used to obtain X-ray images of the core material hidden beneath the core external surface. This data is used to obtain information on the texture and composition of the core material in addition to the more traditional visual core description. The cores were then split in half, photographed, and their lithology, sedimentary structures, and major fossil biotic components, particularly corals, coralline algae, and foraminifers, were carefully described. One half of the cores (i.e., sampling half) was used for sampling while the other half (i.e., archive half) will be kept intact for future research projects.

At the time of writing, a total of 306 samples were collected for sedimentological and geochemical analyses, as well as for the taxonomic identification of scleractinian corals, coralline algae, and foraminifers.

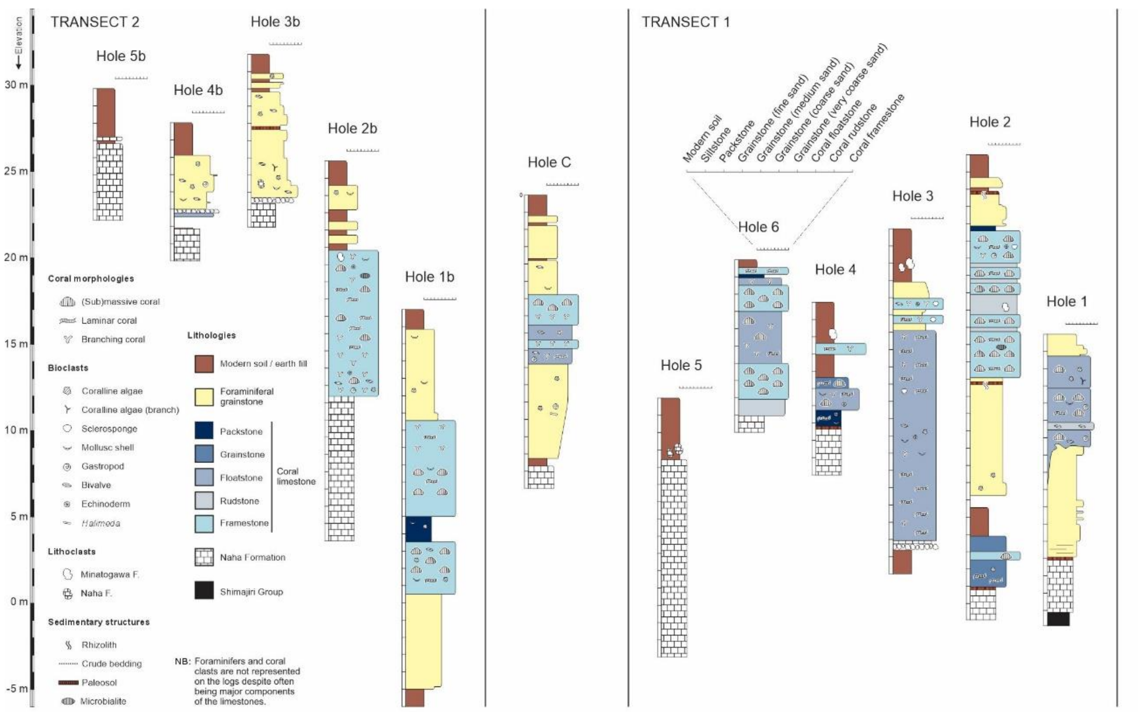

Figure 2: Lithostratigraphic logs of the cores from the 12 boreholes drilled into the Minatogawa Formation in southern Okinawa-jima. The vertical scale bar shows elevations relative to mean sea level.

4. 研究成果

The thickness of the Minatogawa Formation generally decreases inland, varying from 0 m in the most inland holes (Holes 5 & 5b) to a maximum thickness of 24 m in Hole 2 along transect 1 (Fig. 2). The Naha Formation was reached at all but one site (Hole 1b). The contact between the Naha Formation and the Minatogawa Formation ranges in elevation between +27 m to -5 m relative to present-day mean sea level. Like in the Horikawa quarry, the two main lithologies observed in the cores consist of well-sorted foraminiferal grainstones (Fig. 3a) and coral limestones. The coral limestones are characterized by a relatively high abundance of corals and can be classified into various sedimentary facies according to the texture of the carbonate sediments: framestones where in situ corals are abundant (Fig. 3b), packstone (Fig. 3c), grainstone, floatstone (Fig. 3d), and rudstone (Fig. 3e).

There are marked lateral and vertical changes in sedimentary facies and fossil content. Along transect 1, the foraminiferal grainstones are not found inland (i.e., in Holes 4, 5, and 6). The coral content of Holes 1 and 2 is diverse and characterized by abundant massive colonies, mainly *Porites* and Merulinidae. Conversely, the more inland Holes 3 and 4 contain abundant branching and laminar corals, including *Porites*, embedded in a finer-grained matrix. This is however not the case in Hole 6 which is characterized by a large proportion of massive corals, including large *Porites* colonies. The lateral shift to a coral assemblage dominated by thin laminar and branching corals associated with finer sediments could indicate a more protected depositional setting. Along transect 2, coral limestones were only recovered from Holes 1b and 2b. Unlike Holes 1 and 2 of transect 1, branching corals, including robust-branching *Acropora* are common. They are associated with mostly encrusting to submassive corals.

Figure 3: Illustration of the main lithologies and remarkable sedimentary surfaces observed in the cores.

Several remarkable sedimentary surfaces are observed, including sharp boundaries (Fig. 3f), which in some cases show evidence of erosion, and paleosols (Fig. 3g). Among the former, the contact between the base of the coral limestone in Hole 1 of transect 1 and the underlying foraminiferal grainstones likely coincides with the contact between the coral limestone and surrounding foraminiferal grainstones observed in Unit 3 of the Minatogawa Formation in the Horikawa quarry (Figs 2 & 4; Fujita et al., 2018).

The core material also shows evidence of diagenetic alteration following subaerial exposure of the limestones (i.e., abundant vug porosity, moldic porosity, recrystallization of aragonitic coral skeleton into calcite, and dog-tooth calcite cement). Open dissolution cavities and

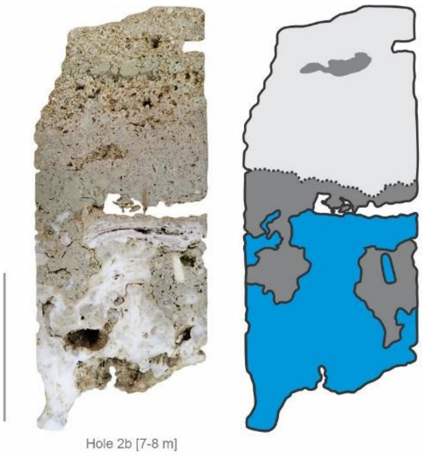

Figure 4: Core interval showing the primary coral framework (blue) and secondary porosity filled with a 1st generation of sediment infill (fine carbonate mud with desiccation cracks; dark grey) and a 2nd generation of sediment infill (grain-stone; light grey). Scale bar is 5 cm long.

dissolution cavities filled with sediments are observed. At least three generations of sediment infill are present. In cores of the second transects, fine carbonate mud with desiccation cracks have filled dissolution cavities, followed by coarser bioclastic sediments (grainstone). The second generation of sediment infill (i.e., grainstone) contains coral clasts and reworked first-generation infill mud (Fig. 4). The latest generation of sediment infill consists of brown clay from modern soil.

The analysis of the fossil content of the core material will continue. Specifically, the taxonomic identification of the coral, algal, and foraminiferal fossil assemblages, and the study of their lateral and vertical distribution in the cores need to be completed. This data is key for the paleo-environmental interpretation of the limestones and for sea-level reconstruction.

Microfacies analysis based on the examination of thin sections using an optical microscope is in progress. This analysis will shed light on the composition of sediments and their diagenetic history.

Samples have also been collected for geochemical analyses. Bulk carbonate samples of the fine sedimentary matrix will be analyzed for major, trace and rare-earth elements, and for $\delta^{18}O$ and $\delta^{13}C$. This data will provide further information on the paleoenvironmental conditions during deposition (e.g., terrigenous input) and subsequent diagenetic alterations, and will facilitate the identification of sedimentary unconformities and stratigraphic correlations among cores.

In addition, we will continue the screening of coral samples to identify pristine aragonitic samples for dating using Raman spectroscopy and XRD analyses. Other ways to clarify the age of the limestones will also be explored, such as using the $\delta^{18}O$ record and its relationship with marine isotope stages, or using the paleomagnetic signatures of the limestones.

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5．主な発表論文等

〔雑誌論文〕　計0件

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　0件）

1．発表者名 Feuillerat, L., Humblet, M., Iryu, Y., Fujita, K.
2．発表標題 Reconstruction of late Middle Pleistocene reef growth history and environmental changes in the Ryukyu Islands
3．学会等名 Japan Geoscience Union Meeting
4．発表年 2023年

1．発表者名 Feuillerat, L., Humblet, M., Iryu, Y., Fujita, K.
2．発表標題 Sedimentological and paleontological study of the late Middle to Late Pleistocene Minatogawa Formation, southern Okinawa Island
3．学会等名 Japan Geoscience Union Meeting
4．発表年 2024年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

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８．本研究に関連して実施した国際共同研究の実施状況

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