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Calcareous nannofossil assemblages of the upper Miocene to Pliocene Shimajiri Group on Okinawa-jima, Ryukyu Islands, southwestern Japan

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ABSTRACT

We investigated the calcareous nannofossil biostratigraphy and paleoceanography of the Shimajiri Group in two exploratory wells (depths, 1243 and 1800 m) drilled on southern Okinawa-jima, Ryukyu Islands, southwestern Japan. Three late Miocene to Pliocene datum planes were identified: the first occurrence of *Amaurolithus* spp. (7.42 Ma), the last occurrence of *Discoaster quinqueramus* (5.59 Ma), and the first occurrence of *Ceratolithus rugosus* (5.12 Ma). These datum planes were also identified in two other deep wells on southern Okinawa-jima. Nutrient levels (reconstructed from the relative abundances of small *Reticulofenestra* spp., and the relative abundances of *Discoaster* spp. plus *Sphenolithus abies*) suggest that deposition of the Shimajiri Group (<8.29–3.50 Ma) occurred under conditions of increasing eutrophication. The eutrophication was likely caused by shallowing of the sedimentary basin, but a stepwise shift was associated with an abrupt eutrophication event that occurred in the northwestern Pacific Ocean at 5 Ma.

1. Introduction

The Ryukyu Islands to the southwest of Japan form an island arc and are ideally placed to help understand paleoceanographic evolution of northwestern Pacific margin. The upper Miocene to Pleistocene Shimajiri Group, which is composed mainly of mudstone and sandstone (thought to have been deposited in a shelf slope to fore-arc basin setting), occurs on some of the Ryukyu Islands, southwestern Japan (Fig. 1). The Shimajiri Group underlies the Ryukyu Group, which consists of Pleistocene coral reef and shelf carbonates. Between these a transitional lithofacies the Chinen Formation is locally developed. The appearance of coral reefs in the Ryukyu Islands is related to the opening of the Okinawa Trough, a back-arc basin of the Ryukyu Island Arc. Although timing of the opening is controversial, it is considered likely that the Trough was opened during the late Miocene (Gungor et al., 2012) to early Pleistocene (Park et al., 1998). The subsequent influx of the Kuroshio Current into the back-arc basin resulted in decreased sediment transport to the islands and the development of clear-water coastal environments that promoted coral growth (Ujiié, 1994; Iryu et al., 2006). Therefore, the Shimajiri Group is important for interpretations of paleoceanographic change that occurred before and during the opening of the Okinawa Trough. Moreover, such interpretations are essential for understanding the evolution of the Kuroshio Current, the western boundary current in the northwestern Pacific (Gallagher et al., 2015).

Biostratigraphic studies of the Shimajiri Group have been conducted using planktonic foraminifers and calcareous nannofossils (Ibaraki and Tsuchi, 1975; Natori, 1976; Nishida, 1980; Tanaka and Ujiié, 1984; Ujiié, 1994; Imai et al., 2013). However, the group is complexly folded and faulted, and most of the group is located in the subsurface; thus, studies based exclusively on samples from surface outcrops provide only a partial record of the group, and are less reliable than studies utilizing well data. Based on their studies on benthic and planktonic foraminifers from the Shimajiri Group in wells as well as at surface outcrops, LeRoy (1964) and Fukuta et al. (1970) reconstructed sedimentary environments during deposition of the Group. The reconstructions, however, were different between the two studies, which was attributed to differentiation of sedimentary basin (Fukuta et al., 1970). Natori (1976) identified nine planktonic foraminiferal datum planes in the Shimajiri Group and the Chinen Formation in wells and at surface outcrops and correlated them to zones N16 to N22 of Blow (1969) (upper Miocene to Pleistocene). This chronological framework has been followed by many workers. Based on the results of Mishima and Ujiié (1983), Tanaka and Ujiié (1984) developed calcareous nannofossil and planktonic foraminiferal biostratigraphies

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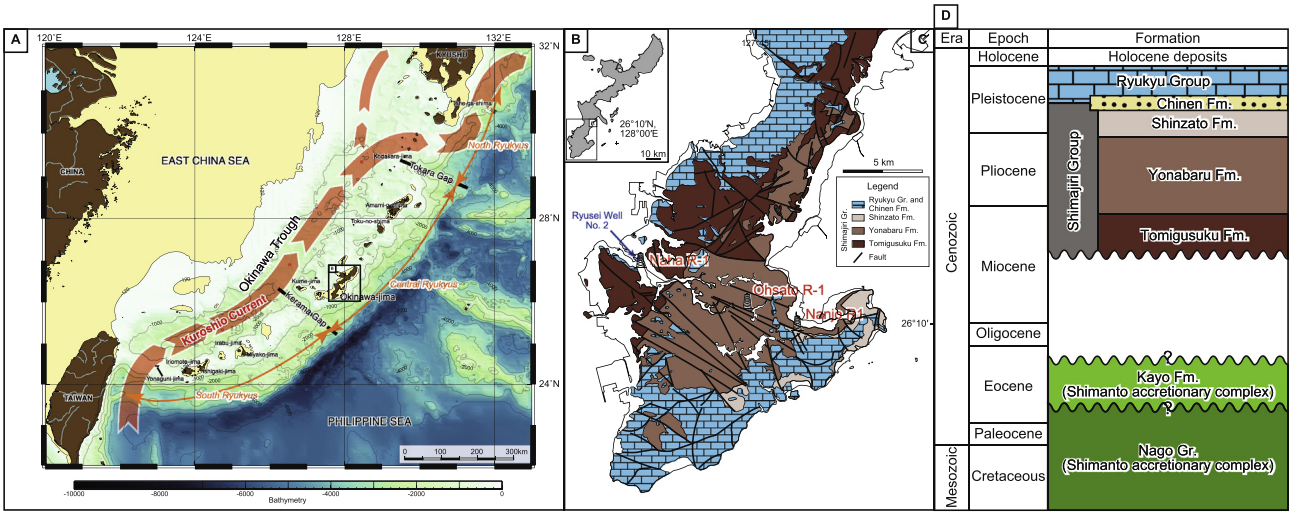

Fig. 1. Locations of (a) Okinawa-jima and (b, c) the Naha R-1 and Ohsato R-1 exploratory wells. (d) Stratigraphic outline of the Miocene to Pleistocene sequence in southern Okinawa-jima.

for the Shimajiri Group and the Chinen Formation in the southern Okinawa-jima region, based on 20 core samples from Ryusei Well No. 2, and 52 surface samples. They recognized eight nannofossil biostratigraphic datum planes, spanning zones CN9a–CN13a of Okada and Bukry (1980), and eight planktonic foraminiferal biostratigraphic datum planes, spanning zones N16–N22 of Blow (1969). Imai et al. (2013) identified four late Miocene to Pliocene datum planes in the Nanjo R1 Exploratory Well (depth, 2119.49 m) on southern Okinawa-jima: the first occurrence (FO) of *Amaurolithus* spp. (7.42 Ma), the last occurrence (LO) of *Discoaster quinqueramus* (5.59 Ma), the FO of *Ceratolithus rugosus* (5.12 Ma), and the LO of *Reticulofenestra pseudoumbilicus* (3.70 Ma). In addition, they reconstructed nutrient levels during the deposition of the Ryukyu Group on the basis of calcareous nannofossil assemblages, using the total number of coccoliths in a given weight of sediment, the relative abundance of *Discoaster* spp. plus *Sphenolithus abies* (%), and the relative abundance of small (2–3 and 3–4 μm) *Reticulofenestra* spp. (%). However, the interpretations of Imai et al. (2013) were based on calcareous nannofossil assemblages from only one well, and therefore their interpretations need to be tested by examining similar data from other wells.

In this study, we analyzed the calcareous nannofossil assemblages from two wells (the Naha R-1 and Ohsato R-1 exploratory wells; Fig. 1b) that were drilled on southern Okinawa-jima during September 2013 to March 2014 (Industrial Policy Division, Department of Commerce, Industry and Labor, Okinawa Prefectural Government and the Joint Venture Group for the Test Drilling, 2014). These wells, together with two previously drilled wells (Ryusei Well No. 2 and the Nanjo R1 Well), form a NW–SE-trending transect perpendicular to the NE–SW-trending axis of the Ryukyu Island Arc (Fig. 1a). Data on calcareous nannofossils from this transect are expected to be useful in constraining the chronology and delineating the stacking pattern of the sedimentary sequence, and in reconstructing sea surface conditions during deposition of the sediments.

2. Geologic setting

The Cenozoic sequence of southern Okinawa-jima, which is underlain by the Eocene Kayo Formation, consists of the Shimajiri Group, the Chinen Formation, and the Ryukyu Group (Fig. 1c). The Shimajiri Group is divided into three formations (from oldest to youngest): the Tomigusuku Formation, Yonabaru Formation, and Shinzato Formation (Natori, 1976).

The Tomigusuku Formation consists of alternating beds of sandstone and mudstone that have been identified as turbidites (Ujiié and Kaneko, 2006). This formation is divided into 13 units (T1 to T13 from youngest to oldest; Fukuta et al., 1970), with the odd numbers corresponding to sandstone-dominated intervals. The basal unit (T13) is dominated by sandstone with basal conglomerates (30 m thick), and is correlated to the Oroku Sandstone Member (Makino and Higuchi, 1967). However, these units were not considered in this study, because they could not be explicitly identified in the studied wells. The Yonabaru Formation and Shinzato Formation are composed mainly of mudstones with thin tuff and sandstone interlayers. The latter formation is distinguished from the former by its more numerous interlayers of tuff. The three formations appear to form a conformable sequence.

2.1. Naha R-1 Well

The Naha R-1 Well was drilled in Ohnoyama Park, southern Okinawa-jima (26°12′13″N, 127°40′36″E, 5 m elevation) and penetrated to 1243 m below the ground surface (mbgs). The interval ranging from 980 mbgs to the base of the well (1243 mbgs) was composed mainly of alternating beds of sandstone and shale, the basement rocks to the Shimajiri Group. On the basis of the lithology and the geologic structure of Okinawa-jima, the beds could be assigned to the middle Eocene Kayo Formation (Hayashi, 1985; Ujiie, 2002). The Tomigusuku Formation, extending above 980 mbgs, unconformably overlay the basement and consisted of alternating beds of sandstone and mudstone. The lithologic units equivalent to the Yonabaru Formation and Shinzato Formation of the Shimajiri Group, the Chinen Formation, and the Ryukyu Group were missing at the drill site.

2.2. Ohsato R-1 Well

The Ohsato R-1 Well was drilled in Nanjo City, southern Okinawa-jima (26°11′3″N, 127°44′24″E, 20 m elevation) and penetrated to 1800 mbgs. The interval from 1547 mbgs to the base of the well (1800 mbgs) was composed of alternating beds of sandstone and shale of the Kayo Formation. The Tomigusuku Formation, which occupied the interval from 1547 to 390 mbgs, consisted of alternating beds of sandstone and mudstone. The