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Disturbances with hiatuses in high-latitude coral reef growth during the Holocene: Correlation with millennial-scale global climate change

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Abstract

Recent studies have reported Holocene millennial-scale climate instability at a global scale. However, the relationship between this climate variability and coral reef growth is still unclear. Field observations and high-precision, *in situ* coral radiocarbon dating of the excavated trench walls of an uplifted middle-to-late Holocene coral reef on Kodakara Island, located in the pathway of the Kuroshio Current in the northwestern Pacific, show evidence of the existence of disturbances with hiatuses in coral reef growth and coral composition differences before and after the disturbances. We found three disconformities in the reef, and the dating results indicate that disturbances with hiatuses in reef growth occurred at approximately 5.9 to 5.8, 4.4 to 4.0, and 3.3 to 3.2 cal yr B.P. The results also indicate that the second and third events were associated with sea-level oscillation. The timing of the disturbances corresponds well with the periods when the Kuroshio Current was relatively weak and was associated with a relatively cold sea surface temperature, which may have enhanced the cold winter Asian monsoons, and with Holocene North Atlantic ice-rafting cold events. The coral composition clearly changed before and after the disturbances, with gradually reduced diversity resulting in a reef dominated by acroporiid coral. These data led to the hypothesis that coral reef growth was interrupted by suborbital millennial-scale global climate change induced by persistent solar activity during the Holocene in high-latitude coral reefs, such as those in the Northwest Pacific, leading to low diversity in the reefs that experienced each disturbance. Our results may provide new insights into theories of past and future coral reef formation worldwide.

Highlights

► Sedimentary discontinuities in high-latitude Holocene raised coral reef rock were discovered. ► Geologic data indicate disturbances with hiatuses in reef growth occurred at approximately 5.9–5.8 ka, 4.4–4.0 ka, 3.3–3.2 ka. ► The events are consistent with events of weakened Kuroshio current linked to Holocene global cooling events. ► The last two events are associated with sea-level oscillations reported elsewhere in the Pacific and Atlantic. ► Changes to low-diversity and acroporiid coral-dominated reefs occurred in many events before human impacts.

Introduction

The Holocene epoch corresponds to the marine isotope stage (MIS) 1. MIS 1 had a relatively warm and stable climate throughout the Quaternary, although there is evidence for unstable millennial-scale climate change characterized by North Atlantic ice-rafted cooling events (e.g., Bond et al., 1997, Bond et al., 2001, deMenocal et al., 2000). Many studies have suggested that modern coral reef deterioration is related to increased anthropogenic activity (e.g., Pandolfi et al., 2003), including climate change such as global warming and ocean acidification (e.g., Kleypas et al., 1999, Hughes et al., 2003). It is still unclear whether or how such millennial-scale climate changes affect reef growth. To accurately evaluate this question, it is necessary to collect precise data on the long-term natural changes in reef growth before the advent of human influence.

To date, a few studies have used geological and paleobiological data from uplifted fossil reefs, such as those near the Huon Peninsula, Papua New Guinea (Pandolfi et al., 2006), Kikai Island in the central Ryukyus (Webster et al., 1998, Abram et al., 2001), to examine how Holocene climate change influenced coral reef growth and whether coral reefs grew continuously before human impact. A well-developed Holocene fossil reef on the Huon Peninsula has provided data on reef growth that was interrupted by natural phenomena before the impact of humans; these particular data were obtained from high-resolution, quantitative geologic measurements of sea cliffs (Pandolfi et al., 2006). Kikai Island also provided a good location for studying the relationship between coral diversity and sea surface temperature (SST) through a detailed survey of paleodiversity in the reefs combined with paleo-SST data reconstructed from fossil corals (Webster et al., 1998, Abram et al., 2001). These studies provide important insights for predicting the impacts of climate changes on future coral reefs. We believe that the relationship between the Holocene millennial-scale climate variability and coral reef growth will also provide insights that are important for assessing future coral reef formation.

Direct observation of continuous reef anatomy is possible because of the uplift of the Holocene fossil reefs on Kodakara Island (29°13′N, 129°19′E) in the northwest Pacific (Fig. 1). On Kodakara Island, three trenches resulting from road construction have cut into middle-to-late Holocene reef flats and spurs perpendicular to the coast, and both the lateral and vertical accretion sequences can be continuously identified. The trench walls provide a rare opportunity for studying continuous reef anatomy, which is difficult to detect in cores, and to confirm the existence of three sedimentological boundaries within the middle-to-late Holocene reef terrace rock. We used high-resolution geological data and absolute accelerator mass spectrometry (AMS) radiocarbon dating to gather the first evidence for the existence of disturbances with hiatuses in reef growth, their significant temporal link to millennial-scale suborbital global climate variability, and the differences in coral composition ratios before and after each disturbance with a hiatus.

Section snippets

Setting

Currently, coral reefs and communities grow in the pathway of the Kuroshio Current and its branches in the Northwest Pacific (Veron and Minchin, 1992). The Kuroshio Current originates in the North Equatorial Current and carries warm, salty water from the western tropical Pacific Ocean along the edge of the continental shelf above the Okinawa Trough northward through the Tokara Strait to the Northwest Pacific (Fig. 1). In the Northwest Pacific around Japan, the lower sea surface temperature…

Field survey

We found excavated trench walls at sites E-1, E-2, and E-3 within Terrace I (Fig. 2), which is composed of reef rock that formed before ~2.6 ka (see Setting). The trench walls, which are up to ~8 m deep and 35 m long across the southern and northern parts of Terrace I (see Fig. 3), show a continuous section of reef development that corresponds with the paleo upper-reef zone (0–8 m). To delineate the excavation profiles accurately, we performed measurements using tape, a 5-m pole, and a level…

E-1 site

The trenches at E-1 are cut out of reef flats and a spur at the southwestern part of Terrace I (Fig. 2). The trenches are up to 2-m deep and 35-m long (Fig. 3). The highest and lowest points are 8.5 m and 5.8 m AMSL, respectively. At E-1, the reef sediment is divided into four reef units by sharp boundaries (Fig. 3). We named these units (from lower to upper) Reef Unit 1 to Reef Unit 4 (RU1 to RU4), and they were confirmed to be of different in age by AMS dating results (Fig. 3 and Table 1).

RU1,…

Interpretation from geologic evidence

To assess the nature of the disturbance boundaries, we first considered whether they may have been caused by SST anomalies, relative sea-level changes, brief storm/cyclone horizons, "death" surfaces associated with previously unknown coseismic uplift events, or earthquake events without uplift but of sufficient size to impact the reefs. The boundaries of the Holocene reef sediments observed on the Huon Peninsula indicate that disturbances in reef growth occurred before the impact of humans (…

Conclusions and perspectives

Many factors, possibly varying across locations, influence coral reef formation (e.g., Kennedy and Woodroffe, 2002, Montaggioni, 2005). The results of this study suggest that the timing of the disturbances with hiatuses in high-latitude coral reef growth, i.e., the timing of the reef growth (Buddemeier and Hopley, 1988), was well-correlated with the millennial-scale global climate changes induced by persistent solar activity and that the paleodiversity changes were well-correlated with the…

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