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Uplift rate of Kitadaito Jima Island on the lithospheric forebulge of the Philippine Sea Plate

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Abstract
Estimates of uplift rates for lithospheric forebulges are needed to understand exact plate motions at plate convergence zones and to delineate the fate of coral reefs atop the forebulges. A carbonate island on a lithospheric forebulge can provide excellent materials for estimating uplift rate because carbonate sediments can be dated and their paleo-water depth determined. We estimated the uplift rate of Kitadaito Jima Island, a carbonate island on the lithospheric forebulge of the Philippine Sea Plate that is subducting beneath the Eurasian Plate. Marine skeletal sands containing pebble-sized bioclasts and filling the concavity of an intertidal erosional notch at an elevation of ~71 m were found near the top of this island. Strontium isotope ages ranging from 1.78 to 2.01 Ma with an average of 1.89 Ma (standard deviation = 0.07 Ma) were obtained from these deposits. As global sea level at 1.89 Ma was ~21 m lower than the present, the mean uplift rate was estimated at ~49 m/million years (Myr) with a compounded uncertainty of ±2.6 m/Myr. This rate is comparable to, or up to ~140 m/Myr less than, rates reported from other Indo-Pacific carbonate islands in similar tectonic settings. This study illustrates how contemporary Sr isotope age models and careful considerations of limestone sample depositional depths can yield more accurate and precise uplift rates of modern forearc bulges than possible in many older studies.

Keywords Kitadaito Jima, Lithospheric forebulge, Philippine Sea Plate, Uplift rate, Sr isotope stratigraphy

1 Introduction

The Daito Islands (Daito Shoto Islands; Fig. 1) is an archipelago composed of three isolated carbonate islands, Kitadaito Jima Island, and Minamidaito Jima Island on the Daito Ridge (Daito Kairei Ridge) and Okidaito Jima Island on the Oki-Daito Ridge (Oki-daito Kairei Ridge). The three islands are located in the northwestern Philippine Sea and are well-known examples of uplifted atolls (Flint et al. 1953; Schlanger 1965). The Daito Islands lie on the lithospheric forebulge of the Philippine Sea Plate, which subducts beneath the Eurasian Plate. Kitadaito Jima Island and Minamidaito Jima Island have been uplifting since the Pliocene (5.5 ± 1.5 Ma; Ohde and Elderfield 1992). The uplift rate of the two islands was estimated by prior workers based on the age and elevation of reef deposits that formed in the last interglacial period (Ota et al. 1991; Ota and Omura 1992) and the modeling of a subsidence-uplift curve (Ohde and Elderfield 1992). But a more rigorous estimate is needed, not only to delineate the final stage of geologic history of the

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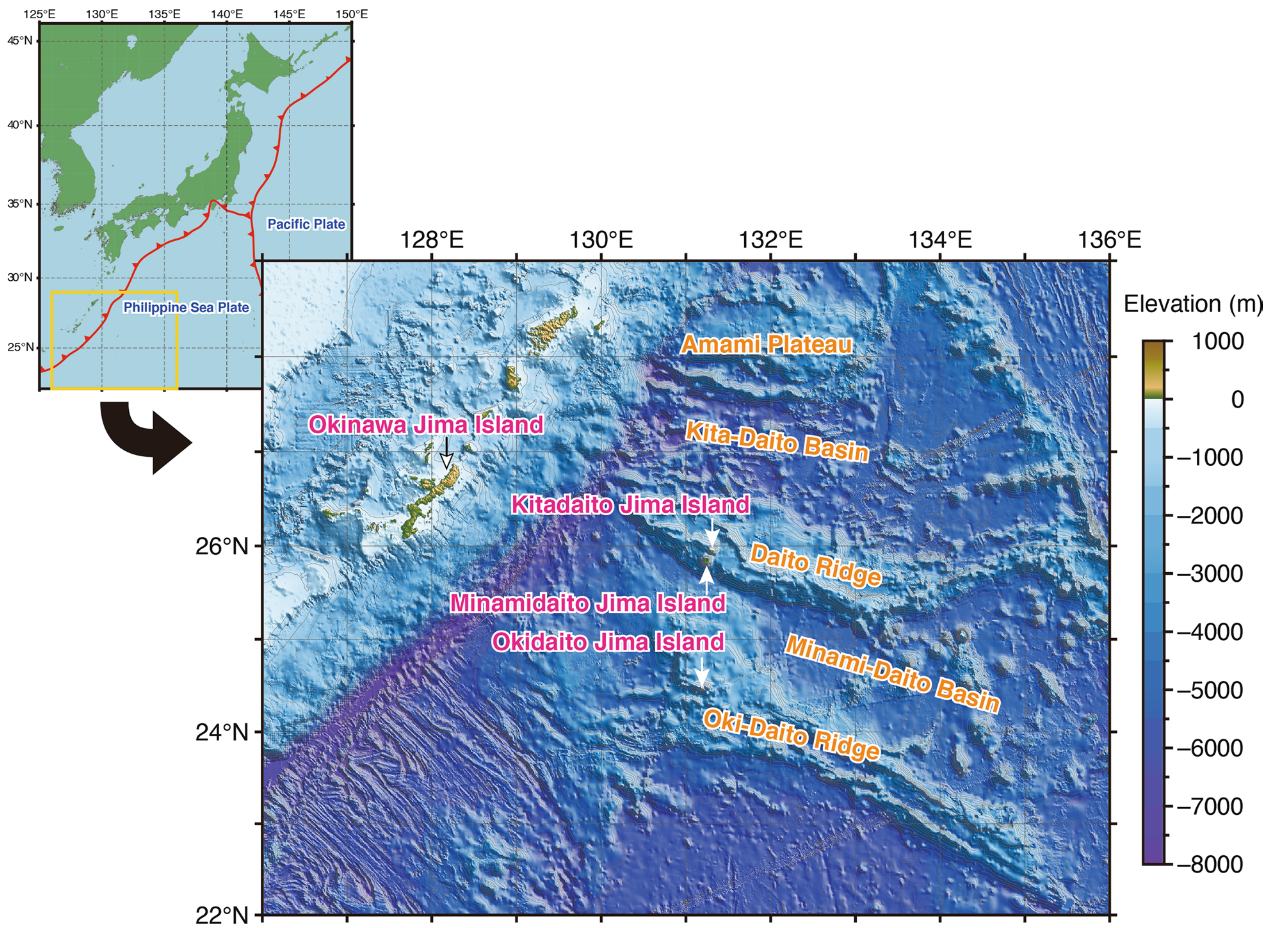

Fig. 1 Location of Kitadaito Jima and Minamidaito Jima atop the Daito Ridge of the Philippine Sea plate. Elevation and depth data from Lindquist et al. (2004) and Iwasaki et al. (2015)

uplifted atolls atop this plate, including Kitadaito Jima Island and Minamidaito Jima Island, but also to understand the nature of deflection of oceanic lithosphere prior to subduction.

This paper aims to provide an accurate mean uplift rate of Kitadaito Jima Island (25°55.7′–57.7′N, 131°17.0′–19.9′E; Fig. 1) for the last ~ 2 million years based on Sr isotope ages of a carbonate sediment deposited in an ancient intertidal erosional notch. Geographical names basically follow Gazetteer of Japan 2007 (Geographical Survey Institute of Japan and Japan Coast Guard 2007). However, in the following sections, the word "Island" will be removed from the official name of the island for a concise description. For example, Kitadaito Jima Island is described as Kitadaito Jima.

2 Geologic setting

Kitadaito Jima and Minamidaito Jima are situated on the Daito Ridge and Okidaito Jima lies on the Oki-Daito Ridge. The two ridges are remnants of an older crust (Hall 2002) or ancient island-arc system (Tokuyama et al. 1980, 1986). Honza and Fujioka (2004) identified two major volcanic events in the area covering the Amami Plateau, the Kita-Daito Basin, the Daito Ridge, the Minami-Daito Basin, and the Oki-Daito Ridge (Fig. 1), which occurred during the Cretaceous to Early Palaeocene (80–60 Ma) and during the Late Palaeocene to Eocene (60–49 Ma). This is supported by the occurrence of Cretaceous nannofossils (Okada 1980) from the Minami Daito Basin and late Eocene to earliest Oligocene shallow-water carbonates from atop the ridges (Takayanagi et al. 2007, 2012).

Kitadaito Jima is semi-triangular in shape (apex to the south) and is about 3.7 km wide from north to south and about 4.9 km wide from east to west (Fig. 2). Geomorphologically, it consists of a peripheral rim and an interior basin. The peripheral rim is approximately 0.5–1.8 km wide and mostly ranges in elevation from 10 to 50 m with the highest point (74 m in elevation) at Kogane-yama (Fig. 2). The peripheral ridge is composed of inner and outer ridges; the former is wider and higher

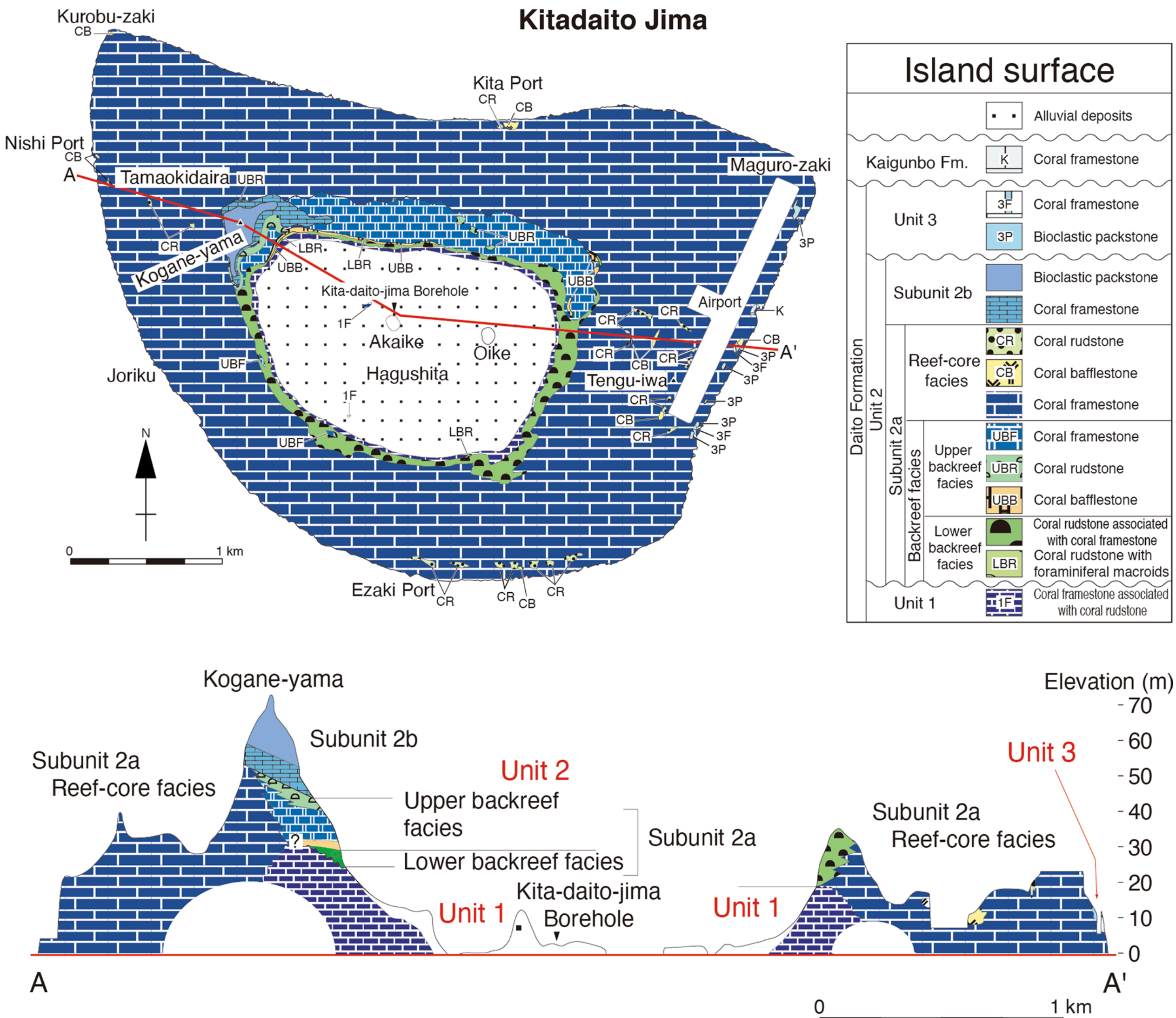

Fig. 2 Geologic map and east–west cross section of Kitadaito Jima (modified from Nambu et al. 2003). Samples for this study come from the Lighthouse Outcrop atop Kogane-yama, the highest point on the island

than the latter. The interior basin is about 1.4 km wide from north to south and about 2.1 km wide from east to west, is < 20 m in elevation, and is surrounded by up to 50 m-high bluffs and slopes. Because of such geomorphologic similarity to modern atolls, Kitadaito Jima has been regarded as an elevated atoll (e.g., Flint et al. 1953; Schlanger 1965). It has also been argued in some studies that erosion is a more critical factor in forming the atoll-like morphology (e.g., Flint et al. 1959; Purdy and Winterer 2001).

Carbonates out cropping on the island comprise two basic stratigraphic units: the Daito and Kaigunbo formations (Nambu et al. 2003). Almost all the carbonate rocks on the island surface are pervasively dolomitized (Suzuki et al. 2006) and can be assigned to the older Daito Formation. The younger undolomitized Kaigunbo Formation, composed mainly of coral framestone, occurs as an abutment on a sea cliff of the eastern coast at elevations less than 11 m (Fig. 2; Nambu et al. 2003).

The Daito Formation is lithologically divisible into three units (1, 2, and 3, in ascending order: Nambu et al. 2003). Unit 1 is composed mainly of framestone with abundant massive corals and exposed in the interior basin. Unit 2 unconformably overlies Unit 1 and is divided into two subunits: lower Subunit 2a and upper Subunit 2b. Subunit 2a consists of reef-core facies and backreef facies. The reef-core facies, which constitutes the main body of the peripheral rim, is represented by framestone accompanied by bafflestone and rudstone. The backreef facies, cropping out at the cliffs lining the interior basin, is divisible into the lower and upper backreef facies. The lower backreef facies is composed mainly of rudstone; the upper backreef facies is chiefly made up of framestone and bafflestone, both of which contain *Halimeda* segments. Subunit 2b is distributed around Kogane-yama from 32.5 in elevation to the summit of this hill at 74 m, near which the studied outcrop, Light House Outcrop (Fig. 3), is located and conformably overlies the rudstone of the upper backreef facies of subunit 2a. Subunit 2b consists mainly of coral framestone and overlying bioclastic packstone, both of which are much less dolomitized (dolomite content < 15 wt%) than the reef deposits of the other stratigraphic units/subunit of the Daito Formation (Suzuki et al. 2006). The framestone contains autochthonous and allochthonous, hemispherical hermatypic corals up to 20 cm in diameter. Nongeniculate coralline algal crusts are rare. *Halimeda* segments are locally present in the lower part of the framestone. The

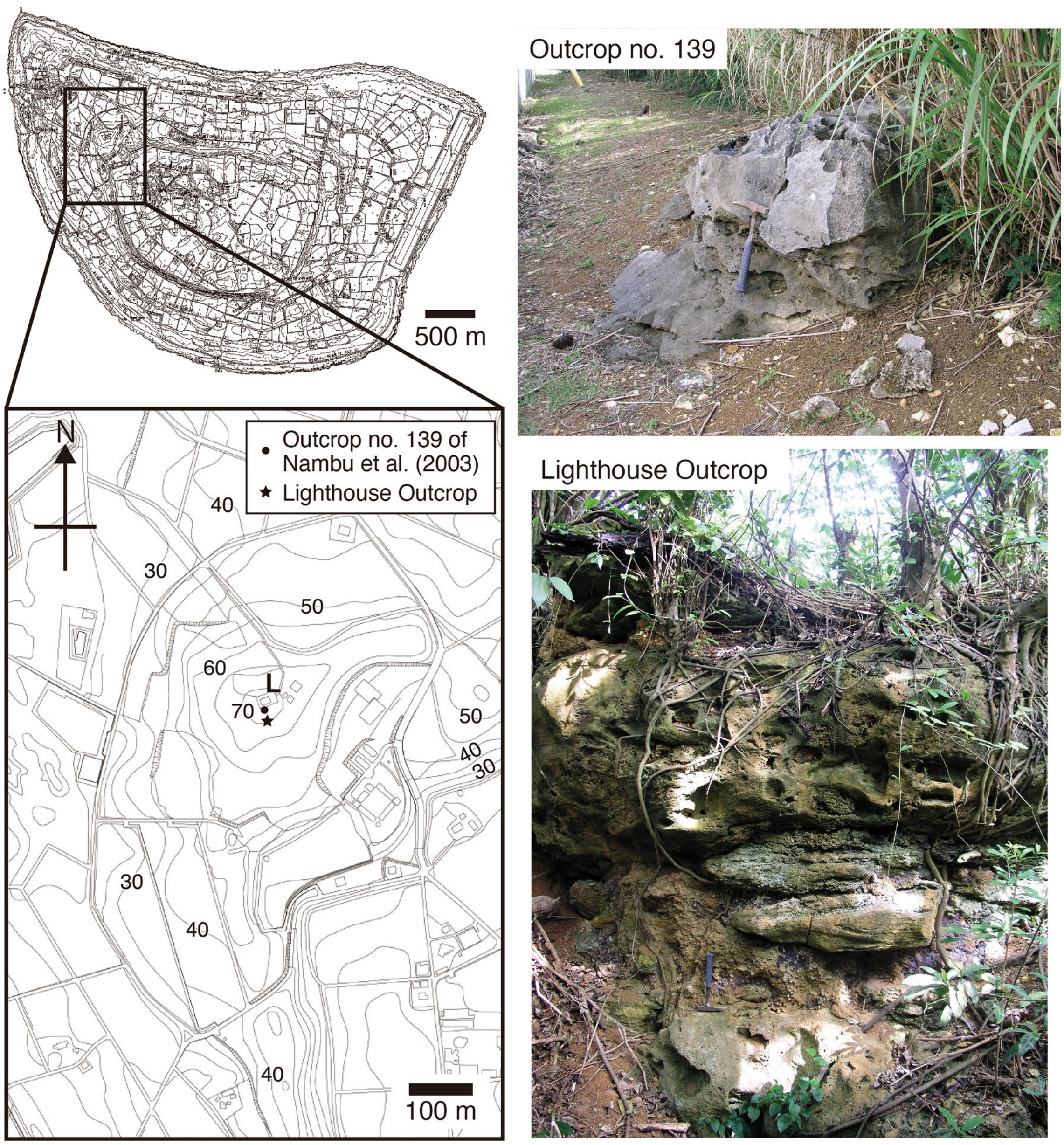

Fig. 3 Locations and photographs of the Lighthouse Outcrop and outcrop no. 139 of Nambu et al. (2003), both of which occur near the top of Kogane-yama

packstone is generally massive, displaying no stratification but locally changes into cross-bedded grainstone. The packstone consists mainly of medium to very coarse sand-sized bioclasts of nongeniculate coralline algae, *Halimeda*, and benthic foraminifers, accompanied by mollusks, bivalves, and encrusting foraminifers. Unit 3 crops out sporadically on the eastern coast at elevations of 10–20 m, and it unconformably overlies the reef-core facies of Subunit 2a. This unit consists of cross-bedded bioclastic packstone associated with framestone.

3 Methods/experimental

Limestone samples (K1, K2, and K3) were collected from within and above an erosional notch (described below) at the Lighthouse Outcrop near the summit of Kogane-yama (Figs. 3, 4). The samples were split into 1- to 2 cm-thick slices for lithological analyses, thin section petrography, X-ray diffraction (XRD) analyses, and Sr isotope measurements. Thin sections of all slices were prepared for identifying carbonate microfacies. Classification of the limestones followed Dunham (1962) and Embry and Klovan (1971). Some thin sections were stained with alizarin red-S to distinguish calcite from dolomite following the method of Dickson (1966).

Sr isotope measurements were taken for 14 subsamples from 11 different slices of two samples (K1 and K3; Table 1). One subsample was taken from eight of the different slices of K1 and K3 samples, and two subsamples were taken from different parts of three other slices (subsamples K1-1-1 and K1-1-2 from slice K1-1, subsamples K1-2-1 and K1-2-2 from slice K1-2, and subsamples K3-1-1 and K3-1-2 from slice K3-1). Before Sr isotope measurements were made, XRD analyses using the methodology described in Suzuki et al. (2006) were performed to confirm that all subsamples were pure calcite. Crushed limestone subsamples were washed in an ultrasonic

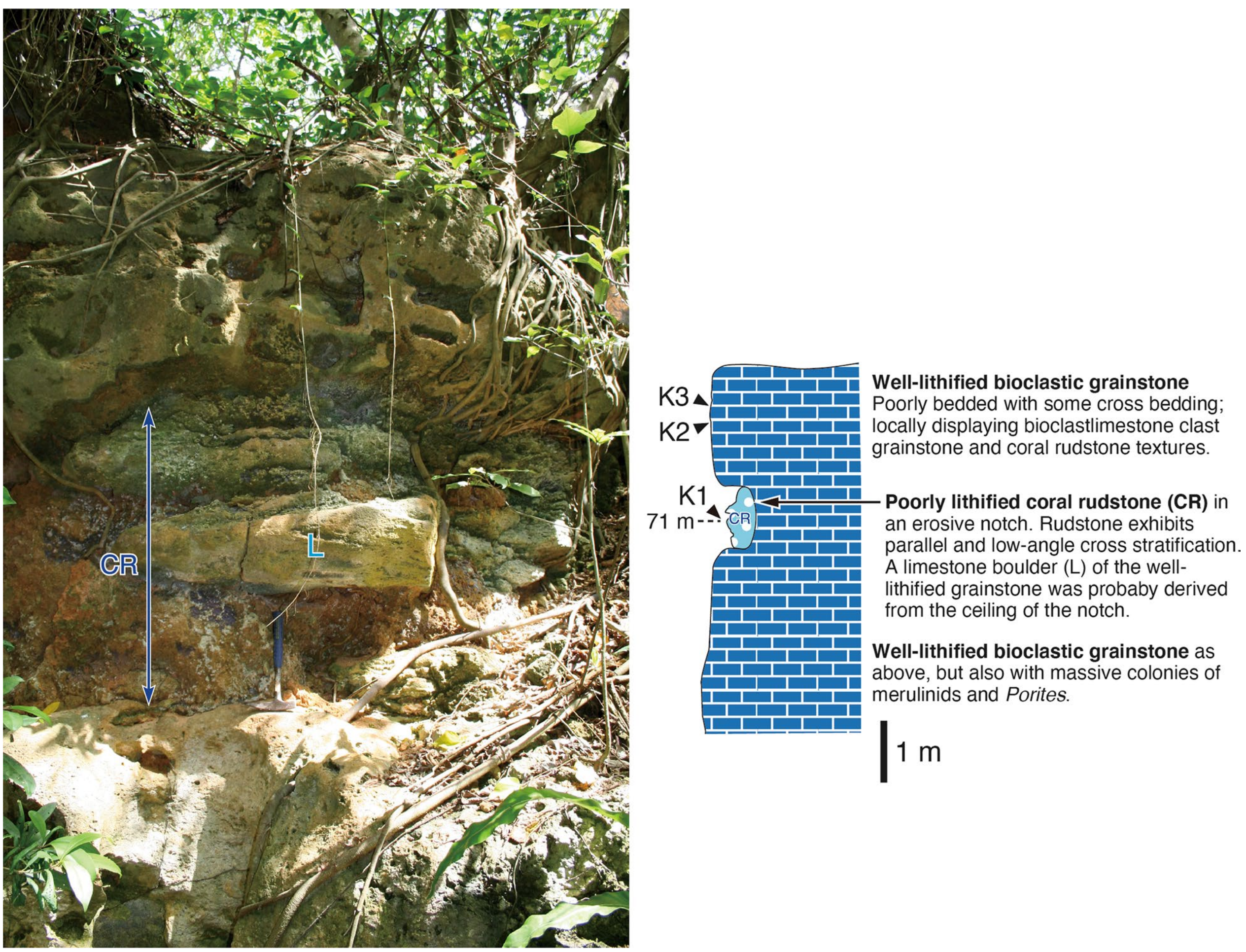

Fig. 4 Photograph of the middle to upper 2.5 m of the Lighthouse Outcrop and columnar section of the entire 6 m-thick Lighthouse Outcrop. Entire field of view in the photo is 2.2 m laterally and 3.3 m vertically with the hammer (30 cm high) for scale; 1 m scale bar is for the columnar section. K1, K2, and K3 refer to samples collected for this study

Table 1 Sr isotope ratios and resultant calibrated ages of samples from the Lighthouse Outcrop

Sample no.	Subsample ID	$^{87}Sr/^{86}Sr$	Error (2SE)	Calibrated $^{87}Sr/^{86}Sr$	Age (Ma)	95% Confidence limit (Ma)
K1	K1-1-1	0.7090970	0.0000066	0.7090910	1.823	±0.133
	K1-1-2	0.7090962	0.0000074	0.7090902	1.880	±0.131
	K1-2-1	0.7090969	0.0000068	0.7090909	1.860	±0.130
	K1-2-2	0.7090955	0.0000064	0.7090895	1.903	±0.131
	K1-3	0.7090919	0.0000084	0.7090859	2.014	±0.122
	K1-4	0.7090935	0.0000066	0.7090875	1.965	±0.126
	K1-5	0.7090992	0.0000074	0.7090932	1.779	±0.135
K3	K3-1-1	0.7090693	0.0000074	0.7090633	2.822	±0.178
	K3-1-2	0.7090691	0.0000072	0.7090631	2.835	±0.174
	K3-2	0.7090799	0.0000062	0.7090739	2.362	±0.125
	K3-3	0.7090732	0.0000062	0.7090672	2.604	±0.145
	K3-4	0.7090696	0.0000062	0.7090636	2.801	±0.174
	K3-5	0.7090651	0.0000070	0.7090591	3.138	±0.264
	K3-6	0.7090732	0.0000066	0.7090672	2.606	±0.145

Ages and confidence limits are based on the calibration curve of McArthur et al. (2020)

cleaner with ultrapure water. Then 60 mg or more of each desalinized subsample was dissolved in 6 M hydrochloric acid, after removing any insoluble residue, dissolved in 6 M hydrochloric acid. After the removal of any insoluble residue, the solutions were evaporated to dryness and dissolved in 3 M nitric acid. Strontium in the nitric acid solutions was then separated and purified using an ion-exchange column with 0.2 mL Sr resin (Eichrom Technologies, USA). Strontium isotope ratios were measured with a TRITON mass-spectrometer (Thermo Scientific, Bremen, Germany) at Kochi Institute for Core Sample Research, JAMSTEC. During the period of this study, 13 separate analyses of a Sr-standard (NIST SRM 987) gave an average $^{87}Sr/^{86}Sr$ ratio of 0.710254 ± 0.000005 (2SD). The $^{87}Sr/^{86}Sr$ ratios obtained for natural samples were corrected for instrumental bias to an NIST SRM 987 value of 0.710248 (McArthur et al 2020). Numerical ages were determined by a comparison between the measured $^{87}Sr/^{86}Sr$ values and the global Sr isotope age calibration curve of McArthur et al. (2020).

4 Results

4.1 Lithological analysis

A distinctive notch cuts into well-lithified limestones at the ~ 6 m-high Lighthouse Outcrop (Fig. 4). The notch forms a depression that has a maximum height of 1.2 m and a depth of at least 0.5 m from the outcrop's surface (total depth is unknown as the back of the notch is not exposed). The lateral extent of the notch is also unknown. Figure 4 shows a front view of ~ 2.5 m of rock that comprises the middle to upper parts of the Lighthouse Outcrop. A well-lithified limestone exists at the top and bottom, and coarse-grained deposits occur between them. The elevation of the midpoint of the notch is ~ 71 m. The well-lithified limestones are primarily grainstones, but the notch itself contains the remnants of a more poorly lithified rudstone. As such the poorly lithified rudstone overlies the well-lithified limestone that forms the floor of the notch, underlies the well-lithified limestone that forms the ceiling of the notch, and presumably lies adjacent to the well-lithified limestone that forms the back of the notch (Fig. 4). The two rock types not only differ in lithology and in their degree of lithification, but also in their constituents.

The well-lithified limestone wall of the outcrop is bioclastic grainstone. The grainstone below the notch contains no internal laminations but does contain allochthonous massive coral colonies (e.g., merulinids and *Porites*). The grainstone above the notch is poorly stratified, but does exhibit some cross-bedding. Locally it contains bioclast limestone-clast grainstone and coral rudstone textures. Within the notch, the presence or absence of a transition or sharp boundary between the two grainstone variants cannot be observed because it is covered by the notch-fill rudstone. However, no sharp boundary (e.g., bedding plane) is apparent in the laterally adjacent but poorly exposed limestones around the summit of Kogane-yama at the same elevation as the notch.

The bioclastic grainstone is generally well-sorted and composed mainly of bioclasts of corals and geniculate coralline algae (Figs. 4, 5A, B). Molluscs and large benthic foraminifers are subordinate. Echinoids, *Halimeda*,

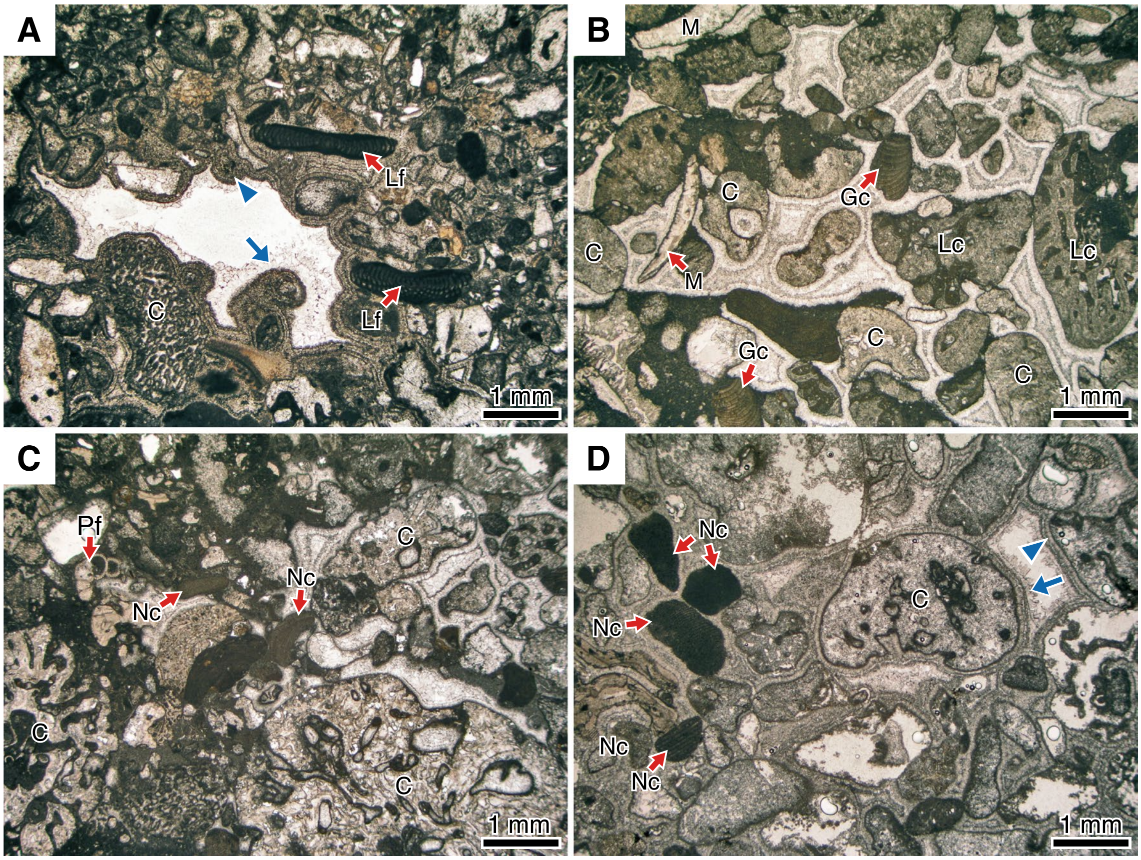

Fig. 5 Photomicrographs of thin sections of limestones from the Lighthouse Outcrop. Blue arrows and arrowheads indicate isopachous bladed cement and multiple generations of isopachous cements that are grayish under transmitted light, respectively. *C* coral, *Gc* geniculate coralline alga, *Lc* limestone clast, *Lf* larger foraminifer, *M* mollusc, *Nc* nongeniculate coralline algae, *Pf* planktic foraminifer. **A** Bioclastic grainstone that constitutes the upper interval of the sampled limestone wall (sample K3). **B** Bioclast limestone-clast grainstone with common limestone clasts derived from coral-bearing limestones (sample K2). **C** Abundant coral fragments in the part showing a coral rudstone texture (sample K2). **D** Bioclatic grainstone matrix of the coral rudstone in the erosional cavity in the limestone wall (sample K1)

benthic foraminifers, and limestone clasts constitute minor components. Skeletal grains are rimmed by multiple generations of bladed isopachous cements that are grayish in plane polarized transmitted light. Blocky equant cement dominates the remaining intergranular pore space, although micrite (carbonate mud) occurs rarely in some intergranular space. Sample K2 (Figs. 4, 5C), with a coral rudstone texture, consists of granule- to pebble-sized coral clasts in a matrix of packstone/grainstone with abundant corals and coralline algae.

The Lighthouse Outcrop is an outcrop discovered after the publication of Nambu et al. (2003) and is different from outcrop no. 139 (altitude of 72 to 74 m) near the summit of Kogane-yama in their paper (Fig. 3). Reef-derived deposits, composed mainly, but not exclusively, of partly dolomitized bioclastic packstone, extend around the upper ~ 20 m of Kogane-yama. They were assigned to Subunit 2b of the Daito Formation by Nambu et al. (2003; Fig. 2). The presence of minor amounts of intergranular micrite in some thin sections of the well-lithified bioclastic grainstone at the Lighthouse Outcrop suggests that the grainstone (altitude of 67.5–73.5 m) is within the range of lithologic variation of Subunit 2b. Thus, the limestones at the Lighthouse Outcrop probably correspond to the uppermost horizon of Subunit 2b of the Daito Formation. The alternative is that those few several meters of grainstones are a previously undefined lithostratigraphic unit that overlies Subunit 2b near the summit of Kogane-yama. This alternative, however, is unlikely since the nearby outcrop no. 139 of Nambu et al. (2003) is a bioclastic packstone.

The poorly lithified rudstone within the notch's depression is composed of coral rudstone with parallel and low-angle cross-stratification (sample K1; Fig. 4). This rudstone is less consolidated compared to the overlying and underlying grainstones of the limestone wall. Limestone boulders (maximum size = 1.0 m wide, 35 cm high, and > 30 cm deep) of cross-bedded bioclastic grainstone occurs in this rudstone (Fig. 4). These boulders are likely derived from the overlying limestone wall because of the similarities in lithology and sedimentary structure (cross-bedded bioclastic grainstone). The rudstone is composed mainly of up to cobble-sized (mostly < 10 mm in diameter) fragments of branching corals. The matrix consists of bioclastic grainstone with abundant corals and nongeniculate coralline algae (Fig. 5D). Molluscs and limestone clasts are subordinate. Echinoids and larger foraminifers are very rare. Some presumably aragonitic bioclasts have been dissolved, which makes it impossible to identify their origin. Grains in the rudstone are fringed by an isopachous cement and isopachous bladed and/or blocky equant cements. Morphology and occurrence of the former indicate it originally may have been isopachous acicular marine cement. Moldic pores are partly to completely fill with blocky equant cements.

4.2 XRD analysis and Sr isotope measurement

XRD analysis revealed that samples K1 (less lithified rudstone within the notch) and K3 (upper interval of well-lithified wall) are composed exclusively of calcite and sample K2 (upper interval of well-lithified wall) contains a small amount of dolomite (~ 11 wt.%) and aragonite (~ 7 wt.%). Observation of thin sections stained with Alizarin Red S indicates that some bioclasts are partly dolomitized.

Sr isotope composition of bulk carbonate in the two pure limestone samples (K1 and K3) were measured (Table 1). Sample K1 exhibits a range in Sr isotope ratio from 0.709086 to 0.709093, which equates to ages of 1.78 to 2.01 Ma (average = 1.89, standard error = 0.012, n = 7), which is Early Pleistocene (late Gelasian to earliest Calabrian). Sample K3 yielded $^{87}Sr/^{86}Sr$ values ranging from 0.709059 to 0.709074, which equates to ages of 2.36 to 3.13 Ma (average = 2.76, standard error = 0.037, n = 7) in the late Pliocene (late Piacenzian) to earliest Pleistocene (earliest Gelasian).

5 Discussion

5.1 Origin of the notch in the Lighthouse Outcrop

The origin of the notch is critical to using the age of the sediments within it to determine an uplift rate for Kitadaito Jima. The notch is clearly an erosional feature as it cuts into the older well-lithified grainstones and is filled with sediments restricted to just the notch. In addition, those sediments are younger, on average, by approximately 0.88 Myr than the overlying limestones.

The first potential origin is that the notch is a preserved structural notch (sensu Pirazzoli 1986, 1996) formed by differential erosion of a weaker (less lithified) rock layer between two stronger (more lithified) layers. However, this is an unlikely explanation due to a paucity of lithologic variation within the well-lithified limestones that make up all of Subunit 2b in general, and the wall rock surrounding the notch at the Lighthouse Outcrop in particular. The rocks in Subunit 2b are all grain-supported limestones and dolomitic limestones that are either unbedded or poorly bedded (Nambu et al. 2003). There is no significant lithologic variability, such as shales or clay-rich carbonate mudstones in Subunit 2b of the Daito Formation that could be a "weak" layer that leads to differential erosion and formation of a structural notch. At the Lighthouse Outcrop, the textural uniformity of the grainstones forming the well-lithified limestone wall rock also does not support an interpretation of differential erosion to form a 1.2 m high and at least a 0.5 m deep notch.

The second option for the notch's origin is that it is an exhumed intrastratal dissolution feature—a cave—originally formed during subaerial exposure and the influx of meteoric water. The absence of a continuous vertical dissolution void through the overlying limestone indicates the notch is not a dissolution fissure. Rather, if a cave, that cave would most likely have formed along the water table of a freshwater lens or at the interface of the water table and the freshwater–seawater mixing zone at the margin of the lens (i.e., a flank margin cave). In either case, the feature probably formed below an island that was no wider than the maximum width of the peripheral ridge around Kogane-yama (~ 1.8 km). On such narrow islands, water tables are typically within tens of centimeters of mean sea level due to low relief and tidal dissipation of the freshwater lens (Budd and Vacher 1991). If a water table cave, the notch is thus a marker of a ~ 0 m paleoelevation.

Arguments against a cave origin are multifold. First, the walls of the notch contain no precipitates, such as small stalagmites, stalactites, or cave wall popcorn that would be compatible with a meteoric cave. No evidence of an overlying soil zone (the source of CO_2 to drive the dissolution) or terra rosa infiltrated into the void was noted. Nor have paleosols or cave features been described at the top of Subunit 2b anywhere on Kotadaito Jima by any prior workers, albeit the lateral extent of remaining uppermost Subunit 2b rocks is limited. Finally, none of the clasts or blocks in the notch infill showed evidence of dissolution (e.g., dissolution pits, scalloped edges) or calcrete coatings on their surfaces.

The third option, which is interpreted to be the most likely, is that the notch is a preserved intertidal notch. Such notches can be formed by wave-induced abrasion (Trenhaile 2015) or by intertidal bioerosion, particularly on limestone coasts (Pirazzoli 1996). In either case, the maximum depth of erosion, known as the retreat point, typically reflects the position of mean sea level (Pirazzoli

1996). The exact location of that retreat point depends on wave energy (Pirazzoli 1996; Trenhaile 2015), with that point being below the center of the notch in high wave-energy settings. As the retreat point is not visible in the rudstone-filled notch at the Lighthouse Outcrop, the elevation of the midpoint of the notch (71 m) is assumed to reasonably approximate the retreat point and mean sea level with uncertainty of a few 10s of centimeters possible. As notches are erosional features, the notch-fill sediment must be younger, with how much younger a critical question. Holocene notches in limestones are overwhelmingly empty, be they at mean sea level or slightly raised or lowered by a few meters due to active tectonics. However, there are examples of marine isotope stage (MIS) 5e notches that are partially to completely infilled by carbonate beach sands (e.g., Sisma-Ventura et al. 2017; Godefroid and Kindler 2013, 2016). In both cases, the notch is interpreted to have formed during the early portion of the MIS 5e high stand, with the infill occurring a few thousands of years later during the late high stand, but prior to the subsequent sea level fall. In the context of the Lighthouse Outcrop notch, a few thousand years between notch formation and subsequent fill is within the standard deviation of the sediment infill's age (1.89 ± 0.11 Ma). In that time frame, the timing between erosion and sedimentary infill is short and thus it is not unreasonable to consider both sediments and the notch to have essentially formed at sea level (~ 0 m) at 1.89 ± 0.11 Ma. The alternative that the notch-fill rudstone is a subtidal deposit requires Early Pleistocene reef deposits at a higher elevation, but there is no evidence for such deposits anywhere on Kitadaito Jima (Fig. 2).

5.2 Uplift rate of Kitadaito Jima

Globally, sea level at 1.89 Ma when the intertidal notch-fill rudstone was deposited was ~ 21 m lower than the present (Miller et al. 2020), thus a mean uplift rate of ~ 49 m/Myr is calculated (uplift from –21 m to 71 m) for the last 1.89 Myr. Uncertainty in that rate is a function of uncertainty in both the age of the rudstone and in the total elevation change due to uplift. For the age, uncertainty is represented by the standard deviation of the seven K1 ages (0.0746 Ma). For elevation change, both the –21 and + 71 m values contain uncertainty. Between the maximum and minimum Sr isotope ages of K1 subsamples, sea level was 23 to 21 m lower than the present (Miller et al. 2020), which is an uncertainty of 2 m. The maximum retreat point of the intertidal notch might also not correspond to the notch's current midpoint at 71 m. Assuming the true retreat point is anywhere between the base and top of the notch, an additional 1.2 m of uncertainty is added to generate a combined uncertainty of 3.2 m in the total elevation change. The standard equation for the propagation of uncertainty during division (www.statisticshowto.com/statistics-basics/error-propagation), as translated for this specific case is:

$$\frac{\text{compounded uncertainty}}{\text{mean rate}} = \sqrt{\left(\frac{\text{uncertainty in elevation change}}{\text{total elevation change}}\right)^2 + \left(\frac{\text{standard deviation in age}}{\text{mean age}}\right)^2}$$

Substituting the appropriate values yields a compound uncertainty of ± 2.6 m/Myr for the uplift rate.

There are two previous studies that estimated the uplift rate of Kitadaito Jima and Minamidaito Jima (both on Diato Ridge, Fig. 1), and their estimates are included in Table 2. First, Ota et al. (1991) and Ota and Omura (1992) dated the last interglacial coral reefs on these islands (Kaigunbo Formation) at 0.12–0.13 Ma by uranium series isotopes. The elevations of notches and benches associated with these last interglacial corals are ~ 10 m on Kitadaito Jima and 12.7 m on Minamidaito Jima and sea level at the last interglacial was about 6 m above present sea level (e.g., Bloom et al. 1974; Stirling et al. 1998). Thus, late Pleistocene uplift rates were estimated at ~ 30 m/Myr for Kitadaito Jima and ~ 49 m/Myr for Minamidaito Jima (Ota et al. 1991; Ota and Omura 1992). Subsequently, Ohde and Elderfield (1992) established a Sr isotope stratigraphy of reef carbonates in a 431.67 m-deep borehole (Kita-daito-jima Borehole; Fig. 2) drilled on Kitadaito Jima in 1934 and 1936 (Hanzawa 1940; Iryu et al. 2010) and estimated an average uplift rate of 10–35 m/Myr over the last ca. 4–7 Myr based on a modeled subsidence-uplift curve. They also developed rate estimates by three additional lines of evidence:

1. The upper limit of occurrence of last interglacial corals is 8.1 m for Kitadaito Jima and 9.6 m for Minamidaito Jima (Ota et al. 1991; Ota and Omura 1992), and thus, minimum uplift rates for the last 0.12–0.13 Myr were 16–18 m/Myr for Kitadaito Jima and 28–30 m/Myr for Minamidaito Jima.
2. They stated that unpublished Sr isotope ages on calcites from island-surface samples of Minamidaito Jima were 0.7 (+ 0.7/− 0.4) Ma at 15.9 m above sea level and 0.9 (+ 0.4/− 0.3) Ma at 17.1 m, giving uplift rates of 19–23 m/Myr for the last approximately 0.7–0.9 Myr.

Table 2 Comparison of estimated uplift rates for Kitadaito Jima and Minamidaito Jima in this and previous studies

	Method of rate determination	Sample elevation (m)	Paleo-water depth of sample(s)	Age		Sea level at the average age (m)	Average uplift rate (m/Myr)	Remarks	References
				Ma	Method				
Kitadaito Jima	Coral date and sample elevation	~ 10 (Raised surf bench)	Near the intertidal zone	0.123 (average)	$^{230}Th/^{234}U$	6	33	The average age of corals collected at < 8.1 m elevation was regarded as the formation age of the raised surf bench at ~ 10 m elevation. Those corals were inferred to have lived near the intertidal zone	Ota et al. (1991), Ota and Omura (1992)
	Modeled subsidence–uplift curve			ca. 4–7			10–35	The rate is not reproduced from the various values given in their paper	Ohde and Elderfield (1992)
	Coral date and sample elevation	8.1 (The upper limit of occurrence of corals)	Not considered	0.12–0.13	$^{230}Th/^{234}U$	6	16–18	Paleodepth at which coral lived is not considered Coral ages of Ota et al. (1991) were cited	Ohde and Elderfield (1992)
	Elevation contrasts between Kitadaito Jima and Okidaito Jima			2			22		Ohde and Elderfield (1992)
	Sr-isotope age of a deposit filling an intertidal erosional notch and its elevation	71	Intertidal	1.89	$^{87}Sr/^{86}Sr$	− 21	49		This study
Minamidaito Jima	Coral date and sample elevation	12.7 (Raised surf bench)	Near the intertidal zone	0.123 (average)	$^{230}Th/^{234}U$	6	54	The average age of corals collected at < 11 m elevation was regarded as the formation age of the raised surf bench at 12.7 m elevation. Those corals were inferred to have lived near the intertidal zone	Ota et al. (1991), Ota and Omura (1992)
	Coral date and sample elevation	9.6 (The upper limit of occurrence of corals)	Not considered	0.12–0.13		6	28–30	Paleodepth at which coral lived is not considered Coral ages of Ota et al. (1991) were cited	Ohde and Elderfield (1992)
	Sr isotope ages of reef deposits (non-dolomitized island-surface samples) and sample elevation	15.9 17.1	Not considered	0.7 (+ 0.7/− 0.4) 0.9 (+ 0.4/− 0.3)	$^{87}Sr/^{86}Sr$	Not considered	23 (11–53) 19 (13–29)	For revised uplift rates, see discussion and Table 3	Ohde and Elderfield (1992)

3. An average rate for the Pleistocene was obtained from a comparison between the highest elevation on Kitadaito Jima (currently 74 m above sea level) and Okidaito Jima (currently 31 m above sea level), which is also migrating toward the Ryukyu Trench at the subduction rate of ~ 5.4 cm/yr) but ~ 100 km farther east (Fig. l). The difference between the two islands suggests a minimum uplift of 43 m over somewhat less than 2 Myr at a rate of 22 m/Myr.

5.3 Accurate and precise estimations of uplift rate

The data in Table 2 show a wide range (10–50 m/Myr) of estimated uplift rates for Kitadaito Jima and Minamidaito Jima, which raise the question, are all those values robust and realistic? Various estimates reflect four types of data: age-dated Pleistocene corals on the island surface, calculations based on a modeled subsidence-uplift curve, topographic differences between islands at different distances from the Ryukyu Trench, and age-dated intertidal deposits at the highest point on Kitadaito Jima (this study). The strengths and weaknesses of each are considered below.

There are a number of issues with respect to the uplift rates of prior workers that are based on the elevation and ages of the Pleistocene corals. The first uncertainty is the estimated paleo-water depth of the last interglacial corals that have been dated. Last interglacial paleo-water depths were not well constrained by Ota et al. (1991) and Ota and Omura (1992) and paleo-water depths were not even considered in approaches (1) and (2) of Ohde and Elderfiled (1992). Yet a few meters of uncertainty in depositional depth is significant given that the corals/deposits in question are now only 8–17 m above present sea level (Table 2). This uncertainty alone can explain the wide variation in uplift rates over the last 0.125 Myr reported in Table 2 for these islands. Second, some of the correlations of the notches and benches to the last interglacial corals by Ota et al. (1991) and Ota and Omura (1992) have not been confirmed by our field survey, making it difficult to evaluate the estimated current elevations of their samples.

Another issue is uncertainty in the ages of the corals, particularly the Lower Pleistocene corals from Minamidaito Jima used by Ohde and Elderfield (1992) for their approach (ii). The Sr isotope age model used by those workers has been replaced by a succession of age models that are based on far more analyses (e.g., McArthur and Howarth 2012; McArthur et al. 2020) and are far more accurate and precise than age models available to Ohde and Elderfield (1992). Although exact Sr isotope ratios for the Lower Pleistocene corals on Minamidaito Jima were not reported by Ohde and Elderfield's (1992), we worked backward from their reported ages and their age model to estimate the measured ratios, added 0.000016 to normalize for Ohde and Elderfield's reported value of NBS SRM 987 (as NIST 987) relative to that standard's known value, and then determined ages based on McArthur et al. (2020). The results suggest those corals are 0.261 to 0.281 Myr older than estimated by Ohde and Elderfield (1992). Accounting for absolute sea level at 0.98 and 1.16 Ma (−33 m and −27 m, respectively (Miller et al. 2020) and assuming a minimum depositional water depth for the corals of ~ 3 m, the resultant uplift rates are revised upward to 38–50 m/Myr (Table 3).

The values estimated by modeling the subsidence-uplift curve and topographic difference between Kitadaito Jima, Minamidaito Jima and Okidaito Jima (Ohde and Elderfiled 1992) are "indirect evidence" and subject to generalizations and numerical uncertainties. This makes them less robust relative to age-dated material from a known elevation. Uncertainties in the modeling occur in many aspects of the subsidence model, assumptions about net global sea level change since the late Oligocene, extent of Plio-Pleistocene erosion on the islands, and the initiation of uplift (as of 1992, known only to have begun sometime between 4 and 7 Ma). The problem with the estimates rates based on elevation differences is that Kitadaito Jima and Minamidaito Jima lie on a different ridge (Daito Ridge) than Okidaito Jima (Oki-Daito Ridge), and thus, the tectonic setting of the former two island is not necessarily analogous to that of the latter island, and uplift rates determined by elevations differences are less easily accepted.

The uplift rates calculated herein may well be the most robust value obtained for Kitadaito Jima (49 m/Myr) and Minamidaito Jima (35–50 m/Myr). The elevation (Fig. 3) and age (Table 1) of the Kitadaito Jima K1 sample in particular is very well constrained, as is the global position of sea level when the K1 sample formed (Miller et al. 2020). The greatest uncertainty is the paleo-water depth at the time of deposition. But deposition at sea level is a reasonable assumption because the sample occurs in an intertidal erosional notch, which is a strong indicator of intertidal erosion (Pirazzoli 1986, 1996; Dickinson 2001). The rock also contains marine cements typical of carbonate shoreline deposits. Lastly, even if the paleo-water depth estimate is off by a few meters (~ 2 m), the compounded uncertainty increase only to ± 3.1 m/Myr, which is still a small amount. The fact our new uplift rate for Kitadaito Jima is identical to that of Ota et al. (1991) and Ota and Omura (1992) indicates that the uplift rate has been constant for the last approximately 2 Myr.

Uplift rates of lithospheric forebulges have also been reported from the Loyalty Islands and Niue Island in the Pacific Ocean, and Christmas Island in the Indian Ocean

Table 3 Uplift rates of carbonate islands on lithospheric forebulges in the Indian and Pacific Oceans

Uplifted atoll	Trench	Uplift rate (m/Myr)	Applicable time interval (Myr)	Method of rate determination	References
Pacific Ocean					
Loyalty Islands	New Hebrides (Vanuatu) Trench	70	last ca. 2.0	Geodynamics model	Dubois et al. (1974)
		160–190	last ca. 0.105	Coral uranium series date and sample elevation	Bernat et al. (1976)
		130	last ca. 0.180	Coral uranium series date and sample elevation	Dubois et al. (1977)
		130–190	last ca. 0.180	Coral uranium series date and sample elevation	Marshall and Launay (1978), Andréfouët et al. (2007)
		24–51	last ca. 0.205	Coral uranium series date and sample elevation	Gaven and Bourrouilh-Le Jan (1981), Bourrouilh-Le Jan (1985)
		≥ 36	last 2.6	Magnetochronology of carbonates	Guymond et al. (1996)
Niue Island	Tonga Trench	100	last ca. 0.7	Geodynamics model	Dubois et al. (1975)
		130–160	last 0.125–1.4	Terrace height and elevation contrasts on plate	Dickinson (2001, 2004)
Kitadaito Jima	Ryukyu Trench	30	last ca. 0.125	Coral uranium series date and sample elevation	Ota and Omura (1991, 1992)
		10–35	last ca. 0.125 to last ca. 4–7	Geodynamics model, elevation contrasts on plate, and coral dates versus sample elevation	Ohde and Elderfield (1992)
		50	last 1.9	Sr isotope age and sample elevation	This study
Minamidaito Jima	Ryukyu Trench	50	last ca. 0.125	Coral uranium series date and sample elevation	Ota and Omura (1991, 1992)
		19–23	last 0.7–0.9	Sr isotope ages of corals and sample elevation	Ohde and Elderfield (1992)
		38–50	last 0.98–1.16	Sr isotope ages of corals and sample elevation	This study (see discussion)
IndianOcean					
Christmas Island	Java Trench	120	last ca. 0.125	Coral uranium series date and sample elevation	Veeh (1985)

(Table 3). The values vary greatly, ranging from 10 to 190 m/Myr. Such a wide range reflects variability of plate motion, age, plate morphology (e.g., plate thickness), configuration (angle of slab subduction), and distance from trench. In addition, these estimates include some of the same uncertainties pointed out above for the uplift rate of Kitadaito Jima and Minamidaito Jima, particularly the estimate, if made, of paleo depositional depths of any dated Late Pleistocene corals. The fact that so many of the rates are > 50 m/Ma adds further confidence to the Kitadaito Jima uplift rate determined herein.

Accurate and precise estimations of uplift rates of coral reef terraces and carbonate islands near plate boundaries, including lithospheric forebulges, require accurate and precise determinations of ages and depositional depths of sediment. However, determining depositional depths is difficult and commonly subject to non-negligible uncertainties. For example, the precision of the depositional depth determination using coral or coralline algal assemblages is not so good, ranging from a few meters to a dozen meters (e.g., Humblet et al. 2019). Such a range in depositional depths could correspond to as much as ~ 13% of the uplift of Kitadaito Jima estimated in this study. In addition, estimations of short-term uplift rates are more affected by the uncertainty of age and depositional depth determinations than long-term uplift rates. Therefore, considerably various uplift rates of carbonate islands on lithospheric forebulges in previous studies (Table 3) may not be solely due to the variability of tectonic settings; the large range may also be partly due to erroneous assumptions, particularly with respect to depositional depths. This study shows a better way to improve the accuracy and precision of estimating the uplift rates. It is preferable, if possible, to use indices by which the depositional depth can be more rigorously determined, e.g., vermetids (Spotorno-Oliveira et al. 2016) and intertidal erosional notches (this study). Younger samples, the ages of which can be dated by ^{14}C or uranium series dating, have been investigated in many previous studies. But it is also recommended to examine older samples beyond the limits of those methods using Sr isotope ratios calibrated to the most recent and robust Sr isotope age models (e.g., McArthur et al. 2020).

6 Conclusions

A new uplift rate for Kitadaito Jima, a carbonate island on the lithospheric forebulge of the Philippine Sea Plate was estimated using new strontium isotope ages (average = 1.89 Ma) of bioclastic sediments filling an intertidal erosional notch at an elevation of 71 m near the top of this island. A mean uplift rate of ~ 49 m/Myr (compounded uncertainty of ± 2.6 m/Myr) is needed to place these deposits at that elevation, considering that sea level at 1.89 Ma was ~ 21 m lower than the present. These rates are identical to one estimated based on ages and elevations of reef deposits formed on Kitadaito Jima during the last interglacial stage (Ota et al. 1991; Ota and Omura 1992), but greater than prior estimates from the same island based on modeling of long-term uplift and subsidence (Ohde and Elderfiled 1992). Published sedimentary histories and dolomitization models for Kitadaito Jima depend more or less on the uplift rates of Ohde and Elderfield (1992), thus they should be revised using the new uplift rates.

The new estimated uplift rate falls within the wide range (10–190 m/Myr) reported from other Indo-Pacific carbonate islands in a similar tectonic setting. While significant regional differences in the forebulge uplift rates should be expected, the possibility that some rates are erroneous due to uncertainties in estimating the depositional depth of samples and now outdated age models. This study provides an example of how to eliminate such uncertainties.

Abbreviations

Ma	Million years ago
Myr	Million years

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Author contributions

YI and DB conceptualized and designed this study. YI, TA, and RT performed a field survey to confirm elevations at Kitadaito Jima reposted in this paper. YI, DB, and AI conducted sedimentological and geochemical analyses. HT and TI undertook Sr isotope analysis. All authors collaborated in the interpretation of the data and preparation of the manuscript. The final manuscript was read and approved by all authors.

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Availability of data and materials

Please contact the corresponding author regarding data requests.

Declarations

Competing interests

The authors declare that they have no competing interests.

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