

Emerged fossil corals on the coast of northwestern Hainan Island, China: Implications for mid-Holocene sea level change and tectonic uplift

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Fossil corals are widespread on the coast of northwestern Hainan Island, China. Most of these corals are exposed during low tide levels, indicating that a higher sea level may have existed during their life time. The radiocarbon data introduced by this paper in combination with those from other sources show that the corals were alive mainly during the mid- to late-Holocene. Mid-Holocene sea levels 1–3 m higher than the present level were confirmed for adjacent coasts; however, the emerged corals on the investigated coast are not necessarily indicators of a higher eustatic sea level. They do predict relative sea levels of 1.5–3.4 m when using 1 m below the tidal datum as the upper limit of coral growth. However, using the Mean Lower Low Water as the coral's upper growth limit, the relative sea level on the non-volcanic coast was almost as high as the present level, whereas that on the volcanic coast was 0.4–2.0 m higher than present. Therefore, the exposure of these dead coral heads and their discrepancy in elevation may be the result of tectonic uplift caused by volcanic activities. From these results, the highest sea level of upward coral growth must be defined first when using fossil corals to reconstruct past sea levels. Meanwhile, vertical tectonics have to be taken into account as a significant factor when conducting high-resolution sea level reconstruction, although the South China coast is located in a “tectonically stable” region.

fossil coral, higher sea level, tectonic uplift, mid-Holocene, coast of northwestern Hainan Island

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Corals have the highest level of survival, which depends mostly on their exposure to air during low tide levels [1]. That is to say levels of survival are essentially controlled by sea level, which is why fossil corals have been widely used as proxies for sea level [2–6]; in particular, microatolls are considered one of the most reliable indicators [7]. Reef flats, commonly formed by the dead top surfaces of large massive *in-situ* massive *Porites* in shallow waters, may also accurately record a paleo sea level [8]. As a result, combining fossil corals with proper dating methods has become an important source of information about paleo sea levels. Especially in the tropical shallow water regions, coral reefs can be regarded as the most effective tool for reconstructing high-resolution sea level curves.

Because coral growth is greatly controlled by water depth, vertical crustal movements causing relative sea level changes must indirectly influence the development of corals or coral reefs; and *vice versa*, coral records of relative sea level changes may contain tectonic information. Therefore, coral reefs have also been deployed for studies of vertical crustal movements [9–12].

Whether the sea level was higher at the South China coast during the mid-Holocene used to be controversially debated. Research techniques and experimental devices have greatly improved, and high-resolution and high-precision data were published during the last few years [13–16]. As a result, the history of sea level fluctuations for the South China coast became better understood [17,18], and the argument for a higher mid-Holocene sea level based on emerged coral heads has become gradually accepted. For example, a mid-

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Holocene sea level 1–3 m higher than present was confirmed for the Leizhou Peninsula [13,19,20], Sanya [16,21], and Qionghai [22] by investigating fossil corals. However, all these results were based on the assumption of a stable crust.

Coral reefs on the northwest coast of Hainan Island are well developed, and most of the coral heads on the reef flat that died *in-situ* are exposed to the atmosphere at low spring tide. From our field investigation, we found that the elevations of these emerged corals varied apparently between different sections of the coast. The question is whether these emerged coral heads indicate a higher sea level during the mid-Holocene? In such a local area of investigation, could the differences in elevations be the result of crustal differential uplift? If so, can inconspicuously vertical movements of the “stable crust” continue to be neglected when carrying out high-resolution reconstruction of sea levels for the South China coast? To answer these questions, this paper focuses on emerged coral heads along the northwest coast of Hainan Island. This study aims to demonstrate the variability of the mid-Holocene sea level at different coasts and, furthermore, to prove that the influence of vertical crustal movements on sea level change can not be disregarded when reconstructing Holocene sea levels in this area.

1 Materials and methods

1.1 Study site

Hainan Island is situated on the northern passive continental

margin of the South China Sea (Figure 1), the intersection of the Eurasian, Pacific and Indian plates, and also the eastward extension of the Red River suture zone. Influenced by the spreading of the South China Sea basin and the compression of the Philippine Sea plate into the Indian plate, three groups of faults have been developed in Hainan Island trending E-W, NE, and NW. In the northern Hainan Island, the NW group is the most active and the fault to which most volcanoes are bound. During the Quaternary, the Leizhou Peninsular and northern Hainan Island went through a stage of strong volcanic activities, resulting in the largest basaltic area in South China, which is 7000 km² [24]. During this active stage, the north coast of Hainan Island was distinctly uplifted. For example, an outcrop of the pre-Holocene marine sediments at Shenjian indicates that the coast was uplifted at least 40 m [25]. During the Holocene, weak volcanic activities continued, and small volcanoes developed along some coastal faults [26], causing slight local crust uplift.

Since the Quaternary, as the climate frequently changed, alternating between cold and warm periods, Hainan Island experienced sea level fluctuations and coastline changes accordingly. During the Last Glacial Maximum, the sea level was more than 100 m lower than at present, and the Beibu Gulf was wholly emerged as mainland [27]. Due to the rising sea level in the Holocene and a suitable environment for coral growth, fringing reefs were extensively developed around Hainan Island. The study area of this paper is one section of the coast with well-developed coral reefs. In this small area, Quaternary volcanic activities resulted in

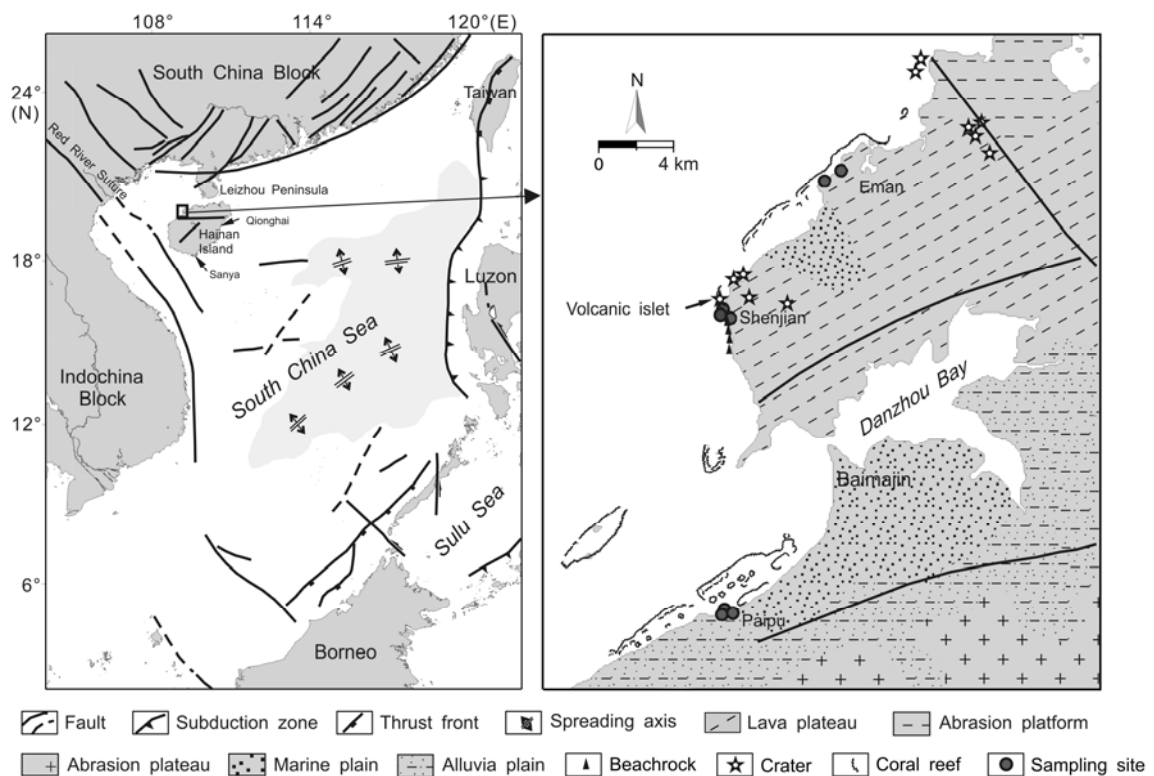


Figure 1 Maps showing the geological setting [23] of the studied area and locations of the AMS ¹⁴C coral samples.

a peculiar geology. With the Danzhou Bay as a boundary, the study area can be divided into two zones greatly different in geological settings. The northern zone belongs to a basalt platform, whereas the southern zone is an alluvial plain (Figure 1). Different geological processes may be the major factor that caused corals from the north and the south to exhibit different features. Based on our field inspection in 2007–2008, *in-situ* massive coral heads sporadically distributed on the reef flat at Paipu emerged 0.2–0.5 m during low tide (Figure 2(a)). They were relatively well preserved and had diameters of 1–3 m. In comparison to the southern zone, fossil corals from Yangpu to Eman grew almost exclusively on basalts or volcanic breccias. Moreover, most of the coral heads had been heavily eroded (Figure 2(b) and (c)), with reef diameters ranging from only 0.5 to 2 m, but, emerged heights of 0.5 to 1 m. In particular, massive dead *Porites*, which were well preserved with discoid flat tops on the volcanic islet of Shenjian, were 1–2 m above low tide level (Figure 2(d)).

In recent years, studies on coral reefs of Hainan Island have mainly focused on the east and south coasts and on the topics of reef development, paleoclimatology, and paleoceanography [21,28–33]. By contrast, little attention has been paid to coral reefs on the northwest coast. Relevant results were last published before 1991 [34–38]. Although research techniques, experimental devices and precision have improved greatly, no new reports concerning the coral reefs of the northwest coast have been issued. As a result, the reef

development, sea level changes and tectonics recorded by fossil corals in the study area are still poorly understood.

1.2 Sampling

Based on the growth characteristics of reef-building corals, relative sea level heights recorded in a dead coral surface can be accurately reconstructed with respect to the age and elevation of the dead surface. Differences in relative sea level heights between adjacent localities at a given time commonly result from vertical tectonic movement, so the rate of vertical crustal displacement can be calculated by comparing the elevations of coral surfaces that died at the same age. Following this principle, we took samples from the emerged coral heads at Paipu, Shenjian and Eman and leveled the elevations of their top surfaces.

To enhance the accuracy of our data, all the sampled corals were required to be massive *in-situ* *Porites* with diameters larger than 1 m. In addition, only the corals with top surfaces near the reef top of the sampling site in elevation were selected. Among the 16 samples we took, 10 fresher and purer ones were picked for AMS ^{14}C dating. The locations of these dated corals are shown in Figure 1, and their detailed information is listed in Table 1.

In particular, we believed that the fossil corals on the Shenjian islet, which were exposed much higher than those at adjacent sites, may have had special implications for tectonics, so we took four samples, numbered SJ-005-1,



Figure 2 Fossil corals exposed on the coasts of Paipu (a), Shenjian (b), Eman (c) and the residual islet near Shenjian (d).

Table 1 Information of samples for radiocarbon dating

Site	Sample No.	Location		Material	Tide gauge station	Elevation ^{a)} (m)
		Longitude	Latitude			
Paipu	PP-001	109°09.482'E	19°38.788'N	<i>In-situ Porites</i>	Baimajin	0.66
Paipu	PP-002	109°09.399'E	19°38.642'N	<i>In-situ Porites</i>	Baimajin	0.59
Paipu	PP-004	109°09.717'E	19°38.696'N	<i>In-situ Porites</i>	Baimajin	0.68
Shenjian	SJ-004	109°09.668'E	19°46.816'N	<i>In-situ Porites</i>	Yangpu	1.30
Shenjian	SJ-005-1	109°09.433'E	19°47.058'N	<i>In-situ Porites</i>	Yangpu	2.40
Shenjian	SJ-005-2	109°09.433'E	19°47.058'N	<i>In-situ Porites</i>	Yangpu	2.40
Shenjian	SJ-006-1	109°09.432'E	19°47.061'N	<i>In-situ Porites</i>	Yangpu	2.26
Shenjian	SJ-006-2	109°09.432'E	19°47.061'N	<i>In-situ Porites</i>	Yangpu	2.26
Eman	NT-001	109°12.390'E	19°50.582'N	<i>In-situ Porites</i>	Yangpu	0.87
Eman	NT-002	109°12.863'E	19°50.875'N	<i>In-situ Porites</i>	Yangpu	0.96

a) Elevation relative to tidal datum.

SJ-005-2, SJ-006-1, and SJ-006-2, respectively, from two well-preserved microatolls (two samples from each coral head) for radiocarbon dating. By such means, not only could more precise ages for the two corals be found, but also the reliability of the dating results could be tested.

Relative sea level heights can be estimated from a dead coral surface by using the elevation of the dead surface relative to the low spring tide or relative to the highest level of survival of modern living corals [8,19]. Considering that the massive living *Porites* in the study area mainly grew on the outer reef flat or reef slope, we only measured the height of a dead coral top relative to the sea surface of the time of measuring. Then, the elevation of the dead coral top could be determined by comparing the leveling height with tidal ranges of nearby tide gauges. For this procedure on the non-volcanic coast, tide gauge data were taken from the Baimajin station. On the volcanic coast, we referred to tide gauge data from the Yangpu station. For the calculation, the present-day tidal datum was used as the base level. Eleva-

tions of the dated samples relative to the base level are listed in Table 1.

1.3 Radiocarbon dating

The 10 coral samples for dating were sent to the State Key Laboratory of Loess and Quaternary Geology, where radiocarbon ages were achieved using accelerator mass spectrometry. The obtained age data are shown in Table 2. Before using the data, all the ¹⁴C ages were converted to calendar years using the program Calib5.0.1 (<http://www.calib.qub.ac.uk>). As fossil corals are marine sediments, the percentage of marine carbon for the 10 dated samples was set at 100%. The difference in reservoir age between the study area and the “global” ocean was determined from the marine reservoir correction database (<http://www.calib.qub.ac.uk/marine>), which was the average of these values in sites 406, 407, and 408 of Xisha.

Table 3 lists some data about coral ages, elevations and

Table 2 AMS¹⁴C data for *in-situ Porites* from the coast of northwestern Hainan Island

Sample	$\delta^{13}\text{C}$ (‰)		pMC (%)		¹⁴ C age (a BP)		Calibrated age ^{a)} (cal. a BP)	
	$\delta^{13}\text{C}$	Error (1 σ)	pMC	Error (1 σ)	¹⁴ C age	Error (1 σ)	¹⁴ C age	Error (2 σ)
PP-001	-0.24	0.55	55.10	0.18	4788	26	5029	86
PP-002	-4.16	0.38	56.91	0.17	4528	24	4713	83
PP-004	-2.90	0.45	57.10	0.16	4502	22	4682	81
SJ-004	-2.71	0.48	49.44	0.16	5658	25	6043	84
SJ-005-1	-1.83	0.65	49.43	0.16	5661	25	6046	84
SJ-005-2	-3.29	0.58	49.39	0.16	5667	25	6053	84
SJ-006-1	-1.28	0.63	50.21	0.16	5534	25	5901	84
SJ-006-2	-2.58	0.56	50.41	0.16	5503	26	5865	86
NT-001	0.59	0.40	53.34	0.17	5048	25	5381	84
NT-002	-1.40	0.40	56.81	0.17	4543	24	4729	83

a) Age calibrated using CALIB (Version5.0.1).

Table 3 ^{14}C ages of *in-situ* corals gathered from other sources

Site	Material	^{14}C age (a BP)	Original elevation (m)	Elevation ^{a)} (m)	Calibrated age ^{b)} (cal. a BP)	Source
Paipu	<i>In-situ Porites</i>	5340±160	0	0.66±0.08	5696±164	[36]
Paipu	<i>In-situ Porites</i>	4720±140	0	0.66±0.08	4963±144	[36]
Paipu	<i>In-situ coral</i>	4510±110	0	0.66±0.08	4671±115	[36]
Paipu	<i>In-situ coral</i>	4007±150	0.2	0.66±0.08	4003±154	[35]
Paipu	<i>In-situ coral</i>	3542±123	0	0.66±0.08	3415±123	[36]
Paipu	<i>In-situ coral</i>	3260±90	0	0.66±0.08	3006±96	[35]

a) Average elevation of emerged corals at Paipu relative to tidal datum; b) age calibrated using CALIB (Version5.0.1).

relevant information gathered from other previous publications. All the listed coral samples were collected at the non-volcanic coast; for the volcanic coast, no valid data are available. To make comparisons, the original ^{14}C datings had to be calibrated to calendar years. Another problem is that the elevation data from previous publications were expressed in terms of altitude without providing any datum plane. According to our leveling data of 8 coral upper surfaces, the *in situ* coral heads on the coast from Paipu to Baimajin exhibited no significant difference in emerged height (≤ 0.15 m), so, we used the average elevation of the 8 coral tops, 0.66 m, as the elevations of the previously published coral samples.

1.4 Results

Based on an age comparison of SJ-005-1, SJ-005-2, SJ-006-1 and SJ-006-2, the radiocarbon dating result was considered to be of reliable accuracy. According to the age data obtained in this paper and those collected from other papers, the life time of massive dead corals along the northwest coast of Hainan Island was estimated to be 6.0–3.0 cal. ka BP. At Paipu, three samples had younger ages of 4.0–3.0 cal. ka BP, and the other six were dated between 5.7–4.5 cal. ka BP. The three coral samples from Shenjian were dated around 6.0 cal. ka BP, and the two from Eman were dated at 4.7 cal. ka BP and 5.4 cal. ka BP. Therefore, the massive dead *Porites* in this area mostly grew in the middle Holocene, indicating that the middle Holocene was a period of prosperity for *Porites*, basically coinciding with the coral bloom or reef-formation stage of adjacent coasts, such as Sanyan in the south [21,28], Qionghai in the east [22], and Leizhou peninsular in the north [19,39].

Figure 3 shows the plot of the coral age-elevation distribution. It illustrates that fossil corals from the three sampling sites have nearly the same ages. However, in terms of elevation, there were obvious deviations, which were confirmed by our field observations. First, at Paipu, where only a small part of the dead coral heads were exposed during low tide, coral elevations were approximately 0.6 m. Secondly, at Eman, the representative elevation for corals was approximately 0.9 m. Last, at Shenjian, where the corals were more emerged than those at Paipu and Eman, most of

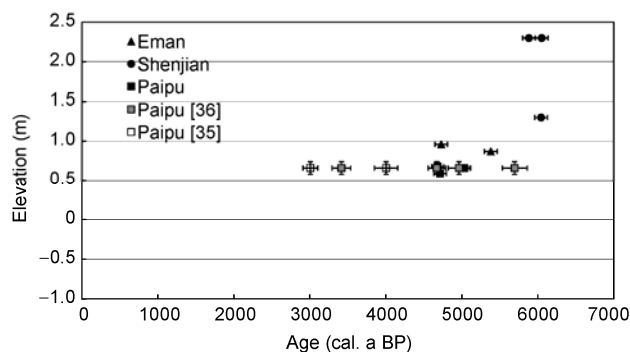


Figure 3 Plot of radiocarbon ages against elevations of *in-situ* fossil corals.

the dead coral heads had elevations around 1.3 m, and particularly in the volcanic islet near Shenjian, the elevations of the *in-situ* coral heads were up to 2 m.

According to the results described above, those mid-Holocene dead coral heads exposed at low tide on the northwest coast of Hainan Island might suggest that the mid-Holocene sea level was higher than present. In addition, their different elevations may imply vertical crustal differential movements.

2 Discussion

2.1 Implications for higher mid-Holocene sea level

In the coral-reef regions of the South China coast (mainly around the Leizhou Peninsula and Hainan Island), several higher mid-Holocene sea-level traces have been recognized. For example, at Denglouliao and Shuiweicun of the Leizhou Peninsula, the reef flats that formed during 6550–5300 a BP are now located 121.0–49.5 cm above the tidal datum, indicating the sea level at that time was 3–4 m higher than at present [19]. Furthermore, based on the TIMS (thermal ionization mass spectrometric) ages of the *Porites* samples collected from a reef terrace at Denglouliao, several episodes of Holocene sea-level highstands were identified [13,14]. On the south coast of Hainan Island, data of elevations and ^{14}C ages of the *in-situ* fossil corals revealed that at least 4 high-sea-level episodes occurred during the Holocene, and the peak of the sea-level highstand could be dated be-

tween 7.3 and 6.0 cal. ka BP [21]. Additionally, on the east coast of Hainan Island, a sea-level highstand of 2.0–2.2 m during 5.5–5.2 ka was found based on the TIMS ages and elevations of massive emerged *Porites* [22]. In addition, coral reefs in adjacent areas, such as Xisha Island, also showed indications of mid-Holocene higher sea levels [8,16,40].

Data presented in this paper in combination with those gathered from other publications showed that massive dead corals in the investigated area mainly lived in the mid- to late-Holocene. Elevations of their dead tops relative to the present-day datum plane vary from 0.5 to 2.4 m (Figure 3). Therefore, the fossil corals in this area may predict a mid-Holocene sea-level highstand. To calculate the elevation of the mid-Holocene sea level relative to the present sea level, the highest level of survival for massive corals must be documented first. According to relevant research, however, this “highest level” is not a fixed or uniform criterion. Different coral species or the same species growing in different seasons, regions or even biological-geomorphologic zones may have different upper growth limits [1,10,41,42]. Previous investigations of coral reefs in the South China Sea discovered that most massive *Porites* lived 1 m below the low-water spring tide level [14,19], and, accordingly, 1 m below the tidal datum was defined as the highest level of survival for *Porites* in application [13,19]. In contrast, the upper growth limit of flat corals mentioned by Zhang [42,43] was the Mean Lower Low Water, which approximately corresponds to the mean low-water spring tide but is somewhat different from the low-water spring tide.

Provided that there is no top erosion of *in-situ* coral heads and using 1 m below the tidal datum as the upper limit for coral growth, the massive dead *Porites* of Paipu indicated the sea level between 5.7 and 3.0 cal. ka BP was 1.5–1.7 m above the present sea level, while at Shenjian and Eman, the mid-Holocene sea level height was estimated to be 2.3–3.4 m and 1.8–2.0 m, respectively. This result coincides well with most previous studies [8,19,22,44]. Therefore, it can be concluded that the massive dead coral heads emerged in growth positions along the coast of northwestern Hainan Island suggest a higher mid-Holocene sea level under the assumption that 1 m below the tidal datum is the upper limit of coral growth. However, using the Mean Lower Low Water as the upper limit for coral growth, the Paipu sea level during 5.7–3.0 cal. ka BP was basically the same as present and only ranged between –0.1–0.1 m. This sea level height was calculated with reference to the Mean Lower Low Water of the Baimajin gauge station (0.6 above the tidal datum). At Shenjian and Eman, the mid-Holocene sea levels were 0.9–2.0 m and 0.4–0.6 m higher than present, respectively. The calculation was performed with reference to the Mean Lower Low Water of the Yangpu gauge station (0.4 m above the tidal datum).

Our analysis demonstrates that reconstructing the sea level using the same indicator but based on different criteria will have remarkably different results, which is why differ-

ent scientists may obtain different sea level histories for the same area and, consequently, controversies about sea level changes inevitably arise. According to our research, the corals emerged on the volcanic coast do indicate a higher relative mid-Holocene sea level but are not necessary indicative of a higher eustatic sea level. Therefore, the occurrence of a higher relative mid-Holocene sea level on the volcanic coast was estimated to be the result of tectonic uplift related to volcanic activities, which suggests that tectonics should be taken into account when reconstructing the Holocene sea level for the South China coast and it might produce diametrically opposing results.

2.2 Implications for vertical crustal movements

Microatolls are among the most precise and useful diagnostic sea-level indicators found on coral reefs [41]. Using massive coral heads (which could also be defined as microatolls) exposed on the northwest coast of Hainan Island, mid-Holocene relative sea level data were obtained for this area, which varied from Paipu to Shenjian and Eman. Regardless of to which datum plane the upper limit of coral growth was defined, differences in the relative sea level change between these sites did not change sensitively with the calculations. For such a local area where the coast extends only tens of kilometers, significant differences in the relative sea level change must be the result of tectonic subsidence or uplift.

Between the non-volcanic coast in the south and the volcanic coast in the north, the differences in the relative sea level heights range from 0.3 to 2.1 m. If erosion of the coral upper surface was taken into consideration, the deviation would increase because coral erosion was severer in the north than in the south. That is to say, the relative sea level of the volcanic coast would be much higher than that of the non-volcanic coast, implying that the volcanic coast, relative to the non-volcanic one, had been uplifted since the mid-Holocene. According to our previous research on the pre-Holocene marine strata outcropping along the coast of Shenjian [25], volcanic activities had led to crustal uplift since the Middle Pleistocene, causing some coastal zones to be turned to terrestrial environments and the pre-Holocene marine sediments to be exposed to subaerial erosion. As volcanic activities decreased later in the Holocene, the intensity of tectonic deformation was remarkably reduced. Then, weathering, denudation and coastal erosion became the major geological processes in this area. However, under the influence of late-stage volcanism, moderate uplift of the crust continued, which finally led to the differences in elevations of the raised coral heads between the volcanic and the non-volcanic coasts. According to the data for modern vertical crustal deformation [45], the volcanic area is an uplift zone with rates of 0–1 mm/a, whereas the non-volcanic area is subsiding with rates ranging from 0 to 1 mm/a. Assuming that the crust of this area always deformed vertically at these rates, the total displacement of the north rela-

tive to the south in the last 5000 years would be 0–10 m. The discrepancies of 0.3–2.1 m in relative sea level heights estimated from the emerged coral heads are within the range, so it can be preliminarily concluded that the estimation is reasonable and reliable.

The significant variations in relative sea level data along the volcanic coast are also indicative of vertical tectonic displacements. For instance, the mid-Holocene relative sea level data between Shenjian and Eman exhibited a difference of 0.3–1.6 m, indicating that volcanism at Shenjian has caused higher uplift. Additionally, on the residual islet near Shenjian, the dead corals, today in a 0.9–1.2 m higher position than those around them, suggested that the islet had been uplifted at least 1.2 m after the Middle Holocene. Based on an abundance of dark red-brown basalts scattered around, the residual islet was inferred to be a small volcano. Its last eruption might have occurred during the mid-Holocene, causing a relatively large uplift. As a result, intertidal microatolls with disc-shaped tops on the islet were paroxysmally exposed to the air, and the whole coral colonies soon died.

The coral samples from Shenjian were predominantly older in age as well as higher in elevation than those from Eman and Paipu. That means *in-situ* corals with higher upper surface would be older, indicating that coral growth might be in synchronism with tectonic uplift. According to this speculation, the corals at Shenjian died earlier because of the relatively rapid uplift, while corals at Eman and Paipu lived longer as the local crusts were slowly raised or the corals died as the eustatic sea level fell gradually since the Middle Holocene. In summary, differences in the recent elevations of *in-situ* fossil corals between the volcanic and the non-volcanic coasts were mainly caused by tectonic uplift.

3 Conclusions

Shallow-water corals are sensitive to environmental change, which makes fossil corals one of the most important records of past sea level changes and tectonic activities. This paper presents a comprehensive study on the chronology and elevation of fossil corals exposed on the coast of northwestern Hainan Island. The results show that the massive dead corals were mainly alive in the mid- to late-Holocene, with the mid-Holocene being a flourishing period. Using 1 m below the tidal datum as the upper limit of coral growth, the elevations of these dead corals predict a mid-Holocene sea level 1.5–3.4 m higher than the present level. However, the results changed remarkably when using the Mean Lower Low Water as the limit of upward coral growth. The mid-Holocene sea level at the non-volcanic coast was almost as high as the present level, whereas that at the volcanic coast was 0.4–2.0 m higher than present. Therefore, whether the emerged fossil corals on the coast of northwestern Hainan

Island indicate a mid-Holocene eustatic sea-level highstand is still uncertain and will require further investigation. What we can confirm now is that the emerged fossil corals on the volcanic coast truly predict a relative higher sea level. The differences in elevations of the dead coral tops, which point to differences in relative sea level heights, are interpreted as the result of differential tectonic uplift caused by volcanic activities.

Finally, according to the results presented above, the upper limit for coral upward growth must first be accurately established when using fossil corals to reconstruct past sea levels. In addition, vertical tectonics have to be taken into account as a significant factor in high-resolution sea level reconstruction, although the investigated area is located in a relatively “tectonically stable” region.

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