Journal of Asian Earth Sciences 156 (2018) 201–206

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Full length article

Variable uplift rate through time: Holocene coral reef and neotectonics of Lutao, eastern Taiwan

Chuan-Chou Shen[a], Chung-Che Wu[a], Chang-Feng Dai[b], Shou-Yeh Gong[c,*]

[a] High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, ROC
[b] Institute of Oceanography, National Taiwan University, Taipei 10617, Taiwan, ROC
[c] Department of Geology, National Museum of Natural Science, Taichung 40419, Taiwan, ROC

ARTICLE INFO

Keywords:
Coral reef
Neotectonics
Holocene
Lutao
Taiwan

ABSTRACT

Significant discrepancies have existed regarding rate and timing of the uplift of Lutao (Green Island), located at the border of the ongoing collision between the Eurasia continental plate and the Philippine Sea Plate. To document its neotectonic history, two cores were drilled into Holocene coral reefs exposed at the southeastern coast of Lutao. Twelve pristine fossil corals, nine taken from cores and three on the surface, were ^{230}Th dated. The results show that the coral reefs started to develop at 8,736 ± 56 yr BP (before 1950 CE) with uplift rate varying from 3.6 mm/yr during 8.7–6.0 kyr BP to 1.2 mm/yr in the past six thousand years. Our study strongly suggests that the uplift rate can vary significantly on millennial time scale. Caution should be used when extrapolating uplift rate estimates based on Mid-late Holocene corals to early times for tectonic active locations, such as Lutao.

1. Introduction

Fossil corals have been used to reconstruct tectonic histories for decades. Many studies acquired fossil corals from outcrops, followed by the use of coral age and elevations to calculate a simple mean uplift rate (Chappel, 1974; Wang and Burnett, 1990; Liew et al., 1993; Ota et al., 1993; among others). However, regional tectonic history could have been oversimplified by such an approach. Recent observations and fossil coral studies using more detailed sampling, for example, in Sumatra and the Solomon islands (e.g., Taylor et al., 2005 (which showed a complete reversal of vertical directions and acceleration of uplift rates); Briggs et al., 2006; Sieh et al., 2008; Meltzner et al., 2015; Philibosian et al., 2016; Thirumalai et al., 2015) have shown that displacement and deformation histories and rates can be very complex and variable overtime along convergent plate boundaries.

Holocene sea level in the tropical western Pacific reached its maximum around six to four thousand years ago (Pirazzoli, 1991; Dickinson, 2004; Rashid et al., 2014; Khan et al., 2015). Corals taken from emerged Holocene reef outcrops represent that time span when sea level in that region was higher than present. Few early Holocene corals can be sampled on the surface because they are either covered by mid-late Holocene reef deposits or still submerged. Reconstruction of detailed history over the entire Holocene is therefore hindered by the paucity of early Holocene samples. Coring of Holocene reefs has been demonstrated to successful access and sample early Holocene corals to constrain sea level before the mid-Holocene (Montaggioni, 1976; Easton and Olson, 1976; Davies et al., 1979; Marshall and Jacobson, 1985; Fairbanks, 1989; Camoin and Montaggioni, 1994; Shen et al., 2010; Gong et al., 2013; Siringan et al., 2016, also see review by Montaggioni, 2005). This approach should also be as helpful in neotectonic studies.

Lutao (Green Island) is a volcanic island off eastern Taiwan, situated at the boundary of an ongoing arc-continent collision between the Eurasian plate and the Luzon Arc that sits on the Philippine Sea plate (Fig. 1). Lutao is located at a critical location to document the deformation and crust shortening of the arc-continent collision (Wang and Burnett, 1990; Chen and Liu, 1992; Liew et al., 1993; Vita-Finzi, 2000; Ota and Yamaguchi, 2004; Yamaguchi and Ota, 2004; Inoue et al., 2011; Shyu et al., 2011). However, those studies have significant differences in timing and rate of uplift. Wang and Burnett (1990) reported that Lanyu-Lutao area had an average uplift rate of 2.2 ± 0.2 m/kyr after correction for paleosea level. Chen and Liu (1992) proposed that the Holocene uplift rate ranged from 0.9 to 3.3 m/kyr in the past 6 kyr based on beach deposits and encrusting algae limestone. Vita-Finzi (2000) estimated an uplift rate at 5 m/kyr from 9 to 5 kyr BP and cessation of uplift after 5 kyr BP.

Most of the previous studies did not use a consistent datum to compare sample elevations, such as the living water-depth of corals or

* Corresponding author at: National Museum of Natural Science, 1 Kuan-Chien Road, Taichung 40419, Taiwan, ROC.
E-mail address: gng@mail.nmns.edu.tw (S.-Y. Gong).

https://doi.org/10.1016/j.jseaes.2018.01.016
Received 20 February 2017; Received in revised form 1 January 2018; Accepted 15 January 2018
Available online 31 January 2018
1367-9120/

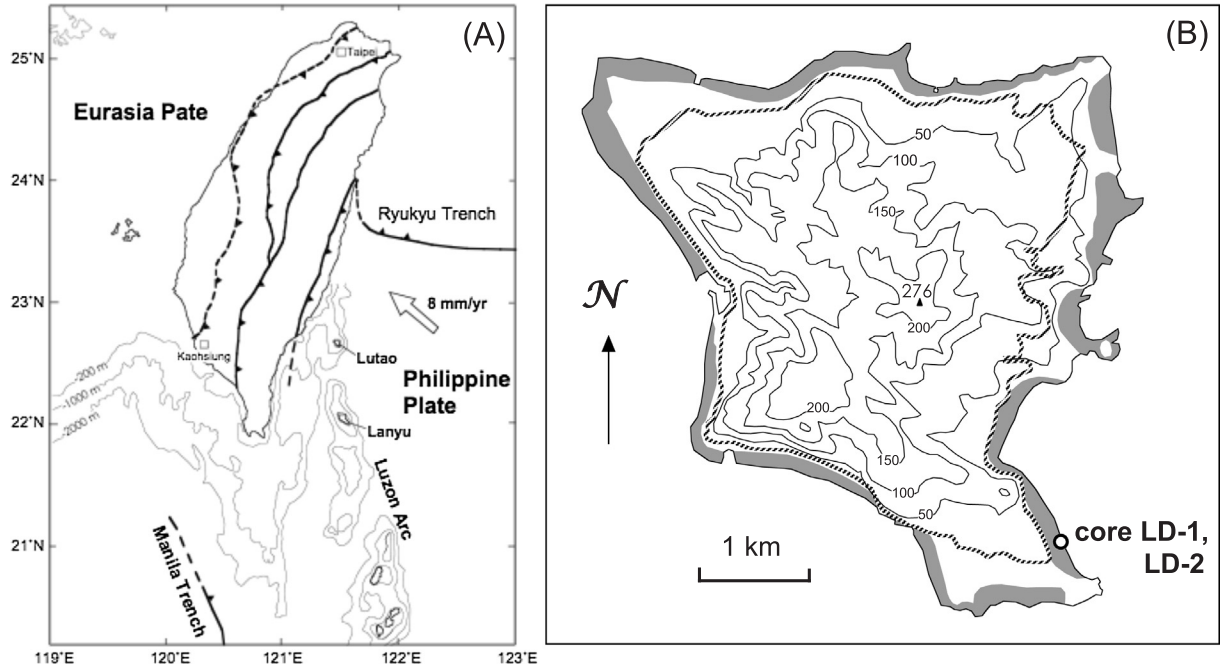

Fig. 1. (A) Location and tectonic setting of Taiwan. Bathymetry data from Taiwan Ocean Research Institute (TORI) database. (B) Topography of Lutao and distribution of Holocene coral reefs, compiled from Chen and Liu (1992), Inoue et al (2011) and our own investigation. A small circle denotes the drill core location.

mean lower low tide. The lack of consistent reference to a datum that allows comparison within and between studies prevents precise estimates and comparisons of uplift rate. Inoue et al (2011) were the first to consider the factor of living water-depth of corals. They identified the *Isopora palifera*, as well as *Acropora digitifera* and *A. gemmifera* as an indicator of paleosea level. This approach made their estimate of uplift rate more reliable than previous studies. Inoue et al (2011) proposed an uplift rate at 1.2 mm/yr since 5,749 cal yr BP, less than the values suggested by previous studies (Wang and Burnett, 1990; Chen and Liu, 1992; Vita-Finzi, 2000). They concluded that uplift was continuous uplift, rather than episodic as other studies had proposed (Liew et al., 1993; Yamaguchi and Ota, 2004).

The objective of our study is to establish the Holocene history of coral-reef development and tectonic uplift of Lutao. To accomplish this objective, we drilled two cores in the Holocene reefs and acquired a continuous record of upward reef growth to explore the relative sea-level history and to interpret the tectonic history of Lutao prior to 6 kyr BP when the sea level was still rising. We demonstrate that the uplift rate may vary through time and subsurface sampling is essential to acquire necessary samples to bridge time gaps and address possible varying uplift rates over a longer time span.

2. Study site

Lutao, with an area of 16.2 km^2, is located about 34 km east of Taiwan and 70 km north of Lanyu, another volcanic island on the same trend as Lanyu Island and a submarine ridge of the Luzon arc off eastern Taiwan (Fig. 1). Lutao is comprised of Pliocene and late Pleistocene andesitic volcanic agglomerates (Juang and Chen, 1990). The Philippine Sea plate, on which Lutao and the inactive Luzon arc is colliding obliquely with the Eurasia plate at ~8 cm/yr (Yu et al., 1997), and the boundary is moving southwards at 9 cm/yr (Suppe et al., 1987). The ongoing collision has been deforming the Coastal Range of eastern Taiwan. Lutao is on the margin of the Philippine Sea plate, and anticipated to collide with Eurasia plate (Teng, 1990; Shyu et al., 2005).

Lutao has a subtropical climate with an annual temperature ranging from 23.3 to 23.9 °C, averaging 23.6 °C, and annual rainfall from 2030 to 3280 mm, averaging 2600 mm during 2005-–2014. The mean tidal range of the island is 0.95 m. Dai et al. (2004) estimated about 300 species of stony coral in the Lutao-Lanyu area. *Isopora palifera*, mostly in encrusting form, and *Acropora digitifera* are observed abundantly in the exposed Holocene reefs. The species *I. palifera* was found to occur extensively from 0.5 to 1.5 m below mean sea level (MSL) in Lanyu, and is very rare at greater depths. No other corals were observed living in shallower water depth (Inoue et al., 2011). Coral *I. palifera* is, therefore, a reliable water-depth indicator in the study area.

Emerged Holocene reef terraces have developed along the coasts of Lutao (Fig. 1B). Most of the emerged reef are less than 2.5 m above MSL, and were named the “lower reef terrace” in Inoue et al. (2011). At the southeastern coast of Lutao, the emerged Holocene reef is well exposed and measures 140 m in width perpendicular to the coastline (Fig. 2). A rampart of 1.8 m in elevation occurs at the seaward edge with a broad, incised depression behind it. The surface elevation increases to about 1.8 m at the landward edge, and then terminates at a narrow beach (Fig. 2).

3. Material and methods

Two cores, LD-1, and LD-2 were drilled on the emerged Holocene coral reef near the seaward margin at the southeastern coast (Figs. 1b, 2). Core LD-1 is a vertical core of 12.9 m in depth drilled from 1.5 m above MSL. Core LD-2 is a 16.1 m in length inclined 45-degree seaward (11.3 m in vertical depth,), drilled from 1.4 m above MSL (Fig. 1b).

Cores were split, photographed and described and thin sections were made to aid core examination. Three additional *I. palifera* corals

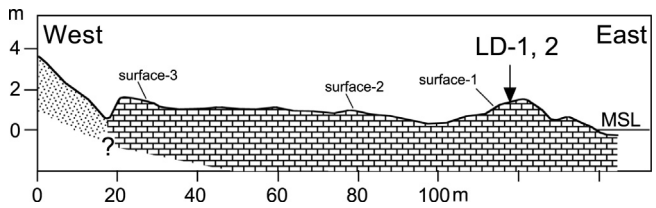

Fig. 2. Topographic profile of the study site, Lutao. Mean sea level (MSL) is based on tide gauge of Central Weather Bureau at Lutao. Locations of cores LD-1 and LD-2 and surface samples are marked.