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Marine terraces caused by fast steady uplift and small coseismic uplift and the time-predictable model: Case of Kikai Island, Ryukyu Islands, Japan

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ABSTRACT

Kikai Island, a part of the Ryukyu Islands in southwest Japan, is rimmed by marine terraces. This island has been studied in detail because these marine terraces record the fastest crustal uplift in Japan. Geological studies of the raised Holocene reef have concluded that coseismic uplift has been generating marine terraces since 6.3 ka. Analysis of GPS data suggests that Kikai Island is steadily uplifted several mm/yr. To examine the discrepancy between geological and geodetic surveys, I numerically modeled nearshore processes and simulated the generation of marine terraces under two conditions: 1) large stepwise uplift and no steady uplift and 2) steady uplift and small stepwise uplift. As a result, the emergence time of the marine terraces is the same and the heights of the terrace cliffs are consistent with the time-predictable recurrence model for large earthquakes. This result shows the possibility of overestimate of magnitudes of the past earthquakes.

1. Introduction

Kikai Island is a raised coral reef located in the Ryukyu Islands of southwest Japan (Fig. 1). It is the closest island to the Ryukyu Trench and the marine terraces in this island record the fastest uplift rate in Japan; that is, 1.8 mm/yr since the last interglacial period (e.g., Ota and Omura, 1991, 1992). In the Holocene, four marine terraces were generated owing to eustatic sea level fall and coseismic uplift by geological studies (Webster et al., 1998; Ota et al., 2000; Sugihara et al., 2003). On the global trend, coseismic uplift is considered to be responsible for the generation of marine terraces by geological studies (e.g., Plafker and Rubin, 1978; Matsuda et al., 1978; Berryman et al., 1989; Chappell et al., 1996). In the case of Kikai Island, Ota et al. (2000) proposed that earthquakes are responsible for the uplift. First, it is because the four marine terraces show different ages of stagnant periods of sea level, followed by emergence periods; however, such eustatic sea level changes are not known. Second, fragmented Holocene terraces are generally limited to Kikai Island, except the Takara Island and Kodakara Island, which are located in a volcanic arc (Fig. 1). Sugihara et al. (2003) concluded that the eustatic sea level fall is approximately 2 m and occurred 7.0–6.3 ka ago; subsequently the coseismic uplift was four times with 1–4 m since 6.3 ka.

Marine terraces were recently used to determine the spatiotemporal patterns and magnitudes of past great earthquakes, especially after the 2011 M9.0 Tohoku-oki earthquake (e.g., southwest Japan by Furumoto, 2012; Kikai Island by Goto et al., 2013; Tokunoshima Island by Osozawa and Tanaka, 2013) (Fig. 1). These studies assume that periods of constant sea level generate terrace plains, whereas coseismic uplift generates terrace cliffs.

On the other hand, in Kikai Island, GPS data suggest steady uplift of several mm/yr, which is interpreted as the collision of the Amami Plateau, subducting northwestward beneath the Ryukyu Islands at Kikai Island (Nishimura et al., 2004), though GPS data cannot be simply extended to the past. So, from the geodetic observation, fast steady uplift and small coseismic uplift is more persuasive.

Here I assume that the terraces are mostly caused by steady uplift and small stepwise uplift. In this study, I focus on nearshore processes, which are associated with fast erosion, sediment deposition, and coral growth near sea level. I constructed the following scenario for the generation of marine terraces. First, fast erosion, deposition, and coral growth generate flat abrasion platforms at sea level. Second, small stepwise uplift generates incipient terrace cliffs, and the sea level is under the abrasion platform if the stepwise uplift is faster than surface erosion. Third, new abrasion

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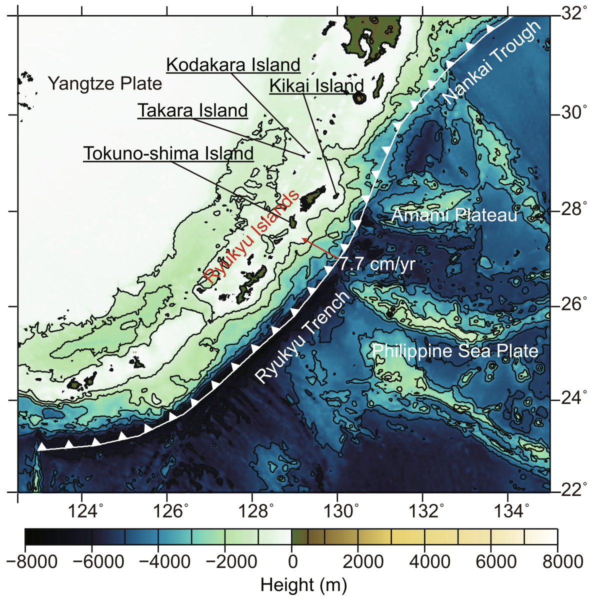

Fig. 1. Topographic map of Ryukyu Islands. The topography is after Smith and Sandwell (1997). The plate boundary is after Bird (2003). The Philippine Sea Plate is subducting beneath the Yangtze Plate in the direction of the red arrow. The relative plate motion was calculated by MOVEL (DeMets et al., 2010).

platforms are generated lower than the previous platforms because of the steady crustal uplift, fast erosion and sedimentation, and coral growth.

I calculate the development of marine terraces for two uplift models. The first model considers all uplift as stepwise without any steady uplift. The second model considers mostly steady uplift and small stepwise uplift. I compare the two models and discuss their validity, aiming to constrain the development of the marine terraces.

2. Model for nearshore process: erosion, deposition, and coral growth

In this study, I use the sediment erosion and deposition model of Storms et al. (2002) and the coral growth model of Nakamura and Nakamori (2007).

The continuity equation is

$$\frac{\partial H}{\partial t} = -\frac{\partial F}{\partial x} + T + P, \tag{1}$$

where t is the time [T], x is the horizontal distance [L], H is the topographic elevation relative to a constant reference level [L], F is the sediment flux [L^{2}T^{-1}], T is the rate of vertical movement of the basement floor [LT^{-1}], and P is the coral growth rate [LT^{-1}]. The spatial derivative of the sediment flux is

$$\frac{\partial F}{\partial t} = E(x,t) - S(x,t), \tag{2}$$

where $E(x,t)$ is the rate of erosion [LT^{-1}], and $S(x,t)$ is the rate of deposition [LT^{-1}].

2.1. Erosion model

The rate of erosion is

$$E(x,t) = c_e G(x,t), \tag{3}$$

where c_e is the maximum coastal erosion rate [LT^{-1}] and $G(x,t)$ is the local erosion efficiency [–]. Fig. 2 shows the schematic presentation of the model. $x_s(t)$ and $H_s(t)$ are the location and height of the coastline, respectively. $x_c(t)$ and $H_c(t)$ correspond to the location and height of the landward boundary of the shoreface erosion window. $x_c(t)$ is given by

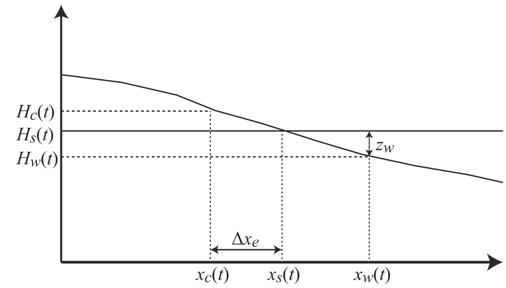

Fig. 2. Schematic representation of the variables in the numerical model.

$$x_c(t) = x_s(t) - \Delta x_e, \tag{4}$$

where Δx_e is the maximum horizontal extent of the inland erosion by wave energy. $x_w(t)$ and $H_w(t)$ correspond to the location and height of the intersection of the storm wave base. $H_w(t)$ is given by

$$H_w(t) = H_s(t) - z_w \tag{5}$$

where z_w is the storm wave base [L]. Erosion is limited to the shoreface erosion window defined by the spatial domain between locations $x_c(t)$ and $x_w(t)$

$$G(x,t) = \begin{cases} \left\{\frac{\max[H_w(t), H(x,t)] - H_w(t)}{H_c(t) - H_w(t)}\right\}^m \\ \quad \text{for } x_c(t) < x < x_w(t) \\ 0 \quad \text{for } x \le x_c(t) \text{ and } x_w(t) \le x, \end{cases} \tag{6}$$

where m is a constant [–] that represents the dependence of erosion rate on water depth.

2.2. Deposition model

The deposition rate is given by

$$S(x,t) = F(x,t)/h, \tag{7}$$

where h is the sediment travel distance [L], and F is the sediment flux in transit and available for deposition [L^{2}T^{-1}]. F is defined as the sum of the local influx F_{in} and the material eroded from the bed F_{ero} or the sediment of local deposition F_{dep} and the local outflux F_{out}:

$$F = F_{in} + F_{ero} = F_{dep} + F_{out}. \tag{8}$$

The cross-shore sediment dispersal is described by the nominal grain diameter D [mm] and h [m], in standard spatial increments of 50 m,

$$h^*(D) = \begin{cases} c_h[110 + 590(D_{ref}/D)^{2.5}] & \text{for } D > D_{ref} \\ c_h[500 + 200(D_{ref}/D)^{0.6}] & \text{for } D \le D_{ref}, \end{cases} \tag{9}$$

where c_h is the coefficient of horizontal factor for deposition and $D_{ref} = 0.125$ mm. For grid sizes other than 50 m, it is

$$\tilde{h}(D) = \begin{cases} h^*(D) & \text{if } \Delta x = 50 \\ \frac{\Delta x}{[1-(1-\frac{50}{h^*(D)})^{0.02\Delta x}]} & \text{if } \Delta x \ne 50. \end{cases} \tag{10}$$

Finally, the depth dependence of travel distance is obtained with

$$h(z,D) = \tilde{h}\left(1 + e^{Az}\right), \tag{11}$$

where