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Letter

Identification of tsunami deposits using a combination of radiometric dating and oxygen-isotope profiles of articulated bivalves

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ABSTRACT

Four tsunami deposits (deposits I–IV) have been identified on Ishigaki Island, southwest Japan. The youngest tsunami deposit (deposit I) was caused by the Meiwa tsunami, which occurred on 24 April 1771 CE, as described in reliable historical documents. Two well-preserved specimens of articulated marine bivalve were collected from the youngest tsunami deposit (deposit I) and an additional two from the second-youngest tsunami deposit (deposit II; 920–620 cal. yr BP). The shells were tightly closed and empty inside. No encrusting epifauna or evidence of erosion was observed on the inner or outer shell surfaces. In each tsunami deposit, the ^{14}C ages of the shells are nearly identical. The mode of occurrence and coincidence of ages mean that these shells were transported and buried alive by tsunamis. We analyzed the oxygen-isotope (δ^{18}O) profiles of these bivalves to determine the seasons of their death, which provides clues to the seasonal timing of tsunamis. Tsunami deposits I and II were formed during spring and fall, respectively. The former supports the proposal that tsunami deposit I was caused by the 1771 Meiwa tsunami and provides regional radiocarbon reservoir age for the late 1700s; the latter provides a chronological constraint on the identification of tsunami deposit II. Thus, a combination of radiometric dating and δ^{18}O profiles of articulated bivalves derived from tsunami deposits provides important chronologic constraints for examining paleo-tsunami events.

1. Introduction

Over the last two decades, the 2004 Indian Ocean earthquake (Mw 9.1) and the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0) caused mega-tsunamis that resulted in approximately 220,000 and 20,000 deaths, respectively. Both tsunamis transported sandy sediments from beaches and beach ridges, and deposited sand sheets across broad coastal lowland regions (Moore et al., 2006; Naruse et al., 2010; Goto et al., 2010; Shishikura et al., 2012; Takashimizu et al., 2012). Age dating of ancient sandy tsunami deposits is essential for determining the recurrence interval and size of mega-tsunamis over timescales of several thousand years (e.g., Minoura et al., 2001; Monecke et al., 2008; Shishikura et al., 2010; Sawai et al., 2012; Kitamura et al., 2013; Kitamura, 2016). Depositional ages of tsunami deposits are commonly based on ^{14}C dating. However, in case of tsunami events with a recurrence interval of 200 years, such as those occurring in the Nankai trough (Ando, 1975), the Kuril trench (Satake et al., 2005), and south-central Chile (Cisternas et al., 2005), the analytical error of the dated samples (especially marine specimens) are generally too large to identify tsunamis. Using a combination of ^{14}C dating and oxygen-isotope (δ^{18}O) profiles of articulated bivalves derived from tsunami deposits, it is possible to determine both the absolute age of a tsunami and the season of the year in which it occurred (Kingston, 2016). Articulated bivalves are targeted in such analyses, as they are assumed to have undergone transport and burial alive as a result of a tsunami (Kingston, 2016).

Before the occurrence of the 2011 off the Pacific coast of Tohoku earthquake, the largest tsunami recorded in Japan was the Meiwa tsunami of 24 April 1771 CE. The tsunami struck Ishigaki and Miyako Islands along the southern Ryukyu Trench (Fig. 1), and resulted in ~12,000 deaths (Kawana and Nakata, 1994). Based on historical records, the run-up heights of this tsunami were up to 27 m (Kawana and Nakata, 1994; Goto et al., 2010). That event and earlier tsunamis left numerous tsunami boulders in island areas (Kato and Kimura, 1983; Kawana and Nakata, 1994). Examination of tsunami boulders has provided information about the recurrence intervals of large tsunamis, but no information about tsunami size (Goto et al., 2010; Araoka et al., 2013). This is because tsunami run-up heights cannot be reconstructed

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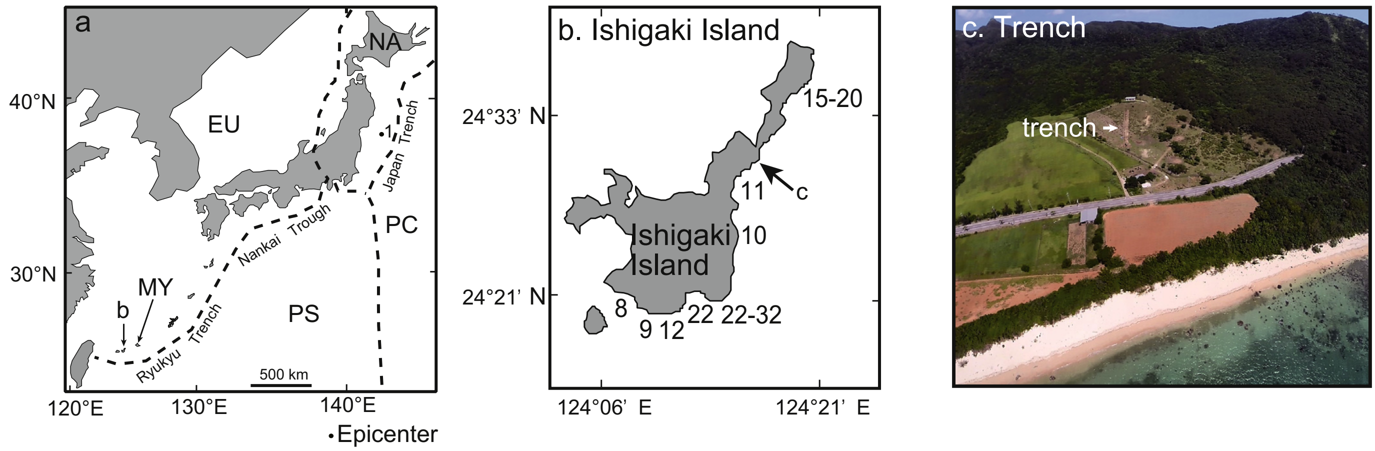

Fig. 1. (a) Plate boundaries around the southern Ryukyu Islands (after Ando et al., 2009). EU: Eurasia Plate; NA: North American Plate; PC: Pacific Plate; PS: Philippine Sea Plate; MY: Miyako Island. 1: epicenter of the 2011 Tohoku-oki earthquake (Mw 9.0). (b) Ishigaki Island, showing the location of the study area and the tsunami run-up heights (m) in 1771 on Ishigaki island (after Goto et al., 2010). (c) Photograph of the study trench.

from the distribution of tsunami boulders, although they can be determined from the landward margins of sandy tsunami deposits (MacInnes et al., 2009; Abe et al., 2012). However, sandy tsunami deposits have not been found on Ishigaki and neighboring islands.

Ando et al. (2018) identified four tsunami deposits (I–IV) in an excavated trench on Ishigaki Island, southwest Japan (Fig. 2). Although there is no terrestrial organic material (e.g., seeds, tree branches, or plant debris) in the tsunami deposits, well-preserved molluscs and corals were collected for radiocarbon dating. ^{14}C dating showed that deposits I–IV were deposited after 248 cal. yr BP, at 920–620 cal. yr BP, at 1670–1250 cal. yr BP, and at 2700–2280 to 1670–1250 cal. yr BP, respectively. Ando et al. (2018) also concluded that deposit I was caused by the 1771 CE Meiwa tsunami.

During the trench survey of Ando et al. (2018), the first author collected well-preserved, articulated marine bivalves, two specimens from deposit I and two from deposit II. The shells were tightly closed and empty inside. The inner and outer shell surfaces did not exhibit encrusting epifauna or evidence of abrasion and dissolution. The ^{14}C ages of the two shells from each tsunami deposit are nearly identical to one another (Fig. 2). Ando et al. (2018) therefore concluded that the shells were transported and buried alive by tsunamis. A similar interpretation was made by Reinhardt et al. (2006) and Donato et al. (2008), who concluded that the presence of allochthonous articulated bivalves in tsunami deposits in Israel or Oman indicates transport of live specimens over a large distance. In these previous studies, the premise is that these articulated shells should would all die at the same time, vs other processes that maybe more gradual (i.e. changes in water conditions).

In Ishigaki Island, Suzuki et al. (2008) identified the emerged massive *Porites* coral boulders using a combination of ^{14}C dating and δ^{18}O profiles. But, bivalves in tsunami deposits are advantageous, because live transport (articulated specimens) can be recognized versus gastropods, foraminifera and corals (Donato et al., 2008).

In the present study, we analyze the δ^{18}O profiles of these specimens to reconstruct the seasonal timing of the two tsunamis in Ishigaki Island.

2. Study site

The trench site is located at a farm on Ibaruma, Ishigaki Island (Fig. 1). The elevation of the trench site is approximately 3–10 m above sea level. The reef located off the study area is 1320 m wide and consists of a reef crest, a reef pavement, and a shallow lagoon that is < 4.0 m deep (Hongo and Kayanne, 2009). Based on the sea surface temperature (SST) recorded in Ishigaki Port from 1914 to 2000 (Mishima et al., 2010), the seasonal SST ranges from 19 to 20 °C (February) to 29–30 °C (late August to early September). Abe et al. (2009) produced continuous δ^{18}O records of sea surface water ($\delta^{18}O_{sw}$) for Ishigaki Port from 1998 to 2004. The annual mean value is 0.22‰, with a range of −0.1‰ to 0.4‰.

3. Samples and methods

The bivalve specimens analyzed in this study are *Fragum loochooanum* and *F. unedo* for deposit I and *Regozara flavum* and *Mactra maculata* for deposit II. As the thickness of the outer shell layer of *F. unedo* was too thin to collect powdered carbonate samples, we did not perform an δ^{18}O analysis on this specimen. Both *F. loochooanum* and *R. flavum* inhabit sandy substrata in the lower intertidal zone to a depth of 20 m (Okutani, 2000). *M. maculata* lives in the lower intertidal zone to a depth of 30 m (Okutani, 2000).

The specimens were embedded directly in polyester resin without any chemical treatment, and cut along the axis of maximum growth. The sections were ground with 1200 SiC grit. Powdered carbonate samples were collected from the outer shell layer using an automated Micromill sampler at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan (Sakai and Kodan, 2011). Individual milling steps ranged between ca. 550 and 1000 μm perpendicular to the direction of growth. Each milling yielded 40–120 mg of aragonite powder. The powdered carbonate samples received no additional thermal or chemical treatment prior to δ^{18}O analysis. The sample was analyzed using a mass spectrometer (IsoPrime, Micromass) at JAMSTEC. Individual samples were reacted with 100% phosphoric acid at 90 °C. Oxygen and carbon isotope values of shell carbonate ($\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$) are reported relative to the Peedee Belemnite (PDB), and the analytical precision (1σ) was better than ± 0.1‰ in all cases. X-ray diffractometer analysis revealed that the shells consist entirely of aragonite.

No previous study has investigated the lifespans of *F. loochooanum*, *R. flavum* and *M. maculata*, however, the lifespans of closely related species are 5 years (*Fragum fragum*), 5 years (*Acrosterigma burchardi*), and 12 years (*Mactra chinensis*), (Limpanont et al., 2010; Moss et al., 2016). Thus, the lifespans of the study species may reach 5 years.

4. Results

The $\delta^{18}O_{shell}$ values of *F. loochooanum* from deposit I are between −0.23‰ and −1.46‰, and become heavier and then lighter toward the distal end (Fig. 3). Except for one exceptionally light δ^{18}O value (−4.73‰), $\delta^{18}O_{shell}$ of *R. flavum* from deposit II ranges from −3.04‰