4 Discussions

4.1 Results of U/Th dating

4.1.1 Comparison to previous research of Suzuki et al. (2008)

Of the six ^{230}Th-dated *Porites* boulders, three (samples IYT2-1, GPS72 and IYT1) could not be attributed to the documented inundation events within the ^{230}Th dating error. Boulder IYT1 was dated to be A.D. 1780 ± 1. The surface part of the coral head was probably several years younger than the date because the dated sample was collected below the surface. It suggested that the coral head might continue growing after the 1771 Meiwa tsunami for about 10 years. One possible explanation would be that the *Porites* boulder was transported by the 1771 Meiwa tsunami from the original location to the shallower moat near shoreline, and that the *Porites* boulder was finally emerged and dead due to such as a severe storm occurred around A.D. 1780.

Boulders IYT2-1 and GPS72 were dead in about two decades before the 1625 event. There are some possibilities to explain the disagreement of the historical events with the ^{230}Th ages of these boulders. It is likely that severe storms may have mined the reef for materials to excavate old coral heads dead before the 1625 and 1771 events. It is also plausible that the surface part of the coral boulders was lost due to the ablation by the subsequent tsunamis and/or severe storms resulted in the older dates than the 1625 event. In addition, the following interpretation is also available: all of these three boulders (samples IYT2-1, GPS72 and IYT3-1) were old dead coral heads excavated by the 1771 Meiwa tsunami. However, I prefer a straightforward interpretation that there were two major inundation events, 1625 and 1771, in the region.

Suzuki et al. (2008) proposed that by combining ^{14}C dating with oxygen isotope microprofiling, paleo-tsunami boulders could be distinguished from those transported by storm events. Because the coral oxygen isotope ratio reflects sea surface temperature, the time of year of the event can be identified by applying the isotope microprofiling technique to the surface of *Porites* boulders (Suzuki et al. 2003). By this means, Suzuki et al. (2008) inferred that boulder IYT4-1-2 was probably transported by the 1771 Meiwa tsunami, and this inference is supported by the ^{230}Th age of A.D. 1772 ± 5 for the surface of the boulder (Table 1). On the other hand, Suzuki et al. (2008) ruled boulder GPS65 out as a Meiwa tsunami boulder, because of its calibrated ^{14}C-date date of A.D. 1858 and because its growth stopped at some time between summer and fall. However, it was dated by the ^{230}Th method to A.D. 1770 ± 3, suggesting that a more careful examination is essential to judge the surface condition of boulders.

4.1.2 Comparison to previous researches of marine reservoir effects

Several studies have reported local ΔR values for this region. Yoneda et al. (2000, 2007) estimated ΔR values by using mollusk shell samples that had been collected alive from the

Ryukyu Islands for taxonomic studies before any atmospheric nuclear bomb testing (Figure 9). Yoneda et al. (2007) obtained a mean ΔR value of 85 ± 45 years (n = 9) for the Taiwan and Ishigaki Island region and concluded that 73 ± 17 years (n = 14) is the typical ΔR value in waters of the Kuroshio Current region, which includes the southern part of the Ryukyu Islands. Estimated mean ΔR values in this study are broadly comparable to previous values obtained for the Kuroshio region, which are slightly smaller than the values reported by Yoneda et al. (2007). The mean ΔR value of 29 ± 18 years for the Okinawa and Amami (north of Okinawa) regions is smaller than that for the Kuroshio headwaters around Taiwan, suggesting active seawater–air carbon exchange or contributions from adjoining regions such as the South China Sea (where the mean ΔR value is –25 years; Yoneda et al. 2007). Water from land may also have affected these values (Yoneda et al. 2000).

Hideshima et al. (2001) investigated a long-lived modern *Porites* coral colony from the northeastern coast of Ishigaki Island and reported temporal variations of ΔR values, varying between –60 and 175 years (the mean ΔR value of 49 ± 41 years) for the interval between 1900 and 1950. My results also indicated temporal ΔR variation in Ishigaki Island. Possible causes of temporal ΔR variation include changes in the upwelling intensity of subsurface water along the Pacific margin, the North Pacific gyre circulation (Kuroshio and North Pacific Equatorial Currents) (Hideshima et al. 2001), hard water effect, and the effect of precipitation. In future research, the proxies of upwelling such as Ba/Ca ratios should be examined to quantify the influence of each of these possible causes.

4.1.3 Causes of paleo-inundation events

High-precision U/Th dating confirmed the previous finding that multiple events were responsible for the transport of massive *Porites* boulders on Ishigaki Island (Suzuki et al. 2008). Four coastal paleo-inundation events are recognized in historical chronicles: two earthquake tsunamis in 1687 and 1771, and two other inundation events in 1625 and 1714 whose causes are not specified. According to our ^{230}Th ages on *Porites* boulders and the revised ^{14}C age calibration, the events in 1771 and 1625 were larger than the other two (Figure 13). So far, I have no direct geological evidence of the 1687 and 1714 events.

The cause of the inundation in 1625 is still uncertain. Following a detailed examination, Higashiyamamori (2009) claimed that the 1625 event may have been caused by a severe typhoon because the inundation pattern was different from that of the 1771 Meiwa earthquake tsunami, which caused dreadful damage to villages along the eastern coast of Ishigaki Island. According to the description in “Yaeyama-jima Nenraiki”, Fukai village on the northwestern coast of Ishigaki Island was mostly destroyed by the event. However, by the hydrodynamic examination, Goto et al. (2009)

suggested that only tsunamis can transport such large boulders over wide reef flats. The result of this study is supportive that the 1625 event was also a tsunami because one of the largest *Porites* boulders (sample IYT3-1) was cast ashore behind the wide Ishigaki coral reef (less than 0.8 km).

The East Ishigaki Fault is drawing attention as a possible source fault of the 1771 Meiwa earthquake, because its length of 44 km, which corresponds to the estimated magnitude of 7.4 of the Meiwa earthquake (Nakamura 2006). If the 1625 event was also a tsunami and if both the 1625 and 1771 tsunamis were caused by the same fault, the recurrence interval could be estimated. But, most recently, Matsumoto et al. (2009a, 2009b) concluded that the East Ishigaki Fault might not be a source fault of the 1771 tsunami because no indication of the entire slip along the fault was found by seafloor observation from a remotely operated vehicle.

The available information is still too limited for reliable discussion of the source fault location and the seismic recurrence period in the region. However, this study shows the potential of U/Th dating of confirming paleo-inundation events through the ages of materials they transport on shore, particularly of large *Porites* boulders.

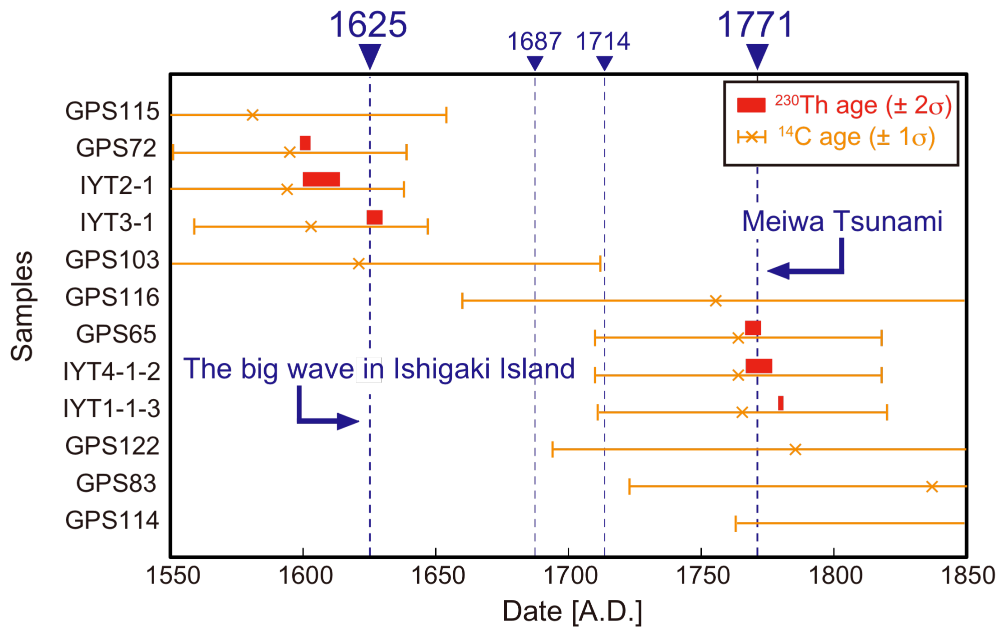

Figure 13. The ^{230}Th and ^{14}C ages of massive *Porites* boulders on Ishigaki Island. Local historical documents describe four paleo-inundation events during the 17–19th centuries in the southern Ryukyus. The 1771 event was the Meiwa earthquake tsunami. A big wave was recorded to have struck Fukai Village on the northwestern coast of Ishigaki Island in 1625, but its cause was not described in the documents.

4.2 Results of Radiocarbon dating

4.2.1 Distributions of the Meiwa-tsunami-derived Porites boulders

As discussed in the previous section, there were probably no large paleo-tsunamis since 1625 except for the Meiwa tsunami. According to the ^{14}C ages of these boulders, 39 boulders from Ishigaki, Tarama, Minna, Miyako and Shimochi Islands were likely attributed to the 1771 Meiwa tsunami. Especially, there were many *Porites* boulders cast ashore by the Meiwa tsunami in Tarama and Minna Islands (Figure 11). This result suggests that the Meiwa tsunami likely caused a considerable damage on not only Ishigaki Island but also Tarama and Minna Islands, considering the low altitudes of these islands (about 33m and 13m at highest points in Tarama and Minna Islands, respectively).

I also newly found several Meiwa-tsunami-derived *Porites* corals located with various geological settings (Figure 14). In northern part of Tarama Island, two boulders derived from the Meiwa tsunami were identified among many Ryukyu limestones of terrestrial origin (samples TRM196 and TRM198; Figure 15a and 15b, respectively). In southern part of the island, many *Porites* boulders are cast ashore along coastal lines in front of sand dunes (Figure 16) and most of them can be attributed to the Meiwa tsunami. I also found one Meiwa-derived boulder on a sand dune with a height of about 5 m for the first time (Sample TRM201; Figure 15c). Goto et al. (2010b) reported the date of the largest *Porites* boulder (more than 4 m in diameter) found in Tarama Island by measuring ^{14}C ages (sample TRM 34; Figure 15d). They also measured a cracked boulder found at southern coast of the island (sample TRM 77; Figure 15e). I conducted ^{14}C dating of these boulders again, and concluded that these were cast ashore by the Meiwa tsunami.

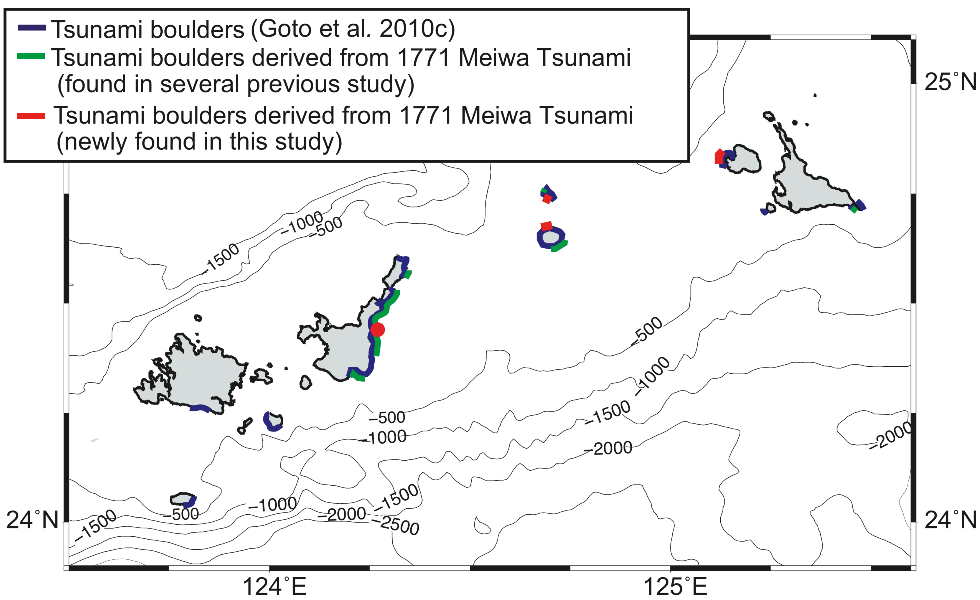

Figure 14. The distribution of the Meiwa-tsunami-derived boulders at Southern Ryukyu Islands. According to calibrated ^{14}C ages, *Porites* boulders cast by the Meiwa tsunami were confirmed.

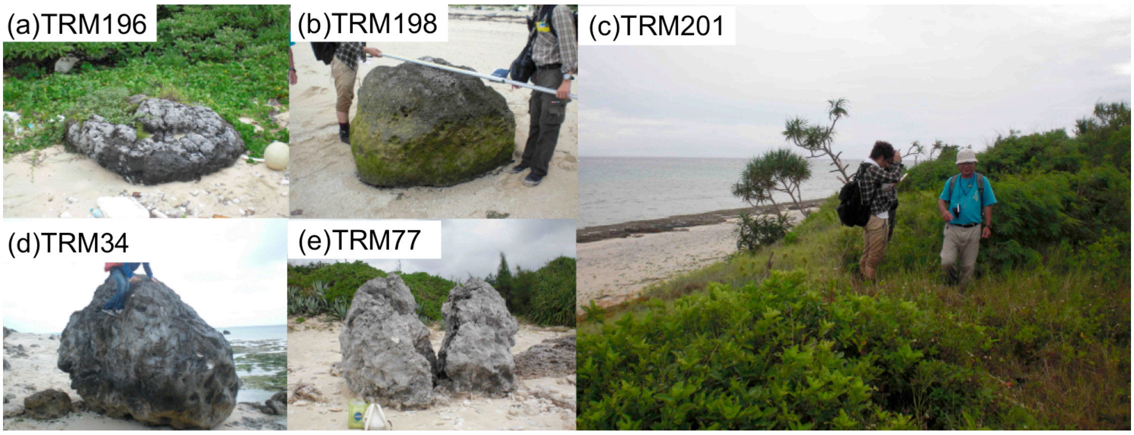

Figure 15. Photographs of the *Porites* boulders cast ashore by the Meiwa tsunami on Tarama Island.

Figure 16. Photograph of the southern coast of Tarama Island. Many *Porites* boulders are scattered along the shore in front of sand dunes. The numbers show the sample ID.

When the Meiwa tsunami struck, the whole area of Minna Island was likely inundated because of its low altitude. Four big boulders exist along the intertidal zone near the Minna harbor (samples GPS240, GPS241, GPS242 and GPS243; Figure 17a-c), and all of these are likely derived by the Meiwa tsunami according to ^{14}C ages determined in this study. Among them, the biggest one was more than 4 meter in diameter (GPS240; Figure 17a). Kato (2000) reported a Meiwa-tsunami-derived boulder at a point 300 m inland from the shoreline, but they did not use an appropriate ΔR value. Goto et al. (2010b) checked the date of this boulder by appropriate ^{14}C dating, but their sample may not be the youngest part of the boulder. In this study I also conducted multiple

^{14}C dating on the surface of the boulder (sample GPS229; Figure 17d-e), and concluded that the boulder was transported there in 1771. I found that the boulder was buried by the Meiwa tsunami because of calibrated ^{14}C date (sample GPS236; Figure 17f-g).

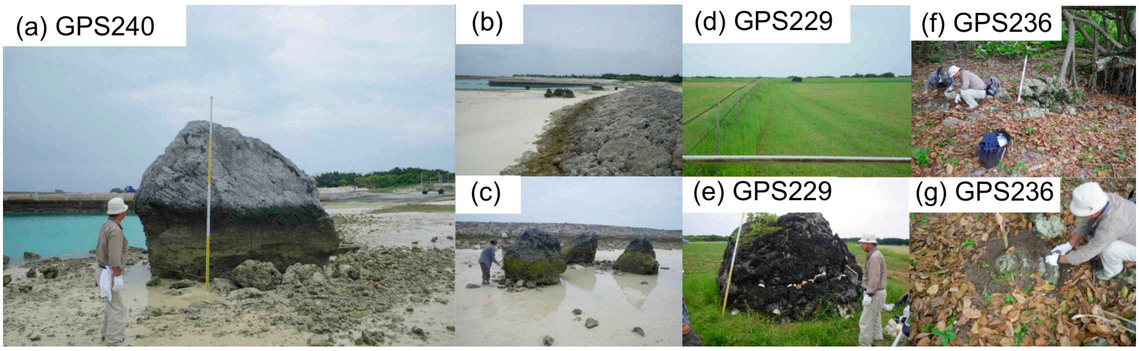

Figure 17. Photographs of the *Porites* boulders cast ashore by the Meiwa tsunami on Minna Island.

In Shimochi Island, calibrated dates of tsunami boulders were reported in this study for the first time. I found two massive boulders derived by the Meiwa tsunami located at the tidal zone, west of the Shimochi Airport (samples GPS277 and GPS278; Figure 18a-b). Their diameters were both more than 5 m.

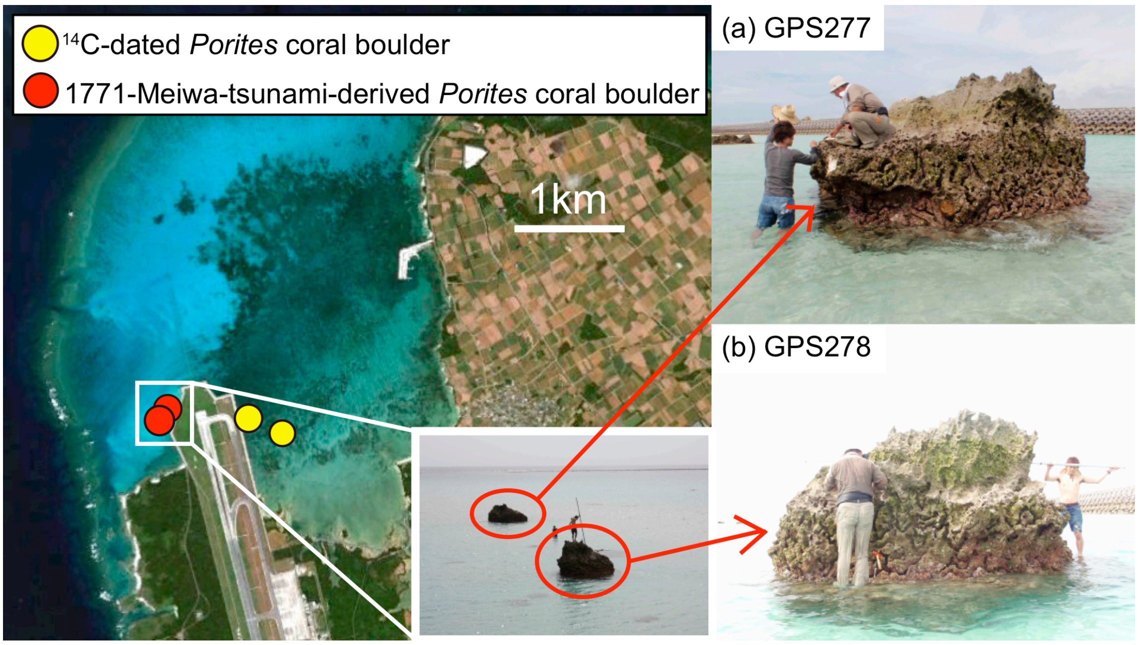

Figure 18. Photographs of the *Porites* boulders cast ashore by the Meiwa tsunami on Shimochi Island. The left map shows long reef moat and beach called “Sawadano-hama”.