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Historical and geological evidence of boulders deposited by tsunamis, southern Ryukyu Islands, Japan

Kazuhisa Goto [a],*, Toshio Kawana [b], Fumihiko Imamura [a]

[a] Disaster Control Research Center, Graduate School of Engineering, Tohoku University, Aoba 06-6-11, Aramaki, Sendai 980-8579, Japan
[b] Faculty of Education, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan

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ABSTRACT

Sedimentary features and identification criteria of boulders deposited by tsunamis and storm waves are highly controversial because of the lack of detailed studies of boulders that are known to have been deposited by tsunami or storm waves. The coastal boulder fields of the Ryukyu Islands, Japan are one of the few places where comparisons can be made between the distribution and characteristics of boulders deposited by a known historical tsunami and storm waves. The 1771 Meiwa Tsunami struck the southern Ryukyu Islands (Miyako–Yaeyama Islands) and reliable historical documents describe run-up heights of up to 30 m. The displacement of specific boulders by the tsunami is also described in detail. Some of the islands away from the Miyako–Yaeyama Islands were unaffected by this tsunami, but they have been extensively affected by typhoon-generated storm waves. On these islands, the boulders were commonly deposited on the reef flat within 300 m of the reef edge as an exponentially fining landward deposit. This provides a useful indication of the transport limit for storm waves on the Ryukyu Islands. In the tsunami-affected islands, boulders of different types have been deposited both on the reef crest and along the shoreline. The reef crest boulders are identified as storm wave emplaced, whereas those along the shoreline are interpreted as tsunami boulders (“tsunami-ishi” in Japanese) because they are exceedingly heavy and are deposited well beyond (ca. 1.5 km from the reef edge) the transport limit for storm waves. Their 1771 Meiwa Tsunami origin is supported by ^{14}C age results, although prior tsunami(s) may have deposited some of the boulders. Based on these results, we infer that the difference between the wave periods of tsunami and storm waves is crucial to differentiating tsunami boulders from other enigmatic boulder deposits around the world. Differences in wave period are reflected in differences between the spatial and clast size distributions of boulder deposits. The distribution and sedimentary characteristics of tsunami boulders therefore provide useful data for estimating possible tsunami sources. The boulders on the Ryukyu Islands are also useful for differentiating between tsunami and storm wave emplacement and for estimating their hydrodynamic properties.

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* Corresponding author. Present address: Planetary Exploration Research Center, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino 275-0016, Japan. Tel.: +81 47 478 4734; fax: +81 47 478 0372.
E-mail address: kgoto@perc.it-chiba.ac.jp (K. Goto).

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1. Introduction

Coastal boulders are important geological phenomena reflecting the occurrence of large tsunami and storm events that have occurred in the past. Many enigmatic boulders with a mass of up to several thousands tons that have been displaced landward from the sea have been reported throughout the world (Fig. 1). Their purported tsunami origins have been asserted for some of these boulders (e.g., Young and Bryant, 1992; Young et al., 1996; Mastronuzzi and Sansò, 2000; Nott, 2000; Bryant, 2001; Nott, 2003; Mastronuzzi and Sansò, 2004; Scheffers et al., 2005; Whelan and Kelletat, 2005; Scheffers and Kelletat 2006; Mastronuzzi et al., 2007; Scheffers and Scheffers, 2007; Scicchitano et al., 2007; Kelletat, 2008; Scheffers, 2008; Frohlich et al., 2009; Pignatelli et al., 2009). Nevertheless, the tsunamis that might have deposited these boulders were not specified. Moreover, some of the proposed tsunami origins remain highly controversial (e.g., Felton and Crook, 2003; Noormets et al., 2004; Dawson et al., 2008; Morton et al., 2008; Spiske et al., 2008; Goto et al., 2009a; Goff et al., 2010) because the sedimentary differences between boulders laid down by tsunami and storm waves are poorly understood.

Few indisputable examples exist of boulders that have been deposited by historical tsunamis. Displacement of small boulders or artificial debris has been reported in some historical tsunamis (e.g., Goff et al., 2006; Bourgeois and MacInnes, in press). Nevertheless, only three cases of spectacular boulder fields have been reported: the 1771 Meiwa Tsunami in southern Japan (e.g. Kawana, 2000), the 1883 Krakatau Tsunami in Indonesia (Simkin and Fiske, 1983), and the 2004 Indian Ocean tsunami (2004 IOT) in Thailand and Indonesia (e.g. Goto et al., 2007). Among these, the boulders deposited by the 2004 IOT provide useful data concerning on the sedimentary features of tsunami boulders as well as local tsunami flow characteristics (Kelletat et al., 2007; Goto et al., 2007, 2009b, 2010a; Yawsangratt et al., 2009; Paris et al., 2009, 2010). However, the 2004 IOT displaced boulders weighing less than 23 tons of boulders, which is a remarkably light compared with other enigmatic boulder groups reported throughout the world. This is probably because a tsunami's boulder displacement capability is related not only to the shape and weight of boulders available for transport and the wave properties (height and period), but also the profile of the coastline, the original boulder placement, their position — whether scattered or attached to the reef rock; and the tsunami waveform — whether a wave trough or crest arrives first (Goto et al., 2009b). Goto et al. (2010a) indicated that there is not a direct relationship between tsunami magnitude and the boulder weights and numbers it transports. Therefore, studies of

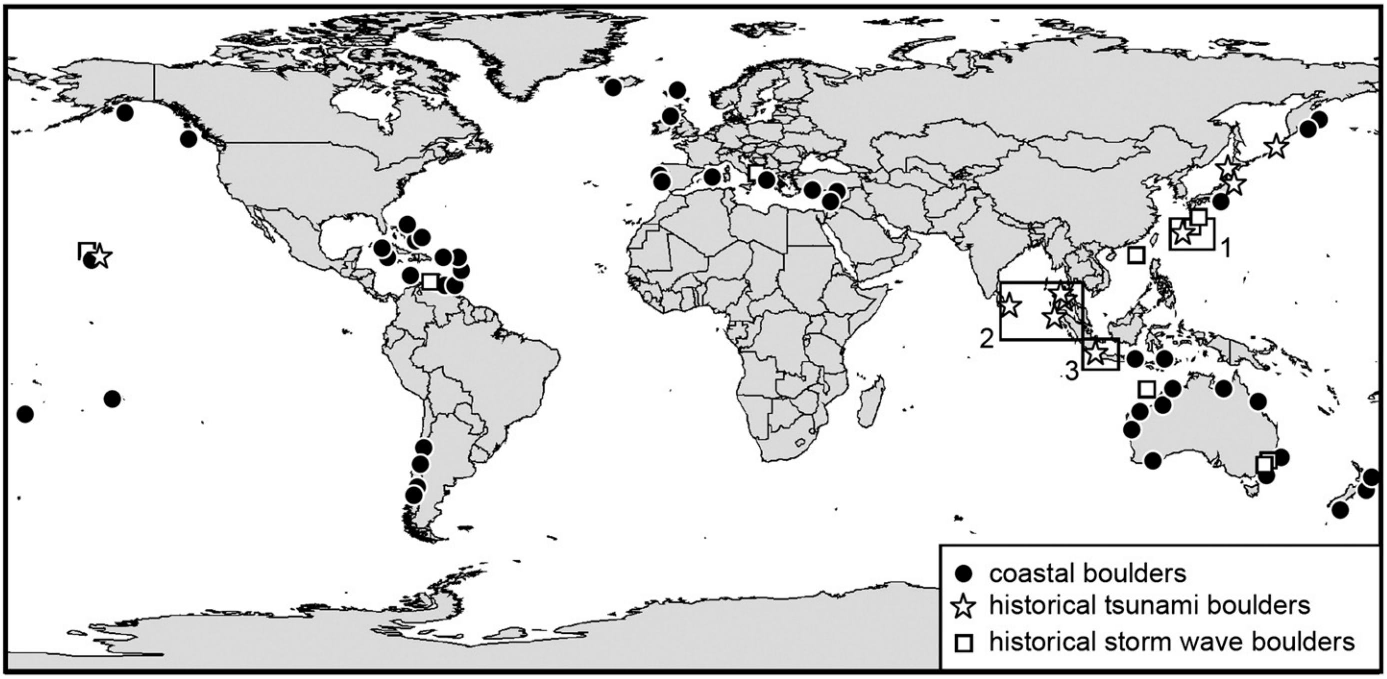

Fig. 1. Distribution of coastal boulders (modified after Scheffers, 2008). 1, 1771 Meiwa Tsunami; 2, 2004 Indian Ocean Tsunami; and 3, 1883 Krakatau Tsunami. Historical tsunami and storm wave boulders were defined here as those purporting to show clear depositional evidence based on historical descriptions, direct observations, and analyses of aerial photographs during the historical age.

the boulders deposited by the 2004 IOT are of limited use in understanding the formation of enigmatic boulder fields.

The 1883 Krakatau Tsunami also deposited numerous large boulders along the coast of the Sunda Strait in Indonesia (e.g. Simkin and Fiske, 1983). However, this event is considered atypical because the tsunami was accompanied by submarine volcanism (e.g. Nomanbhoy and Satake, 1995) and therefore the generation mechanism was different, making it difficult to compare with other seismic related events. Therefore, it remains uncertain whether boulders deposited from this tsunami have similar sedimentary features to boulders deposited by earthquake-related tsunamis.

Numerous (more than 5000) large coralline reef and limestone boulders with individual weights of up to 2500 tons are found along the coast of the Miyako–Yaeyama Islands, southern Ryukyu Islands, Japan (Figs. 2 and 3). Their 1771 Meiwa Tsunami origin has long been suspected. Subsequent to the pioneering studies by Iwasaki (1927) and Imamura (1938), extensive investigations of tsunamis and possible tsunami boulders have been carried out over the last 40 years by Japanese historians, archaeologists, geologists, and coastal engineers (e.g., Makino, 1968; Kato and Kimura, 1983; Kato and Oyama, 1987; Kawana and Nakata, 1987; Kato, 1987, 1989; Kawana and Nakata, 1994; Nakata and Kawana, 1995; Kawana, 2000; Imamura et al., 2001, 2008; Suzuki et al., 2008; Goto et al., 2010b; Araoka et al., 2010). Importantly, many historical documents related to the 1771 Meiwa Tsunami describe the maximum run-up heights and damage to humans, houses, and coastal environments. Moreover, it is particularly interesting that the movements of specific boulders are described in these documents (Table 1, Kawana and Nakata, 1994; Kawana, 2003). Scientific evidence also supports their 1771 Meiwa Tsunami origin (e.g. Araoka et al., 2010). For these reasons, the boulders are unique among coastal boulder deposits throughout the world.

The boulder fields formed by the 2004 IOT and the 1883 Krakatau Tsunami are at low latitudes where they are unlikely to be reworked by strong tropical cyclones. Consequently, the presence of the large storm wave boulders within these fields is unlikely. The Ryukyu Islands site is therefore the only known boulder field in the world where the sedimentary differences between historical tsunami and storm wave boulders can be studied. Furthermore, some of the islands away from the Miyako–Yaeyama Islands only have storm boulder deposits and there appear to be striking contrasts between the boulder distributions of these two island groupings (storm/tsunami versus storm) (Goto et al., 2010b).

The studies carried out on the boulders deposited by the 1771 Meiwa Tsunami and by storm waves on the Ryukyu Islands provide valuable data for determining the sedimentary features of tsunami boulders and to establish identification criteria that can be used for studying the origin of enigmatic boulders throughout the world. However, despite the importance of these studies, most papers were only written in Japanese and are difficult for non-Japanese researchers to access. It is therefore valuable to review the series of Japanese studies of this event and coastal boulders in the Ryukyu Islands for a readership of broadly related fields. For this purpose, we review the historical and geological evidence of the 1771 Meiwa Tsunami. We then discuss the distribution and sedimentary features of tsunami and storm wave boulders deposited on the Ryukyu Islands in order to determine criteria for the identification of tsunami boulders, and to use the boulders as useful markers to constrain tsunami source models.

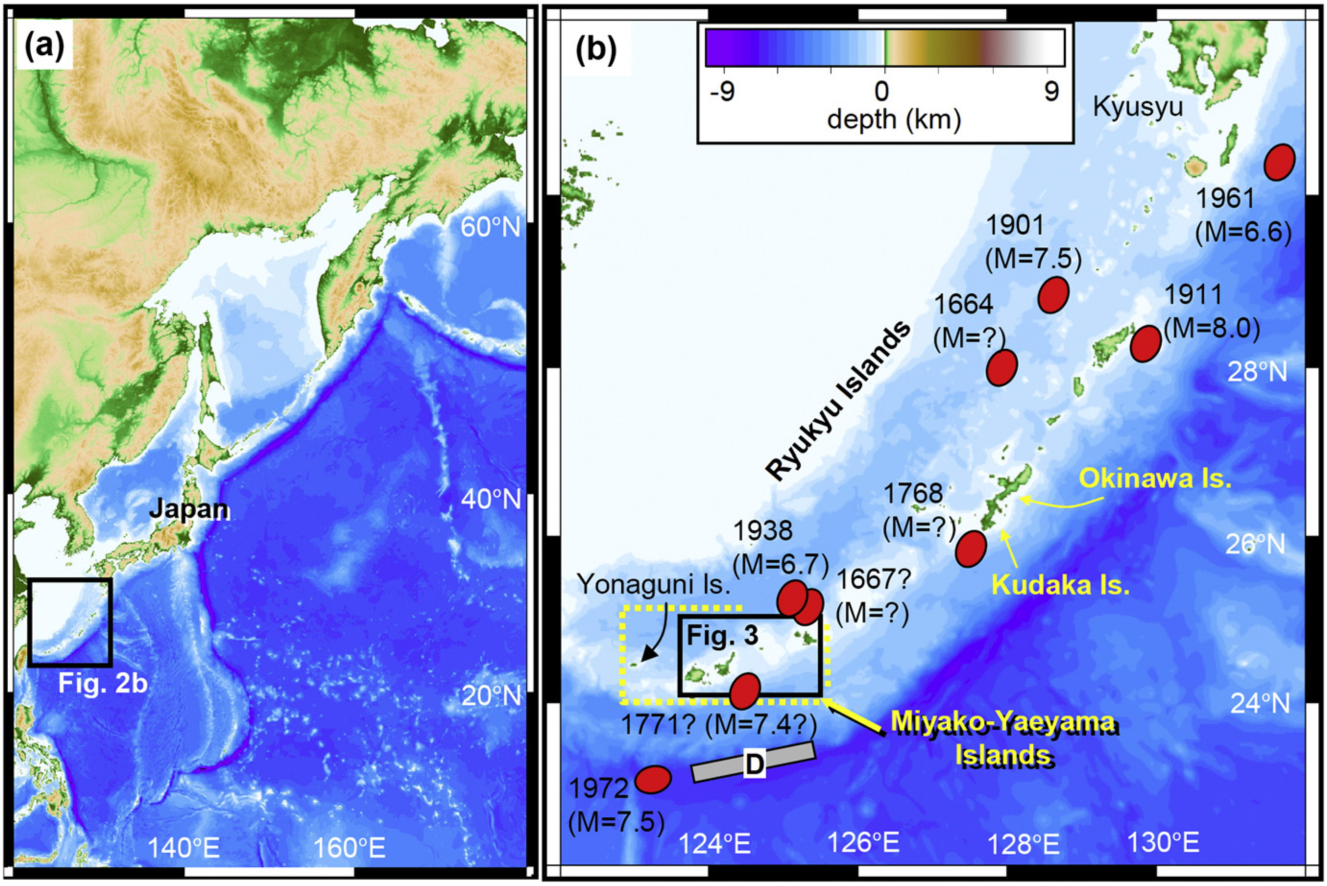

Fig. 2. (a) Map showing the location of Japan and the Ryukyu Islands. (b) Map showing the location of Miyako–Yaeyama Islands. Locations, ages, and magnitudes of historical earthquakes are shown (as red ovals) based on Nakata and Kawana (1995). D = fault rupture area for tsunami source model proposed by Nakamura (2009).

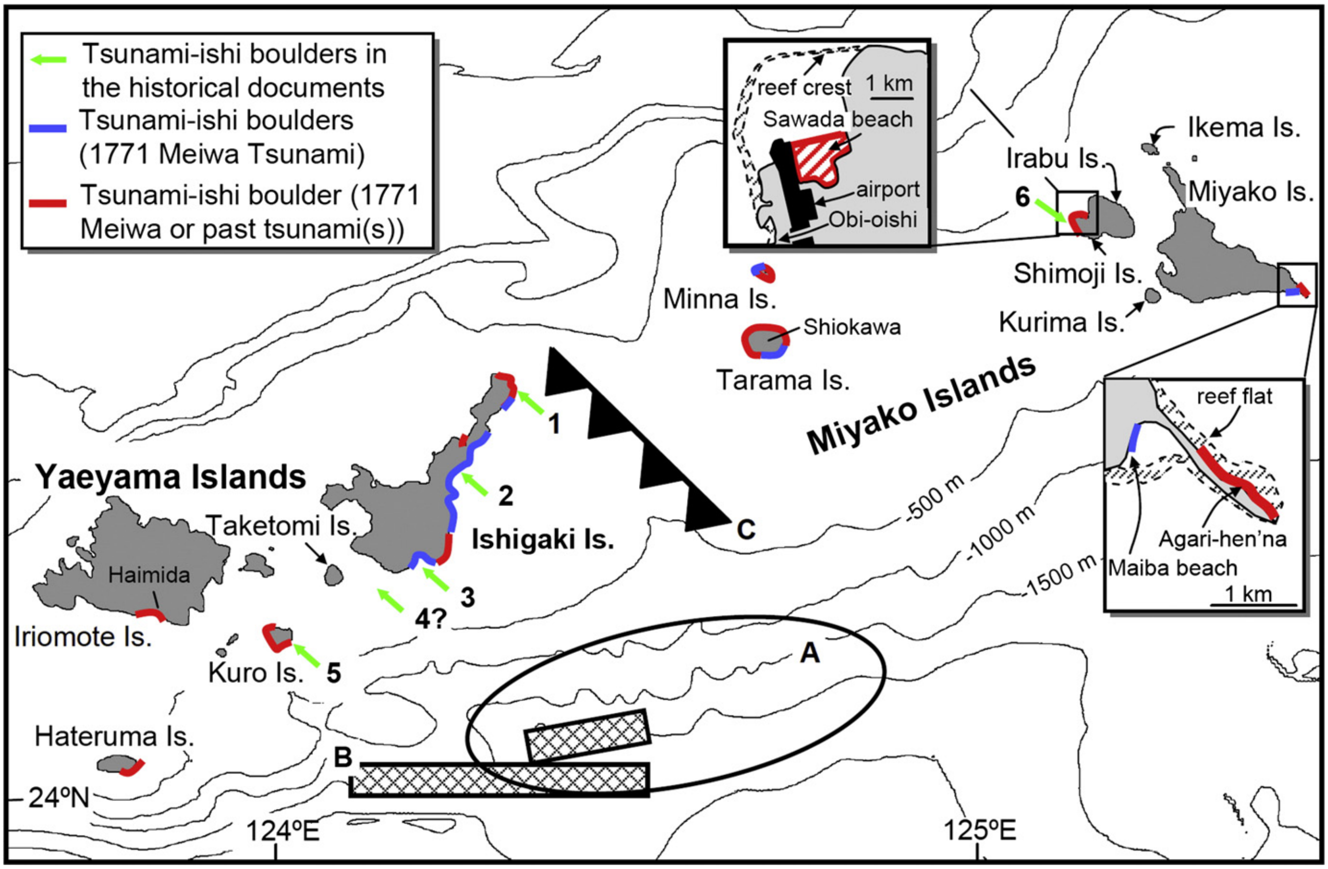

Fig. 3. Map showing the location of the damaged area by the 1771 Meiwa Tsunami. Overall distribution areas of boulders and fault rupture area for proposed tsunami source models are also presented: A = Nakata and Kawana (1995); B = Imamura et al. (2001, 2008); and C = Nakamura (2006). For boulders numbered 1–6, please refer to Table 1.

Table 1
Historical description of boulders moved by the 1771 Meiwa Tsunami.

Number in Fig. 3	Island and name of the village	Name of boulder	Original description	Presence of possible boulders	Size of boulder (m)	Distance from the reef edge (m)
1	Ishigaki Island[*1] Yasura	Yasura-ufukane	There is a big boulder of about 3.6 m ("2 *ken* [*3]" in old Japanese unit of distance) at Iha area, north of Yasura village. The boulder looks like an iron body. It was moved approximately 54.6 m (30 *ken*) north by the tsunami.	Yes "*Ifan-gani*"[*6]	6×3×3	1500 (along the shoreline)
2	Ishigaki Island[*1] Inoda	Amatariya–Suuari	There are two boulders at Inoda. The dimensions are approximately 5.5 m and were transported from the sea. These boulders were known as "*Amatariya-Suuari* ". It was originally located approximately 327 m ("3 *chou* [*4]") from the shoreline, known as "*amatariya* ", and was transported landward later by the 1771 Meiwa Tsunami, and deposited approximately 218 m ("2 *chou* ") inland from the shoreline.	Yes	5×5×6 11×9×6	1400 (10 m elevation)
3	Ishigaki Island[*1] Ohama	Taka-Koruse ishi	There is a boulder of about 7.3 m (4 *ken*) near the northern edge of the channel of the reef at Ohama, approximately 747 m (6 *chou* plus 51 *ken*) east from the Ohama village. Another boulder of similar size is located at Tofuriya area, 523 m (4 *chou* plus 48 *ken*) north along the S15W direction from the Ohama village. These two boulders were originally located in the property of "*Koruse–Utaki* " Shrine but were displaced by the 1771 Meiwa Tsunami.	One only (TK-2)	Split into several pieces	>600 (5 m elevation)
4	Ishigaki Island[*1] on the reef flat	Fukuraori-ishi	On the reef flat "*Awasa-hise* ", approximately 7.6 km south along the N15E direction from Kuramoto area near Hirae, there is a large boulder of 10.9×3.6×6.1 m. It was called "*Fukuraori-ishi* " and was deposited at Itokazu beach in Hirae village. It was displaced by the tsunami backwash and deposited at its position. Surprisingly, it was not deposited on the sea bottom during the displacement by the tsunami.	Not yet identified	N/A	N/A
5	Kuro Island[*1] Nobaru	None	There is a 7.3 m (4 *ken*) boulder at Nobaru, Kuro Island. The origin of the boulder is unknown.	Not yet identified	N/A	N/A
6	Shimoji Island[*2] N/A	None	Three extremely large boulders were deposited on the cliff top with height of 15 m (10 *hiro* [*5]) at southern island. Sizes are 1) 13.5 m in height and 60 m in overall circumference, 2) 18×12×9 m, and 3) 12×6×6 m. In addition, many boulders of 4.5–6 m were also deposited.	Not yet identified	N/A	N/A

*1: Data source: Kawana (2003).
*2: Data source: Kato (1989).
*3: 1 *ken* = approximately 1.8 m.
*4: 1 *chou* = approximately 109 m.
*5: 1 *hiro* = approximately 1.5 m.
*6: Present local nickname.

2. Geographical and geological setting of the Miyako–Yaeyama Islands

The Ryukyu Islands extend approximately 1000 km northeast to southwest along the Ryukyu Trench between Taiwan and Kyushu, Japan (Fig. 2). Most of the islands and islets of the Ryukyu Islands are rimmed by fringing reefs (Kan et al., 1995). The Miyako–Yaeyama Islands are located in the southwestern Ryukyu Islands (Fig. 2b). The Miyako Islands comprise the islands between Miyako and Tarama islands and the Yaeyama Islands consist of the islands between Ishigaki and Yonaguni islands (Figs. 2b and 3). At Ishigaki Island, the tide is semidiurnal, with a spring range of 2.0 m and the mean low water level is 1.0 m below mean sea level (Iryu et al., 1995).

Coral reefs vary between the islands, but in general terms the reef is divided into the reef flat and reef slope. From shore to offshore, the reef flat can be subdivided into a moat (shallow lagoon, typically <4 m deep), reef crest (and reef pavement), and reef edge. Generally, the reef slope is a steep escarpment at the reef edge (approximately 1/10 slope inclination); with spurs and grooves extending down to depths of several tens of meters at each island (Hongo and Kayanne, 2009). At

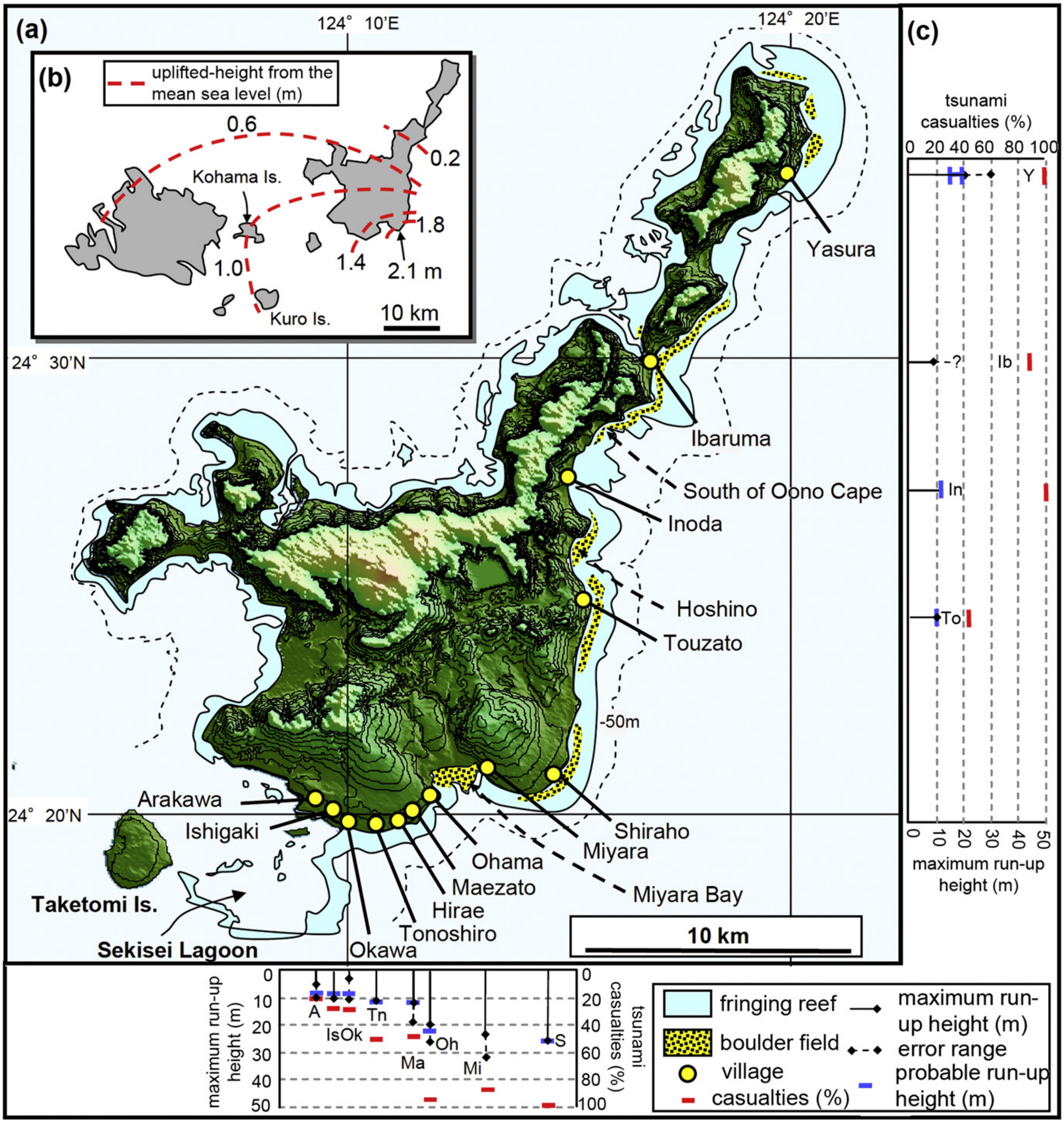

Fig. 4. (a) Map showing locations of damaged villages and coastal boulder fields on Ishigaki Island. Contour lines show 10 m intervals between 0 and 100 m altitude; (b) Distribution of uplift-heights above mean sea level, as estimated from wave cut notches (Kawana, 1987, 1989); (c) Maximum run-up height (m) and tsunami casualties (%) (red line) at each village after Kawana (2003) (see also Table 2). Y = Yasura, Ib = Ibaruma, In = Inoda, To = Touzato, S = Shiraho, Mi = Miyara, Oh = Ohama, Ma = Maesato, Tn = Tonoshiro, Ok = Okawa, Is = Ishigaki, and A = Arakawa. Uncertainty of the run-up height is recognized in the error range. Probable run-up height (blue line) is estimated by Kawana (2003) and this study with consideration of geomorphic features.

Ishigaki Island, well developed reefs are found along the Pacific windward coast, and poorly developed reefs are found in more protected leeward areas (Ministry of the Environment and Japan Coral Reef Society (ME and JCRS), 2004). At Miyako Island, coral reefs have developed along the northeastern coast, although the southern coast has sheer cliffs and narrower reefs (ME and JCRS, 2004). Irabu and Shimoji Islands are surrounded by weakly developed reefs. Tarama and Minna Islands are surrounded by simple fringing reefs and the sea bottom is mostly bare rock (ME and JCRS, 2004). Sekisei Lagoon, formed within the barrier reefs (Kan and Kawana, 2006) between the southwestern coast of Ishigaki Island and the eastern coast of Iriomote Island including Taketomi and Kuro Islands, is about 10–20 m deep (Machida et al., 2001).

The Holocene reefs around Ishigaki Island initiated around 8500–7800 cal year BP at depths of around 20–25 m below the present sea level (Yamano et al., 2001; Kan and Kawana, 2006; Hongo and Kayanne, 2009). Eustatic sea level reached its present level at about 6000 cal year BP and it has generally remained stable since then (Yamano et al., 2001, 2003). The reef crest reached present sea levels at around 4700 yr BP on the windward reefs (ME and JCRS, 2004). Elevations of erosional notches suggest about 0.6–0.8 m of uplift at northwestern part of Ishigaki Island, 2.1 m at the southeastern part of Ishigaki Island, and 1.0 m at Kuro Island (Fig. 4b, Kawana, 1987). This coastal uplift might have occurred because of a large earthquake that occurred at the reverse fault along the landward fringe of the deep submarine terrace between Ishigaki Island and the Ryukyu Trench southeast of Ishigaki Island about 2000 yr BP (Kawana, 1989). At Miyako Island, on the other hand, no marked uplift or tilting has been recorded (Kawana and Pirazzoli, 1985; Kawana, 1987).

Ishigaki Island comprises pre-Cenozoic basement rocks (Ishigaki Group; Permian Tomuru Formation and Jurassic Fusaki Formation), Upper Eocene Miyara Formation, and Pleistocene Ryukyu Group (e.g. Nakagawa, 1983). The Ryukyu Group of Ishigaki Island consists of conglomerate, sandstone, and mudstone (Nagura Formation), along with limestone of several types (Ohama Formation) (e.g. Kaneko et al., 2004). The limestone of the Ohama Formation covers part of the lowlands and forms the coastal terraces at Ishigaki Island. Miyako Island and surrounding small islands are composed mainly of Pleistocene limestone of the Ryukyu Group, comprising mudstones and sandstones (Nakamori, 1982; ME and JCRS, 2004).

The Ryukyu Islands are struck by several severe typhoons every year. Approximately 110 typhoons have passed near the Miyako–Yaeyama Islands since 1951 (Fig. 5, Japan Meteorological Agency (JMA), undated; Kitamoto, undated) with a maximum low pressure of 905 hPa and highest wind speed of around 60 m/s. The possible maximum significant wave height (SWH) is expected to reach 20 m (Yamashita et al., 2008). In contrast, nine historical tsunamis have affected the area since 1644 (Fig. 2b, Watanabe, 1985). Among them, three tsunamis occurred near the Miyako–Yaeyama Islands: two of the three were assumed to have occurred north of Shimoji Island and the other one (the 1771 Meiwa Tsunami) hit southeast of Ishigaki Island. The 1771 Meiwa Tsunami was the largest tsunami to strike the Ryukyu Islands since 1644 (Nakata and Kawana, 1995).

3. Historical evidence of the 1771 Meiwa Tsunami

Damage from the 1771 Meiwa Tsunami is recorded in detail in "*Kyuyo*", the official history of the Dynasty of the Ryukyus (e.g., Kyuyo-Kenkyu-kai, 1974; Kawana, 2000, 2003; Shimabukuro, 2004; Kawana et al., 2006a). Moreover, local histories "*Nariyuki-syo*" for Ishigaki Island (Fig. 6, Iwasaki, 1927; Makino, 1968) and "*Otoiai-gaki*" for Miyako Island (Shimajiri, 1988; Kato, 1989) as well as local legends (e.g., Yoshizawa and Isozaki, 2009) describe the tsunami damage.

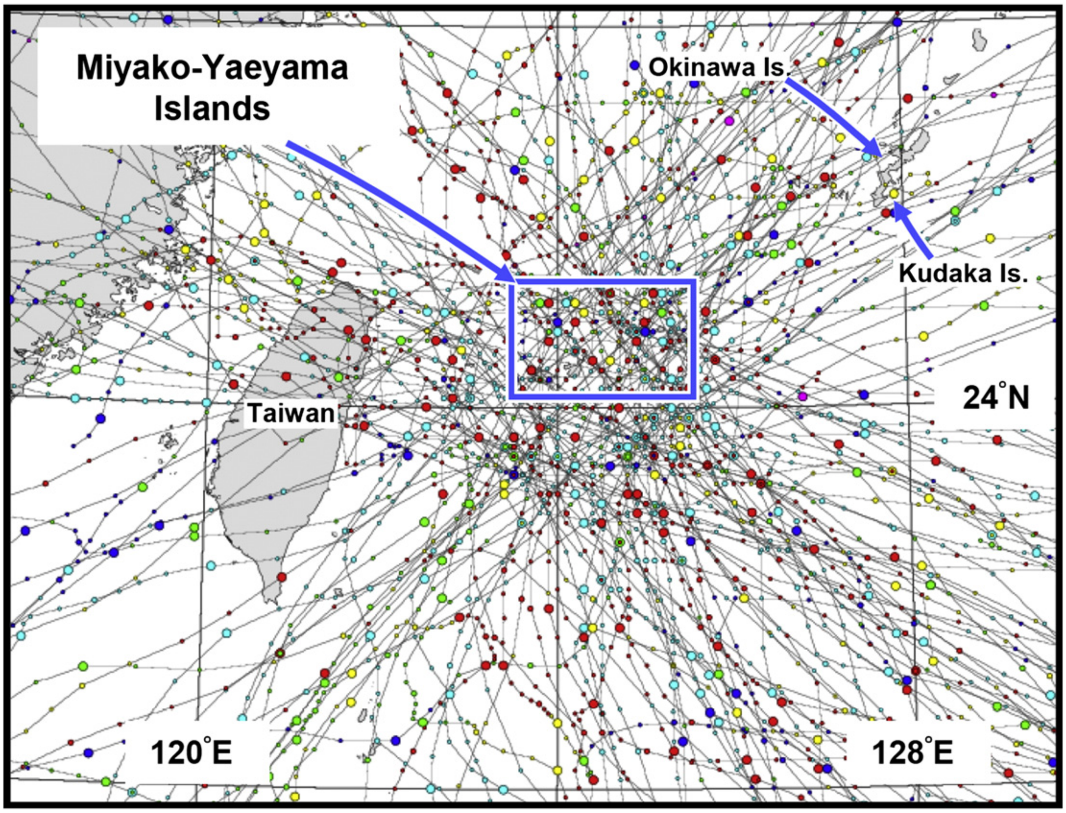

Fig. 5. Passes of 113 typhoons that approached the Miyako–Yaeyama Islands after 1951(blue — tropical depression; green — tropical storm; yellow — severe tropical storm; red — typhoon; purple — extratropical cyclone; and light blue — others). Data are from the Japan Meteorological Agency. The figure was created for the following web-site (http://agora.ex.nii.ac.jp/digital-typhoon/index.html.en, Kitamoto, A/National Institute of Informatics. All Rights Reserved.).

Fig. 6. Original text of the tsunami damage recorded in the historical document "*Nariyuki-syo*". The text is in the possession of K. Kisyaba. The source of this picture is Makino (1968) (courtesy: H. Makino).

According to these historical documents, the 1771 Meiwa Tsunami was generated around 8:00 am on 24 April 1771, the tidal level at the time was around the mean sea level. The tsunami killed 9393 people on Ishigaki Island—a third of all inhabitants—and 2548 people on the Miyako Islands (Table 2, e.g., Kyuyo-Kenkyu-kai, 1974; Kawana, 2000). At that time, large villages were mostly located in the lowlands of the southern part of Ishigaki Island. Consequently, the tsunami casualties at the southern part of Ishigaki Island were high (Table 2, Nakata and Kawana, 1995). In contrast, only slight damage was reported at Taketomi Island, just 5 km south of Ishigaki Island (Makino, 1968). It is probably that the island was protected by the Sekisei Lagoon, with the tsunami energy greatly reduced before reaching the island. Apart from the Miyako–Yaeyama Islands, no tsunami damage was reported in the Ryukyu Group.

Historical documents describe the maximum run-up heights in each village on the Miyako–Yaeyama Islands, as measured by administrators of the Dynasty of the Ryukyus and local residents (Table 2, Makino, 1968; Kawana et al., 2006b). According to these documents, maximum run-up heights at the major islands were 85 m on Ishigaki Island, 11 m on Miyako Island, and 36–39 m on Shimoji Island (Table 2, Kato, 1989; Kawana, 2000). However, the maximum value of 85 m for Miyara village on southern Ishigaki Island, has been questioned by many researchers (e.g. Kawana, 2000) because the height is greater than the maximum elevation in the area. Similarly, 36–39 m on Shimoji Island is questioned (Kato, 1988; Nakata and Kawana, 1995) because the island's highest point is 21.7 m. It remains uncertain how people measured such run-up heights.

Based on the historical descriptions, Shimabukuro (2004) inferred that people probably used a simple tool called a "*Toita* (a panel of a house)", to measure the run-up heights at Ishigaki Island because precision measuring instruments, which were in the central office of Ishigaki Island, were probably swept away by the tsunami. Shimabukuro (2004) and Kawana et al. (2006b), tested the errors of this form of measurement using a *Toita* and found that a vertical error of about 11 cm for 3.03 m in horizontal distance. The errors were compounded with increasing horizontal distance from the shoreline. Therefore, they suggested that a large error could be expected for a measurement of 85 m at Miyara village because the horizontal distance from the shoreline to the damaged area was >3 km (Table 2, Kawana, 2003). On the other hand, the documented run-up heights on Miyako Island seem accurate (Kawana, 2003). This is because precision measuring instruments were probably safe at the office, where tsunami damage was minor.

Maximum run-up heights can be estimated independently from the historical descriptions. For example, damaged or undamaged shrines, water wells, and infrastructure are also described in these documents. All were critically important for the daily life of local residents. Importantly, most of their positions have been identified (Fig. 7, Nakata and Kawana, 1995; Kawana, 2000, 2003). Moreover, these documents relate to the eyewitness accounts of surviving residents. Table 2 presents the relevant information used to estimate run-up heights at each village on each island. The table shows that the documented run-up heights are precise at villages where the distance between the shoreline and the damaged area was short (Fig. 7b, e.g., Arakawa, Ishigaki, Okawa, and Tonoshiro villages). In contrast, the difference between the historically documented run-up heights and our own estimates were remarkably large for great horizontal distances (e.g., Miyara, Ohama, and Shiraho villages). Based on these evaluations and geomorphological considerations, the maximum run-up heights of the tsunami are estimated as about ~30 m at Ishigaki Island (Kawana, 2000), ~10 m at Miyako Island (Nakata, 1990) and ~15 m at Tarama Island (Nakata, 1990), although some uncertainty remains and this is recognized in the error range shown in Fig. 4c.

4. Earthquake magnitude and tsunami source model

Historical documents are useful for helping to estimate magnitude of the 1771 earthquake and for developing a tsunami source model. Imamura (1938) estimated the 1771 earthquake magnitude as Mw = 7.4 based upon the few descriptions of earthquake damage. However, this magnitude is remarkably small when compared with

Table 2

Historical description of tsunami damage and run-up heights (m) in the Miyako–Yaeyama Islands (refer to Figs. 3 and 4 for locations).

Location	Name of village	Pre-tsunami population	Tsunami casualties	Documented Run-up height (m)[*1]	Maximum inundation distance (m)[*2]	Damaged elevation (m)[*3]	Undamaged elevation (m)[*3]	Report of survivors (survived elevation (m))	Elevation with coral fragments (m)	Probable run-up height (m)[*4]	Note
Ishigaki Is.[*5]	Arakawa	1091	213	8.2	250	5	N/A[*6]	10	N/A	8	
Ishigaki Is.[*5]	Ishigaki	1162	312	9.2	275	5	10	10 (slightly inundated)	N/A	9	
Ishigaki Is.[*5]	Okawa	1290	412	9	430	2.5	9.5, 16	16	N/A	9	Close to 9 m in run-up height?
Ishigaki Is.[*5]	Tonoshiro	1141	624	12.2	600	2.5	N/A	Climbing up a tree at 10 m	N/A	12	Close to 12 m in run-up height?
Ishigaki Is.[*5, *7]	Hirae	1178	560	26.1	2100	15.5	21	20	12	12	Close to 12 m in run-up height?
Ishigaki Is.[*5, *7]	Maezato	1173	908	19.4	2000	N/A	N/A	N/A	N/A	12	Close to 12 m in run-up height?
Ishigaki Is.[*5]	Ohama	1402	1287	44.2	N/A	N/A	N/A	Climbing up a tree at 20 m	N/A	22	River and deep channel exists at coral reef in front of the village. Boulder movement in documents.
Ishigaki Is.[*5]	Miyara	1221	1050	85.4	3250	15	70	Tsunami reached <32 m but Survived at 88.7 m, 50 to 70 m Climbing up a tree at 22–23 m	20	22–32	Close to 30 m in run up height? ca. 22 m in elevation without inundation?[*14] River exists in front of the village.
Ishigaki Is.[*5]	Shiraho	1574	1546	59.9	2000	6	N/A	Tsunami reached 20 to 25 m	20 to 25	25	
Ishigaki Is.[*5]	Touzato	888	199	9.7	300?	N/A	27 to 33	N/A	<10	10	
Ishigaki Is.[*5]	Mt. Kara			39.8	500?	N/A	N/A	N/A	N/A	N/A	Uncertain how to measure at undeveloped land.
Ishigaki Is.[*5]	Inoda	283	283	10.7, 16.4	300?	N/A	N/A	N/A	<10	11	Boulder movement in documents.
Ishigaki Is.[*5]	Ibaruma	720	625	32.1, 32.7	500	N/A	30.3	Village moved at 30 to 40 m	N/A	N/A	>9 m in run-up height?
Ishigaki Is.[*5]	Yasura	482	461	56.4, 61.4	300?	20 to 30?	34	N/A	no fragments at 24 to 45	15 to 20	Deep channel exists at coral reef in front of the village Boulder movement in documents.
Kuro Is.[*5]	Hori	1195	293	N/A	N/A	N/A	N/A	N/A	N/A	N/A	West-half of Hori village was destroyed
Iriomote Is.[*5]	Haimida	489	11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Village was partly destroyed
Miyako Is.[*5]	4 villages[*8]	N/A	2042	10.6	N/A	N/A	Approximately 10	N/A	N/A	10	Sandy tsunami deposit at 9–10 m
Ikema Is.[*15]	2 villages[*13]	N/A	22	7.6	N/A	N/A	N/A	N/A	N/A	7 to 8	Maximum elevation is 28.6 m
Kurima Is.[*9]		N/A	0?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Maximum elevation is 33.8 m
Irabu Is.[*9, *16]	3 villages[*10]	N/A	23	10.6	>1000	7.5, 6 to 7, 10 to 11	N/A	N/A	N/A	10 to 11	
Shimoji Is.[*9]		Not inhabited	N/A	36 to 39	N/A	N/A	N/A	N/A	N/A	N/A	Maximum elevation is 21.7 m Boulder movement in documents.
Tarama Is.[*11, *16]	Shiokawa	3324[*12]	362	N/A	>500	10 to 15	15	N/A	N/A	15	
Miyako-Minna Is.[*9]		N/A	No survivor	N/A	N/A	All wells, houses	N/A	N/A	N/A	N/A	Maximum elevation is 10 m

*1 Described in historical documents in Japanese old unit. Recalculated (m) by Kawana (2000). Note that tidal level during measurement was uncertain. Thus, there is 1 to 2 m error here.

*2 Estimated by Kawana (2000).

*3 Estimated from damaged/survived shrine, wells, and houses by Kawana (2003).

*4 Estimated by Kawana (2003) and this study with consideration of geomorphic features.

*5 Based on Kawana (2003).

*6 Not Available.

*7 Shimabukuro (2004).

*8 Miyaguni, Shinzato, Sunagawa, and Tomori.

*9 Based on Kato (1989).

*10 Irabu, Nakaji, and Sawada villages.

*11 Kato and Oyama (1987).

*12 Population at Tarama Island.

*13 Ikema and Maezato.

*14 Tradition after Makino (1968).

*15 This study with consideration of geomorphic features.

*16 Nakata (1990).

Fig. 7. (a) The "*Tourin-ji*" temple in the old-Ishigaki village. It was the first temple built on the Yaeyama Islands in 1614. Although completely destroyed by the 1771 Meiwa Tsunami, it was rebuilt in 1786. The temple was located at 5 m altitude. On the other hand, *Miyatori-Utaki* shrine, at 10 m in altitude, was not damaged. (b) Summaries of the historical records at southern Ishigaki Island.

the magnitude of the tsunami (~30 m run-up height). It is probably that there are few records for groundshaking damage because of the subsequent destruction caused by the severe tsunami which would have obscured earlier earthquake-related effects (Nakamura, 2006). There was undoubtedly groundshaking damage because the main shock was felt on Okinawa Island over 350–400 km away from the epicenter (Nakamura, 2006). In addition, Yamamoto (2008) recently reported ground cracks on the eastern coast of Ishigaki Island, which is closest to the probable epicenter. He interpreted these cracks as being formed by the strong ground tremors of the 1771 earthquake. Therefore, the earthquake magnitude could have been considerably greater than Imamura's (1938) original estimates. Further work is needed to clarify this issue.

Several tsunami source models have been proposed. Imamura (1938) and Nakata and Kawana (1995) used seismological fault models with Mw = 7.4 and 7.8, respectively (model A in Fig. 3). However, these models greatly underestimated the maximum run-up heights on respective islands (Imamura et al., 2001). Hiyoshi et al. (1986) proposed submarine landslides as a possible tsunami source, while Hiraishi et al. (2001) and Imamura et al. (2001, 2008) assumed a fault (Mw = 7.7) plus submarine landslide model (model B in Fig. 3). Evidence for a landslide was indeed found near Ishigaki Island (e.g. Matsumoto et al., 2001). The model B reproduced the documented tsunami run-up heights well, especially at Ishigaki Island (Imamura et al., 2001). Nakamura (2006), on the other hand, assumed a NW–SE striking fault east of Ishigaki Island (Mw = 7.6) (model C in Fig. 3). Nakamura (2009) recently rejected models A to C and proposed a new model (model D in Fig. 2b). He concluded that the 1771 tsunami resulted from thrust faulting in the subducted sediment beneath the accretionary wedge near the axis of the Ryukyu Trench, which is a characteristic feature of a "tsunami earthquake". However, ground tremors at Ishigaki Island were stronger than previously thought. This contradicts the "tsunami earthquake" hypothesis along the Ryukyu Trench. Moreover, no tsunami damage was recorded away from the Miyako–Yaeyama Islands such as Okinawa Islands. This suggests that a large, locally focused tsunami occurred close to Ishigaki Island at 1771. It seems likely therefore that the model B is the most plausible among possible sources for the 1771 Meiwa Tsunami.

According to the model B, the first wave arrived at the southeastern coast of Ishigaki Island within 10 min, at the eastern coast of Ishigaki Island and the southern coast of Tarama Island within 15 min, and the southern coast of Miyako Island within 20 min (Fig. 8,

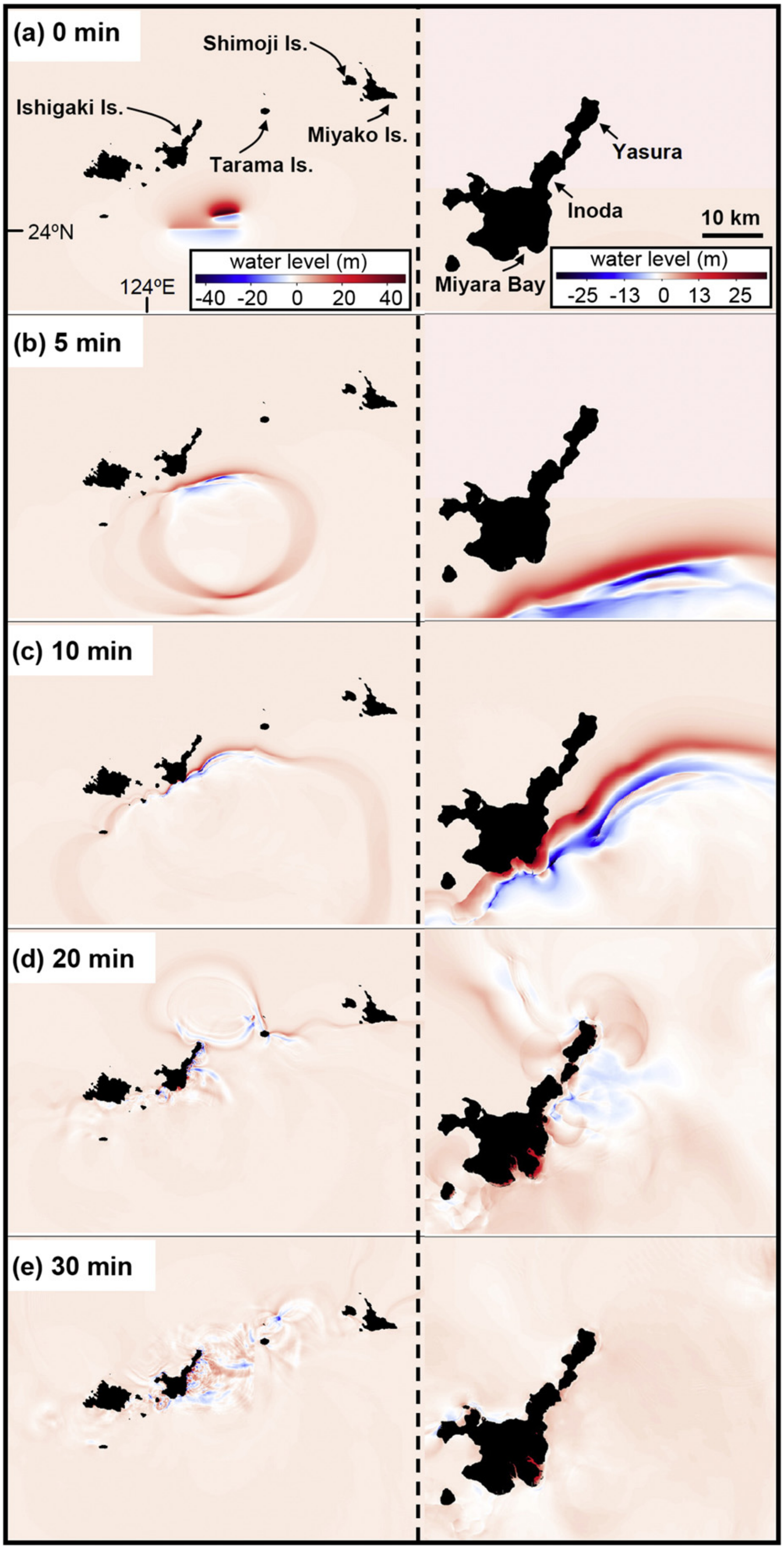

Fig. 8. Numerical results for propagation of the tsunami at the Miyako–Yaeyama Islands (left panel) and Ishigaki Island (right panel) at (a) 0 min, (b) 5 min, (c) 10 min, (d) 20 min, and (e) 30 min after tsunami generation (modified after Imamura et al., 2001, 2008). Positive (red) and negative (blue) values indicate the sea level above and below the still water level.

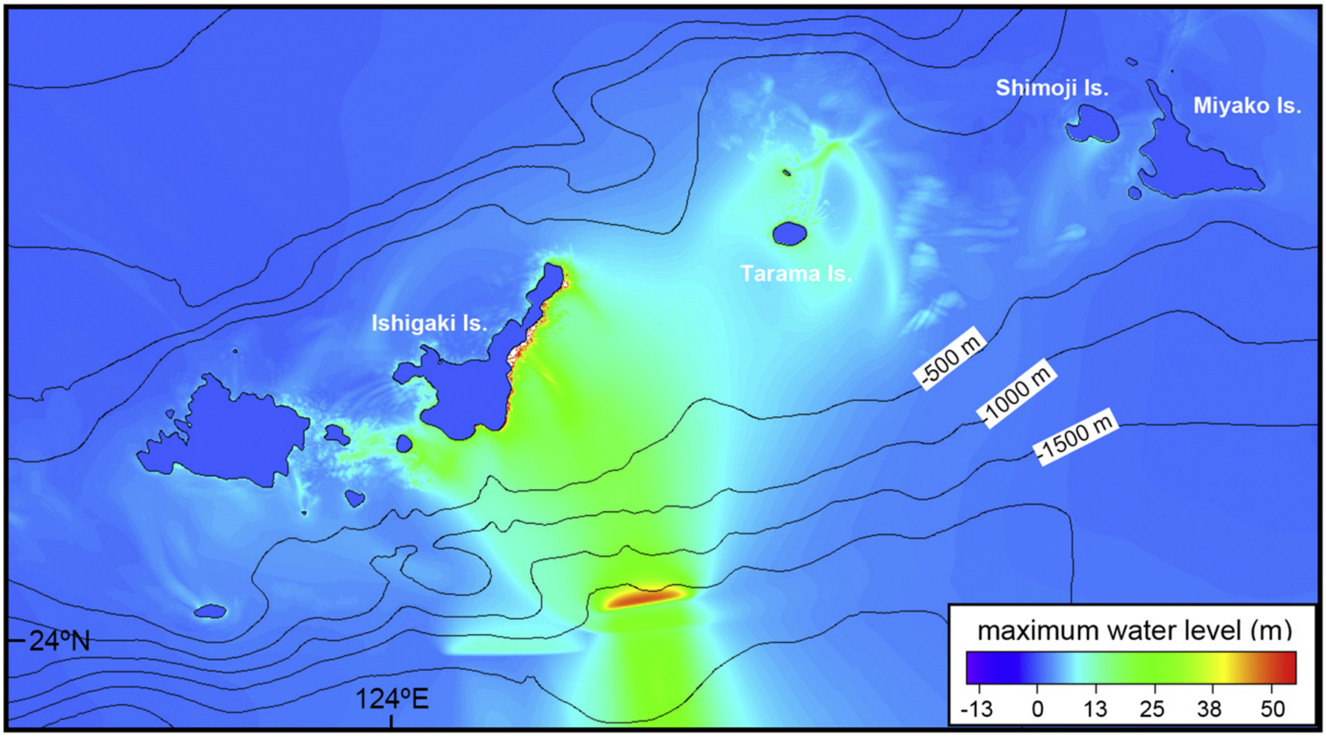

Fig. 9. Distribution of the maximum water level 45 min after tsunami generation. Areas where the maximum water levels were high correspond well with the distribution of tsunami-ishi boulders (compare with Fig. 3).

Imamura et al., 2001, 2008). Fig. 9 shows the maximum water level at 45 min after tsunami generation, which is consistent with the historically documented heights.

5. Displacement of boulders described in the historical documents

On the Miyako–Yaeyama Islands, there is a tradition of giving nicknames to large boulders. Even before the 1771 Meiwa Tsunami, local residents may well have used several large boulders as markers. Notably, detailed descriptions exist about the displacement of several specific boulders by the 1771 Meiwa Tsunami. On Ishigaki and Kuro islands, there are noted in the historical document "*Kimyo-hen'iki*" (Kawana, 2000), and on Shimoji Island in the "*Otoiai–gaki*" (Kato, 1989). Both were written within few years after the 1771 tsunami. These boulders have been called "tsunami-ishi (stone)" in these islands. Although a similar term was described by Imamura (1938), it was first described clearly in the modern literature by Makino (1968) and has been cited in several international papers (e.g., Imamura et al., 2008; Goto et al., 2010b; Bourgeois and MacInnes, in press). Respecting the original naming system and previous cited works, we hereafter call the tsunami boulders in the Ryukyu Islands "tsunami-ishi" boulder. This refers to all boulders that can be identified based on historical and geological evidence. In addition, several tsunami-ishi boulders have nicknames that were given before the 1771 Meiwa Tsunami. Therefore, we keep the original nicknames of these boulders in this paper.

Table 1 presents original descriptions of movements of six tsunami-ishi boulders in the historical documents (see Fig. 3 for their locations). Kawana (2000, 2003) and Kawana et al. (2006a) identified some of these boulders in Ishigaki Island. Herein, we review their results and evaluate the validity of the historical descriptions based on field evidence and numerical results.

5.1. Yasura: "Yasura-Ufukane" boulder

This is a dusky-red boulder approximately 6.2 m long, and was originally part of an intrusive rock (Fig. 10a, Kawana, 2003). Local people currently call this boulder "*Ifan-gani* (iron at Iha area)" (Ishigaki City, 1998), which is consistent with the description in historical documents. While numerous reef boulders are deposited in the same area, there are, however, no other large intrusive rocks and therefore this boulder is probably "*Yasura-Ufukane*" as described in the historical document (Table 1, Kawana, 2003). If this is the case, then the boulder size is underestimated in the historical document. However, the people did not necessarily measure its size along the long axis. The short axis and height are about 3 m, which are close to the historical description (3.6 m).

5.2. Inoda: "Amatariya–Suuari" boulders

These two boulders are approximately 5 × 5 × 6 m (hereinafter "AS-1", measured by Imamura et al., 2008) and 11 × 9 × 6 m (hereinafter "AS-2", measured by Kawana, 2000) in size. Each boulder is approximately 200 m inland from the shoreline, which is consistent with the historical description. These boulders are composed of the Pleistocene Ryukyu Limestone from the local bedrock (Kawana, 2000). However, well-preserved Holocene coral skeletons are accreted. Therefore, these boulders have been transported landward from the sea (Kawana, 2000). Considering that the boulders' sizes and horizontal displacement distances are consistent with those in the historical document, they are probably the "*Amatariya–Suuari*" boulders. Numerical modeling further supports this interpretation (Imamura et al., 2008). On the other hand, local people described another boulder of similar size 100 m northeast of the AS-1 boulder, but it was destroyed during construction work a few decades ago. This boulder might have been another candidate, although this can't be confirmed (Kawana, 2000).

5.3. Ohama: "Taka-Koruse ishi" boulders

Hundreds of boulders have been deposited on land and on the Miyara Bay reef flat (Fig. 11a, Goto et al., in press). Among them, a huge coralline boulder of approximately 600 tons is deposited at the

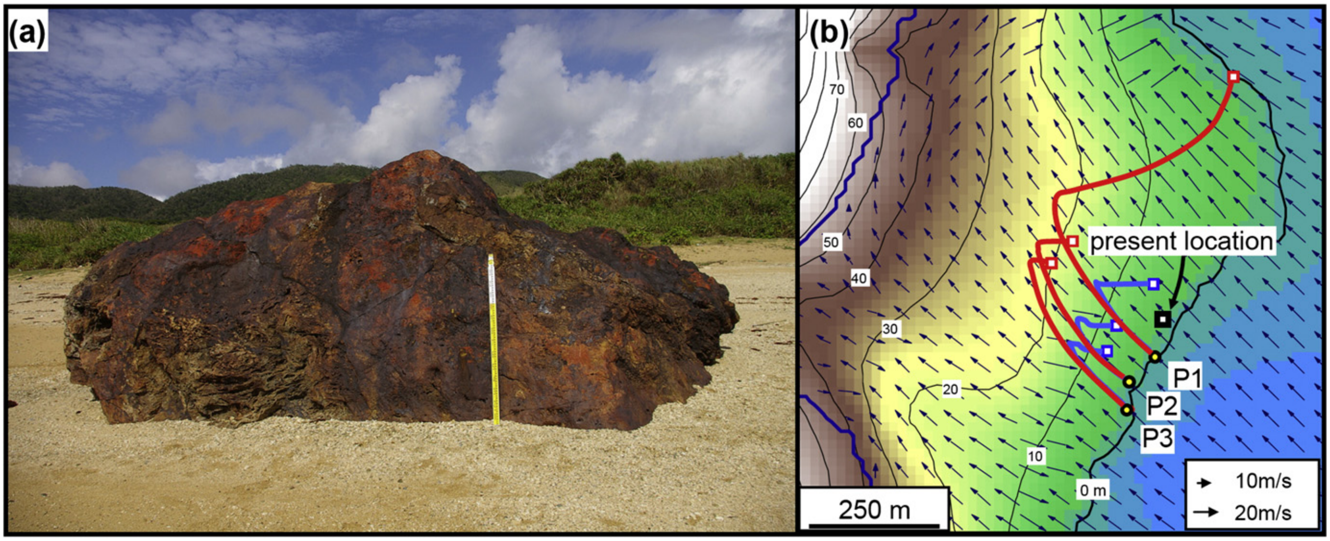

Fig. 10. (a) A tsunami-ishi boulder, the so-called "*Yasura-ufukane*", at Yasura, Ishigaki Island. (b) Diagram showing the trajectory of the boulder transported by the tsunami at Yasura using the variable coefficient of friction (red) and normal coefficient of friction (blue) (after Ohkubo et al., 2004). Arrows indicate the maximum velocity during the calculation time.

reef edge near the deep channel (Fig. 11b). The distance of this boulder from the "*Koruse–Utaki*" shrine is approximately 760 m east, which is consistent with the historical description (Table 1). Therefore, Kawana et al. (2006b) suggested that the boulder might be a "*Taka-Koruse ishi*" boulder described in the documents (hereafter TK-1). However, questions remain: (1) it is uncertain how such a large boulder crossed

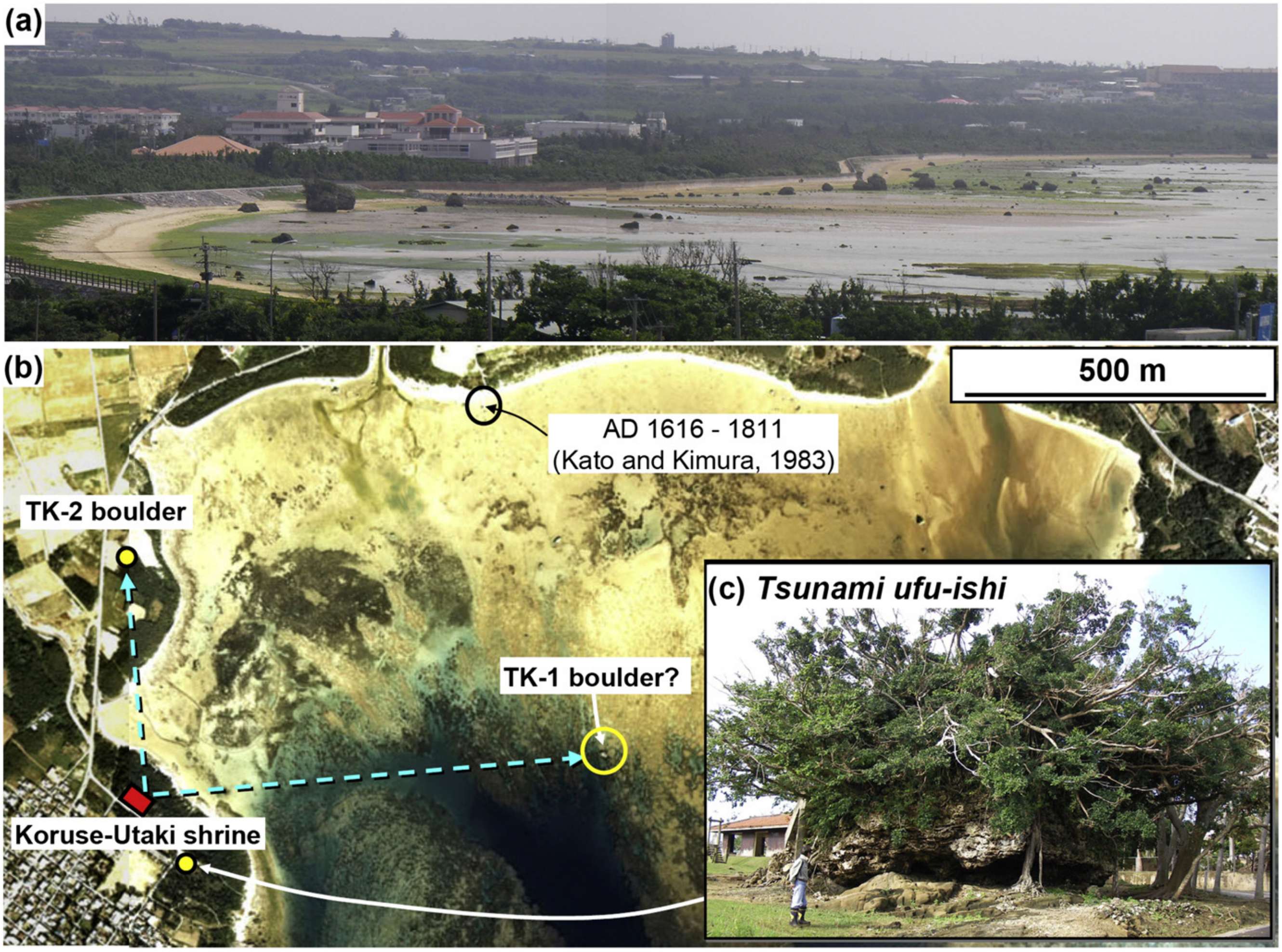

Fig. 11. (a) Tsunami-ishi boulders in the Miyara Bay, southern Ishigaki Island. (b) Aerial photograph showing key boulders at the Miyara Bay. The aerial photograph was provided by the National Land Image Information (Color Aerial Photograph), Ministry of Land, Infrastructure, Transport and Tourism, Government of Japan (1977 photograph). (c) A tsunami-ishi boulder, the so-called "*Tsunami ufu-ishi*" that located near the Koruse–Utaki shrine.

over the deep channel and came to a halt at the reef edge, in an unstable position; and (2) the eastward movement of this boulder by the tsunami is not supported by numerical modeling (see Section 5.4). Therefore, additional careful sedimentological and hydrodynamic analyses are necessary to confirm whether TK-1 is the "*Taka-Koruse ishi*" boulder.

On the other hand, another coralline boulder (Fig. 12a) is found at Tofuriya near the old road, approximately 500 m north of the shrine (Fig. 11b, hereafter TK-2, Kawana et al., 2006a). The boulder has been split into several pieces, although its total weight was estimated as 250–400 tons (Kawana et al., 2006a). Its direction from the shrine, the horizontal distance, and the boulder size are all consistent with the historical description. Therefore, Kawana et al. (2006a) identified this as another "*Taka-Koruse ishi*" boulder.

5.4. Numerical evaluation of the historical description of the boulder movements

We use a numerical model for the tsunami transport of a boulder to assess the proposed movements. The model was developed by Noji et al. (1993). Imamura et al. (2008) improved the model to incorporate various transport modes. They introduced an empirical variable coefficient of friction to explain various modes of transport, e.g. sliding, rolling, and saltation. They applied this improved model to the AS-1 boulder at Inoda to test model validity. The calculated distance of boulder transport was approximately 650 m, which is consistent with the description in the historical document (Imamura et al., 2008). We have subsequently used numerical modeling to assess boulder transport by the 1771 Meiwa Tsunami. This was carried out on the "*Yasura-Ufukane*" boulder at Yasura and the "*Taka-Koruse ishi*" boulder (TK-2) at Ohama to evaluate whether the clasts are those in the historical documents.

5.4.1. Numerical method and initial conditions

We adopted the tsunami source and boulder transport models proposed by Imamura et al. (2008). The spatial resolution of the grid for Yasura and Ohama is 16.7 m. The time step is 0.1 s. We assume that the original boulder location at Yasura (locations P1 to P3 in Fig. 10b) was approximately 50 m (P1) to 100 m (P3) south of its present position. Furthermore, we also assumed a rectangular solid boulder. The projected area of the boulder facing the current was assumed to be 6.2 × 2.8 m (Ohkubo et al., 2004). At Ohama, we assumed that the original location of the TK-2 boulder was approximately 400–600 m south to southeast of the present position (locations P1–P4 in Fig. 12b). The size estimation of this boulder is difficult because it was split into several pieces. We tentatively assume a rectangular solid boulder. The projected area of the boulder facing the current was assumed to be 7.0 × 7.0 m in accordance with the historical description (Ohkubo et al., 2004).

5.4.2. Numerical results

At Yasura, the tsunami inundated ca. 500 m inland from the shoreline (Fig. 10b). The boulder was transported northwestward (landward) by the first wave. Following this, the boulder was transported seaward by the backwash. The trajectory and displacement distance of the boulder varied greatly depending upon the initial boulder position. This was largely because the direction and velocity of the current varied significantly with the topography. The boulder displacement was 300–700 m depending on the original location, but all values were greater than that given in the historical description (55 m). We determined that this boulder is beyond the application limit of the model developed by Imamura et al. (2008) because it is a triangular pyramid rather than a rectangular solid and has a wide base (Fig. 10a). A high density boulder of this shape might have been displaced by sliding as opposed to rolling or saltation. The displacement distance of the boulder calculated using a constant coefficient of friction that assumed sliding as a transport mode was 100–150 m (Fig. 10b), which shows far better agreement with the estimation presented by Kawana (2003).

At Ohama, the boulder was found to have been transported northwestward by the first wave (Fig. 12b), with only a minor effects as a result of the subsequent backwash. Boulder displacement was approximately 150–650 m depending upon the original location used. When we assumed the original boulder location to be at P3 or P4, the final boulder position closely approximated its present placing (Fig. 12b).

While there needs to be further evaluation of the boulder movement at Yasura, those modeled for Inoda and Ohama closely approximate the historical descriptions. These results support the validity of the identification carried out by Kawana (2000, 2003) and Kawana et al. (2006a) and we infer that these boulders are the tsunami-ishi boulders reported in the historical documents.

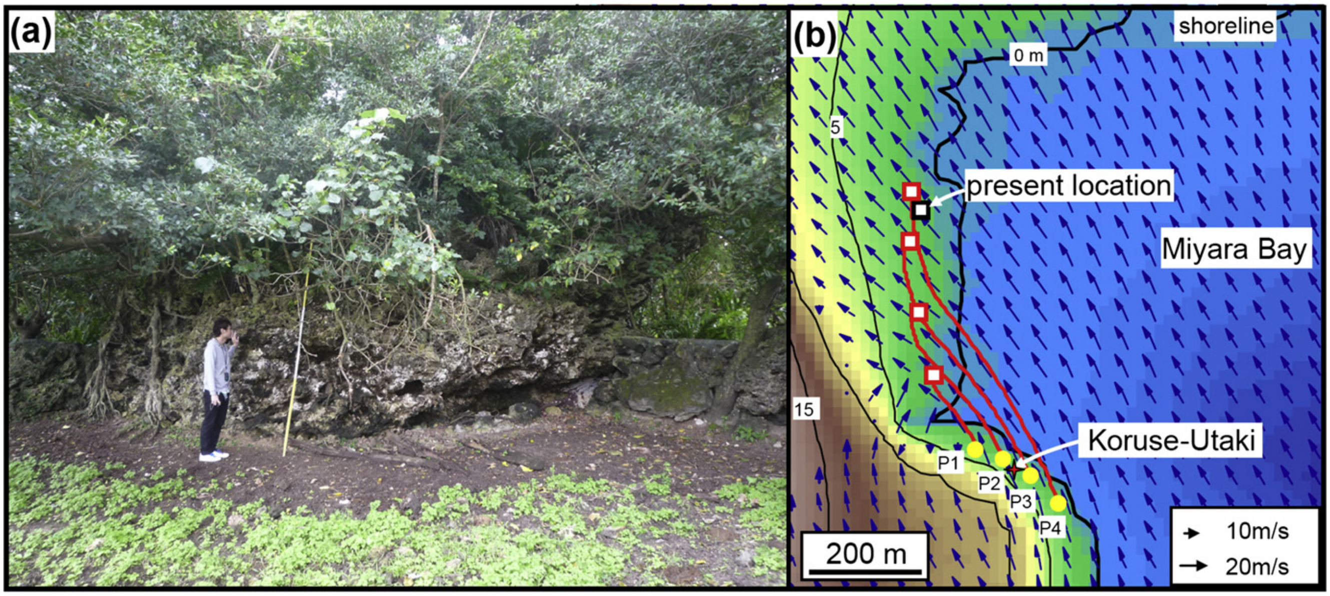

Fig. 12. (a) A tsunami-ishi boulder (TK-2), known as "*Taka-Koruse ishi*", at Ohama, Ishigaki Island. (b) Diagram showing the trajectory of the boulder (TK-2) transported by the tsunami at Ohama (after Ohkubo et al., 2004). Arrows indicate the maximum velocity during the calculation time.

6. Discrimination and sedimentary features of boulders deposited by tsunamis and storm waves

There are numerous other boulders deposited on the reef and on land in the Ryukyu Islands, especially in the Miyako–Yaeyama Islands. However, many large typhoons strike these islands every year. It is known that even heavy boulders can be deposited by storm waves on the Ryukyu Islands (e.g. Kato et al., 1991). For those reasons, the possible tsunami origin of these boulders must be evaluated carefully based on sedimentological and hydrodynamic analyses. Moreover, their possible 1771 Meiwa Tsunami origin needs to be verified using appropriate chronological techniques.

Based upon the depositional setting, boulders on the Ryukyu Island are classifiable into three types: 1) on the reef and coast up to the sand dunes, 2) on the lowlands landward of the sand dunes, and 3) on the high cliff tops. We first summarize the reports that discuss differentiating between boulders deposited by tsunamis and storm waves on the Ryukyu Islands in each depositional setting. We then discuss the origins of possible 1771 Meiwa Tsunami or past tsunami(s) boulders, as well as their sedimentary features.

6.1. Boulders on the reef flat and lowlands

6.1.1. Discrimination of boulders deposited by tsunamis and storm waves on the reef

To date, hydrodynamic models that estimate the wave height necessary to overturn boulders (Nott, 1997, 2003) have been used to identify tsunami boulders (e.g., Nott, 2004; Scheffers and Kelletat, 2006; Mastronuzzi et al., 2007; Scicchitano et al., 2007) or storm wave boulders (Spiske et al., 2008). However, storm wave impacts at the reef of the Ryukyu Islands are strong and boulders of approximately 100 tons have been deposited on reefs or cliff tops by recent typhoon-generated storm waves (Kato et al., 1991; Onda, 1999; Kawana, 2008; Goto et al., 2009a). Therefore, different model criteria are required.

One important geomorphologic feature of the Ryukyu Islands is their wide fringing reefs, which extend up to 1.5 km offshore. This width is sufficient to dissipate storm wave energy before it reaches the shore. For example, Egashira et al. (1985) directly measured the significant wave height (SWH) of the storm wave by typhoon 8310 in 1983 at the reef near Okinawa Island and found that it was less than 12 m at 250 m offshore of the reef edge, less than 3 m at the reef edge, and less than 2 m at 700 m shoreward from the reef edge (including effect of wave setup). With a shallow reef, storm waves would be breaking on the offshore of the reef edge. Therefore, the storm wave force would be strong immediately offshore of the reef edge, although it would decrease exponentially during wave propagation across the reef (Egashira et al., 1985). This general wave propagation process of a storm wave is expected to be reflected in the boulders' distribution on the Ryukyu Islands.

Imamura et al. (2008) and Goto et al. (2009a, 2010b) reported a significant difference between tsunami and storm waves characterized by the wave period rather than the wave height. For example, the storm wave period around the Ryukyu Islands is expected to be less than 20 s (e.g. Yamashita et al., 2008), although that of a large tsunami is several tens of minutes to hours. Therefore, the duration of a tsunami wave force acting on the boulder is considerably longer than

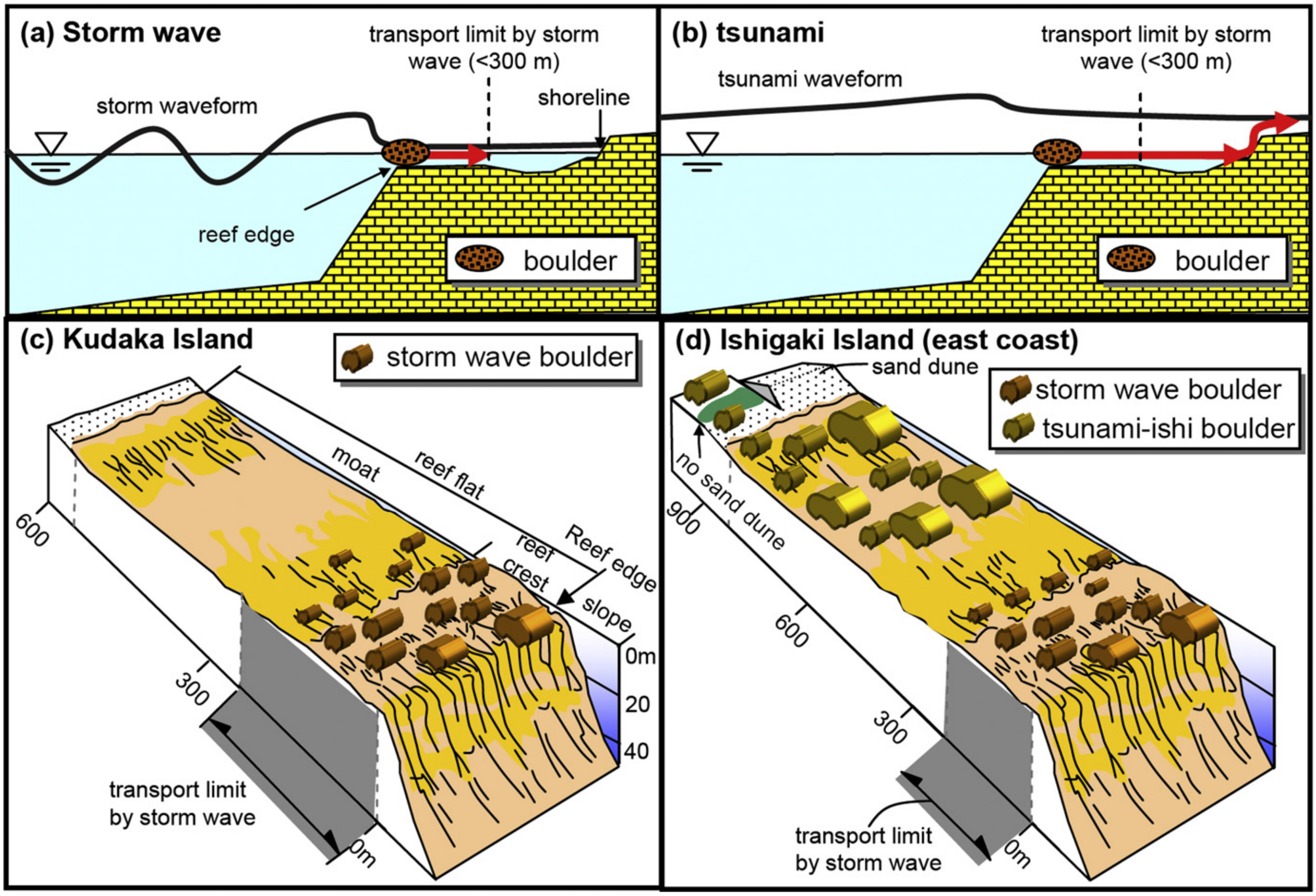

Fig. 13. Schematic diagrams showing waveform and boulder displacement by (a) storm wave and (b) tsunami on the Ryukyu Islands (after Goto, 2009). The storm wave boulders have a clear distribution limit (<300 m from the reef edge), and tsunami-ishi boulders are deposited significantly landward of this limit. Schematic diagrams showing reef topography at Ryukyu Islands (modified after Sagawa et al., 2001) and distributions of the (c) storm wave boulders at Kudaka Island and (d) storm wave plus tsunami-ishi boulders at Ishigaki Island. High sand dunes or steep slopes at the beach played an important role in determining whether tsunami-ishi boulders reached far inland or were deposited in front of the sand dune close to the shoreline.

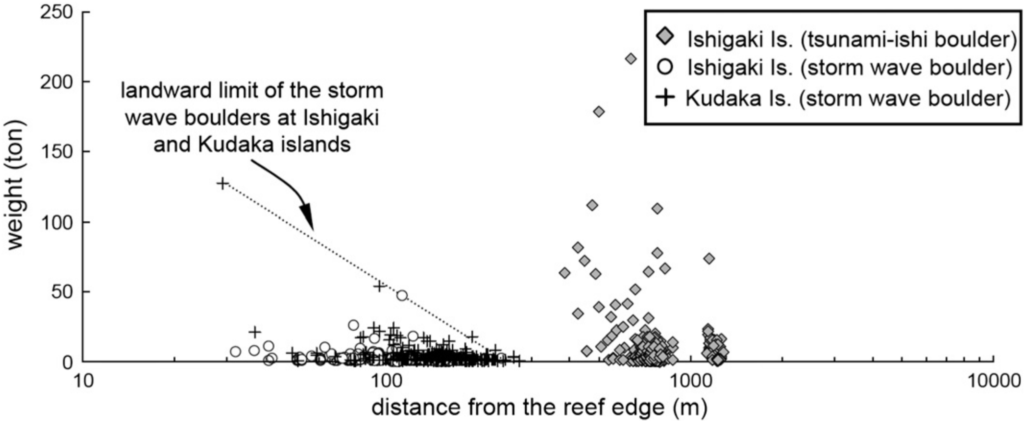

Fig. 14. Clast size (ton) distribution from the reef edge (m) on Ishigaki and Kudaka islands (modified after Goto et al., 2010b). The horizontal axis is logarithmic.

that of a storm wave. Therefore, the difference in transport distance of boulders by a storm or tsunami might be a useful way to differentiate between them (Fig. 13a and b).

To test this, Goto et al. (2009a) investigated the distribution of boulders (>1 m long axis) deposited at Kudaka Island (Fig. 2b), which was unaffected by the 1771 Meiwa Tsunami. These boulders, up to 127 tons, were distributed up to 275 m landward from the reef edge (Fig. 14). According to analyses of aerial photographs, the present distribution of boulders was controlled by the largest storm waves generated by typhoon 0704 in 2007. The clast size distribution of boulders shows an exponential shoreward fining trend (Fig. 14), which is consistent with the SWH distribution on the reef. No boulders were observed from the moat to the shoreline at this island (Fig. 13c), which indicates that past storm waves at the island had insufficient power to displace boulders more than 275 m.

In contrast to Kudaka Island, two distinctly different types of boulders can be found at Ishigaki Island, the area damaged by the 1771 Meiwa Tsunami — boulders are deposited on both the reef crest and the shoreline (Fig. 15, Goto et al., 2010b). Boulders (<47 tons) are deposited on the reef crest at the eastern coast of Ishigaki Island. The reef crest width is ca. 350 m, including the platy reef and coralline boulders originating from the reef slope and reef crest. These boulders were deposited within 210–240 m landward from the reef edge, but no boulders were observed on the reef crest between 240 and 350 m from the reef edge (Fig. 14, Goto et al., 2010b). It is inferred from aerial photographs that the boulders on the reef crest were deposited at their present locations by storm waves (Goto et al., 2010b). The landward limit of boulders is consistent with those on Kudaka Island (<275 m) and those on the reefs of other islands in the Ryukyu Islands group that face toward the Pacific Ocean (<300 m, Goto et al., unpublished data), even though these islands are located ca. 800 km apart.

A well-defined landward limit of storm wave boulders can be found on the Ryukyu Islands. In general, the reef slope inclination and storm wave intensity are uniform throughout the Ryukyu Islands. In this case, we can state that, if the reef edge is rectilinear with no channels that deeply penetrate the reef flat, then it is unlikely that boulders more than 300 m from the reef edge were displaced by storm waves (Goto et al., 2010b). Therefore, boulders located landward of this limit can be assigned a tsunami origin.

In contrast to storm wave boulders on the reef crest at the eastern coast of Ishigaki Island, abundant reef and coralline boulders including

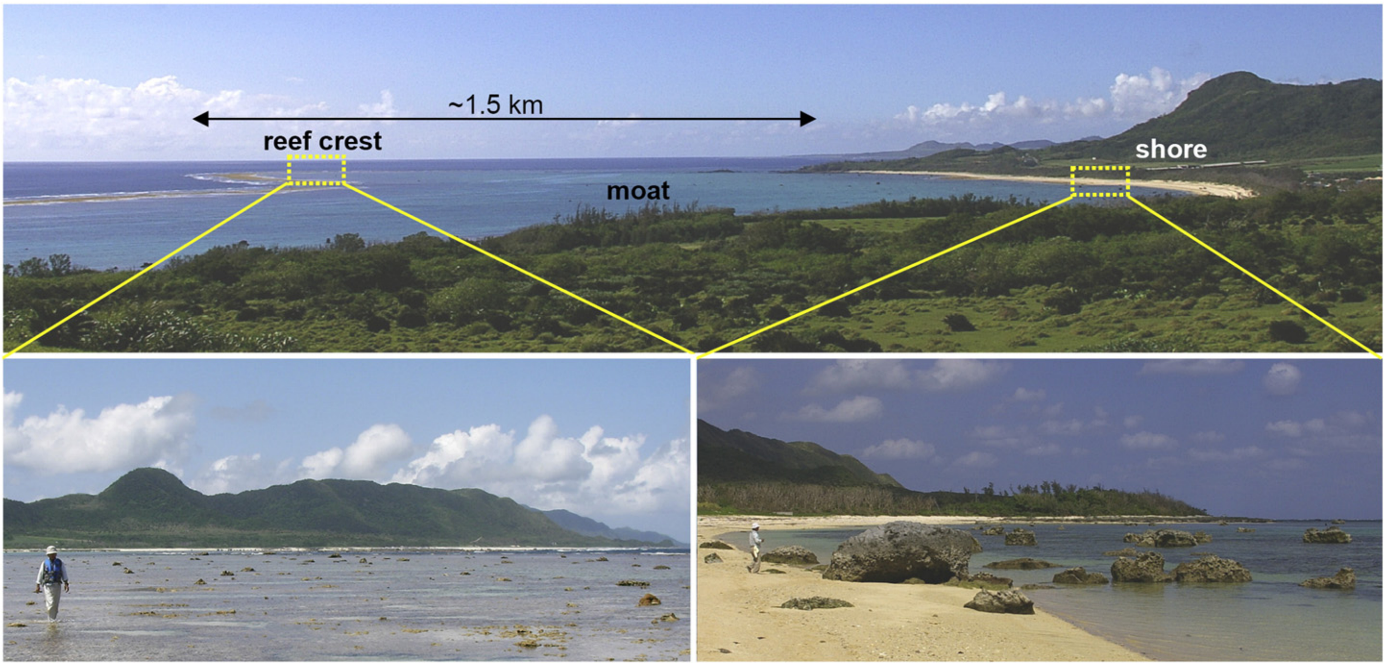

Fig. 15. (a) Storm wave boulders on the reef crest (left bottom) and tsunami-ishi boulders along the shoreline (right bottom) at Ibaruma, eastern Ishigaki Island.

single large colonies of massive *Porites* sp. are scattered along the shoreline ~1.5 km from the reef edge (Fig. 16a and b). This is far beyond the transport limit of boulders by storm waves (Fig. 13d, Goto et al., 2010b). Some *Porites* boulders are clearly microatolls, suggesting their origin in the moat. A huge *Porites* boulder of approximately 216 tons, which is locally called "*Bari-ishi* (a boulder split into two pieces)", is deposited near the shoreline about 670 m from the reef edge at Ibaruma. Hydrodynamically, the source, size, and horizontal displacement distance of these boulders cannot be explained by storm wave action on the Ryukyu Islands. Therefore, Goto et al. (2010b) concluded that boulders along the shoreline of the eastern coast of Ishigaki Island were deposited by tsunamis.

Based upon the sedimentary differences between storm wave and tsunami boulders on the Ryukyu Islands, we identified tsunami-ishi boulders concentrated along the shoreline of the southern to eastern coasts of Ishigaki Island, on all coasts of Tarama and Minna Islands, on the southeastern coast of Miyako Island, and on the northwestern coast of Shimoji Island (Fig. 3). It is particularly interesting that these areas closely match those that were severely damaged by the 1771 Meiwa Tsunami and were identified in numerical modeling results (Fig. 9).

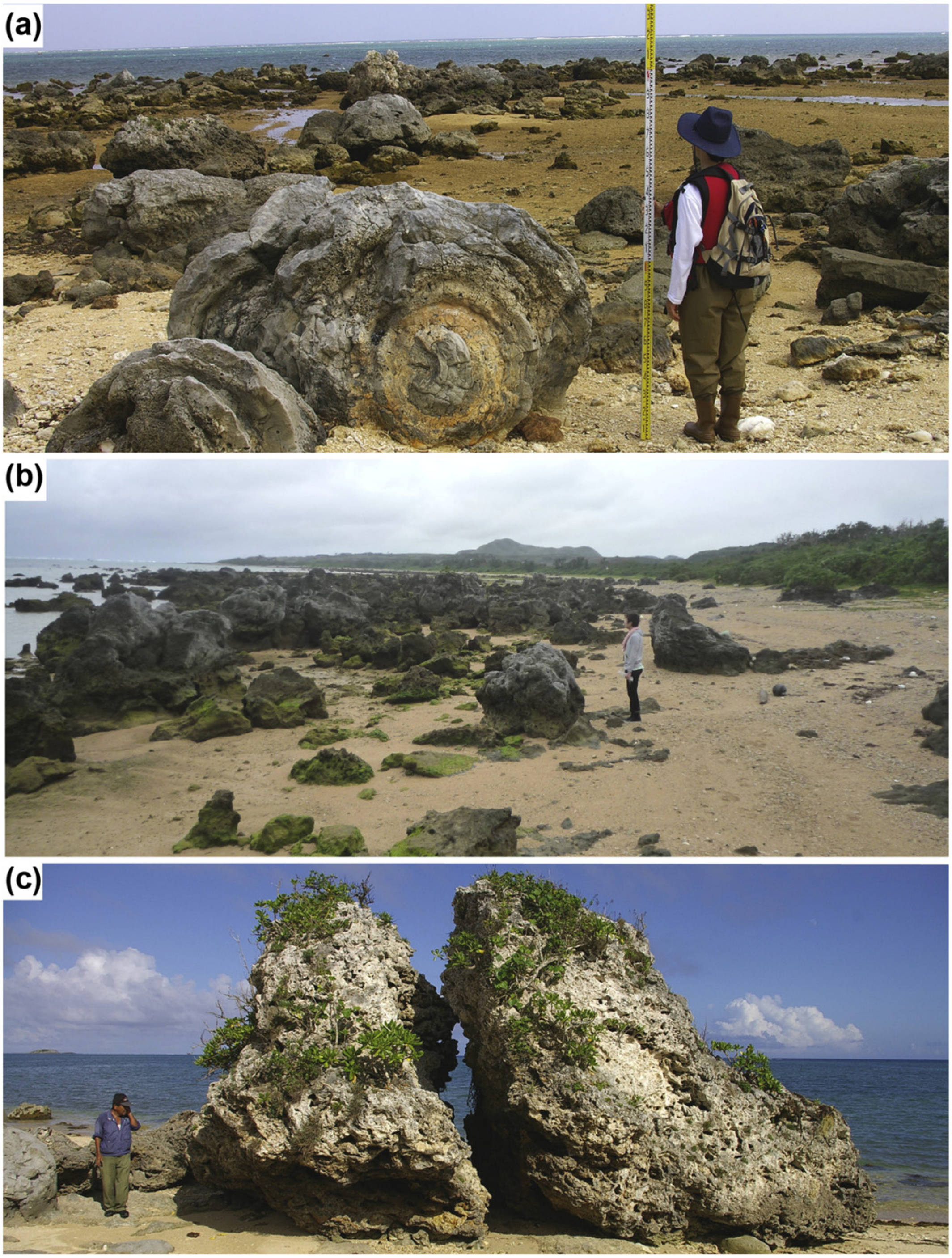

Fig. 16. (a) Tsunami-ishi boulders deposited at the beach near Hoshino in Ishigaki Island. Microatoll-shape *Porites* boulders were originally located in the moat prior to the tsunami. (b) Overview of the tsunami-ishi boulders near Hoshino. The boulders were mostly deposited near the shoreline. No boulders were observed behind the sand dune. (c) The large tsunami-ishi boulder at the shoreline of the south of Oono Cape. This boulder is split into two pieces at the center of its long axis.

Among these boulders, the ^{14}C ages of the youngest (or nearly the youngest) coralline or *Porites* clasts deposited at the southern and eastern coasts of Ishigaki Island, southeastern coast of Miyako Island, and the southern and eastern coasts of Tarama Island (Fig. 17a) are consistent with the 1771 Meiwa Tsunami (Table 3, Kato and Kimura, 1983; Kawana and Nakata, 1994; Nakata and Kawana, 1995; Kato, 2000; Suzuki et al., 2008; Kawana, 2009; this study). Considering the fact that the 1771 Meiwa Tsunami was the largest event since 1644 and no large tsunami was observed after 1771, the boulders in Table 3 were most likely deposited by the 1771 Meiwa Tsunami. The "*Bari-ishi*" boulder on Ibaruma coast on Ishigaki Island is the largest *Porites* tsunami-ishi boulder known, and has distinct evidence of a 1771 Meiwa Tsunami origin (Goto et al., 2010b). On the other hand, as shown in Fig. 18, the age determination results of other boulders show that they are much older than 1771 (see also Supplementary data, Kawana and Nakata, 1994; Nakata and Kawana, 1995). As a result of these findings, Kawana and Nakata (1994) proposed that large tsunamis occurred around 500–600, 1100, 2000, and 2400 yr BP (measured radiocarbon age). Among these events, the tsunami that occurred at about 2000 yr BP is the best constrained, because the coastal uplift might have occurred simultaneously (Kawana, 1989). It was named the "*Okinawa–Sakishima* Tsunami" by Kawana and Nakata (1994).

6.1.2. Tsunami-ishi boulders on lowlands

Not only are there boulders on the reef and the beach, but they are also found on the respective lowlands of Ishigaki, Tarama, Minna and Kuro islands, although their distribution is limited in comparison to those on the reef. Makino (1968) and Miyoshi (1968) studied the distribution of terrestrial boulders on the southern part of Ishigaki Island (near Miyara and Shiraho). Boulders were deposited up to 50 m in elevation, and they concluded that the boulders were deposited by the 1771 Meiwa Tsunami. However, Kato and Kimura (1983) reexamined these boulders and pointed out that it is difficult to estimate the inundation area and wave height simply from the boulders' distribution because Pleistocene boulders, which were floaters from the backland limestone, contaminated the real tsunami-ishi boulders. Kato (1987) investigated boulders that were less than 2 tons in weight and had fresh Holocene corals still composed of aragonite. His results showed that they were distributed up to 25 m in altitude on southern Ishigaki Island. Consequently, he interpreted that the run-up height of the 1771 Meiwa Tsunami was 25 m or higher. However, although the tsunami origin of these boulders is widely accepted, the 1771 Meiwa Tsunami origin was questioned by Kawana and Nakata (1994) because the ^{14}C ages of these boulders were much older than 1771 (around 2000 yr BP, Kato, 1987). Unfortunately, most of these boulders have been destroyed by human activities. Therefore, it is impossible to reevaluate their 1771 Meiwa Tsunami origin.

One coralline boulder, the so-called "*tsunami ufu-ishi*", is deposited at the southern coast of Ishigaki Island (Fig. 11c, 13 × 12 × 7.5 m, measured by Kawana and Nakata, 1994). Makino (1968) speculated that this boulder is direct evidence for the 1771 Meiwa Tsunami. However, Kawana and Nakata (1994) dismiss its 1771 Meiwa Tsunami origin for several reasons: 1) corals on this boulder date to 3480 yr BP at the boulder's base and 1980 yr BP at its top; 2) the Tertiary sandstone around the boulder is eroded but not beneath it

Fig. 17. *Porites* boulders of possible 1771 Meiwa Tsunami origin (a) at southern coast of Tarama Island and (b) at Minna Island. A *Tridacnidae* is attached on the boulder at Minna Island.

(Fig. 11c) —this differential erosion cannot be explained by such short term exposure to subaerial processes (ca. 240 years); and 3) no historical description on this boulder exists, although the movement of much smaller boulders ("*Taka-Koruse ishi*", see Section 5.3) is reported in the area. The presence of this boulder at 10 m in elevation is difficult to explain using uplift or sea level change. Consequently, Kawana and Nakata (1994) reported that the boulder was displaced by the "*Okinawa–Sakishima* Tsunami", not by the 1771 Meiwa Tsunami.

A tsunami-ishi boulder that can be reliably inferred to have been deposited on land by the 1771 Meiwa Tsunami was found at Minna Island by Kato (Fig. 17b, Kato, 2000). An approximately 30 ton *Porites* boulder was deposited about 350 m inland from the shoreline at 7 m altitude. The calendar age for a *Tridacnidae* on this boulder is AD 1515–1814 (2σ) (Table 3). This result supports the proposed 1771 Meiwa Tsunami origin of the boulder.

Table 3
The calender ages of boulders of possible 1771 Meiwa Tsunami origin.

Island	Location	Sampling position	Measured radiocarbon age (yr BP)	Conventional age (yr BP)	Calendar age (cal AD) (1σ)	Weight (tons)	Type of boulder	Distance from the reef edge (m)	Reference
Ishigaki	South coast (Miyara Bay)	–	210 ± 75	620 ± 75 *1	1616–1811 (98%) *2	40 *3	piled up coralline boulder	680	Kato and Kimura (1983)
Ishigaki	On land near east coast (Oono)	Near the youngest part	295 ± 75	705 ± 75 *1	1526–1668 *2	30 *4	piled up coralline boulder	430*4	Kawana and Nakata (1994)
Ishigaki	East coast	The youngest part	–	–	1713 ± 125 *5	<216 *6	*Porites* boulder	<1200 *6	Suzuki et al. (2008)
Ishigaki	East coast (south of Tamatorisaki)	The youngest part	210 ± 65 *7	600 ± 60 *7	1660–1760 and 1780–1800 *7 (1590–1870)(2σ) *7	60–110 *4	*Porites* boulder (divided into 4 pieces)	500 *4	This study
Ishigaki	Northeast coast (Yasura)	The youngest part	190 ± 60 *7	590 ± 60 *7	1660–1810 *7	<10 * 4	*Porites* boulder	1500 *4	This study
Tarama	East coast	Near the youngest part	320 ± 60	730 ± 60 *1	1522–1643 *2	1.5–2 *4	*Porites* boulder	~915*4	Kawana and Nakata (1994)
Tarama	South coast	The youngest part	190 ± 30	536 ± 29 *1	1709–1814 *2	40 *4	*Porites* boulder	700*4	This study
Minna	On land (7 m in altitude)	The youngest part	240 ± 60	650 ± 60 *1	1560–1705 *2 (1515–1814)(2σ) *2	30 *8	*Tridacnidae* on the *Porites* boulder	~900*8	Kato (2000)
Miyako	Southeast coast (Maiba Beach)	The youngest part	190 ± 60 *7	570 ± 60 *7	1670–1820 *7	15–20 *4	*Porites* boulder	700 *4	Kawana (2009)

*1 : Calculated by this study as $\delta^{13}C = 0 \pm 0$‰.
*2 : Calibrated by means of Calib 5.0.1 with Marine04 and $\Delta R = 0 \pm 0$ yr.
*3 : Estimated by Goto et al. (in press).
*4 : Estimated by Kawana.
*5 : Average of 14 *Porites* boulders.
*6 : Estimated by Goto et al. (2010b).
*7 : Measured by BETA ANALYTIC INC.
*8 : Estimated by Kato (2000).

6.1.3. Sedimentary features of the tsunami-ishi boulders on the reef and lowland

Tsunami-ishi boulders on the Miyako–Yaeyama Islands were not necessarily deposited by the 1771 Meiwa Tsunami, some might have been deposited by an earlier event. Nevertheless, there has been no larger event since the 1771 Meiwa Tsunami and it was responsible for depositing the largest *Porites* boulder on Ibaruma coast (216 tons). Most boulders on the shoreline and the moat, which are deposited further offshore or are smaller than this 216 ton individual, should have at least been re—deposited by the 1771 Meiwa Tsunami even if they were originally emplaced and deposited somewhere else by an earlier tsunami (Goto et al., 2010b). Consequently, the distribution and sedimentary features of tsunami-ishi boulders can be useful in understanding the1771 Meiwa Tsunami flow characteristics.

Goto et al. (2010b) reported that most boulders (>1 m long axis) at the eastern coast of Ishigaki Island were concentrated along the shoreline and not deposited beyond the high-tide line (Fig. 16b). A similar arrangement is observed for boulders at Miyara Bay, Ishigaki Island (Goto et al., in press), Maiba beach, Miyako Island, and Sawada beach, Shimoji Island (Fig. 3). Furthermore, as described by Goto et al. (2007), all boulders at Pakarang Cape, Thailand that were displaced by the 2004 IOT were deposited below the high-tide line, irrespective of their size, even though the tsunami inundated more than 2.5 km inland. Numerical modeling results presented by Goto et al. (2010a) show that current velocity becomes much lower along the high-tide line at Pakarang Cape because of the generation of a reflected wave at the beach slope. The sudden decrease of current velocity upon reaching the land would have therefore stopped the boulders below the high-tide line. Similarly, the concentration of boulders at the shoreline of Miyako–Yaeyama Islands probably suggests that the tsunami energy decreased upon reaching the land (Goto et al., 2010b, in press). This is plausible because well-developed sand dunes landward of these reefs could have served to reduce the energy of landward wave run-up. On the other hand, some tsunami-ishi boulders were deposited far inland at Inoda, Miyara, Ohama, Maezato, and Tonoshiro on Ishigaki Island, and on Tarama and Minna Islands. Common geomorphologic features of these areas are the absence of well-developed sand dunes and high cliffs along the shoreline, where the generation of a strong reflected wave would be unexpected (Fig. 13d). Therefore, the tsunami might have inundated far inland without a remarkable reduction of the energy at these areas. The boulders consequently reached far inland. Alternatively, if the tsunami energy had been exceedingly great in these areas, then the boulders would have been deposited on land irrespective of the presence of steep slopes or sand dunes.

Goto et al. (2010b) also reported that many tsunami-ishi boulders along the shoreline of Ishigaki Island have been split into two or more pieces (Fig. 16c). Considering that the pieces had mutual contact, they were probably broken after they were deposited at the present

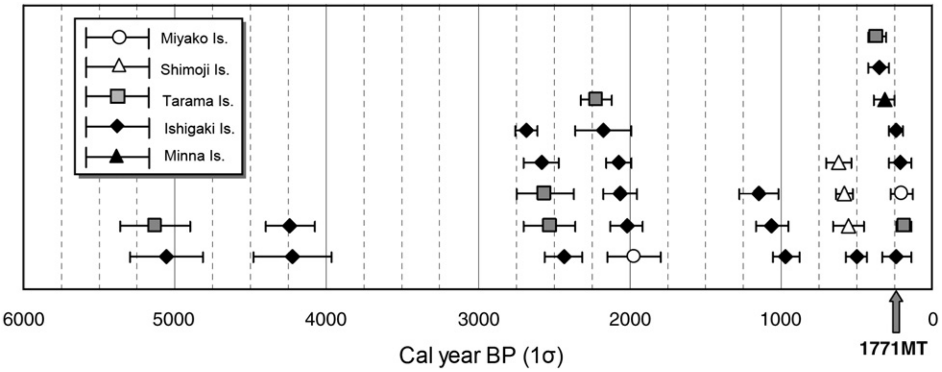

Fig. 18. The ^{14}C calendar ages of the tsunami-ishi boulders at Miyako–Yaeyama Islands (after Kawana and Nakata, 1994; Nakata and Kawana, 1995; Kawana, 2000; this study). See Table 3 and Supplementary data for original data.

position rather than during the displacement process by the tsunami. Most boulders were split across the center of the long axis, a mechanically weak part, suggesting that they were split by the instant action of force. This feature probably reflects the sudden drop of boulders to the ground out of the current because of the drastic reduction of the tsunami's velocity (Goto et al., 2010b). Importantly, this feature is not observed in the proposed storm wave boulders deposited on the reefs on Ishigaki and Kudaka islands, probably

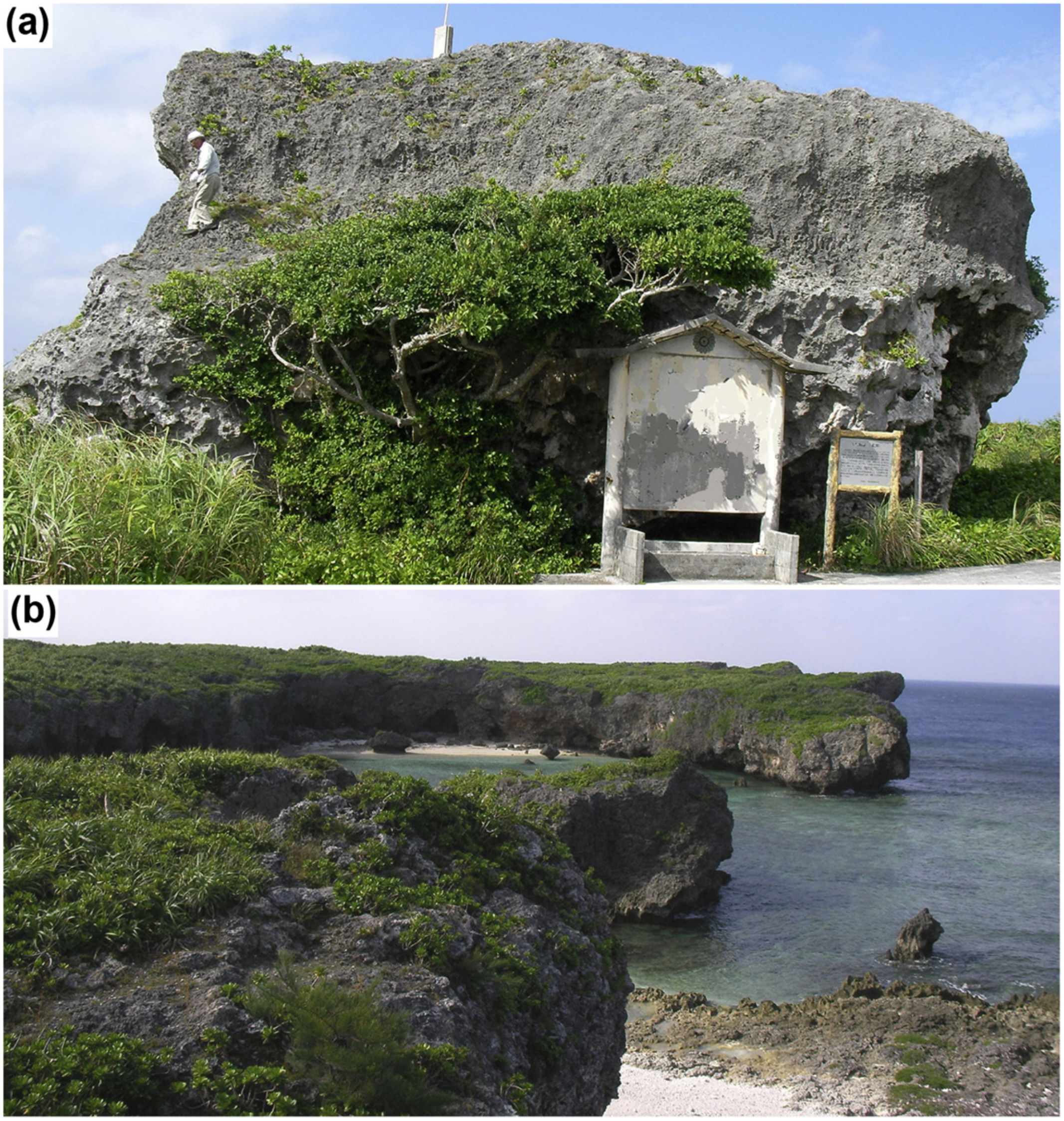

Fig. 19. (a) A cliff-top tsunami-ishi boulder, named "*Obi-Oishi*", at the western coast of Shimoji Island. Note the notch-like concave structure. The weight of this boulder was estimated as 2500 tons (Kato, 1989). (b) A field photograph of the cliff (12.5 m elevation), where the "*Obi-Oishi*" is deposited.

because platy storm wave boulders are generally displaced by sliding (Goto et al., 2009a). Therefore, they did not hit the ground as hard as the tsunami-ishi boulders.

6.2. Discrimination between sedimentary features of cliff-top tsunami and storm wave boulders

Cliff-top boulders, even on a ca. 50 m high cliff, have been reported, but their origins remain controversial (e.g., Williams and Hall, 2004; Kelletat, 2008). On the Ryukyu Islands, cliff-top boulders of both storm wave and tsunami origins are observed. For example, up to 94 ton boulders were moved to a cliff top (approximately 15–19 m altitude) by typhoon 9021 in 1990 at Zanpa Cape, Okinawa Island, Japan (Kato et al., 1991), where no fringing reef had developed around the cliff. This observation suggests that storm waves around the Ryukyu Islands have sufficient power to transport nearly 100 tons of boulders onto the high cliff top.

A possible cliff-top tsunami-ishi boulder was found on Shimoji Island (Fig. 3). It is a huge Pleistocene limestone boulder, called "*Obi-Oishi*"; the boulder is 14 × 14 × 9 m, weighing 2500 tons and deposited on a 12.5 m high cliff top (Fig. 19, Kato, 1989). The distance from the shoreline is estimated as about 50 m. The boulder shows a notch-like concave structure, and has Holocene corals attached (Kato, 1989). According to Kato (1989), the ^{14}C ages of coral skeletons were 880 ± 70 yr BP and 1280 ± 70 yr BP. Therefore, the boulder is thought to have once been on the reef. Later, it was emplaced on the 12.5 m high cliff-top by wave activity. The weight of this boulder is more than 20 times that of known storm wave boulders in the Ryukyu Islands. In addition, unlike the Zanpa Cape case, there is a 200 m wide fringing reef in front of the cliff. Therefore, if a storm wave broke offshore of the reef edge; its energy would be expected to have decreased markedly before reaching the cliff. Considering weight of the boulder and distance from the reef edge, the "*Obi-Oishi*" clast was most likely emplaced by a large tsunami, although it remains uncertain whether it was the 1771 Meiwa event. Importantly, the "*Obi-Oishi*" boulder is the heaviest boulder of tsunami origin in the world reported to date.

Other examples at Cape Agari-henna, Miyako Island (Fig. 3) are composed of Pleistocene limestone (Fig. 20). About 30 Pleistocene limestone boulders of up to 1200 tons with fresh Holocene coral skeletons between 540 ± 130 yr BP and 2680 ± 90 yr BP are deposited on the 20 m high cliff top (Kawana and Nakata, 1994). At the northeastern coast of the cape, many large Pleistocene limestone boulders were also deposited on the fringing reef. These boulders are derived from the northeastern cliff, and were probably scattered by tsunami. There are no other sources for the cliff-top boulders.

7. Implications and future perspectives

7.1. Possible use of geological evidence to constrain the 1771 Meiwa Tsunami source model

Development of a historical tsunami source model is extremely important for local communities so that they can be prepared for future tsunamis. However, source models for historical tsunamis that occurred prior to start of modern tidal measurement systems are usually difficult to verify solely from historical documents (e.g., 1755 Lisbon Tsunami at Portugal, Baptista et al., 2003; Santos et al., 2009; 1771 Meiwa Tsunami) even if detailed documents are available. Even though maximum run-up heights can be estimated from historical documents in some places for the 1771 Meiwa Tsunami, the information is limited to a few villages. Consequently, determining the accuracy of the source model for the 1771 Meiwa Tsunami remains incomplete. While the "fault plus landslide" model (model B) is currently accepted as the most reasonable source model, it was developed before detailed historical and geological evidence had been gathered, and before high-resolution topographic data were available.

In order to determine the historical tsunami source model, all available historical, geological, and archaeological data should be gathered (e.g., Imamura et al., 2001; Goff and McFadgen, 2003; McFadgen and Goff, 2007). The 1771 Meiwa Tsunami would be a good example whether historical tsunami source model can be determined accurately using such various types of data.

Geological evidence of the 1771 Meiwa Tsunami is useful for complementing historical descriptions. For example, the tsunami hydrodynamic force must have been stronger than those necessary to displace the boulders presented in Table 3. Massive *Porites* boulders on the eastern coast of Ishigaki Island were probably located in the moat before tsunami inundation (Goto et al., 2010b). The depth of the original position of the *Porites* boulders can be estimated from their height because they cannot grow higher than the sea surface. This allows the original location of these *Porites* boulders to be estimated and that their movements can be tested using a well-tuned numerical model for boulder transport by tsunami. Moreover, information of boulders that were not displaced by the 1771 Meiwa Tsunami, such as the "*tsunami ufu-ishi*" boulder at Ohama, Ishigaki Island, is important

Fig. 20. Northward overview of the boulders deposited on the fringing reef and top of the cliff (20 m elevation) at Cape Agari-Hen'na, Miyako Island.

to constrain the tsunami source model. This is because the calculated maximum tsunami hydraulic force here must have been lower than the critical force necessary to displace this boulder.

In addition to that of boulders, the distributions of cobble-sized to pebble-sized coral fragments and sandy tsunami deposits will be useful to constrain the tsunami source model. This is useful to estimate the minimum tsunami inundation area (e.g. Koshimura et al., 2002). Although such studies have been poorly conducted on the Miyako–Yaeyama Islands, Yamamoto (2008) recently reported a sheet-like sandy tsunami deposit wedged between soil layers with earthenware fragments from the 14–16th centuries below and 18th century above it, near the Touzato area at the eastern coast of Ishigaki Island. Investigation of sandy tsunami deposits is necessary especially at the places where boulders were not distributed. For example, tsunami casualties were reported from the western coast of Ishigaki Island, although the damage was not severe in comparison to that of the eastern coast (Makino, 1968). Our numerical modeling predicts moderate-to-low wave heights in this area (Fig. 9). Even if the tsunami was too weak to displace large boulders at the western coast of Ishigaki Island, it might have transported and deposited sand or coral fragments onto the land.

Archaeological studies should also be conducted to constrain the tsunami source model. For example, pre-event and tentative post-event occupation have been discovered by archaeologists (e.g. Kawana, 2003). Post event sites are likely to have been located higher than the maximum run-up height (e.g. Kawana, 2003). Therefore, this information is important for constraining maximum run-up. Additionally, it is interesting that the only debris of sunken ships in the Sekisei Lagoon was emplaced after the Meiwa period (A. Shimabukuro, personal communication). It is possible therefore that the 1771 Meiwa Tsunami removed earlier shipwreck debris that had been deposited in the lagoon prior to 1771.

7.2. Implications for identification of tsunami boulders among enigmatic deposits around the world

The identification of tsunami boulders must be extremely thorough because the implications compel local governments to consider the tsunami hazard and risk for local communities. We infer that the difference in wave period is critical to differentiating between tsunami and storm wave boulders, especially on reefs. As shown in Figs. 13 and 14, the distribution and sedimentary features of storm and tsunami-ishi boulders on the fringing reef show striking contrasts. Such sedimentary differences might be common among enigmatic boulders on the fringing reefs or atoll islands (e.g. Bourrouilh-Le and Talandier, 1985). In other reefs, wave intensities and topography might differ from those of the Ryukyu Islands. Nevertheless, it may be possible to determine the landward distribution limit of storm boulders based on field observations, analyses of aerial photographs, and hydrodynamic modeling of the storm waves based upon local tidal records. Therefore, it might also be possible to identify tsunami boulders deposited far beyond the distribution limit of storm clasts.

Numerical modeling of boulder transport is a key method for differentiating between tsunami and storm boulders. The model proposed by Imamura et al. (2008) is also applicable to the transport of boulders by large waves generated by storms or by swells. It facilitates the testing of the processes behind such transport. Analyses of this kind might provide important information for use in the debate of the origins of enigmatic boulders. Further improvement of the model, however, is necessary to analyze transport processes. Imamura et al. (2008) proposed several improvements to the model (see their Section 6). Additionally, results showed that most storm wave boulders deposited on the Ryukyu Islands had a platy shape (Goto et al., 2009a). Such boulders are likely to have been displaced by sliding rather than rolling or saltation. Furthermore, the displacement might be overestimated if one were to apply the model by Imamura et al. (2008) to these platy boulders. Similarly, a tsunami-ishi boulder at Yasura might have been displaced by sliding. Therefore, the boulder shape should be developed as a criterion for whether a variable coefficient of friction is adopted or not.

For disaster prevention purposes, identification of tsunami boulders itself is insufficient. Local tsunami hydrodynamic features (e.g., wave height, inundation depth, inundation area, or current velocity) should be estimated from the boulders. Such estimation can be done using numerical modeling based upon the spatial and clast size distributions of boulders (Goto et al., 2009b, 2010a). For boulders at Pakarang Cape, Thailand and those on the east coast of Ishigaki Island, the tsunami hydraulic force was strong enough to transport the maximum boulder near the high-tide line, but it was weak enough to deposit the small boulders below the high-tide line. This is a key limit for the tsunami hydraulic force. Preliminary cross-sectional calculation at Pakarang Cape by Goto et al. (2009b) revealed that only a tsunami with similar wave height and period to those of the 2004 IOT could have reproduced the present distribution of boulders. That calculated result in turn suggests that, if the local topography and boulders' spatial and clast size distributions and their approximate source area are known, then the local hydrodynamic features of past tsunamis might be calculated from boulders deposited throughout the world.

8. Summary

1. On the Ryukyu Islands, Japan, spectacular boulder fields are readily apparent on the fringing reefs, lowlands, and cliff tops. The Ryukyu Islands provide exceptional research areas for understanding sedimentary features and identification criteria of boulders deposited by tsunamis and storm waves because both boulders of possible historical tsunami and storm wave origins are located here according to scientific evidence and historical descriptions.
2. The 1771 Meiwa Tsunami devastated the Miyako–Yaeyama Islands. Reliable historical documents give information sufficient to estimate maximum run-up heights as about 30 m on Ishigaki Island, about 10 m on Miyako Island, and about 15 m on Tarama Island.
3. Detailed descriptions exist of the displacement of several specific boulders by the 1771 Meiwa Tsunami on Ishigaki, Kuro, and Shimoji islands in the historical documents. Such boulders have been known as “tsunami-ishi” in Japanese. Some of these boulders are identifiable and their historically documented movements were supported by numerical modeling results.
4. The Ryukyu Islands include several islands, such as Kudaka Island, where only storm wave boulders are observed. Storm wave boulders are distributed on the reef flat within 300 m landward of the reef edge. They show an exponentially fining landward feature. This distribution characteristic is useful to identify tsunami–ishi boulders on the Ryukyu Islands that are deposited far landward of this limit.
5. Boulders of different depositional origin were emplaced both on the reef crest and along the shoreline at the eastern coast of Ishigaki Island, which was damaged by the 1771 Meiwa Tsunami. Boulders on the reef crest are identifiable as storm wave origin, whereas boulders along the shoreline were deposited far beyond the transport limit of those by storm waves on the Ryukyu Islands. These are inferred to be tsunami-ishi boulders. Based on these criteria, we identified tsunami-ishi boulders on the Miyako–Yaeyama Islands. ^{14}C age dating further supports their 1771 Meiwa Tsunami origin, although pre-historical tsunami(s) might also have deposited boulders.
6. Tsunami-ishi boulders are commonly deposited below the high-tide line, where sand dunes are well developed. Furthermore, tsunami-ishi boulders were typically split into several pieces. Such

features are not observed in storm wave boulders deposited on the reefs at both Ishigaki and Kudaka islands. Therefore, this feature might be unique for tsunami-ishi boulders.

7. To identify the tsunami boulders from enigmatic clasts, it is important to devote attention to the difference of the wave periods of tsunami and storm waves rather than the wave heights. Differences should be apparent in the variability in spatial and clast size distributions of boulders. More precise numerical modeling of boulder transport is a key method to assist in differentiating between tsunami and storm wave boulders.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.earscirev.2010.06.005.

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