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# Emplacement and movement of boulders by known storm waves — Field evidence from the Okinawa Islands, Japan

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ABSTRACT

Field observations from previous studies of boulder movements were compiled to augment our own work on boulders that have been displaced by storm waves during recent typhoon events in the Okinawa Islands, Japan to elucidate the ability of storm waves to move boulders. Our observations reveal that recent storm waves displaced by sliding and overturning 100-ton boulders emplacing them on the reef or high cliff tops and that storm waves might also be capable of displacing 200 ton boulders on the reef. The weights of storm wave boulders at the Okinawa Islands are of comparable order to those boulders displaced by historical tsunami origins. Consequently, boulder weight alone is an inappropriate parameter to discriminate between tsunami or storm wave processes. However, these heavy storm wave boulders are close to the reef and cliff edges, while tsunami boulders can be deposited much further inland. Hence, horizontal displacement distance of boulders could be a useful parameter to discriminate boulders deposited by the tsunami and storm waves on the wide fringing reef. The storm wave boulders were characteristically concentrated on the southeastern (Pacific Ocean) sides of each island but large boulders are rarely found on the northwestern (East China Sea) side. This is probably because the storm wave intensities are generally stronger at the southeastern side than at the northwestern side, although differences of reef strength and initial condition of boulders should also be taken into account. Consideration of the high frequency of typhoons at the area suggests that effects of the storm waves and the consequent displacement of boulders on the reef might have contributed to the formation of the reef-moat framework that typifies the Okinawa Islands especially, if the moat is located within the transport limit of the storm wave boulders (approximately 300 m from the reef edge at the islands).



## 1. Introduction

Boulders of what size can be emplaced or displaced on a reef or rocky platform by storm waves? This is a critical issue underpinning the evaluation of the impact of the storm waves on a reef framework or coastal geomorphology and selection of useful parameters to discriminate boulders deposited by tsunami or storm waves (e.g. Kelletat, 2008). Nevertheless, the answer to this question remains obscure because case studies of boulders deposited by recent storm waves are very limited. The movements of boulders of several to hundreds of tons (up to 235 tons) by storm waves, which can be specified as the responsible storm events, have been reported throughout the world (e.g., Sussmilch, 1912; Kato et al., 1991, 1995; Onda, 1999; Mastronuzzi and Sansò, 2004; Noormets et al., 2002; Nott, 2004; Saintilan and Rogers, 2005; Gilmour and Smith, 2006; Scheffers and Scheffers, 2006; Kawana, 2008; Goto et al., 2009; Suanez et al., 2009). Etienne and Paris (2010) also reported boulders (<70 tons) of possible storm wave origin in Iceland, where tsunami impacts have not been recorded historically. The possible storm wave origin of cliff-top boulders in Ireland and Scotland are also proposed (Williams and Hall, 2004; Hall et al., 2006), although their tsunami origin is also suggested (Kelletat, 2008). Another approach that is frequently used to evaluate the degree to which heavy boulders can be moved by storm waves is the use of simple hydrodynamic models proposed by Nott (2003). Scheffers and Kelletat (2006) and Kelletat (2008) suggested, based on Nott's (2003) model, that storm waves might not have overturned >20 ton boulders in the joint bounded condition.

Confusion about the capabilities of storm waves to move heavy boulders relates to the scarcity of reliable field evidence to collaborate such process and response (e.g. Goto et al., 2009). Therefore, collecting field evidence related to boulders that were deposited by recent storm events is necessary for guiding the ongoing discussion. For this issue, the Okinawa Islands, Japan

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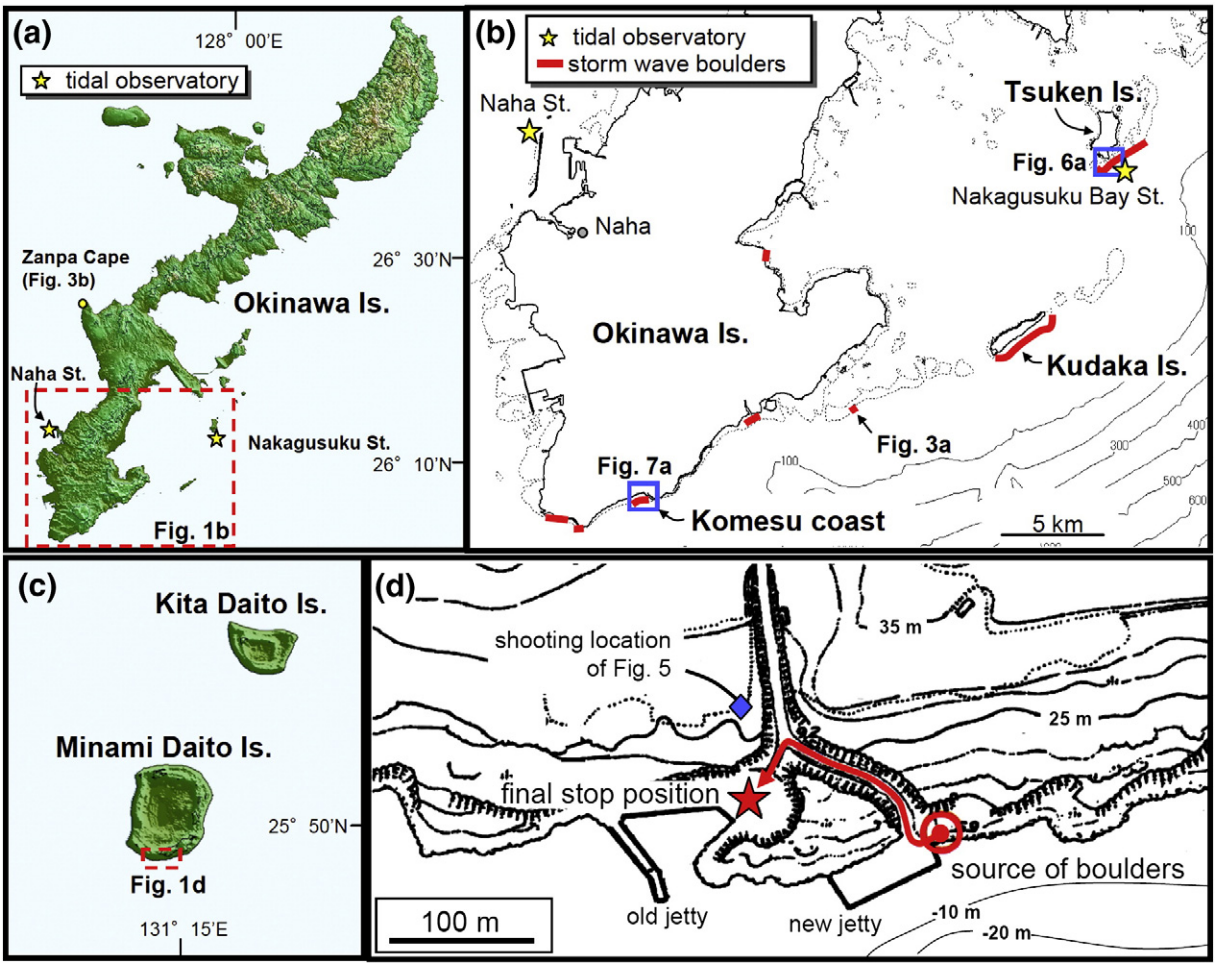


**Fig. 1.** (a) Map showing the location of Okinawa Island. Star marks show tidal observatories near the islands (Nakagusuku Bay and Naha Stations). (b) Map showing the locations of our studied area (Tsuken Island and the Komesu coast of Okinawa Island). Boulder fields are also shown based on our own observations. Dotted lines denote the low tide line (data provided by Japan Hydrographic Association). (c) Map showing the location of Minami Daito Island. (d) Map showing the original and final stop positions as well as the paths of boulders displaced by storm waves generated by typhoon 0418 in 2004 (after Miyagi, 2004).

(Fig. 1) have remained one of the best research fields to study boulders for the following reasons: 1) several severe typhoons have attacked it every year and the significant wave height (SWH) and period (SWP) are very large (up to 13.6 m and 14.9 s, respectively in the record after 1972), 2) no large tsunamis have attacked the islands since 1768 (Watanabe, 1985), except for the limited impact by the 1960 Chilean Tsunami, 3) a series of aerial photographs and tidal records are available for evaluating the relation between the movements of boulders and storm wave intensities, and 4) many local residents living along the coasts are valuable eyewitnesses. For this study, we compiled field observation data on boulders that were moved by the recent typhoon events in the Okinawa Islands. We will discuss the capability of storm waves to move boulders.

## 2. Previous studies of boulders deposited by storm waves at the Okinawa Islands and the Daito Islands

The Ryukyu Islands extend approximately 1000 km from northeast to southwest along the Ryukyu Trench between Taiwan and Kyushu, Japan. The Okinawa Islands are located in the central Ryukyu Islands, comprising more than 30 islands including the islands discussed herein (Okinawa, Tsuken, and Kudaka). Fringing reefs surround most of the islands. As like the other islands in the Ryukyu Islands, the reef is generally divided into the reef flat and reef slope. From shore to offshore, the reef flat can be subdivided into a moat (shallow lagoon), reef crest, and reef edge. Generally, the reef slope is a steep escarpment at the reef edge (approx. 1/10 slope inclination); with spurs and grooves extending down to depths of several tens of meters at each island. Several severe typhoons have attacked these islands every year (Japan Meteorological Agency (JMA), undated). In total, approximately 110 typhoons and tropical cyclones had approached within 150 km from Okinawa Island since 1951 (Fig. 2, JMA, undated; Kitamoto, undated). Tidal records for the area are available after 1972.

In this section, we will review the previous studies of boulders deposited by storm waves at Okinawa, and Kudaka islands in the Okinawa Islands, and Minami Daito Island in the Daito Islands. Table 1 presents characteristics of boulders and storm events described in this section.

### 2.1. Okinawa Island

#### 2.1.1. Boulder on the reef deposited by typhoon 5115 in 1951

Typhoon 5115 approached Okinawa Island on 14 October 1951. Its minimum pressure was 924 hPa (JMA, undated). The typhoon reached the island during the high tide. The resultant storm surge, recorded onshore, severely damaged the area (Kawana, 2008).