Seafloor morphology and sediment magnetic fabric in a putative 1771 Meiwā tsunami source region in the southern Ryukyu Islands, SW Japan

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Abstract: The Meiwā tsunami of AD 1771 is regarded as an extremely strong tsunami event causing devastating damage in Japan in historical times. Earlier studies explored the possibility that a submarine landslide enhanced the Meiwā tsunami waves. We collected detailed seafloor bathymetry data, sub-bottom structure data and surface sediments in a putative Meiwā tsunami source region to ascertain any signature related to a submarine landslide in the forearc region, which is located south of Ishigaki-jima. The forearc-region seafloor is characterized by its surface submarine landslide morphology. However, the investigated magnetic fabric of surface sediment revealed that there was no landslide mass deposit during historical times. The described landslide morphology in the basin is unrelated to the generation or enhancement of the AD 1771 Meiwā tsunami, although the disturbed relief in the topography of the study area indicates that the forearc region is susceptible to slope failure because of its tectonic setting.

Supplementary material: Function of lightness (L*) and anisotropy of the magnetic susceptibility (AMS) datasets for this study are available at https://doi.org/10.6084/m9.figshare.c.4835076

The Meiwā tsunami, which struck the Sakishima-shoto (Sakishima Islands) in AD 1771, is regarded as one of the largest tsunami events and caused devastating damage in Japan in historical times. The run-up height of the Meiwā tsunami reached up to 30 m at its maximum (e.g. Nakata and Kawana 1995; Goto et al. 2010). Large tsunami boulders distributed on the shore of Ishigaki-jima (‘jima’ means ‘island’ in Japanese) are thought to have been transported from the sea by large tsunami waves such as those of the Meiwā (e.g. Imamura et al. 2008; Goto et al. 2013). Their depositional ages reveal repeated tsunami occurrence every 150–400 years (Araoka et al. 2013). Nevertheless, the mechanism generating the Meiwā tsunami remains controversial; it is especially unclear how the Meiwā tsunami became so large. The major inferences for the origin of the Meiwā tsunami include generation as a result of the Yaeyama earthquake (e.g. Nakata and Kawana 1995). The proposed types of faulting that induced the Meiwā tsunami include an intraplate fault (Nakamura 2006), a plate boundary fault (Nakamura 2009) or a splay fault (Arai et al. 2016). Moreover, non-earthquake mechanisms have also been proposed because such a large discrepancy exists between maximum run-up heights by faulting models and observations (Imamura et al. 2001), and between the earthquake and the tsunami magnitudes (Nakamura 2006). Submarine landslides have also been suggested as contributing to the enhancement of the Meiwā tsunami (Imamura et al. 2001). Indeed, submarine landslides on continental margins are regarded as a general mechanism that generates tsunami waves (e.g. Locat and Lee 2002; Tappin et al. 2008). Some source models assume a fault dislocation plus a submarine landslide as being the source of the Meiwā tsunami (e.g. Hiyoshi et al. 1986; Miyazawa et al. 2012). In the trench landward slope, Okamura et al. (2018) recognized a large seafloor depression of an accretionary prism. They proposed that a large area of earthquake-induced rotational sliding generated the Meiwā tsunami.

As described above, the cause of the Meiwā tsunami remains controversial. One reason for this controversy is a lack of direct evidence from the seafloor record in this region. Detailed bathymetry, sub-bottom structure and surface sediment data are required to make further verification of the proposed possibilities. To acquire these data, we conducted geological investigations to obtain information...
particularly addressing recognition of any signature related to submarine landslides. The Meiwa tsunami source has not been clarified but damaged areas of Ishigaki-jima are concentrated on the south side of the island (e.g. Goto et al. 2010). Earlier work (e.g. Imamura et al. 2001; Miyazawa et al. 2012) proposed that submarine landslides to the south of Ishigaki-jima are possible additional sources of the Meiwa tsunami. Indeed, the forearc basin (Hateruma Basin) located to the south of Ishigaki-jima is considered as the most likely place where mass-transport deposits resulting from submarine landslide around the forearc are preserved. We selected that area to seek signs of submarine landslides.

**Geological setting**

The Ryukyu subduction zone extends from SW of Kyushu Island to an area east of Taiwan (Fig. 1). The strike of the Ryukyu Trench changes off Miyako-jima from NE–SW in the east to east–west in the west; and the plate subduction is normal to the trench in the east and oblique to it in the west. The oblique subduction in the west has generated complex deformation in the outer accretionary wedge as a result of trench-parallel right-lateral shear zones (Kao 1998; Lallemand et al. 1999; Hsu et al. 2013). The west Ryukyu subduction zone is characterized by a large area of the forearc basin (Okamura et al. 2017; 2018) that is divided into subsedimentary basins (Lallemand et al. 1999; Font et al. 2001; Izumi et al. 2016; Hsiung et al. 2017). The Hateruma Basin is located south of Iriomote-jima and Ishigaki-jima (Fig. 1b). Some studies use the term ‘Yaeyama Basin’ instead of Hateruma Basin (e.g. Okamura et al. 2017). In this basin, the pre-Neogene rocks are widely recognized as the basement, which is over lain by the early Miocene Yaeyama Group and the late Miocene–Pliocene Shimajiri Group (Aiba and Sekiya 1979).

**Methods**

**Bathymetry and sub-bottom profiler records**

Research cruises were conducted mainly in the forearc basin of the Ryukyu Trench using the Japan Agency for Marine Science and Technology (JAMSTEC) research vessels in cruises YK15-01, KR15-18, KR16-E01 and MR18-01C. Detailed bathymetric mappings were conducted to elucidate possible features of the submarine landslide in surface morphology. Data were collected using multibeam echo sounders SeaBeam 3012 and Kongsberg EM 122 at 12 kHz frequency. Bathymetrical grid data were generated using software GMT5.4.4 (Generic Mapping Tools; Wessel and Smith 1991). Sub-bottom profiler (SBP) records were collected to infer sub-bottom structure and sedimentary facies from acoustic images (e.g. lkehara et al. 1990) using a Bathy 2010 SBP system with a 3.5 kHz frequency. Surface sediments were also collected using a conventional piston corer (4–8 m pipe length) to assess evidence of a recent submarine landslide or mass-transport deposit (Table 1). Any submarine failure occurring in connection with the

![Fig. 1. Location map. (a) Legend map of the research area. (b) Bathymetry around the Hateruma Basin corresponding to the red lined box in (a). The figures were prepared using GMT 5.4.4 with data from ETOPO 1 (Amante and Eakins 2009) and data collected during the cruises.](image-url)
Yaeyama earthquake would be expected to leave mass-transport deposits (slump, debris flow or other chaotic depositions) from that failure as an archive on the seafloor.

**Sediment samples**

Visual descriptions on split sections of samples were conducted to characterize their lithologies. The colour reflectance spectra were taken on the split core PC13 using a Konica Minolta CM-700d spectrophotometer with a 2 cm interval for additional lithological information (see dataset 1 in the Supplementary material). Colorimetric information as a function of lightness (L*) in a Lab colour space system was used to represent the colour change of the split core floor. This geometrical feature is presumed to have been formed by a submarine landslide of the margin at some time in the past. Scattered blocks are recognized to the SE of the submarine fan (Fig. 2e). The estimated maximum distance of blocks from the fan margin is about 12 km. They are a few kilometres in length. Their elongation axes are dominantly aligned to NE–SW orientations. The dimensions are similar to submarine slide blocks defined by Alves (2015). Their orientations parallel to the margin suggest that the slide blocks were originally associated with the submarine fan.

A topographical high (Fig. 2c) bounds the eastern margin of the Hateruma Basin. Aiba and Sekiya (1979) reported that there is basement level uplift in this area. The topographical high is probably attributable to this basement rise.

There is a remarkably wide and sharp arcuate escarpment (Fig. 2d) opening to the west, hollowing out the topographical high described above. The dimensions of this escarpment are 10 km in length, 4 km in width and 200–300 m in height. Matsumoto and Kimura (1993) considered that the formation of the escarpment is related to the generation of the
Meiwa tsunami. Its morphology resembles a typical slumped seafloor (e.g. Hampton and Locat 1996).

South of the study area, a 4–5 km-wide, enigmatic shallow graben cuts the forearc region, extending in a WNW–ESE direction (Fig. 2f). The sidewalls of the graben are a few tens of metres high. A series of similar offsets accompanying this graben can be clearly identified. The orientation of the structure is not straight but is, instead, gently curved. The structures extend southeastward and converge to a steep escarpment at the edge of forearc (Fig. 2g). A 5 km wide terrace is located in the foot of escarpment (Fig. 2). A farther low seafloor displays complicated surface structures in a broad area, which was inferred to be depressed seafloor by Okamura et al. (2018).

Sub-bottom profiler records

SBP surveys were conducted in the forearc basin; one line transversed the arcuate escarpment and the graben (Fig. 2a, b). The acoustic image inside the arcuate escarpment is characterized by a sharp and continuous bottom echo (Fig. 3b). In the northern part of the escarpment bottom, the reflector inclines to the north. A stratified layer, c. 20 m thick, can be found on the southern side. Considerable sediment accumulation might have taken place after the formation of the arcuate scar.

The sub-bottom profiler record, shown in Figure 3c, that crosses the graben shows the clear and more than c. 20 m-thick stratified layers. No difference in acoustic thicknesses can be recognized between the intact layers and the subsided layers. This image presents an opportunity to measure the precise offset depths along line A–B in Figure 2. The offset is estimated to be 30 m on the north side and 10 m on the south side.

Sediment record

Two cores were studied in the Hateruma Basin. The sampling position of YK15-01PC11 was near the arcuate scar. YK15-01PC03 was taken downslope
from the submarine fan (Fig. 2). YK15-01PC13 was collected from the topographical high isolated from the forearc basin for reference to the results of an earlier study (Xu and Ujiie 1984). In the visual descriptions, no chaotic deposition formed by slump or debris flow was observed in these collected cores (Fig. 4a–c), and no overconsolidation of sediment was recognized. The major lithology of YK15-01PC03 is calcareous silt with intercalations of calcareous very-fine and fine sand layers (Fig. 4a). The calcareous sand layer has sedimentary structures suggesting turbidite, it shows a sharp contact at the bottom and is upward fining. The coarse-layer intercalation generally corresponds to magnetic susceptibility lows in YK15-01PC03. YK15-01PC11 consists of a homogeneous calcareous silt. An intercalation of a thin coarse silt layer was only found at a depth of 123 cm below the core top. A small magnetic susceptibility low is recognized at this horizon in YK15-01PC11. YK15-01PC13 consists of a homogeneous silty clay with bioturbation, and no visible sandy layers. Intercalations of tephra layers are apparent 378.8–387.0 and 405.3–406.3 cm below the core top. The tephra layer at 378.8–387.0 cm is regarded as a ‘Ata’ tephra (105–110 ka: Machida and Arai 2003) because it was identified c. 320 cm below seafloor in the previously studied core RN87-PC4 taken from the same location (Xu and Ujiie 1984). The averaged sedimentation rate calculated from 14C conventional ages (Table 2) obtained from the upper interval of YK15-01PC13 is c. 5 cm ka⁻¹.

Fig. 3. Records of the sub-bottom profiler. (a) Cross-section image of the line A–B in Figure 2. (b) & (c) are close-up views of the areas shown in rectangles in (a). In (c), 1 is the offset of the north side; 2 is the offset of the south side. Water depths are calculated using a constant sonic velocity of 1500 m s⁻¹.
Fig. 4. (a)–(c) Lithological columns of piston cores YK15-01PC13 (PC13), YK15-01PC11 (PC11) and YK15-01PC03 (PC03): grey, hemipelagic clay-silt; dark grey, event deposits (turbidite); and red tephra patch or layer. The red arrow marks the position of the magnetic susceptibility low. Sand: vf, very fine; f, fine; m, medium; c, coarse.

(d) Marine isotope record of LR04 benthic stack (Lisiecki and Raymo 2005). (e) L* variation and magnetic susceptibility variations (MS) of YK15-01PC13 with conventional ¹⁴C ages. (f) & (g) Magnetic susceptibility variations of YK15-01PC11 and YK15-01PC3. The red arrow marks the position of the magnetic susceptibility low.

(h) SINT800 (Guyodo and Valet 1999). (i) NRM intensities at 20 mT normalized by ARM at 20 mT (NRM20mT/ARM20mT) of YK15-01PC13. (j) NRM20mT/ARM20mT of YK15-01PC11. (k) NRM20mT/ARM20mT of YK15-01PC03. Tie lines are shown in purple.
Intervals of yellowish silt occurring in the upper several centimetres are recognized in the core tops of three cores (Fig. 4a–c). Only in YK15-01PC13 are repeated downward colour changes recognized. The results demonstrate that the L* variation of YK15-01PC13 displayed in Figure 4e has similar fluctuation patterns to those of the benthic oxygen marine isotope variation in Figure 4d (Lisiecki and Raymo 2005). This interpretation matches the age of the ‘Ata tephra. In addition, the magnetic susceptibility fluctuation of YK15-01PC13 shows a generally reversed image to the L* change (Fig. 4e), although the upper interval is more fluctuated. We regard the magnetic susceptibility as useful for core correlations (Fig. 4e–g). We verified this possibility using palaeointensity-assisted stratigraphy of the cores. The normalized NRM intensity of YK15-01PC13 (Fig. 4i) correlates well to the interval of 0–140 ka of the global stack record of palaeointensity (Fig. 4h: SINT800) (Guyodo and Valet 1999). The most notable palaeointensity lows at 170 cm in YK15-01PC13 (Fig. 4h) and 320 cm in YK15-01PC11 (Fig. 4i) clearly correspond to the ‘Lascshamp excursion’ at c. 41 ka (Laj and Kissel 2015). Based on these possible correlations, the time coverage for YK15-01PC11 and YK15-01PC03 are regarded as younger than 60 and 30 ka, respectively.

**AMS fabric**

The results of the AMS measurements of YK15-01PC03, YK15-01PC11 and YK15-01PC13 are displayed in Figure 5. YK15-01PC03 and YK15-01PC11 are characterized by a high F value (oblate type) (Fig. 5d, e). The $K_{max}$ axis distributions of YK15-01PC03 and YK15-01PC11 do not show strong clustering (Fig. 5a, b). However, NW–SSE and NE–SW trends are recognized in YK15-01PC03 and YK15-01PC11, respectively, which could have been induced by bottom currents. The $K_{max}$ declinations are generally constant throughout all depths in YK15-01PC03 and YK15-01PC11, and the $K_{max}$ declinations in the coarse-grained layers show similar trends to those of other intervals (Fig. 5g, h). The $K_{min}$ inclinations of the fabric induced by slumping are largely divergent from the vertical and ultimately become horizontal (e.g. Schwehr et al. 2007, Kanamatsu et al. 2014). However, no such fabric was observed in the AMS results. This observation is consistent with the results of the visual descriptions. The fabric shape of YK15-01PC13 is clearly different to those of YK15-01PC03 and YK15-01PC11. The $K_{max}$ directions are biased towards the NE with small plunges (Fig. 5c). The anisotropy results from YK15-01PC13 are generally very weak (Fig. 5f). The AMS axis alignments and shape parameters of YK15-01PC13 indicate a fabric formed by grain rotation along the longest axis. Such a fabric pattern is possibly formed in fast bottom current conditions (Tauxe 1998). Because YK15-01PC13 was collected on a southward-dipping slope, it is interpreted that the AMS direction indicates a southeastward bottom current.

**Discussion**

Detailed topography of the Hateruma Basin reflects the geometrical signatures of slope failure. In particular, the arcuate escarpment and slide blocks (Fig. 2) can be regarded as a typical slumped seafloor (e.g. Hampton and Locat 1996). However, the visual core descriptions indicate no signature of mass-transport deposit. The sediment magnetic fabrics collected from the area also suggest no mass-transport deposition in the collected samples but, rather, coherent deposition. Therefore, the results suggest no indication of submarine landslide in YK15-01PC03 and YK15-01PC11.

Even presuming that the youngest sandy (silty) layer at 27.0–28.5 cm of YK15-01PC03 is a distal facies of a submarine landslide, it is estimated to have occurred c. 7 kyr ago by referring to YK15-01PC13’s conventional $^{14}$C age with magnetic susceptibility tie points. This estimate is much earlier than the age of the Meiwa tsunami (AD 1771). No observations of the sediments reveal any evidence

| Sample ID | Interval (cm) | Conventional $^{14}$C age (years BP) | Error (years) | $\delta^{13}$C Material |
|-----------|---------------|--------------------------------------|---------------|------------------------|
| YK15P13-01 | 1–5 | 2220 | 30 | 2.7 | G. sacculifer |
| YK15P13-06 | 37–39 | 10 680 | 40 | 1.6 | G. sacculifer |
| YK15P13-08 | 41–43 | 11 040 | 50 | 1.8 | G. sacculifer |
| YK15P13-10 | 71–73 | 15 900 | 50 | 2.1 | G. sacculifer |
| YK15P13-12 | 119–121 | 25 170 | 110 | 2.4 | G. sacculifer |
| YK15P13-14 | 169–171 | 35 490 | 300 | 1.7 | G. sacculifer |
indicating a submarine landslide during historical times. Consequently, one can infer that the failed topography identified in bathymetric data in the forearc region has no connection to the AD 1771 Meiwa tsunami generation. 

Araoka et al. (2013) suggested that tsunamis have occurred in the southern Ryukyu Islands repeatedly at intervals of c. 150–400 years over the past 2.4 kyr. The lithology of surface sediment in the Hateruma Basin does not show evidence of mass-transport events since c. 60 ka. Therefore, it is interpreted that not only the Meiwa tsunami but also older tsunami events recorded in the southern Ryukyu Islands are not related to submarine landslides in the Hateruma Basin. It is interpreted that the observed morphology is not old enough. 

Nevertheless, the graben structures observed in the studied area are visibly distinct around the front of Ishigaki-jima (Fig. 6), suggesting that the area does undergo active deformation. The graben structure crossing the forearc region obliquely exhibits a clear appearance of seafloor deformation (Fig. 2). The sidewall with rather sharp and continuous lines over 40 km can be regarded as an active surface structure. The graben structure extends southeastwards and converges with the southern edge of the forearc basin. In the north, it disappears around the submarine fan (Fig. 2h). A lack of different thicknesses of the sub-bottom layers between the subsided and the host seafloors suggests that the structure was formed recently in a tension-stress environment. This kind of seafloor deformation might generate a tsunami. A tsunami was generated by a normal faulting earthquake mechanism 40 km off the coast of Fukushima Prefecture, north Japan on 22 November 2016 (Mw = 6.9: e.g. Gusman
et al. 2017; Adriano et al. 2018), which was considered as one of the aftershocks of the 2011 Tohoku-Oki earthquake. The largest tsunami amplitude of 1.44 m was observed at Sendai’s port. The detailed seafloor survey after the earthquake around the epicentre found a 1 km-wide graben structure in a NE–SW orientation and 2 m of surface seafloor displacement (http://www.jamstec.go.jp/j/about/press_release/20170301/). This seafloor offset is possibly related to the earthquake and the consequent tsunami off Fukushima.

Therefore, it should be also considered that the graben structure found in the Hateruma Basin has the potential to generate a tsunami. The origin of this structure is currently unclear. However, since the distribution of the graben structure is sub-parallel to the margin of the forearc basin (Fig. 5g), the formation of the graben might be related to a tectonic event in the forearc, such as a depression event interpreted to have been formed by a seaward sliding of the slope (Okamura et al. 2018).

Fig. 6. Bird’s-eye view of the bathymetry of the forearc region off Ishigaki-jima. The azimuth and elevation of the perspectives are 250°and 40°, respectively. The bathymetric data used in this figure are available from the JAMSTEC DARWIN database (http://www.godac.jamstec.go.jp/darwin/e). The figure was prepared using GMT 5.4.4 with data collected during cruises.

Conclusions

The seafloor of the forearc region in the south of Ishigaki-jima is characterized by distinct failed geomorphological features which suggest the occurrence of submarine landslides in the past. Observations of surface-sediment lithology and sediment fabric revealed no submarine landslide signatures in the sediment records, even though the investigated time interval of the sediment core is sufficiently old. Therefore, we infer that the observed failed morphological features in the Hateruma Basin are sufficiently old but have no connection to the generation or exacerbation of the Meiwa tsunami in 1771.

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