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Benthic foraminiferal evidence of deep-sea sediment transport by the 2011 Tohoku-oki earthquake and tsunami

Kazuko Usami [a,*], Ken Ikehara [a], Robert G. Jenkins [b], Juichiro Ashi [c]

[a] Institute of Geology and Geoinformation, Geological Survey of Japan, AIST, Tsukuba, Ibaraki 305-8567, Japan
[b] College of Science and Engineering, Kanazawa University, Kanazawa 920-1192, Japan
[c] Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Chiba 277-8564, Japan

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ABSTRACT

Benthic foraminiferal assemblages within turbidites recovered from two upper slope stations off Sendai Bay, northeast Japan, have been analyzed to estimate the source area of the turbidites resulting from the 2011 Tohoku-oki earthquake and tsunami. The turbidite at one station (St. 5; 893 m water depth) is composed of a surface layer that contains foraminiferal species living on the outer shelf or inner bay, and a lower part with bathyal species. In the turbidite at the second station (St. 6; 1446 m), the assemblage consists of only bathyal species (living in 800–1000 m). The composition of the St. 6 assemblage gradually changes from the base to the top of the turbidite, consistent with the upward-fining graded structure (i.e. thin-walled, tiny species are increased in the upper layer). The lower part of the turbidites at both sites, St. 5 and St. 6, are considered to have originated from turbidity currents triggered by earthquake shaking. In contrast, the most probable generation mechanism for the turbidity current that formed the surface layer at St. 5 is the tsunami-related agitation of sediment in shallow water. The relatively good preservation of benthic foraminiferal tests in the turbidites suggests transport processes with minimal internal friction and/or collision of grains within the turbidity current. These results show that benthic foraminifera are useful in turbidite paleoseismology.

1. Introduction

The 2011 earthquake that occurred off the Pacific coast of Tohoku and its related tsunami (hereinafter called the 2011 Tohoku-oki earthquake and tsunami) had a large impact not only on land but also on the seafloor. Previous studies have reported displacement of the seafloor and deformation structures in the sedimentary strata around the epicenter (Fujiwara et al., 2011; Lay et al., 2011; Kodaira et al., 2012; Kanamatsu et al., 2013; Satake et al., 2013). The large tsunami resulted from a fault rupture that nearly reached the Japan Trench axis, in conjunction with a large displacement of the seafloor (Kodaira et al., 2012; Strasser et al., 2013). Disturbance of deep-sea environments by the earthquake and tsunami has been reported in coastal and offshore areas of Tohoku (e.g., Noguchi et al., 2012; Arai et al., 2013; Oguri et al., 2013; Ikehara et al., 2014; Toyofuku et al., 2014; Tamura et al., 2015). Generation of tsunami-induced turbidity currents was inferred from turbidites on the upper-mid slope (Arai et al., 2013) and on the Sendai shelf (Ikehara et al., 2014), close to the earthquake epicenter. Therefore, the turbidity currents are currently thought to have been spatially extensive. Intensification of the tsunami by submarine landslides has also been suggested (Kawamura et al., 2012).

Turbidity currents can be triggered also by earthquake shaking (e.g., Heezen and Ewing, 1952; Syvitski and Schafer, 1996; Thunell et al., 1999; Nakajima and Kanai, 2000; McHugh et al., 2006; Strasser et al., 2006; Noda et al., 2008; Gutiérrez-Pastor et al., 2013). Submarine cables along the Japan Trench slope were broken just after the main shock of the 2011 Tohoku-oki earthquake (Shirasaki et al., 2012). The estimated peak ground acceleration of the 2011 event is thought to have been sufficient to generate slope failure around the epicenter (Noguchi et al., 2012). Many sediment core samples containing turbidites considered to be related to the 2011 earthquake have been recovered from the outer shelf, the inner (landward) slope, and the Japan Trench floor, off Sanriku (Ikehara et al., 2012; Oguri et al., 2013).

Benthic foraminifera are important in interpreting the origin and transport of tsunami deposits, both on land and in shallow marine environments, as their bathymetric distribution in continental shelf and slope environments can be related to properties of the water mass (Nanayama and Shigeno, 2006; Mamo et al., 2009; Sugawara et al., 2009; Pilarczyk et al., 2012). Bathyal benthic foraminifera have been found in inner bay tsunami deposits formed during the Flandrian transgression (Uchida et al., 2004, 2010). These results suggest that tsunami can entrain upper slope sediments. Benthic foraminiferal assemblages have also been used to estimate the water depth of the source region

* Corresponding author.
E-mail addresses: k-usami@aist.go.jp (K. Usami), k-ikehara@aist.go.jp (K. Ikehara), robertgj@staff.kanazawa-u.ac.jp (R.G. Jenkins), ashi@aori.u-tokyo.ac.jp (J. Ashi).

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for deep-sea turbidites (Ujiié et al., 1997; Uchida et al., 2006; Ito, 2008; Noda et al., 2008; Polonia et al., 2013). Benthic foraminiferal assemblages from muddy sediments forced into the hard hat (protection cover for pressure-resistant glass sphere in which observation materials such as sensor, recorder and battery are equipped) of ocean-bottom seismometers (OBS) by the 2011 Tohoku-oki earthquake and tsunami do not suggest long-distance transport of sediments (Hasegawa and Miura, 2012; Fig. 1), even though the tsunami-induced turbidity currents are thought to have been spatially extensive in this area, as indicated above (Arai et al., 2013). Although there are many reports of sediment resuspension, transport, and turbidite deposition associated with the 2011 Tohoku-oki earthquake and tsunami, the triggering mechanism, the site of origin, travel distance, and the pathway of the turbidity currents remain poorly understood.

Here we present detailed analyses of benthic foraminiferal assemblages from turbidites recovered from two stations off Tohoku. Along-core changes in benthic foraminiferal assemblage are closely connected with the sediment facies. Because the detailed bathymetric distributions of modern benthic foraminiferal assemblages off Sendai Bay before the 2011 Tohoku-oki earthquake and tsunami have been investigated by previous studies, comparisons of the results with the assemblages identified in this study can provide information on the water depth of the source area for the turbidites in our cores. The results indicate that turbidity currents generated by the 2011 Tohoku-oki tsunami transported sand-size grains from the outer shelf or inner bay to the bathyal slope. Surprisingly, the foraminiferal tests transported over such long distances are relatively well preserved. These results may contribute to a better understanding of sediment transport processes resulting from earthquakes and associated tsunamis, the interpretation of event deposits, and submarine paleoseismology.

2. Study area

The study area is located on the upper slope off Sendai Bay, northeast Japan (Fig. 1). The seafloor in this area is gently sloping (~1°) from the shelf edge (water depth = 125 m) down to 1600 m water depth (Ogawa and Kobayashi, 1994). There are several isolated forearc basins at 1000–3000 m water depth along the Japan Trench (Arai et al., 2014). These isolated basins are filled by stratified sediments (Arai et al., 2014). Few distinct submarine canyons are found on the upper slope of the Japan Trench in the study area, although small gullies occur along the landward slope of the isolated basins. Coseismic horizontal displacements in this area, resulting from the 2011 Tohoku-oki earthquake, range between 15 and 50 m (Fujiwara et al., 2011; Kido et al., 2011; Sato et al., 2011). The main ocean currents influencing the study area are the Oyashio Current (from the north) and the Kuroshio Current (from the south), which form the "mixed water region" in the surface water (Kawai, 1955; Ohtani, 1991; Sendai Regional Headquarters, JMA, 2011). The vertical distribution of water masses off Sendai Bay comprises the surface water (0–170 m water depth), "transition water" (170–220 m), the intermediate water (220–550 m) originated from the Oyashio Current, "transition water" (550–900 m), the oxygen minimum layer (900–1400 m and 1400–1800 m), and the deep water (>1800 m) (Matoba, 1976). A previous study, carried out before the 2011 Tohoku-oki earthquake, discriminated six foraminiferal assemblages in the sublittoral zone (>170 m) and another six

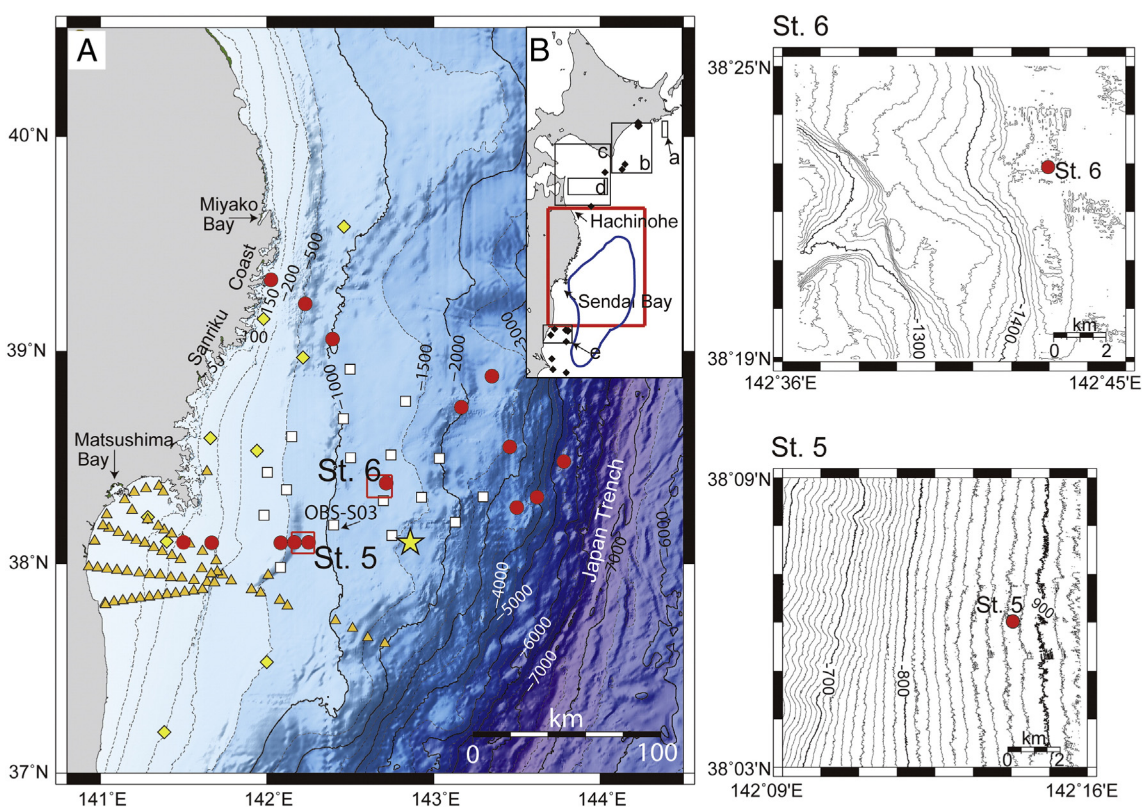

Fig. 1. Location map (A, B) and topography of the coring sites at St. 5 and St. 6. A. Red circles: sites sampled using a multiple corer during the KT-11-17 cruise. Yellow star: epicenter of the 2011 Tohoku-oki earthquake. Yellow diamonds: sampling sites of Ishiwada (1964). Orange triangles: sampling sites of Matoba (1976). White squares: ocean-bottom seismometers (OBS) sampled by Hasegawa and Miura (2012) for analyses of benthic foraminiferal assemblages. OBS-S03 is deployed at almost the same latitude and longitude as ocean bottom pressure gauges (OBP) P03, which was transported by tsunami-induced turbidity currents (Arai et al., 2013). Red rectangles around St. 5 and St. 6 indicate the areas shown on the topographic maps to the right. Bathymetric chart (shaded-relief) is based on J-EGG500 (JODC-Expert Grid data for Geography; http://www.jodc.go.jp/data_set/jodc/jegg_intro.html). B. Map showing the location of Fig. 1A, located in northeast Japan (red rectangle), showing the study area and sample sites of previous studies. Black diamonds (Ishiwada, 1964), a: off Hamanaka (Matsuo et al., 2004), b: off Tokachi (Abe et al., 2003; Matsuo et al., 2004), c: off Tokachi-Hachinohe (Ikeya, 1971), d: off Hachinohe (Fontanier et al., 2014), and e: off Fukushima (Kaiho and Hasegawa, 1986). Blue line: generalized fault rupture area of the 2011 Tohoku-oki earthquake inferred from GPS data (Ozawa et al., 2011).

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