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Tsunami-generated turbidity current of the 2011 Tohoku-Oki earthquake

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ABSTRACT

We show the first real-time record of a turbidity current associated with a great earthquake, the Mw 9.0, 2011 Tohoku-Oki event offshore Japan. Turbidity current deposits (turbidites) have been used to estimate earthquake recurrence intervals from geologic records. Until now, however, there has been no direct evidence for large-scale earthquakes in subduction plate margins. After the 2011 Tohoku-Oki earthquake and tsunami, an anomalous event on the seafloor consistent with a turbidity current was recorded by ocean-bottom pressure recorders and seismometers deployed off Sendai, Japan. Freshly emplaced turbidites were collected from a wide area of seafloor off the Tohoku coastal region. We analyzed these measurements and sedimentary records to determine conditions of the modern tsunamigenic turbidity current. We anticipate our discovery to be a starting point for more detailed characterization of modern tsunamigenic turbidites, and for the identification of tsunamigenic turbidites in geologic records.

INTRODUCTION

Turbidity currents are sediment-laden subaqueous density flows generated by processes such as submarine landslides, river floods, and storms (Normark and Piper, 1991). Because turbidity currents were detected immediately after the A.D. 1908 Messina (Italy) earthquake and the 1929 Grand Banks (offshore Newfoundland) earthquake, which were both characterized by the occurrence of large submarine slumps (Heezen and Ewing, 1952; Ryan and Heezen, 1965), paleo-earthquakes and paleotsunamis have been assumed to be recorded as turbidity current deposits (turbidites) in sedimentary sequences (e.g., Goldfinger, 2011; Polonia et al., 2013), and several turbidites have been used to estimate earthquake recurrence intervals (e.g., Kastens, 1984). However, there has not been direct evidence for the generation of turbidity currents by large-scale earthquake-generated tsunamis in the absence of related submarine landslides at subduction margins. Here we show the first real-time record of such a turbidity current associated with a major tsunami, the Mw 9.0 2011 Tohoku-Oki tsunami offshore Japan that is inferred to have triggered the current. The turbidity current was recorded by ocean-bottom pressure recorders (OBPs) with thermometers and ocean-bottom seismometers (OBSs). Freshly emplaced turbidites were collected from a wide area of seafloor.

ANOMALOUS EVENT ON THE SEAFLOOR

After the main shock of the Tohoku-Oki earthquake, the OBPs and OBSs recorded an anomalous event on the seafloor off the Tohoku coast, i.e., the displacement of an OBP, anomalous records of temperature and ground motion in one OBP and one OBS recorded anomalous event, and sediment infilling inside the OBPs and OBSs. Tohoku University had deployed 8 OBPs and 19 OBSs offshore of Miyagi Prefecture over the range of 38°–39°N and 142°–144°E, and at water depths of 300–5700 m, before the earthquake (Hino et al., 2009; Suzuki et al., 2012) (Fig. 1; Table DR1 in the GSA Data Repository[1]). All but two of these OBPs and OBSs were recovered between 14 March and 26 November 2011.

Displacement of an OBP

One of the OBPs and OBSs set on the seafloor, sensor OBP-P03, was displaced by 1 km after the 2011 Tohoku-Oki earthquake and tsunami. It was recovered lying on the seabed at 38.1819°N, 142.4132°E, ~1 km east of the installed position of 38.183°N, 142.400°E (Figs. 1 and 2; Table DR1 in the Data Repository). Moreover, sensor OBP-P03

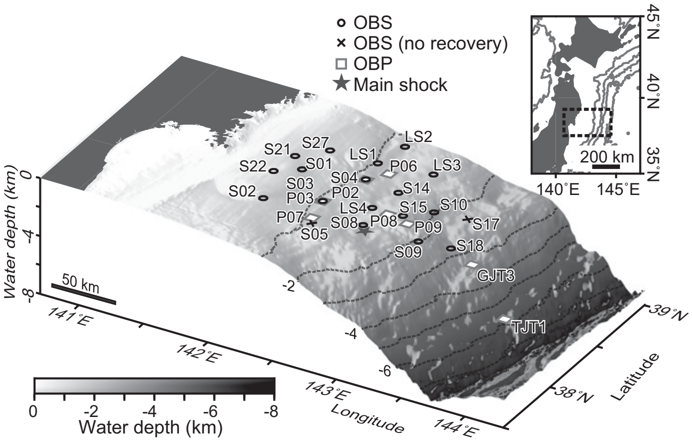

Figure 1. Locations of ocean-bottom pressure recorders (OBPs) and ocean-bottom seismometers (OBSs) off Miyagi, Tohoku region, northeastern Japan. Seafloor map is from J-EGG500 (JODC-Expert Grid data for Geography-500 m; http://www.jodc.go.jp/data_set/jodc/jegg_intro.html). Star indicates epicenter of main shock on 11 March 2011.

[1]GSA Data Repository item 2013335, supplementary figures, tables, methods, and results, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

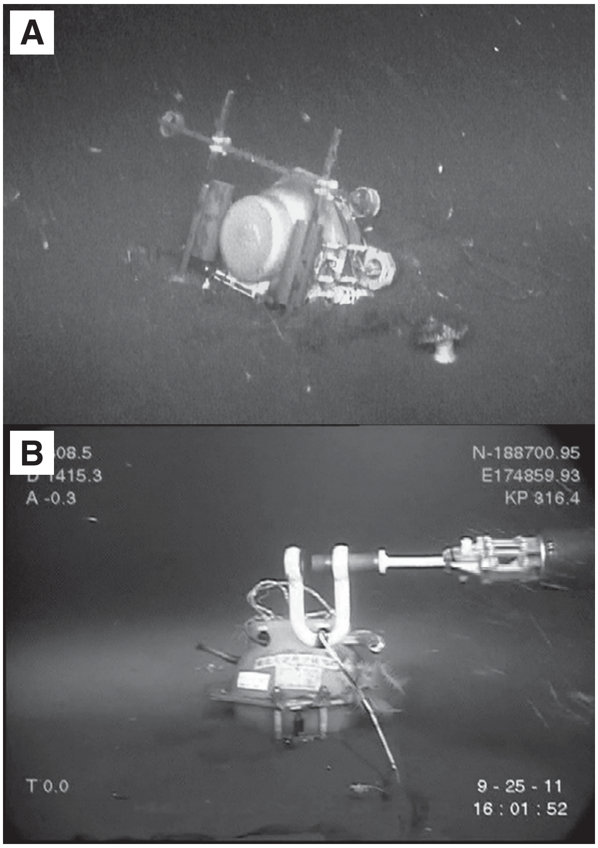

Figure 2. Photos of ocean-bottom pressure recorders (OBPs) when recovered by remotely operated vehicle. A: Sensor OBP-P03 was found on seabed at recovery position. B: Sensor OBP-P08. Some recorders such as OBP-P08 were partially buried into very smooth seafloor, composed of unconsolidated fine sediments. Sensor is 60 cm wide.

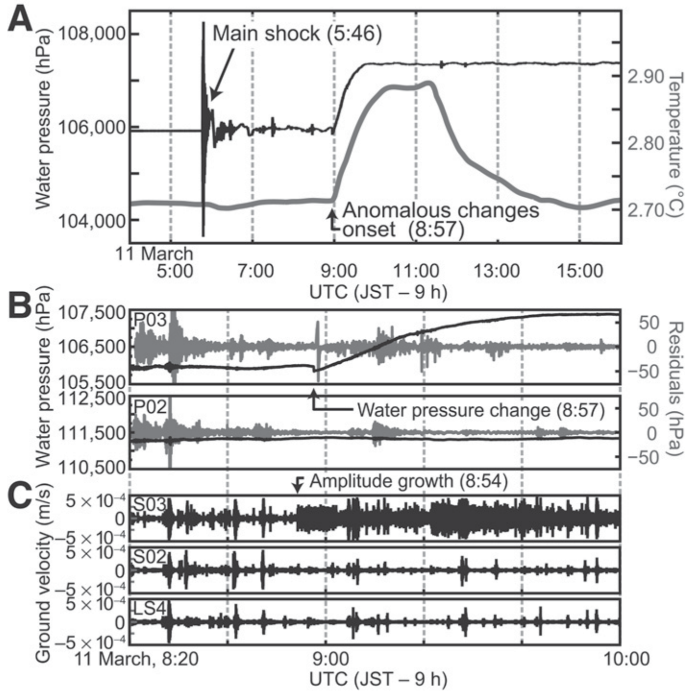

Figure 3. Water-pressure, temperature, and ground-motion records from ocean-bottom pressure recorders (OBPs) and ocean-bottom seismometers (OBSs). Anomalous changes started ~3 h after main shock. A: Water-pressure (fine black line) and temperature (bold gray line) records at sensor OBP-P03. B: Details of water-pressure records at sensors OBP-P03 and OBP-P02. Black line is water pressure. Gray line shows residuals from moving averages of water-pressure records. High-frequency and low-amplitude fluctuations were recorded by sensor OBP-P03, whereas data were recorded at OBP-P02 when no aftershocks were recorded. C: Ground-motion records of sensors OBS-S03, OBS-S02, and OBS-LS4. Amplitude growth starting at 08:54 UTC was recorded only by sensor OBS-S03.

recorded water pressure that increased abruptly from 105,845 hPa to 107,389 hPa (Fig. 3), marking the onset of an event ~3 h after the main shock occurrence (08:57 UTC). This pressure change began with a small drop; subsequently, water pressure increased continuously for ~50 min. Furthermore, high-frequency and low-amplitude fluctuations (6–10 s in period and 10–100 hPa in amplitude) were found to be superimposed on the trend of increasing pressure recorded at sensor OBP-P03. The water pressure became constant from 09:47 UTC. The observed increase (1410 hPa) is equivalent to a vertical displacement of 14 m and is too large to be interpreted as static seafloor displacement resulting from the earthquake (Ito et al., 2011). We interpret this pressure change to have been caused by downslope transport of the instrument, because the location of the OBP recovery was ~14 m deeper than the installed position. Thus sensor OBP-P03 was transported ~1 km east over ~50 min, starting ~3 h after the main shock.

Temperature Anomaly and Anomalous Ground Motion

Associated with the displacement of the OBP, both a temperature anomaly and an anomalous high-frequency ground motion were recorded by sensors OBP-P03 and OBS-S03 (Fig. 3). In the record of OBP-P03, the temperature anomaly occurred at 08:57 UTC, coinciding with the abrupt increase in water pressure. The seawater temperature increased ~0.19 °C for 90 min, and remained at this temperature for 50 min. Temperature then gradually decreased for ~180 min. An anomalous ground motion was recorded by OBS-S03, which was located close to OBP-P03 (Fig. 1). No large aftershocks were recorded in any other of the OBSs deployed off Miyagi at the time. Therefore, this increase of ground-motion amplitude was likely not associated with aftershock activity. A burst-like increase of ground motion started at 08:54 UTC and continued for at least 70 min.

Characteristics of New Sediment on the Seafloor and in OBSs

After the Tohoku-Oki event, we examined surface sediment deposited on a wide area of seafloor off the Tohoku coastal region using remotely operated vehicle (ROV) surveys, recovered cores collected at eight sites by R/V *Tansei-maru* (Cruise KT-12–9), and sediment that infilled OBSs. Video taken by the ROV indicated that the OBPs were partially covered in sediment (Fig. 2). We estimate the sediment covering the antecedent bed to be ~6.5–15 cm in thickness on the basis of the ROV observations. We collected eight sediment cores at the locations of several OBS positions ~1 yr after the event, in May 2012 (Fig. DR3; Table DR2). Sediment samples (82 mm in diameter) were collected using a multiple-core sampler (Rigosha) without disturbance of surface sediments. Soft-sediment layers 3.5–9.5 cm thick and with high water contents were observed at the tops of four core samples below 1000 m depth. These layers were sandy silt–clayey silt sized, normally graded, and less bioturbated than the lower layers (Fig. 4; Fig. DR3). Brittle stars were buried 6–8 cm below seafloor of the MC08 core sample. In addition, the antennas of and cavities inside the OBSs, which were recovered 3 d to 8 mo after the main shock, were filled with dark olive sediments (Fig. DR2). Intrusion of sediments into the OBSs had never been reported prior to the Tohoku-Oki earthquake (Fig. DR2). The grain size of the cover sediments ranged from fine sand to silt (2.34–5.86 ϕ [phi] in mean grain size) (Fig. 4; Fig. DR4; Table DR3). The sand fraction is distributed mainly on the upper part of the continental slope (300–700 m in depth), where large submarine canyons or slump

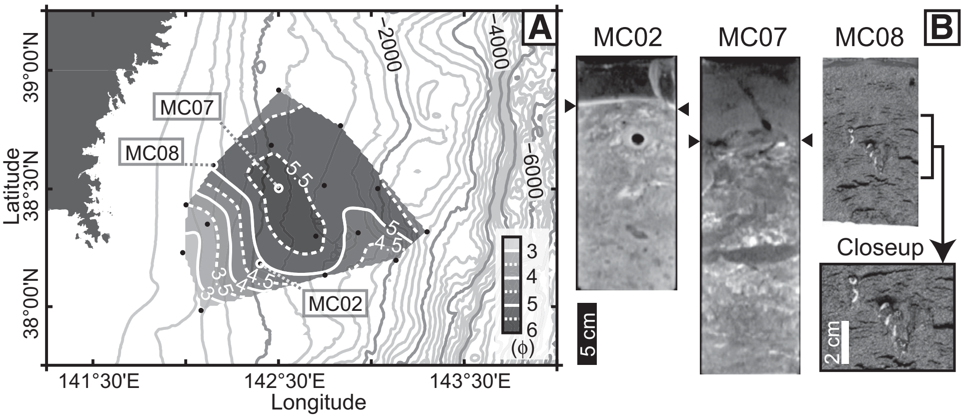

Figure 4. Cover-sediment emplacement near filled ocean-bottom seismometers (OBSs) and sediment cores taken around OBS recovery positions off Miyagi, Japan. A: Mean grain size of cover sediments. B: X-ray computed tomography images (WL 550, WW 800) and photograph of sediment cores at positions of MC02 (OBS-S03, OBP-P03), MC07 (OBS-S04, OBP-P02), and MC08 (OBS-S27). New unconsolidated sediment layers without bioturbation can be observed in uppermost parts of sediment cores. Brittle stars were buried at 6–8 cm depth at MC08. Triangles show bottom of soft sediment layers.

scars are not recognizable (Fig. 4; Figs. DR4 and DR6; Table DR3); with the sediments becoming gradually finer offshore on the continental slope from 300 to 1100 m depth. In deeper water, they show coarsening slightly toward the fringe of the downslope basin (1100–1400 m deep).

DISCUSSION

Sheet-Like Turbidity Current as a Cause of the Anomalous Event

We propose that the downslope sediment flow indicated by the movement of the OBPs and sediment infilling in the OBPs and OBSs resulted from a sheet-like turbidity current (Izumi, 2004; Straub and Mohrig, 2009). The movement of the OBP clearly indicates the occurrence of a current down a slope. Sediment cores and the sediment infilling the OBPs and OBSs indicate that the flow caused extensive recent sedimentation on the seafloor near the epicenter after the Tohoku-Oki earthquake. In general, turbidity currents can widely disseminate unconsolidated sediments over a downslope basin (Hughes-Clarke et al., 1990). The graded bedding and fining-offshore trend of the sediments collected from the OBSs are typical features of turbidites (Walker, 1967). The high-frequency fluctuations in the pressure records of sensor OBP-P03 could be interpreted as saltation of the device during displacement. The temperature anomaly in OBP-P03 indicates that a warm water mass was transported rapidly from upslope (Mikada et al., 2006). The anomalous ground motion of sensor OBP-S03 could have resulted from seawater turbulence and impacts of sediment particles during the passage of the turbidity current. In addition, it is likely that the turbidity current was sheet-like in form, because submarine canyons and distinct gullies are not recognizable in this area (Fig. DR6).

Triggering Mechanism of the Turbidity Current

We infer that the 2011 Tohoku-Oki tsunami triggered the turbidity current (Fig. DR1) on the basis of several lines of evidence. A numerical simulation of the Tohoku-Oki tsunami estimated that a long oscillation of the tsunami could suspend sandy sediments of maximum size 0.4–2.5 ϕ within this offshore region as much as 98 km from the coastline (Sugawara and Goto, 2012) (Fig. DR7). The same numerical simulation indicated virtually vanishing friction velocity at a depth of 450 m, implying that the tsunami could not directly erode or transport seafloor sediments deeper than this. Thus, the sandy cover sediments distributed deeper than 450 m cannot have been transported by the backwash flow of the tsunami, but instead must have been transported by a turbidity current. This turbidity current would have developed from the downslope motion of a sheet-like suspension cloud of seafloor sediment particles stirred up by the tsunami at shallower depths (Parker, 2006; Traykovski et al., 2007). The turbidity current could further grow by a self-acceleration process caused by sediment entrainment from the seafloor of a submarine slope (Parker et al., 1986; Sequeiros et al., 2009). Sensors OBP-P03 and OBS-S03 were especially affected by the flow in this region; this may be explained by local enhancement of the self-acceleration process due to (1) the abundant supply of sandy sediment from Sendai Bay, or (2) flow through small, steep local gullies and slopes.

Alternative processes in the deep sea cannot explain the displacement of the OBP and concomitant deposition of sediment. Earthquake-induced vibrations could not have transported the OBP, because no large aftershock was recorded by the other OBSs off Miyagi during its movement. Sensor OBP-P03 was transported downslope, indicating that the flow was not a contour current. Furthermore, submarine landslides are also unlikely to have been the cause of transport of the OBP, because the OBPs and OBSs showed little damage, and cavities inside these units were only partially infilled with sediment. In addition, submarine slump scars and submarine landslides are not detected with the subbottom profiling data in this area after the earthquake (Fig. DR6). The extensive but thin-bedded distribution of new sediment, as well as the lack of evidence of submarine slump scars, indicates that the flow was a relatively low concentration, sediment-gravity current.

Estimated Flow Velocity of the Turbidity Current

The estimated flow velocity of the turbidity current reported herein is within the range recorded for modern turbidity currents in previous studies. The delay between the OBP movement and the occurrence of the tsunami and earthquake can be interpreted as the travel time of the turbidity current from its provenance. It took 2–3 h for the turbidity current to travel from the shallower area (~100–450 m in depth), where the tsunami could have affected the substrate. The average velocity of the head of the turbidity current thus should have reached at least 2.4–7.1 m/s. In addition, when we suppose that the flow was 20 m in thickness (Straub and Mohrig, 2009) and <9% in sediment concentration (Bagnold, 1954), the maximum velocity of the body of the turbidity current can be estimated as ~8.0 m/s using the Sequeiros (2012) method, which assumes that the body of the flow was in nearly quasi-steady condition. On the other hand, the minimum flow velocity required to move sensor OBP-P03 is estimated to be 2.3 m/s, assuming that the coefficients of drag and friction of the OBP are approximately the same as a boulder-sized clast (Noormets et al., 2004; Parker, 2005). These values are below that of the 1929 Grand Banks turbidity current, which was estimated as ~7.8 m/s on the basis of the time difference between underwater cable cuts (Shepard, 1963). Furthermore, a series of turbidity currents off Oahu, Hawaii, was estimated to have velocities of ~3.0 m/s as measured by current-meter displacement (Dengler et al., 1984); this velocity is in the range of those reported in our study.

CONCLUSION

We provide the first real-time documentation of a probable tsunamigenic turbidity current, which implies a clue for identifying tsunamigenic turbidites in geologic records. This study reveals the features of a tsunamigenic turbidity current that was spatially extensive (covering a region >100 km in width). This can be interpreted as a consequence of the ability of large tsunamis to erode broad areas of the upper continental slope, whereas many other mechanisms, such as slope failure, for turbidity current genesis occur mainly in limited areas (Tokuhashi et al., 2001), and are more likely to be point sources. Analysis of sediment cores in the Cascadia Basin (eastern Pacific Ocean) system suggested that seismogenic turbidites are likely to be identified from other mechanisms, by their spatial extent and synchronous deposition in wide areas (Goldfinger, 2011). The result of our study supports this view from the modern observations. Future investigation of the sediment cores from the seafloor off the Tohoku region, Japan, will provide further characterization of tsunamigenic turbidites and can aid in (1) the development of criteria to distinguish them from other types of turbidites, and (2) validation of predictive numerical models for sheet-like turbidity currents. Tsunamigenic turbidites also provide a clue to more precise estimation of the recurrence interval of large tsunamis.

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