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

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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 the turbidity current associated with a great earthquake; in this case with the Mw 9.0, 2011 Tohoku-Oki event. Turbidity current deposits (turbidites) have been used to estimate earthquake recurrence intervals from geologic records. Until now, however, there has been no direct of evidence for the large-scale earthquake in subduction plate margins. After the 2011 Tohoku-Oki earthquake and tsunami, an anomalous event on the sea floor consistent with a turbidity current was recorded by ocean bottom pressure recorders and ocean bottom seismometers deployed off Sendai. 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 toward their identification 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). Since the turbidity currents were detected immediately after the 1908 Messina and the 1929 Grand-bank earthquakes that are characterized both by the occurrence of large submarine slumps (Heezen and Ewing, 1952; Ryan and Hezzen, 1965), paleo-earthquakes and paleo-tsunamis have been assumed to be recorded as turbidity current deposits (turbidites) in sedimentary sequences (e.g.

Goldfinger, 2011; Palonia et al., 2013) and several turbidites have been used to estimate earthquake recurrence intervals (e.g., Kastens, 1984). There has not been, however, 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, in this case with the Mw 9.0 2011 Tohoku-Oki tsunami is inferred to have triggered the current. The turbidity current was recorded by ocean bottom pressure recorders with thermometers (OBPs) and ocean bottom seismometers (OBSs). Freshly-emplaced turbidites were collected from a wide area of seafloor.

ANOMALOUS EVENT ON 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 such as the displacement of the OBP, anomalous record of temperature and ground motion in the OBP and OBS, and sediment infilling inside the OBPs and OBSs. Tohoku University had deployed eight OBPs and 19 OBSs offshore of Miyagi Prefecture over the range 38°N–39°N, 142°E–144°E, and at water depths of 300–5700 m before the great earthquake (Hino et al., 2009; Suzuki et al., 2012) (Fig. 1; Table DR1). All but two of these OBPs and OBSs were recovered between March 14th and November 26th, 2011.

1 km Displacement of the OBP

One of the OBPs and OBSs set on the seafloor, i.e. OBP-P03, was displaced by 1 km after the 2011 Tohoku-Oki earthquake and tsunami. It was recovered ~1 km east of the installed position of 38.183°N, 142.400°E, lying on the seabed at the position 38.1819°N, 142.4132°E

(Figs. 1 and 2; Table DR1). Moreover, the OBP-P03 recorded water pressure that increased abruptly from 105,845 hPa to 107,389 hPa (Fig. 3), marking the onset of an event that was ~3 h after the main shock occurrence (8:57 UTC). This pressure change began with a small drop, subsequent to which 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 OBP-P03. The water pressure became constant from 9:47 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 water depth of the location of the OBP recovery is ~14 m deeper than the installed position. Thus OBP-P03 was transported ~1 km east over ~50 min, starting at ~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 OBP-P03 and OBS-S03 (Fig. 3). In the record of OBP-P03, the temperature anomaly occurred at 8:57 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. Hence, this increase of ground motion amplitude is likely not associated with aftershock activity. A burst-like increase of ground motion started at 8:54 UTC and continued for 70 min at least.

Characteristics of New Sediment on 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 by Remotely Operated Vehicle (ROV) surveys, recovered cores at 8 sites by R/V Tansei-maru (Cruise KT-12-9), and sediment that infilled OBSs. Movies taken by 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 8 sediment cores at the locations of several OBS positions ~1 year 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 content were observed at the top of 4 core samples below 1000 m in depth. These layers were sandy silt – clayey silt sized, normal graded and less bioturbated than the lower layers (Fig. 4 and DR3). A brittle star was buried at 6-8 cm of MC08 core sample below seafloor. In addition, the antennas of and cavities inside the OBSs, which were recovered 3 days to 8 months after the main shock, were filled with greenish dark-gray sediments (Fig. DR2). Intrusion of sediments into 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 phi in mean grain-size) (Fig.4 and 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 scars are not recognizable (Fig. 4, DR4 and DR6; Table DR3), with the sediments becoming gradually finer offshore on the continental slope from 300 to 1100 m in depth. In deeper water, they show coarsening slightly toward the fringe of the downslope basin (1100 to 1400 m deep).

DISCUSSION

Sheet-like Turbidity Current as a Cause of 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 Mohring, 2009). The movement of the OBP clearly indicates the occurrence of a current down a slope. Sediment cores and 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 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 OBP-S03 could have resulted from seawater turbulence and impacts of sediment particles during the passage of the turbidity current. Additionally, it is likely that the turbidity current was sheet-like form because submarine canyons and distinct gullies are not recognizable in this area (Fig. DR6).

Triggering Mechanism of the Turbidity Current

We infer the 2011 Tohoku-Oki tsunami to have triggered the turbidity current (Fig. DR1), based on several lines of evidence. A numerical simulation of the Tohoku-Oki tsunami estimated that a long oscillation of the tsunamis could suspend sandy sediments of 0.4–2.5 phi maximum within this offshore region up to 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 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 that is caused by sediment entrainment from a sea floor 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, which may be explained by local enhancement of the self-acceleration process due to a) the abundant supply of sandy sediment from Sendai Bay, or b) 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. 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. Additionally, submarine slump scars and submarine landslides are not detected with the sub-bottom 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 relatively a low-concentration sediment-gravity current.

Estimated Flow Velocity of the Turbidity Current

The estimated flow velocity of the turbidity current reported in this study is within the range recorded for modern turbidity currents in previous studies. The delay between the OBP movement and the tsunami and earthquake occurrences 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 to 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 0-9% in sediment concentration (Bagnold, 1954), the velocity of the body of the turbidity current can be estimated as ~8.0 m/s in maximum by the method of Sequeiros (2012) that assumes the body of the flow was nearly quasi-steady condition. On the other hand, the minimum flow velocity required to move 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 to ~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 in Hawaii was estimated to have velocities ~3.0 m/s as measured by current meter displacement (Dengler et al., 1984). This velocity is in the range of those reported in this study.

CONCLUSION

We thus provide the first real-time documentation of a probable tsunamigenic turbidity current, which implies a clue to identify the tsunamigenic turbidite in geologic records. This study reveals the features of a tsunamigenic turbidity current that was spatially extensive (covering a region more than 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. Indeed, the analysis of sediment cores in the Cascadia Basin system suggested that the 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 this study supports this view from the modern observation. Future investigation of the sediment cores taken from the seafloor off the Tohoku region will provide further characterization of tsunamigenic turbidites and, can aid in a) the development of criteria to distinguish them from other types of turbidites and b) 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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FIGURE CAPTIONS

Figure 1. An index map of OBSs and OBPs positions off Miyagi, Tohoku region, Northeastern Japan. Seafloor map is made from J-EGG500 data. Circle: OBS positions (recovery), cross: OBS positions (no recovery), square: OBP positions (recovery), star: Epicenter of main shock on March 11th, 2011.

Figure 2. Appearance of OBPs when they were recovered by ROV. A: P03 OBP-P03 was found lying on the seabed at recovery position. B: P08. OBPs such as OBP-P08 were partially buried into a very smooth seafloor, composed of unconsolidated fine sediments.

Figure 3. Water pressure, temperature and ground motion records from OBPs and OBSs. Anomalous changes started at ~3 h after the main shock. A: Water pressure (fine line) and temperature (bold line) records at OBP-P03. B: Details of water pressure records at OBP-P03 and P02. Black line: water pressure records. Gray line: residuals from moving averages of water

pressure records. High-frequency and low-amplitude fluctuations were recorded by OBP-P03, whereas data when no aftershocks were recorded in OBP-P02. C: Ground motion records of OBS-S03, S02, and LS4. Amplitude growth starting at 8:54 UTC was recorded only by OBS-S03.

Figure 4. Characteristics of the cover sediment emplacement near the filled OBSs and the sediment cores taken around OBS recovery positions off Miyagi. A: Mean grain size of the cover sediments. B: X-ray CT images (WL:550, WW:800) and photograph of the sediment cores at positions of MC02 (OBS-S03, OBP-P03), MC07 (OBS-S04, OBP-P02), MC08 (OBS-S27). New unconsolidated sediment layers without bioturbation can be observed in the uppermost parts of sediment cores. Additionally, a brittle star was buried at 6-8 cm of MC08. Triangles show the bottom of the soft sediment layers.

[1]GSA Data Repository item 2013xxx, 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 1
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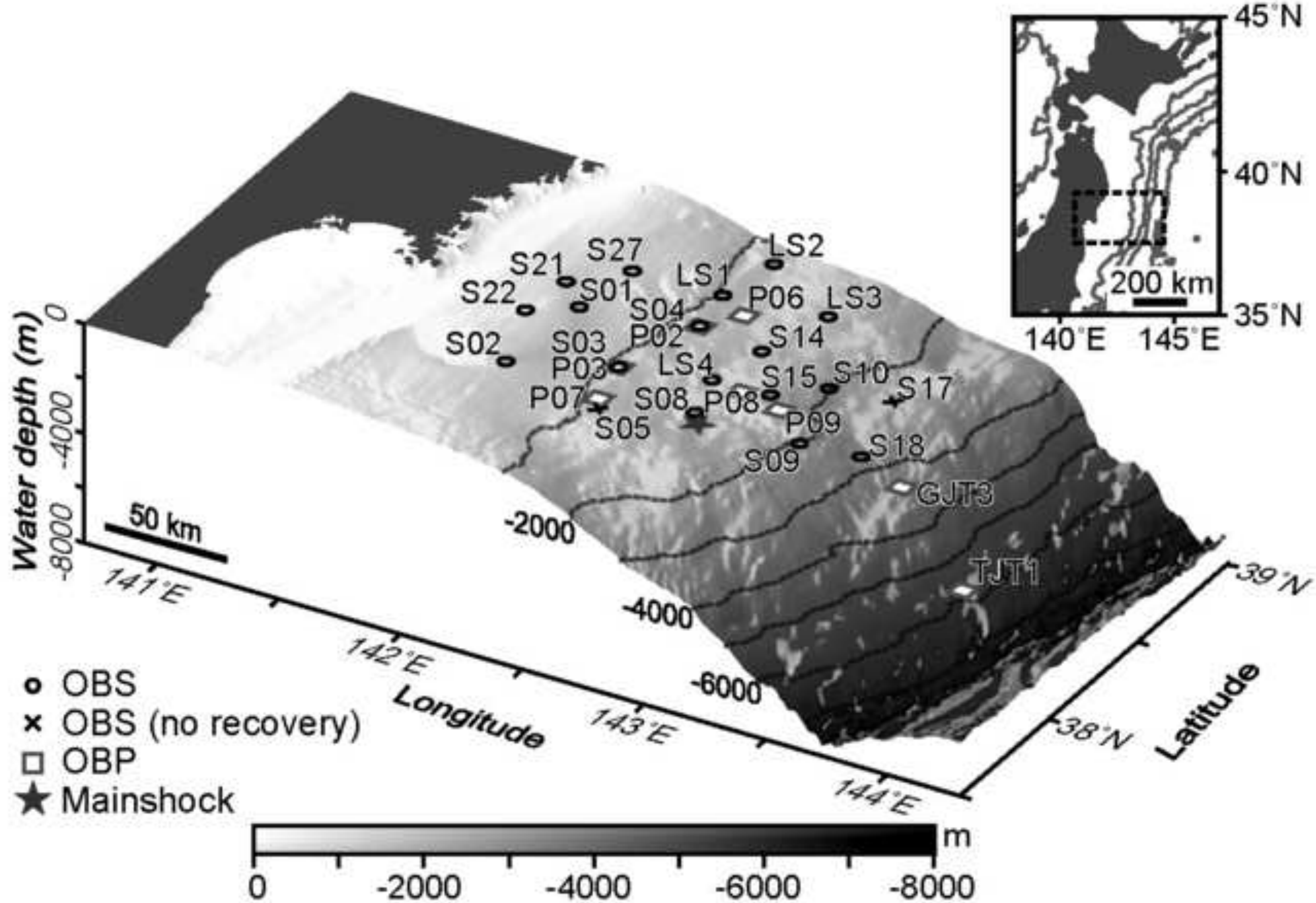

Figure 1

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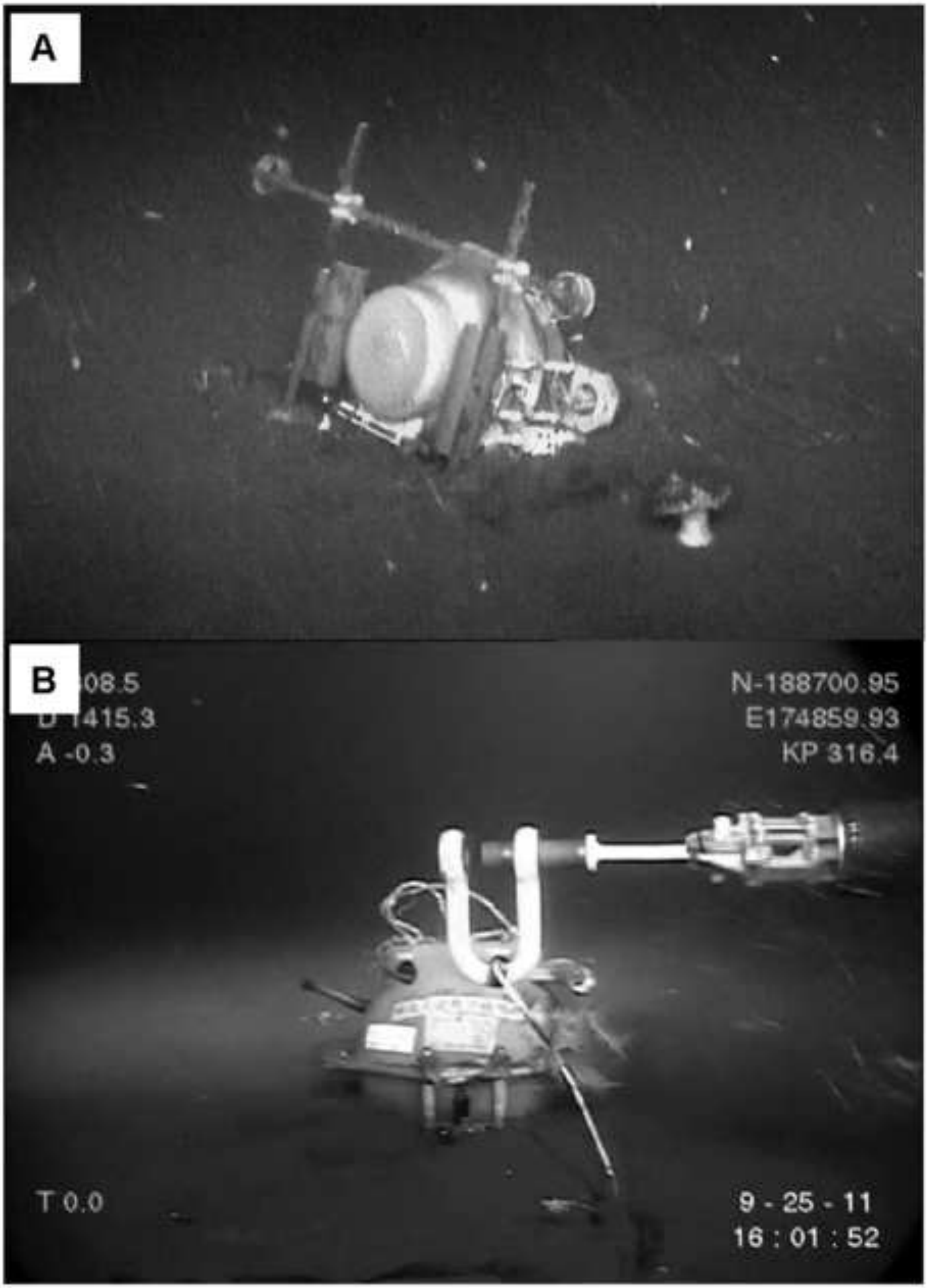

Figure 2

Figure 3
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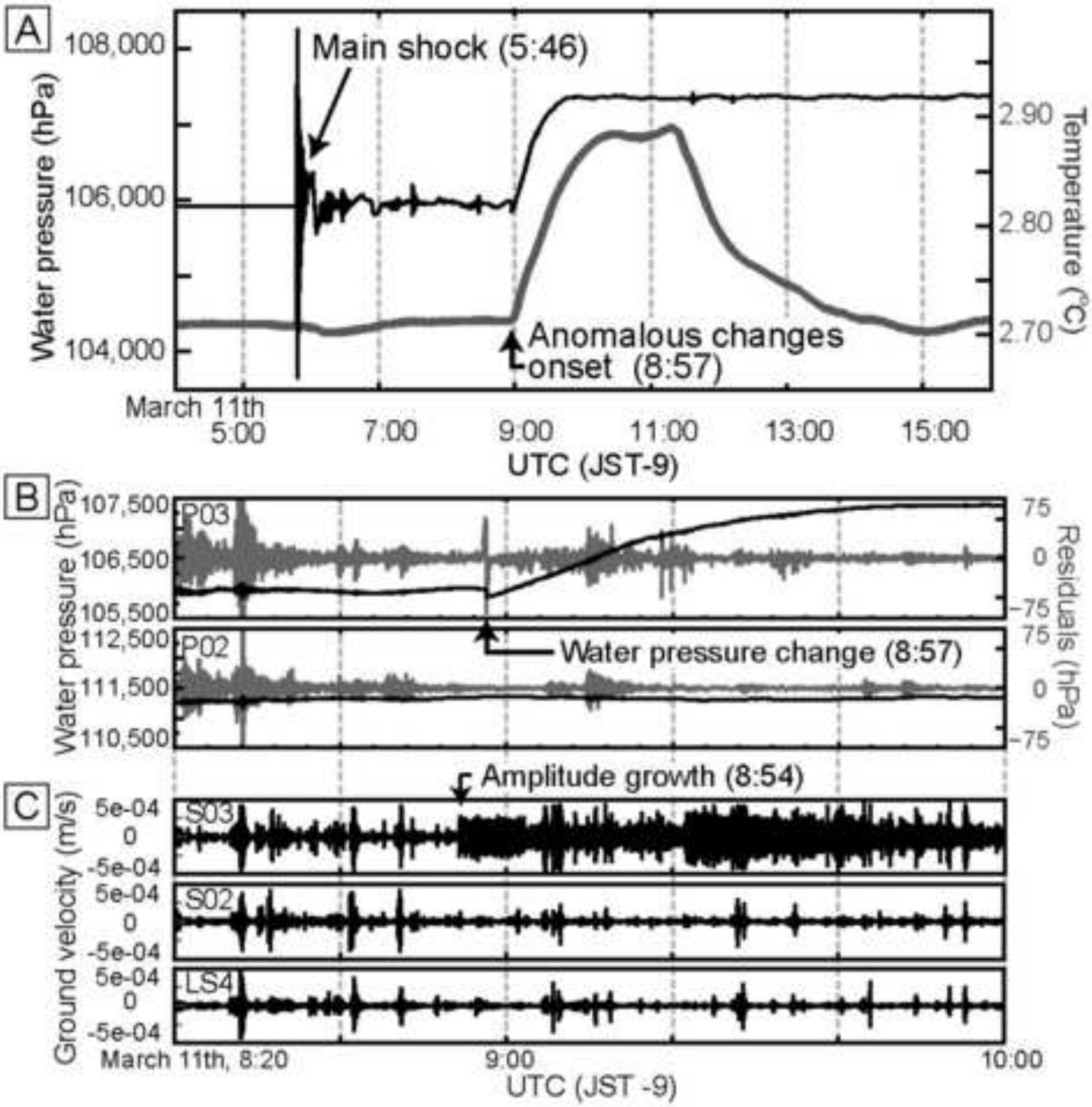

Figure 3

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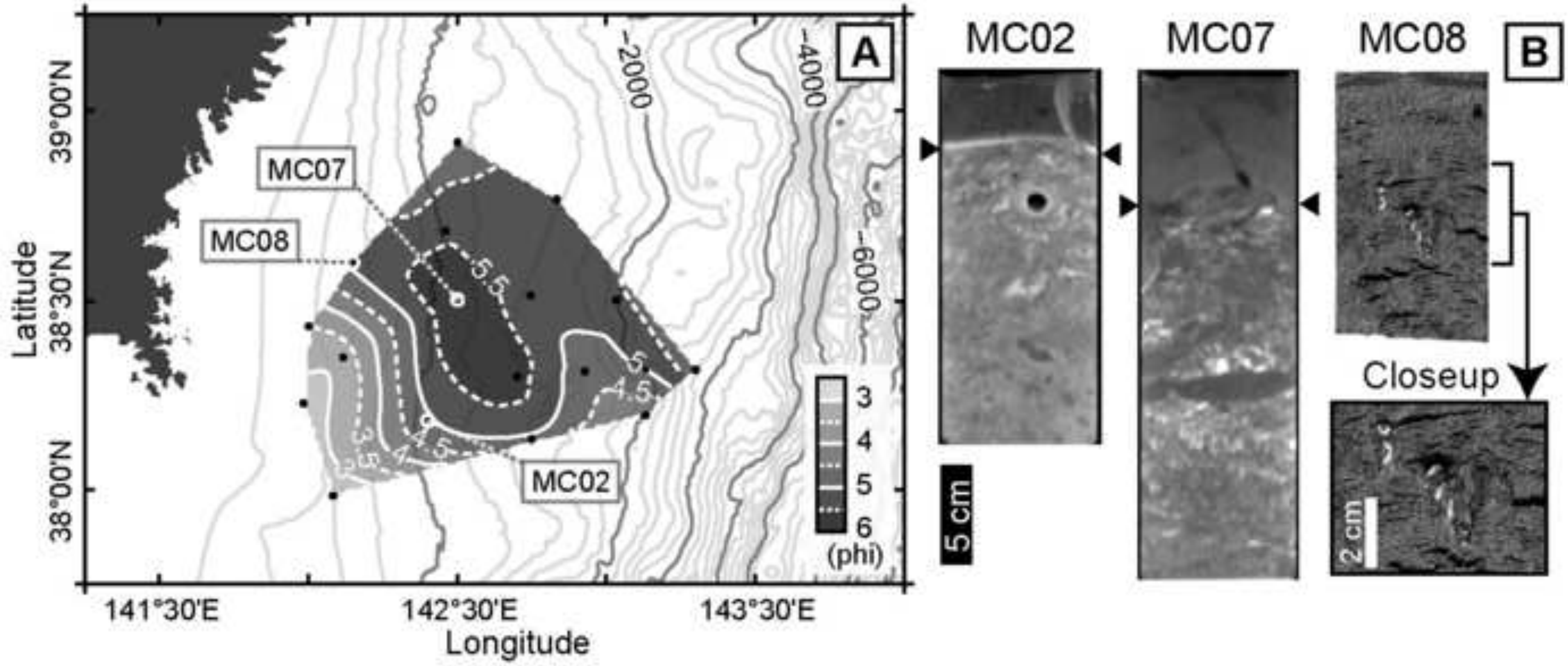

Figure 4