Evidence for surface sediment remobilization by earthquakes in the Nankai forearc region from sedimentary records

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Abstract: Submarine landslides triggered by earthquakes can generate turbidity currents. Recently, several studies have reported that the remobilization of surface sediment triggered by earthquakes can also generate turbidity currents. Such sedimentary processes may be influenced by sediment characteristics, seafloor morphology and seismic motions. Here, we verify surface sediment remobilization using sedimentary records from the Nankai forearc region, SW Japan. We collected multi-core and piston core samples from a small confined basin, mainly composed of silty clay or very fine sand. Radiocaesium measurements of the multi-core show consistently high values in the upper 17 cm and low values below this depth. Rapid sediment deposition after 1950 is assumed, and the most likely cause is the 2004 off the Kii Peninsula earthquake. Based on calculations using bathymetric maps and palaeocurrent data, settlement of the upper 17 cm can be explained by re-deposition of the surface (c. 1 cm) slope sediment around the basin. Muddy turbidites are also identified in the piston core. The gap in radiocarbon age observed around 2.0 m bsf (metres below seafloor) implies similar sedimentary processes. Our study represents the first examination of surficial remobilization from sedimentary cores in the Nankai forearc region.

The recurrence intervals of great subduction earthquakes have been estimated using historical documents and ruins, terrestrial archives (e.g. Cisternas et al. 2005; Nelson et al. 2006) and marine archives (e.g. Adams 1990; Patton et al. 2015). However, palaeoseismic records obtained from historical documents and ruins are limited in number and can only be found up to a certain time after earthquakes. Moreover, terrestrial archives may incompletely record past seismic events due to erosion over time.
(Nelson et al. 2009). Marine archives such as marine seismo-turbidites can therefore be a useful tool for obtaining long-term palaeoseismic records (Goldfinger et al. 2003a, b). Major earthquakes are known to trigger submarine landslides and generate turbidity currents (e.g. Piper et al. 1988, 1999), and recent work has proposed that they also impact subaqueous sedimentation processes. Based on radioisotopes in sediments, McHugh et al. (2016) quantitatively documented seismo-turbidites generated by remobilization of a few centimetres of surficial sediment triggered by the 2011 Tohoku-oki earthquake (Mw = 9).

Studies that propose an earthquake trigger for the dislodging of surficial sediments are limited around the Japan Trench (e.g. Oguri et al. 2013; Ikehara et al. 2016) and Chilean lakes (e.g. Moernaut et al. 2017). This type of sedimentary process would depend on factors such as surface sediment characteristics, seismic motion and seafloor morphology. Understanding how these factors affect sediment remobilization is important for more precisely interpreting and correlating palaeoseismic events from seismo-turbidites. Suspended sediments with extremely high turbidity have been observed soon after earthquakes in several studies (Noguchi et al. 2012; Oguri et al. 2013; Ashi et al. 2014). Although these high-turbidity plumes are assumed to be evidence for the remobilization of surface sediments, it is important to confirm this assumption. Further studies linking major earthquakes to surface remobilization of slope sediments are therefore required. This study uses sedimentary cores collected from a small confined basin in the Nankai forearc region to verify the surface remobilization phenomenon.

**Geological setting**

The Nankai Trough is a convergent margin where the Philippine Sea Plate is subducting beneath the Amur (or Eurasian) Plate at a rate of 4–6 cm a−1 in a northwestwards direction (Seno et al. 1993; Demets et al. 2010). Based on sedimentary archives and historical documents, plate boundary megathrust earthquakes have repeatedly occurred in the Nankai Trough with a recurrence time of 100–200 years (Ando 1975). Between these great earthquakes, few earthquakes have been confirmed since the onset of seismic monitoring. The most recent event is the 1944 Tonankai earthquake. However, smaller, magnitude 7 earthquakes occurred offshore of Kii Peninsula earthquake sequence in 2004 (Mw = 6.6, 7.3, and 7.4; Satake et al. 2005) (Fig. 1). These events were interpreted as earthquakes within the bending Philippine Sea Plate near the trough axis (Sakai et al. 2005).

Offshore of Kii peninsula, there are continuous outer ridges and elongated depressions with a NE-SW-aligned trend (Fig. 1a). These depressions separate the prism slope from the Kumano forearc basin, and are interpreted to have been formed by the strike-slip component of oblique subduction (Ashi et al. 2007; Martin et al. 2010). These features also block direct sediment supply from the river-submarine canyon system. The study area of this research is one
such basin, elongated in an ENE–WSW direction (Fig. 1) and located at the hanging wall of the megasplay fault. Because the basin is 250 m deeper than its surroundings, it preserves most sedimentary records and can be classed as a ‘terminal basin’ (Ashi et al. 2014). Figure 1b shows side-scan imagery around the basin, which was obtained by the 95/100 kHz WADATSUMI side-scan sonar (1 km swath) during the KY04-14 cruise. A side-scan image typically shows low backscattering intensity at the basin floor due to its flat bottom and high-porosity surface sediment. Similarly, the basin floor in our study site is characterized by bright colours (Fig. 1b), corresponding to low backscattering intensity.

Materials and methods

We collected a 46 cm multi-core (MC01) and a 6.7 m piston core (PC03) from the small basin during the R/V Shinsei Maru KS-14-8 cruise (latitude 33° 16.1024′ N, longitude 136° 40.6280′ E, water depth 2372 m; Fig. 1). X-ray computed tomography (CT) images were acquired of the sediment cores using an X-ray CT scanner (LightSpeed Ultra 16; GE Healthcare Japan, Japan) at the Center for Advanced Marine Core Research, Kochi University. The CT image analysis parameters were set at 0.625 mm for the slice width, 512 x 512 pixels for image resolution, and 100 mA and 120 kV for current and voltage. The split working half was described after. For MC01, we conducted radioactivity measurements for Cs-137, Pb-210, and Pb-214 using an ORTEC GEM-FX5825P4 low-background plane-shape Ge-semiconductor detector equipped with a SEIKO EG&G MCA7600 multi-channel analyser at the Faculty of Environmental Earth Science, Hokkaido University. ‘Excess Pb-210’ was defined as the difference between activities of measured Pb-210 and Pb-214 (Kato et al. 2003). Particle size analysis was performed at an interval of 0.5–1 cm using a laser diffraction particle-size analyser (SALD-3000S; Shimadzu Corporation) at the University of Tokyo. Electrical resistivity was measured at 1 cm intervals using a Bedford Institute of Oceanography probe. Cubic samples were measured with a KLY-4S Kappabridge magnetic susceptibility meter at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Natural Institute of Polar Research (NIPR).

To reorient the core and determine the palaeocurrent direction (e.g. Ellwood & Ledbetter 1979; Abdeldayem et al. 1999), we used a palaeomagnetic method. Demagnetization and natural remanent magnetization measurements were conducted on samples using a cryogenic magnetometer (Model 755R, 2G Enterprises) at NIPR. Samples 7 cm³ in size were demagnetized up to 80 mT. Zijderveld demagnetization plots were produced using the visualization software ‘Progress’, programmed by Shibuya (Kumamoto University, Japan). This software also enables principal component analysis (Kirschvink 1980). Magnetic properties such as magnetic susceptibility and anisotropy of magnetic susceptibility (AMS) depend on the size of magnetic grains and magnetic minerals. To extract information on the domain state characteristics of the magnetic minerals within the sample, we conducted a magnetic hysteresis measurement using MicroMag 2900 at NIPR.

Radiocarbon ages were obtained from planktonic foraminifera using an accelerator mass spectrometer at the Atmosphere and Ocean Research Institute, University of Tokyo. Samples for radiocarbon dating were taken from hemipelagic sediment just below and near the basement of each turbidite layer. We used OxCal 4.3 calibration software (Bronk Ramsey 2009a) to convert time using the Marine13 model (Reimer et al. 2013). We then applied local reservoir correction (Delta R = 77 ± 32 years) for the Pacific coast of central Japan (Shishikura et al. 2007).

Results

Multi-core sediment characteristics

Undisturbed surface sediment collected by the multiple corer is mainly composed of olive-black clay and characterized by a very thin, 6 mm thick fine sand layer at 17 cm below the seafloor (cm bsf) (Fig. 2). We recognize two lithological units: an upper unit (0–17 cm bsf) and a lower unit (17–46 cm bsf). The upper unit shows, from bottom to top, a very thin, fine sand layer, laminated silt and a thick homogeneous clay layer. Electrical resistivity is constant in the laminated silt layer (6–15 cm bsf) of the upper unit, and increases upwards in the overlying clay layer.

Mean volume magnetic susceptibility ($K_v$) of the laminated silt layer (6–15 cm bsf) decreases upwards, and the lowest value is in the overlying homogeneous clay layer. Magnetic properties can be used for grain fabric analysis. The parameters of magnetic hysteresis, which are plotted on a Day plot (Day et al. 1977), are grouped within the pseudo-single domain (PSD) region. This classifies the long axis of the grains as the maximum magnetic susceptibility ($K_1$). The shape of magnetic ellipsoid can be described by two parameters: $P$ represents the anisotropy degree and $T$ represents the shape parameter (Jelinek 1981), which is considered prolate if $-1 < T < 0$ and oblate if $0 < T < 1$. There is a sharp increase in the anisotropy degree $P$ and shape parameter $T$ at the boundary from the lower unit into the upper unit. The lower unit (17–46 cm bsf) is also mainly composed of olive-black clay.
with a bio-fragment-enriched thin layer (bristles of polychaete worms) and a thin, very fine-grained sand layer at a depth of 32 cm bsf. AMS directions oriented by remanent magnetization reveal that most $K_1$ axes are projected on the bedding plane (Fig. 3a). Structural observations of X-ray CT images reveal a chaotic zone at 22–29 cm bsf exhibiting variably oriented lamina. $P'$ and $T$ gradually increase downwards while the inclination of minimum susceptibility axes ($K_3$) remains 90° (Fig. 3b).

Cs-137 profiles show two clear trends: consistently high values in the upper unit (0–17 cm bsf) and low values in the lower unit (17–46 cm bsf) (Fig. 2). Moreover, excess Pb-210 profiles show consistently high values in the upper unit, which decrease rapidly below it.

**Piston core sediment characteristics**

The sediment piston core sample is mainly composed of olive-black clay. Coarse silt layers 2–3 cm thick are evident in the X-ray CT images (Fig. 4a). Each coarse silt layer has a sharp lower boundary with an underlying clay layer, and is
overlain by a homogeneous or bioturbated clay layer. Moreover, each coarse silt layer is a visually observable foraminifera-enriched layer. Although most coarse silt layers are single-layered, several silt layers have parallel or convolute lamination above them. The thickest coarse silt layer (10 cm) is observed c. 5.0 m bsf (metres below seafloor) (Fig. 4a, b). We also observe a black patch probably formed by bioturbation throughout the entire core. The upper part of the core above 0.7 m bsf appears to have been disturbed by the coring process, and convex-up layers observed at 0.7–2.0 m bsf suggest slight deformation of the core edges during core penetration. A yellowish-grey volcanic ash layer enriched with pumice is present at c. 5.3–5.4 m bsf. The deeper section of the core is characterized by strong bioturbation.

There are significant changes in $K_m$ close to 3.0, 5.0 and 6.0 m bsf. According to detailed AMS observations of the thick silty layer at c. 5.0 m bsf (Fig. 4b), $K_m$ and $P'$ increase sharply at the basement of the thick silty layer. AMS directions oriented by remanent magnetization show highly scattered values. Because of sediment disturbance above 2.0 m bsf, we only plot data below the disturbed section. Most $K_1$ axes are projected in the WNW and ESE direction, and the trends are similar to those of the multi-core sample.

Fig. 4. Columnar section, radiocarbon age of planktonic foraminifera and magnetic properties of the piston core sample. (a) Columnar section of the piston core with radiocarbon age of planktonic foraminifera and magnetic susceptibility. (b) Columnar section and magnetic properties of the piston core sample between 3.8 and 5.8 m bsf. A thick silt layer is observed at 5.0 m bsf.
We obtained five radiocarbon ages of foraminifera (Table 1). Age reversals are apparent between 2.1 and 2.15 m bsf, and between 5.0 and 6.1 m bsf.

Discussion

Muddy seismo-turbidites triggered by earthquakes in 2004 and earlier

Based on its sedimentary structure and magnetic profiles, the upper unit (0–17 cm bsf) of the multi-core can be interpreted as a muddy turbidite. The sharp bottom boundary, thin regular laminae and a thick homogeneous clay layer from the bottom to the top of the upper unit are similar to those muddy turbidites, which are described as fine-grained turbidites by Stow & Shanmugam (1980). Upwards decreases in particle size, $K_n$ and thickness of the laminated silt layer in the sediment cores suggest sequential deposition by a waning current. Cs-137 and Pb-210 measurements reveal that the upper unit (0–17 cm bsf) was formed after 1950 and represents a short sedimentation event. Because the sampling site is isolated from the river-submarine canyon system, earthquakes are the most likely trigger for the muddy turbidites. The 2004 Kii peninsula earthquake sequence included the only magnitude 7 earthquake in this region after 1950; it is therefore the earthquake sequence included the only magnitude 7 earthquake in this region after 1950; it is therefore the earthquake sequence included the only magnitude 7 earthquake in this area. Sedimentary structures include, from bottom to top, a coarse silt layer with a sharp base, parallel or convolute laminae, and a homogeneous clay layer. These features are characteristic of fine-grained turbidite (Stow & Shanmugam 1980). Some structures also display sudden changes in values of $P$ and $T$. These results suggest that the coarse silt layer can be interpreted as the bottom of a turbidite layer.

Surficial remobilization triggered by earthquakes

Muddy turbidites observed within both core samples can be interpreted as the product of surficial sediment remobilization. Within the multi-core, Cs-137 and Pb-210 measurements indicate remobilization of the young surface sediments.

As described previously, the palaeocurrent of sedimentary flow in this area has a WNW–ESE direction. Based on this result and the bathymetric map, we infer the sediment source area and budget of the study site (Fig. 1b). The size of the basin bottom and the basin area are 0.54 and 19.00 km$^2$, respectively. The average sedimentation rate at IODP Site C0002 (Ashi et al. 2009), close to our study site (Fig. 1b), is c. 10 cm ka$^{-1}$. Electrical resistivity for both the muddy turbidite and hemipelagic mud layers are almost constant, suggesting no significant difference in porosity. Based on the inferred area and thickness of the turbidite layer, we infer that redeposition of c. 1 cm of surface sediments occurred due to artificial deformation of a distorted core liner by core splitting. However, a careful check of the sample diameter indicated no deformation. The second possibility is also excluded because the surface sediment collected by the multiple corer is unlikely to have been affected by lateral compression. We therefore infer that the dominant $K_1$ orientation reflects the palaeocurrent generated by the WNW–ESE-directed current.

We also observed 23 muddy turbidites within the piston core, which may include significant palaeo-earthquakes in this area. Sedimentary structures include, from bottom to top, a coarse silt layer with a sharp base, parallel or convolute laminae, and a homogeneous clay layer. These features are characteristic of fine-grained turbidite (Stow & Shanmugam 1980). Some structures also display sudden changes in values of $P$ and $T$. These results suggest that the coarse silt layer can be interpreted as the bottom of a turbidite layer.

Table 1. Radiocarbon ages of planktonic foraminifera

| No. | Laboratory number | Lithology     | Depth (m bsf) | $^{14}$C age (years BP ± 1$\sigma$) | Delta $R^*$ | Calibrated age (cal years BP) | Dated material                      |
|-----|-------------------|---------------|---------------|------------------------------------|------------|-------------------------------|-----------------------------------|
| a   | YAUT-024417       | Hemipelagic mud | 1.52          | 793 ± 29                           | 77 ± 32    | 307–411                       | Planktonic forams (mixed)         |
| b   | YAUT-024205       | Bottom of turbidite | 2.1           | 2027 ± 20                          | 77 ± 32    | 1440–1554                     | Planktonic forams (mixed)         |
| c   | YAUT-024413       | Hemipelagic mud | 2.12          | 1862 ± 38                          | 77 ± 32    | 1280–1376                     | Planktonic forams (mixed)         |
| d   | YAUT-020127       | Bottom of turbidite | 4.97          | 13 067 ± 37                        | 77 ± 32    | 12 591–12 677                 | G. inflata, P. obliquiloculata    |
| e   | YAUT-020128       | Hemipelagic mud | 6.12          | 11 847 ± 30                        | 77 ± 32    | 10 756–10 924                 | G. inflata, P. obliquiloculata    |

*Local reservoir correction for the Pacific coast of central Japan (Shishikura et al. 2007).
Age data are given as conventional radiocarbon and calendar ages. Calendar age is calibrated based on the Marine 13 curve (Reimer et al. 2013).
Foraminifera species are also shown.
could produce the 17 cm thick muddy turbidite observed in the multi-core.

The areal extent of the basin was determined from the low backscattering intensity of the side-scan image (Fig. 1b), considering that a basin typically has a flat bottom and consists of high-porosity surface sediment. The side-scan image was acquired 3 months after the 2004 earthquakes. We therefore infer that anomalously low-intensity values in the basin (Fig. 1b) likely indicate seafloor conditions prior to complete settling of the turbid materials. These acoustic characteristics are consistent with remotely operated underwater vehicle (ROV) observations made soon after the 2004 earthquakes (Ashi et al. 2014). After the Tohoku-oki earthquake, Oguri et al. (2013) also observed high turbidity in the bottom water of the Japan Trench, and Noguchi et al. (2012) reported remobilization of surficial sediments triggered by the earthquake based on turbidity sensor monitoring and surface sediment sampling.

Within the sediment piston core, C-14 ages between 2.10 and 2.15 m bsf and between 5.0 and 6.1 m bsf are reversed, which is indicative of sediment remobilization and resedimentation. Specifically, the age gap of 170 years between 2.10 and 2.15 m bsf may indicate the surface sediment remobilization and resedimentation. Taking the sedimentation rate of c. 10 cm ka⁻¹ into consideration and converting the age gap of 170 years into sediment thickness, remobilization of a few centimetres of surface sediment could explain this age gap.

In addition to surficial remobilization, we assume that slumps were also triggered by the earthquakes. The silty bed at 5.0 m bsf, which has a 10 cm thick coarse silty layer and a thick clay layer (45 cm thick) above it, shows a large age reversal. This large age gap and the thick sediment layer suggest sediment remobilization by submarine slumping.

Conclusions

We studied sediment remobilization in the Nankai forearc region by analysing sediment cores. The sampling location was a small confined basin that collects almost all sediments supplied from a limited area, isolated from river-submarine canyons. High concentrations of Cs-137 in the upper 17 cm of the multi-core and none below it indicate that the unit was deposited during the 2004 Kii Peninsula earthquake sequence. Based on the bathymetric map and palaeocurrent analysis, the areal extent of the sediment source area and sedimentary budget were estimated. The result showed that c. 1 cm of surface slope sediment was remobilized by the 2004 earthquakes, resulting in deposition of muddy turbidites in the upper unit (0–17 cm bsf). The age gap of 170 years obtained in the piston core implies a few centimetres of surficial sediment remobilization. However, the large age gap in the thick turbidite layer lower in the sequence may suggest remobilization of deeper sediments by slumping.

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