Can turbidites be used to reconstruct a paleoearthquake record for the central Sumatran margin?

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ABSTRACT

Turbidite paleoseismology aims to use submarine gravity flow deposits (turbidites) as proxies for large earthquakes, a critical assumption being that large earthquakes generate turbidity currents synchronously over a wide area. We test whether all large earthquakes generate synchronous turbidites, and if not, investigate where large earthquakes fail to do this. The Sumatran margin has a well-characterized earthquake record spanning the past 200 yr, including the large-magnitude earthquakes in 2004 (M_w 9.1) and 2005 (M_w 8.7). Sediment cores collected from the central Sumatran margin in 2009 reveal that surprisingly few turbidites were emplaced in the past 100–150 yr, and those that were deposited are not widespread. Importantly, slope basin deposits preserve no evidence of turbidites that correlate with the earthquakes in 2004 and 2005, although recent flow deposits are seen in the trench. Adjacent slope basins and adjacent pairs of slope basin and trench sites commonly have different sedimentary records, and cannot be correlated. These core sites from the central Sumatran margin do not support the assumption that all large earthquakes generate the widespread synchronous turbidites necessary for reconstructing an accurate paleoearthquake record.

INTRODUCTION

Paleoseismic records that extend back beyond historical records are essential for understanding and modeling subduction earthquake processes over multiple earthquake cycles. These records can lead to improved hazard assessment and help mitigate tragedies of the scale experienced around the Indian Ocean in 2004. Turbidites (deposits of submarine sediment gravity flows) are increasingly being used worldwide to reconstruct records of major earthquakes on active margins (Table DR1 in the GSA Data Repository[1]). Turbidite paleoseismology can provide greater spatial and temporal coverage than other paleoseismological methods, such as coseismically submerged supratidal marsh records (e.g., Nelson et al., 1995) and uplifted or subsided coastal corals (e.g., Zachariasen et al., 1999).

To apply turbidite paleoseismology, it is necessary to be able to recognize turbidites caused by earthquakes rather than other triggers such as storms, river discharge, and slope failure due to sediment loading (Piper and Normark, 2009). Turbidites caused by storms and river discharge are, as much as possible, avoided by coring in deep water away from direct terrestrial inputs. Turbidites caused by earthquakes are inferred through evidence of synchronous triggering of multiple turbidity currents over a wide geographic area. Synchronous triggering is often established by counting the number of turbidites before and after a channel confluence (Table 1; Goldfinger, 2011). Along the central Sumatran margin this test is not possible due to the lack of through-going channel systems. Instead, synchronous triggering can be identified by the presence of turbidites of similar age within multiple independent slope basins (Table 1; Gràcià et al., 2010), and between adjacent slope and trench locations.

Turbidite paleoseismology is underpinned by the assumption that large earthquakes generate widespread turbidites. The Sumatran margin is a good place to test this assumption, as it experienced two very large earthquakes in 2004 (M_w 9.1) and 2005 (M_w 8.7) and has a good independent record of large magnitude earthquakes over the past 200 yr (Figs. 1 and 2).

We examined sediment cores from the Sumatran margin to investigate whether recent major earthquakes (in 2004 and 2005) and previous earthquakes in 1797, 1861, 1907, and 1935 (Fig. 1) generated synchronous widespread turbidites. We also consider: What predisposes different margins to being more or less suitable for turbidite paleoseismology (Table 2)?

Regional Setting

The Sumatran margin results from subduction of the Indian-Australian plates beneath the Sunda plate. The subduction zone is divided into structural segments that commonly define the earthquake rupture length and hence magnitude (Fig. 1). Within the study area, the accretionary prism comprises elongate trench-parallel slope basins that are generally poorly connected. No canyons extend across the entire accretionary prism and most Sumatran terrestrial sediment is trapped within the forearc basin (Fig. 1).

METHODS

Coring Rationale

Piston cores and multicores were collected on the RV *Sonne* in February 2009. To minimize the risk of direct terrestrial input, cores were

TABLE 1. METHODS FOR RECOGNIZING EARTHQUAKE-TRIGGERED TURBIDITES

How do you know if a turbidite records earthquake triggering?	Comment
1. **Confluence test:** Same number of turbidites on upstream and downstream sides of confluence indicates synchronous widespread triggering (Goldfinger et al., 2003)	Number of turbidites can vary with height above channel floor, as flow thickness is variable
2. **Synchronous deposition of turbidites in multiple basins** indicates widespread slope failure (e.g., this study; Gràcià et al., 2010)	Uncertainties in dating "synchronous" turbidites
3. **Turbidite volume** is much larger than that expected for other trigger mechanisms such as river floods (e.g., Talling et al., 2007)	Deposit volume rarely precisely known; flows may incorporate sediment
4. **Earthquake timing is independently known**, as observed, or through reliable historical records (e.g., 2004 and 2005; Sumatra earthquakes, this study)	Need to date turbidite precisely, and/or core seafloor soon after event; most reliable

Note: Only method 4 could also test whether some large earthquakes fail to produce a widespread turbidite.

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[1]GSA Data Repository item 2013212, supplemental methods, Tables DR1–DR4 (locations and data), and Figures DR1–DR4 (Pb profiles and seafloor bathymetery), 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.

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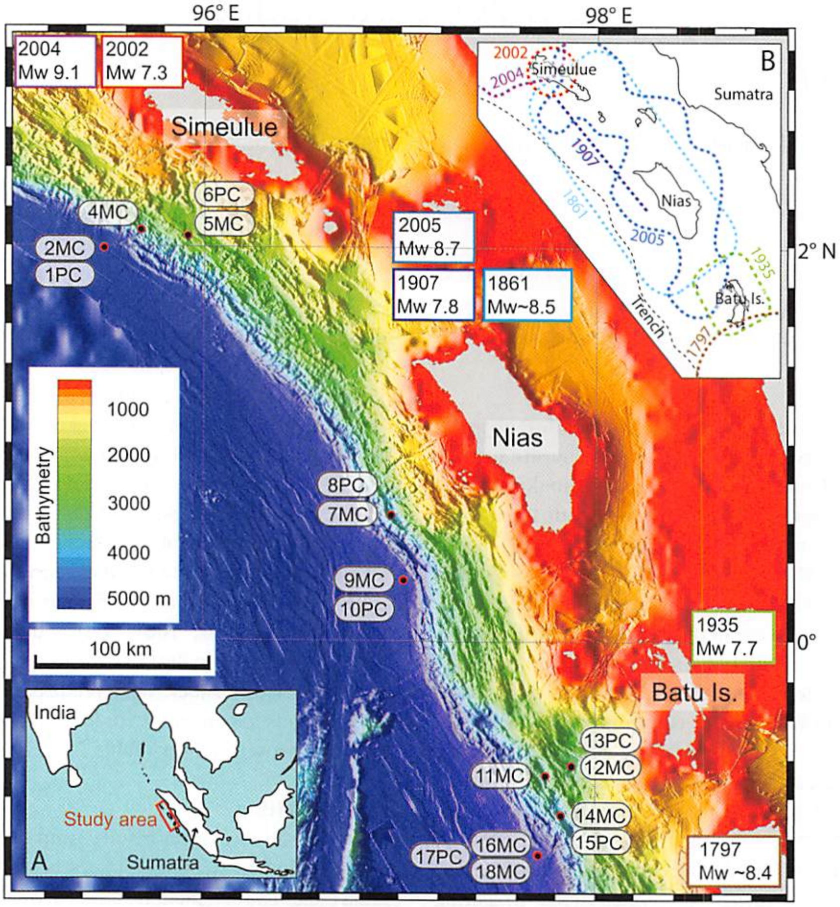

Figure 1. Bathymetric map of the study area (data from Dean et al. [2010] and Franke et al. [2008]) showing core locations (MC—multicore, PC—piston core). A: Study area in a regional context. B: Rupture zones of historical earthquakes (based on Briggs et al. [2006], Chlieh et al. [2007], and Kanamori et al. [2010]).

collected in slope basins on the accretionary prism and from the trench; the forearc basin was avoided (Fig. 1; Table DR2). Piston cores can provide a sediment record that extends back thousands of years; however, they are unsuitable for analyzing the most recent record because sediment can be lost from core tops and is often absent from trigger cores. Multicores (MC) are short cores (<60 cm) that sample and preserve the sediment-water interface and the youngest sediments; they therefore sample turbidites emplaced on the seafloor in recent times.

Three regions were chosen for coring in order to (1) analyze the distribution of turbidites related to the 2004 and 2005 earthquakes, (2) analyze the distribution of turbidites related to historical earthquakes, and (3) assess whether synchronous triggering of events occurred in different slope basins and the trench. Cores were collected (Figs. 1 and 2) from the segment boundary between the 2004 and 2005 rupture zones (2MC, 4MC, and 5MC); within the segment that ruptured in 2005, in 1861, and partially in 1907 (7MC and 9MC); and from a short segment that last ruptured in 1935 (11MC, 12MC, 14MC, 16MC, and 18MC). Core locations were chosen using multibeam bathymetric (Simrad EM120 12 kHz) and sub-bottom profile (Parasound 4 kHz) data. Our sampling density across the whole study area is comparable to other studies (e.g., Adams, 1990; Gràcià et al., 2010; Table DR1), and collecting cores in three locations allows the applicability of turbidite paleoseismology to be tested at repeat locations.

Core Analysis and Dating

Cores were analyzed by visually logging lithology, grain size, thickness, character, and sedimentary structures. Multisensor core loggers (Geotek MSCL-XYZ and MSCL-S) were used to measure magnetic susceptibility and bulk density and to acquire high-resolution photographs.

On the Sumatran margin, hemipelagic sediment (hemipelagite) is ungraded, is yellow-gray in color, and contains randomly distributed foraminifera when sampled above the carbonate compensation depth (3500–4100 m water depth). Turbidite sediments are dark gray, often coarser than hemipelagite, normally graded, and may contain sedimentary structures. Debrites (debris-flow deposits) comprise a chaotic mix of contorted layers with different grading patterns (normal and ungraded) as well as outsized grains and mud clasts.

Accelerator mass spectrometry (AMS) ^{14}C dating was used to date sediments containing sufficient planktonic foraminifera (*Globigerinoides ruber* and *G. sacculifer*) (Table DR3). Sediment age was also constrained using excess ^{210}Pb, and sedimentation rates were calculated using a constant sedimentation rate model (see supplementary methods in the Data Repository, and Table DR4).

RESULTS

Simeulue Region

The two slope basin cores (4MC, 5MC) contain no evidence for a turbidite associated with the 2004 and 2005 earthquakes (Fig. 2). There are no turbidites in the past ~3000 yr within core 5MC. The uppermost 3 cm of 4MC comprises hemipelagite: if the underlying turbidite were emplaced in 2004 or 2005 we would expect to see no hemipelagite above it. ^{210}Pb modeling yields sedimentation rates of 0.13–0.17 cm/yr for 4MC, indicating that 18–23 yr has passed since the last turbidite, and allowing estimation of the ages of turbidites deeper in the core. The youngest turbidite (ca. A.D. 1988–1993) does not appear to be associated with a large earthquake, while a cluster of three adjacent turbidites (ca. 1909–1933) and an underlying turbidite (ca. 1822–1866) could correlate with known major earthquakes (Fig. 2B).

Trench core 2MC contains a thicker (16 cm) and two overlying thinner (<2 cm) turbidites (Fig. 2) that were deposited in the past 150 yr. These turbidites may have been generated by any of the four major earthquakes during this 150 yr period (Fig. 2B).

Nias Region

Slope basin core 7MC contains no turbidites that could be associated with the 2004 and 2005 earthquakes. Sediment at 21.5 cm contains no excess ^{210}Pb, demonstrating that no turbidites have been emplaced in at least 100–150 yr. Trench core 9MC contains four fine-grained turbidites. Analysis of ^{210}Pb demonstrates that the upper three turbidites were emplaced in the last 100–150 yr, whereas the lowermost turbidite is of indeterminate age. These four turbidites may be associated with all or some of the 2005, 2004, 1907, and 1861 earthquakes (Fig. 2B).

Batu Region

^{210}Pb data demonstrate that slope basin cores 11MC, 12MC, and 14MC contain no turbidites emplaced in the past 150 yr (Fig. 2). Trench core 18MC and replicate core 16MC comprise part of a debrite, which contains excess ^{210}Pb (Fig. 2). The debrite is not overlain by hemipelagite and therefore could be associated with the 2004 or 2005 earthquakes.

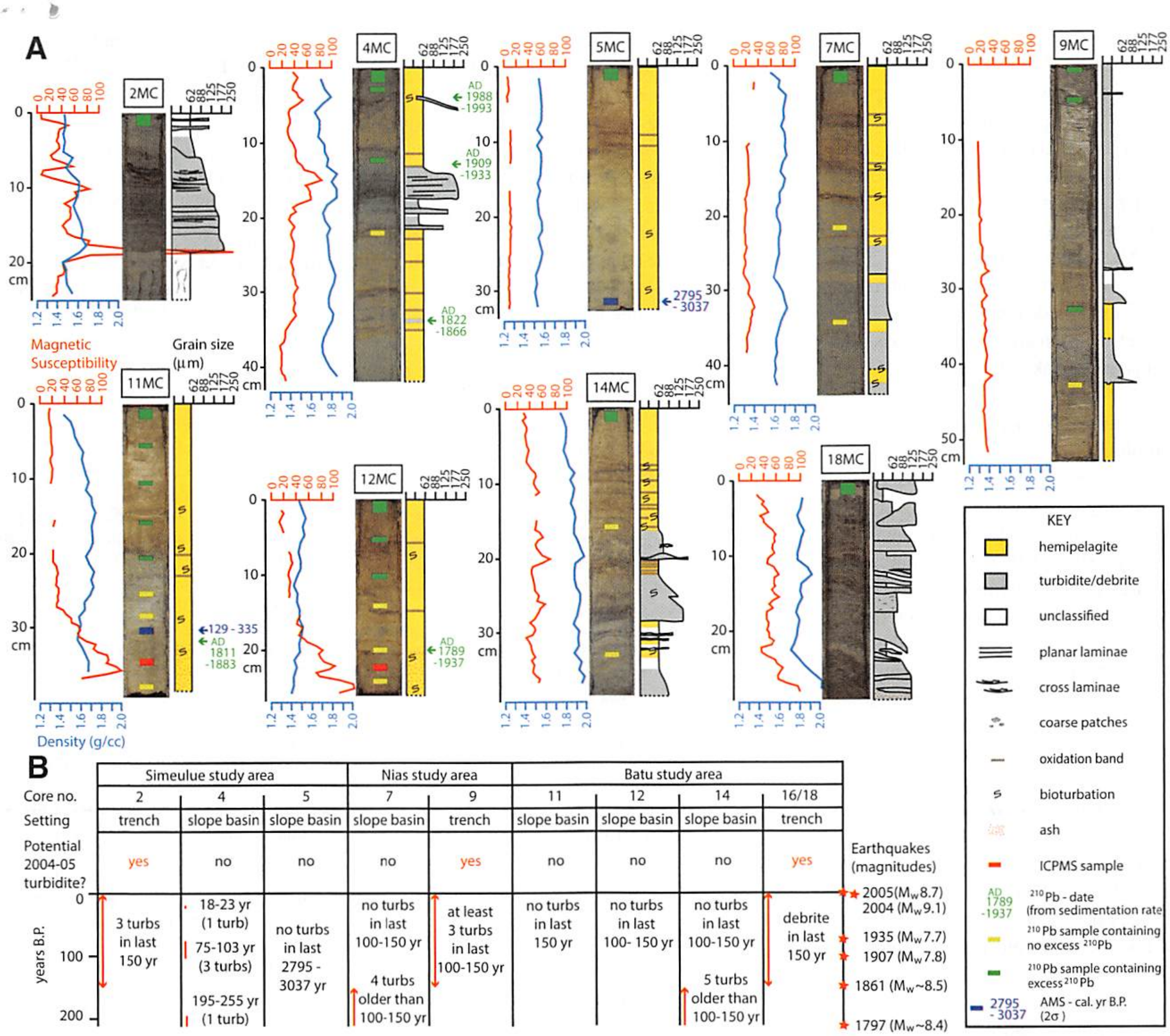

Figure 2. A: Multicore data including photographs, density (blue) and magnetic susceptibility (red) measurements, lithological logs, and locations of ^{14}C and ^{210}Pb samples. Standard errors were used to provide range in sedimentation rates for ^{210}Pb dates, and accelerator mass spectrometry (AMS) dates are quoted with 2σ errors. ICPMS—inductively coupled plasma mass spectrometry; cal. yr B.P.—calibrated years before present (1950). B: Summary of turbidite (turb) ages, turbidite locations, and their relationship with major earthquakes (stars). Note most cores do not have turbidites for the A.D. 2004 and 2005 earthquakes.

Erosion

The lack of recent turbidites in many of the multicores cannot be explained by erosional rather than depositional turbidity currents. The cores do not exhibit abrupt changes in density indicative of erosional hiatuses (Fig. 2A), and all core tops (0.2–1.5 cm) contain excess ^{210}Pb demonstrating the presence of sediment younger than 150 yr old.

TABLE 2. CHARACTERISTICS THAT MAY PREDISPOSE MARGINS TO BEING SUITABLE FOR PALEOSEISMOLOGY

What makes a margin more suitable for turbidite paleoseismology?	Comment
1. Depocenters of rapidly accumulating sediment, which are more prone to failure when shaken by earthquakes	Large slope failure also occurs in areas of slow sediment accumulation (Urlaub et al., 2012)
2. Lack of connection to areas of rapid shelf deposition, to avoid additional flow events triggered by floods or storms	Many locations may fulfill either point 2 or point 3. Floods can also generate long-runout turbidity currents through canyon-channel systems (e.g., Carter et al., 2012)
3. Flow paths that link wider areas to those depocenters, allow sediment disintegration, and provide confluence test	
4. Sediment with weak layers or properties, that fail when shaken	Character of weak layers poorly understood at present
5. Steeper seafloor gradients—more likely to fail (?)	Many large failures occur on low seafloor gradients
6. Large but infrequent earthquakes	Frequent shaking can consolidate sediment
7. Datable material across study area	Needed to date turbidites

DISCUSSION

The simplest test of turbidite paleoseismology on this margin is to assess whether the 2004 and 2005 earthquakes generated widespread turbidites. None of the slope basin cores contain turbidites related to these recent earthquakes, demonstrating that large earthquakes do not reliably generate widespread turbidites in slope basins in this study area. Furthermore, five out of six slope basin multicores do not contain turbidites emplaced within the past 100–150 yr. In the single slope core (4MC) that does contain turbidites younger than 100–150 yr, the youngest turbidite (A.D. 1988–1993) does not correlate in age with a known large earthquake. We find no evidence in slope basin cores that even very large plate-boundary earthquakes produced synchronous and widespread triggering of turbidity currents during the past ~150 yr on this part of the Sumatran margin.

In contrast, turbidites or debrites occur at or near the seafloor in all trench cores. Excess ^{210}Pb demonstrates that these flow deposits were emplaced in the past 150 yr (Fig. 2), and they could have resulted from the 2004 or 2005 earthquakes. Flows triggered from a single source can run out for long distances along trenches, as shown by a non–earthquake-triggered flow in 2009 that reached the Manila Trench (Carter et al., 2012); therefore, extensive flow deposits in submarine trenches may not provide unambiguous evidence of widespread, along-margin synchronous triggering or of an earthquake-triggered flow.

Wider Implications for Turbidite Paleoseismology

Turbidite paleoseismology is based on the ability to distinguish turbidites triggered by earthquakes from those triggered in other ways (Table 1). Despite the relatively small number of cores (although comparable in density to many other studies), we see a consistent pattern that gives us confidence in our results. The proportion of cores with no evidence of recent flows is high, and the lack of such evidence is ubiquitous on the forearc slope. This suggests that large earthquakes on the Sumatran margin do not always generate widespread turbidites. This is further supported by bathymetric and seismic data collected soon after the 2004 earthquake showing that landslides are relatively rare on the Sumatran margin (Henstock et al., 2006; Tappin et al., 2007). Völker et al. (2011) also found no large landslides near the epicenter of a large (M_w 8.8) earthquake that occurred offshore of Chile in 2010. It is important to understand where and when large earthquakes fail to produce distinctive widespread turbidites. This must be assessed in locations like Sumatra where the location and timing of large earthquakes is known. Such studies will also help to define criteria used to distinguish earthquake-triggered turbidites.

This leads us to consider the question: can we determine which settings are most suitable for turbidite paleoseismology? High sedimentation rates are likely to precondition a submarine slope to fail due to buildup of excess pore pressures, although very large-scale slope failures can occur in areas of slow sedimentation (Urlaub et al., 2012). Frequent earthquake shaking may cause consolidation of sediment rather than trigger failure (Lee et al., 2004), and continental slopes shaken by small, frequent earthquakes may be less prone to fail than those shaken by large, infrequent earthquakes. Indeed, Lee et al. (2004) found an inverse relationship between landslide occurrence and seismicity levels on U.S. continental slopes. Confluence tests are favored if there are through-going drainages on the continental slope that provide failed masses time to transform into turbidity currents (Piper and Normark, 2009). However, this can also complicate the stratigraphic record of earthquake-triggered flows by enabling non–earthquake-triggered flows from rivers and storms to reach the deep ocean (Carter et al., 2012) (Table 2). Ground-shaking measurements overlying subduction earthquake ruptures are rare, meaning the degree and variability of ground motion is not well known in these environments. Various factors in addition to earthquake magnitude affect seafloor ground motion; e.g., nature of slip and forearc material properties. Until a better understanding is reached about why some slopes are more prone to widespread failure, we suggest cautious use of turbidites in developing paleoearthquake histories.

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