A 7,500 year earthquake history in the region of the 2004 Sumatra-Andaman Earthquake

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144 sediment cores were collected along the entire length of the Sumatra margin in order to interpret the strata as they relate to seismogenic triggering of submarine landslides. Cores were collected in the trench and in lower slope piggyback basins of the accretory prism. Based on correlation of at least 19 turbidites, the ¹⁴C age based Recurrence Interval (RI) estimate for large to great earthquakes in the 2004 rupture region for the last 7.5±0.6 ka is 330±60 years, consistent with the nascent terrestrial paleoseismic record. ²¹⁰Pb age control is used to evaluate the timing of the most recent sedimentary deposits, most likely generated by the 2004 earthquake. We find that the seismic shaking trigger interpretation may be related to seismic moment release and relative amplitude.

Introduction

Following the unexpected 26 December 2004 Sumatra-Andaman and 11 March 2011 Tohoku-Oki subduction zone earthquakes and tsunamis, earthquake geologists have been evaluating their global models of subduction zone earthquake recurrence. Given the short record of historic earthquakes (a few centuries) and the knowledge that many subduction zones have great earthquake return periods that span multiple centuries, it has been difficult to properly characterize the recurrence of these earthquakes. Many aspects of plate tectonics have been evaluated in order to estimate the likelihood of any given size or any given timing of these future earthquakes¹,²,³. These include studies of materials that are thought to occur at depth along the fault zone⁴, geophysical models and studies of the crust and mantle that likely contribute to earthquake potential⁵, borehole analysis of the plate setting and sedimentary record⁶, geodetic measurements of crustal motion during the earthquake cycle⁷, etc. Paleoseismology stands out as a method that can reveal the behavior of the fault through multiple earthquake cycles⁸. Terrestrial paleoseismology is limited in that surface expression of fault rupture, and thus the fault trenches used to expose those rupture histories, is limited by the ability to dig deep enough or by the destruction of the deformation record by younger ruptures or geomorphic processes. Submarine (and sublacustrine) paleoseismology is benefitted since the sedimentary record, while secondary evidence for earthquakes can be preserved for much longer time scales.

Strong ground shaking from rupture of earthquakes has been inferred to trigger turbidity currents that potentially leave a very long record of past earthquakes in the form of turbidites⁹. The combined evidence from sedimentology, tests of synchronity, stratigraphic correlation, and analysis of non-earthquake triggers can be used to develop a reliable earthquake record for submarine fault zones in some cases¹⁰,¹¹.

This paper describes initial results from a submarine paleoseismic investigation conducted offshore Sumatra in the region of the 26 December 2004 Mw 9.1-9.3 earthquake²¹,²²,²³,²⁴. Marine turbidite stratigraphy is first examined and tested for suitability for paleoseismology, then interpreted to estimate earthquake recurrence for the last ~7,500 years.

1.1 Sumatra Andaman Subduction Zone

The Sumatra Andaman subduction zone (SASZ) is a convergent plate boundary where the Indo-Australia plate is subducting northeastwardly beneath the Burma microplate of Eurasia (Fig. 1). Historic SASZ earthquakes in this region²⁵,²⁶ (1679, 1762, 1847, 1881, and 1941) were much smaller (magnitude < 8.0) than the 2004 earthquake (Fig. 1). Recent investigations of secondary evidence left behind by tsunami as sand sheets in northern Sumatra²⁷, western Thailand²⁸, and the Andaman-Nicobar Islands²⁹, along with coral microatoll evidence³⁰ suggest the last penultimate large earthquake most likely occurred 500-700 years ago, and an ante-penultimate earthquake/tsunami in Sumatra²⁷, the A-N Isles³⁰, and India³¹ (Rajendran, 2007) likely occurred ~900-1,200 years ago. These studies, while temporally short, suggest that recurrence of Mw>8 earthquakes is probably about half a millennia.

1.2 Submarine Landslides

Earthquakes are well known as subaerial landslide triggers, with a triggering minimum earthquake magnitude of Mw 5⁰ and landslide density is found to be greater in areas of stronger ground acceleration³². Earthquakes are posed as one of the dominant submarine landslide triggers³³,³⁴, with most historic examples attributed to ground accelerations from earthquakes³⁵. Minimum magnitudes for recording seismoturbidites are probably larger, above Mw 7.1⁰ or Mw 7.4⁴.

Of the many possible landslide triggers listed by Adams³⁵, Sultan et al. ³⁶, and Goldfinger³⁷, only bolide impacts, tides, wave loads, gas hydrates, and

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was not until the submarine record was developed that the spatiotemporal linkages could be made between the existing terrestrial records. The terrestrial record of palaeoearthquakes in Sumatra and the surrounding Indian Ocean basin is less well developed, but does provide some paleoseismic comparisons for the marine record.

Globally, sites have been evaluated by correlating seismogenic sedimentary deposits: Lake Baikal, Ecuador, Iberian margin, Chile, Kumano trough, Japan, Lake Washington, Lake Tahoe, Okinawa trough, Japan, central Switzerland, Saguenay Fiord, Canadian arctic, Kuril trench, Lake Biwa, southern margin Japan, Gulf of California, Santa Barbara, Lake Biwa, eastern Japan Sea, and Marmara Sea. These sites are in different settings, with widely varying conditions (climate, sedimentation rate, subaqueous setting). Turbidite paleoseismology is new to Sumatra.

Earthquakes can be triggers as other phenomena simply precondition the slope for failure. Slope stability is a balance between downward forces (gravitational or otherwise) and resisting forces. When the downslope force (shear stress) exceeds the resistance force (shear strength), the “factor of safety” is less than 1, and the slope is susceptible to failure. Rapid changes in pore pressure accompanied with liquefaction-induced sliding are considered to be the mechanisms responsible for changing the factor of safety sufficiently to trigger landslides. As the effective shear strength changes during the earthquake, triggering magnitude changes and this possibly causes a change in sediment flux into the landslide system. This change in sediment flux may be recorded in the sedimentary record as seismoturbidites.

1.3 Turbidite Paleoseismology

Turbidite paleoseismology is most well developed for the Cascadia margin related to the Cascadia subduction zone (CSZ). Seismoturbidite correlation in Cascadia benefited highly from the geomorphology of the turbidite channel systems, probably formed at low stands when the channel systems were dominated by sediment-rich erosive flows as they were connected to fluvial systems. These pre-existing channel systems today provide a depositional setting that allows the seismic signal to be preserved well in turbidite structure. What also contributed highly to the success of this work are the volumes of work done on terrestrial paleoseismology in the region, which provided a chronologic framework with which to compare with submarine results. Beginning as early as 1987, Atwater found evidence of paleodeformation related to subduction zone earthquakes along the CSZ. Thereafter evidence of paleotsunami and paleoliquefaction compiled to generate a large catalog of paleoseismic events that had variations in space and time (references therein). Researchers were unable to correlate evidence from site-to-site because the sedimentary evidence was discontinuous along strike. It

Figure 1. Plate-Tectonic Setting. India-Australia plate subducts northeastwardly beneath the Burma plate at modern rates (GPS velocity based on Nuvel-1A). Historic ruptures are plotted in grey. Paleotsunami and paleoearthquake sites are plotted in grey and labeled with a letter: a, b, c, d, e, f, g, h, i, j. RR0705 cores are plotted in white. SRTM bathymetry and topography is in shaded relief. Location of Fig. 5 and Fig. S2 is shown as black rectangle.
physiography to narrow the selection of sites to correct sites is critical. We use continental margin As in all paleoseismic investigations, selecting the correct sites is critical. We use continental margin physiography to narrow the selection of sites to those most likely to preserve seismiturbidites at the expense of other possible sources. Sumatra presents some physiographic difficulties in this respect, and some advantages, in comparison to Cascadia where significant work has been conducted. The Cascadia margin has low relief folds in the slope with partially filled basins, allowing the piggy-back basin slopes to be linked with submarine canyon systems. These canyon systems permit the multiple sampling of the system, longitudinally and branch-wise (in different canyon branches that meet and combine at confluences). In contrast, the accretionary prism offshore Sumatra is comprised of basins that are more closely spaced, more highly dissected by landslide erosion, and are not linked as well as Cascadia, promoting local flow conditions to influence the structure of the turbidity currents and their deposits (autopathic forcing). Most slope-basin sites are generally near well-developed high relief landslide amphitheaters, so are more proximal to their sediment source than in Cascadia. Hydrate Ridge is an exception in Cascadia, where proximity dominance changes over a few kilometers, similar to turbidites in Crater Lake.

Seismoturbidites are triggered when seismic waves propagate through the landslide source area. If the source-time function of the earthquake drives the sediment flux into the landslide system, and allopathic forcing dominates, the vertical structure of the turbidity current is expected to have coarse pulses of sediment corresponding to each pulse in seismic energy. As a result of a seismogenic trigger, one could expect a turbidite deposit that had vertical sedimentary structure representing the longitudinal structure of the turbidity current. The general structure would have a coarse grained base and fine upwards, with multiple coarse sub-units for each peak in seismic energy.

With other triggers, one could expect deposits reflecting those other processes. For example, hyperpycnal storm flow related deposits (hyperpycnites) could have a finer sediment base that initially coarsens upwards (during waxing flow), then fines upwards (as the flow wanes). With wave triggers, the landslide source area would be much shallower than the source areas in the region of this study. Gas Hydrate destabilization would leave behind highly localized deposits. Bolide impacts may also lead to turbidites, but their recurrence is far too long to explain the chronostratigraphy in our cores.

2.2 Site Selection

As in all paleoseismic investigations, selecting the correct sites is critical. We use continental margin physiography to narrow the selection of sites tocontinental margin morphology in western Sumatra is dominated by the upper plate structure of a Tertiary and Quaternary accretionary prism with structural highs and forearc basins. Fold and thrust belt topography forms longitudinal, discontinuously linked basins that can be either isolated, or drain to the trench. Canyon systems tend to be short and drainage catchments are relatively small, limiting the areal extent of source areas for turbidity currents. This is a significant disadvantage as most coring sites are therefore more proximal to their source.

Mostly in the northern margin of Sumatra is there a sufficient sediment supply history (Bengal and Nicobar fans) to have archaic turbidite channel systems in place where turbidity currents generated locally on the slope flow into. Currently the trench is isolated from turbidity currents from further north however. Possibly contributing to this is the cut-off of Himalaya derived sediment by a large landslide at 14º north and the intersection of the ninety-east ridge with the subduction zone trench (Fig. 1). The outer forearc is isolated from northern Sumatra terrestrial sediment sources by the broad, unfilled Aceh forearc basin, though limited input from the offshore islands of Simeulue, Nias, and Siberut Island is possible for some nearby basins south of this study.

The trench deepens southward from 4.5 km. to 6.5 km. from 5º N to 7º S, and is filled with sediment several km thick in the north from the Nicobar fan, partially burying lower plate structures that trend across the trench. The central and southern margins of Sumatra are sediment starved, so the seafloor topography is dominated by bending moment normal faults and north-striking fracture zones. Canyon systems have turbidite channels only on the flanks of the lower slope and these channels die out within 10's of km

Methods

2.1 Seismoturbidite Rationale

Adams and Goldfinger suggest eight plausible triggering mechanisms for turbidity currents: 1) storm wave loads, 2) earthquake, 3) tsunami wave loads (local or distant), 4) sediment loads, 5) hyperpycnal flows, 6) volcanic explosions, 7) submarine landslides, and 8) bolide impacts. Other mechanisms may reduce slope stability, but are likely random and not regional nor synchronous. The principle basis for attributing a seismogenic trigger to the turbidite record is that regional and synchronous deposition is unlikely to have been generated by a trigger other than an earthquake.

We test the plausibility of a seismogenic trigger in northern Sumatra by 1) using tests for synchronous triggering of sedimentologically isolated turbidite systems and 2) using secondary constraints that consider sedimentologic characteristics of the turbidites. When turbidites can be correlated between sites separated by a large distance or between sites isolated from land sources and from each other, synchronous triggering can be inferred and most other triggering mechanisms can be eliminated.

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from the mouth of the canyons at the trench. This morphology controls turbidite channel flow within the trench, which is largely unmixed and is dominated by proximal sedimentary processes.

Most trench cores are more successfully recovered when located in places that are not directly at the mouth of any canyon leading to the trench, but in locations that were more distal. In contrast, most slope-basin cores are collected in locations proximal to their sedimentary source, while some cores did have canyons draining to them.

Cores will ideally preserve stratigraphy with deposits that have the greatest dynamic range in particle size (texture) above the background sediment particle size or density. In addition, with a large dynamic range, the distinction between hemipelagic mud and turbidite sediment is enhanced, important for calculating background sedimentation rates and sampling for age control. Cores that are too distal have turbidites with very little variation in density, making it difficult to characterize the structure of any given deposit.

The Sumatra slope and trench physiography results in trench segments that are isolated from each other, and from isolated slope basins in part, and therefore offers numerous opportunities to compare the stratigraphic sequences in sites that have unique sediment sources. The basins and trench segments are fed by small canyons that have limited drainage areas on the slope and form small fan/aprons. Slope sites used in this study include cores 108, 104, 103, and 96, which all have isolated sediment sources. In the trench, cores 03, 05, 107, 105, 98, and 94 receive sediment from both upstream in the trench and downslope transport from the continental slope. Fig. 2 shows the source and flow relations for these cores.

Subsurface data, collected with a Knudsen EM300, was used to evaluate the seismic character of sediments prior to coring trench and core sites. Seismic facies correlate well with our cores, so these may prove suitable for extending the earthquake history back further in time.

2.3 Stratigraphic Correlation

We use integrated stratigraphic correlation techniques, including visual lithostratigraphic description (color, texture, and structure, etc.), Computed Tomography (CT) image analysis, and core log "wiggle matching" of Multi Sensor Core Logger (MSCL) geophysical data (Fig. 2). The most sensitive criteria for correlating fine grained turbidites (which may not be visible to the naked eye) is the density profile13, which we augment with very high resolution CT density profiles and 3D CT imagery.

The spatial extent of any given set of correlated turbidites reveals the spatial extent of the triggering process responsible for the generation of their source turbidity currents. Therefore, the primary goal of correlating turbidite strata is to establish spatial extent of individual turbidites that are carefully “fingerprinted” with geophysical data. Geophysical wiggle matching (fingerprinting70) of turbidites is based on the correlation of identifiable unique stratigraphic characteristics using MSCL core log data: gamma density and magnetic susceptibility (ms). These “fingerprints” represent the time-history of deposition of the turbidite and have been shown to correlate between independent sites separated by large distances and depositional settings10,11,2,39. A large dynamic range in particle size maximizes the signal to noise ratio for the fingerprinting process. The turbidite itself is commonly composed of multiple coarse fraction pulses, probably deposited over minutes to hours which form much of the basis of the turbidite “fingerprint.”

The fact that these cores, in sedimentologically isolated and hydrodynamically unique systems, share turbidites with depositional histories that match in considerable detail, suggests that they also share a common trigger mechanism. Goldfinger et al.10,11,12 have proposed this shared characteristic is, in part, the time history of ground shaking causing a change in sediment flux during the earthquake. Correlation of strata is further supported by 14C ages of individual turbidites and hemipelagic intervals between earthquakes.

2.4 Age Control

Age control for stratigraphy is provided by Accelerator Mass Spectrometer (AMS) 14C and 210Pb radiometric techniques. 14C data is based on decay with a half-life of 5,730 years and is useful for strata between ~300 - ~35,000 years old78. 210Pb data, based on a shorter half-life of 22 years99, provides information about sedimentary deposition for the past ~150 years. We use 210Pb age data to constrain the timing of deposition for the most recently deposited sediments. (Detailed radiocarbon methods are in Table S1).

Radiocarbon ages provide an important test to our correlations and there can be some exceptions. Trench cores are deeper than the CCD, so they do not contain calcareous material sufficient for 14C age control. For this reason, correlations between these and other cores do not have an independent test for the fingerprint correlation. Therefore some of our correlations in the trench cores are tentative (as shown in the Fig. 2).

The radiocarbon ages are reported in years before present (BP, measured from 1950) with a two standard deviation lab error80. 14C ages are calibrated81 and a marine reservoir correction of 16±11 years is made using the INTCAL09 database82. Only two delta R values are available for the Sumatra area, and while constraints are few on this correction, we here are
Figure 2. Regional Stratigraphic Correlations and Source Areas. A. Core locations (orange dots) on bathymetric map also showing key channel flow paths (light blue) to eight core sites. Slope basin source areas (orange) were determined by outlining drainage divides surrounding all submarine topography contributing potential gravity flows to a given core site. While the region that drains to core 104PC then drains to the trench, the three other slope basins are closed (they do not drain to the trench). B. Flow path profile depth (km) vs. forearc distance (km) are plotted in brown for basin flow paths and blue for trench flow paths. C. Stratigraphic correlations between key cores using lithology, CT, geophysical property, and 14C data. MSCL data are plotted and CT imagery displays lower density material in darker grey and higher density material in lighter grey. Slope cores are labeled brown; trench cores are labeled blue. Trench core sites were deeper than the Carbonate Compensation Depth (CCD), the depth below which foraminiferid CaCO3 tests dissolve faster than they are deposited. Foraminiferid abundance was nil in trench core sediments, so 14C age control applies only to the slope cores. Grey rectangles refer to Fig. 3.
correlating marine sites to other nearby marine sites, thus the local correlations are valid while absolute ages may contain additional uncertainty. One additional correction we make to the calibrated age is the sediment gap thickness correction (thickness of sediment between the turbidite and the sample; see OxCal code Table S1). For individual ages, we propagate these uncertainties using RMS (root mean square) calculations using estimates of the uncertainties at each step. This calculation includes the lab uncertainties and results in the final reported 95% range for each radiocarbon age. In later sections of the paper, we calculate region wide mean event ages. For these, we average the ages (using the combine function in OxCal), and then apply RMS calculations to the averaged error ranges to produce the 95% RMS ranges for each averaged age. No lab multipliers were applied to the data.

Results

Lithostratigraphy in northern Sumatra slope cores is dominated by turbidites interbedded with massive hemipelagic mud and less common tephra. Bioturbation is common and core-induced deformation is observed in some cores. Turbidites are composed of coarse silt to coarse sand bases, with fining upward sand and silt to clay sub-units. The coarse fraction is composed of mica and quartz grains with rare mafics. Some basal turbidite sub-units are foraminiferal hash. Sand sub-units commonly range in thickness from 0.5 to ~20 cm and are laminated and cross bedded, commonly underlying massive sand units. Finer material is composed of silt to clay sized particles. 0.5- to 10.5-cm thick primary tephra are rare and can be correlated between sites using electron microprobe and laser ablation ICPMS data.

Trench turbidite lithology is also dominated by fine mature quartz sand and mica, consistent with the well-known Himalayan source of the accreting Bengal and Nicobar fans. At 2- to 4-km depth, slope basins contained similar lithology, which we interpret to have been accreted and recycled into the slope basin stratigraphy, with the addition of abundant forams.

Fig. 2 shows core data for cores 108, 105, 104, 103, and 96 (all regional cores are in Fig. S2). The light-grey sand bases of turbidites are easily identified and MSCL maxima correlate well with the CT density maxima. CT data permit a refined view of the strata and the effect of core disturbance, while gamma and magnetic data reflect signals that average these effects. Similar turbidite stratigraphy is found in all slope basins (cores 108, 104, 103, and 96) and trench sites (cores 107, 105, 98, and 94), spanning 350 km along strike.

We interpret that the uppermost turbidite in cores 108, 105, 104, 96, and 95 is most likely the 2004 turbidite. The lack of hemipelagic sediment overlying this turbidite, the lack of consolidation when compared to older strata, its great thickness (over 3m) at one site, and excess 210Pb activity of the uppermost material are consistent with this interpretation. In addition, the MSCL maxima correlate generally with seismologic observation maxima.

The stratigraphic sequences with the most unique “fingerprints” carry the strongest correlative weight and act as “anchor points” for our correlations (Figs. 2 and 3). We note that some turbidites are absent across some intervals in the 2004 rupture region. For example, T2 to T6 are not present in core 108 (Fig. 2). Likewise, T1 to T4 appear to be absent in core 103. We interpret this as the result of site physiography, which is more proximal than ideal in most cases, and would be expected to generate greater variability as has been observed in Cascadia. The missing section may also be the result of over penetration or erosion of the seafloor while coring. As the sequence correlates well overall, local variability due to basal erosion, heterogeneous source areas within the region, coring deformation, and site geomorphology would be expected, regardless of the triggering mechanism.

We observe some sites with persistent sedimentary structures that may be due to local geomorphologic conditions or basin effects (ref for basin effect). Core 104 records turbidites (T6, T10, T13, T14, and T17) that we correlate to other sites, but which also have many thin coarse pulses as part of their structure. The core location for 104 is at the base of a steep slope and canyon mouth with 1.5 km of relief within 1 km (Fig. S3), possibly the site of local retrogressive failure (possibly explaining turbidite structure). Another example is Core 96, which has finer grained turbidites overall. Core 96 is located in a closed slope-basin fed by very low relief terrain that does not form large channels, possibly explaining the fine-grained multipulse structure. Core 103 is in a location that has a low gradient, wide floodplain channel directly upslope possibly explaining the dynamic range of turbidite texture.

Comparing three trench cores that have somewhat different turbidite records, core 98 is located in a location insulated from high relief upslope sources due to a landward vergent fold that deflects higher energy channelized flow further to the southeast (Fig. S3). This isolation may explain the distal nature of the turbidite structures in core 98. In contrast, cores 94 and 105 are directly downslope from active canyon systems and have more structurally varying and coarser turbidites, suggesting that mixing in the trench is minimal.
Discussion

4.1 Submarine Landslides, Sedimentology, and Triggers

Seismoturbidites in Cascadia have fingerprint-based correlations with sufficient similarity to suggest the vertical structure indeed represents allocyclic forcing\textsuperscript{42}, probably related to the source-time function of an earthquake\textsuperscript{12}. Turbidites here have been correlated in channel systems above and below confluences, in order to pass the confluence test\textsuperscript{20}. This test assumes that if the channel system has the same number of turbidites above and below a confluence, it can be surmised that the deposits in all locations were laid in the same short period of time(s) that lasted minutes to hours. Because of this similarity in stratigraphy between cores in this example, the researchers conclude that the trigger for these turbidity currents were triggered over a broad region (1000's km\textsuperscript{2}). Cores from channels that sample unique source areas (Cascadia and Juan de Fuca canyons) are also correlated, further supporting the areal extent of the trigger for these turbidites. Thirdly in support of their findings, a sedimentologically isolated site (Hydrate Ridge) is also correlated to a site at Rogue Canyon.

4.1.1 Correlation

Because of the difference in basin effects and turbidite channel architecture in Sumatra (when compared to Cascadia), the tests for seismogenic triggering are slightly different. Like in Cascadia, we base our correlations largely on three factors (1) deposit “fingerprint,” (2) timing or age control, and (3) sedimentary source isolation. Like Hydrate Ridge cores in Cascadia, Sumatra cores in slope basins are isolated from each other, so this is used as the primary way to test for regionality of triggers: cores with unique sedimentary sources that have turbidites that share fingerprints demonstrate that triggers are regional, not local. This relation shows that, while cores are biased towards proximal processes, the seismogenic source-time information factors predominates turbidite deposition.

4.2 Earthquakes?

4.2.1 Source Time Function

During earthquake rupture, seismic energy released after centuries of stress and strain build-up is heterogeneous and lasts seconds to minutes. Magnitude-duration relations show that large
subduction zone earthquakes generally last several minutes. Goldfinger et al.12 pose that the vertical structure (characterized as a fingerprint) of seismoturbidites is directly related to the source-time function of the earthquake rupture. This is evidenced by the 1906 San Andreas earthquake that has a two pulse rupture and the associated turbidite has two major upward fining sand pulses70,86.

4.2.2 Earthquake as trigger

Of all cores core, 96PC has the most expanded section of what we interpret to be the 2004 seismoturbidite. The expanded section is likely due to the core site, which is in the middle of a long (7 km) slope basin that probably does not drain, thus providing ample accommodation space for thicker deposits. Underlying turbidites are also thicker than in other cores, suggesting the reason for thicker deposits is site related (basin effect). The source-time functions produced by others21,23,87 are plotted in comparison to the upper turbidite in core 96PC Fig. 4. There is good agreement between these plots of seismic energy release and the vertical sedimentary structure. The relation between the earthquake source-time function and the corresponding deposit originally led previous authors to suggest the deposit structure can be used as a “paleoseismogram” 88,89,70, leading us to the comparison in Fig. 4.

We note that the 2004 turbidite has three fining upward coarse pulses in our cores, and also that the 2004 SASZ earthquake has three primary slip sub-events90. The success of turbidite correlation in Cascadia, the northern San Andreas, and Sumatra suggests that some first order structure of the turbidity current maintains integrity despite the fluid dynamic complexity of turbidity currents. We suggest that the longitudinal heterogeneity of the current, imparted by the heterogeneous earthquake rupture itself (the source-time function of the earthquake) may be recorded in the deposits11,12,89. Our model predicts
that these sub-events, minutes apart, may be recorded as discernable coarse pulses within the turbidite that can be correlated over large distances. (Fig. 4). A similar conclusion was drawn for Cascadia earthquake turbidites; the mechanism has been tested in flume studies, and is predicted by theory and analog models and references therein.

Because core 96 has the most expanded section, this core is the core with the most detailed structure and the best core to use to examine seismic cycles. Turbidites in core 96 suggest that there are three general magnitudes of turbidite deposition. If the mass/thickness of the turbidite is related to earthquake magnitude, we could infer earthquake magnitude cycling from the turbidite mass cycling. Superquake turbidites are designated by deposits greater than one meter, smaller large to great earthquakes are designated by non-bioturbated turbidites about 1/3 of a meter thick, and smallest earthquakes are designated by highly bioturbated turbidites less than 10 cm thick. Turbidites in the larger two size classes all contain at least two main pulses, possibly suggesting multiple earthquake slip patches during these ruptures.

4.3 Correlation in the SASZ 2004 Region

The correlated framework shown in Figs. 2 & 5 represents a depositional history of turbidites spanning 7,500 years, with potential for a longer record with further work. But what triggered them? The detailed depositional structure of turbidites is likely a combination of trigger source (e.g. hyperpycnal vs. seismogenic), source proximity (e.g. proximal vs. distal), and flow dynamics (e.g. site or

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**Figure 5. Earthquake Chronology.** Space-Time relations for stratigraphy cored in the 2004 rupture region are plotted (vs. forearc distance) as blue circles with error reported with 95% error bars. Green tie-lines show stratigraphic correlations (thicker = correlation more certain, dashed = less certain). Region-wide events are designated by a dashed grey line and labeled with peak ages on the left margin, along with the probability density functions for these event ages. Terrestrial paleoseismic and paleotsunami data are plotted by dots/diamonds and triangles respectively. Data plotted to the left of 108PC are not plotted vs. forearc distance as they are further north than the figure limits. The 2004 earthquake extends beyond the latitudinal extent of this figure. See Figs. S1 and S5 for more detailed radiocarbon methods.

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* Single $^1$C age calibrated and reported according to Stuiver and Reimer, calculated using marine reservoir correction ($\Delta R = 16 \pm 11$). Error reported to 2 standard deviations.

* Probability Density Function (PDF) of combined event ages; error reported to 2 standard deviations.

** Peak age selected from peak of PDF for each event. Error is reported to 2 standard deviations.

¥ OxCal v4.1.3 Bronk Ramsey; Marine data from Reimer et al.
flow-path geomorphology). These forcing factors may compete depending upon core location and local physiography. Slope cores are proximal to the source and this proximity likely dominates the structure and contributes to high variability in sedimentary structures. Trench cores are located in varying proximity to the source, thus some trench cores appear to reflect a more distal setting (98PC, Fig. S3). Trench cores in this region also may record turbidity currents from sources further north along the margin in Indian waters which were inaccessible to this project, but based on comparisons between cores 103 and 94, this seems less likely.

While many core sites were in settings more proximal than ideal, the coherence of the turbidite “fingerprints” and radiocarbon ages between isolated basin and trench sites over ~350 km along strike suggests that many or most of the correlated turbidites have a common trigger. One of the few potential triggers that may be both regional and geologically synchronous would be very large storms. Hyperpycnites are reported to initially coarsen upwards and then fine upwards, representing the waxing and then waning of the hyperpycnal flow17,92, but the core sites in this study are much deeper that would be affected by storm or tsunami waves12. Amalgamation is an indicator that the turbidites were deposited from multiple turbidity currents, merging and forming a longitudinal structure reflected in the deposit93, possibly from multiple slides on slopes. In Lake Biwa, Nakajima and Kanai93 conclude these multiple pulses are the results of synchronous triggering of multiple parts of the canyon system. Cascadia margin cores contain deposits that pass multiple tests of synchronous earthquake origin, and generally contain multiple coarse fining upward sub-units, consistent with other seismo-turbidites11,12. Goldfinger et al.12 correlate the turbidite mass and the number of coarse units to the rupture length of the causative earthquakes. Sumatra turbidite bases are sharp and generally fine upwards, with some deposits composed of multiple upwards fining sub-units, similar to Cascadia12. Coarser Sumatra turbidites commonly are amalgamated and this results in incomplete or irregular structure sequences, suggesting multiple turbidity current pulses and a longitudinally heterogeneous turbidity current. We do not find support for a hyperpycnal origin for the turbidites investigated in this study.

Here are a few examples of turbidites correlated between cores. We give two examples, (1) seismoturbidite #10 across three slope cores and (2) all upper turbidites flattened to each other on a depth grid with regular vertical spacing. Fig. 4 shows the process of flattening MCSL core data for turbidites between cores 108PC, 104PC, and 103PC. Fig. S4 shows flattening for all cores in Fig. S2, correlated turbidite bases are flattened to evenly spaced horizons. This flattening removes bias from flattening to a single core and also permits one to see how fingerprints vary along strike.

The good stratigraphic correlation between sites isolated from each other, land sediment sources, and from other triggering mechanisms, coupled with compatible radiocarbon ages suggest that the most likely triggering mechanism is regional earthquakes. Uncorrelated events present at some sites may be random sediment failures or smaller local earthquakes. These uncorrelated turbidites are thin and have low mass with non-unique fingerprints, making it difficult to interpret their trigger origin. We note that the lack of cyclones in equatorial waters all but rules out massive regional storms as a sediment source. The isolation of our sites from Sumatra also prevents terrestrial input to the outer forearc slope. Were cyclones present in the past, such storms would not likely trigger turbidity currents on the forearc slope with minimum depths relevant to this study of ~1,000 m.

There is evidence that cores from this study record dominantly proximal processes. This interpretation is supported by looking at some trench cores, 105, 98 and 94; along with some slope cores, 104 and 103. Core 98 is located in the trench in a position protected from slope processes by a landward vergent anticline, so turbidites are thin and less sandy than core 94. In contrast, cores 94 and 105 are located near the mouth of numerous canyon systems, with thicker and sandier turbidites. Proximal dominance is further supported by stratigraphy in cores 103 and 104. While these cores are closely spaced (thirty-five km) and correlate well with each other, the differences in turbidite style (thickness, structure) reflect autogenic forcing. Core 104 is located at the base of steep slope faces, so the turbidite thicknesses are thicker than in core 103, which is located downstream of several small canyon confluences with turbidites thinner and more organized.

### 4.4 Age Model

Upwelling induced variability in the reservoir age of radiocarbon in sea water offshore Sumatra was maximal during glacial periods, but deep and intermediate water masses are less stratified during interglacials, with a decrease in deep water ventilation94,95. Because of this oceanographic setting, we do not consider variability of the reservoir effect to be significant during the Holocene.

Based on 14C ages and the oldest turbidite in core 108PC, the average recurrence interval for earthquakes in the region of the 2004 earthquake is 330 ± 60 years. Based on the age of the oldest, most well correlated seismoturbidite, the RI is 340 ± 60 years. Given a fault normal convergence rate of 34-37 mm a-1 in this region94, earthquakes like the 2004 earthquake (slip of ~20 m22) would yield an
average recurrence of 530 - 590 years. This estimate is close to our estimate, particularly given that we know little of the magnitudes of past earthquakes, nor of the coupling ratio along the SASZ (e.g. for earthquake slip < 20m, recurrence would decrease). This is consistent with the RI estimate from Chlieh et al. of 140-420 yrs. Given a RI of ~330 years for events large enough to generate observable turbidites, and that smaller earthquakes may be unrecorded, our estimate is a maximum. If turbidite thickness is consistent along strike and relates to earthquake magnitude, thickness may be used to distinguish between earthquakes of different magnitude. Given the variation and frequency of larger turbidites, recurrence of earthquakes similar to the 2004 events may be approximately 3ka.

Where multiple $^{14}$C ages exist for correlated turbidites, we test whether they agree with our stratigraphic correlation model by using the ‘combine’ function in OxCal software. “Combined” ages for turbidites 5, 8, 9, 11, and 14, are computed with the combination of either two or three ages (Table S5). Combinations are substantiated by three measures of success: chi-squared, agreement index “Acomb” (>90), and convergence integral “C” (>95) (Table S4). After some ages are excluded, the remaining ages satisfy these measures and they support our stratigraphic correlations so are combined statistically.

Lithostratigraphy, radiocarbon ages and geophysical fingerprinting suggest a good correlation of turbidites T1 through T19 between cores 108, 105, 104, 103, through T12 in core 96, and through T7 in 107; spanning the 2004 rupture zone (Figs. 2 & 5). Less well correlated are turbidites 20 through 24, in cores 108 and 103. Some ages are inconsistent with the stratigraphic interpretation made in this paper. We can explain some of them. For example, the age for seismoturbidite T10 is best represented by the age in core 103. Based upon the age incongruence and the erosional base of the overlying turbidite, we think the age is too old in core 108. The age in core 104 has a 95% error that is very large, so we do not use it. Likewise, turbidite 19 in core 108 is 600 years too young, which may be due to variations in marine reservoir corrections that are not yet resolvable.

Based on paleotsunami evidence in Thailand, the last tsunamiigenic earthquake recorded onshore in Phra Thong was 500 - to 700 - years ago. $^{14}$C ages of the previous events were ~600 and 1,000 years ago. Paleotsunami, microatoll, and uplifted abrasion platform evidence also may not record all earthquakes and thus may also represent maximum intervals for recurrence of great earthquakes sensitive to the recording thresholds of the different methods.

The temporal distribution of these earthquakes shows apparent clustering, with four gaps of 500- to 700-years; ending at ~ 6.5, 3.8, 2.7, and 1.4 ka. We also note that cluster timing based on the paleoearthquake record of the Mentawai segment is consistent with the four youngest turbidite ages from this study, but inconsistent with earthquakes on Simeulue. Thus while long earthquake sequences such as the 2004-2010 sequence along Sumatra may have occurred in the past, they are not necessarily the rule over the 7,500 year record. Further analysis of the turbidites in the 2004-2005 rupture areas may determine whether the 2004-2005 stress triggering relations are a persistent feature along the Sumatra margin. Cores in the 2005 region contain sandy turbidites that appear less frequent. Historic earthquakes in this region are smaller and possibly further down-dip from our outer forearc high sites, possibly explaining this observation.

**Conclusion**

Turbidite stratigraphy is ubiquitous in isolated slope basin and trench sites along the northern Sumatra margin. Physiography isolates these sites from terrestrial sediment input, from Himalayan derived sediment, and from large storms, providing good localities to investigate the potential for earthquake paleoseismology. Stratigraphic correlation and radiocarbon ages support serial deposition of synchronous turbidites over the past ~ 7500 years. Detailed correlation between sites with no sedimentologic communication supports a regional earthquake origin for most of these turbidites.

The youngest turbidite most likely correlates with the 26 December 2004 great SASZ Mw 9.1-3 earthquake. This event triggered turbidity currents in multiple submarine drainage systems that left stratigraphic evidence in the form of multi-pulse turbidites in isolated slope basin and trench depocenters. Previous great earthquakes in the same region have shaken sufficiently to trigger at least 19 (and as many as 24) turbidity currents and deposit corresponding turbidites during the past ~ 7.5 ka, with an average repeat time of ~ 330 years. The offshore turbidite record is consistent with both plate motion and land paleoseismic ages for eight previous earthquakes approximately 400, 600, 800, 1,000, 1,500, 2,300, 6,000, and 7,100 years ago. This long record includes possible earthquake clustering with gaps of 500- to 700-years between events large enough to trigger recordable turbidity currents. The timing of the four most recent earthquakes is similar to tight clusters of earthquakes recorded by live
corals along the Padang/Mentawai segment of the Sumatra subduction zone, 400 km to the south, suggesting along-strike sequences of earthquakes over relatively short time intervals.

Acknowledgements This research was funded by the Ocean Sciences and Earth Sciences Divisions of the National Science Foundation. We thank Morgan Erhardt, Amy Monica Garrett, and Bran Black for conducting lab analyses; Sarah Strano, Summer Praetorius, and Maureen Davies for their kind assistance in preparing and running the $^{14}$C age samples; Chris Romso for mapping the seafloor for site development; NOC, IFREMER, and BGR for providing key bathymetry and sub-bottom data; UTM, for providing science crew; NOC for providing Russ Wynn; BGR for providing Stefan Ladage; and AIST/GSJ for providing Ken Ikehara. We also thank coring volunteers and faculty from OSU including Bart DeBaere and Maureen Davies. Further details regarding the cruise and the core locations, please refer to the cruise report here: http://www.activetectonics.coas.oregonstate.edu/sumatra/report/index.html


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