Sedimentary Dispersal of Seismoturbidites Offshore Sumatra and Cascadia: Forcing Factors from Physiography

OS43C-1831

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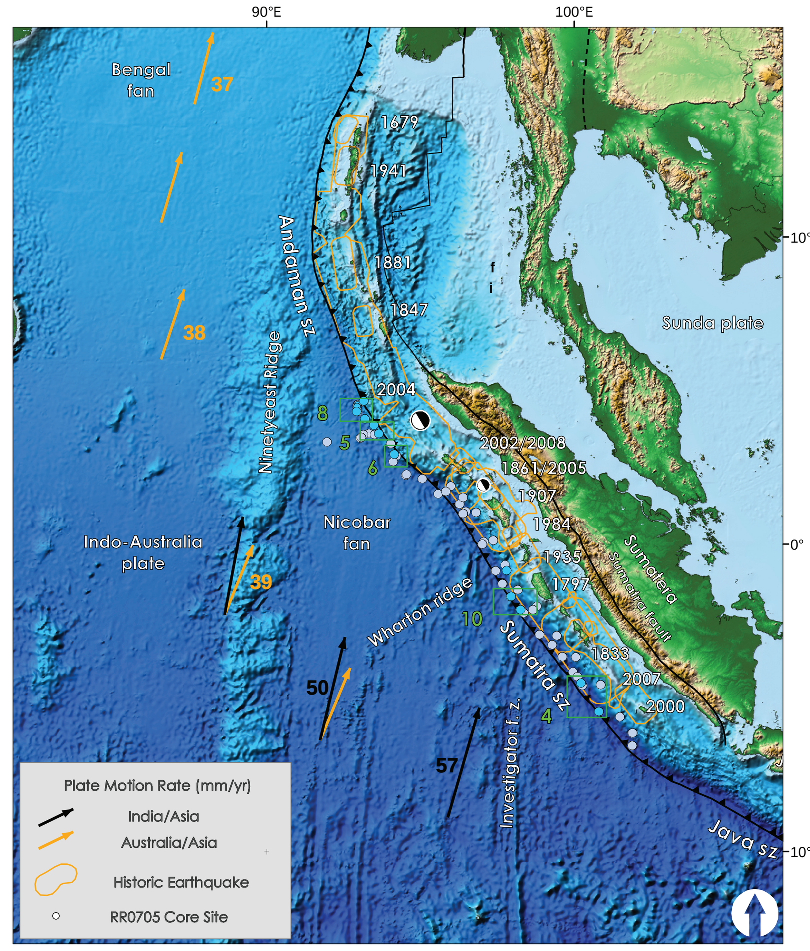
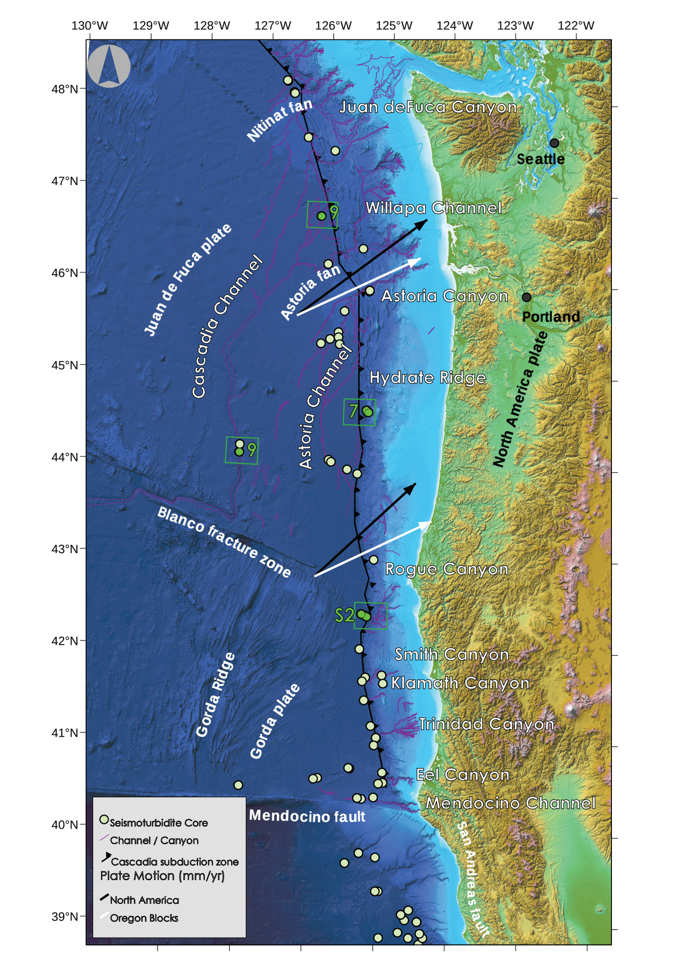
Correlation of turbidite beds among disparate sites is an important technique for testing for regional similarity of depositional sequences, and regional synchroneity of the triggering mechanism. For seismogenic turbidity currents, the flow and deposition is governed by a number of factors, including source proximity, local site conditions, flow path (hydraulic) geometry, temporal and spatial patterns of earthquake rupture, hydrodynamics, and topography. These factors likely provide a first order control on the sedimentary structure of the deposits, and will vary in importance among sites, regions, and variable earthquakes.

Using sedimentary cores offshore the Cascadia and Sumatra-Andaman subduction zones, we investigate turbidite structure as it relates to some of these forcing factors. Channel systems tend to promote and preserve low-frequency components of the content of the current over long distances. More proximal slope basins and base-of-slope apron fan settings tend to preserve turbidite structure that is likely influenced by local physiography, stacking of sources, retrogressive failure, and other details of the failure process. Cascadia's margin is dominated by glacial cycle constructed pathways which promote turbidity current flows for large distances. In contrast, the Sumatra margin pathways did not inherit a large channel fed sedimentary system and the outer forearc is separated from Sumatra by an unfilled forearc basin. For this reason, the sediment source for the Sumatran trench and outer slope is from the north, delivered to the trench and recycled by accretion and repeated slope failures. Canyon systems are short, acting as more variable proximal sources to the trench axis and canyon mouth fans, increasing the variability of the resulting deposits. The trench in both systems is likely also fed by sheet flows from the lower slope, based on the continuity of 3.5 kHz Chirp profiles over long distance parallel to the margin.



Sumatra core location and plate setting map.

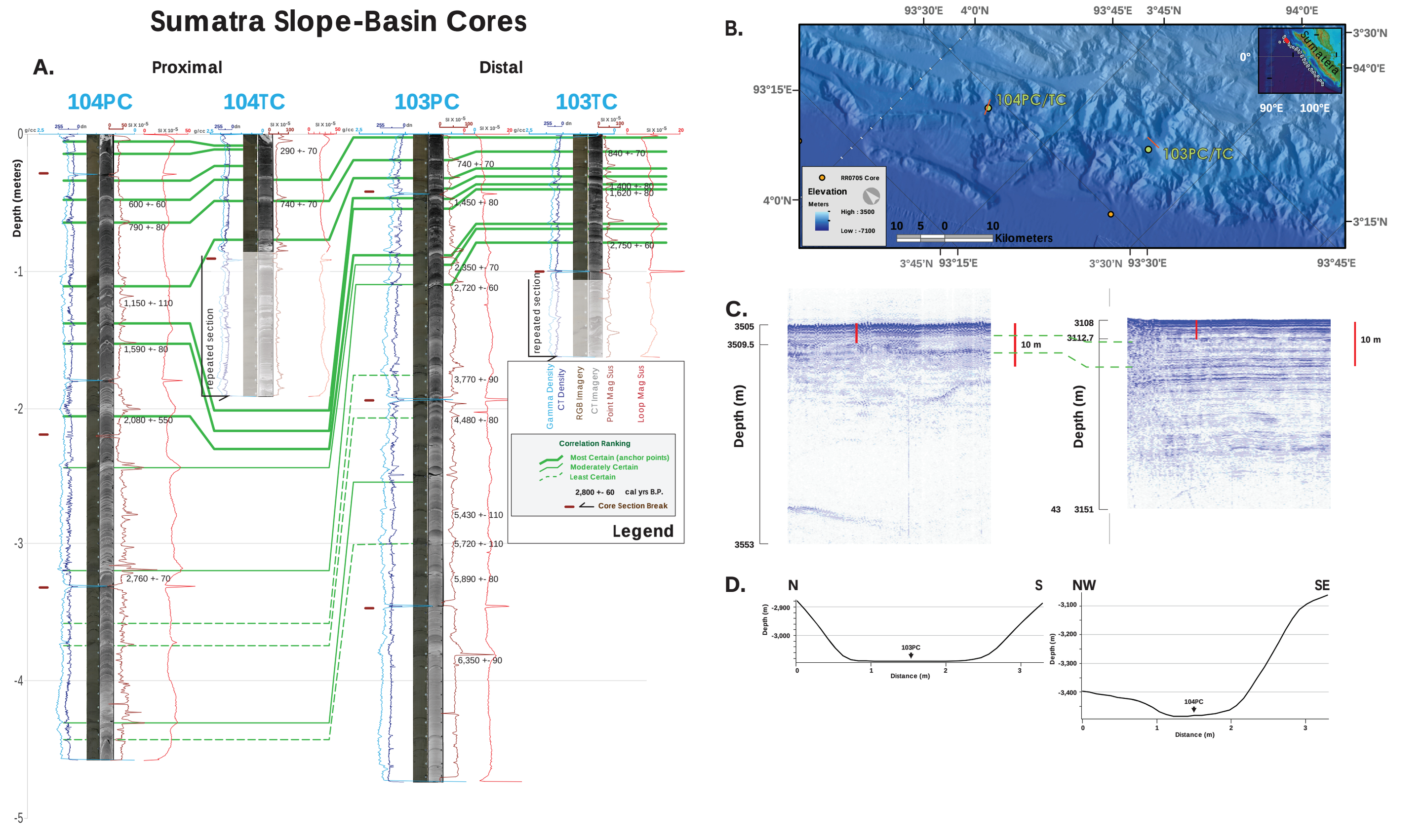
India-Australia plate subducts northeastwardly beneath the Sunda plate (part of Eurasia) at modern rates (GPS velocities are based on regional modeling of Bock et al, 2003 as plotted in Subarya et al., 2006). Historic earthquake ruptures (Bilham, 2005; Malik et al., 2011) are plotted in orange. Bengal and Nicobar fans cover structures of the India-Australia plate in the northern part of the map. RR0705 cores are plotted as light blue and cores discussed in this paper are darker blue. General location for cores in this poster are designated by green rectangles. SRTM bathymetry and topography is in shaded relief and colored vs. depth/elevation (Smith and Sandwell, 1997).



Cascadia margin turbidite canyon, channel, and 1999, 2002, and 2009 core location map.

Core sites are displayed as green circles and cores discussed in this paper are darker green. Bathymetric grid constructed from multibeam data collected in 1999, 2002, and 2009, Gorda plate swath bathymetry collected in 1997 (Dziak et al., 2001), and archive data available from NGDC. Bathymetry and topography in regions outside these higher resolution data sets are from the SRTM global data set (Smith and Sandwell, 1997). General location for cores in this poster are designated by green rectangles. Multibeam bathymetry data collected recently was compiled by Chris Romsos at Oregon State University (pers. comm. Romsos, 2012).

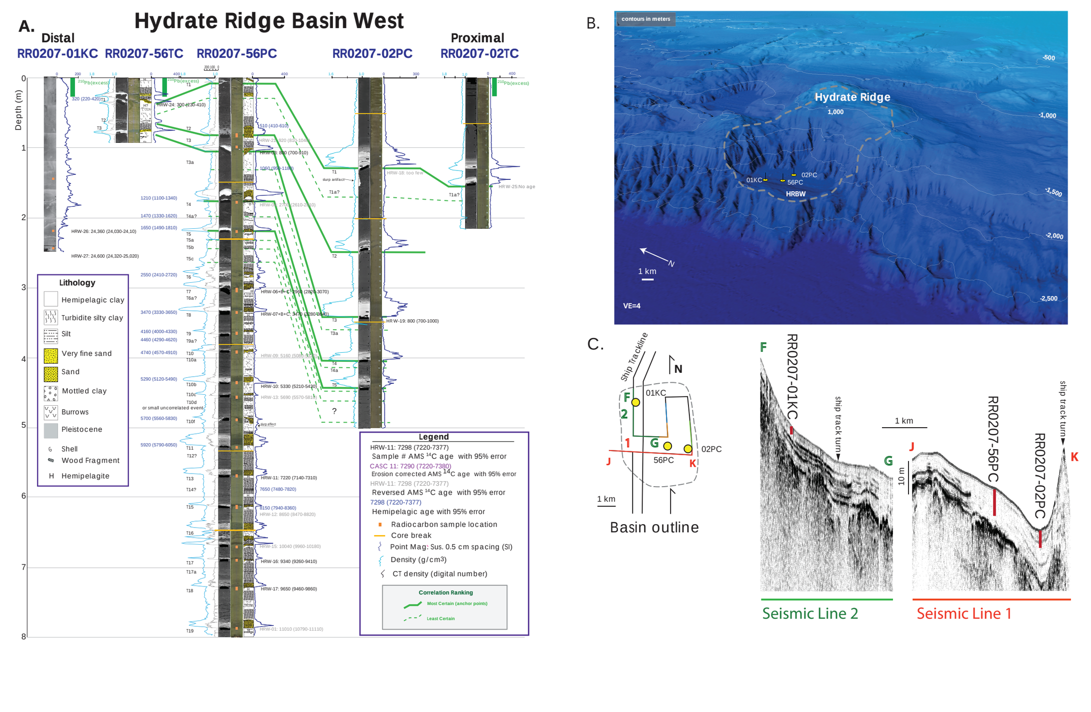
Sumatra Slope-Basin Cores



Sumatra slope basin cores RR0705-104PC and RR0705-103PC.

A. Stratigraphic correlations between these cores using lithology, CT, geophysical properties, and 14C data. Multi Sensor Core Log (MSCL) data are plotted beside RGB imagery and CT imagery that displays lower density material in darker grey and higher density material in lighter grey. Gamma density, CT density, point magnetic susceptibility, and loop magnetic susceptibility are plotted left to right as light blue, dark blue, dark red, and light red. Radiocarbon ages are calibrated and reported with 95% error as is true for all ages in this poster. "Repeated section" refers to strata that have been double cored. This happens when the core barrel is accidentally inserted into the sea floor twice or more, thus sampling the same sediments twice or more (104TC has double repeated section). B. Core sites are plotted as orange circles on compiled bathymetry data set described in the text (Ladage et al., 2006). Inset map shows location of large map in red (northern margin) and cores in main map are orange dots. **C**. 3.5 kHz CHIRP seismic data collected at core sites are processed in SioSeis and plotted in SeiSee (seismic envelope). Core locations are designated by a red line scaled to core length. The X axis for the seismic plots is not distance, but shot number. These seismic data were collected while the ship was staying on position during coring. **D**. Elevation is plotted versus distance across the basins for cores 104 and 103. Profile locations are plotted as orange lines in B.

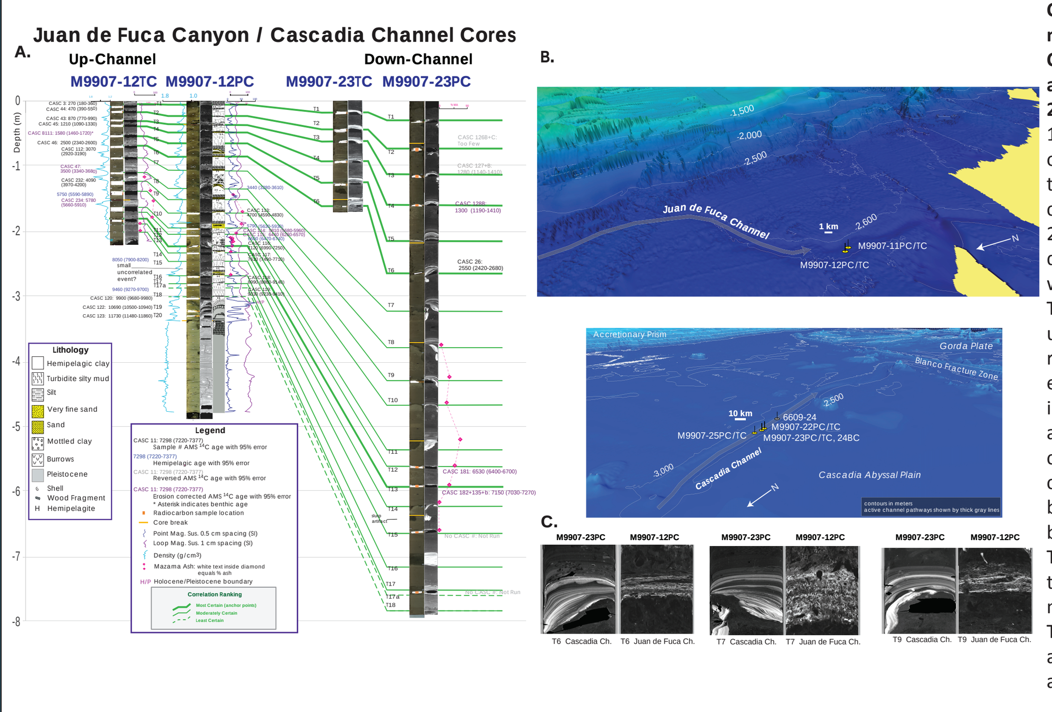
Hydrate Ridge Basin West



Cascadia slope basin cores at Hydrate Ridge West Basin: RR0207-01KC, 56PC/TC, and 02PC/TC.

A. Site-correlation diagram for Hydrate Ridge Basin West (HRBW) cores. Individual coarse pulses in these turbidites, 02PC/TC in particular, are well-defined, consistent with their proximal setting. MSCL data are plotted along with CT density: gamma density in light blue, CT density in black, and magnetic susceptibility in dark blue. Calibrated radiocarbon ages (Goldfinger et al, 2012) are reported with 95% error. 210Pb activity ("excess"), measured in some cores, shows to what depth recent sediments were deposited (approx. 150 years; Noller, 2000). **B**. Low angle oblique view of core sites. **C.** 3.5 kHz seismic data collected during transit for our coring cruise TN0909 are processed with Sioseis and the envelope is plotted in Seisee. Inset map: Track lines associated with seismic data are plotted with colors that match the seismic data. Core location is designated by a red line scaled to core length. Cores are plotted in yellow and basin is outlined as dashed grey line.

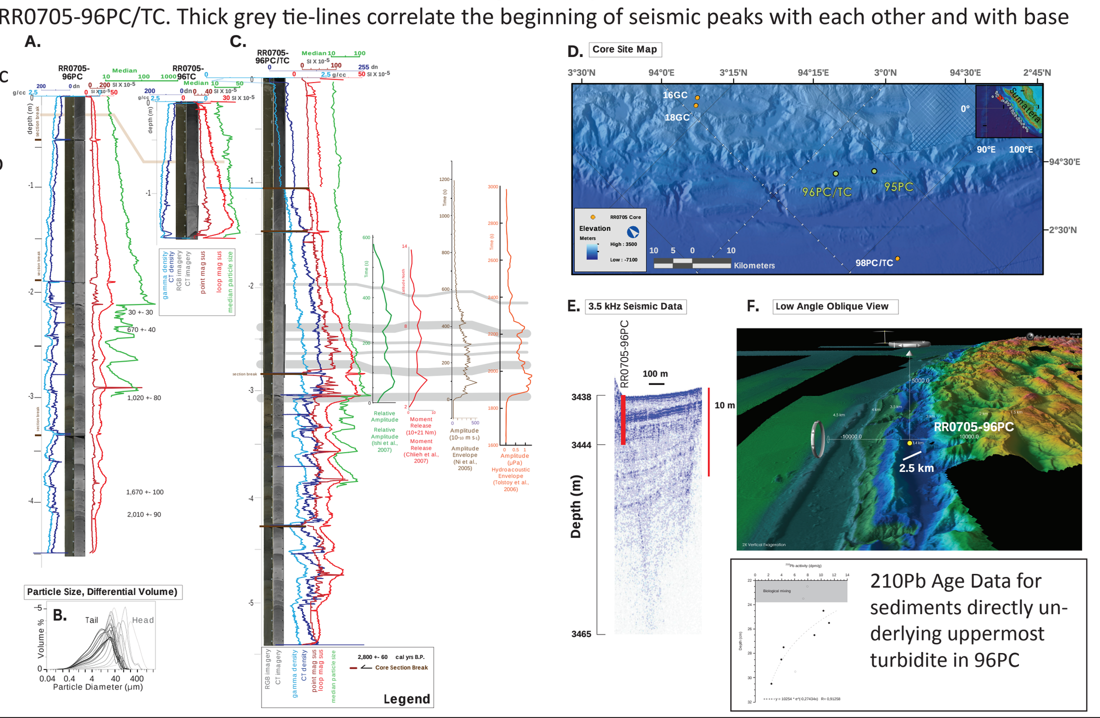
Juan de Fuca Canyon / Cascadia Channel Cores



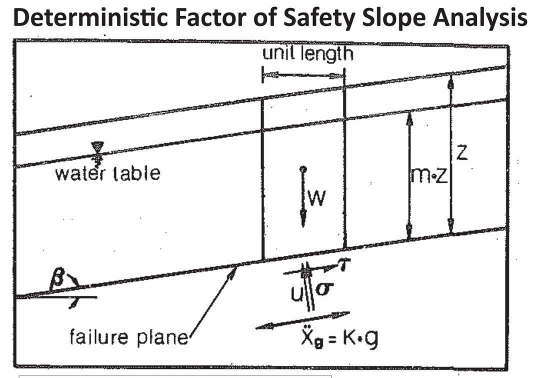
Cascadia trench: Juan de Fuca (JDF) channel (a tributary to Cascadia channel) and Cascadia channel cores MM9907-12PC and M9907-23PC/TC (Goldfinger et al., 2012). A. Correlation diagram for cores 12PC and 23PC. **B.** Low angle oblique view of core sites. Because the map is oblique, the scale bar is only relevant nearest the core locations. **C.** CT scan data from cores 23PC (Cascadia channel) and 12PC (Juan de Fuca channel) are compared for three well correlated turbidites T-6, T-7, and T-9. The JDF imagery is "flattened" to the upper and lower sand contacts of the corresponding Cascadia channel units. These examples show the relatively unchanged internal structure of these typical events after passing the confluence at Willapa channel and ~350 km of transport. JDF channel imagery is degraded significantly by numerous small gas evolution voids, but the structural similarity is still evident. The primary structure of two pulses and three pulses for T9 and T6, respectively, is matched by density and magnetic peaks. T7 shows more pulsing (~7) than is resolvable with the geophysical data, but it is apparent in both cores.

Sumatra slope basin cores with an expanded Holocene section.

A. RR0705-96PC is plotted with the same configuration as above. Median grain size data are plotted in green with 1 cm spacing. **B.** Particle size distribution data from sample locations at 10 cm spacing found in A are plotted by volume (%) vs. particle size (µm, log scale) with lines generally designating samples' depth where the lighter lines have a larger mean size and are generally lower in section. Differential volume displays the percent volume of each particle size. **C.** Core 96TC is scaled to 96PC and graphically spliced above 96PC to generate this composite core 96PC/TC. Moment release (vs. latitude) in red (Chlieh et al., 2007) and relative amplitude (vs. time) in green (Ishi et al, 2007), brown (Ni et al., 2005), and orange (Tolstoy and Bohnenstiehl, 2006) are scaled to match peaks in the loop ms data from composite core RR0705-96PC/TC. Thick grey tie-lines correlate the beginning of seismic peaks with each other and with base of peaks in the core geophysical data. Thin grey lines show secondary correlations (lower seismic energy and lower amplitude core geophysical data). **D.** Core site locations for cores RR0705-96PC/TC. Inset map shows location of large map in red (northern margin) and cores in main map are orange dots **E.** 3.5 kHz CHIRP seismic data collected at core sites are processed in SioSeis and plotted in SeiSee (seismic envelope). Core location is designated by a red line scaled to core length. **F.** Low angle oblique view of core site, designated by yellow dot. Due to nature of oblique maps, the scale is only relevant nearest the core location.

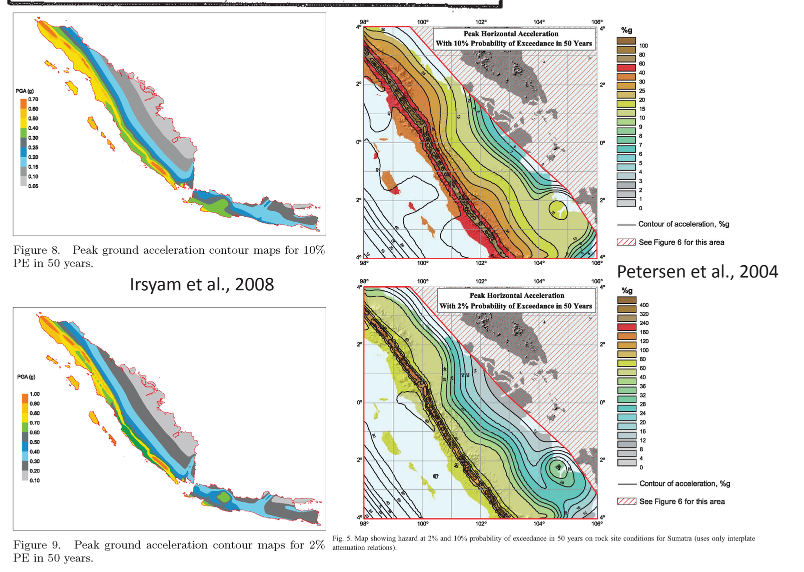


Deterministic Factor of Safety Slope Analysis



	Equation #[‡]	Seismic Force	Cohesion	Total Unit Weight	Water Unit Weight	Excess Pore Pressure	Angle of Internal Friction	Tangent Phi	Slide Thickness	Slide Thickness
Variable		Ah	c'	γ_t	γ_w	δu	ϕ	tanϕ	h	h
Units		g	kPa	pcf	pcf	kPa	degrees		m	m
									0.1	1
No Seismic	4	0	1.8[†]	98.67	62.45	na	34	0.675	all stable	stable < 19°
	5	0	0	98.67	62.45	na	34	0.675	stable < 34°	stable < 15°
Seismic	7	0	na	98.67	62.45	1.25	34	0.675	stable < 28°	stable < 14°
	7	0.1	na	98.67	62.45	1.25	34	0.675	stable < 24°	stable < 8°
	7	0.25	na	98.67	62.45	1.25	34	0.675	stable < 16°	all unstable
	7	1	na	98.67	62.45	1.25	34	0.675	all unstable	all unstable

‡ Hadj-Hamou and Kavazanjian, 1985
† Johnson et al., 2012



Irsyam et al., 2008

Petersen et al., 2004

in which γ_t = the total unit weight of the material; γ_w = the unit weight of water; Z = the depth of the assumed failure plane; mZ = the distance from the water table to the failure plane; and β = the slope angle. Combining Eqs. 1–3 the following equation for the static factor of safety FS_o is obtained:

Eq. 4

$$FS_o = \frac{c' + \gamma_t\left(1 - m\frac{\gamma_w}{\gamma_t}\right) z \cos^2\beta \tan\phi'}{\gamma_t \cdot z \cdot \cos\beta \cdot \sin\beta}$$

Assuming the soil to be cohesionless

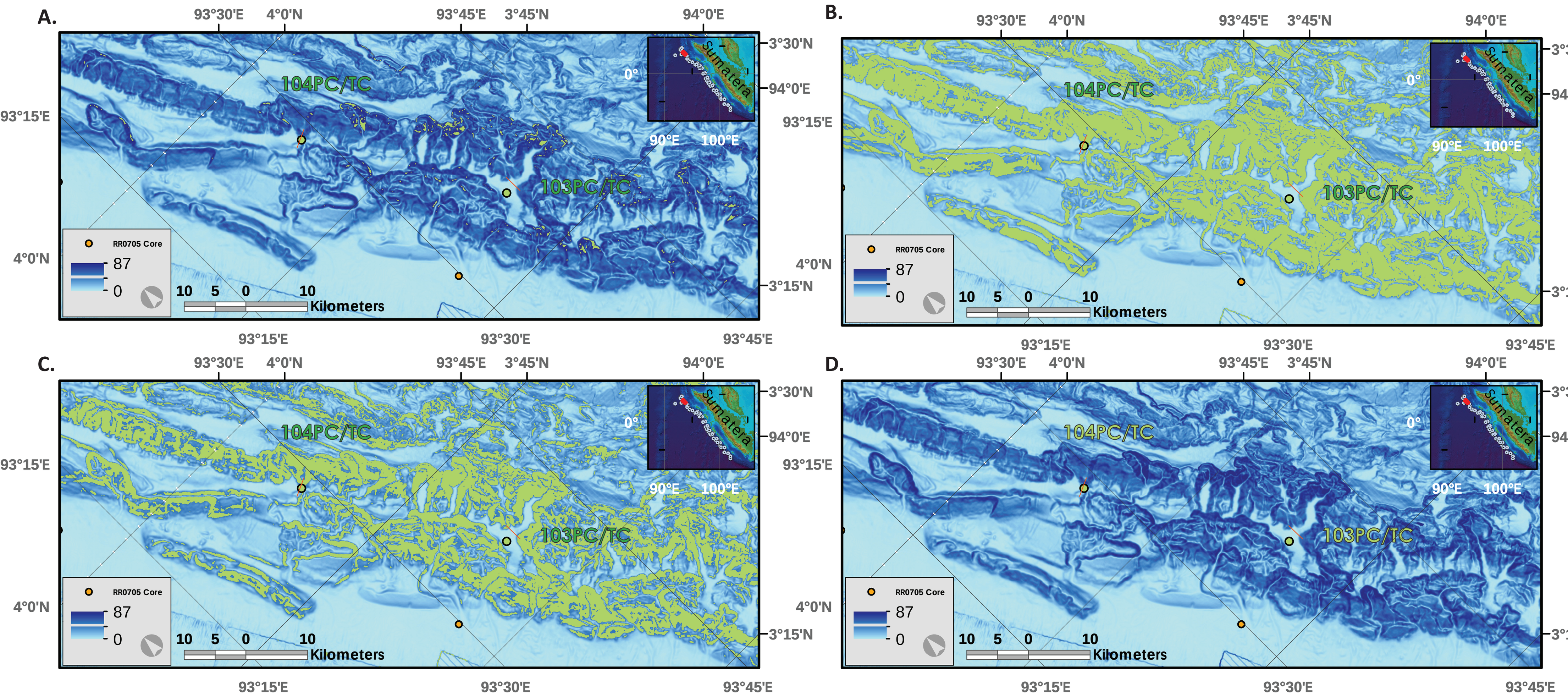
Eq. 5

$$FS_o = \left(1 - m\frac{\gamma_w}{\gamma_t}\right) \cdot \frac{\tan\phi'}{\tan\beta}$$

in which K = the acceleration in g's, ($1\ g = 9.81\ \mathrm{m/s^2} = 32.2\ \mathrm{ft/sec^2}$). If the increase in pore pressure along the failure plane due to the earthquake ground motions is Δu, and the effect of cohesion ignored, Eq. 4 becomes

Eq. 7

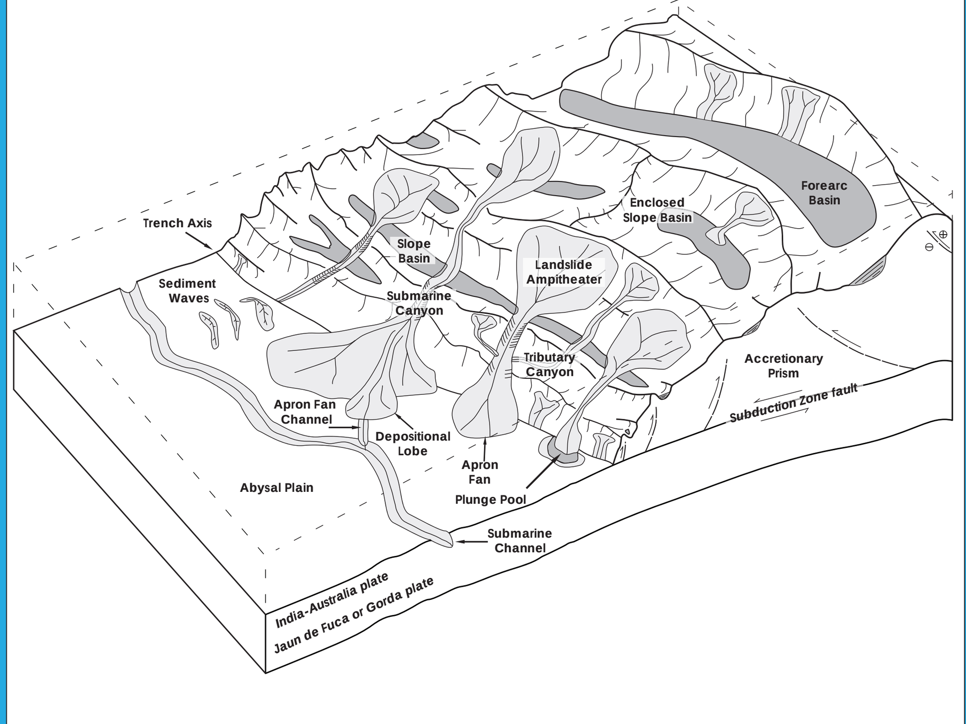
$$FS = \frac{\left[\left(1 - m\frac{\gamma_w}{\gamma_t}\right) z \cdot \gamma_t \cos^2\beta - \Delta u\right] \tan\phi'}{\gamma_t z \cos\beta \sin\beta + K\gamma_t z \cos\beta}$$



Deterministic analyses of the stability of gentle infinite slopes subject to seismically induced excess pore pressures and inertia forces are conducted using formulas developed by Hadj-Hamou and Kavanjian, 1985. Hadj-Hamou and Kavanjian (1985) rewrote classical equations for infinite slope stability to include excess pore (du) pressure and seismic acceleration (Ah).

Equations for the Factor of Safety (FOS) are developed that include these factors. Sediment geotechnical data from cores collected in the region (Sultan et al., 2009) are combined with in-situ measurements of marine sediments (Johnson et al., 2012) to calculate FOS given a range of factors (see table).

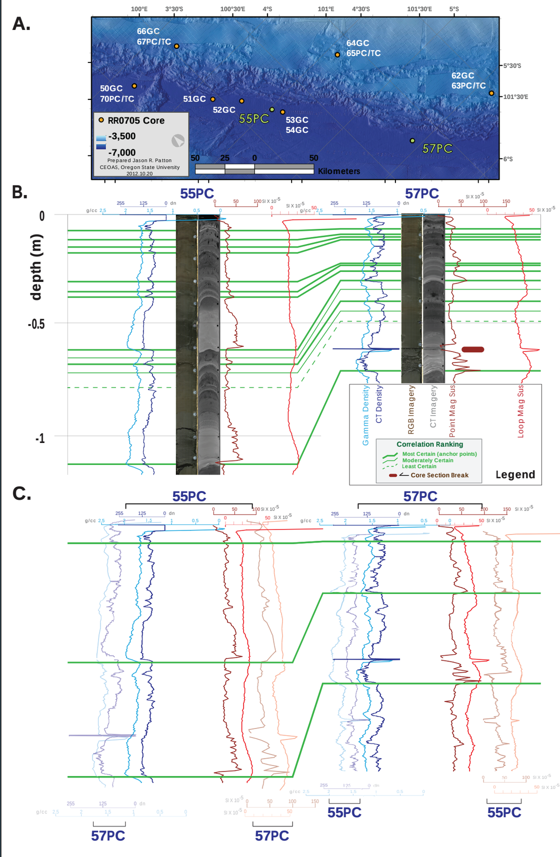
A. shows FOS analysis where slopes are stable < 28 deg. Regions in green are unstable (FOS < 1). **B.** FOS analysis where slopes are stable < 14 deg. **C.** FOS analysis where slopes are stable < 16 deg. **D.** Slope map of region surrounding cores RR0705-103PC/TC and RR0705-104PC/TC



Schematic illustration of geomorphic elements of subduction zone trench and slope sedimentary settings.

Submarine channels, submarine canyons, dune fields and sediment waves, abyssal plain, trench axis, plunge pool, apron fans, and apron fan channels are labeled here.

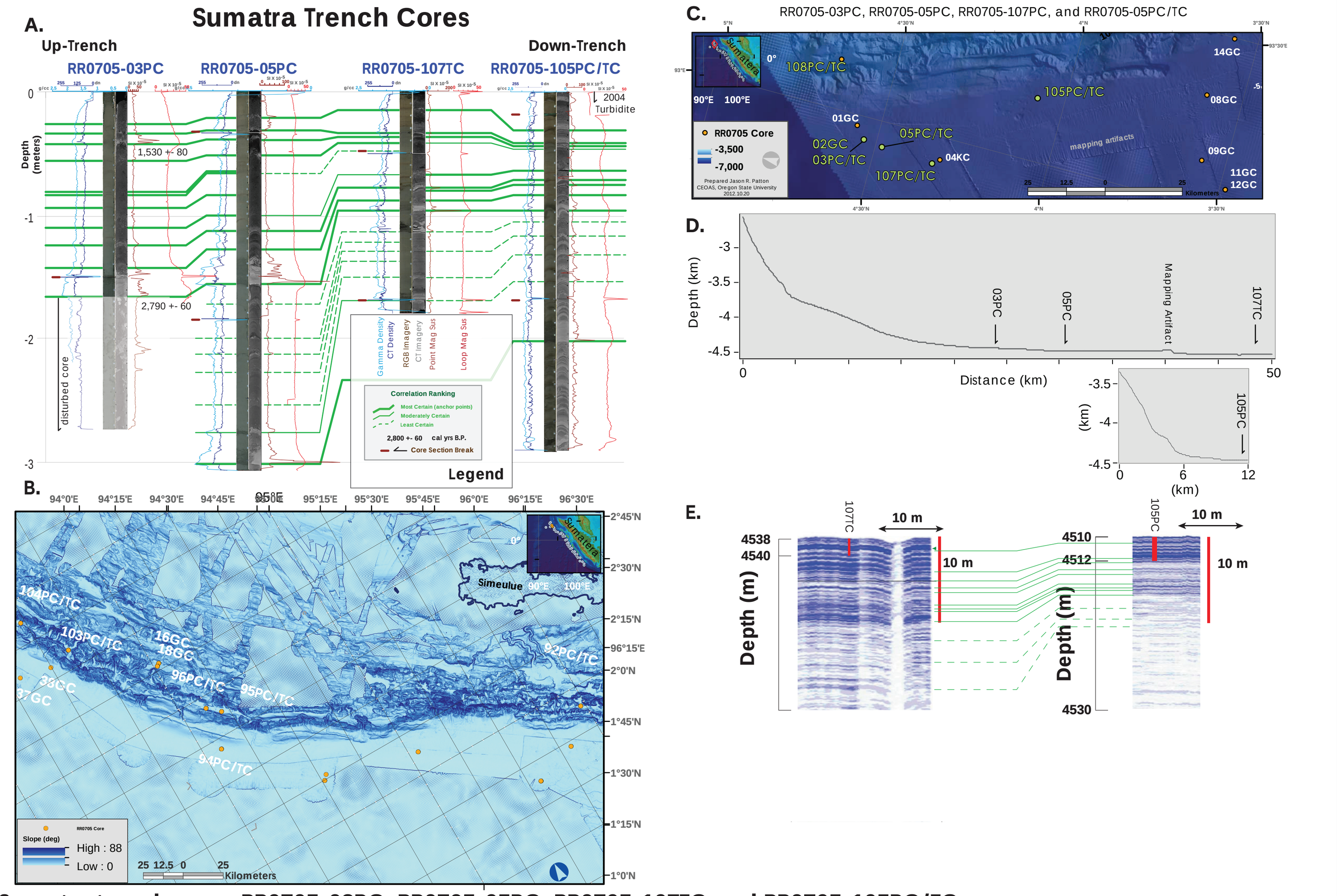
References



Correlation of sedimentary units using standard stratigraphic correlation techniques between cores RR0705-55PC and RR0705-57PC.

A. Bathymetric map with cores plotted as brown dots and depth contours with 500 m spacing. Cores 55PC and 57 PC are located in the trench approximately 120 km from each other. **B.** Stratigraphic correlations between these cores using lithology, CT, and geophysical properties. Multi Sensor Core Log (MSCL) data are plotted beside RGB imagery and CT imagery that displays lower density material in darker grey and higher density material in lighter grey. Gamma density, CT density, point magnetic susceptibility, and loop magnetic susceptibility are plotted left to right as light blue, dark blue, dark red, and light red. The certainty of any individual correlation is ranked and designated by line symbology. **C.** MSCL data for core 57PC is "flattened" to stratigraphic horizons in core 55PC on the left, and 55PC is flattened to 57PC on the right. The core data being flattened is transparent and plotted on the outside of the core data they are being flattened to. The unflattened core data are scaled at the same vertical scale as in B.

Sumatra Trench Cores



Sumatra trench cores RR0705-03PC, RR0705-05PC, RR0705-107TC and RR0705-105PC/TC.
A. Cores are plotted in same configuration as above. Radiocarbon ages are displayed with 95% error. These ages are from below correlated turbidites in the slope core 108PC/TC. **B.** Low angle oblique view of core sites. Flow pathway from landslide source area to core sites is designated by a grey dashed line. Cores sites are plotted as yellow dots. **C.** Map showing core locations. **D.** Flow pathway profiles as shown in B are plotted with elevation versus distance. Core locations are labeled. **E.** 3.5 kHz CHIRP seismic data collected at core sites are processed in SioSeis and plotted in SeiSee (seismic envelope). Acoustically opaque sediments are marked by a green arrow. Core locations are designated by a red line scaled to core length. The profile is smaller than the dot that designates the core location in B.