PRELIMINARY COMPARISON OF DECEMBER 26, 2004 TSUNAMI RECORDS FROM SE INDIA AND SW THAILAND TO PALEOTSUNAMI RECORDS OF OVERTOPPING HEIGHT AND INUNDATION DISTANCE FROM THE CENTRAL CASCADIA MARGIN, USA

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ABSTRACT

Measurements of recent tsunami runup and inundation from India and Thailand are compared to corresponding proxy records of paleotsunami sand deposition in the central Cascadia margin, Oregon. Runup and inundation measurements of the December 26, 2004 tsunami are reported from 10 localities each in SE India and SW Thailand. Representative flooding elevations and inundation distances are as follows for SE India; Chenai (2-3m MSL; 150 m distance), Devanaampatnam, (2-4 m MSL; 150-340 m distance) and Nagapattinam (4-5 m MSL; 800 m distance), and for SW Thailand; Kao Khaw Beach (7.2 m MSL; >500 m distance), Khaw Lak Princess (8.2 m MSL; >2000 m distance), and Nangtong (10 m MSL; >2000 m distance). Tsunami sand transport occurred in mean flow depths of 0.4-1.3 m where flooding overtopped foredunes and beach plains in the SE Indian sites. By comparison, ovetopping flows in proximal settings (100-200 m from the beach) in SW Thailand ranged from 2 to 5 m in depth. The maximum transport distances of tsunami sand, *i.e.*, sand sheet extent, were quite variable within and between tsunami inundation localities in the SE Indian Ocean. Contiguous sand sheets were not present at some of the SE Thailand tsunami localities.

Prehistoric tsunami runup in the central Cascadia margin has been estimated from tsunami sand deposits that were produced by four paleotsunami between 0.3 and 1.3 ka. The sand deposits are thought to represent minimum overtopping and inundation distances. The overtopping records come from wetlands developed on previously uplifted coastal terraces (6-8 m MSL), and in coastal plains fronted by abandoned, *i.e.*, stabilized, dune ridges (4-8 m MSL). For this study we focus on five Cascadia localities including Cannon Beach, Rockaway, Neskowin, Salishan, and Ona in the northern Oregon coast. The ovetopping evidence yields onshore tsunami heights of at least 6-8 m MSL. Sand sheet deposition from the 1.3 ka paleotsunami at the Neskowin and Ona wetlands exceeds 1.3 km in shore-normal distance. Sand sheets from the three remaining tsunami reach 500-900 m in overland distance from the beach. The tsunami sand sheets are thought to likely

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underestimate maximum inundation of the central Cascadia tsunami, but do provide minimum estimates of flooding distance.

Preliminary comparisons of the Cascadia paleotsunami deposits and the SE Asian tsunami records tentatively suggest a similar scaling between the near-field tsunami in the central Cascadia margin and the 2004 Sumatra-Andaman tsunami runup in SW Thailand. Flow velocities, structural damage, and potential mortalities from a future central Cascadia event might be roughly comparable to the SW Thailand experience.

Introduction

The tragic Mw 9.4 earthquake and resulting tsunami from the December 26, 2004 Sumatra-Andaman rupture (Stein and Okal, 2005) provides potential modern analogs to prehistoric ruptures of the Cascadia margin (Figure 2). In this paper we examine proxies for tsunami runup at observed localities in SE India and SW Thailand (Peterson *et al.*, 2005, Yeh *et al.*, 2005; Francis *et al.*, 2005), and at paleotsunami deposit sites on the northern Oregon coast (Peterson *et al.*, 1995; Alhadeff *et al.*, 1998; Schlichting and Peterson, 2005). These proxies include geologic records of distinctive sand sheets deposited by the modern tsunami and paleotsunami. The modern 2004 tsunami yielded both the geologic records of sediment transport and corresponding ephemeral data on runup height, *i.e.*, maximum still water (MSW) height, and flooding distance, *i.e.*, maximum inundation distance. The Cascadia paleotsunami are currently lacking constraints on runup height and maximum inundation distance.

Microfossil, geochemical, and debris-caps have been proposed for use to establish paleotsunami records of MSW height and/or maximum inundation distance in the Cascadia marign (Hutchinson, *et al.*, 1997; Abramson, 1998; Schlichting, 2000). Rigorous tests of these techniques have not been completed for overland tsunami runup in proximal settings, *i.e.*, back-barrier beach plains and low marine terraces. At the present time only the tsunami sand sheet deposition by barrier over-topping and high-velocity inundation provide established constraints on overland paleotsunami flooding in proximal settings.

We compile minimum overtopping heights and minimum inundation distances from the central Cascadia margin based on existing reports of tsunami sand sheet deposition. These minimum-inundation proxies are compared to measured runup heights and maximum inundation distances of the December 26, 2004 tsunami in SE Indian and SW Thailand. Such calibrations of paleotsunami runup should permit some rough approximations of mortality and structural damage that could accompany Cascadia near-field tsunami in the future.

Results

India and Thailand

Ten localities in the Tamil-Nadu coastline of SE India (Figure 1 and Table 1) were surveyed for runup flooding and sediment deposition from the December 26, 2004 tsunami (Yeh *et al.*, 2005). Maximum still water (MSW) height ranged from ~3.0 to ~5.0 m above the Indian datum, *i.e.*, above approximate mean sea level (MSL) (Table 1). Maximum inundation ranged from 150 to 800 m in shore-normal distance from the beach swash zones. Measured tsunami flow depth, *i.e.*, the difference between MSW height and the ground surface elevation, range from 0.4-2.0 m depth in the SE Indian study localities.

Table 1: Inundation Parameters for the December 26, 2004 Tsunami at Selected Sites in SE India and SW Thailand

Locality	Latitude	Run up Height (m MSL)[1]	Inundation Distance (m)[2]	Ground Elevation (m MSL)[3]	Flow Depth (m)[4]
India					
Pulicat	13.384° N	2.7	160	2.3	0.4
Chennai	13.021° N	2.9	150	2.1	0.8
Kovalam	12.791° N	3.4	180	2.1	1.3
Kalpakkam	12.505° N	3.1	360	2.4	0.7
Periakialapet	12.029° N	3.7	170	3.7	--
N.Devanaapatnam	11.749° N	2.3	160	1.8	0.5
S.Devanaapatnam	11.740° N	--	340	1.5	--
Parangipettai	11.513° N	--	600	1.8	--
Tarangambadi	11.027° N	4.4	400	3.5	0.9
Nagapattinam	10.775° N	4.3	800	2.3	2.0
Thailand					
Ko Kao Khaw					
Kao Khaw Beach	08.891° N	7.2	>500	~5	~2
Unnamed	08.803° N	7.9	>1000	~4	~3
Andaman Princess	08.743° N	7.5	>1000	~5	2.5
Khaw Lak Princess	08.704° N	8.2	>2000	~6	~2
Khao Lak					
Bang Niang	08.663° N	10	>2000	~5	~5
Nangtong	08.637° N	10	>2000	~6	~4
Army Relief Cent.	08.627° N	10	>1500	~7	~3
Phuket					
Bang Tao	07.949° N	8.0	>500	~4	~4
Kamala	07.946° N	8.0	>500	~5	~3
Royal Thai Rest.	07.884° N	5.0	>100	~3	~2

1. Runup Height, *i.e.*, maximum still water elevations, as given in meters above approximate, mean sea level (MSL) are taken from mud lines on standing structures.

2. Inundation distances, as given in meters (m) are taken from maximum landward extent of tsunami debris, *i.e.*, floatsam, in shore-normal distance from the beach.

3. Ground Elevation is measured (SE India) or estimated from photographs (SW Thailand) at proximal distances of 50-100 m from the beach. The ground elevations represent overtopping points at abandoned foredune ridges or beach plains.

4. Flow Depth is taken from the difference between measured runup height and ground elevation. This value represents the mean flow depth at the over-topping point, as calculated from maximum still water depth and proximal ground elevation. Surge elevations, and corresponding surge depths are greater than mean still water elevations. Flow depth of surge (not still water depth).

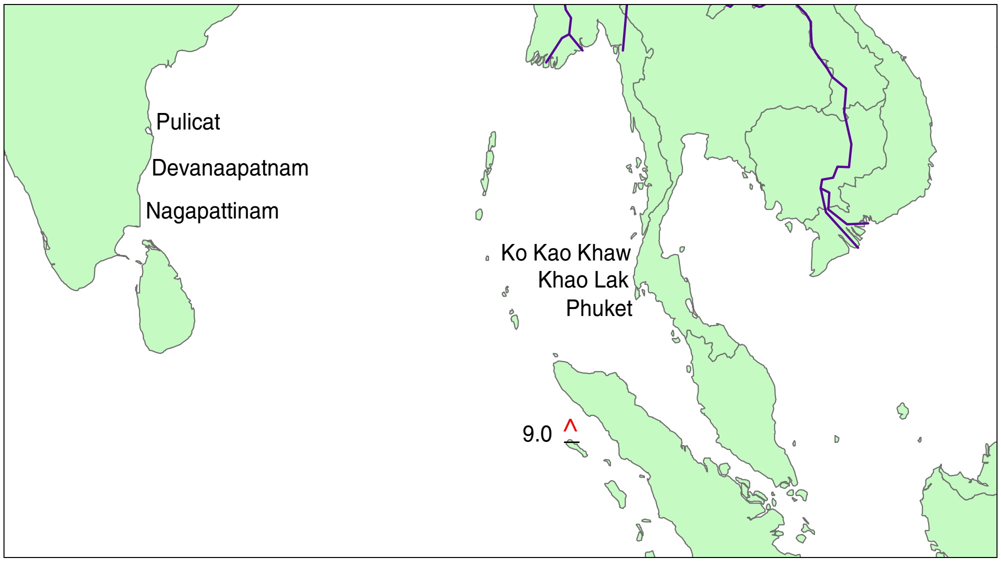

Figure 1. Location of places discussed in the text, and in tables 1 & 2. The location of the 2004 earthquake epicenter is shown with a star off the coast of NW Sumatra. This point was the initiation of rupture, which propagated north to the Andaman Islands.

Three of the SE Indian localities, at Chenai, Devanaampatnam, and Nagapattinam, are selected for comparison to the central Cascadia paleotsunami records. These three localities each contain 1) relatively-flat, low topographic profiles (1-2 m MSL) behind low foredunes, and 2) slightly raised profiles (3-5 m MSL) developed on higher stabilized dunes (Peterson *et al.* 2005). Tsunami flow depth (0.4-1.3 m), relative flow competence (sand or cobble transport), and associated structural damage are shown for proximal settings, *i.e.*, ~ 100m distance from the beach (Table 2). The structural damage ranged from none (none), to damaged details (details), to collapsed unreinforced masonry (URM) in ascending order of impact. The structural damage scaled up with increasing tsunami flow depth, increasing maximum inundation distance, and increasing flow competence in the representative SE Indian localities.

Tsunami runup height, flow depth, and tsunami impact are reported for ten localities in the Ko Kao Khaw, Khao Lak, and Phuket areas of SW Thailand (Figure 1). Runup height ranged from 5 to 10 m MSL in the ten localities (Table 1). Inundation distances ranged from >500 to >2,000 m in shore-normal distance from the beach, as based on observed tsunami flotsam/debris lines and/or saltwater wilted vegetation. Water columns of overtopping flows ranged from 2 to 5 m depth in the proximal settings.

Three representative SW Thailand localities are evaluated for tsunami impact. These localities are developed on relatively-flat beach plains of 4-6 m elevation above sea level. Vegetation is sparse in the proximal settings, but URM and RCS in residential and commercial developments are common in the selected localities. Relative flow competence at the three sites is characterized by boulders, *i.e.*, the largest of the remobilized clast sizes. The remobilized boulder-size clasts were derived from collapsed URM but were entrained for 10's meters by tsunami flow. The photographed structural damage ranges from Displaced to damaged reinforced concrete structures (RCS) in the proximal settings of the three localities. The sparsity of heavy vegetative debris suggests that the extensive structural damage at these localities resulted directly from the tsunami flow forces.

Table 2: Representative Tsunami Impact Localities in SE India and SW Thailand

Locality	Latitude	Inundation Distance (m)	Proximal Settings, 100 m Distance Flow Depth[1] (m)	Maximum Clast Size[2] (Type)	Structural Damage[3] (Type)
India					
Chennai	13.021° N	150	0.8	Sand	None
N. Devanaapatnam	11.749° N	160	0.5	Sand	Details
Nagapattinam	10.775° N	800	2.0	Cobble	URM
Thailand					
Kao Khaw Beach	08.891° N	> 500	~2	Boulder	Displaced
Khaw Lak Princess	08.704° N	> 2000	~2	Boulder	RCS
Nangtong	08.637° N	> 2000	~4	Boulder	RCS

1. Flow Depth is taken to be the difference between runup height and ground surface (Table 1). It represents the depth of the mean or sustained flow. Spatial and/or temporal variation in flow depth, *i.e.*, surges, are reported from the SE Indian tsunami localities (Peterson *et al.*, 2005).
2. Maximum Clast Size of transported or remobilized clasts, *i.e.*, sand, cobble, or boulder, are used as relative indicators of flow competence in proximal settings, *i.e.*, ~100 m distance from the beach.
3. Structural damage is identified by type, *i.e.*, damage of siding or roofing (Details), collapse of unreinforced masonry (URM), displaced concrete structures (Displaced), and failure of reinforced concrete structures (RCS).

For the India and Thailand tsunami analogs we do not use the extent of tsunami sand sheets to characterize the flooding inundation. In SE India the landward extents of the tsunami sand sheets ranged from 37 to 80 percent of the maximum inundation distances (Peterson *et al.*, 2005). In SW Thailand the tsunami sand sheets were relatively thin and discontinuous in the proximal settings and patchy or non-existent in the distal settings. The thin, discontinuous sand sheets in the proximal settings might reflect supercritical flow velocities, and/or limited nearshore sand availability in the SW Thailand localities. Sand dilution, by settling and entrapment during transport over long distances (1,000-2,000 m), might account for the lack of sand sheets in the distal settings. The sand sheets do provide reliable evidence of tsunami flow overtopping in proximal localities of both SE India and SW Thailand, but under represent the maximum inundation distances in distal settings of both study areas.

Cascadia Margin

Five localities have been mapped for paleotsunami sand sheet deposition in Northern Oregon, in the central Cascadia margin (Figure 2). These localities contain wetlands developed on back-barrier beach plains or flood plains (1.5-3 m above present MSL) at Cannon Beach, Rockaway, Neskowin, Salishan, and Ona, and/or on low marine terraces (6-7 m MSL) Salishan, and Ona (Table 3). The wetlands are fronted by stabilized dune ridges that contain paleosols at 6-8 m above present MSL. The paleosols indicate dune abandonment and stabilization prior to the arrival of non-native dune grasses that increased the height of some modern foredunes. We use the evidence of paleotsunami sand deposits on the landward side of the paired stabilized foredune ridges or on the low marine terraces to establish tsunami overtopping. The low ridge is used to establish the landward extent of paleotsuami sand deposition, and the high ridge or marine terrace is used to establish minimum overtopping elevations.

The stabilized foredune surfaces, *i.e.*, paleosol elevations, are used to estimate minimum heights of overtopping. Dating of the paleodune surfaces by TL or OSL methods is pending future funding. For this paper we only discuss the last four Cascadia tsunami events, which date from 0.3 to 1.3 ka (Schlichting, 2000). Tsunami overtopping heights ranged from 6 to 8 m above MSL in the study area. Inundation distances ranged from <300 to greater than 1,300 m in shore-normal distance from the present beaches. These paleotsunami sand deposits represent limiting conditions, *i.e.*, minimum values, of runup height and inundation distance for the four Cascadia events.

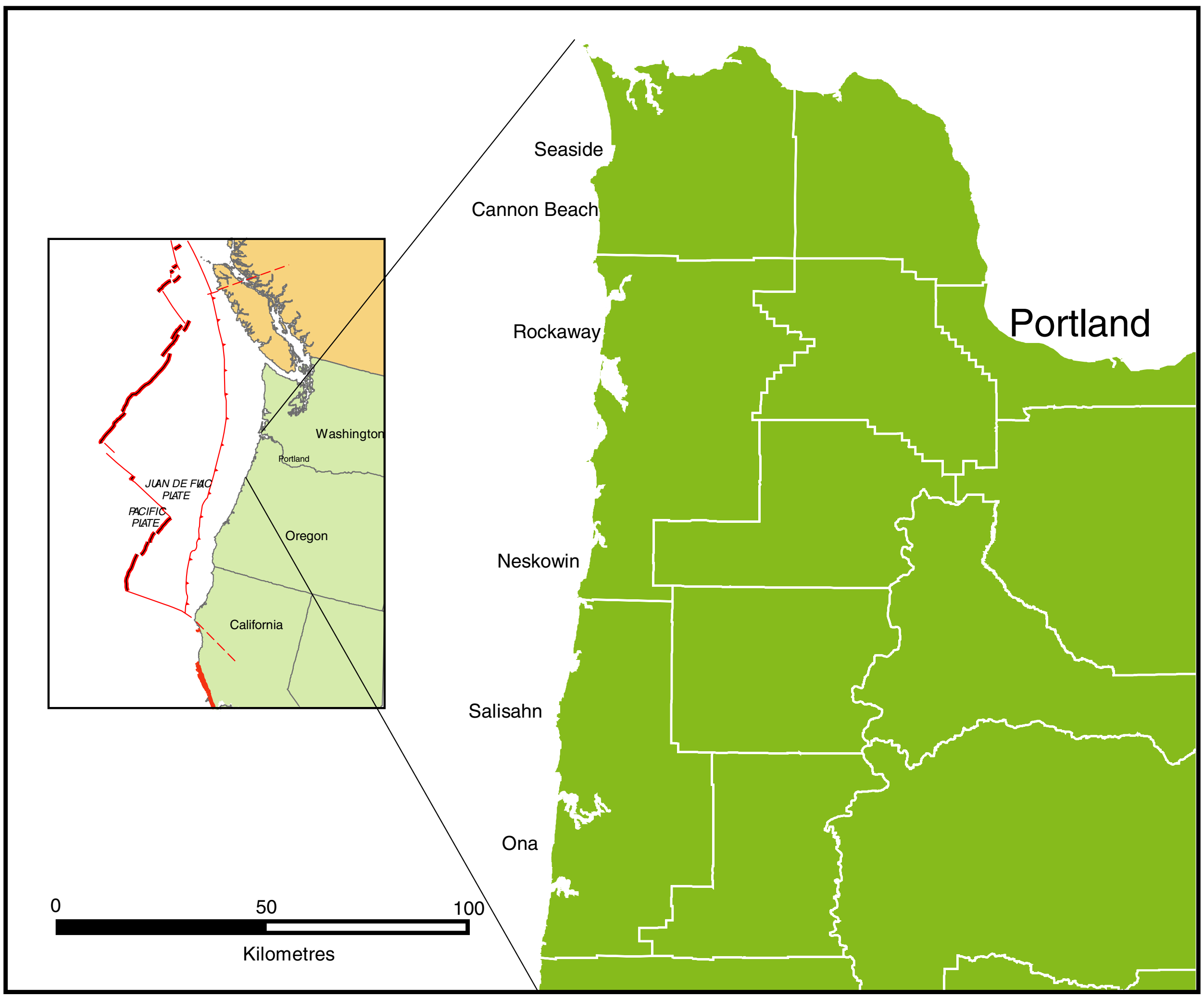

Figure 2. Location of places discussed in the text, and in table 3. The sites in table 3 are on the Northern Oregon coast, which is in the central Cascadia Margin

Table 3 . Cascadia Paleotsunami Overtopping and Inundation Records from 0.3-1.3 ka

			Tsunami Sand Sheet Deposition		
Region Locality / Site	**Latitude**	**Cascadia Event Age (ka)**	**Overtopped Dune Ridge/ Terrace**	**Ridge/Terrace Elevation (m MSL)**	**Maximum Transport Distance (m)**
Cannon Beach	45.891° N				
High Ridge		0.3	Dune Ridge	10-15	No Record
		0.8	Dune Ridge	10-15	No Record
		1.1	Dune Ridge	10-15	No Record
		1.3	Dune Ridge	10-15	No Record
Low Ridge		0.3	Dune Ridge	5	500
		0.8	Dune Ridge	5	800
		1.1	Dune Ridge	5	900
		1.3	Dune Ridge	5	1,100
Rockaway	46.613° N				
High Ridge		0.3	Dune Ridge	7-8	No Record
		0.8	Dune Ridge	7-8	400
		1.1	Dune Ridge	7-8	600
		1.3	Dune Ridge	7-8	>700
Low Ridge		0.3	Dune Ridge	6	500
		0.8	Dune Ridge	6	600
		1.1	Dune Ridge	6	700
		1.3	Dune Ridge	6	>700
Neskowin	45.106° N				
High Ridge		0.3	Dune Ridge	7	No Record
		0.8	Dune Ridge	7	900
		1.1	Dune Ridge	7	900
		1.3	Dune Ridge	7	>1000
Low Ridge		0.3	Dune Ridge	5	800
		0.8	Dune Ridge	5	1000
		1.1	Dune Ridge	5	1,100
		1.3	Dune Ridge	5	>1,300
Salishan	44.891° N				
		0.3	Terrace	8	No Record
		0.8	Terrace	8	No Record
		1.1	Terrace	8	>300
		1.3	Terrace	8	>300
		0.3	Dune Ridge	6	>300
		0.8	Dune Ridge	6	?
		1.1	Dune Ridge	6	>300
		1.3	Dune Ridge	6	>300

Table 3, ctd.

Region Locality / Site	Latitude Decimal Degrees	Cascadia Event Age (ka)	Tsunami Sand Sheet Deposition: Overtopped Dune Ridge/ Terrace	Ridge/Terrace Elevation (m MSL)	Maximum Transport Distance (m)
Ona	44.504° N				
		0.3	Terrace	7	No Record
		0.8	Terrace	7	?
		1.1	Terrace	7	360
		1.3	Terrace	7	>500
		0.3	Ridge	4	750
		0.8	Ridge	4	>1000
		1.1	Ridge	4	>1000
		1.3	Ridge	4	>1,300

Conclusions

Paleotsunami deposits from the last four Cascadia earthquakes (0.3-1.3 ka) serve as proxies for minimum values of tsunami runup height and inundation distance in the central Cascadia margin. Inundation distances in particular are likely to be underestimated from the extent of paleotsunami sand sheets in some settings. The minimum estimates of paleotsunami runup height (6 -8 m MSL) and shore-normal inundation (500-1,300 m distance) are similar to the recent (December 26, 2004) Sumatra-Andaman tsunami in SW Thailand. Three of the four central Cascadia paleotsunami were substantially greater in runup height and inundation distance than the recent tsunami in the SE India localities. The overtopping elevations of at least two of the Cascadia paleotsunami (> 8 m MSL) would yield flow depths of at least three meters in beach plain communities that average about 5 m MSL. Scaling from the SW Thailand tsunami experience would suggest substantial structural damage and mortality from a future Cascadia tsunami in these coastal communities.

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