EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2011)

Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.2126

Evaluation of the use of paleotsunami deposits to reconstruct inundation distance and runup heights associated with prehistoric inundation events, Crescent City, southern Cascadia margin

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Received 25 January 2010; Revised 17 November 2010; Accepted 29 November 2010

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Earth Surface Processes and Landforms

ABSTRACT: Historic- and prehistoric-tsunami sand deposits are used to independently establish runup records for tsunami hazard mitigation and modeled runup verification in Crescent City, California, located in the southern Cascadia Subduction Zone. Inundation from historic (1964) farfield tsunami (~5–6 m runup height) left sand sheet deposits (100–200 m width) in wetlands located behind a low beach ridge [3–4 m elevation of the National Geodetic Vertical Datum of 1988 (NAVD88)]. The most landward flooding lines (4·5–5 m elevation) in high-gradient alluvial wetlands exceed the 1964 sand sheet records of inundation by 1–2 m in elevation. The most landward flooding in low-gradient alluvial wetlands exceed the corresponding sand sheet record of inundation distance by 1000 m. Nevertheless, the sand sheet record is an important proxy for high-velocity inundation. Sand sheet deposition from the 1964 historic tsunami closely corresponds to the landward extent of large debris transport and structural damage in the Crescent City waterfront. The sand sheet deposits provide a proxy for maximum hazard or 'kill zone' in the study area.

Six paleotsunami sand sheets (0·3–3 ka) are recorded in the back-ridge marshes in Crescent City, yielding a ~450 year mean recurrence interval for nearfield Cascadia tsunami. Two paleotsunami sand deposit records, likely correlated to Cascadia ruptures between 1·0 and 1·5 ka, are traced to 1·2 km distance and 9–10 m elevation, as adjusted for paleo-sea level. The paleotsunami sand deposits demonstrate at least twice the runup height, and four times the inundation distance of the farfield 1964 tsunami sand sheet in the same marsh system. The preserved paleotsunami deposits in Crescent City are compared to the most landward flooding, as modeled by other investigators from a predicted Cascadia (~ Mw 9) rupture. The short geologic record (~1·5 ka) yields slightly lower runup records than those predicted for the modeled Mw 9 rupture scenario in the same marsh, but it generally verifies predicted maximum tsunami runup for use in the planning of emergency response and rapid evacuation. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: tsunami deposits; runup height; inundation distance; recurrence interval; Cascadia margin

Introduction

Geologic records of tsunami inundation in Crescent City, California (Figure 1) are presented here following recent predictions of nearfield tsunami runup in the southern Cascadia margin. There is widespread interest in using geologic records of paleotsunami deposition to establish inundation from prehistoric events. For example, paleotsunami deposits are reported to record prehistoric inundation events in Japan (Fujiwara *et al*., 1999), the North Sea Shetland Islands (Bondevik *et al*., 2005) and Greece (Scheffers *et al*., 2008), among others. These studies demonstrate anomalous strong currents in coastal settings, but do not establish maximum runup lines. There is uncertainty about the accuracy of using geologic records to establish maximum tsunami runup and flow conditions. Both criteria are important to tsunami evacuation strategies (Dengler, 2006; Kelley *et al*., 2006).

In the absence of local historical tsunami events the paleotsunami records take on a greater role in establishing potential tsunami hazard. For example, portions of subduction zones can vary in the distributions of coseismic- and aseismic-slip along the megathrust, as proposed for the Hikurangi margin in New Zealand (Wallace *et al*., 2010). The frequency and magnitude of coseismic ruptures, as predicted from seismology and other fields, need to be directly tested by the local record of prehistoric tsunami inundation, before large expenditures are made for the mitigation of potential tsunami hazard.

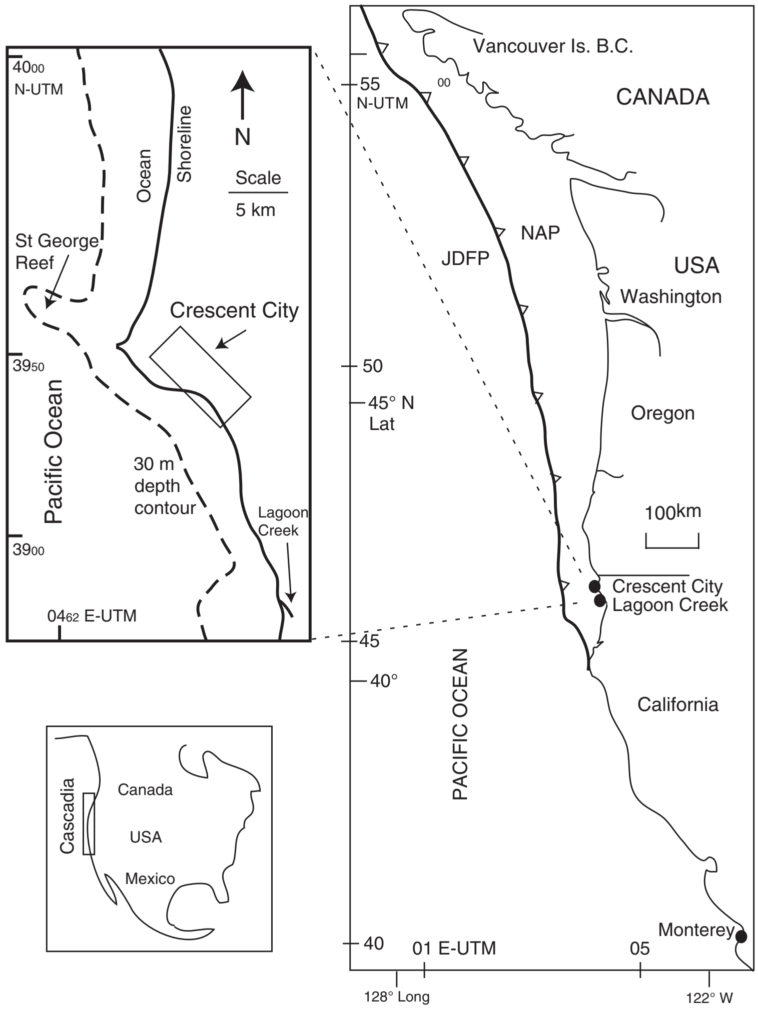

Figure 1. Map of Crescent City study area (boxed and inset) near the south end of the Cascadia subduction zone, West Coast of North America. The surface exposure of the megathrust fault (bold line) is shown between the subducting Juan De Fuca Oceanic Plate (JDF) and the North American Continental Plate (NAP). Map coordinates are in latitude and longitude (degrees) and in UTM northing and easting (meters).

In this study the preserved geologic records of tsunami flood deposition in Crescent City are compared to (1) historic tsunami inundations (Magoon, 1966; Dengler and Magoon, 1966), (2) modeled inundations based on nearfield rupture scenarios (Uslu *et al.*, 2007), and (3) waterfront settings exposed to mobilization of large debris by tsunami surges. The first sand sheet deposits to be linked to paleotsunami in the southernmost Cascadia margin were found in marshes and ponds located behind low beach ridges in Crescent City. However, the focus of paleotsunami investigations shifted 18 km south to Lagoon Creek, California (Figure 1) due to superior preservation of paleotsunami deposits in an elongate pond and pallustrine marsh there (Abramson, 1998; Garrison-Laney, 1998). The return of tsunami deposit investigations to Crescent City is motivated by recent recognition of paleotsunami hazard from the mobilization of large debris (Peterson *et al.*, 2006), and by opportunities to compare the geologic records of tsunami deposition against modeled runup lines for the locality (Uslu *et al.*, 2007).

The results presented here demonstrate overland inundation records from tsunami that inundated stable shorelines of the southern Cascadia margin (Figure 1). Such records have been reported from the central Cascadia margin (Peterson *et al.*, 2008, 2010a, 2010b), but not from the southernmost Cascadia margin. Comparisons of inundation frequency from tsunami should help to direct mitigation strategies for vulnerable communities throughout the region (Dengler, 1998). The comparison of numerically-modeled runup predictions with geologic records of surge inundation should have broad application in other coastlines that are susceptible to tsunami or storm surge.

In this paper several procedures are demonstrated for extending proximal paleotsunami records from back-beach lagoons and marshes to alluvial floodplain wetlands. Such alluvial floodplain settings provide the (1) mud hosting deposits, (2) landward distance, and (3) vertical gradient that are needed to record the limits of paleotsunami runup, as established from preserved paleotsunami sand sheets. The alluvial wetland records of paleotsunami sand deposition are briefly contrasted with paleotsunami records from other settings including, headland erosion features (Bryant *et al.*, 1992), anomalous gravel deposits (Nichol *et al.*, 2007), and displaced marine shell deposits (Fujiwara *et al.*, 2003). Paleotsunami sand deposits in alluvial floodplain settings provide unique opportunities for establishing long-term records of tsunami runup hazard in exposed communities.

Records of Paleotsunami in Lagoon Creek

Paleotsunami records are well preserved in Lagoon Creek, California (Figure 2) located 18 km south of the Crescent City study locality. Six distinct sand sheets are hosted in peaty mud that date back to ~3 ka (Abramson, 1998). Several of the sand sheets are traced ~1 km inland from the ocean shoreline in the narrow freshwater pond and submerged marsh. Brackish and/or marine diatoms are associated with the sand sheet deposits (Garrison-Laney, 1998). The catastrophic inundations (#1–6) of Lagoon Creek are thought to have originated from ruptures of the Cascadia megathrust (Figure 1) (Abramson, 1998).

The most recent paleotsunami inundation in Lagoon Creek (event #1) is tentatively correlated to the last Cascadia rupture at AD 1700 (Garrison-Laney, 1998). It is neither robust in terms of sand sheet thickness (0·5–3 cm thick) nor in terms of inland extent of the sand sheet (~750 m distance to site 9) (Figure 2). However, a corresponding tsunami debris layer consisting of organic detritus and marine diatoms is traced an additional 350 m landward to site 2. Three older paleotsunami sand sheets (events #2, 3, and 5) are tracked to the full length (1·1 km) of the submerged marsh. The older sand sheets were not traced further landward due to dense shrubby vegetation and associated bioturbation in the flood plains that extend landward of the submerged marsh. Distinct layers of peaty mud separate the paleotsunami sand sheets in Lagoon Creek, permitting optimal conditions for preservation and radiocarbon dating of the inundation events. Descending roots, bioturbation, and abundant tsunami rip-up debris in the alluvial marshes in Crescent City pose more challenging conditions for dating the inundation events there. The well-preserved inundation records in Lagoon Creek are used to help constrain the ages of paleotsunami sand sheet deposits in the Crescent City wetlands. Comparisons between the sequences of dated sand sheets in Lagoon Creek and Crescent City are presented later in the Discussion section.

Methods

Marshes in three back-barrier marshes located south of Crescent City, California, were investigated (1991–1995) for evidence of paleotsunami inundation on the basis of preserved beach sand

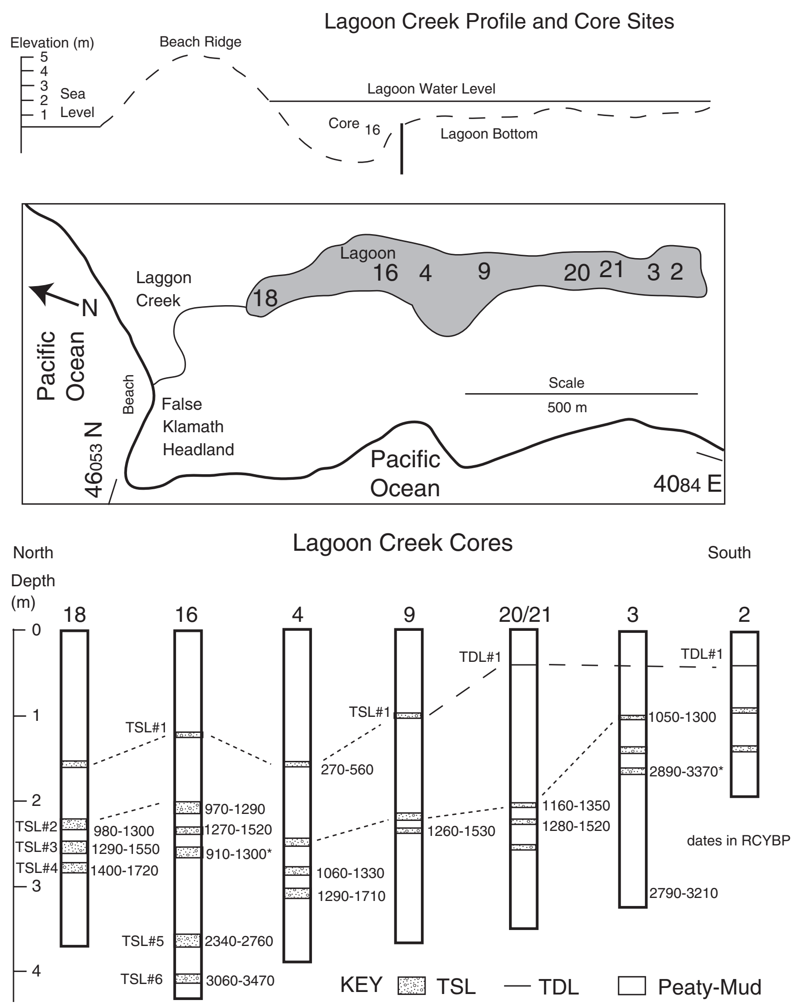

Figure 2. Longitudinal profile, core-site map, and cross-section of key core logs and radiocarbon dates from Lagoon Creek, California (Figure 1), as redrafted from Abramson (1998) and Garrison-Laney (1998). The Lagoon Creek core sites establish the age and relative inundation distance of paleotsunami in the Crescent City study area. Anomalous brackish/marine diatom abundances in the freshwater lagoon are associated with event sand layers #1, 2, 3, 4, 5, and 6 in site 16, layers #1, 2, 3, and 4 in site 20, and layers #1, 2 and 3 in site 2 (Garrison-Laney, 1998). Reversed dates (marked with an asterisk) in site 16 and 3 demonstrate the difficulties of dating overland paleotsunami inundations in settings with descending roots, bioturbation, and tsunami rip-up debris.

layers that are hosted in accumulated peat deposits (Figure 3). The prehistoric deposits are compared to near surface deposits that were left in the same three marshes by a historic farfield tsunami that inundated the Crescent City lowlands in 1964.

Tsunami debris, including large drift logs and wood frame structures, and small flotsam, that were transported by the historic 1964 tsunami are mapped from field surveys and airphoto mosaics (10 sheets at 1:1200 scale) (Crescent City, 1969). Site elevation data for the strandline debris are taken from photogrammetric topographic maps at 1:1200 scale and 0·6 m contour interval (Davis, 1977). The 0 m datum [National Geodetic Vertical Datum of 1988 (NAVD88)] used in this paper approximates the NGVD29 datum and the Mean Lower Low Water (MLLW) datum (NOAA-COOPS, 2008), as used for measurements of historic (1964) tsunami runup (Magoon, 1966; US Army Corps of Engineers, 1968).

Sand sheet deposits from the 1964 tsunami were mapped using shallow trenches (10–20 cm depth) and shallow cores. Subsequent coring (1–3 m depth) with gouge cores (2·5 cm diameter) and ram cores (7·5 cm diameter) in the back-ridge marshes was used to reach deeper paleotsunami deposits, which are hosted in peat bog deposits. Radiocarbon dating included standard radiometric analysis of bulk peat from below the tsunami sand contacts.

The reconnaissance work was followed by vibracoring in the Sand Mine marsh (1996–1998) to establish the recurrence interval of paleotsunami inundation in the Crescent City locality. Vibracores (7·5 cm diameter) were taken to 2–3 m depth using a floating platform in the Sand Mine marsh lagoon. Subsamples were collected for radiocarbon dating, grain-size analysis, and diatom microfossil analysis (Abramson, 1998; Garrison-Laney, 1998). Selected cores from the Sand Mine marsh were cut to 1·0 cm thickness for X-ray radiography with low-density high-contrast film at 35 kV. Digitized radiographs reveal subtle sand lamiae in the tsunami sand sheets that are not visible to the naked eye.

Gouge cores taken in the upland flood plains of the Crescent City marshes (2005–2008) extend the landwardmost record of paleotsunami deposits in Sand Mine, Anchor Way, and Elk River valleys (Figure 3). Core site positions (wassGPS 5 m EPE) were compared to high-resolution topography (Davis, 1977) to establish core top elevations (0·5 m accuracy). Cores were photographed (10 mp dSLR) and logged for evidence of basal contacts (sharp or gradational), sand fining-upward sequences, and interbedded mud or organic rip-ups.

Sand mineralogy was used to establish beach sand sources of the tsunami sand layers and debris layers from the upland alluvial wetlands in the Sand Mine and Anchor Way valleys. Heavy mineral grain separates were examined under petrographic microscope at 250× for rounded mono-mineralic amphibole grains. These heavy mineral grains are diagnostic of beach sand at the Crescent City locality. Creek sand

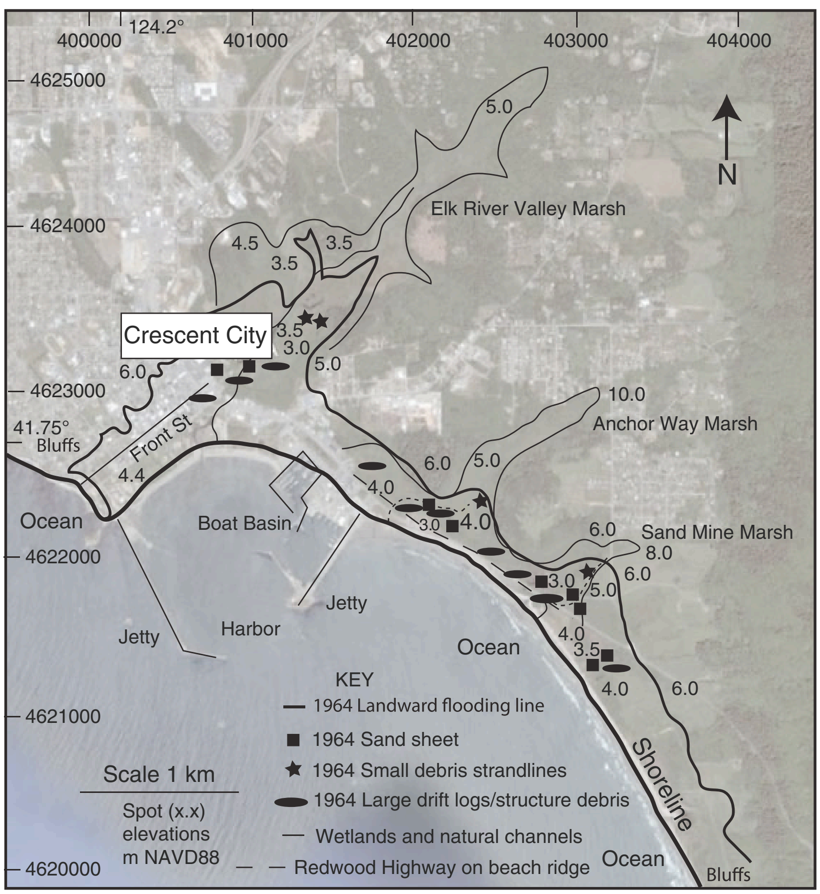

Figure 3. Map of marshes formed at Elk River valley, Anchor Way and Sand Mine creeks, located near Crescent City. The back-ridge or barrage marshes transition to floodplain swamps with increasing distance (0·5–1·0 km) landward of the Redwood Highway (dashed line) on the paleo-beach ridge (3–4 m elevation NAVD88). Spot elevations are shown for the marshes and several shoreline features, based on high-resolution topography (0·6 m contour) (Davis, 1977). Maximum runup of the 1964 tsunami (bold line) is redrafted from US Army Corps of Engineers (1968). Landward extents of mapped tsunami sand sheet (black square), tsunami driftwood strandlines (black star), and tsunami drift logs or large structural debris (black ellipse) are from field surveys conducted in 1991–1993. Base map image is from Google Earth earth.google.com/ (2010).

composition is dominated by angular lithic fragments in the heavy mineral fraction. Radiocarbon dating of the paleotsunami deposits is based on accelerator mass spectrometry (AMS) analysis of small leaf, twig, or organic rip-up fragments from within the tsunami sand layer or standard radiometric analysis of bulk peat deposits from below the tsunami sand contacts. About 75 core sites were occupied in the Crescent City marshes over the duration of field investigations from 1991 to 2008.

Results

1964 Tsunami debris and sand sheets in Crescent City

The 1964 farfield tsunami that reached Crescent City from the Gulf of Alaska rupture (Mw 9·2) inundated the City's south waterfront, the adjacent harbor, low beach ridges, and multiple back-ridge marshes in the Crescent Beach embayment (Figure 3). Large drift logs (0·5–1·5 m diameter) and littoral sand were transported up the low beach ridges. The ridge crests are 3–4 m elevation (NAVD88). Four successively larger surges were observed with the last surge locally reaching 6·5 m elevation (Landers *et al.*, 1993). A slightly-earlier farfield tsunami from the 1960 Chile rupture reached only 4 m elevation in the Crescent City waterfront (Landers *et al.*, 1993). Storm surge deposition reaches 3–4 m elevation in the protected Crescent City beach embayment (Peterson *et al.*, 1994). The 1964 tsunami runup exceeded the maximum reach of both historic storm surge and the farfield 1960 tsunami runup by 2–3 m in elevation.

A direct correspondence exists between the maximum landward extents of the large drift logs and the preserved sand sheet deposits from the 1964 inundations (Figure 4). The landward extents of these features (100–200 m from the Redwood Highway on the paleo-beach ridge) also correspond to structural damage at Front Street in Crescent City, and along the Redwood Highway on the beach ridge (3–4 m elevation) fronting the Anchor Way and Sand Mine marshes (Griffin *et al.*, 1984; Dengler and Magoon, 2006). Large debris transported by the tsunami surges damaged buildings along the length of the Crescent City waterfront at 3–5 m elevation (Magoon, 1966; Landers *et al.*, 1993).

Figure 4. The 1964 tsunami drift logs and thin sand sheet (foreground) in front of Crescent City Motel beach cabin (see Redwood Highway at Sand Mine Marsh in Figure 3). Large drift logs and associated sand sheet deposits are documented in both historic photographs and in trench sites occupied in 1991–1993. Geologically preserved sand sheets should serve as proxy data for large debris transport in paleotsunami inundations of the Crescent City shorelines. Photograph (1964) supplied by motel owner, Mr Brown.

Further landward extents of the 1964 tsunami flooding in the back-ridge marshes are recorded by strandlines of small driftwood fragments, including cedar shingles, wood siding, and tar paper. The small debris strandlines, 4·0–4·5 m elevation in the Anchor Way and Sand Mine marshes respectively, were partially entombed in muddy peat by the time of the initial field study in 1991–1993. Comparisons between small debris, large drift logs, and sand sheet deposits are shown in Figure 3.

The preserved deposit records of the 1964 tsunami are compared to historic accounts of flooding, as reported by Magoon (1966) and compiled by the US Army Corps of Engineers (1968). The elevations of the most landward flooding line, as observed by Magoon (1966) are conservatively established from high-resolution topographic maps (Davis, 1977). The most landward flooding lines are 4·5 m and 5·0 m elevation in the Anchor Way and Sand Mine marshes, respectively, but only 3·5 m elevation in the lower-gradient Elk River Valley (Figures 3 and 5). Artificial fill constriction at the mouth of the Elk River Valley might have attenuated tsunami flooding relative to the corresponding shoreline runup of 5·9 m elevation near the creek mouth in the harbor (US Army Corps of Engineers, 1968).

There is relatively little difference in separation distance (~200 m) between the maximum landward extents of the 1964 tsunami sand sheets and the landward flooding lines in the high-gradient Anchor Way and Sand Mine alluvial wetlands (Figure 5). The separation distance between the mapped sand sheet extent and the most landward flooding line in the low-gradient Elk River Valley reaches 1000 m. In low-gradient wetlands the sand sheet extent can underestimate tsunami inundation distance.

Paleotsunami deposits in Sand Mine marsh

Shallow coring (1–3 m depth) was performed in the back-ridge marshes and small tributary flood plains in Crescent City to establish the landward extent of paleotsunami sand sheets (Figure 6). Representative core logs are shown in Figures 7 and 8. Beach sand identified in the tsunami sand layers is based on rounded amphibole grains, greater than 30% by volume, in the heavy mineral fraction. The Sand Mine marsh lacks through-running creeks, dunes, or eroding marine terrace deposits that could supply the rounded beach sand to the peaty mud deposits. Marine diatoms are also associated with the tsunami sand layers, as recorded in continuous vibracores from the Sand Mine marsh/lagoon (Figure 8) (Carver *et al.*, 1998). The diatom record is variable between core sites and within individual tsunami deposit layers, as might be expected from the chaotic nature of multiple marine surges and backwash events (Garrison-Laney, 1998). Such taxa complexity is demonstrated in recent (2004) Indian Ocean tsunami deposits containing mixed diatom assemblages (Sawai *et al.*, 2009). Primary sedimentary structures in the tsunami sand layers include (1) sharp basal contacts, (2) sand fining-upwards sequences, and (3) interbedded-mud or peat rip-ups (Figures 7).

The youngest tsunami sand layer, at 5–10 cm depth, corresponds to the historic (1964) tsunami (Figures 7 and 8). An adjusted radiometric date of 260 + 50 yr BP for bulk peat (58–61 cm depth) under the second tsunami sand layer (23 cm thick) in cc18 confirms this layer as the last Cascadia nearfield tsunami. The calibrated date range of 0 to 467 cal BP is acceptable for the youngest paleotsunami event #1 (Atwater *et al.*, 1995), which is correlated to calendar year AD 1700 (Satake *et al.*, 1996). Five additional paleotsunami sand sheets are recorded below the AD 1700 tsunami, in core sites VB5, cc41/42b, and ccWL. A muddy peat at ~2·5 m depth separates

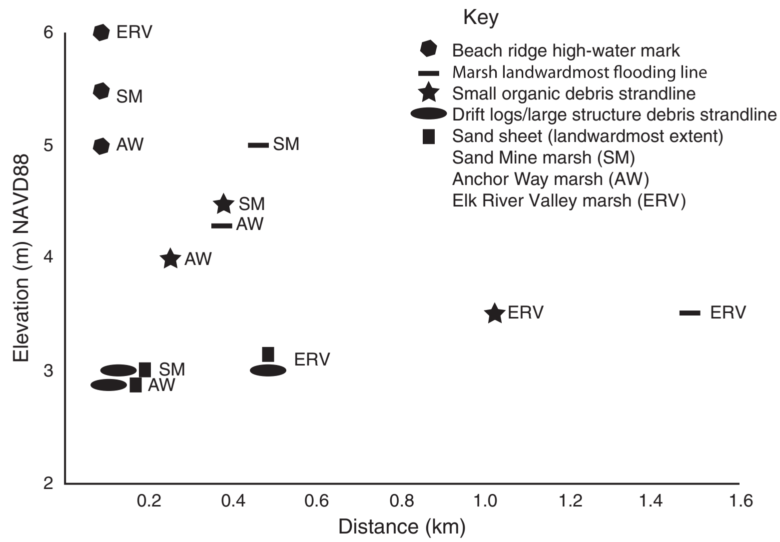

Figure 5. Elevation versus distance plots of beach-ridge high-water mark and most landward flooding lines from the historic 1964 tsunami runup in Cresecent City (US Army Corps of Engineers, 1968). The most landward extents of small debris, large debris, and tsunami sand sheets produced by the 1964 tsunami runup are also shown for the three marsh systems including Sand Mine, Anchor Way, and Elk River Valley (see Figure 3 for marsh locations). Selected core sites that host the 1964 tsunami sand sheet are shown in Figures 6 and 8).

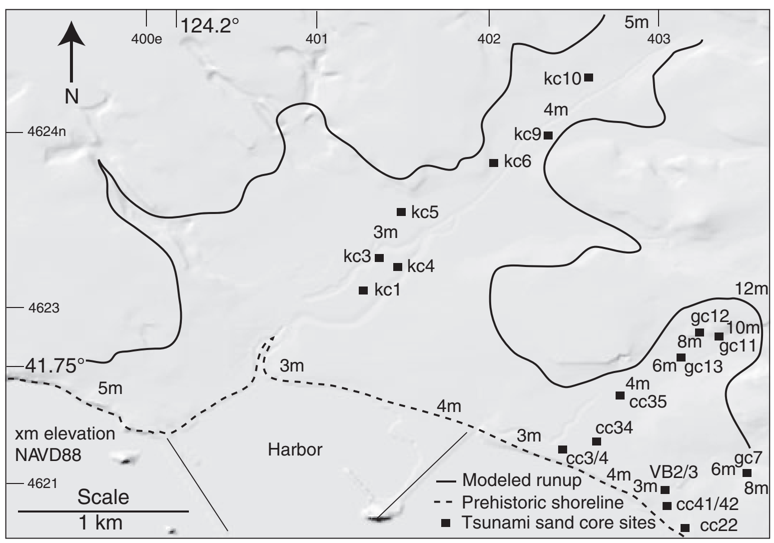

Figure 6. Hillslope-shaded map of core sites containing paleotsunami sand layers (black squares) in Crescent City marshes and adjoining creek flood plains. Potential runup from a nearfield Cascadia tsunami (bold line) was numerically modeled from predicted Mw 9 rupture scenario(s) as published by Uslu *et al.* (2007). A larger scale map of core site positions in the Sand Mine marsh is show in Figure 7 inset. The digital elevation model (DEM) used for the base map image is from the US Geological Survey Seamless Map (http://seamless.usgs.gov/, 2010). Representative spot elevations are rounded to the nearest meter from high-resolution topography maps (0·6 m contour) (Davis, 1977).

the two oldest paleotsunami sand layers in core sites VB5, ccWL, and cc42b. The peat is dated at 2488–2920 cal BP in cc42b (Table I), yielding a long-term sedimentation rate of ~1 m/1000 year in the marsh/lagoon at site cc41/42b. Net peat accumulation in the back-ridge marsh is attributed to rising groundwater level, presumably tracking relative sea level rise in the Crescent City locality.

Fewer preserved sand sheets in some of the proximal marsh sites might reflect tsunami erosion of pre-existing tsunami sand layers. Abundant peat rip-ups in the tsunami sand layers attest to tsunami scour in the back-ridge marshes. Several sandy-silt laminae (<1 cm thickness) are observed between the paleotsunami sand sheets in proximal cores sites in the Sand Mine marsh (Figure 8). The origin(s) of these sandy-silt laminae are not established (see further discussion later). They fail to meet the criteria of contiguous sand sheets that can be traced between adjacent core sites.

Paleotsunami deposits in Anchor Way marsh

The 1964 tsunami sand sheet is well recorded in the most proximal sites of the Anchor Way marsh, including adjacent sites cc3 and cc4 (Figures 6 and 9). Four paelotsunami sand

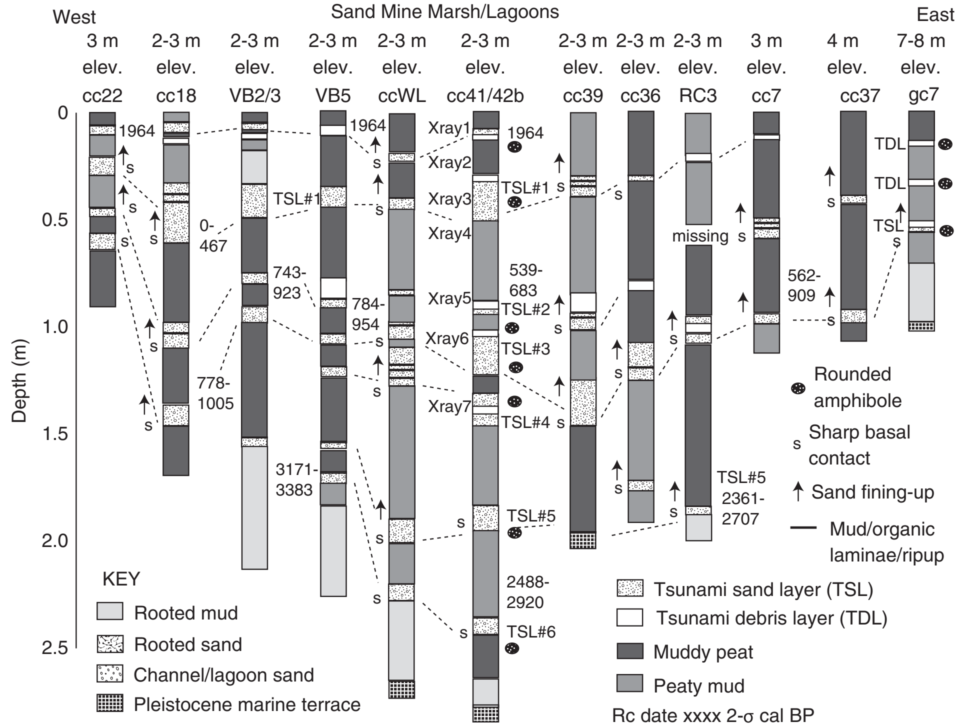

Figure 7. Core logs from the Sand Mine marsh sites in Crescent City (see Figures 6 and 8 for core site locations). Core top elevations are shown in meters NAVD88, as established from high-resolution (0·6 m) contour maps (Davis, 1977). The first and third paleotsunami deposits, events #1 and #3, contain relatively thick sand layers in the proximal core sites. The second paleotsunami deposit (event #2) displays a particularly thick tsunami debris layer (TDL) in several core sites including VB5, cc41, and cc39. The historic tsunami sand sheet is designated 1964. Calibrated radiocarbon dates are from Table I. High-resolution sedimentary structures are shown for core cc41 in X-ray radiographs, designated Xray1–7 (Figure 11).

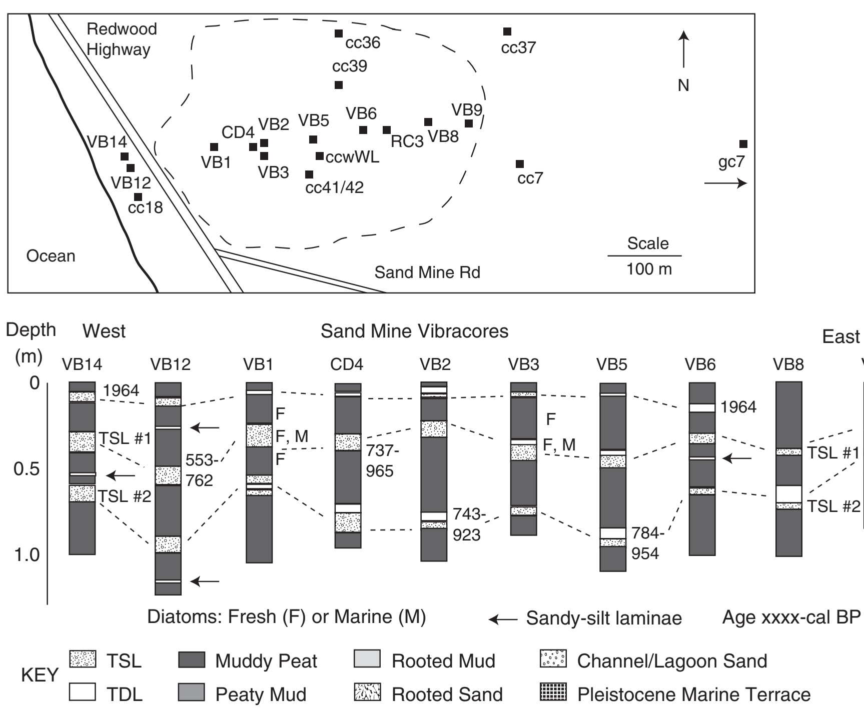

Figure 8. Map of core sites and corresponding vibracore logs showing the 1964 tsunami deposits and the last two paleotsunami sand sheets (TSL#1, TSL#2) from the Sand Mine marsh. Reconnaissance core sites (from Figures 6 and 7) are also shown for reference. Particularly thick tsunami debris layers, also called trash layers by Carver *et al.* (1998), are associated with paleotsunami layer #2 in core sites VB8 and VB9. Several intervening sandy-silt laminae (arrows) are shown for intervals between the identified tsunami sand layers. Key diatom assemblages summarized in VB1 and VB3 include marine (M) taxa (*Coscinodiscus marginatus*, *Coscinodiscus radiatus*, *Cocconeis scutellum*, and *Rhaphonels psammicola*) and freshwater peat (F) taxa (*Diploneis ovalis, Rhopalodia gibberula, Gomphonema affine*, and *Pinnularia flexousa*) (Carver *et al.*, 1998).

Table I. Radiocarbon dates from Crescent City core sites

Site	Sample	Depth (cm)	Adjacent C14 (yr BP)	cal 1 – σ (cal BP)	cal 2 – σ (cal BP)	Laboratory beta #
cc18	Bulk peat	61	260 ± 50	152–429	0–467	73 245
cc18	Bulk peat	130	1000 ± 60	798–967	778–1005	73 246
cc41	Bulk peat	100	650 ± 60	559–667	539–683	89 153
cc42	Bulk peat	240	2630 ± 70	2621–2847	2488–2920	89 156
cc39	Bulk peat	25	150 ± 70	0–282	0–292	67 436
cc7	Bulk peat	75	780 ± 80	662–785	562–909	67 435
VB12	Bulk wood	50	720 ± 60	568–724	553–762	101 550
VB2	AMS wood	75	920 ± 40	791–908	743–923	101 542
VB3	AMS peat	170	3080 ± 40	3262–3358	3171–3383	101 546
VB5	AMS wood	85	960 ± 40	798–927	784–954	101 540
RC3	AMS wood	180	2460 ± 40	2368–2700	2361–2707	101 541
CD4	Bulk wood	40	960 ± 60	795–929	737–965	101 553
kc9	AMS peat	88	980 ± 40	830–930	790–960	252 508

Calibrated ages for radiometric (bulk) and AMS dates are based on the Calib 5.0 program by Stuiver *et al.* (2008).
Bulk peat samples are taken from the peat contact underlying the tsunami sand.
AMS samples are from organics (wood fragment or peat rip-up) in the tsunami sand layer.
Calibration parameters are provided in Reimer *et al.* (2004).
Dates from the VB2, VB3, VB5, VB12, CD4 and RC3 are from Carver *et al.* (1998).

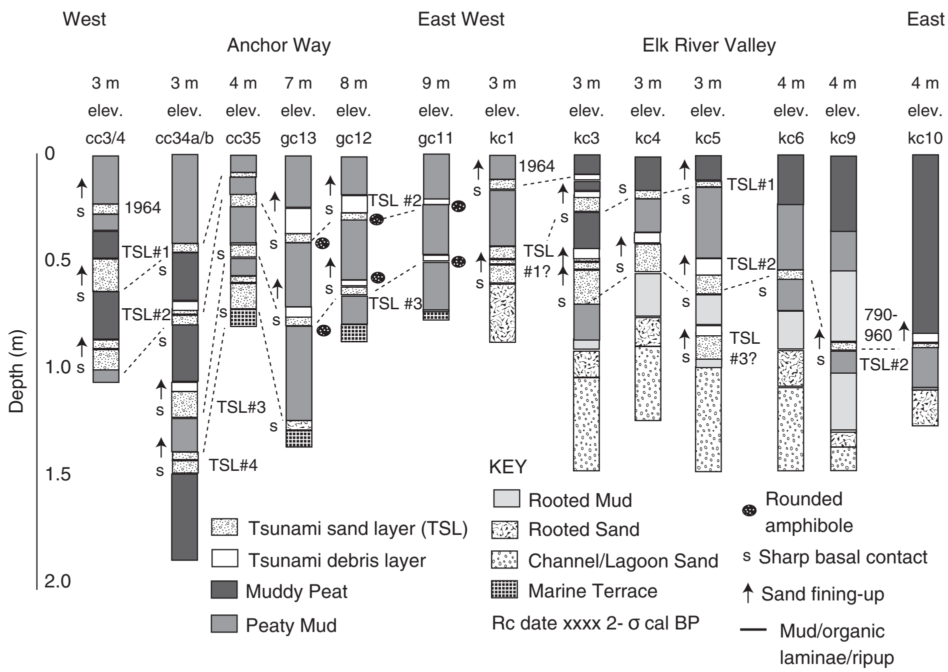

Figure 9. Core logs from the Anchor Way and Elk River Valley marsh sites in Crescent City (see Figure 6 for core site locations). Core top elevations are shown in meters NAVD88. Four paleotsunami sand layers (TSLs) are hosted in the Anchor Way marsh (site cc34). The second paleotsunami deposit (TSL #2) is associated with a thick debris layer (TDL). The event #2 layer is dated 743–923 cal BP and 784–954 cal BP in vibracores from the adjacent Sand Mine marsh (Figure 8). The hosting peaty mud sections of the Elk River Valley are relatively young (~1 ka) limiting the record of paleotsunami inundation in the low-gradient wetland. A radiocarbon date of 790 to 960 cal BP is shown for the terminal sand sheet from event #2 in core site kc9. Radiocarbon data are from Table I.

layers are recorded in core site cc34, located about 250 m landward of the beach. The paleotsunami sand layers range from 7 to 10 cm in thickness. Sand layer #2 has a distinctively thick debris layer, both in the Anchor Way and Sand Mine marsh (Figures 6, 7 and 9). The Anchor Way marsh transitions to a shrubby flood plain with increasing landward distance and elevation gain (Figure 6). Site gc13 contains two distinct paleotsunami sand layers at elevations of 6 to 7 m. A third possible paleotsunami sand layer occurs above the basal Pleistocene terrace surface. The two distinct tsunami sand layers, #2 and #3, are traced to sandy-organic debris layers in site gc11, at an elevation of 8 to 9 m and at a distance of 1·2 km from the beach ridge (Figure 10). Rounded amphibole mineral grains in both of the sandy detrital-organic layers confirm beach sand sources in the tsunami debris layers from events #2 and #3. Thinning peaty-mud deposits at the head of the Anchor Way Valley limit the paleotsunami record to only 2–3 distinct inundation events in a total of 13 core sites.

Figure 10. Bioturbated sand laminae (63–65 cm depth) in site gc12 from the Anchor Way marsh flood plain, at an elevation of 7 to 8 m (Figures 6 and 9). The rounded quartz grains (125–175 microns in diameter) are distinctive in the dark peaty mud. Rounded amphibole grains in the heavy-mineral fraction confirm a beach sand source for the sand layer, which corresponds to paleotsunami event #3 (Figure 9).

Paleotsunami deposits in Elk River Valley

The paleotsunami inundations of the Elk River Valley are limited in record by a short period of peaty mud accumulation above basal lagoon and/or creek sand (Figures 6 and 9). The 1964 historic tsunami sand layer is present at site kc1, located about 0·5 km distance from the beach, but it pinches out to a sandy-silt debris layer at kc3. The shallowest prehistoric sand sheet (event #1) is traced to kc5 at a distance of 1·5 km from the beach in the low-gradient flood plain of the Elk River Valley. At least one older paleotsunami sand sheet is preserved in peaty mud deposits along the valley margins. The distal sand sheet is dated 790–960 cal BP at site kc9 (Figure 9; Table I). The sand sheet is traced to kc10 at a distance of 2·5 km, which corresponds to an elevation of 4 m (Davis, 1977). The corresponding tsunami debris layer likely continues landward in the low-gradient Elk River Valley marsh, but root bioturbation limits preservation of the landward-thinning tsunami deposit.

X-ray radiographs of core site cc41

X-ray radiographs of core cc41 from the Sand Mine marsh (Figures 6 and 7) are shown in Figure 11. The radiographs document sand layers from the historic 1964 tsunami and four additional paleotsunami (events #1–4). A deeper extension to the cc41 section is provided from the adjacent core cc42b, but the deeper section was not included in the X-ray imaging. The tsunami deposits include (1) sharp bases, (2) multiple sand layers, (3) many sand laminae, (4) interbedded mud laminae and peat rip-ups, and (5) gradational tops that fine upwards into sandy or silty detrital organics.

A particularly thick tsunami debris layer (19 cm thick), with at least 10 sandy-silt/organic laminae, occurs in tsunami deposit #2. A thick peat rip-up layer (7·5 cm thick) occurs between two sand layers from deposit #4. The sedimentary structures shown in the radiographs are infrequently described in modern tsunami sand sheets. Such variable lithology occurs in high-preservation potential environments, such as marshes and lagoons, which are susceptible to tsunami scour. The complex interbedding of the sand sheets likely represents the chaotic nature of multiple wave trains, interacting surges, and backwash flows that are associated with tsunami inundation in proximal marsh settings.

Discussion

Discrimination of paleotsunami deposits

In this paper the geologic records of tsunami sand deposition are used to establish paleotsunami inundation. We briefly address the question of paleotsunami deposit recognition in contrasting study areas. The Crescent City barrage marshes back low-gradient sandy beaches in a protected embayment (Figures 3 and 6). This locality differs from several southeast Australia sites where headland erosion and cobble deposits on marine terraces might have been produced by very-large paleotsunami (Bryant *et al*., 1992; Bryant and Knott, 2001). Headlands and marine terraces are located several kilometers to the south and north of the back-barrier marshes in Crescent City. However, the scale of paleotsunami runup estimated for the Crescent City locality (~10 m as discussed later) would probably be insufficient to significantly modify the resistant headlands in the study area (Liew *et al*., 2009).

Unlike some New Zealand sites that record gravel sheet deposition by paleotsunami (Nichol *et al*., 2007) the sandy beaches in the Crescent City embayment do not provide significant gravel sources for tsunami transport and deposition in the back-ridge marshes. Gravel beaches are located several kilometers north and south of the Crescent City embayment (Peterson *et al*., 1994). Preliminary searches for paleotsunami gravels have been undertaken in those sites, but conclusive results on the origin(s) of terrace top pebbles and small cobbles from those areas have yet to be established.

Remobilized molluscan shells in layers that fine upwards in bay mud deposits have been used to identify catastrophic tsunami inundation in Japan (Fujiwara *et al*., 2003). Carbonate shell fragments were observed but not routinely logged in proximal sand sheet deposits from the Crescent City freshwater lagoons (Figure 7). Shell fragments from paleotsunami sand sheet deposits are now being used to confirm marine inundation in other proximal runup localities in the central Cascadia margin (Peterson *et al*., 2010b), where windblown ocean spray could import marine diatoms by non-surge mechanisms.

The tsunami sand sheet deposits documented in this study provide particularly useful combinations of transport and deposition under wide ranges of tsunami flow competence. For example, sand deposits from the 1964 farfield tsunami inundation in Crescent City extend from the most proximal back-ridge ponds to the upland marshes. Whereas sand sheet deposition likely corresponds to high-velocity sheet flow conditions (Figure 5) the disseminated beach sand that floated in with detrital organics probably represents the near terminal extent of tsunami inundation (Figure 10). Several other attributes of the tsunami sand sheets are (1) widespread source sand in the nearshore and beaches, (2) macroscopic identification of target sand layers in reconnaissance cores, and (3) several marine surge tracers including sand grain mineralogy.

Early in the Crescent City investigations the possibilities of storm surge origins for the prehistoric sand sheets were raised. Morton *et al*. (2007) provide some guidelines for discriminating between paleotsunami and storm surge origins for inundation sand sheets. The sand sheets recorded in the Crescent City barrage marshes generally reflect paleotsunami characteristics

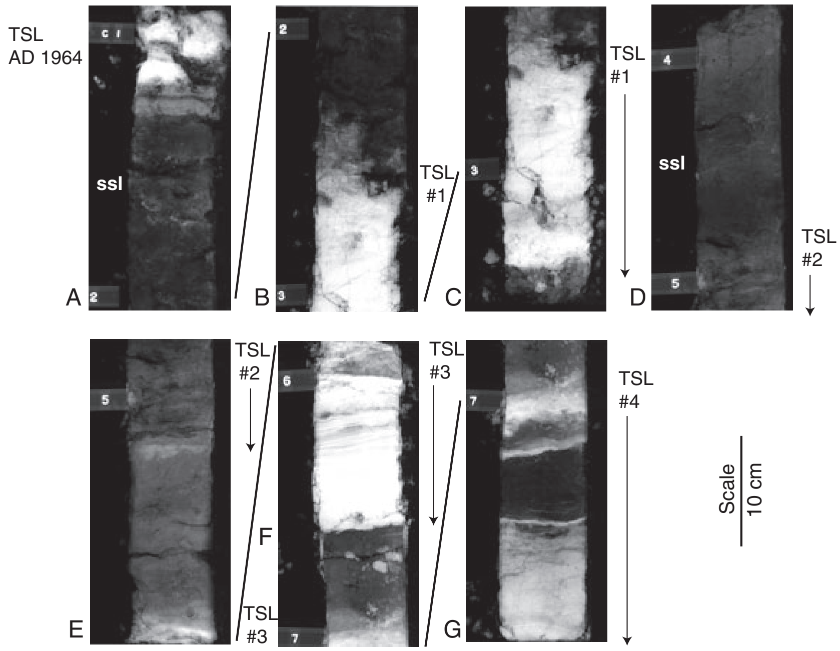

Figure 11. X-ray radiograph of core slab between X-ray markers C1 and 7 from core cc41 (see Figure 7 for core log). X-ray marker tags are 1·7 cm in width. Gray layers immediately below the 1964 tsunami sand sheet could represent either silty debris layers deposited by preceding surges of the 1964 tsunami, or by silty debris layers from the 1960 Chile farfield tsunami. Sandy-silt laminae (ssl) occur between X-ray markers 1 and 2, and between X-ray markers 4 and 5. The origins of the sandy-silt layers are not known. Four high-density sand layers (light) occur below the 1964 tsunami sand sheet. Those tsunami sand layers (TSLs) and associated overlying debris layers (dark) correspond to events #1–4.

in that they (1) are thin (less than 50 cm thickness), (2) mantle, but do not fill, pre-existing lagoon topography, and (3) extend inland for substantial distances (greater than 1·0 km). However, differentiating between small inundation events (sustained runups less than 5 m) of either paleotsunami or storm surge origins could prove difficult. In Crescent City the distinct sand sheets are directly correlated to nearfield Cascadia paleotsunami based on the number and ages of dated inundation events (see further discussion later).

Tsunami sedimentary structures

Two important aspects of paleotsunami sand deposition in the Crescent City marshes are (1) the local variability of sand sheet thickness, and (2) the wide range in sedimentary structures. Dense sampling of the last Cascadia tsunami (event #1 at AD 1700) in the Sand Mine marsh (Figures 3 and 6) demonstrates a wide range of thickness (1–35 cm thickness) over a 500 m distance (Figures 7 and 8). The mean and standard deviation for this layer in the Sand Mine marsh are $10{\cdot}6 \pm 9{\cdot}6$ cm for $N = 11$ sites. Though there is a general thinning with landward distance, some adjacent sites yield substantial differences (100%) in corresponding event sand layers. Caution is advised in relating local deposit thickness to runup magnitude.

The variability of tsunami deposit internal bedding is well documented in the sequence of sand sheets recorded at site cc41 in the Sand Mine marsh (Figures 6 and 7). Fine details of the tsunami deposit sedimentary structures are revealed in X-ray radiographs of the successive sand layers (Figure 11). The historic sand sheet (AD 1964) contains two sand layers, each composed of multiple sand laminae. The deposit from event #2 is dominated by layers of sandy-mud and organic detritus, which overly a thin basal sand (2–3 cm thick). The event #3 deposit is dominated by sand (15 cm thick), containing tens of thin sand laminae. The event #4 deposit contains (1) multiple sand layers, (2) thick organic debris layers, and (3) many thin sand laminae. This variability in the sedimentological record of successive paleotsunami at the same site denotes the complicated mechanisms of varied wave trains, surge interactions, and reversing backflow deposition.

Historic tsunami runup records

The runups of the 1960 and 1964 historic tsunami, measured for height above predicted tide level in Crescent City, are 1·7 m and 4·9 m, respectively (Landers *et al.*, 1993). The 1960 tsunami might have left a silty-debris layer at cc18, VB12, and cc41, located near a drainage creek in the Sand Mine marsh (Figures 7 and 11). However, the 1960 tsunami (4 m elevation) (Figure 12) did not yield sand sheet deposits landward of the low beach ridge (3–4 m elevation) fronting the Anchor Way marsh. By comparison, the 1964 tsunami (~5–6 m elevation) widely overtopped the low beach ridges, inundating the low marshes (3–5 m elevation). The 1–2 m deep surges from the 1964 tsunami deposited narrow sand sheets (100–200 m width) landward of the Sand Mine and Anchor Way beach ridges, and also along the Elk River Valley drainage channel to a distance of ~500 m from the beach (Figure 5). These events demonstrate a sustained surge threshold of at least 5 m elevation to produce a preserved sand sheet in the back-ridge marshes of Crescent City.

The preserved 1964 sand sheet deposits in the Crescent City marshes (3–4 m elevation) under-predict the 1964 runup mapped in the back-ridge wetlands by 1·5 to 2·0 m elevation (Figure 5). The sand sheets under-predict the historic tsunami runup distances by 100 to 300 m in the high-gradient wetlands. The small-debris strandlines provide a better measure of the 1964 tsunami runup, approaching to within 100 m of the

Figure 12. Photograph of 1960 tsunami flooding at Citizens dock in Crescent City (south end of boat harbor in Figure 3). The small runup (1·7 m) occurred during high tide, causing the flooding of Citizens dock and the adjacent beach ridge in the foreground (4 m elevation). This small tsunami locally overtopped low beach ridges (3–4 m elevation) possibly leaving a silty debris layer (Figure 11) but no sand layers in the Anchor Way marsh (Figure 8). Image modified from photograph by Wallace Griffin in Landers *et al.* (1993).

published landward flooding line in the Anchor Way and Sand Mine wetlands. The 1964 sand sheet extent in the low-gradient flood plain of the lower Elk River Valley substantially under-predicts the published most landward flooding line, by 500 to 1000 m in inundation distance.

The sand sheets do serve as important geologic records for high-impact inundation zones (Figure 4). Those zones correspond to potential structural damage from large debris transported by tsunami surges in Crescent City (Figures 3 and 5). Of the 10 drowning deaths from the 1964 tsunami in Crescent City (Landers *et al.*, 1993) all occurred within the landward extent of the 1964 tsunami sand sheet.

Paleotsunami recurrence interval

Based on the apparent runup necessary to produce sand sheets in the Crescent City marshes (see earlier) the six paleotsunami sand layers in the Sand Mine marsh (Figures 7 and 8) all exceeded 5 m runup elevation at the shoreline. The same sequences of tsunami inundations are recorded in the nearby Lagoon Creek locality (Figure 13) (Abramson, 1998). The six paleotsunami recorded in these two southern Cascadia localities can be all accounted for by known ruptures of the central Cascadia margin (Darienzo *et al.*, 1994; Atwater *et al.*, 2004). The results presented here suggest that the six ruptures could have propagated to, or from, the southern Cascadia margin. One farfield tsunami deposit recorded in some central Cascadia estuaries at ~800 yr BP (Peterson *et al.*, 2008) is not observed at Crescent City.

A total of six paleotsunami inundations in 2700 years in Crescent City yield a mean recurrence interval of 450 years. Two recorded paleotsunami events, #2 and #3, demonstrate a recurrence interval of only 200 years. The Crescent City locality contains only one farfield tsunami sand sheet (1964 tsunami) during the ~3000 year period of record. Discontinuous sandy-silt laminae (less than 1 cm thickness) do occur in several of the proximal cores sites in the Sand Mine marsh (Figures 8 and 11). The origin(s) of these sandy-silt laminae are not known, but

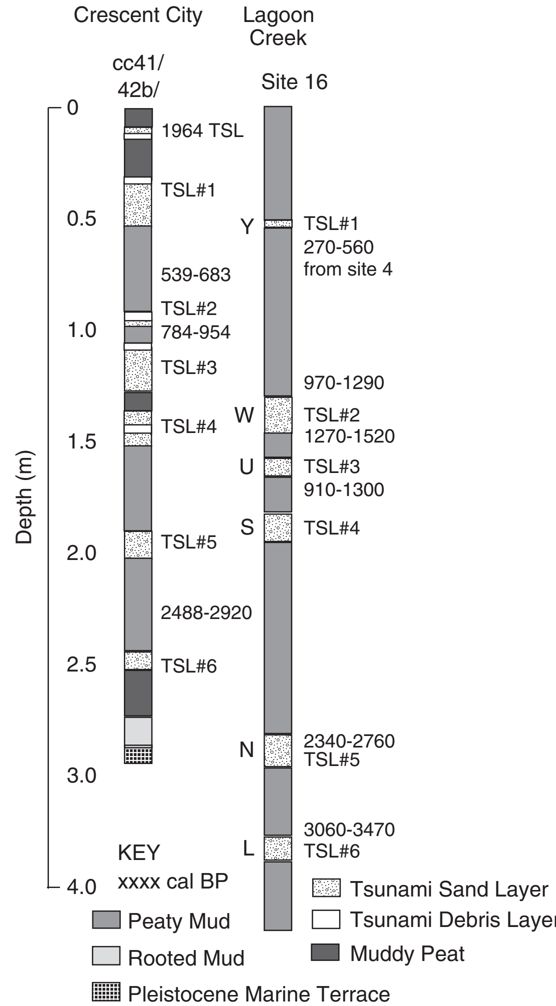

Figure 13. Representative stratigraphic records of paleotsunami sand layers in Crescent City and Lagoon Creek, at the southern end of the Cascadia margin. One date (784–954 cal BP) from site ccVB5 in Crescent City is shown for combined core sites cc41/42b, and one date (270–560 cal BP) from site 4 in Lagoon Creek is shown for site 16 (Abramson, 1998).

could possibly include minor tsunami inundations (Carver *et al.*, 1998), strong wind-storm events, and/or storm-surge inundations. In any case, they fall below the runup threshold (5 m elevation) for catastrophic flooding hazard in Crescent City.

Comparison of paleotsunami inundation distance and height

Two or three paleotsunami sand sheets are traced to their landward limits in each of the three Crescent City wetland localities. In terms of maximum-recorded paleotsunami inundation the Anchor Way wetlands offer the best combination of (1) number of sand sheets, (2) length of wetland setting, and (3) wetland elevation gradient ((Figures 7 and 9). The maximum-recorded inundations for two latest-Holocene paleotsunami, #2 and #3, in the Anchor Way wetlands reach 8–9 m elevation at a distance of 1·2 km from the paleo-beach ridge that fronts the Anchor Way marsh (Figure 14). The beach-ridge, which locally underlies the Redwood Highway (Figure 3), is located about 150 m landward of the MLLW or 0 m NAVD88 beach shoreline.

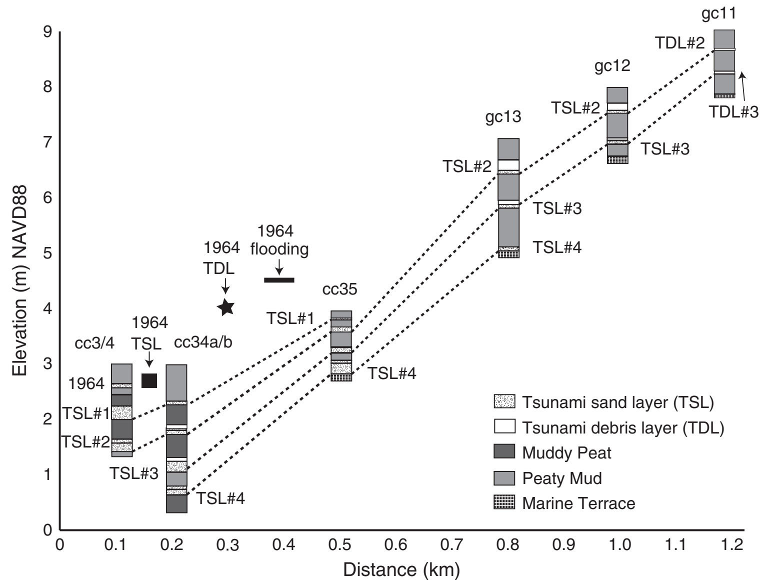

Figure 14. Paleotsunami runup elevation versus distance data are shown for the historic (1964) tsunami, and four paleotsunami inundation events #1–4, in the Anchor Way marsh, Crescent City. Additional data points include the most landward extents of the 1964 tsunami sand sheet, tsunami debris layer, and reported flooding line (US Army Corps of Engineers, 1968). Two paleotsunami events, #2 and #3 are correlated to central Cascadia ruptures, dated between 1·0 and 1·5 ka (Figure 13). Landward distance is from the low beach ridge under the Redwood Highway (Figure 3). Elevations of the core sites are taken from high-resolution topographic maps (0·6 m contour) (Davis, 1977).

The #2 and #3 tsunami events are correlated to Cascadia margin ruptures that occurred between 1000 and 1500 cal BP (Figure 13). Using the measured core depths (0·25–0·50 m depth) of tsunami debris layers #2 and #3, and an assumed net sea level rise of 1 m per 1000 years, the paleo-sea level adjusted runups for the two inundations are 9–10 m at 1·2 km landward distance in the Anchor Way marsh. The tsunami debris layers are expected to reflect the maximum recorded inundation in the upland wetland setting.

The #2 and #3 paleotsunami sand sheets approach, but do not reach, the runup lines modeled for a predicted full margin Mw 9 rupture scenario CSZ-L (Figure 6) (Uslu *et al.*, 2007). Uslu *et al.* (2007) modeled the runups from predicted Cascadia subduction zone (CSZ) rupture scenarios using the numerical model MOST (Titov and Synolakis, 1998), as benchmarked against historic 1964 tsunami runup in Crescent City (Magoon, 1966). The scenario (CSZ-L) used to generate the runup line shown in Figure 6 is based on full margin rupture (Mw ~ 9) using fault dimensions, and average slip from Satake *et al.* (2003). Partial northern margin ruptures, and slip limited to local faults in the deformation front yield much smaller modeled runups (Uslu *et al.*, 2007). Coincidentally, the AD 1700 tsunami, used, in part, to justify full margin rupture parameters in the Cascadia subduction zone (Satake *et al.*, 1996; Satake *et al.*, 2003) produced only modest runups in Crescent City, as has been reported for some central Cascadia localities (Peterson *et al.*, 2008).

Conclusions

Crescent City, California, suffered damaging floods from a historic (1964) farfield tsunami, leading to heightened tsunami awareness in the US West Coast. Sand sheets from the 1964 tsunami in Crescent City provide minimum estimates of tsunami inundation, but they do correspond to the most dangerous inundation zones. The sand sheets were deposited in waterfront beach ridges and back-ridge mashes, which contain large drift logs and structural debris that floated in with the historical tsunami flooding.

Some 25 years later the same Crescent City marshes were examined for nearfield paleotsunami deposits that could demonstrate coseismic ruptures of the southern Cascadia subduction zone. The potential for megathrust seismicity in the south end of the subduction zone was widely debated. Multiple sand sheets, up to several decimeters in thickness, recorded catastrophic inundation from nearfield Cascadia paleotsunami in the Crescent City marshes. The paleotsunami deposits helped confirm late-Holocene seismicity of the subduction zone, and initiated searches for other paleotsunami records in the study region. Six paleotsunami sand layers deposited in the last 3000 years in the Crescent City marshes match the same dated sequence in nearby Lagoon Creek, California, permitting the estimation of a mean recurrence interval for large nearfield tsunami in the southernmost Cascadia margin. These results confirm that oblique convergent strain is accumulated in the southernmost Cascadia margin, and that episodic megathrust ruptures result in 'fast' tsunamigenic sea floor displacements. The paleoseismic record, including paleotsunami deposits, plays a key role in promoting seismic hazard awareness in the Cascadia subduction zone, which has not ruptured in historic time.

Recently two of these authors returned to the Crescent City marshes to establish the maximum-recorded paleotsunami runup, based on the landward extent of preserved paleotsunami sand layers. The paleotsunami sand sheets were traced in alluvial floodplain wetlands that extend landward from beach-ridge marshes and freshwater ponds. The floodplain settings suffer from relatively short geologic age and bioturbation that obscures thin paleotsunami sand layers. However, continuity and gradual elevation rise of the alluvial wetlands provide ideal conditions for establishing paleotsunami runup. Nearfield Cascadia paleotsunamis have exceeded twice the runup height and four times the inundation distance of the historic (1964) farfield tsunami in Crescent City.

Most paleotsunami studies worldwide have focused on paleotsunami event recognition and dating. In this study we show that the selection of appropriate depositional settings and sufficient core sampling in those settings can yield additional information on paleotsunami inundation distance and runup height. These measures are needed to independently verify predicted runup from numerical models where fault rupture mechanics are uncertain or unknown. Credible predictions of potential inundation distance and runup height from future tsunami are necessary for effective emergency response planning in communities with limited financial resources.

Acknowledgements—Kennett Peterson and Galen Peterson assisted with coring and field logistics in the Crescent City wetlands. Paul Britt performed the X-ray radiograph digitization at Providence Hospital Radiology, Portland, Oregon. Airphoto mosaics and contoured flood elevation maps of Crescent City were provided by Crescent City. Support for field logistics, radiocarbon dating, and diatom analysis of vibracore sites in Crescent City was provided by Pacific Gas & Electric, Inc. Dr Lane provided valuable reviews of this manuscript.

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