Age Estimation for Landforms at Tolowa Dunes State Park

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INTRODUCTION

Tolowa Dunes State Park (TDSP), approximately 7 kilometers miles northwest from Crescent City, California (Figure 1), has a sandy beach and dune complex that has a rich cultural history that has been substantially modified by geologic events and processes during the late Holocene. Ground deformation, tsunami, and sedimentation associated with large Cascadia earthquakes, have substantially altered the local landscape and given rise to its current expression. Sedimentation from timber harvesting in nearby watersheds and within the park, and vegetation changes due to cattle grazing before park acquisition, have also affected the landscape. Concerns about the effects of climate change on the landscape and the cultural materials within have given rise to the need for an understanding of the geological influences on coastal geomorphic evolution and the indigenous people. Specifically, there is a need to understand the approximate ages of the landforms at TDSP so that cultural specialists can evaluate the relative risk from sea level rise and other climate change effects.

Excluding Point St. George, a small parcel at the south end of the park that has had substantial archeological and geomorphic investigation, this report provides age estimates for landforms throughout the park based on a variety of dating and mapping methods. This is a companion report to other studies focusing on sea level rise and collection of traditional ecological knowledge from the Tolowa people. These studies have been funded by the North Pacific Landscape Conservation Cooperative (NPLCC project number F12AP00828) as part of a larger program to help understand the past and future effects of climate change on Native Americans in the Pacific Northwest.

Scope of Work

This assessment is based on review of available literature and examination of historical air photos that date to the 1940’s, topography developed from LiDAR (light detection and ranging) data obtained in 2007, limited field mapping of beach, dune and fluvial stratigraphy, discussions with other coastal dune geomorphologists, and reconnaissance site visits to the project area and environs. Radiocarbon dating drew from the work of Tushingham et al. (no date), Meyer et al. (2011), Bicknell and Austin (1991) and unpublished data developed by park staff. Optically stimulated luminescence (OSL) dating drew from work by Michaela Spiske (University of Munich, unpublished data 2013) and our resources using funding provided by the North Pacific Landscape Conservation Cooperative.

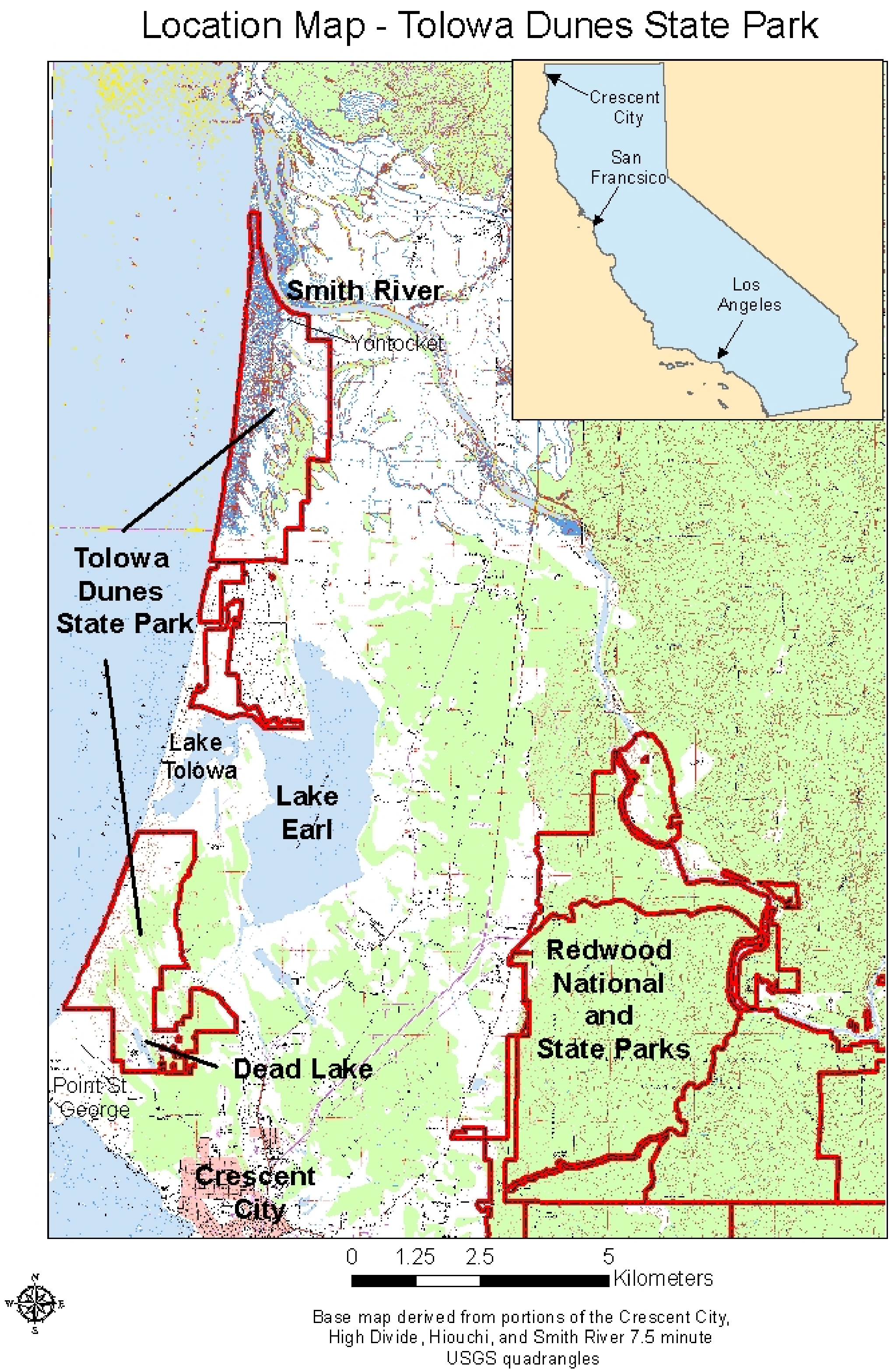

Figure 1. Location of Tolowa Dunes State Park

Location and Setting

TDSP is located on a northeast trending, generally gradually uplifting coastline, between Point St. George and the Smith River. The Smith River crosses the northern boundary of the park. Lakes Earl and Tolowa are linked coastal lagoons that drain the central portion of the park. The informally named Sweetwater Creek drains Dead Lake through the south side of the park. The western side of the park is dominated by an active beach and foredune complex, a deflation plain and a backdune complex that locally has interspersed wetlands. The deflation plain is not continuous and has numerous higher dunes that merge with the foredune. East from the backdunes the northern half of the park has a series of higher, nearly coast parallel dune ridges. The easternmost of the these ridges bears Yontocket Cemetery, a sacred location to the Tolowa people and one of the original foci for dating as part of this study. East from Yontocket Cemetery are the floodplain of the Smith River and sloughs associated with previous oxbows of the river or nearby drainages. Waters from extreme flooding of the Smith River can reach Lake Earl in the central portion of the park.

The southern portion of the park has similar physiography on its western side as the northern part of the park but I interpret its eastern side to be underlain by a sequence of marine terraces that have been overrun by relatively small parabolic dunes. Although the marine terrace surfaces are relatively flat and have a gentle slope towards the north, discreet topographic breaks between individual terraces are not pronounced, suggesting that dune migration has buried the terraces' back edge. However, projection of geomorphic surfaces (Polenz and Kelsey 1999) from outside the dune complex and other data supports the presence of a marine terrace sequence below the dunes. Wetlands are also being overrun by migration of larger dune fronts near Dead Lake, in the southeast corner of the park.

The foredunes, deflation plain and backdunes were stabilized by planting of European beach grass (*Ammophila arenaria,* hereinafter referred to as *Ammophila*) for cattle grazing by early settlers. Initial efforts at removing the beach grass to restore the ecology of the park are underway but the *Ammophila* blankets nearly the entire western half of the park. My most intensive surficial mapping was within the deflation plain. Accessibility was much poorer within dune ridge, marine terrace and some backdune complexes due to forested (mostly shore pine and Sitka Spruce) conditions. The forest was harvested by early settlers and therefore dendrochronology to help date the older dunes was not an available option. Older stumps were not observed and work by Bicknell and Austin (1991) indicated the remaining trees are not more than about 200 years old.

PHYSICAL OBSERVATIONS

Earth Materials

A blanket of Holocene beach and dune sands covers TDSP between Point St. George and the Smith River. Underlying the dune sands Davenport (1982) maps Holocene river terrace sediments, primarily associated with the Smith River at the north end of the Park; Holocene lake deposits, primarily associated with Lake Earl; the Pleistocene Battery formation, comprised of older dune deposits and some of the marine terrace deposits of Polenz and Kelsey (1999); the Pliocene St. George Formation, comprised of poorly bedded marine siltstone and shale; and the Cretaceous to Jurassic Franciscan Mélange, comprised of greywacke, sandstone, mudstone, conglomerate, chert, greenstone, serpentine and rare blueschist in a sheared argillaceous matrix. The latter three units are also exposed at the ground surface at Point St. George but are deformed by folding and tilted to the north, which contributes to their burial by dune sand.

Fine sand is the dominant earth material of the foredune and backdunes. I also observed abundant fine shell fragments in the backdunes, suggesting the possibility of high energy disaggregation of shell to produce the source materials (tsunami?). Fine to medium sand and discontinuous cobble concentrations in the swash zone, comprise the beach deposits. A gravel, cobble and coarse sand deposit crops out in the lee of the foredune within the deflation plain and in low points between back dunes on the west side of the park. This deposit has been interpreted as dominantly tsunamigenic (Leroy et al. 2009). These coarser materials increase surface roughness that in turn inhibits sand transport and movement initiation. Abundant medium grained sand underlies low hummocky dunes that form part of the eastern deflation plain. The medium sand is less prone to wind transport than finer grained material that caps the backdune complex to the east and the foredune to the west.

Geologic Structure

The northwest-striking, northeast-dipping Smith River Fault, mapped as a thrust fault (relatively low angle dip) crosses the north side of the park (Figure 2). I infer another fault, exploited by Sweetwater Creek, crosses the southern part of the park. The inferred fault projects through Dead Lake to the Cemetery scarp, a paleo-shoreline mapped to the southeast by Polenz and Kelsey (1999). The alignment of Dead Lake, offshore projections of displacement in the subaqueous Pleistocene coastline (Meyer et al. 2011), changes in bedrock elevation at depth, and the presence of horsetails (*Equisetum*, a phreatophyte) at the generally well drained foredune crest, support the presence of a fault. This inferred fault is part of the St. George fault complex, about 2000+ meters to the southwest.

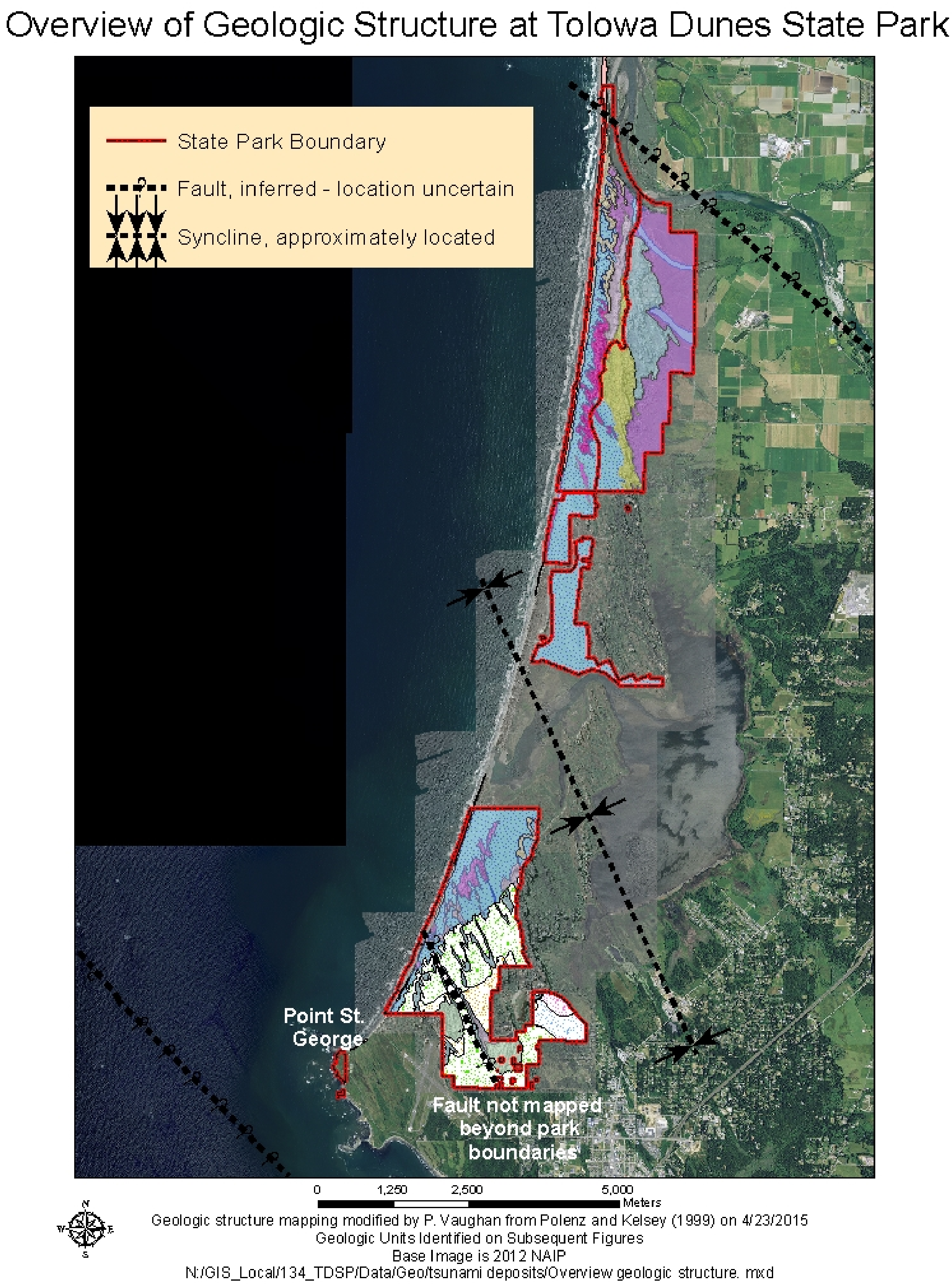

Figure 2. Geologic structure at Tolowa Dunes State Park

Sweetwater Creek loses confinement on its water surface near the location of the southwestward projection (under a series of dunes) of a prominent scarp that runs south-southwest from a peninsula between lakes Tolowa and Earl toward the coastline at the south end of the park. I interpret this scarp as partially reflecting the western edge of the marine terrace sequence (a paleo coastline), which would be underlain by bedrock and help with containment of seaward flow from Dead Lake. This hypothesized terrace edge is more clearly expressed in the imagery much nearer the coastline south from the mouth of Sweetwater Creek. The marine terrace interpretation is consistent with the projection of a flight of late Quaternary marine terraces from Point St. George and southeast from the park below a veneer of dunes in the southern part of the park.

The axis of the northwest-trending Lake Earl Syncline (an upward “U” shaped fold with youngest units in the axis of the fold) crosses through lakes Earl and Tolowa in the central part of the park (Figure 2). LiDAR imagery generally supports a northeastward tilting marine terrace sequence on the southwestern limb of the syncline – this imagery suggests the synclinal axis is slightly farther north than mapped by Polenz and Kelsey (1999). Based on reconstructions and age estimates for the marine terrace sequence, the syncline likely has deformed for at least the last 125,000 years in the hanging wall of the St. George Fault. This syncline and other geologic structures contribute significantly to the geomorphology of the park and help explain; the presence of lakes Earl and Tolowa, local drainage patterns; and the progressively more elevated terrace surfaces south from the lakes on the ascending southwestern limb of the fold. However, the northeastern limb of the syncline is less well expressed morphologically immediately north from Lake Earl, leaving open the possibilities that the syncline is asymmetrical and/or the deposits at that location are too young to record a moderately low rate of deformation. The pattern of erosion at the coastline appears to mimic the pattern of deformation recorded inland. As subsequently discussed this plays a role in the assessing the threat to cultural resources.

PHYSICAL PROCESS RATES

Sediment supply, sea level trends, and coastal erosion and deformation

Limited bathymetric data (United State Geological Survey [USGS] 7.5 minute quadrangle maps for Smith River and Childs Hill) indicate that the nearshore area west from Tolowa Dunes drops off at a moderate rate. While there is a small subaqueous fan at the mouth of the Smith River, it is not pronounced, suggesting that at least some of the sand travels farther offshore and is lost to the terrestrial system. The Smith River produces about 137,000 meters^3/year of sand and gravel (Hapke et al. 2006), or almost an order of magnitude less sediment than the Klamath River to the south. The coastline between the mouth of the Smith River and lakes Earl and Tolowa has prograded about 0.7 meters/year since about 1870 (visual estimate of Figures 15 and 17 in Hapke et al. 2006). Just north from lakes Earl and Tolowa, the coastline has been static or generally eroding since 1870. This could be due to depletion or attenuation of sediment from the

Smith River and/or due to slow deformation of the coastline related to asymmetrical folding of the Lake Earl Syncline. The USGS described the potential for coastal erosion from anticipated, climatically driven sea level rise, based on a coastal vulnerability index that evaluates several physical parameters, as high just north from Point St. George and moderate for the coastline north from lakes Earl and Tolowa (Thieler and Hammar-Klose 2000).

Using two scenarios the International Panel on Climate Change (IPCC 2014, Figure SPM.6) forecast mean sea level rise projections associated with climate change to be between 0.44 and 0.73 meters (~1.44 to 2.4 feet), with an uncertainty maximum of about 0.97 meters (~3.18 feet), by the year 2100, assuming the marine based part of the Antarctic ice sheet does not collapse. If the ice sheet collapses, up to 5+ meters of sea level rise could occur within the next few centuries, which would inundate much of the deflation plain behind the foredune. Elevation data suggests ice sheet collapse could result in a future coastline near the paleo coastline interpreted to front the marine terraces on the south side of the lakes Earl and Tolowa. Every 0.3 meters of sea level rise translates into about 15 to 30 meters of landward erosion on relatively low slope beaches, assuming no secondary factors (e.g., beach stabilization or sand transport in or out of the studied compartment [Day 2004]). This is a static assumption because a variety of factors could affect sediment loading that in turn helps control the location of beach and dune progradation and erosion: increased storm frequency or Cascadia earthquakes could generate additional sediment; deformation of the syncline or faults could alter bathymetric and terrestrial elevations; improvements in upwatershed landscape management could reduce sediment loading; and changes in climate, or dune restoration activities, could affect vegetation and therefore dune stability. A detailed study of extrinsic factors on the sand balance is beyond the scope of this assessment but I have illustrated the location of geologic structures and historical erosion as a guide to the areas most likely to experience future tectonic change.

Confirmation of local tectonic deformation comes from a study by Bicknell and Austin (1991). They used opal phytoliths and pollen to reconstruct recent vegetation changes as interpreted in cores, and reported sudden changes in the groundwater level of approximately 0.6 to 0.9 meter (~2 to 3 feet) both upward and downward in Yontocket Slough, on the northeast side of the park. These rapid vegetation changes are compatible with broader scale coastline deformation, although stream capture (likely tectonically driven) or other mechanisms could also explain Bicknell's and Austin's observations. Their radiocarbon dating of bulk soil matrix in the cores (Susan Bicknell, personal communication 2009) lead them to suggest that these ground level changes were compatible with age ranges for two Cascadia earthquakes. Bulk soil is not the ideal medium for dating, though subsequent coring work by Pacific Watershed Associates (2005) suggests Bicknell may have dated peats, which can yield more accurate ages than bulk soil. What is clear, however, is that rapid vegetation changes have occurred at TDSP that are compatible with a tectonic deformation interpretation. Radiocarbon dates obtained from the south bank of the Smith River near Yontocket Slough as part of this study support significant changes in depositional style synchronous with the A.D. 1700 Cascadia estimated magnitude 9 earthquake and an earlier Cascadia earthquake.

The park is within a zone that has been modeled as having interseismic strain (accumulating deformation between large Cascadia subduction zone earthquakes) of about 4 millimeters per year (Fluck et al., 1997). A Plate Boundary Observatory (PBO) station at Point St. George reveals recent geodetic uplift of about 2-3 millimeters per year. The modeled data is very coarse and the PBO data does not have a sufficiently long record to make a definitive deformation rate estimate; the PBO station is also adjacent to the Point St. George fault, which may have a local effect on the uplift signal. However, recent uplift at the south end of the beach is compatible with the longer term marine terrace stratigraphy of Polenz and Kelsey (1999) and mostly higher rates of coastal erosion south from lakes Earl and Tolowa since the 1950’s to 1970’s (Hapke et al. 2006). Data from an offshore buoy also indicates this section of the coast is currently uplifting, causing sea level to actually drop relative to the coastline. This would likely reverse suddenly during a Cascadia earthquake.

Goldfinger et al. (2012) estimated the probability for a magnitude 8+ southern Cascadia subduction zone earthquake, capable of affecting vertical change along significant portions of the North Coast, as having a probability of occurrence of about 32 to 43% before 2060. They estimated the probability for full rupture of the Cascadia fault zone (~earthquake magnitude 9) at 7-11% over the same time frame. An earthquake of magnitude 8 or greater could produce sufficient displacement to alter the characteristics of entire coastal segments. Together, the sea level rise predictions and earthquake probabilities, evidence for recent-prehistoric ground deformation, and the presence of a synclinal axis that could subside during an earthquake, suggest a high potential for increasing seasonal inundation of the deflation plain, at an elevation of about 4 meters above mean sea level, over the next 100 years. There is a moderate potential for substantial, possibly long-term, inundation over the next 150 years, the management horizon for California State Parks.

Historical beach accretion and river migration

Short term progradation (since the 1950’s to 1970’s) at the immediate mouth of the Smith River has roughly doubled (to about 2 meters per year) when compared to the over the long term rate (mid-late 1800’s to 2006) (Hapke et al. 2006). This likely relates to deposition related to the 1964 flood, the flood of record since Euro-American occupation, and more intensive upwatershed land use practices. South from the immediate mouth of the river the long- and short-term horizontal accretion rates gradually decrease until there is an approximately static coastline just north from lakes Earl and Tolowa. The long term coastline position has been generally static from lakes Earl and Tolowa to Point St. George, though there is an increase in long term erosion near the inferred fault at Sweetwater Creek. Shorter term erosion has been more significant immediately west from Lake Tolowa and at the southern end of the southern half of the park. These data indicate that the current foredune crest is comparatively youthful in the northern part of the park and within a few tens of feet of its plan view location in the mid-late 1800's at the northern end of the southern part of the park. The foredune dating to the 1800's is mostly eroding (or has eroded) at the south end of the of the southern park's coastline; this area is currently vulnerable for loss of pre-historic cultural materials.

The coastal plain between the Smith River and Lake Earl has minimal relief. Sea level rise of two to three meters could also encourage capture of the Smith River due to headward erosion by Lake Earl, which in turn could significantly alter the morphology of the beach as the river flowed through the breach at Lake Tolowa. Back (1957) interprets the Smith River as having flowed though Lake Earl around the time of the Pleistocene-Holocene transition. All things being equal I would expect the easternmost boundary of the Yontocket dune field to be at least as far from the coast at Smith River as at South Dune, a large dune in the southeast corner of the park, in light of its greater sand supply. This not being the case suggests that the dune field near Yontocket has been modified and the logical implication is that the Smith River has affected the current eastward extent of the dunes. Assuming this to be the case the age of the eastern dunes provides a minimum constraint for the last significantly erosive southward excursion of the Smith River. Floodwaters have ponded across the coastal plain during historical floods but the river thalweg has been at its current location or to the north during the latest Holocene (see subsequent discussion for more accurate age estimates). If capture of the Smith River was to occur it would have a substantial impact on cultural sites by redirecting the river's locus of deposition and erosion.

The banks of the Smith River are migrating southward. Easily erodible dune sands, fluvial sands and gravels and a marsh deposit comprise the south bank of the Smith; the river has marched southward at an annual rate of about 4 meters per year since 1950. Cultural deposits have been eroded from this bank over the last few years. The southward migration of the Smith River could facilitate future capture by Lake Earl. In the absence of its capture the Smith River will reach Yontocket Cemetery in ~100-125 years at current migration rates. Though the character of the river's future hydraulic geometry is speculative there are no earth materials that would help impede the river's continued southern migration.

Tsunamis

Most of the west side of the park is within a high tsunami hazard zone with the potential for high wave velocity (Figures 3 and 4). Figures 3 and 4 reflect tsunami modeling by the California Geological Survey (CGS 2009a and 2009b) associated with a large Cascadia earthquake. The modeling reflects the current coastline elevation and landform distribution of the park. Previous tsunamis may have encountered different elevations or landforms, though a Native American legend about tsunami floodwaters virtually encircling the dunes (as the tsunami migrated up the Smith River) is compatible with the modeling near Yontocket Cemetery on the northeast side of the park. Because tsunami floodwaters essentially obliterate most low profile terrestrial features in their

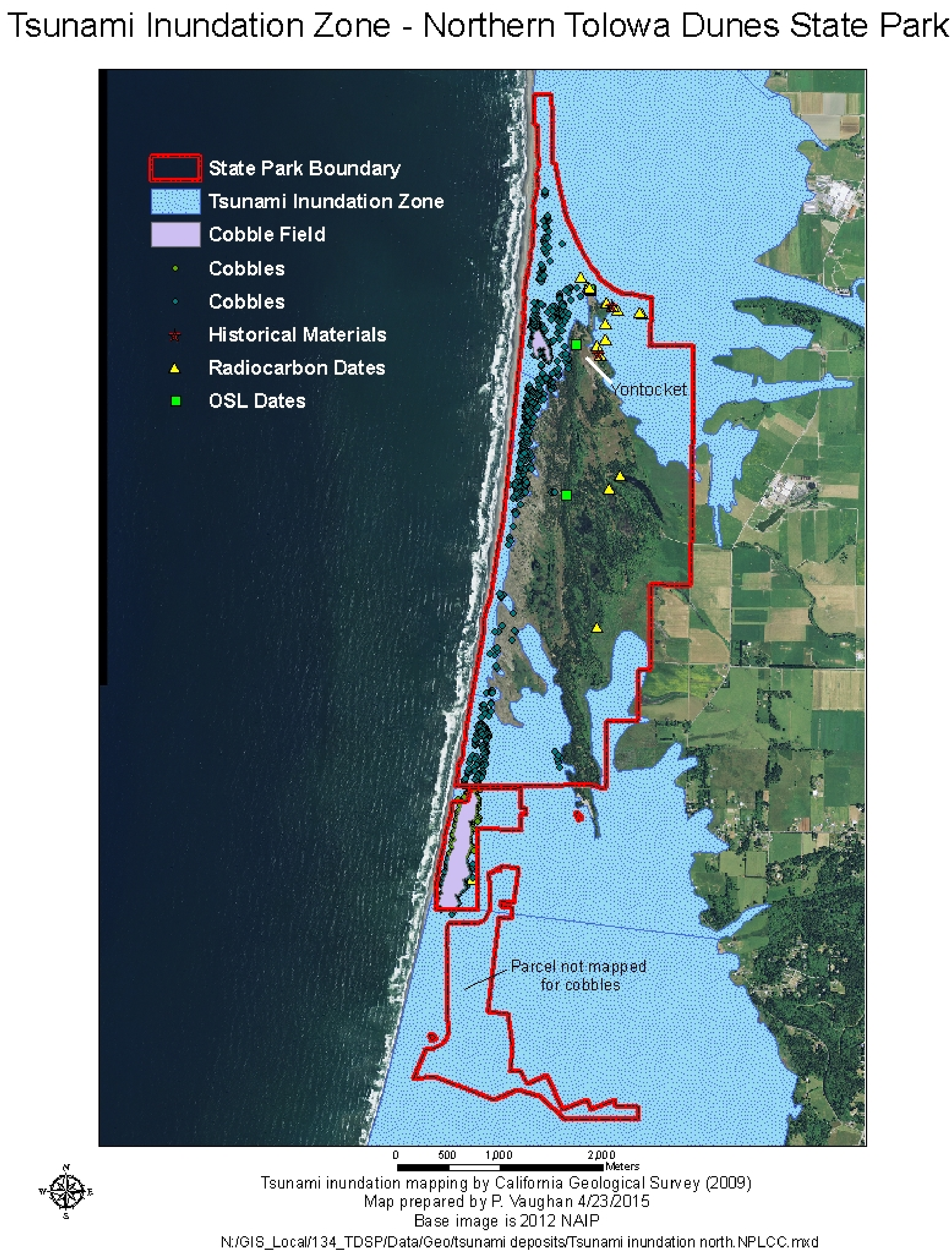

Figure 3. Tsunami inundation zone, cobble and dated sites in the northern part of Tolowa Dunes State Park

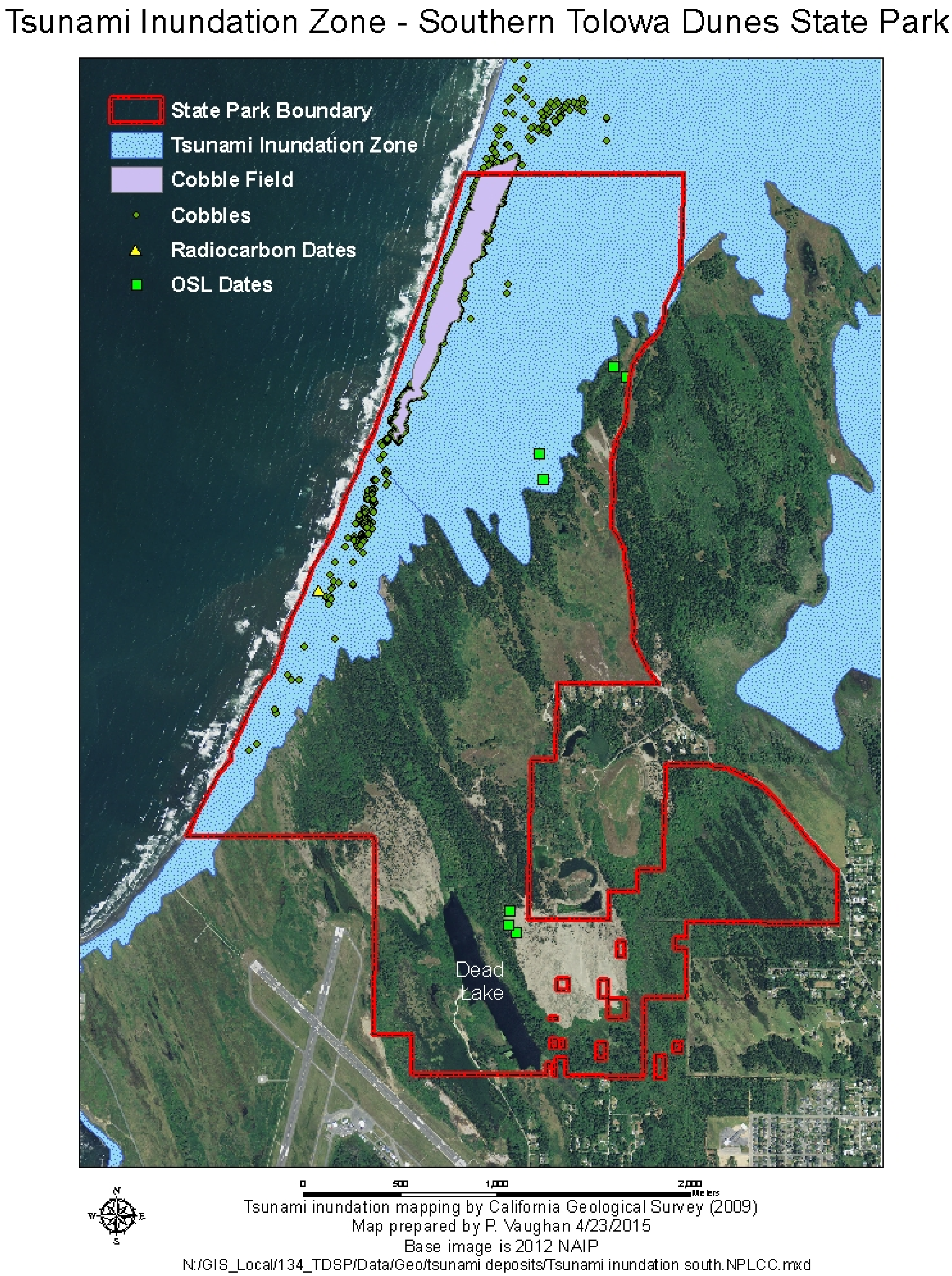

Figure 4. Tsunami inundation zone, cobble and dated sites in the southern part of Tolowa Dunes State Park

path, evidence for tsunami is important for assessment of the potential for encountering intact cultural materials. Knowledge of tsunami history can, by inference, help limit the ages of cultural materials found with tsunami hazard zones. That said, tsunami can leave landscape areas relatively unscathed (e.g. pedestal remnants of foredunes following tsunami have been reported in the South Pacific), though they do not represent large areas of the overall landscape.

Evidence for the run up locations and energy associated with past tsunamis comes from a unique deposit (c.f. Nichol et al. 2003; Leroy 2006; Leroy et al. 2009). Cobble and gravel that crops out east from the foredune, mostly within the deflation plain but with exposures in interdune swales, represents potentially unique geologic information (Figures 3, 4 and 5). Examination of several lines of evidence excludes fluvial deposition, storm surge, or cultural origins as its principal depositional mechanism. Fluvial deposition is excluded for the following reasons: 1) the deposit is asymmetrically cobbly (coarser toward the ocean) and locally deposited over the lee of foredune deposits on the western side of the deflation plain - its asymmetry and position with respect to the foredune indicates the deposit is not derived from the axial swales that help drain some of the deflation plain; 2) there is virtually no geomorphic evidence for tributary channels or sheet wash to the axis of the deflation plain with the stream power to subsequently re-transport the larger cobbles from the site, thus creating an eastward facing slope for some of the deposits; 3) the cobble deposits have pholad bored clasts, clasts found only offshore (Point Saint George Formation) and marine (polychete) worm shells , indicating a marine source, rather than a fluvial terrestrial source (such as the Smith River) that might have flowed through lakes Earl and Tolowa or along the beach; and 4) the lighter and/or smaller clasts and shells are farther inland, consistent with greater buoyancy and landward fining if derived from the ocean.

I discount an old beach or storm surge deposit for the majority of the clasts because: 1) they locally mantle lesser dunes in the lee of the foredune and these dune forms likely would not survive on an active beach capable of depositing material a few hundred meters farther east; 2) the eastward-facing slope of the deposit is opposite the slope of the westward-facing beach profile that would be most typical of a storm surge or beach deposit; and 3) the elevation of the uppermost cobbles appears higher than the potential for current storm surge to somewhat uniformly deposit large cobbles to small boulders with limited buoyancy.

Though the beach may have been uplifted by post- or syn-depositional tectonic deformation and thus could be within the range of earlier storm surges, the other reasoning still discounts a dominantly storm surge or uplift explanation. That said I observed some light weight anthropogenic marine debris (a Styrofoam float) in an interdune swale that suggested storm surge could reach the middle of some of the cobble fields. The thickness of the cobble field exposed in a road cut shown in Figure 5 is fairly astounding, suggesting that co-seismic uplift of the beach could be a contributing, though not dominant factor. The peak elevation and comparative youthfulness of some of the cobbles (see subsequent age dating discussion) would

Figure 5. Road cut exposing cobble deposits interpreted as tsunamigenic. Hand held GPS instrument for scale.

require about 5 to 7 meters of latest Holocene uplift at the north end of the beach. This is neither consistent with longer term rates of uplift for marine terraces in the area (0.1-0.3 millimeters per year, Polenz and Kelsey 1999), nor the general geomorphic expression of the beach and dune complex. Localized co-seismic subsidence near fold axes could create depressions that would promote collection of tsunami driven cobble deposits.

The abundance of the clasts and their range of particle size preclude Native American beach gathering and subsequent deposition for cooking or curing of fish, though their activities have affected or relocated some of the deposits. I mapped all cobble concentrations and most outliers west from the dune ridge complex. A few outliers could have been carried by Native Americans or park visitors onto the higher dune margins, higher than estimated tsunami surge elevations. These areas were not considered to have been affected by tsunami.

The general eastward reduction in clast size, marine source materials, and deposition over dune landforms (cobbles could fall from a turbulent water column created by a tsunami though survival of the dune forms would not be a common occurrence) all support a tsunamigenic origin. The coincidence of the cobbles and the CGS tsunami modeling, especially more inland just south from the Smith River (Figure 3) also supports a tsunami origin. Assuming the cobbles reflect tsunami deposits, locations where intact cultural materials of certain ages might be encountered can be constrained.

Coastal Flooding

Accretion of the foredune may have inhibited coastal erosion and thus contributed to the preservation of sensitive resources within or eastward from the foredune over the last century. Air photos dating to the 1940's and late 1950's show tonal contrasts that indicate areas of active sand movement. However, most of the dunes were stabilized by vegetation by that time. Oblique aerial photography from 1972 (California Coastal Records Project 2015) showed extensive wood on the beach seaward from an *Ammophila* steepened but nearly continuous foredune (possibly residue from the 1964 flood, which contributed copious amounts of wood to North Coast beaches). A small breach in the foredune appears on the 1972 photography down gradient from a series of small ponds in the southern part of the park (this breach was subsequently closed by foredune accretion). These ponds likely experienced some overflow that made its way through the foredune. Stereo aerial photography from 1986 did not reveal blowouts at the southern foredune (other than Sweetwater Creek) even though this photo set only slightly post-dated the heavy storm years of the early 1980's, when substantial retreat occurred along much of the erodible California coastline. Much of the woody debris on the beach in the early 1970's was not observed in aerial photography from the mid-1980's suggesting the storms of the early 1980's relocated the wood.

The tsunamigenic deposits in the lee of the foredune and throughout the deflation plain provide some constraint on the longer term incursion of coastal flooding. They semi-continuously mantle the western deflation plain and a few small dune deposits up to about 6 meters in elevation (NAVD 88); the cobbles crop out in isolated patches up to 7+ meters in elevation. Some dunes in the lee of shore pines within this deposit lack cobbles suggesting either these dunes post-date cobble deposition and that they formed from some component of sand that passed through the foredune or reactivated from the deflation plain, or that their crests may have cobbles that were subsequently coated with a veneer of fine sand (no invasive testing was performed to resolve this question). Tsunamis in 1960 that originated in Chile and 1964 that originated in Alaska did not attain these elevations along this section of coast (maximum reported water elevation was 4.5 meters above Mean Low Low Water at Pebble Beach, south from Point S. George [Magoon, 1966]). Therefore the cobble deposits predate those tsunamis (some of the cobbles also have a patina on their exposed sides, suggesting their stability predates the 1960's). Local evidence of cultural manipulation of the deposit supports a pre-1964 age for the cobble deposit (Greg Collins, California State Parks archeologist, personal communication 2009). Back (1957) reported small boulder slabs of St. George Formation in the lee of the foredune just north from Lake Tolowa, and although he ascribed a storm surge origin for the deposits, his work predated current knowledge of the tsunami potential for this section of coastline. His observations also predate 1960, supporting an older age for the deposit. Diatom analysis for sediments on the southern bank and floodplain of the Smith River and in a bog on the east side of the cobble field north from Lake Tolowa did not corroborate a marine origin (Hemphill-Haley 2012). Historical debris later encountered in the river bank and subsequent radiocarbon dating indicates the sites analyzed for diatoms were too young to be associated with pre-historic Cascadia generated tsunami. Together these data suggest the 1964 tsunami was not a source for the cobble fields and did not substantially affect the park. This is also confirmed by historical aerial photography along the beach. Aerial photography from 1965 showed landscape changes along the floodplain of the Smith River but these appear to be associated with the December 1964 flood, rather than the March 1964 tsunami.

The most significant tsunami that shortly predates the 1964 event, as recorded in cores in southern Crescent City, is associated with the well age constrained, estimated Magnitude 9 Cascadia earthquake in A.D. 1700 (Dengler and Magoon, 2006). Because the cobbles are preserved I infer that processes related to coastal flooding have not substantially affected the majority of the deposits for at least 300+ years, except perhaps at the southernmost end of the park, where the coastline is eroding and the western side of the foredune appears more dynamic and less elevated. Secondly, their elevation and large clast size and widespread distribution well inland suggest the cobbles have not been substantially buried by, or associated with storm surges. However, more buoyant wood, mostly associated with the westernmost cobble deposits, cannot be precluded as having a storm surge origin. Together these data suggest that coastal flooding has not encroached significantly landward from the foredunes over the last few hundred years. However, more buoyant wood as far inland as ~125 meters landward from breaches in the foredune, cannot be precluded as having a coastal flooding origin.

For the timing of latest Holocene tsunamis associated with Cascadia earthquakes I examined the record Goldfinger et al. (2012) developed from cores advanced into turbidite deposits along the length of the Cascadia fault zone (Northwestern California to Northern Washington). Turbidites are accumulations of offshore shelf sediments deposited by density currents. Goldfinger et al. assumed the turbidites recorded Cascadia earthquakes and I infer that these events caused tsunami at TDSP. Specifically, I examined the record at the Smith River Canyon offshore from TDSP. Goldfinger et al. report that the southern segment of the Cascadia subduction zone (Southern Oregon to Mendocino County in Northwestern California), which includes the Smith River Canyon, has a Holocene earthquake mean recurrence interval (RI) of about 240 years. This estimate includes earthquakes that rupture the entire Cascadia fault zone, which has a mean RI of about 500-530 years. This indicates the southern segment at TDSP has more frequent, smaller earthquakes (still estimated at Magnitude estimated ~7.5 to 8+ based on fault length) interspersed within ruptures of the entire fault zone (estimated at ~ Magnitude 9 to 9+). Earthquakes of these magnitudes associated with thrust fault movement of the Cascadia subduction zone could produce tsunami at TDSP. Smaller earthquakes that are potentially associated with a southernmost sub-segment of the southern segment could also produce tsunami, though they are less likely to produce large scale landscape changes at TDSP (e.g. ~ Magnitude 7 1992 Petrolia earthquake).

The ages reported here reflect the averages and OxCal radiocarbon error range corrections for all correlated earthquakes from turbidite data along the length of the fault zone (Table 10 in Goldfinger et al. 2012). Where present, the Smith River Canyon turbidite ages correspond well with the average ages. Typically “years BP” refers to years before A.D. 1950, when the atomic bomb was set off, which essentially set the clock to zero for radiocarbon dating. The ages I am using for terrestrial dating at TDSP combine both radiocarbon dating, and optically stimulated luminescence dating, which uses a normal Gregorian calendar based on the time of OSL dating. Therefore, all ages reported herein have been converted to the Gregorian calendar to facilitate comparison.

Using this reporting methodology Goldfinger et al. described: event T1, A.D. 1682 (A.D. 1611-1750 or 265 to 404 calendar years before A.D. 2015) - this event is well dated and likely occurred in late January A.D. 1700 based on Japanese historical accounts of tsunami (Satake et al. 1996); event T2, A.D. 1456 (A.D. 1402-1502 or 413 to 513 calendar years before A.D. 2015); event T2a (southern segment only), A.D. 1349 (A.D. 1222-1484 or 531 to 793 years before A.D. 2015); event T3, A.D. 1149 (A.D. 1110-1190 or 825 to 905 calendar years before A.D. 2015); event T3a (southern segment only), A.D. 874 (A.D. 739-1003 or 1012 to 1276 calendar years before A.D. 2015); event T4, A.D. 722 (A.D. 672-772 or 1243 to 1343 calendar years before 2015); and event T4a (southern segment only), A.D. 564 (A.D. 430-704 or 1311 to 1585 calendar years before A.D. 2015) (Table 1). Aalto et al. (1999) inferred a tsunami deposit recorded in a bog on a marine terrace above Pebble Beach, just south from Point St. George, dated to between A.D. 130 and A.D. 650, compatible with events that either date to T4a or predate T4a. All things being equal rupture of the entire fault would be more likely to generate the most landscape change due to longer shaking, and more deformation, sedimentation and possibly higher tsunami run up.

Table 1. Age estimates for latest Holocene Cascadia subduction zone earthquakes

Earthquake Event	Best Estimate	Error Range	Calendar Years before A.D.2015
T1	A.D. 1700	A.D. 1611-1750	265-404
T2	A.D. 1456	A.D. 1402-1502	413-513
T2a	A.D. 1349	A.D. 1222-1484	531-793
T3	A.D. 1149	A.D. 1110-1190	825-905
T3a	A.D. 874	A.D. 739-1003	1012-1276
T4	A.D. 722	A.D. 672-772	1243-1343
T4a	A.D. 564	A.D. 430-704	1311-1585

Age Control for Tolowa Dunes State Park Landforms

Several dating methods helped constrain the development of the stabilization of geomorphic surfaces at TDSP (Appendix A). Radiocarbon dating, optically stimulated luminescence dating of dune sands, and observation of buried anthropogenic materials helped constrain the timing of earth material deposition. Interpretation of historical air photos and historical maps, historical literature, and regional geological correlations all contributed to the age estimates and development of the mapping units reported here (Figures 6 and 7). The maps are not intended to reflect geologic “truth”. They should be considered a first approximation to help guide cultural investigation as to the ages of landforms in the general vicinity of site specific investigation. The maps have areas within individual units that will likely fall outside the indicated range due to map scale issues. The digitization of the maps is somewhat coarse for site specific application. Some of the mapping involves distant extrapolation. If age dating is crucial to understanding a specific site then further work is recommended. Site specific improvements are possible but can’t be presented at the map scale of the park.

The following interpretations relied heavily on optically stimulated luminescence dating of fine sands found in the dune complex. Electrons that are generated in the earth materials from decay of radioactive isotopes in the soil are trapped by imperfections in sand dunes’ quartz and feldspar grains. We collected sands in an opaque medium for analysis. When the sands’ crystal traps are exposed to light in the laboratory the electrons leave the trap, counted and then compared with background radiation levels. The more electrons leaving the trap the longer the site has been shut off from light (buried). In this manner the timing of burial/stabilization of the sampled site and/or the age of the overlying deposit, if present, can be determined. The estimated ages for any landform reflect ages of deposits within about 0.5 to 2 meters of the current ground surface (except as noted in Appendix A). One meter was the nominal sampling depth for most OSL dating; radiocarbon dates may have been obtained from slightly deeper earth materials. Earth materials at greater depths could be within the indicated age range but also could be older.

Inherent to the following characterization of TDSP landform ages is the assumption that landscape was altered substantially by Cascadia earthquakes. Goff et al. (2008) report that development of dune ridges, such as those observed in the northeastern part of TDSP, can be derived from sediment carried to the coast following instability caused by major earthquakes. This, the development of landward sand sheets caused by tsunami damage to existing dunes, and possibly increased exposure of beach deposits due uplift or erosion associated with relatively higher sea levels due to subsidence, provide a ready source of sand to initiate processes conducive to the development of coast parallel dune ridges. The more extensive development of dune ridges in the northern part of the park is compatible with its proximity to the current course of the Smith River.

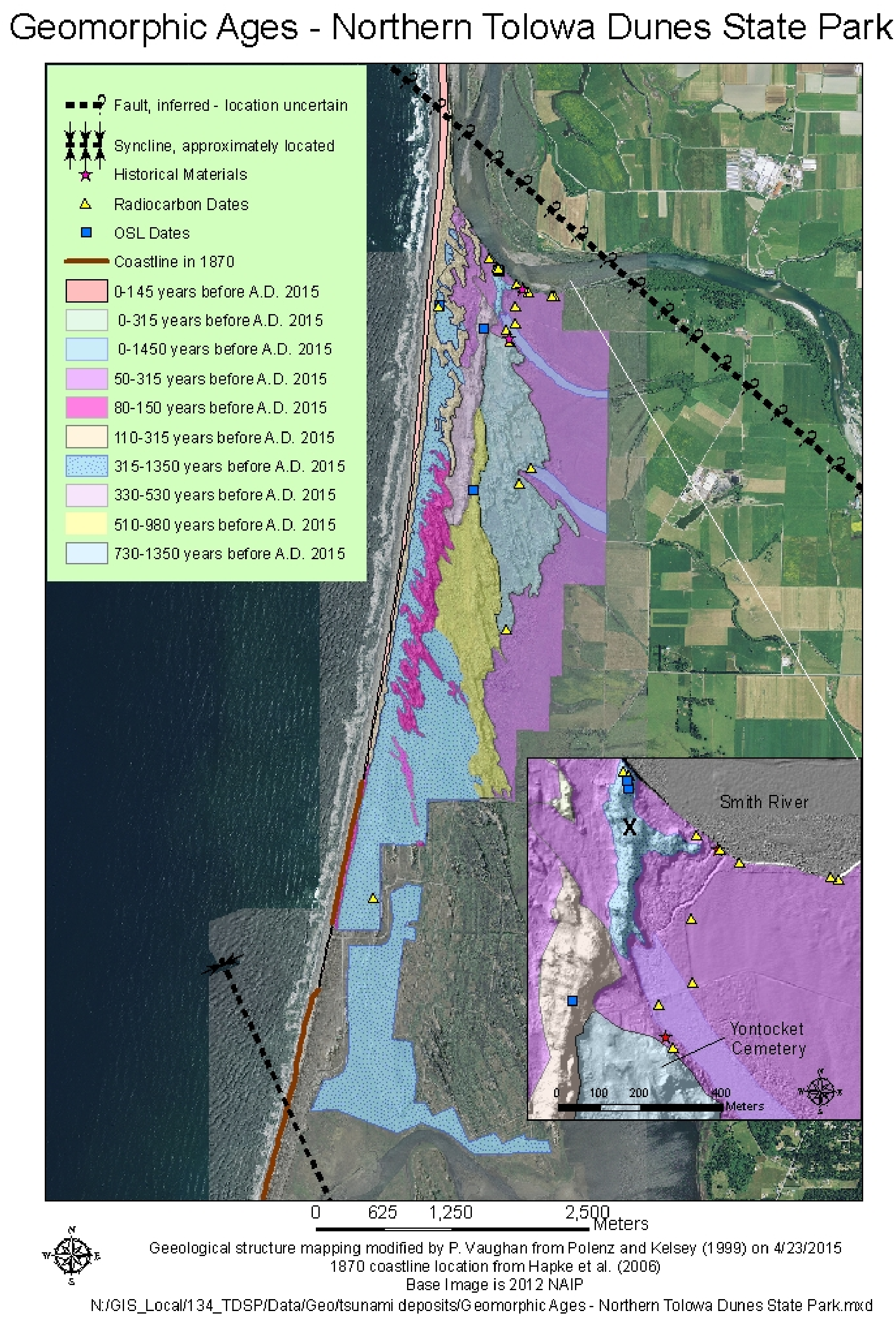

Figure 6. Geomorphic ages for landforms in northern Tolowa Dunes State Park.

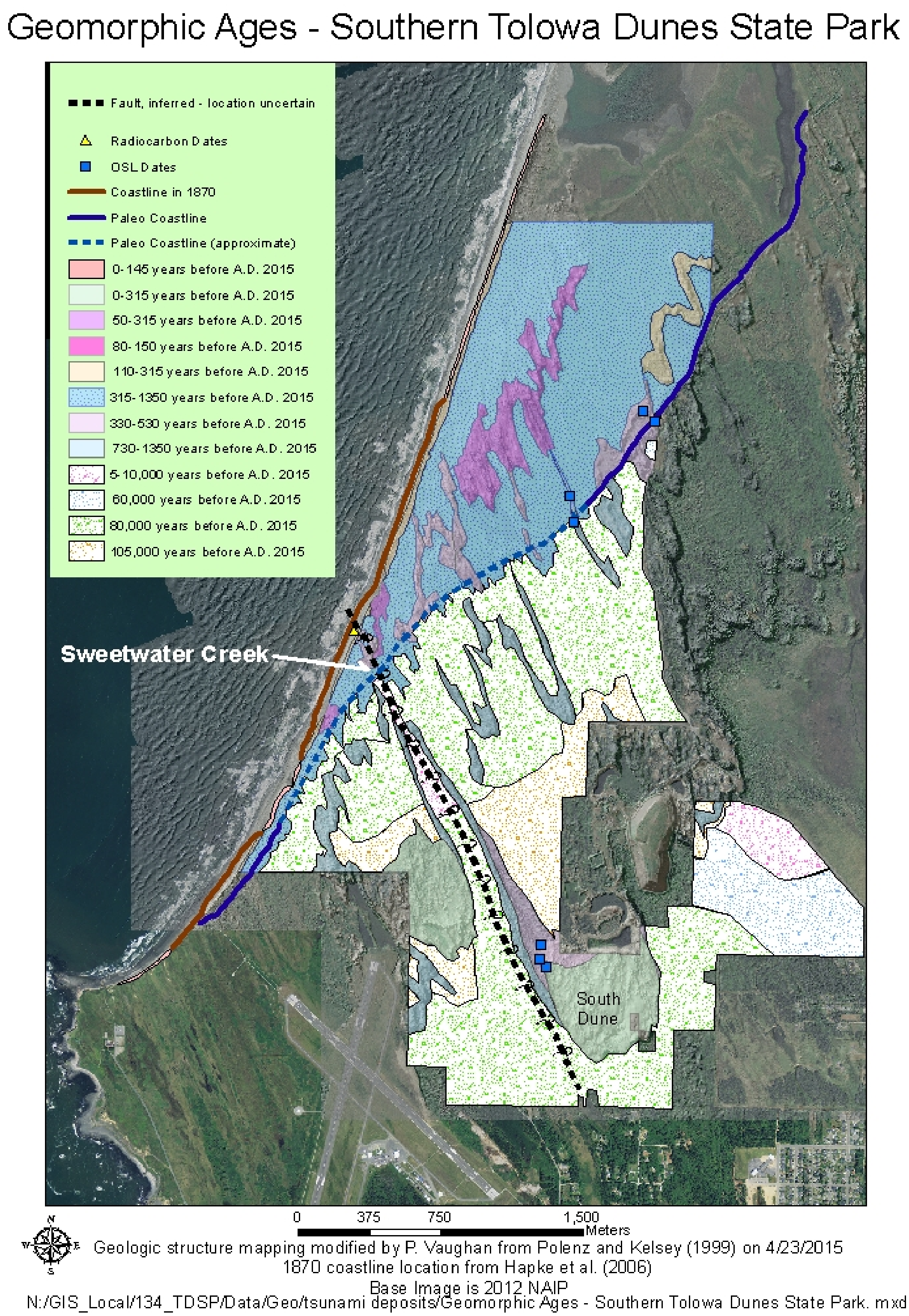

Figure 7. Geomorphic ages for landforms in southern Tolowa Dunes State Park.

More extensive, older (Pleistocene) dunes southeast from the park (Davenport 1982) are compatible with the mouth of the Smith River previously reaching the vicinity of Lake Earl.

South bank and floodplain of the Smith River

From bottom to top the 2 to 3 meter high southern bank of the Smith River locally exposes coarse fluvial gravel at its base, a root-cast rich, silty clay, marsh deposit with abundant wood at the base and top of the unit, and a series of overbank sands and silts that underlie the active floodplain. Closer to the dune and beach complex, the overbank sands and silts are intercalated with sand dune and beach deposits. Young radiocarbon dates (T4-YON1-U1, T3-YON1-U5) and a piece of beer glass (YCEM-COR2) from test pits and/or hand augered cores in the southern floodplain deposits of the river, east from the dune ridges, attest to the youth of the floodplain (post - A.D. 1480 but likely post - A.D.1850 based on the historical materials and the statistical probability for younger ages for the radiocarbon dates). This estimate is also corroborated by a piece of barbed wire (Panel 39) observed in the river bank near the base of the overbank deposits and limiting ages for the marsh deposit.

The top of the marsh deposit locally has soft sediment deformation and liquefaction flame structures at the elevation of peat (PANEL38N2P1) and wood (BE-YON1-02, BE-YON2-01, BE-YON2-02, PANEL38N2P1) that consistently date to about A.D. 1700. An intercalated overbank-dune deposit that transitions to the top of the marsh deposit (PANEL86N4) has a similar age. This suggests that cessation of marsh deposition probably dates to Cascadia event T1. Multiple radiocarbon dates on wood at the base of the marsh deposit that range in age from A.D 1290 to A.D. 1410 (DNO-4Cu-300, BEMEYER-A275 and DNO-5Cu-400 - 2 sigma correction), are most consistent with Cascadia event T2a, though the younger event T2 cannot be precluded, because the dates reflect a maximum age for the base of the unit. This event probably initiated a change from coarse fluvial deposition to finer grained marsh deposition and was associated with initiation of abundant wood deposition from the upper watershed. Clustering of the dates suggests that the wood source was derived from a single event that likely affected the entire Smith River basin (e.g. an earthquake). An intermediate age from the middle of the marsh deposit (DNO-3Ab-150-160) is consistent with the radiocarbon ages for the top and bottom of the unit.

Slough deposits

Two prominent sloughs cross the floodplain east from the dune ridges: Yontocket Slough, immediately east from the Yontocket Cemetery; and the informally named Crescent Slough. Crescent Slough is south from the cemetery and terminates at a high angle to the dune ridge trend. Cores indicate the slough deposits were overrun by and intercalated with dune sand. Yontocket Slough, the location of a Tolowa massacre by Euro-American settlers in A.D. 1853, is subparallel to the dune ridge. Exposures of peat, slough vegetation and soft sediment deformation in the south bank of the Smith River indicate the slough merged with the marsh deposit slightly farther west than its current confluence. Dune migration appears to have subsequently deflected the confluence eastward.

Bicknell and Austin (1991) obtained radiocarbon two dates on bulk sediment from a core in Yontocket Slough (LE CORE 2) near the access road to the cemetery. They used sediment, pollen and opal phytolith stratigraphy to characterize environmental conditions and found abrupt changes in the water table that they attributed to earthquake generated deformation of the ground surface around A.D. 1000 and A.D. 1650. Assuming their interpretations are correct, these events would likely correspond to events T3a and T1, respectively. LE CORE 2 had five pulses of sand in the slough deposits younger than about A.D. 560.

A radiocarbon date on bulk soil (CPRD-CR1BS-193) from a core advanced in Crescent Slough as part of this study show that the oldest dune deposits at that location dated from about A.D. 889 to A.D. 994; the median probability for this date is A.D. 945. This is the oldest direct radiocarbon age control for the east side of the dunes. Based on the dunes' location relative to the beach, this reflects the age range for initial accumulation of the dune ridge complex. This could be compatible with initial sand accumulation following event T3a and is compatible with the earthquake interpretation by Bicknell and Austin (1991). An in situ grass blade (CPRD-CR1GB-68) higher in the same core post-dates A.D.1650 but no unique sedimentation signals are associated with this date.

<u>Pond deposits</u>

There are a number of ponds on the east side of the dune ridge complex that align with alluvial fan channels or sloughs that project eastward from the Smith River floodplain. Two radiocarbon dates (EP1-COR2WD35 and EP1-COR1SD35) from marsh deposits in one of the northernmost ponds post-date A.D. 1950. A third radiocarbon date (EP2-COR1-50) from marsh deposits in one on the southernmost of these ponds post-dates A.D. 1660. These dates indicate the uppermost marsh deposits are relatively young but do not fully constrain the initiation of marsh deposition. A large gravel clast encountered in the auger core from the southernmost of these ponds supports the concept that the ponds have fluvial deposits at their base.

Radiocarbon dates from a root (KESBG-TP1R26) and soil (KESBG-TP1BS26) within cobble strata in a bog on east side of the cobble field post-dated A.D. 1950. In the absence of marine diatoms in the soil (Hemphill-Haley 2012) and other evidence indicating the 1964 tsunami did not contribute to the cobble fields these dates did not illuminate tsunami history. The significance of the absence of marine diatoms within the cobble strata at this site has not been resolved.

Beach and dune cobble deposits

A somewhat rotted redwood log is partially buried in a 50-centimeter thick marine sand and cobble deposit at an elevation of about 6.5 meters above sea level and ~150 meters from the coast, on the north side of the park. There are no redwood trees on the western beach and dune complex and currently no forested conditions at the log, indicating it likely washed ashore with the other marine deposits. The 2 sigma radiocarbon date (TOLN-LOG1-1) from this log is A.D. 1160 to A.D. 1260 with an intercept for the radiocarbon age and the calibration curve at A.D. 1220. This represents a minimum age for the deposit. About 40 centimeters below the base of the marine deposit an underlying, cobble-free dune sand has an OSL date (BTC-L1) of A.D. 814 to A.D. 1234 with a best estimate of A.D. 1024. Assuming the marine deposit has a tsunamigenic source its deposition is compatible with event T3 or younger. The underlying dune sand dates to event T2a or older based on the OSL date but assuming the dune ridge to the east began forming ~ A.D. 945, the dune is likely not older than event T3a. Because the dune sand stabilized and began accumulating “age” when it was buried by the marine deposit, its burial could date to either event T2a, T3 or T3a. The overlap for the estimate of the marine and dune age ranges best supports event T3.

Cross cutting relationships also help constrain the age of the tsunamigenic cobbles. A few cobbles crop out in exposures of the south bank of the Smith River and litter the ground surface south from the river. These cobbles stratigraphically overlie the top of the marsh unit that is interpreted to have ceased deposition coincident with event T1 (A.D.1700). The cobbles at the river bank are less common than in deflation plains to the south and could have an anthropogenic source. However, they also roughly coincide with the modeled run up pattern for tsunami. The dated log and stratigraphic relations indicate that the cobble deposits could reflect multiple tsunamis (at least from events T1 and T3 and likely others).

Sand dune deposits

Historical maps (United State Coast and Geodetic Survey) reveal the northern dune ridge that is currently eroding in the south bank of the Smith River, extended much farther north in 1870. East-facing cross bedded sands from the northernmost dune ridge complex exposed in the south bank of the river overlie the A.D. 1700 marsh deposits; this provides a maximum age for dune sands directly overlying the marsh. The now eroded northernmost extension of this dune ridge was less elevated in the 1870’s than ridges farther south. Its lower elevation and lesser volume suggests it was younger and had not received sediment for as long as the ridges to the south. The eroded dune segment was likely within the zone that was flattened by tsunami in A.D.1700, based on current modeling. From this I infer that a large dune ridge can form in about 150 to 200 years on the east side of the dune complex following tsunami (A.D.1700 – A.D.1870). This is a very rough estimate because the distance for the sand to travel to its stabilization location would vary based on the coastline configuration and the area of beach exposure following earthquakes. It also assumes a constant rate of dune migration, which has generally been accurate, with minor excursions, at historical decadal scales in the general vicinity of Humboldt Bay (c.f. Vaughan 2015).

Numerous OSL dates help constrain the age of the northeastern dune ridge complex; the following reports the full error range for the dates. Based on cross cutting relationships and topographic expression, western, central and eastern deposits comprise the topographic expression of the dune ridge complex. The crest of the western ridge has an age range of A.D. 1434 to 1634 (WD-C1) and the central ridge an age range of A.D.1034 to 1534 (MD-Silva1). These two dates are in stratigraphically correct order as the dune complex should age toward the east. Assuming the source of the sand was a tsunami flattened/earthquake deformed beach and it takes ~ 150 to 200 years to create a notable ridge on the east side of the beach and dune complex this would indicate that the western dune ridge's sand source was exposed sometime between ~ A.D. 1234 and A.D.1484. This would be compatible with event T2 and T2a and most likely T2a based on the overlap of the age ranges and the best estimated age of the sand dune crest stabilization (~A.D.1534), about 185 years after the best estimate for the T2a earthquake (A.D. 1349). Similarly, the central ridge sand source would have been exposed between ~ A.D. 834 and A.D. 1384, compatible with events T2a, T3 and T3a. Based on the overlap of the age ranges and the best estimated age of the central dune ridge stabilization (~A.D. 1284), it best correlates with event T3, about 135 years earlier (A.D. 1149). It would be interesting to estimate the volume of the sand dune units, similar to the volumes for turbidites estimated by Goldfinger et al. (2012), to help calibrate the magnitude (and related area of beach disturbance) of the respective earthquakes. The beach and dune cobble dates support evidence for a T3 earthquake that could have generated the central dune. In plan view this unit has more area than the western dune, which is compatible with the relative size of the T3 and T2a earthquakes based on their estimated rupture length.

The eastern dune deposit has both internally consistent and conflicting data to support its age estimate. OSL dates from the dune eroding in the south bank of the Smith River are about A.D. 664 to A.D. 1224 (best estimate of A.D. 944) at a depth about 4+ meters below the crest (SRD-M1) and about A.D. 884 to A.D. 1284 (best estimate of A.D. 1084) at a depth about 1 meter below the crest (SRD-C1). These ages are stratigraphically correct for the specific dune and are also consistent with aging of the dune complex toward the east. Unfortunately, this particular dune, which aligns with the eastern dune complex, is a proxy for the dune that underlies Yontocket Cemetery, where sampling was not permitted. This particular dune does not have dunes to the west that would inhibit welding of younger sediments. There is evidence for younger sands overlying the well dated marsh deposit exposed in the south bank of the Smith River, which constrain much of the dune to be no older than A.D. 1700. Exposure of the internal dune structure at the OSL dating sites does not support welding at that location, though it cannot be precluded on the west side of the dated ridge. However, even the OSL dates appear to be located in an area that would be no older than A.D. 1700, unless the marsh deposit terminates abruptly to the south, below the OSL dated sands (the southern extent of the marsh deposit is unknown due to its burial by sand at this location). That said, the OSL dates at this site are compatible with the maximum age for the base of the east side of the dune complex suggested by radiocarbon dates at Crescent Slough (A.D. 889 to A.D. 994). Because of the conflicts I considered the entire possible range for the age of the segment of the eastern dune ridge adjacent to the Smith River, though the other limiting ages from nearby sites better constrain the age of the eastern dune ridge unit farther south.

Using similar earthquake correlation methodology for the eastern dune based on estimates of migration rate, its crest stabilization at the OSL dated site is consistent with a sand source exposed between A.D. 664 and A.D. 1074. This would be compatible with events T3a, T4 and T4a. The best estimate for stabilization of the sand dune crest (A.D. 1084) is most consistent with correlation to event T3a (best estimate of A.D. 874), which occurred about 210 years before crest stabilization near the Smith River.

The south side of the park has a number OSL dates on sand dunes as well. A prominent scarp, interpreted as the back edge of a marine terrace (a paleo coastline), backs the more recently active beach and dune complex south from Lake Earl (Figure 7). The scarp is partially buried by sand dunes. Dating the sand dunes would limit the timing of potential recent erosion of the scarp by tsunami. Two sets of dunes were dated: the northern dune set, closer to Lake Earl, consists of two separate dunes on either side of the scarp. The southern dates were obtained on the crest of a linear dune, the remnant wing of a parabolic dune front that travelled farther to the southeast. The linear dune continuously buries the projection of the scarp between the two dated sites. Based on their dune morphology and distance from the coastline, the proximity of the northern site to potentially greater tsunami energy (erosivity potential) due to lesser surface roughness, more accommodation space and additional freshwater volume closer to lakes Earl and Tolowa, the southern dates are expected to be older.

Unfortunately, there was either a sample labeling error in the field or a reporting error from the laboratory for these sites. The reported dates were almost identical for each site (2 dates for each site, total of 4) with the exception that two of the dates appeared to be inverted based on location. I regarded the laboratory reported ages as highly improbable, as the dates required stratigraphically incorrect relationships based on distance from the beach (linear dune on the west side of the scarp was reported ~ two times older than on the east side). Yet there were two sets of ages that were nearly identical. The geomorphology suggests younger ages for the northern dunes. I interpreted samples LES-R1E (A.D. 1484 to A.D. 1684) and LES-S1W (A.D. 1474 to A.D. 1694) to be paired for the northern set of distinct dunes on either side the scarp. LES-R1W (A.D. 974 to A.D. 1274) and LES-S1E (A.D. 964 to A.D. 1304) are paired at the linear dune. I am unable to determine which date is specific to which sampling site but the dates likely reflect the accurate age ranges for each of the two general features. The total error for each paired feature suggests that the northern dune set could be associated with events T2 or T2a. The southern linear dune could date to events T3, T3a, or T4. Correlation based on overlap and best estimates shows the northern dune set had event T2 for its source (A.D. 1456, with 139 years of migration and accumulation) while the southern, linear dune is best associated with event T3a (A.D. 874, with ~266 years of migration and accumulation). The best estimates suggest that tsunami from event T1 did not scour the scarp at the northern site and that tsunami erosion has not scoured the scarp south from the linear dune since event T3a, even though the southern site is at the distal end of modeled tsunami run up under current conditions (Figure 4).

In the southeastern corner of the park, Michaela Spiske (unpublished data 2013) used OSL to date a large active sand dune (South Dune) that, based on air photo evidence for a log pond and a road to nearby Dead Lake, and historical accounts, likely was reactivated following logging in the late 1800's or early to mid-1900's. The dune shows progressively older ages with depth that range in age from about A.D. 1396 to A.D. 1878 (samples CRE 5a, 5b, 3a, 3b). Active sections of the dune have been buried approximately within the last decade (CRE 6). South Dune is too far from the coast to be associated with fresh sand exposures associated with tectonically driven beach disturbances evaluated here. The dates indicate that some sand migration could have been ongoing on the eastern edges of the current forest but the shallow burial depths of the dated sites indicate the sand was moving either in thin sheets and/or intermittently. Its distance from the coast suggests the bulk of South Dune could date to earlier tectonic or climatic events (mid-late [?] Holocene based on estimated migration rates) but more specific determination is beyond the scope of this analysis.

Other than the dune and beach deposits that are exposed in the south bank of the Smith River there is no numeric age control for dunes that likely directly correlate with event T1. However, it is assumed that the more active dune complex between the dune ridges to the east and the coast partially result from changes in the beach and dunes during the A.D. 1700 earthquake and tsunami. Ages for dunes in those locations are derived from cross cutting relationships and some historic imagery that indicate some of these features were active in the mid-20th Century. Charcoal from a hearth eroded by surf from the foredune near Sweetwater Creek has a high probably for post-dating event T1 (CAMS-114834), indicating the lower elevations of the foredunes in the southern part of the park post-date that earthquake.

Fluvial terrace deposits

Terraces in Sweetwater Creek, on the south side of the park, likely date to fluvial deposition related to base level changes associated with early-mid Holocene sea level rise.

Marine terrace deposits

Polenz and Kelsey (1999) used soil chronology, aminostratigraphy and well data to help determine the ages and elevations of late Pleistocene marine terrace deposits that underlie dune sheets in the southeast side of the park. Comparisons with soils from dated terraces, and the elevations of the terraces' back edge, eroded at well age constrained late Pleistocene sea levels, help define the various terrace ages.

Criteria for map units age ranges (in years before A.D. 2015)

0-145 (A.D. 1870 to A.D. 2015) – This unit reflects the accreting foredune crest west from the 1870 coastline mapped by Hapke et al (2006), that bounds the west side of the foredune complex. This coastline position is also noted on Figures 6 and 7 to help portray where the coastline has eroded.

0-315 (A.D. 1700 to A.D. 2015) - This unit is localized to the nearby terrace surface of the Smith River and to areas a short distance inland from breaches in the foredune. At the Smith River, the surface is underlain by a marsh deposit that is well constrained in its upper section by radiocarbon dating as having a change in depositional style and soft sediment deformation interpreted to date to the A.D. 1700 Cascadia earthquake. At the breached sections of the foredune, cobbles inland from the breaches generally date to the last major tsunami (see Tsunamis and Coastal Flooding sections). The younger end of the range reflects fluvial and coastal flood deposits that post-date the 1964 flood.

0-1450 (A.D. 565 to A.D. 2015) – This range reflects deposition within the sloughs east from the dune ridge complex in the north east side of the park. The sloughs are still actively depositing materials. The older end of the range reflects the approximate maximum for radiocarbon dates on bulk soils reported by Bicknell and Austin (1991).

50-315 (A.D. 1700 to A.D. 1965) - The younger end of this range reflects the coastal breach and fluvial terraces areas thought to be inundated by the 1964 flood and likely the 1861-1862 flood, primarily between the Smith River and Lake Earl and south of the Smith River and west of the northernmost dune ridge. See 0-315 for the older end of the range.

80-150 (A.D. 1865 to A.D. 1935) – This dune complex had active dunes apparent in air photos dating to the mid-20th century. The older end of the range reflects cross cutting limiting ages determined from onlap onto dunes that have numerical age control and to a limited extent, deposition over presumed A.D. 1700 tsunami run up zones. 150 years also reflects the approximate minimum time needed for significant dune formation assumed to have occurred following the A.D. 1700 tsunami, based on historical maps.

110-315 (A.D. 1700 to A.D. 1905) – The older end of the range primarily reflects foredune recovery since the landform was presumably flattened by the A.D. 1700 tsunami. The younger end of the range reflects dune stabilization by vegetation associated with cattle grazing.

315-1350 (A.D. 665 to A.D. 1700) – The maximum of this unit's age range approximates the maximum error for event T4 (A.D. 672) reported by Goldfinger et al. (2012) while the minimum end of the range reflects the presumed last major tsunami in A.D. 1700. Earthquake T4a could also be a trigger for deposition of this unit but its age range is less consistent with other dates that help constrain the age of eastern dunes. The landward extent of the unit is generally compatible with the CGS modeling for tsunami run up but the mapping is also guided by radiocarbon and OSL dating results. I also used this unit to characterize the northernmost dune ridge that is being eroded by the Smith River (dune "X" on the inset of Figure 6). This dune unit had internally consistent radiocarbon dates and internally consistent OSL dates that conflicted and so the entire range of ages from this site of dates was used to characterize this particular dune. OSL and radiocarbon dates on the western beach and dune complex interpreted to date to event T3 indicate that evidence of pre-T1 tsunami events survived subsequent tsunami, allowing a greater maximum age for the unit.

330-530 (A.D. 1485 to A.D. 1685) - The range reflects the best estimate and error range for an OSL date on a relatively distinct dune form; the range is also constrained by older dated landforms onto which they overlap and is consistent with their geomorphic position on the distal end of presumed tsunami run up. The range is consistent with time needed to form significant dunes following presumed beach flattening (and sand exposure due to vegetation exposure and possibly due to uplift) during the T2 earthquake/tsunami.

510-980 (A.D. 1035 to A.D. 1505) - This range reflects OSL dating of a dune crest in the middle of the dune ridge complex. It is also constrained by ages for adjacent dune landforms and cross cutting relationships. The range is consistent with time needed to form significant dunes following presumed beach flattening (and sand exposure due to vegetation exposure and possibly due to uplift) during the T3 earthquake/tsunami.

730-1350 (A.D. 665 to A.D. 1285) – This age range reflects limiting radiocarbon dating of Crescent Slough, which interfingers with the easternmost dune ridge, and constraints from OSL and radiocarbon dating of surrounding landforms that overlap or constrain the unit's age. Ponds on the east side of the dune ridge were also investigated but marsh deposits obtained on the pond margins post-dated A.D. 1660 and are only useful as limiting minimum ages for the dated pond. However, large gravel in one of the cores indicate that the ponds were probably underlain by fluvial deposits. Sloughs and drainages to the east project toward the ponds, which are now surrounded by dunes, indicating that the ponds are remnants of fluvial channels now overrun by dunes. The range is consistent with time needed to form significant dunes following presumed beach flattening (and sand exposure due to vegetation exposure and possibly due to uplift) during the T4 earthquake/tsunami. This unit encompasses the Yontocket Cemetery (see inset on Figure 6), which was one of the original foci of this study; however, we were unable to directly access this site for dating because of cultural concerns. A best estimate for the ground surface age of the cemetery location is about A.D.1000 to A.D.1100 based on radiocarbon dating of the base of the dune and OSL dating of the dune crest at the Smith River.

5,000-10,000 (B.C. 3,000 to B.C. 7,000) - This unit is localized to a small valley fill associated with Sweetwater Creek at the inferred fault in the southern park and to an apparent abandoned terrace surface at the south end of Lake Earl. This unit is assumed to reflect deposition associated with rising base level controls as sea level rose during the early-mid Holocene.

60,000 (B.C. 58,000) – This unit is localized near the paleo coastline in the southern part of the park and at the south end of Lake Earl (Figure 7). It appears as a discrete terrace surface on the LiDAR imagery. The age assignment is very provisional as it requires a slightly higher uplift rate on the southern syncline limb than estimated by Polenz and Kelsey (1999) to fit into marine terrace sequences found along the Pacific coastline.

80,000 (B.C. 78,000) - This marine terrace surface is inland from the paleo-coastline in the southern part of the park. Its geomorphic surface projects under a Holocene dune deposit mapped by Polenz and Kelsey (1999). Though they mapped a continuous dune at this location I interpret the generally flat surface as a marine terrace that may have more than 2 meters of topographically poorly defined dune sand. Locally, younger, better defined dunes overlie the terrace surface.

105,000 (B.C. 103,000) - This marine terrace surface is inland from the paleo coastline in the southern part of the park. Its geomorphic surface projects under a Holocene dune deposit mapped by Polenz and Kelsey (1999). Though they mapped a continuous dune at this location I interpret the generally flat surface as a marine terrace that may have more than 2 meters of topographically poorly defined dune sand. Locally, younger, better defined dunes overlie the terrace surface.

CONCLUSIONS

The timing of changes in depositional regimes, interpreted from exposures of the south bank of the Smith River, are well constrained and coincide with well-dated Cascadia earthquakes. This, paleo-environmental evidence and dates from slough deposits, folded marine terrace surfaces, and the roughly coincident exposure of tsunamigenic cobbles and tsunami run up modeling, indicate that landforms at TDSP have been strongly affected by late Pleistocene to latest Holocene tectonic processes. Radicarbon and OSL numerical age control, aminostratigraphy, soil chronostratigraphy, and historical information help constrain the ages of landforms that are influenced by these processes. From this, maps of the estimated ages of the landforms have been developed that can be used to guide cultural assessments necessary to assess risk of information loss due to climate influenced sea level rise and tectonic processes. The dynamic nature of this coastline could accentuate or help defeat the effects of sea level rise at specific locations throughout the park and these effects could vary over time due to interseismic deformation of the ground surface.

This concludes this report.

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Appendix A

Compilation of Historical, Radiocarbon and Optically Stimulated Luminescence Data from Tolowa Dunes State Park (excluding Point St. George)

Date reported	Submitter	Field Sample #	Lab number	Laboratory	Material	Geomorphic position	Exposure	Northing	Easting	Measured RC age	Conventional age	2 sigma calibration (yr before 1950)	13C/12C
Radiocarbon													
1991	S. Bicknell/Austin	LE CORE 2	ND	ND	Bulk sediment	Slough	Auger Core~57 cm bgs	4640283*	400732*	ND	780+80	ND	ND
1991	S. Bicknell/Austin	LE CORE 2	ND	ND	Bulk sediment	Slough	Auger Core~104 cm bgs	4640283*	400732*	ND	1260+130	ND	ND
4/13/2005	S. Tushingham	CA-DNO-XX7	CAMS-114834	Lawrence Lab	Charred wood	Hearth in dune	Ocean cut	4628571	397180	165±50	ND (AMS)	60-293 (.826); -3 to 42 (.174)	-25
4/13/2005	S. Tushingham	CA-DNO-22	NOS-83588	National Ocean Sciences	Clam	Hearth in dune	Ocean cut	4628571	397180	860±25	ND	171***	ND
4/13/2005	S. Tushingham	CA-DNO-22	NOS-83589	National Ocean Sciences	*Mytilus califomianus*	Hearth in dune	Ocean cut	4628571	397180	765±35	ND	109***	ND
4/13/2005	S. Tushingham	CA-DNO-22	NOS-83590	National Ocean Sciences	*Mytilus californianus*	Hearth in dune	Ocean cut	4628571	397180	750±40	ND	730***	ND
1/5/2009	P. Vaughan	BE-YON1-02	Beta-253110	Beta Analytic	Wood	Floodplain/Marsh#(mid?)/Fluvial	Stream Bank	4640628	400930	250±60	250±60	0-30;140-220;260-470	-24.6
2/17/2009	P. Vaughan	T4-YON1-U1	Beta-254903	Beta Analytic	Charred material	Floodplain	Test Pit	4640496	400813	140±40	130±40 (AMS)	0-280	-25.5
2/17/2009	P. Vaughan	T3-YON1-U5	Beta-254904	Beta Analytic	Wood	Floodplain	Test Pit	4640337	400816	80±40	50±40	post 1950;30-140;220-260	-27.2
10/22/2010	J. Meyer	DNO-5Cu-400	Beta-285155	Beta Analytic	Wood	Floodplain/Dune/Marsh/Fluvial/Marsh#(?)	Stream Bank	4640852w	400656w	570±60	560±60 (RC extended count)	510-660	-25.9
10/22/2010	J. Meyer	DNO-4Cu-300	Beta-285154	Beta Analytic	Wood	Floodplain/Marsh# (base)	Stream Bank	4640581w	401132w	550±50	560±50	510-660	-24.3
10/22/2010	J. Meyer	DNO-3Ab-150-160	Beta-285153	Beta Analytic	Charred material	Hearth in marsh	Stream bank	4640798w	400713w	300±50	330±50 (RC extended count)	290-500	-23.3
3/22/2011	J. Meyer	CRPD-CR1BS-193	OS-86025	National Ocean Sciences	Bulk sediment	Slough#/Dune	Auger Core ~193 cm bgs	4639015	400957	1100±25	1100±50	956-1061 (median prob 945 AD)	-28.1
4/6/2012	P. Vaughan	YCEM-COR1-41	Beta-319252	Beta Analytic	Charred material	Floodplain	Auger Core~41 cm bgs	4640178	400770	90±30	60±30 (AMS)	post 1950;30-80;90;100-110;110-140;220-260	-26.9
4/6/2012	P. Vaughan	EP2-COR1-50	Beta-319251	Beta Analytic	Wood	Marsh#/Dune	Auger Core~50 cm bgs	4637544	400728	170±30	170±30 (AMS)	post 1950-30;70-120;140-230;250-290	-25.1
4/6/2012	P. Vaughan	EP1-COR1SD35	Beta-319250	Beta Analytic	Seeds	Marsh#/Dune	Auger Core~35 cm bgs	4638879	400850	125.4±0.5 pMC	125±0.5 pMC (AMS)	post 1950	-24.9
4/6/2012	P. Vaughan	BE-YON2-01	Beta-319249	Beta Analytic	Charred material	Dune/Marsh#	Stream bank	4640850	400648	140±30	170±30 (AMS)	post 1950-30;70-120;140-230;250-290	-23.2
4/13/2012	P. Vaughan	TOLN-LOG1-1	Beta-319254	Beta Analytic	Wood	Beach#/Dune	Log at Surface	4640501	400117	810±30	840±30	690-790	-22.9
4/13/2012	P. Vaughan	BE-YON2-02	Beta-319253	Beta Analytic	Wood	Dune/Floodplain#/Marsh	Stream Bank	4640697	400827	310±30	310±30	300-470	-25.1
5/2/2012	P. Vaughan	EP1-COR2WD35	Beta-320743	Beta Analytic	Wood	Marsh#/Dune	Auger Core~35 cm bgs	4638879	400850	110.6±0.3 pMC	111.7±0.3 pMC (AMS)	See Beta curve - 1957;1993-1996;1996	-30
5/2/2012	P. Vaughan	CRPD-CR1GB-68	Beta-320742	Beta Analytic	Grass blade	Slough#/Dune	Auger Core~68 cm bgs	4639015	400957	230±30	190±30 (AMS)	post 1950-30;140-220;260-300	-27.2
5/21/2012	P. Vaughan	KESBG-TP1R26	Beta-320744	Beta Analytic	Root	Back Beach Bog	Test Pit~26 cm bgs	4635089	399519	105.6±0.3	106.2±0.3 pMC (AMS)	post 1950	-30.2
6/24/2013	P. Vaughan	BEMEYER-A275	Beta-350388	Beta Analytic	Wood	Floodplain/Marsh#(base)/Fluvial	Stream Bank	4640588	401174	620±30	620±30 (AMS)	540-660	-24.7
6/24/2013	P. Vaughan	KESBGTP1BS26	Beta-350389	Beta Analytic	Bulk sediment	Back Beach Bog	Test Pit~26 cm bgs	4635089	399519	102.4±0.4 pMC	102.8±0.4 pMC	post 1950	-26.9
6/24/2013	P. Vaughan	PANEL38N2P1	Beta-350390	Beta Analytic	Peat/plant	Floodplain/Marsh#(top)/Fluvial	Stream Bank	4640660	400882	240±30	140±30 (AMS)	post 1950; 0-50;60-150;170-280	-31.1
6/24/2013	P. Vaughan	PANEL86N4	Beta-350391	Beta Analytic	Wood	Dune/Fluvial#/Dune&Marsh	Stream Bank	4640852	400645	240±30	190±30 (AMS)	post 1950-30;140-220;260-300	-28.1
Historical													
9/26/2012	P. Vaughan	Panel 39	ND	ND	Barbed wire	Floodplain	Stream Bank ~200 cm bgs	4640664	400877	NA	Historical	NA	NA
10/28/2011	P. Vaughan	YCEM-COR2	ND	ND	Beer glass	Floodplain	Auger Core~ - 45 cm bgs	4640211	400749	NA	Historical	NA	NA
OSL										**Years before 2014**	**Depth**	**Comment**	
5/2/2012	M. Spiske	CRE 3b	ND	Univ. Munich?	Sand	Dune	Pit (?)	4626920	398160	153±18&	0.35 m bgs		
5/2/2012	M. Spiske	CRE 3a	ND	Univ. Munich?	Sand	Dune	Pit (?)	4626920	398160	474±55&	0.75 m bgs		
5/2/2012	M. Spiske	CRE 5a	ND	Univ. Munich?	Sand	Dune	Dune Bank	4626847	398153	280±32&	0.4 m bgs		
5/2/2012	M. Spiske	CRE 5b	ND	Univ. Munich?	Sand	Dune	Dune Bank	4626847	398153	523±94&	0.9 m bgs		
5/2/2012	M. Spiske	CRE 6	ND	Univ. Munich?	Sand	Dune	Pit (?)	4626804	398188	12±3&	0.6 m bgs		
8/7/2014	P. Vaughan	LES-S1E	LS1432	Laber Scientific	Sand	Dune	Pit	4629676	398756	880±170**	1 m bgs	Dates, geo. position and content indicate reporting error	
8/7/2014	P. Vaughan	LES-R1W	LS1433	Laber Scientific	Sand	Dune	Pit	4629282	398307	890±150**	1 m bgs	Dates, geo. position and content indicate reporting error	
8/7/2014	P. Vaughan	LES-R1E	LS1434	Laber Scientific	Sand	Dune	Pit	4629146	398331	430±100**	1 m bgs	Dates, geo. position and content indicate reporting error	
8/7/2014	P. Vaughan	MD-Silva1	LS1435	Laber Scientific	Sand	Dune	Pit	4638821	400426	730±250	1 m bgs		
8/7/2014	P. Vaughan	SRD-M1	LS1436	Laber Scientific	Sand	Dune	Stream cut	4640830	400654	1070±280	.6 m bgs, .8 m from cutface	Cut exposed in last 2 years - had slough at cut face	
8/7/2014	P. Vaughan	LES-S1W	LS1437	Laber Scientific	Sand	Dune	Pit	4629729	398694	430±110**	1 m bgs	Dates, geo. position and content indicate reporting error	
8/7/2014	P. Vaughan	SRD-C1^	LS1438	Laber Scientific	Sand	Dune	Stream cut	4640812	400657	930±200	1 m bgs, .2 m from cutface	^Lab reported sample as SND-C1; cut exposed last 2 years	
8/7/2014	P. Vaughan	BTC-L1	LS1439	Laber Scientific	Sand	Tsunami(?)/Dune#	Pit	4640503	400117	990±210	1 m bgs		
8/7/2014	P. Vaughan	WD-C1	LS1440	Laber Scientific	Sand	Dune	Pit	4640292	400521	480±100	1 m bgs		

* Location within ~30 meters based on P. Vaughan discussion with S. Bicknell ~2011

**Because of geomorphic relationships LES-S1E and LES-R1W are paired at 880-890 and LES-R1E and LES-S1W paired at 430. Lab reported dates, which appear to be in error, are listed in table.

*** Includes marine correction of -316+85

w = wgs1984 datum- all other data reported as UTMZ10 NAD83

\# = landform with dated sample

& - years before 2013